



A Grand Tour of the Ocean Basins by Declan G. De Paor, ddepaor@odu.edu

Welcome to the Grand Tour of the Ocean Basins! Use this document in association with the Google Earth tour which you can download from <http://geode.net/GTOB/GTOB.kml>. Ocean floor ages are from <http://nachon.free.fr/GE/>, based on Müller et al. (2008).

See earthbyte.org/Resources/agegrid2008.html. Plate boundaries are from Laurel Goodell's SERC web page: http://serc.carleton.edu/sp/library/google_earth/examples/49004.html based on Bird (2003) and programmed by Thomas Chust. Colors and line sizes were changed to improve visibility for persons with color vision deficiency, and I added other minor adjustments.

The Tour Stops are arranged in a teaching sequence, starting with continental rifting and incipient ocean basin formation in East Africa and the Red Sea and ending with the oldest surviving fragments of oceanic crust.

Transforms and fracture zones are introduced, also abandoned basins, convergent boundaries, and marginal basins. Instructors can easily change the sequence of stops to suit their courses using the Google Earth desktop app or by editing the KML file. Because large placemark balloons tend to obscure the Google Earth terrain behind them, you are advised to keep Google Earth and this PDF document open in separate windows, preferably on separate monitors or devices. Fig. 0 caption acknowledges all data and imagery sources.

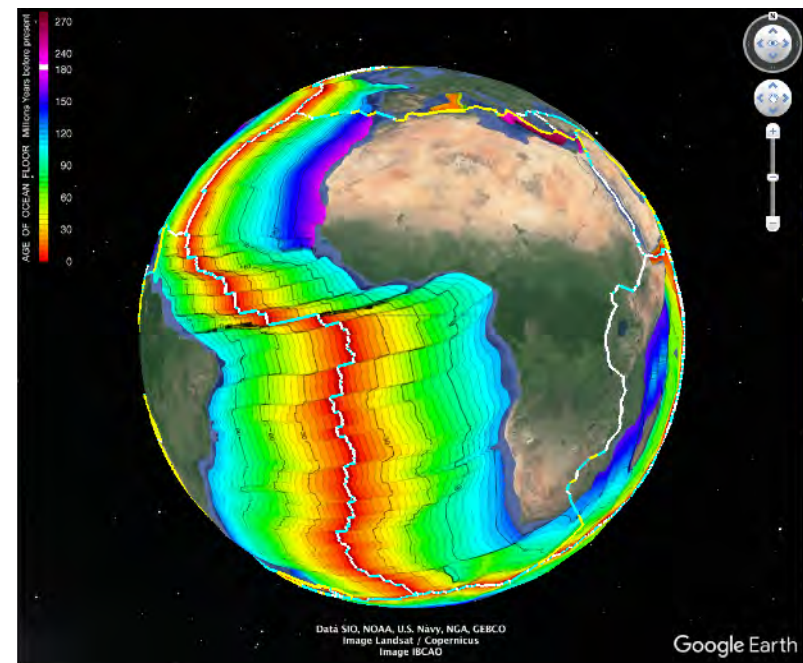


Fig. 0. Plate Tectonics on Google Earth. ©2017 Google Inc. Data SIO, NOAA, US Navy, NGA, USGS, GEBCO, NSF, LDEO, NOAA. Image Landsat/Copernicus, IBCAO, PGC, LDEO-Columbia.

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- Tour Stop 64: Alpine Fault
- Tour Stop 65: The End of an Ocean
- Tour Stop 66: Semail Ophiolite, Oman

Tour Stop 1: East African Rift

Africa is splitting apart along the East African Rift

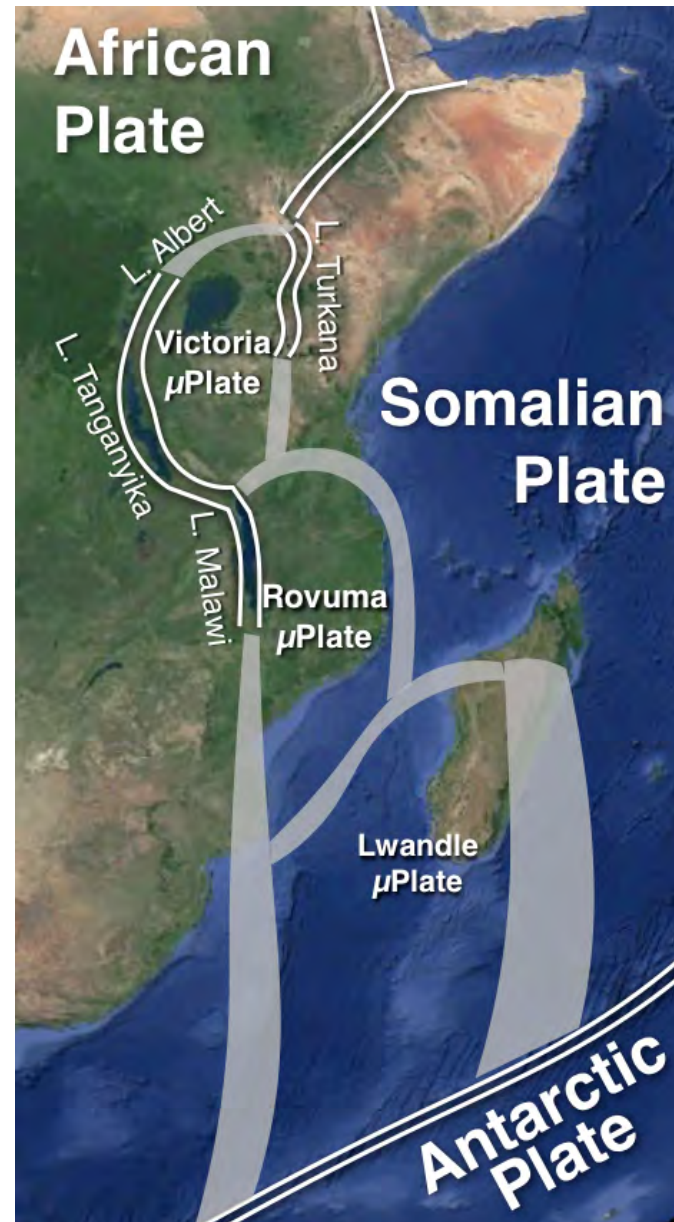
(Turn on Google Earth's earthquake and volcano layers)

It may seem odd to start a tour of Earth's oceans in the continental *East African Rift Valley* where humanity evolved (Fig. 1), but GPS readings, major earthquakes, and volcanism reveal that the Somalian Plate to the east of the rift is splitting away from the African Plate to the west, potentially giving birth to a new ocean in about 1 million years' time. Some authors call the western plate the Nubian Plate to conform to the tradition of renaming plate parts after fragmentation. However, the name African Plate seems more representative and continues to be more widely used.

The two branches of the rift valley are home to narrow elongate lakes such as Lake Albert, Lake Tanganyika, and Lake Malawi in the west, and Lake Turkana in the east.

The Somalian Plate includes three microplates—Victoria, Rovuma, and Lwandle, with slightly different GPS velocities. The boundaries are not well defined as they are zones of diffuse deformation. The major plates are thus not as rigid as originally envisaged in Plate Tectonic Theory.

Fig. 1. a) The East Africa Rift, plates, and microplates. Gray=diffuse deformation zones. Small transforms not shown.



Tour Stop 2: Rift Volcanism

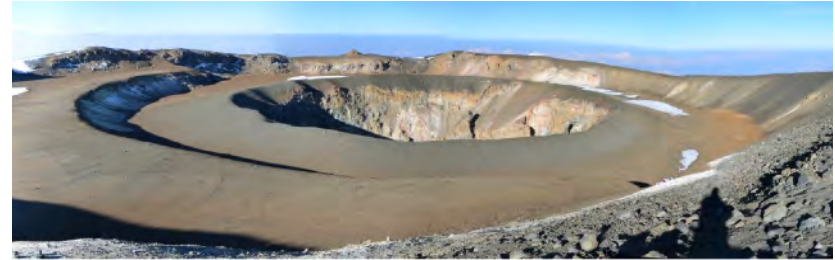
Rifting draws up the asthenosphere and leads to decompression melting

Famous rift volcanoes include Mt. Kenya and Mt. Kilimanjaro, Africa's tallest mountain, situated on the margin of the East African Rift (Fig. 2 a). Its lava flows include basalt, andesite (Fig. 2 b), and rhyolite.

As continental lithosphere rips apart, a drop in pressure leads to decompression melting and magma collects in magma chambers at the base of the thinned crust. Earthquakes open pathways for magma to rise to the surface and build volcanoes. Some magma cools in the crust to form dikes and some slowly solidifies to form gabbro in magma chambers, thickening the stretched lithosphere.

Mafic magma partially melts the continental crust through which it passes, causing *sodic*, and *felsic* contamination. These magmas are viscous and erupt violently to form pyroclastic andesite and rhyolite. Continental rift volcanoes can thus produce a range of rock types depending on the amount of crustal contamination.

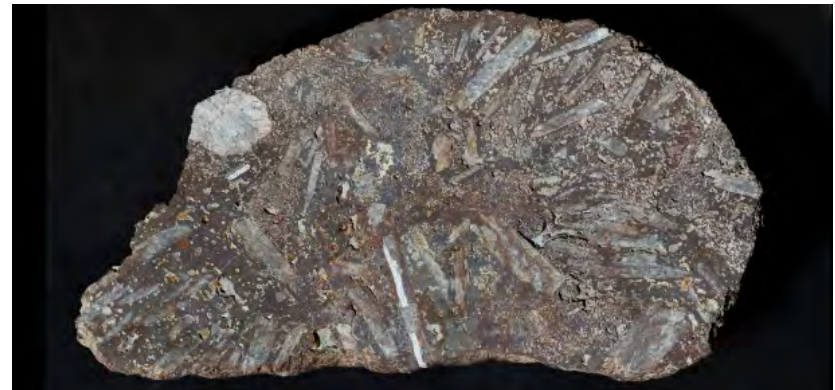
a)



<http://www.gigapan.com/gigapans/118049>

Source: Doug Hardy.

b)



<http://www.gigapan.com/gigapans/168843>

A GIGAmacro image of volcanic rock from the summit of Mt. Kilimanjaro scanned by Robin Rohrback.

Fig. 2. a) Summit of Kilimanjaro. b) A specimen from the Kibo volcanic cone. Click the links to view the GigaPans

Tour Stop 3: Mechanics of Rifting

Continental crust is too strong to rift all at once—rifting must propagate like tearing a piece of paper

Early models of rifting envisaged symmetrical steep normal faults. Today, we know that when you break the brittle lid of the lithosphere, the lower levels behave plastically, like the ductile toffee under the brittle chocolate in a Mars bar. The result is that extensional faults are spoon shaped or *listric* (Fig. 3 a). See this animation:

www.geode.net/GTOB/Rifting.mp4

There is a problem with this model of continental rifting, though. Calculations of the strength of continental lithosphere suggest it should be impossible to rift a continent. Thanks to GPS measurements, we know that Africa is indeed rifting apart so we conclude that if it does happen, it can! The means by which continental rifts initiate is a matter of on-going research. Mantle hotspots or prior tectonic events may weaken the lithosphere. But the main way to split a continent is like how you would tear a sheet of paper in half (Fig. 3 b). If you pull the sides all at once, it will not tear, but you can easily cause a tear to propagate laterally.

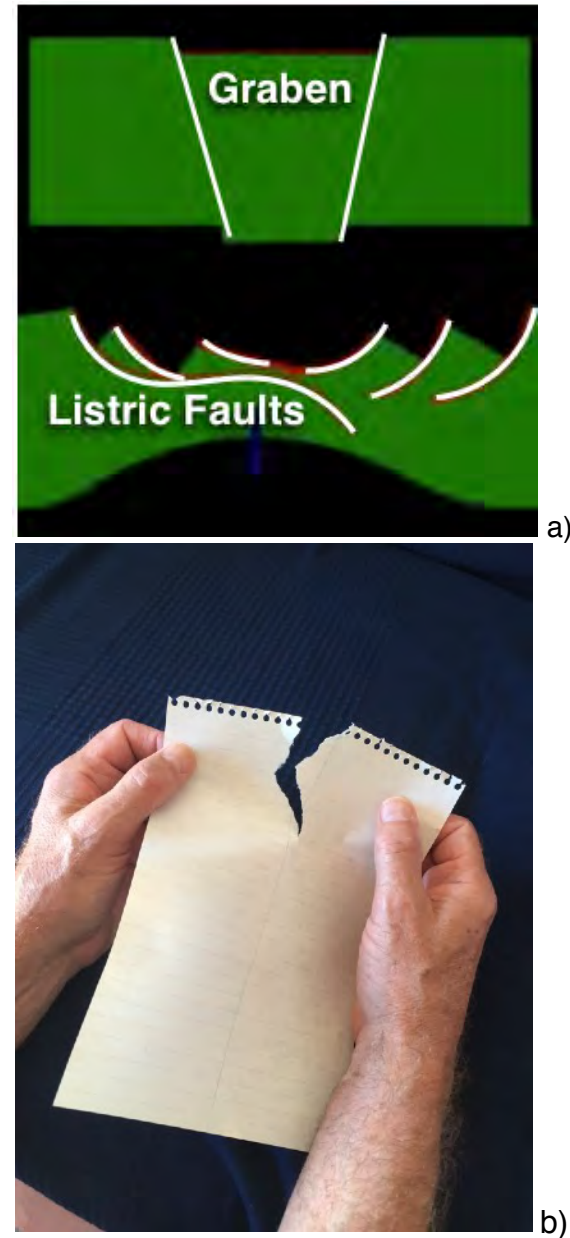


Fig. 3. a) Symmetric versus asymmetric rifting, from the author's animation above. b) Tearing a sheet of paper is analogous to propagating a rift. Photo: C. Simpson.

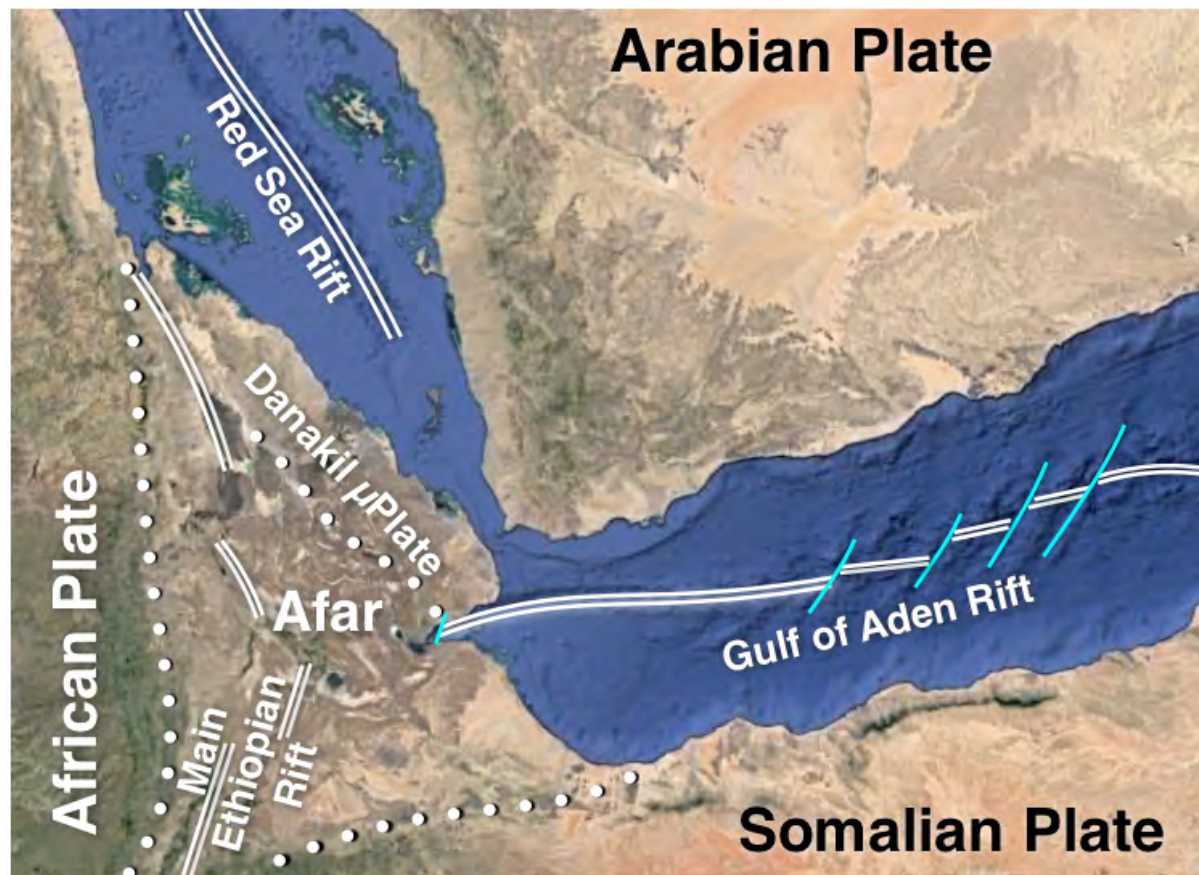
Tour Stop 4: Afar Triangle

The East Africa Rift, Red Sea, and Gulf of Aden meet at a rift-rift-rift triple junction centered on Afar, Ethiopia

The Afar Triangle is the only rift-rift-rift triple junction above sea level (Fig. 4). Its location is thought to be controlled by a mantle hotspot.

All plate movements can be described as a rotation about a pole of rotation. The Danakil Microplate rotated away from Africa creating the Afar Depression, the lowest topographic elevation in Africa.

Fig. 4. The Afar Triangle on Google Earth outlined by dots.



Tour Stop 5: Oceanic Core Complexes

Very slow-spreading ocean basins may extend by detachment faulting and oceanic core complex formation

Even when divergence and rift propagation succeed in ripping apart a continent and creating oceanic crust, there is no guarantee it will continue to grow into a major ocean basin. At very slow spreading ridges, there may not be enough upwelling to supply the necessary new crust through volcanism. In these settings, oceanic core complexes can form (Fig. 5)—ridges up to 150 km long where lower crust and upper mantle has been exhumed on low-angle normal faults called oceanic detachment faults.

It is important to prefix the adjective “oceanic” because there are very different core complexes and detachment faults on the continents, as in the Basin and Range Province of western North America.

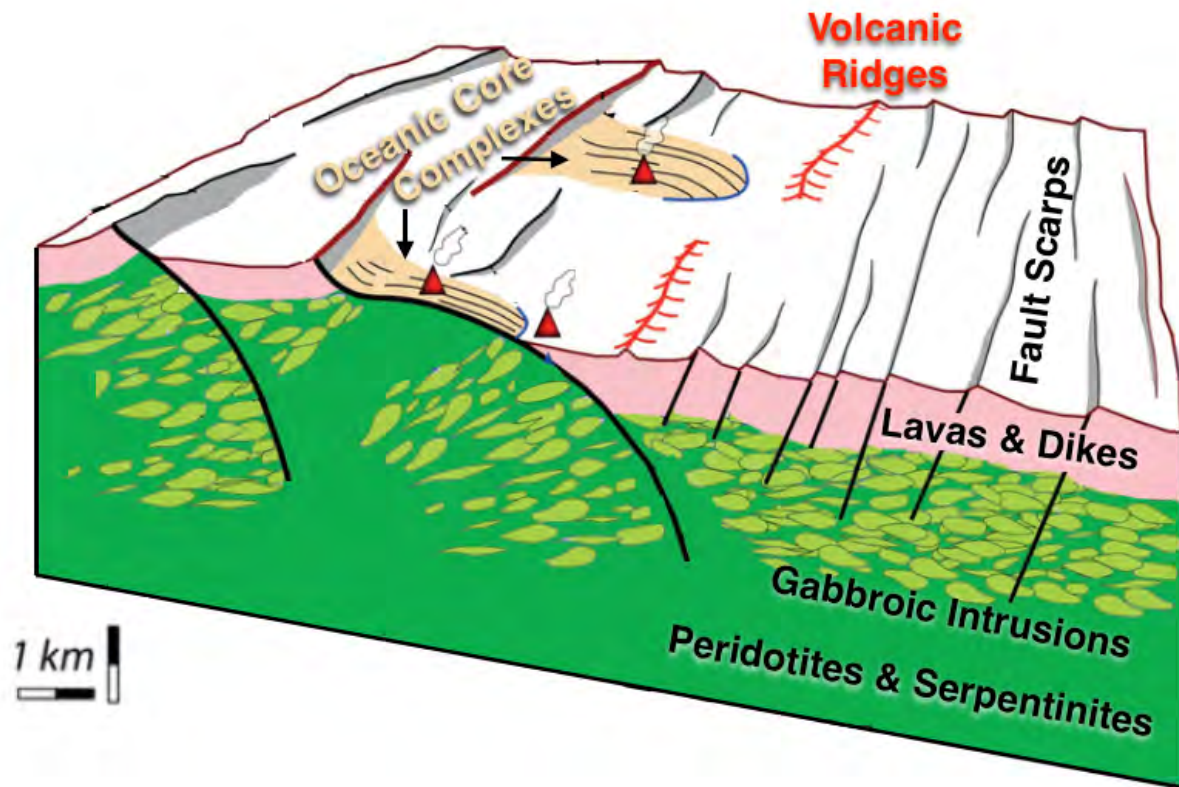


Fig. 5. Oceanic core complexes. Simplified from Maffione et al. (2013).

Tour Stop 6: Gulf of Aden

The Gulf of Aden has 30 m.y. old oceanic crust

Compared to the East Africa Rift, extension is more advanced in the Red Sea, and even more so in the Gulf of Aden (Fig. 6).

Red Sea crustal extension began about 45 million years ago. Continental crust stretched to its limit and new ocean floor began to form 3 to 4 million years ago. Magnetic stripes, and by implication ocean floor ages, are not well defined but magma no longer passes through significant continental crust so the nascent mid-oceanic ridge is basaltic.

An older, wider passive-margined basin is represented by the Gulf of Aden east of Afar, where new oceanic crust injects between Somalia and Arabia. Here the mid-ocean ridge is well established over 30 million years and there is geochemical evidence of black smokers.

The western Indian Ocean, also called the Arabian Sea, is wider and older than the Gulf of Aden. Before the Gulf opened, there was a long transform boundary between the combined Somalian-Arabian Plate and the Indian Plate. India moved rapidly along that transform on its path to collision with Eurasia, throwing up the Himalayan Mountains. Today, the Somalia-India boundary

is represented by the Owen Transform Fault and Fracture Zone. However, the Arabian-Indian relative motion is so slow that these two plates may be classified as a single Arabian-Indian Plate.

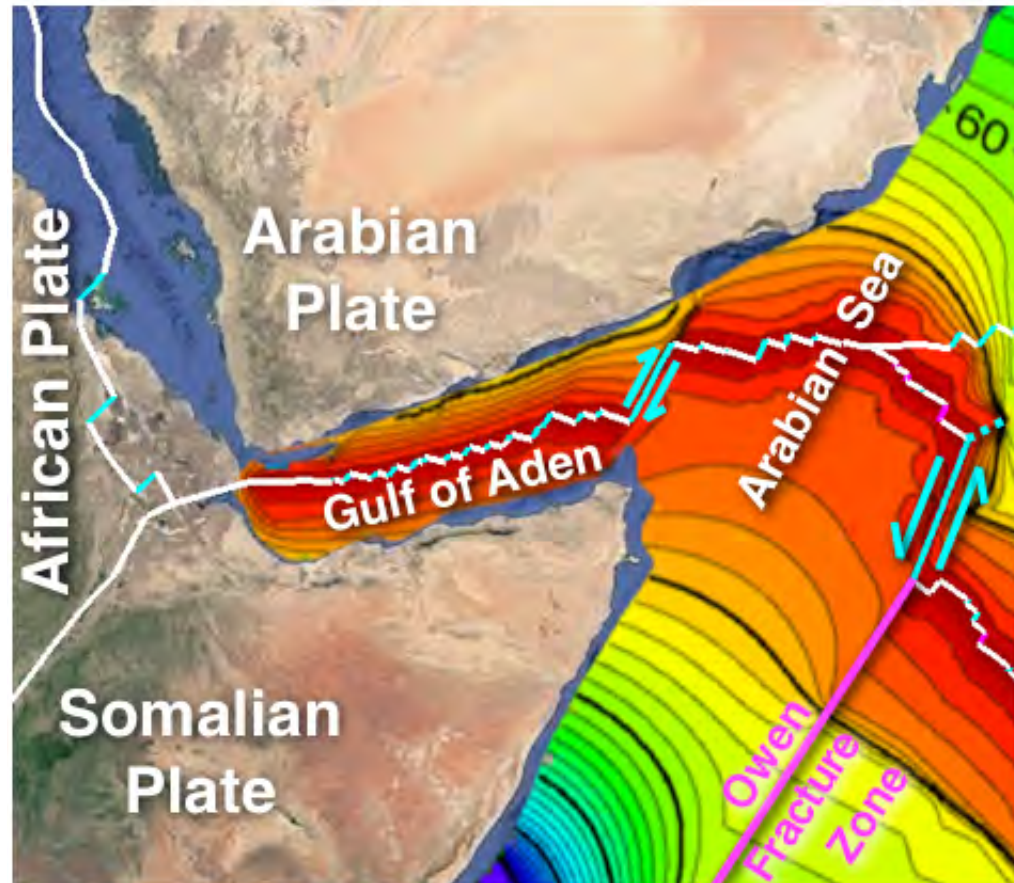


Fig. 6. Gulf of Aden and Arabian Sea.

Tour Stop 7: Western Indian Ocean

The western Indian Ocean has two passive margins

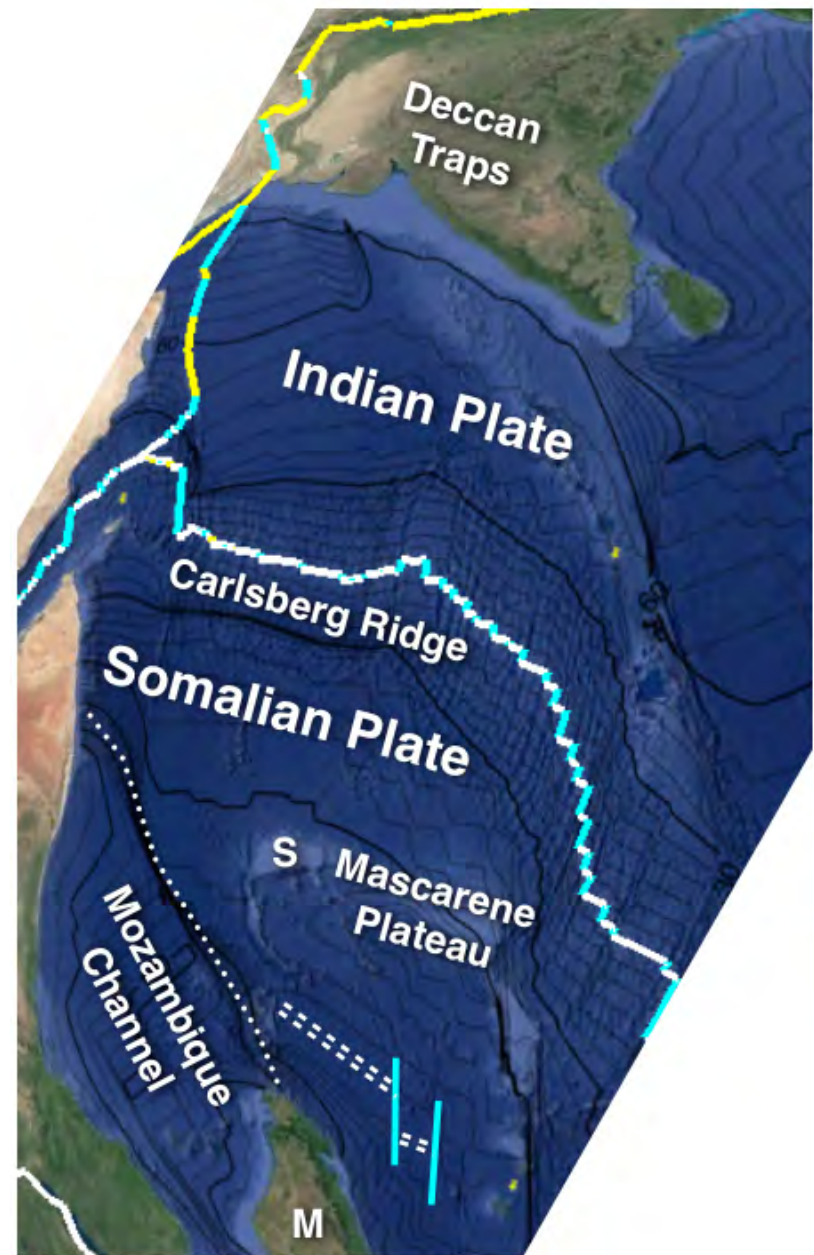
[Turn off the isochrons folder to see the Arabian sea floor]

In the Arabian Sea, also called the Western Indian Ocean Basin, the Somalian and Indian Plates are spreading away from the Carlsberg Ridge (Fig. 7). Rifting between India and the submerged Mascarene Plateau began over 60 million years ago. The Seychelles (S) are a subaerial emergence of that plateau. Precambrian granites and flood basalts show that this is not an oceanic plateau, but rather a fragment of continental crust that rifted from the Deccan Traps region of India during the breakup of Supercontinent Pangea. Prior to that rifting, there was seafloor spreading between the Mascarene Plateau and Madagascar, as indicated by an abandoned rift (dashed double lines at bottom of Fig. 7).

Turning the ocean ages back on, note the sudden change in age and direction of seafloor spreading in the Mozambique Channel west of the dotted line in Fig. 7, as discussed in the next tour stop.

Fig. 7. The Arabian Sea's Carlsberg Ridge separates the continental crust of India and the Seychelles. A wide region of continental crust called the Mascarene Plateau is submerged.

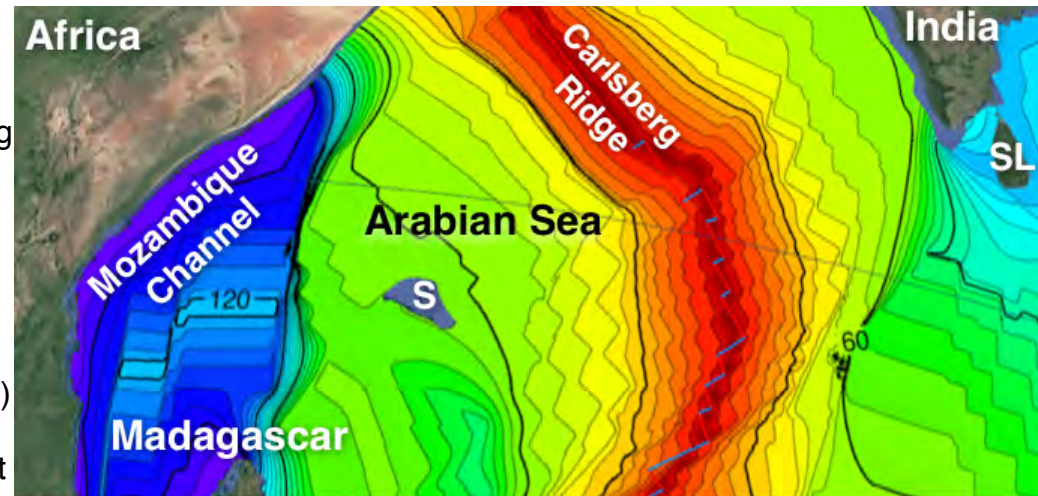
M=Madagascar. S=Seychelles. Dashed lines are an abandoned ridge. Dotted line is boundary of Mozambique Channel.



Tour Stop 8: Mozambique Channel

Mozambique Channel formed as Madagascar rifted away from Africa

The united continental crust of Madagascar, Seychelles, and India rifted from the African continent about 165 m.y. ago (Fig. 8 a), creating oceanic crust in the Mozambique Channel. About 120 m.y. ago, spreading in Mozambique Channel ceased and about 90 m.y. ago, Madagascar migrated over the Marion mantle hotspot and began to separate from the Mascarene Plateau. The lithosphere under Madagascar may have delaminated (peeled off) as a result of its passage over the hotspot resulting in recent volcanism despite the ancient nature of the microcontinent. Old, cold lithosphere sank, replaced by hot mantle causing volcanism (Fig. 8 b).



a)

b)

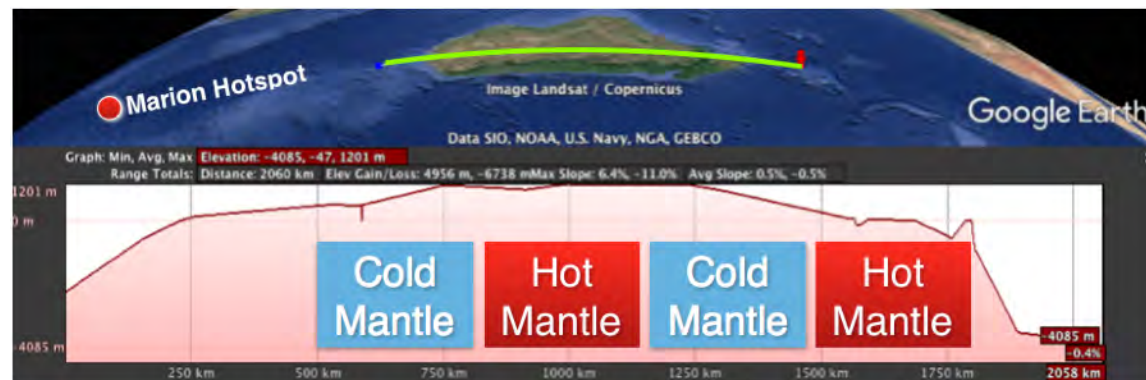


Fig. 8. a) The Mozambique Channel. Blue colors west of Madagascar are the oldest sea floor. Reds in the Arabian Sea are the youngest. b) Profile showing hot mantle feeding Madagascar's recent volcanism and elevation.

Tour Stop 9: Eastern Indian Ocean

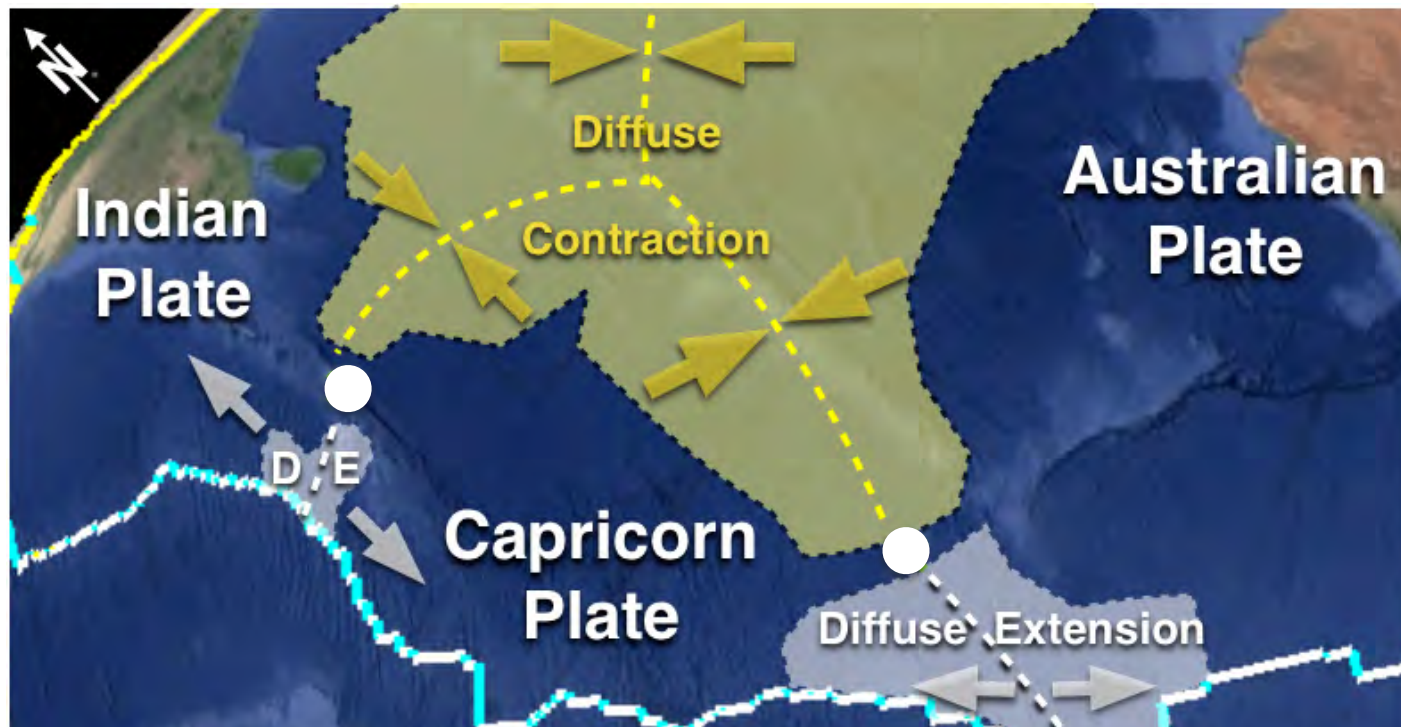
This region has wide zones of diffuse deformation

[Turn off the ocean ages to view this frame].

The Indian and Australian Plates were long referred to as one Indo-Australian Plate, but GPS data and strong earthquakes suggest that in fact three plates—Indian, Australian, and Capricorn—are moving somewhat independently with large regions of diffuse deformation separating them (Fig. 9). India's collision with Eurasian

slowed its forward motion, causing the Australian and Capricorn Plates to crash into its trailing boundary like being rear-ended in a highway pile-up. For mechanical reasons, poles of rotation of the two plates involved tend to be in diffuse deformation zones creating zones of diffuse contractional and extensional deformation separated by neutral zones of little deformation. Median boundaries (dashed lines) define a diffuse triple junction.

Fig. 9. Eastern Indian Ocean floor. Arrows indicate contraction / extension. DE=Diffuse Extension between Indian and Capricorn Plates. Circles=poles of rotation surrounded by neutral zones of little deformation.



Tour Stop 10: Indian Ocean Ridges

Spreading in the eastern Indian Ocean has changed direction

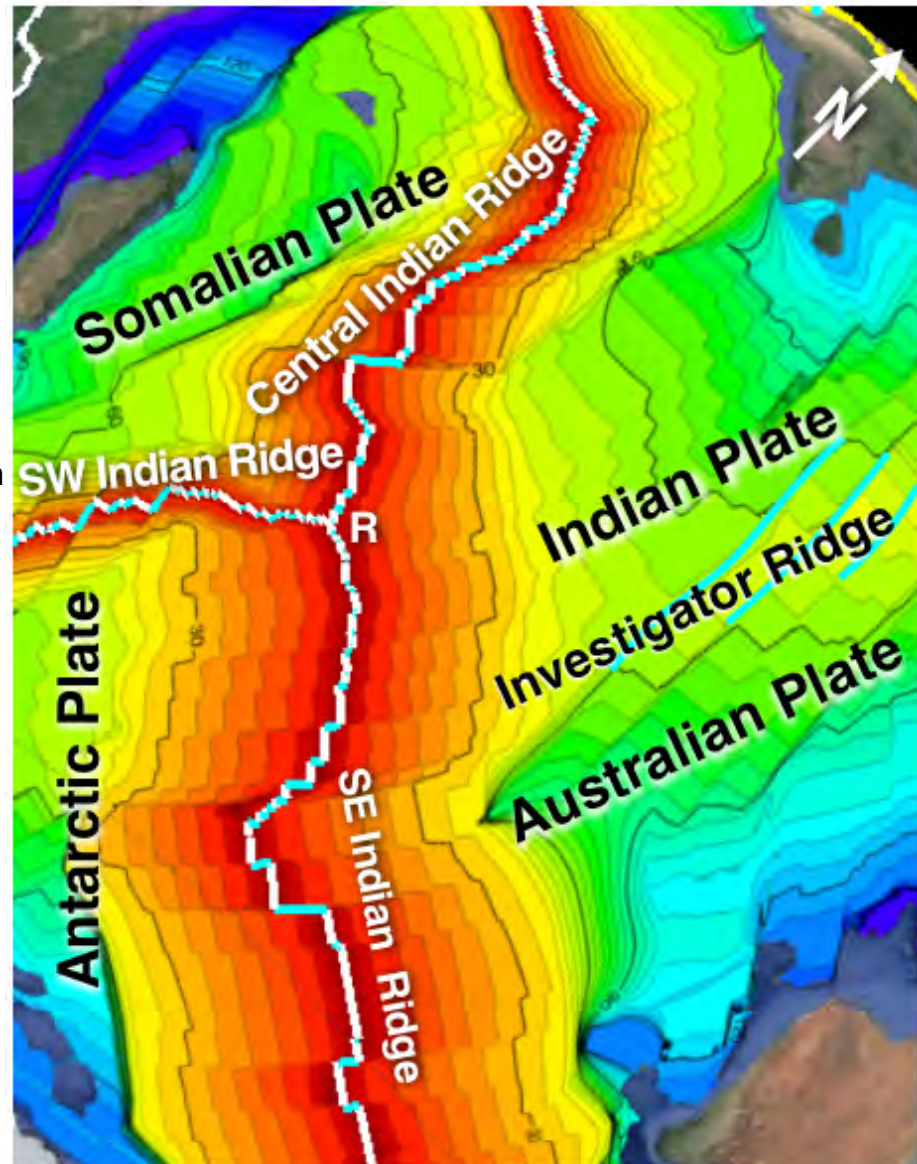
The recent diffuse deformation zones between the Indian, Capricorn, and Australian Plates have not yet impacted older seafloor age patterns in the eastern Indian Ocean (Fig. 10).

Before independent movement of the Indian, Australian, and Capricorn plates, Rodriguez Triple Junction separated Somalian, Antarctic, and Indo-Australian Plates along the Central Indian Ridge, Southwest Indian Ridge, and Southeast Indian Ridge.

The differences in widths of age stripes on the three branches of the triple junction represent differences in spreading and rift propagation rates.

Looking at older ages, spreading between separate Indian and Australian Plates occurred across the *Investigator Ridge* from about 150 to 45 million years ago. The spreading direction was closer to North-South (in today's geographic reference frame). This affected the trends of hotspot trails as discussed in the next tour stop.

Fig. 10. Rodriguez Triple Junction (R) and the abandoned Investigator Ridge. Note the diagonal North arrow.



Tour Stop 11: Indian Ocean Hotspot Trails

The Indian Ocean has two prominent hotspot trails

[Turn off the ocean ages to view this frame]

In addition to the volcanoes that define the spreading ridges, there are trails of volcanic oceanic islands and *seamounts* (shallowly submerged volcanoes) made out of progressively older volcanic rocks that line up as a result of plate motion over relatively stationary mantle hotspots. Think of moving a sheet of paper over a candle. One hotspot created the islands of Reunion, Mauritius, the British Indian Ocean Territory, and the Maldives (Fig. 11). Another created the 90-East hotspot trail and the Kerguelen Plateau. Both trails are now split by recent spreading which separates Reunion and Mauritius from the British Indian Ocean Territory and the 90E trail from the Kerguelen Plateau. Kerguelen is a large oceanic plateau most of which is submerged.

Not all Indian Ocean islands are volcanic, however. Madagascar, the Seychelles, and Sri Lanka are made of continental crust.

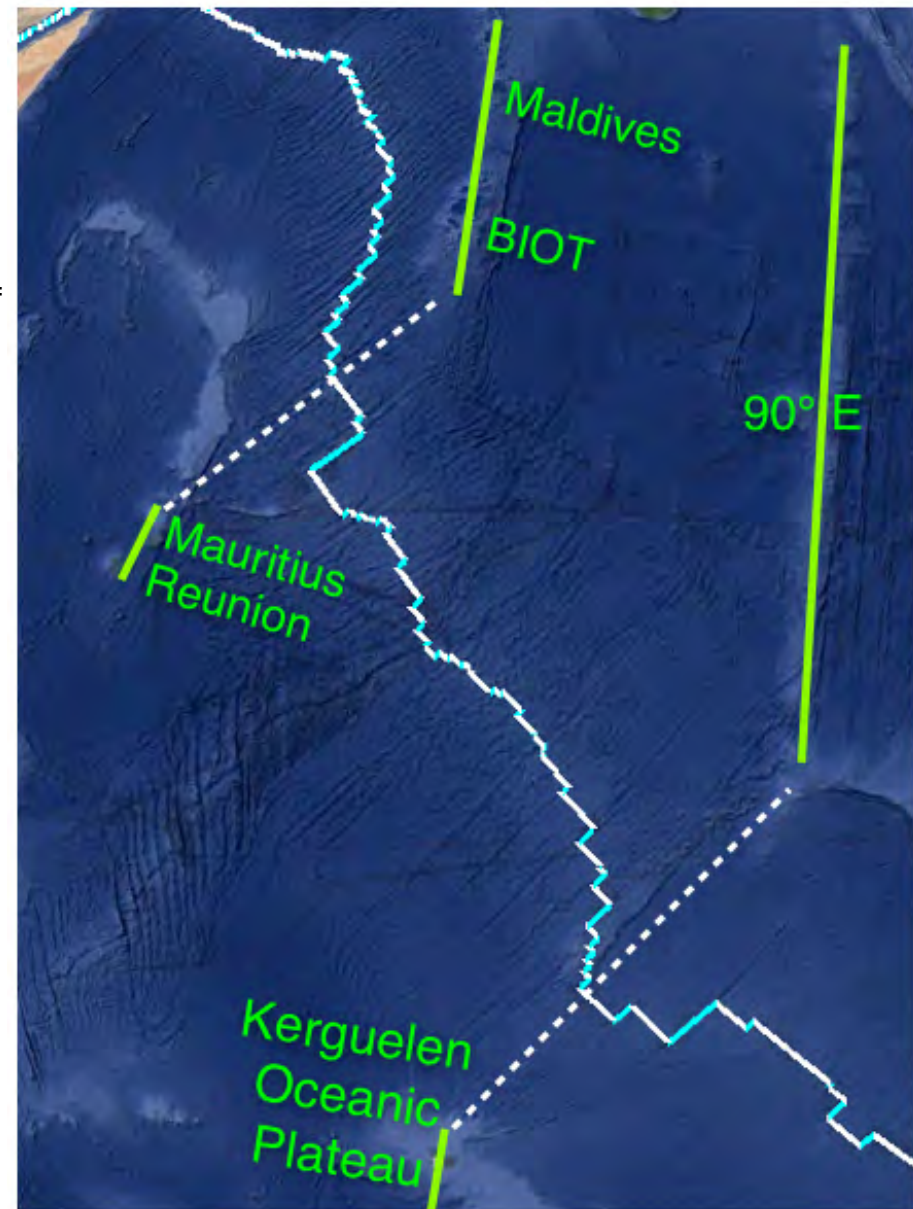


Fig. 11. The Western Indian Ocean hotspot trails (green lines) are offset by recent spreading (white dashed lines).
BIOT=British Indian Ocean Territory.

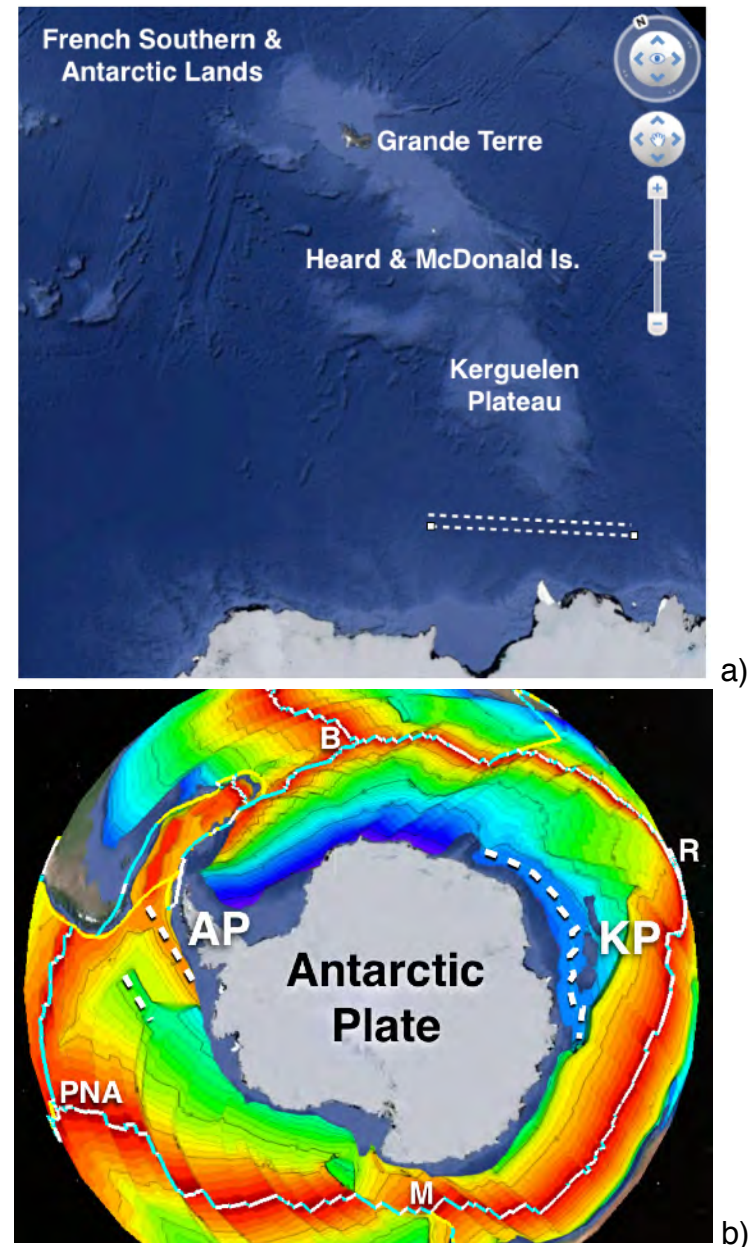
Tour Stop 12: The Southern Ring of Peace

The Southern Ocean surrounds Antarctica with a ring of passive continental margins and spreading ridges

A prominent feature of the Southern Ocean is the Kerguelen Plateau (Fig. 12 a), an almost entirely submerged region of thickened oceanic crust the size of Japan. This is Earth's second largest oceanic plateau, after the Ontong Java Plateau in the western Pacific. It breaks surface to form islands such as the Heard & McDonald Islands and Grande Terre, part of the French Southern and Antarctic Lands and one of the most remote places on Earth. The plateau was probably formed by a hotspot during the breakup of Gondwana. It is separated from Antarctica by an abandoned ridge (dashed).

In the Southern Ocean, the continent of Antarctica is surrounded by a ring of passive margins and spreading ridges plus transform faults that outline the Antarctic Plate (Fig. 12 b). They resulted from breakup of Gondwana, when South America, Africa, India, Australia, and New Zealand all spread away from different sides of Antarctica. The age of the oldest oceanic crust indicates the sequence of rift propagation.

Fig. 12. a) Kerguelen Plateau. b) Ring of spreading ridges and passive margins surrounding Antarctica. AP=Antarctic Peninsula, KP=Kerguelen Plateau. Triple Junctions: B=Bouvet, R=Rodriguez, M= Maquarie, PNA=Pacific–Nazca–Antarctic. Dashed lines are abandoned ridges.



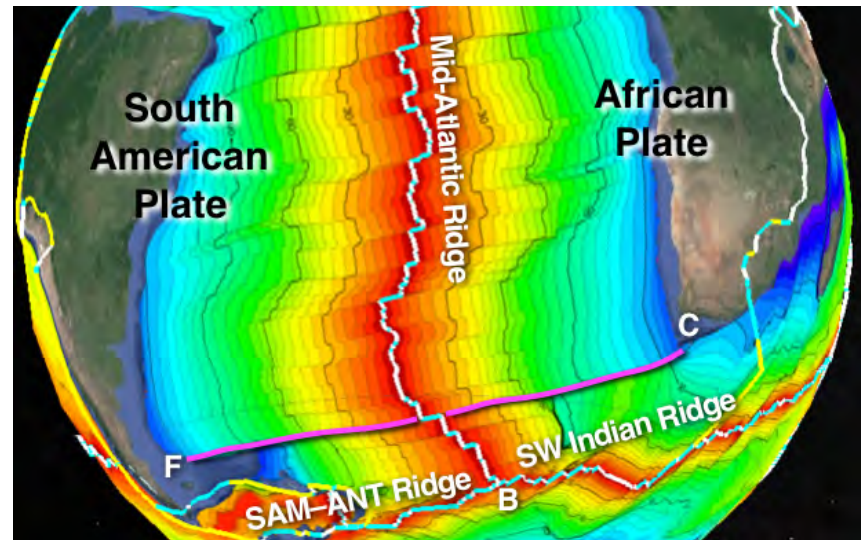
Tour Stop 13: South Atlantic Ocean

The South Atlantic is simpler than the Indian Ocean

Three spreading ridges meet at the Bouvet Triple Junction (Fig. 13 a), the Southwest Indian Ridge, the South American–Antarctic Ridge, and the Mid-Atlantic Ridge. They separate the African, Antarctic, and South American Plates. Except for the Scotia and Lesser Antilles island arcs (which are discussed later), the South Atlantic Ocean is bounded by passive margins. Crustal ages indicate spreading since the Cretaceous. A long fracture zone extending from north of the Falklands / Malvinas continental shelf to the coast south of Capetown shows that southernmost South America used to wrap around the Horn of Africa.

Hotspot trails gave rise to islands such as Tristan da Cunha and St. Helena (Napoleon Bonaparte's exiled home), and seamounts such as the Rio Grande Rise (Fig. 13 b). However, some island chains are not in the plate motion direction and off-ridge volcano locations may alternatively be controlled by magma channeling along fracture zones. Ascension Island is an example.

Fig. 13. a) The South Atlantic Ocean. B=Bouvet Triple Junction. F=Falklands/Malvinas. C=Capetown. SAM=South America. ANT=Antarctica. b) South Atlantic volcanic chains. Green=Hotspot-controlled. Purple=fracture zone controlled.



Tour Stops 14: Plate Tectonics Finds Oil!

Valid scientific models often lead to technological advances and economic success stories

An Irish exploration company, Tullow Oil Plc, had already discovered oilfields such as the Cretaceous Jubilee field off the coast of Ghana in western Africa. Their Exploration Director Angus McCoss thought to himself: if oilfields formed as Africa and South America split apart in the Cretaceous opening of the South Atlantic Ocean Basin, maybe the company should explore the conjugate margin—the part of the opposite continental margin that rifted away from Ghana. In this case, that lay off the northern coast of South America. He studied tectonic restorations and pinpointed a

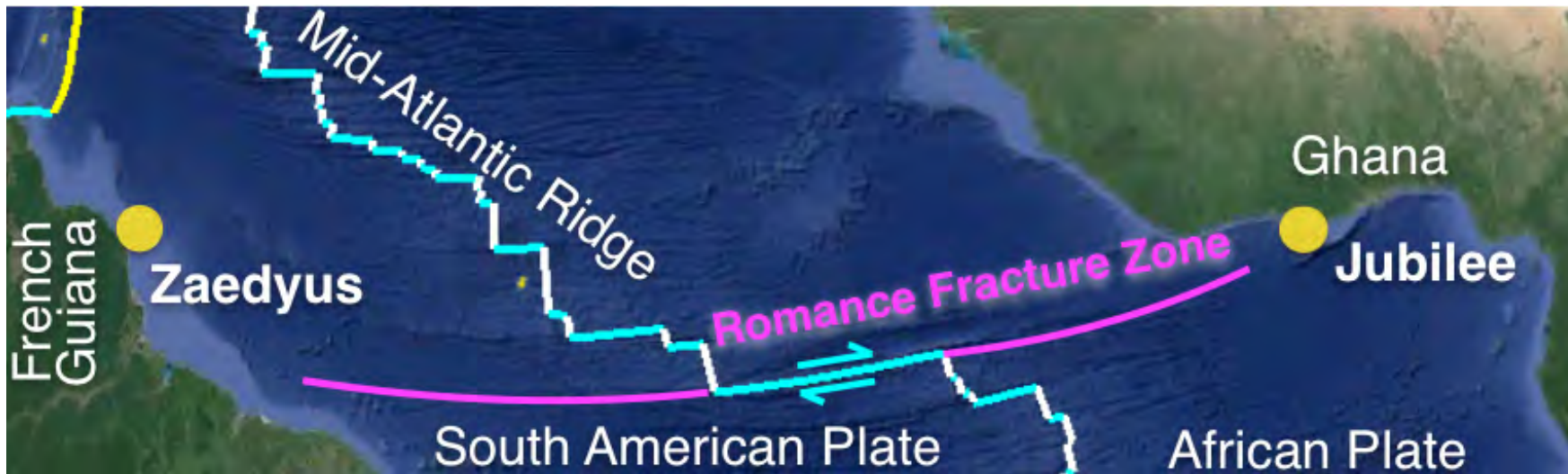
region off French Guiana that had the right stratigraphy and structure (Fig. 14). Drilling revealed the new Zaedyus oilfield. In 2011, Tullow Oil made \$1.1 billion profit.

Plate tectonic reconstructions are not just academic. They can lead to economic benefits!

Here's an interview with Angus McCoss:

<https://youtu.be/CVubIFRd6go>

Fig. 14. Knowing the location of Jubilee oilfield lead to the discovery of the Zaedyus field.



Tour Stop 15: West African Island Clusters

There are four hotspot-related ocean island groups offshore of Western Africa

It is thought that mantle hotspots created the Cape Verde Islands, the Canary Islands, the Madeira Islands, the Azores, and associated seamounts, collectively known as Macaronesia (Fig. 15). Oceanic islands go through a series of phases: birth and submarine growth; sub-aerial growth through volcanism; erosion after cessation of volcanism; and sub-marine guyot / seamount formation (Fig. 15 inset). These islands and seamounts are shield volcanoes that rise from the 4 km deep abyssal plain. The Cape Verde islands form a west-opening horseshoe shape getting younger from east to west on both the northern and southern chains. Mantle fragments in Cape Verde lavas suggest that there may be continental lithosphere at depth that was detached during opening of the Atlantic Ocean.

Advanced Discussion:

The Africa Plate has moved very little in the past 30 million years and its pole of rotation lies in the Cape Verde archipelago. This explains why the western African hotspot islands occur in short chains and clusters rather than long Hawaii-style chains (see below).



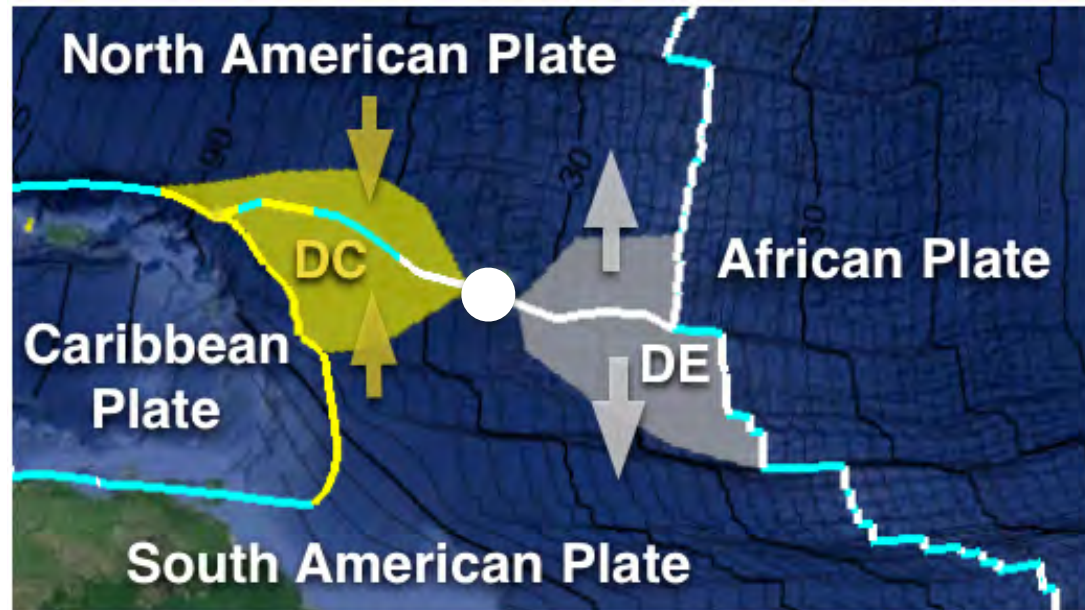
Fig. 15. The Azores, Madeira, Canaries, and Cape Verde Islands. Inset: Elevation profile for Madeira–Porto Santo–Seine Seamount–Ampère Seamount.

Tour Stop 16: NAM–SAM Boundary

There is a region of diffuse deformation between the South American and North American Plates

Turning off the ocean floor age data, you will see shaded regions of diffuse deformation surrounding the boundary between the South American and North American Plates (Fig. 16 a).

Turning the ages back on, note that the passive margins of eastern USA and western Africa contain the oldest oceanic crust in the Atlantic Ocean, some 180 to 200 million years old (Fig. 16 b).



a)
b)

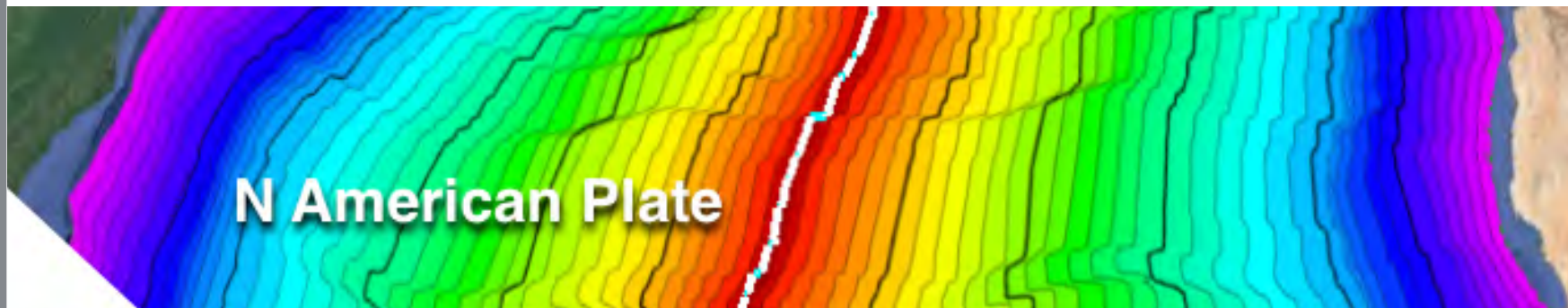


Fig. 16. a) Diffuse deformation surrounds the boundary between the South American and the North American Plates. DC=Diffuse Contraction, DE=Diffuse Extension. White circle=pole of rotation. b) The Mid Atlantic region hosts the oldest oceanic crust in the Atlantic Basin (purple stripes).

Tour Stop 17: Gulf of Mexico

The Gulf of Mexico was abandoned when the South Atlantic began to spread

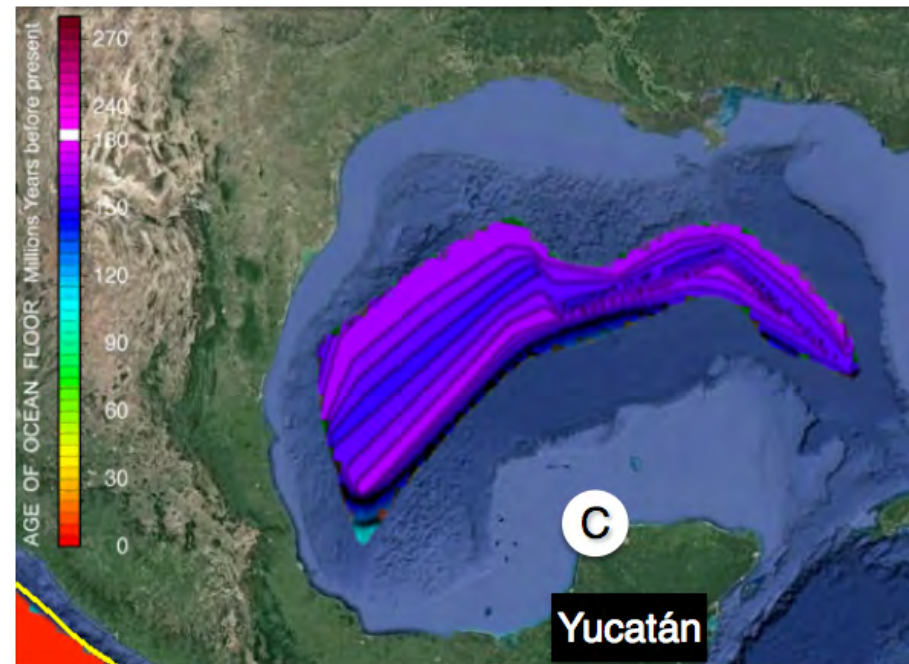
About 200 m.y. ago, a mid-ocean ridge extended from the North Atlantic Basin through the Gulf of Mexico (Fig. 17). South America and Africa were still connected as part of Gondwana and Florida was sandwiched between them. The Yucatán Peninsula that is now part of southern Mexico pulled away from North America, creating the Gulf of Mexico.

However, as the South Atlantic began to open about 120 m.y. ago, spreading in the Gulf was abandoned. Hence there are only dark blue and purple stripes in Fig 17 a.

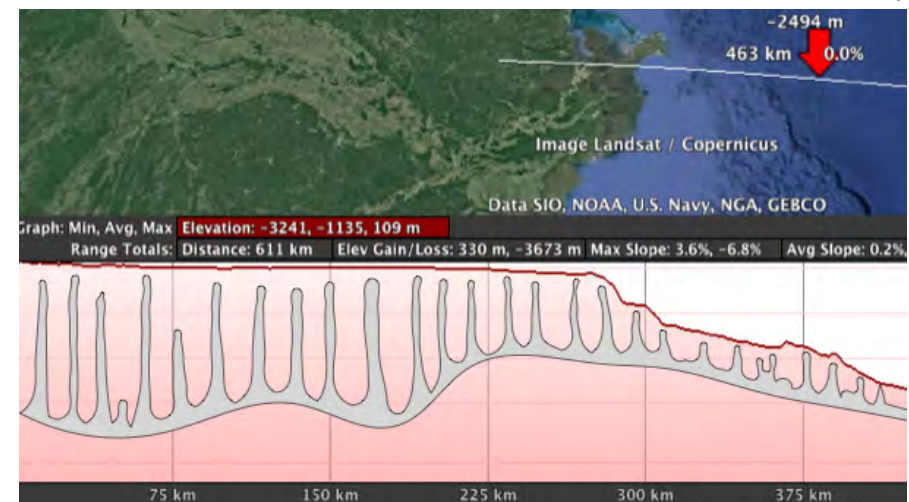
The Yucatán shelf is the site of the Chicxulub impact crater that is believed to have contributed to the demise of the dinosaurs 65 million years ago.

The stretched, thinned, continental shelf of the Gulf is covered with salt diapirs that create hydrocarbon traps, Fig. 17 b.

Fig. 17. a) The Gulf of Mexico was created by splitting off Yucatán from North America. Purple and blue stripes indicate abandonment of spreading. C=Chicxulub crater. b) Salt diapirs (gray) under the Gulf coast drawn on top of a Google Earth elevation profile.



a)
b)



Stop 18: Bahamas and Turks & Caicos

The Bahamas and Turks and Caicos Islands are limestone banks

The Bahamas and Turks and Caicos islands (Fig. 18 a) form predominantly submarine limestone banks that rise 3000 meters from the surrounding oceanic floor (Fig. 18 b). The limestone built up on top of fragments of continental crust that rifted away from North America during the opening of the Atlantic Ocean in the Triassic Period. During the Cretaceous Period, there was a barrier reef stretching 1600 kilometers along the eastern coast of North America, competing in stature with today's Australian Great Barrier Reef.

If sea level were 15 meters lower, the Turks and Caicos islands would form one landmass larger than Puerto Rico. The beaches are mainly coral and brilliant white. Evaporation leads to salt flats or cays which were mined in Victorian times. The islands are separated from Cuba by a thrust belt (purple).

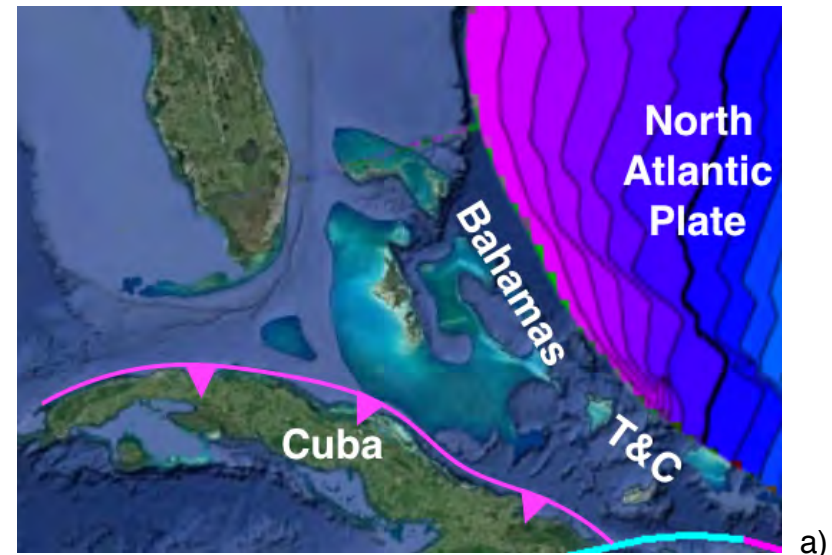
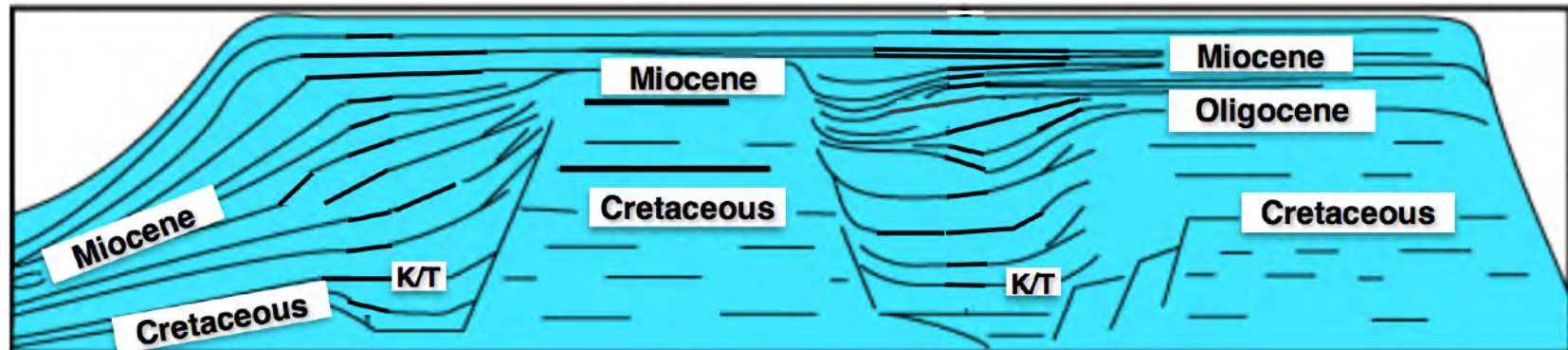


Fig. 18. a) Bahamas and Turks and Caicos (T&C) Islands. b) Bahaman Bank in cross section. Modified from www.sepmstrata.org/page.aspx?pageid=51.



Tour Stop 19: Bermuda

Bermuda formed on or near the Mid-Atlantic Ridge but is now far from its birthplace

[Turn off the Ocean Floor Ages to view.]

Bermuda (Fig. 19 a) is 2000 km from the Mid-Atlantic Ridge today but it started life as a group of submarine volcanoes either on or close to the ridge about 33 million years ago. The group of calderas that break surface form an elongate chain but are part of a submerged “pedestal” and do not follow a time sequence like the Hawaiian chain (below). They have been compared to lava lamp blobs.

As the volcanism subsided, limestone reefs built the pedestal around the calderas in atoll style (Fig. 19 b). The island is the emergent southern side of a shallow (<20 m) seamount and formed from aeolian (wind blown) dunes that became emergent in the Pleistocene. Limestones completely cover the underlying volcanic rocks.

Bermuda is at the same latitude as Georgia but due to the Gulf Stream, it never gets colder than 10°C / 50°F.



a)
b)

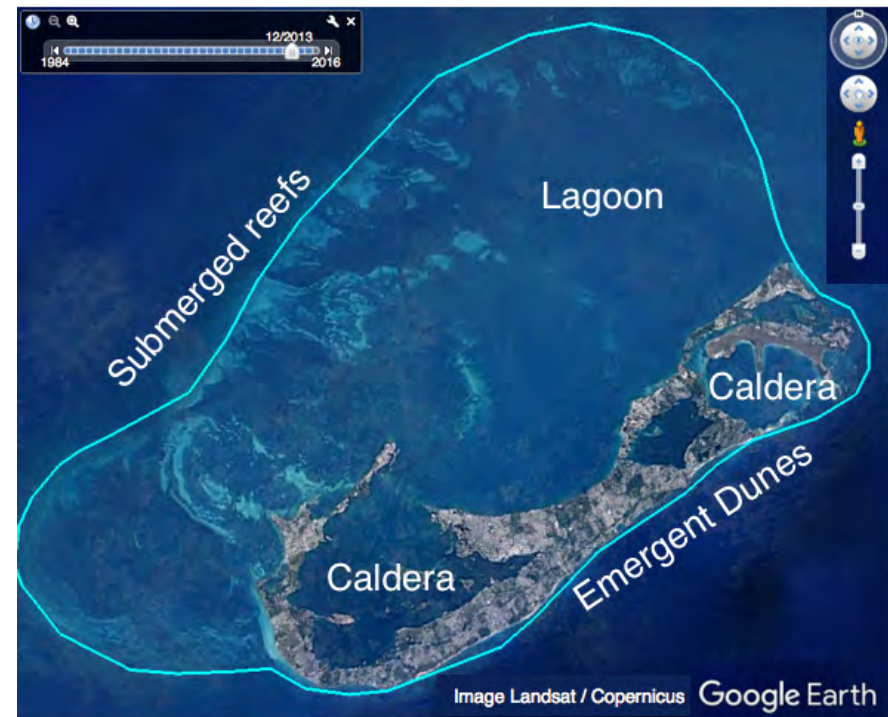


Fig. 19. a) Bermuda is far from the Mid-Atlantic Ridge. b) Remnant volcanic calderas are covered by submerged reefs and emergent limestone dunes.

Tour Stop 20: The Azores

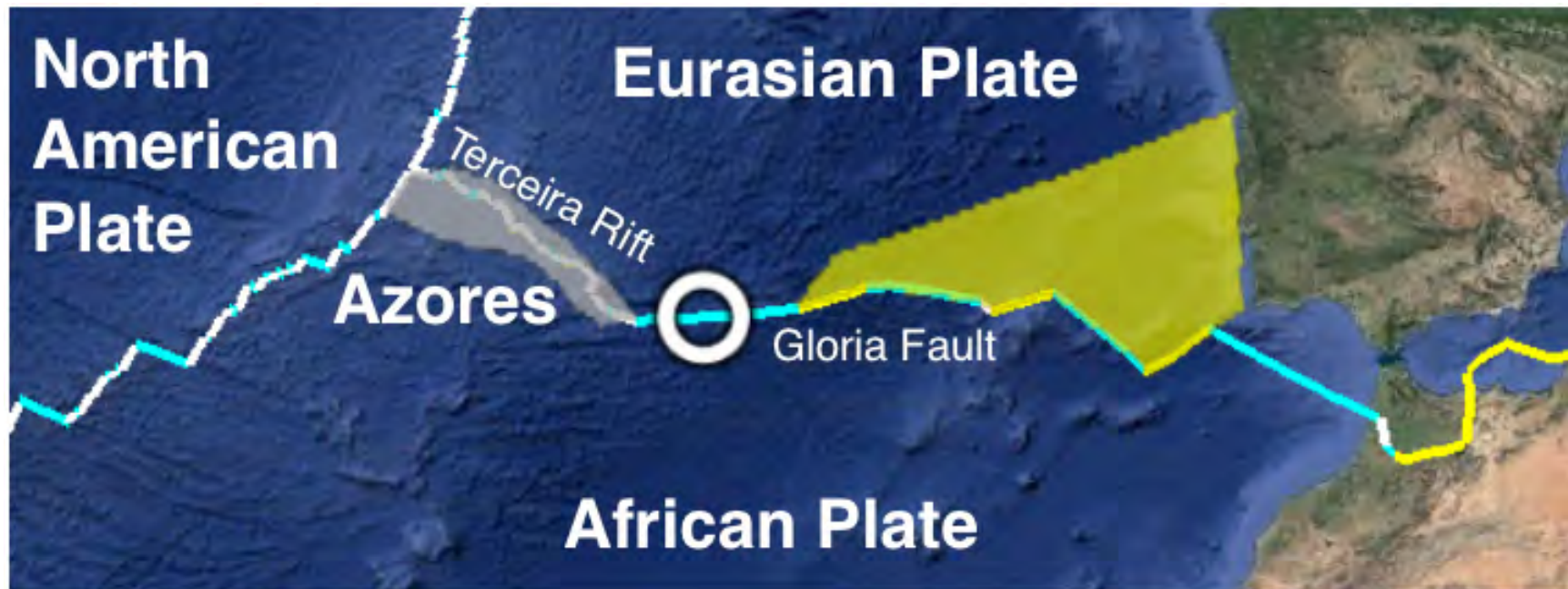
The North American, Eurasian, and African plates meet at a diffuse triple junction at the Azores

[Turn off Ocean Floor Ages to see the Azores.]

There are nine volcanic islands in the Azores. Two lie west of the Mid-Atlantic Ridge, the others to the east. The North American, Eurasian, and African plates meet in a triple junction at the Azores Hotspot (Fig. 20).

Former plate boundary models placed a small triangular microplate around the Azores but spreading between Eurasian and Africa is not concentrated on the Terceira rift but rather is distributed among the islands in a diffuse extensional deformation zone. The Azores-Gibraltar Transform (Gloria Fault) becomes a progressively more diffuse convergent boundary as it approaches the west coast of Spain. Movement on the Gloria Fault caused the disastrous 1755 Lisbon earthquake.

Fig. 20. The Azores. Gray=diffuse extension. Yellow=diffuse contraction. Circle=pole of rotation.



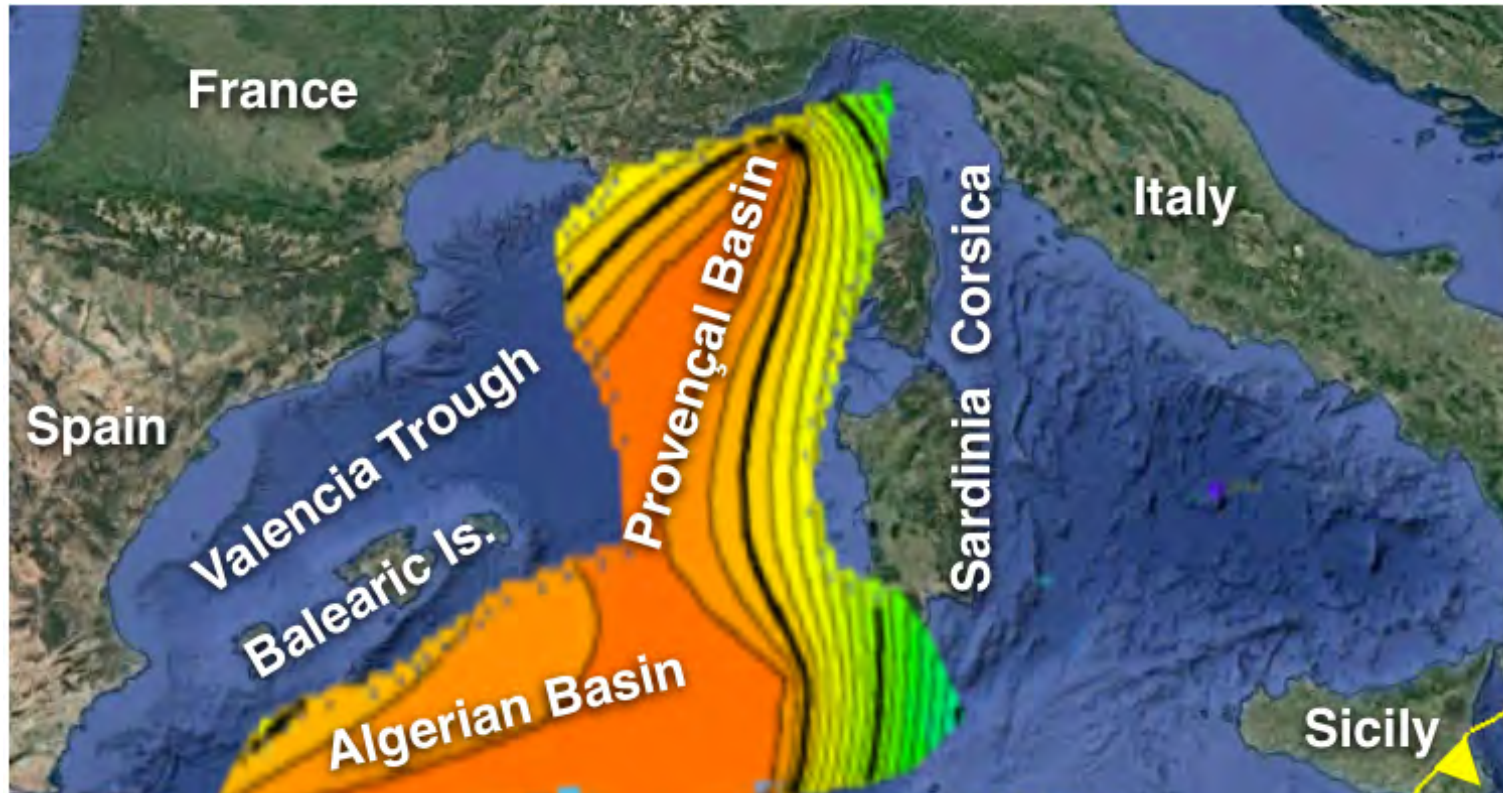
Tour Stop 21: Western Mediterranean Sea

Portions of the western Mediterranean Sea were abandoned

Much of the Mediterranean Sea does not have well-defined magnetic stripes, either because it is stretched, thinned continental margin, or it is just too complicated. However, in the western Mediterranean (Fig. 21), the continental crust of Corsica and Sardinia separated from

Europe, and Algeria separated from the Balearic Islands (the author's home), creating the Cenozoic oceanic crust of the Algerian and Provençal Basins. Seafloor spreading ceased about 16–20 m.y. ago as indicated by the central orange stripe. Valencia Trough between the Balearic Islands and the mainland is thinned continental crust.

Fig. 21. Seafloor spreading in the western Mediterranean separated the continental crust of Corsica and Sardinia from Europe and the Balearic Islands.



Tour Stop 22: Bay of Biscay

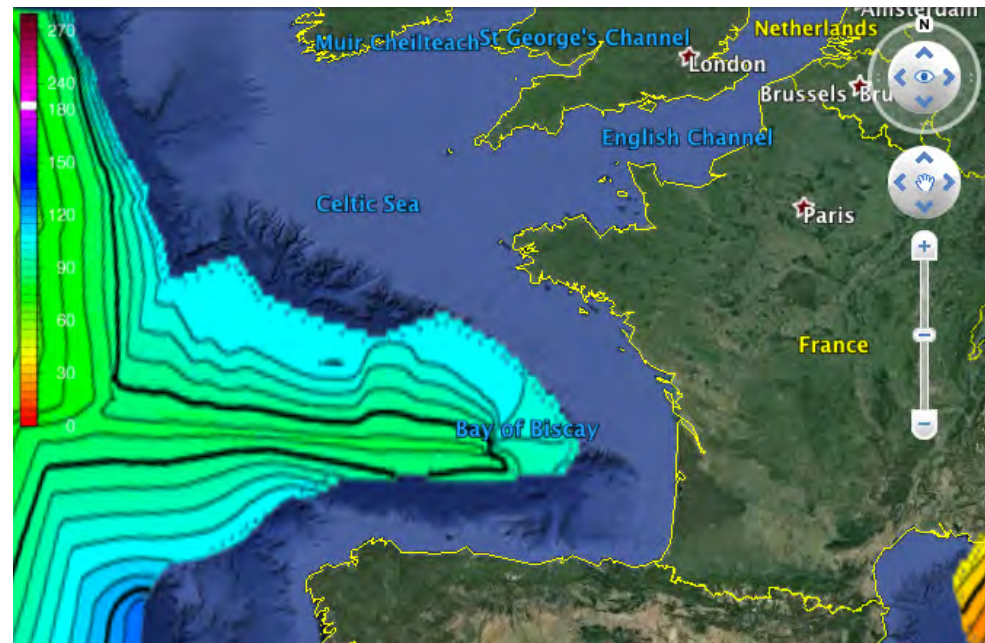
Opening of the Bay of Biscay was accompanied by compression and upthrusting of the Pyrenees

Restoring the fit of continents around the North Atlantic ocean basin requires Spain's north continental margin to rotate back against France's western continental margin, otherwise there is an overlap with the Grand Banks offshore Newfoundland.

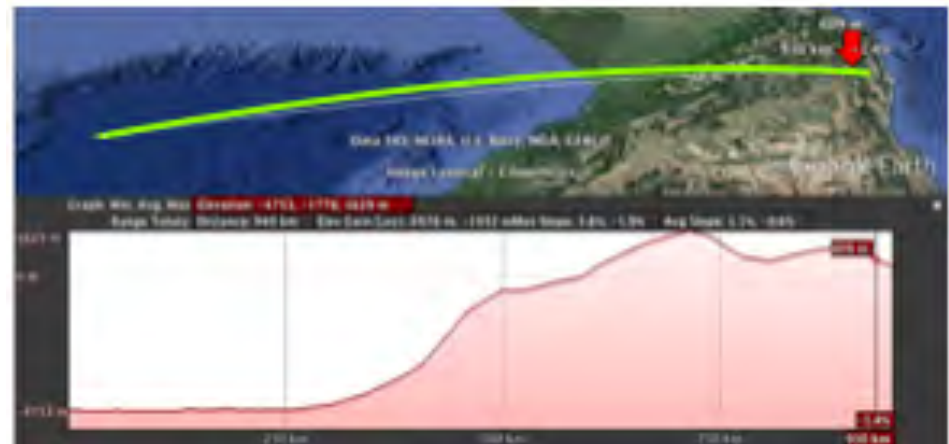
Because Earth is a sphere, all plate motions are rotations about a pole. The rotation pole can be a long way away from the plate, but in the case of Iberia, it is nearby and it caused an Alpine "near-pole orogeny" in the Pyrenees.

Evidently, the Iberian Peninsula rotated counter-clockwise away from the rest of Europe after the Atlantic Ocean opened (Fig. 22 a). However, this required a block of Earth's crust to be pushed up as the Pyrenees Mountains (Fig. 22 b). Compression in the Pyrenees built up to the point where it prevented further opening of the Bay of Biscay about 80 m.y. ago. Thrusting also deformed the Spanish coast of the Bay of Biscay.

Fig. 22. a) Bay of Biscay in Google Earth. Absence of red stripes indicate abandonment of seafloor spreading. b) Elevation profile ranges from nearly -5000 meters in the Bay of Biscay to +1600 meters in the Pyrenees.



a)



b)

Tour Stop 23: Horsts and Grabens

Rifting sometimes fails to create new oceanic crust

North of the prominent Charlie-Gibbs Fracture Zone (Fig. 23 a), the Rockall Trough, Irish Sea, and North Sea are failed continental rifts (Fig. 23 b). Normal faulting and stretching of the continental crust led to upthrown horsts (Rockall Plateau, Ireland, and England) and down-dropped grabens (the intervening seas).

The anoxic conditions that existed in shallow stagnant waters during this extension became the source of North Sea and Irish offshore oil and gas deposits.

Note that the Baltic Sea between Sweden and Finland and the Gulf of Bothnia south of Finland are not rifts. Their continental crust was not thinned but was depressed by the weight of Pleistocene ice sheets and has not yet fully rebounded.

You can use the Google Earth Elevation Profile tool to explore the topography of this region.



a)



b)

Fig 23. a) The Charlie-Gibbs Fracture Zone. b) Rockall Trough, Irish Sea, and North Sea can be examined with the Google Earth elevation profile tool.

Tour Stop 24: Iceland

A mantle plume intersects the Mid-Atlantic Ridge in Southeast Iceland

[Turn off the Ocean Floor Ages overlays to view Iceland.]

The Mid-Atlantic Ridge emerges above the waves to form Iceland (Fig. 24 a). There is a hotspot under Vatnajökull icecap in southeastern Iceland (Fig. 24 b). The plume creates an elevated and therefore icy plateau. Greenland lay southeast of the hotspot 70 m.y. ago causing the volcanics in Davis Strait, the south end of Baffin Bay. Greenland drifted northwest as it split from western Europe, creating the 55 m.y. old volcanics of east Greenland, the Faroe Islands, Scotland, and Northern Ireland. The Mid-Atlantic Ridge jumped from west to east, dragged by the hotspot magma source (Fig. 24 b).

North of Iceland lies the island of Jan Mayen, however it is continental crust that rifted off Greenland. Similarly the Orkney and Shetland Islands east of the Faeroes are an extension of the Scottish Highlands continental crust.

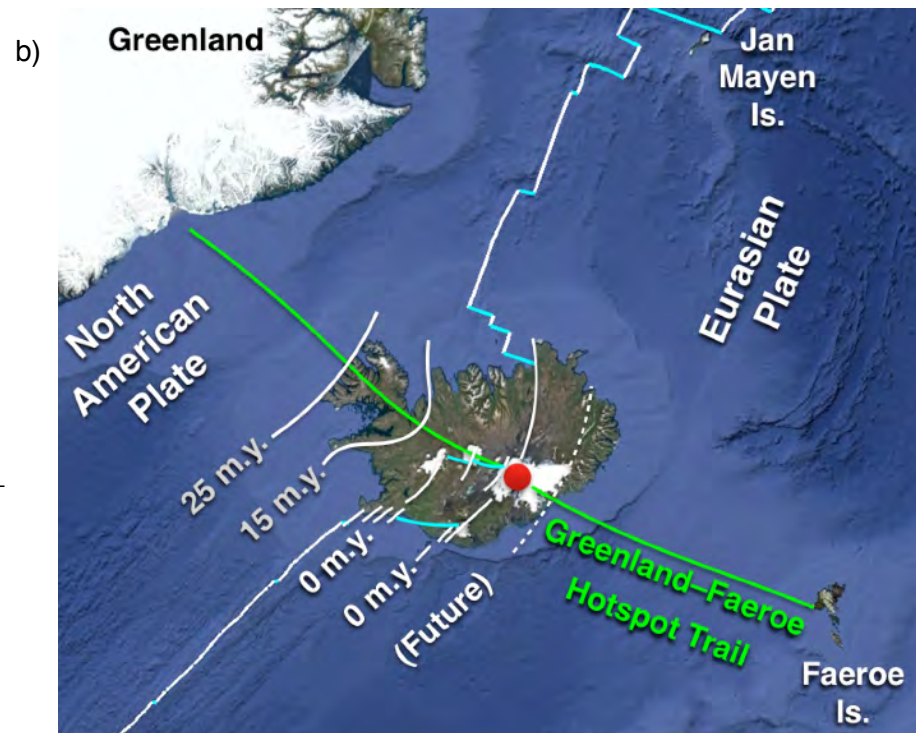


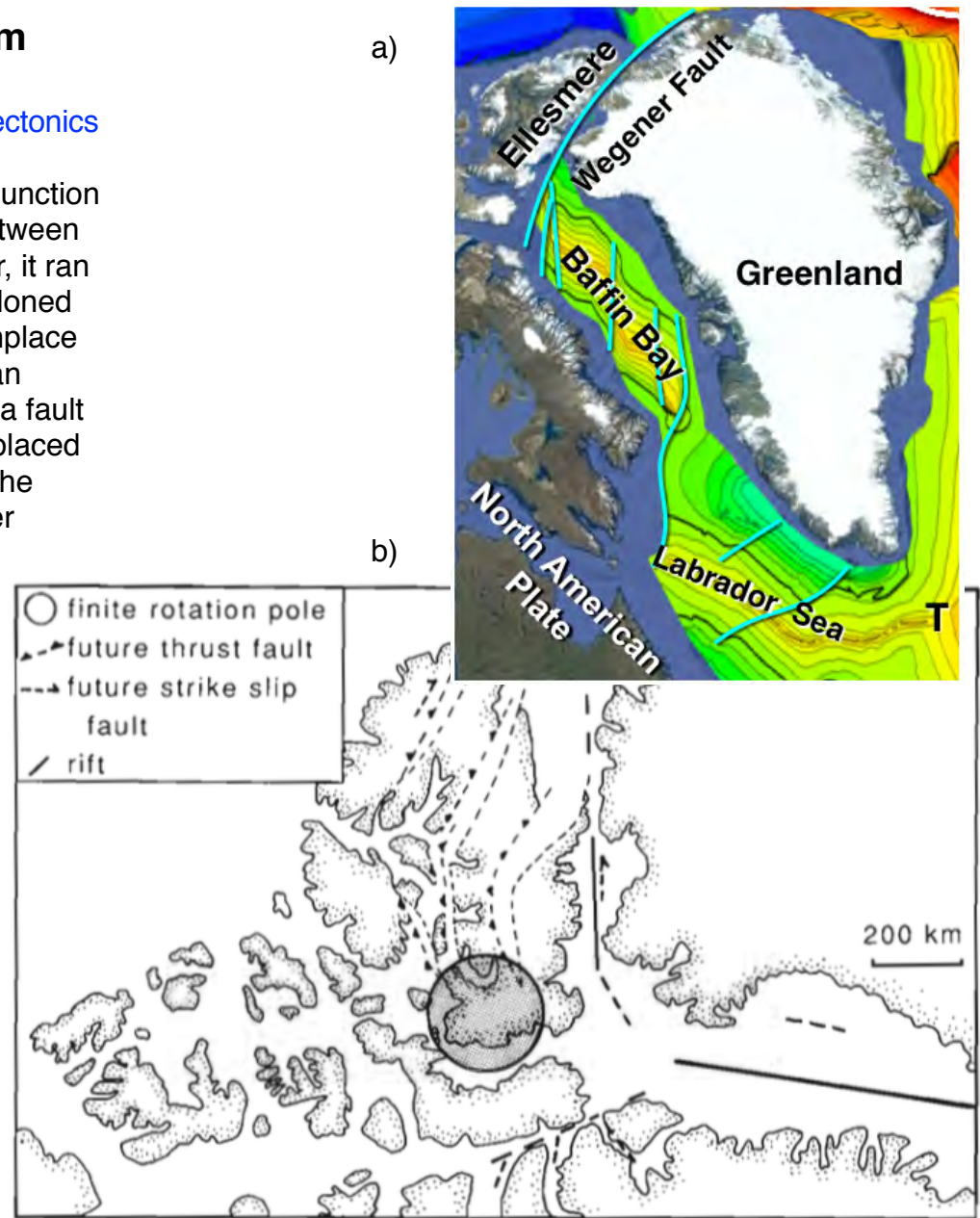
Fig. 24. a) Columnar basalts in southern Iceland. Photo: Kathryn Moore. b) Iceland has drifted over the Vatnajökull hotspot (red) cause sequential ridge jumps.

Tour Stop 25: The Nares Strait Problem

Nares Strait tested the explanatory power of plate tectonics

There used to be an active ridge-ridge-ridge triple junction south of Greenland. An incipient rift propagated between North America and Greenland (Fig. 25 a). However, it ran out of steam south of Ellesmere Island. This abandoned ridge is especially interesting because it is the birthplace of the concept of continental drift. In 1912, American geologist Frank Taylor (1860–1938) proposed that a fault in Nares Strait (now called the Wegener Fault) displaced Greenland vis-a-vis Ellesmere Island, opening up the Labrador Sea and Baffin Bay. This started Wegener thinking about continental drift during his Greenland fieldwork. The problem is that matching geological features show no more than 25 km of strike-slip movement, much less than the 330 km required to fit Greenland back against North America. In 1985, the author and his students mapped folds and thrust faults of the “Eurekan” near-pole orogeny in Ellesmere Island and determined that contraction, combined with minor strike-slip movement in Nares Strait, could account for the observed opening (Fig. 25 b).

Fig. 25. a) Wegener Fault between Greenland & Ellesmere Island. T=Former triple junction. b) Eurekan thrusting in Ellesmere, from De Paor et al. (1989). Circle=pole of rotation.



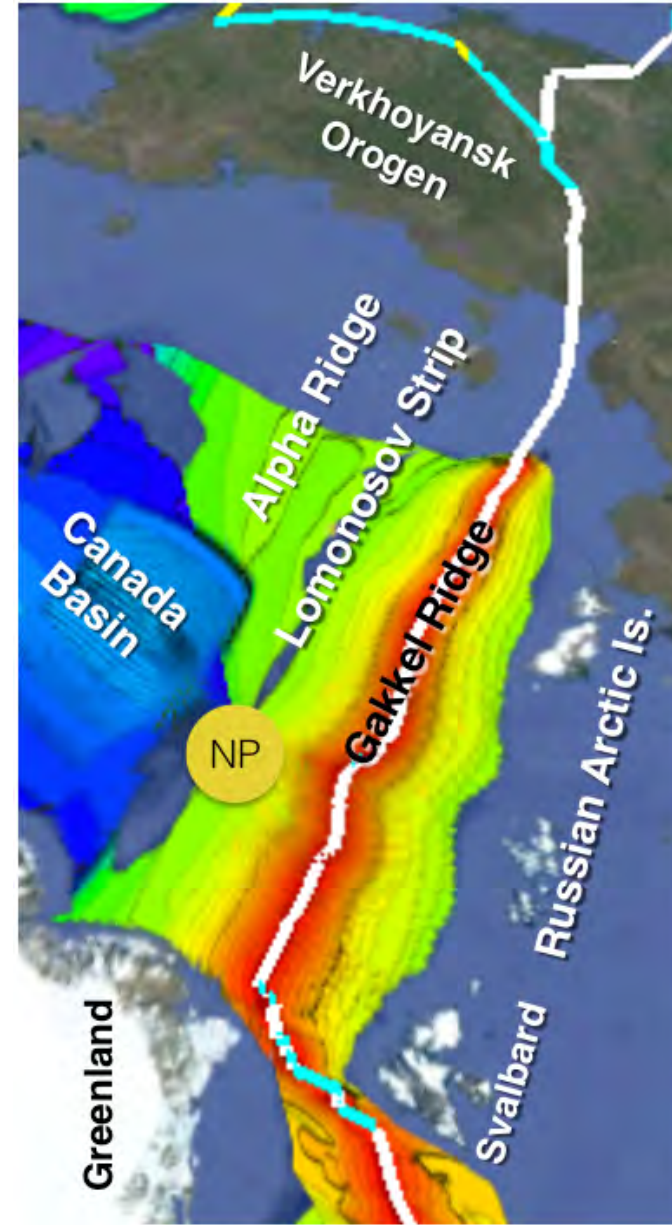
Tour Stop 26: The Eastern Arctic Ocean

Gakkel Ridge is the propagating tip of the Mid-Atlantic Rift

The Eastern Arctic Ocean is actively rifting and represents the northward propagation of the Mid-Atlantic Ridge, except that the tip is now past the north pole and heading south into Siberia (Fig. 26). Beyond the tip, compression causes shortening and uplift in the near-pole Verkhoyansk Orogen, a situation similar to Labrador Sea / Baffin Bay, and the Eurekan Orogen of Ellesmere Island. The Eastern Arctic Gakkel Ridge has passive margins with shallowly submerged continent shelf of the Lomonosov Strip and continental crust of Svalbard and the Russian Arctic Islands. About 60 million years ago, the Lomonosov Strip was attached to the islands and spreading was happening on the Alpha Ridge to the west. This is an example of “ridge jump,” probably caused by interaction with a mantle hotspot. The result is that the Lomonosov Strip is a two-sided passive margin (we eschew the common name Lomonosov Ridge to avoid confusion with spreading ridges).

Note the very different ocean floor age pattern in Canada Basin.

Fig. 26. The Arctic Ocean. West is at the top. NP=North Pole. Canada Basin opened first. Then spreading switched to the Alpha Ridge. That spreading jumped to the Gakkel Ridge, ripping off the Lomonosov Strip.



Tour Stop 27: Canada Basin

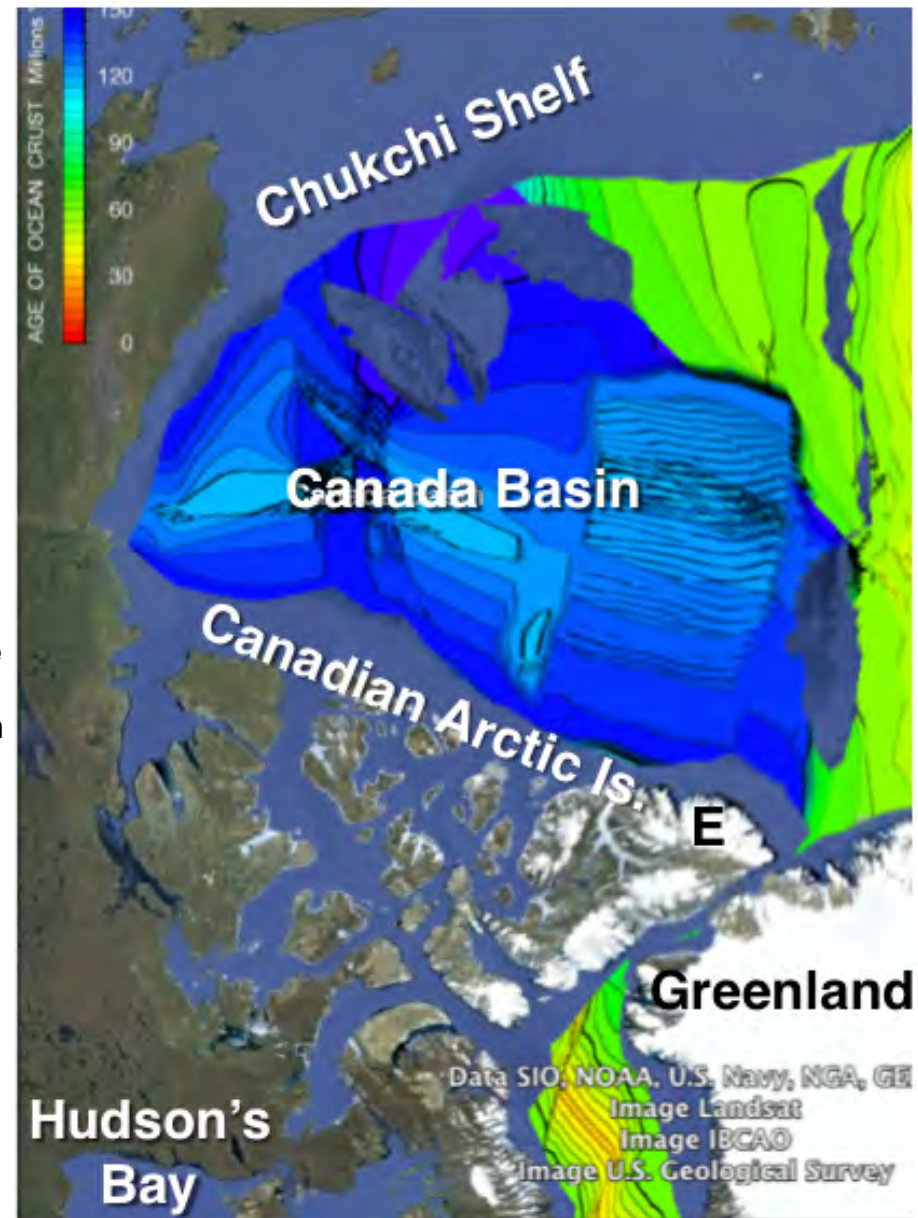
Canada Basin was hidden under ice until very recently and therefore was not well understood

Canada Basin, the western part of the Arctic Ocean, is an abandoned ocean basin (Fig. 27). Until the onset of recent global warming and sea-ice melting, this region was almost entirely covered by Arctic Ice. Consequently the sea floor was not well-mapped. The Chukchi continental shelf may be a conjugate margin of Canada Basin but its origin is subject to debate.

There was a lot of debate about how Canada Basin formed—whether scissor-style like the Bay of Biscay or by strike-slip motion. What is not in dispute is that it has been abandoned and truncated by active spreading of the Arctic Ocean to the east (green and yellow stripes to the right in Fig. 27). Only blue and cyan age contours occur in Canada Basin to the left, showing that it was abandoned 100 m.y. ago.

Note that there are no magnetic stripes in Hudson's Bay at the bottom left. Hudson's Bay is continental crust that was depressed by the weight of ice and has not yet fully rebounded, just like the Baltic Sea.

Fig. 27. Canada Basin crust is much older than the eastern Arctic Ocean floor. E=Ellesmere Island.



Interlude: Balancing Seafloor Spreading with Subduction

Seafloor spreading without global expansion requires that portions of Earth's surface be destroyed in places

If continents move apart by adding strips of new ocean floor between them at spreading ridges—the process we call seafloor spreading—then either Earth must be getting larger or a balancing amount of oceanic crust must be destroyed elsewhere. The idea that the Earth might be expanding was first put forward by Charles Darwin based on his observation of raised beaches in Patagonia during the voyage of the Beagle. Others, on the other hand, suggested that mountain belts might form from Earth's cooling and shrinking.

It took a long time to decide whether Earth is expanding, contracting, or staying the same size, because some local regions are rising or sinking for various reasons, but NASA scientists have now determined that the annual global average change in Earth's Radius is no more than the thickness of a hair. That means that the increase in surface area due to seafloor spreading must be exactly balanced by destruction of crust elsewhere.

We now continue our tour to include such convergent plate boundaries. Note, however, that this is a tour of the oceans so we do not discuss continent-continent collisions.

Tour Stop 28: Lesser Antilles Island Arc

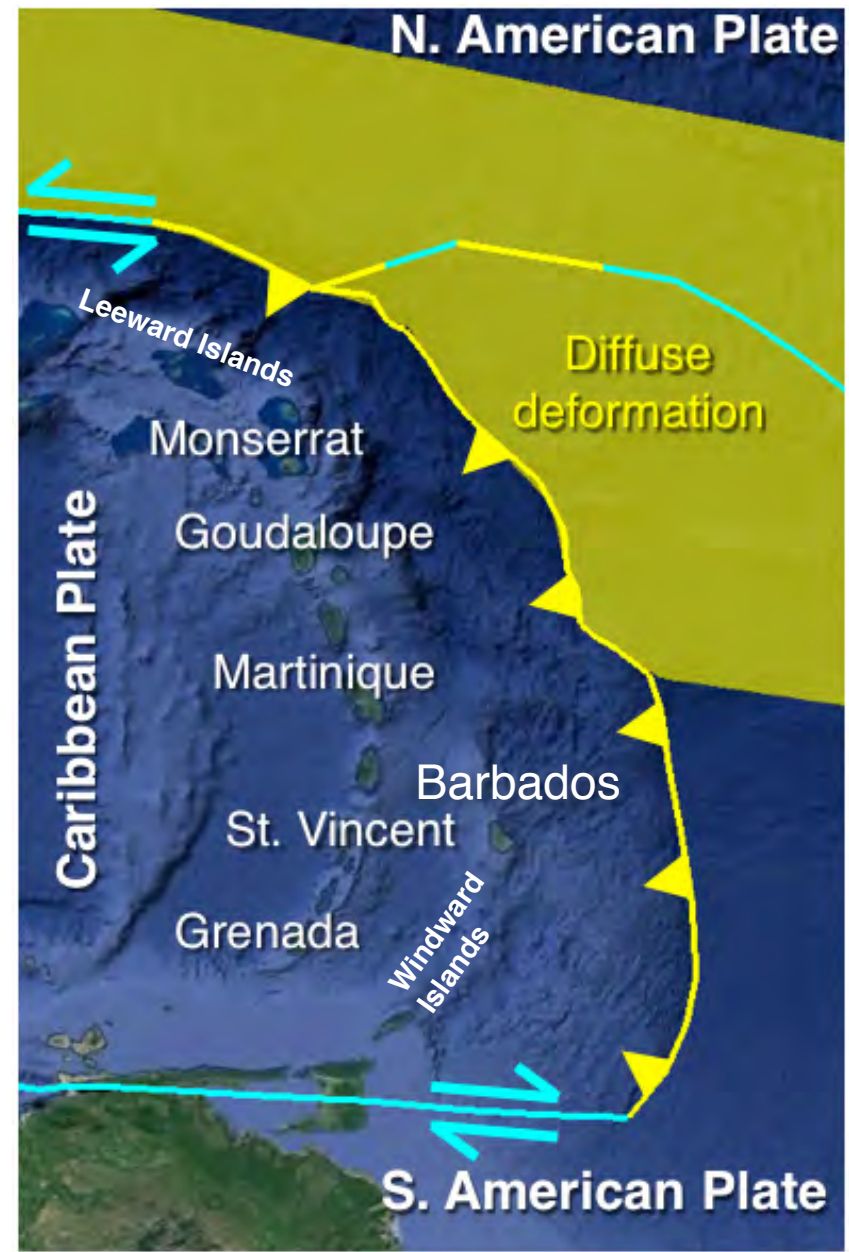
The Lesser Antilles Arc gives the North Atlantic its only active plate boundary

The Leeward Islands at the northern end of the Lesser Antilles Island Arc mark the convergent boundary between the North American and Caribbean Plates (Fig. 28). The Windward Islands at the south end mark the South Atlantic–Caribbean convergence. The subducting diffuse deformation zone was discussed at Tour Stop 16. Active volcanoes occur on Monserrat, Guadeloupe, Martinique, St. Vincent, and off-shore Grenada. An eruption of Martinique's Mt. Pelé killed 30,000 people in 1902.

The island arc formed above a west-dipping subduction zone (yellow line in Fig. 28 with teeth on the overriding plate). Trench rollback caused the island arc to move eastward, leading to back-arc seafloor spreading in the Caribbean Basin. Barbados lies east of the arc and is an emergence of the accretionary prism.

The Lesser Antilles are bounded to the north and south by transform faults with opposite senses of shear, sinistral in the north and dextral in the south.

Fig. 28. The Lesser Antilles Island Arc. The North and South American Plates are subducting under the arc, which is bound by northern and southern transform faults of opposite shear sense.



Stop 29: Greater Antilles Part 1

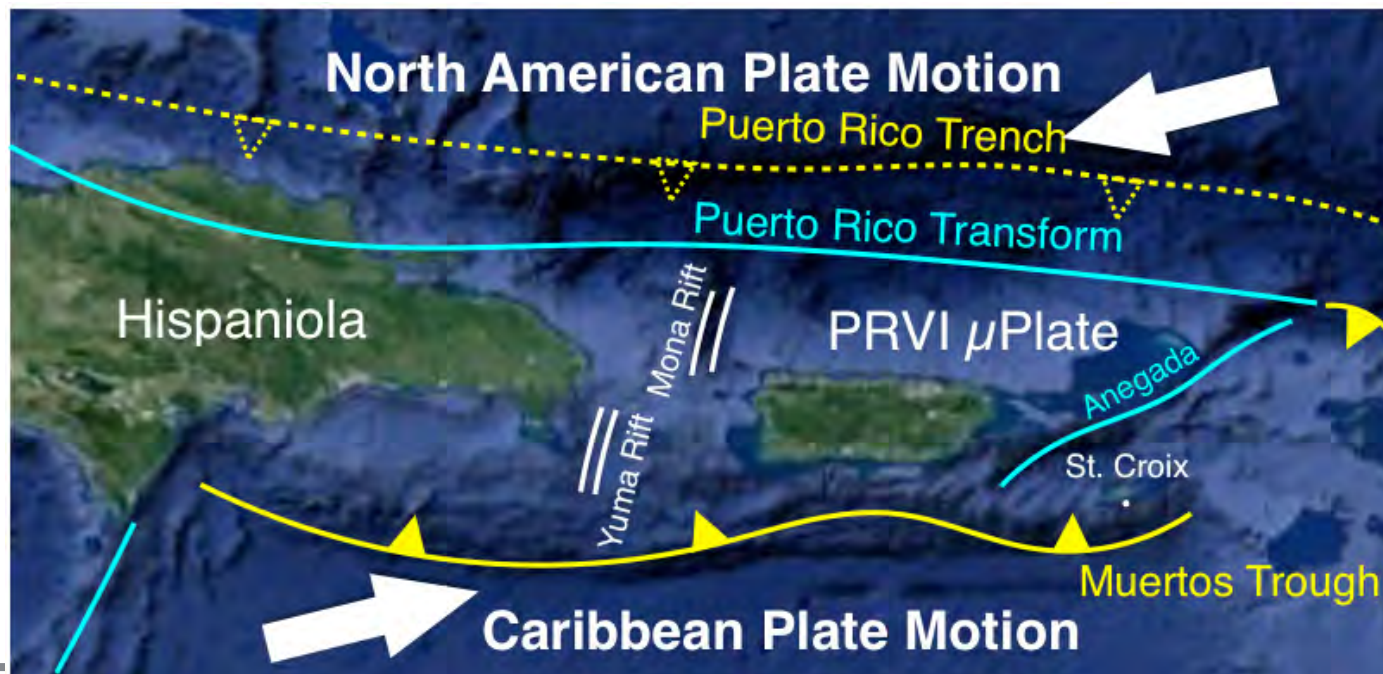
The Greater Antilles are in oblique convergence

Initially, the region now occupied by Puerto Rico was moving north over North American oceanic crust. Convergence built up Puerto Rico's central volcanic-magmatic arc and created the offshore Puerto Rico Trench, the deepest water in the Atlantic at over 8000 m. However, today's more easterly Caribbean Plate motion has turned the plate boundary into a mainly transform fault (Fig. 29). The component of convergence is accommodated in the Muertos Trough.

The Puerto Rico–Virgin Islands Microplate is defined by the Puerto Rico Trench/Transform, Muertos Trough, Mona and Yuma Rifts, and Anegada Transform.

Because of sea level change, banks of coral reef limestone were plastered onto the north and south sides of Puerto Rico during periods of high sea level and exposed during low periods.

Fig. 29. Tectonics surrounding the Puerto Rico and Virgin Islands (PRVI) Microplate. Dashed trench is extinct.



Tour Stop 30: Greater Antilles Part 2

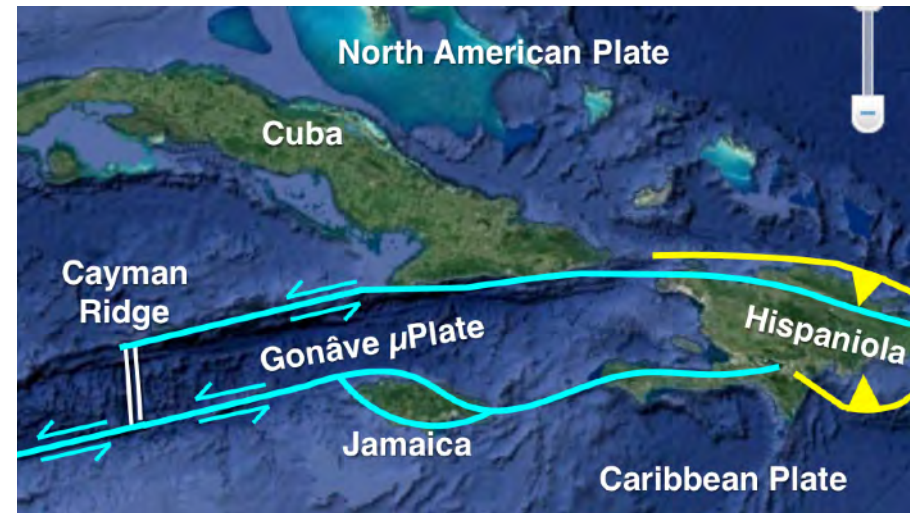
The Caribbean Plate is bounded by propagating transform faults and subduction zones

Around Hispaniola, the island conquered by Christopher Columbus, oblique convergence is partitioned into subduction and transform faulting (Fig. 30 a). There is a small area of seafloor spreading called the Cayman Ridge south of the Cayman Islands but the main plate boundaries in this region are two long transform faults that bound the Gonâve Microplate. One caused the devastating Port-Au-Prince earthquake in Haiti in 2011.

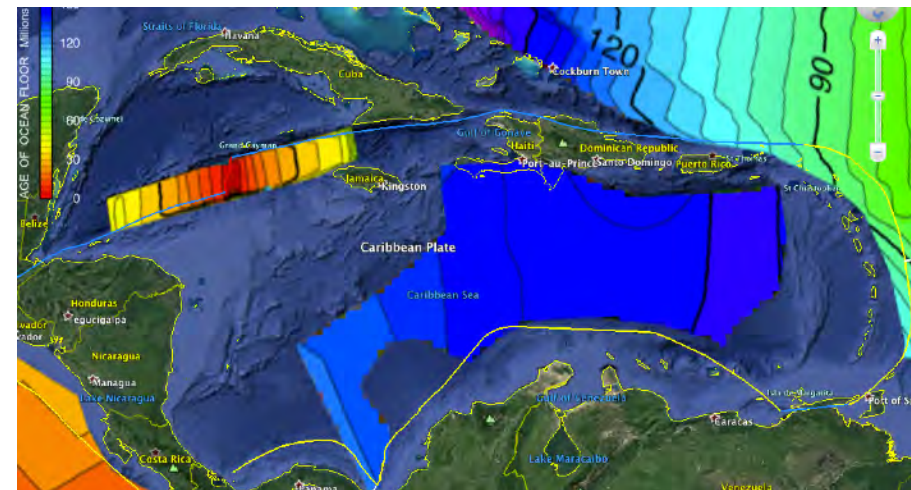
Surprisingly, both transforms are left lateral because the Caribbean Plate moves eastward faster than the Cayman Ridge spreads. Jamaica is uplifted at a bend in the southern transform fault that creates a component of compression. This is called a restraining bend.

Cuba is the largest of the Greater Antilles islands. It was originally part of the Caribbean Plate but collision and transform fault development transferred it to become part of the North American Plate.

The ocean ages in the Caribbean Basin south of the Gonâve Microplate are much older showing that back-arc spreading has long been abandoned there (Fig. 30 b).



a)



b)

Fig. 30. a) The Caribbean Plate. b) The Gonâve Microplate.

Tour Stop 31: Trinidad

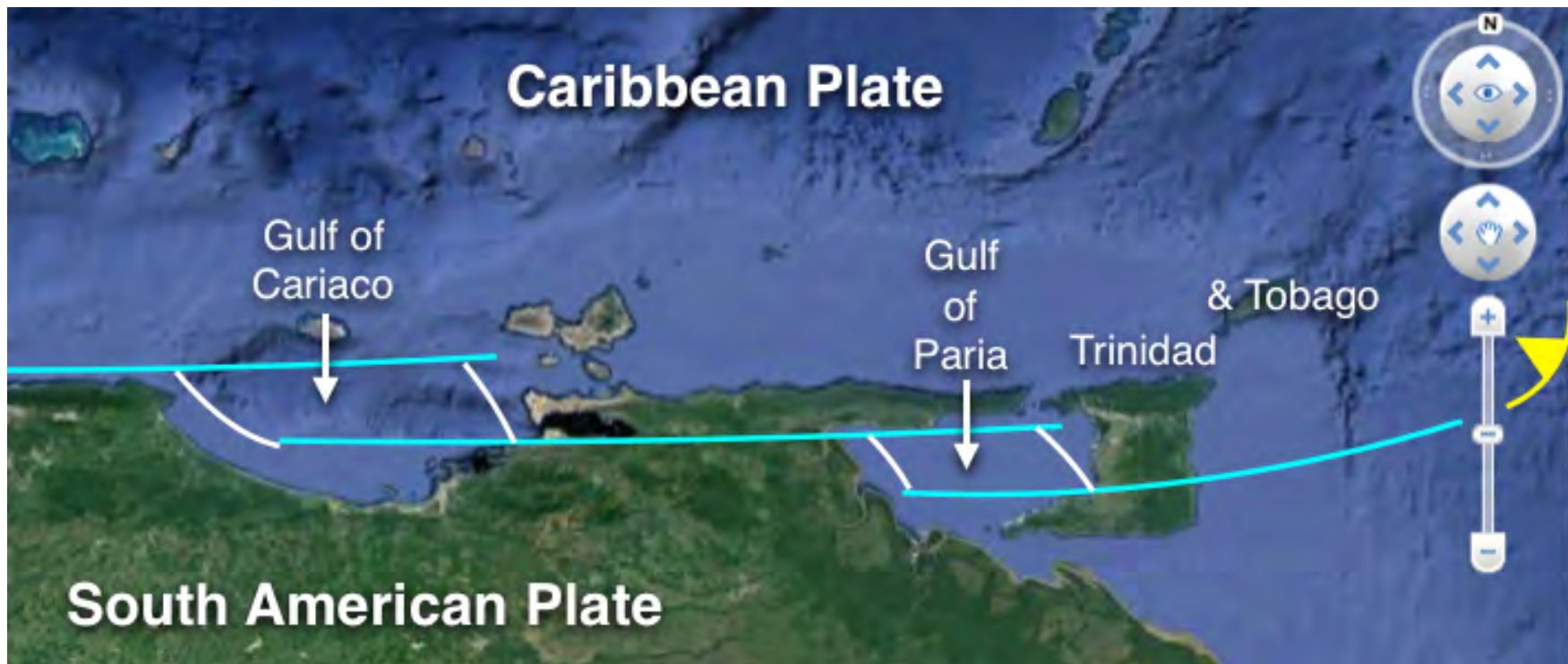
The Southern Caribbean transform includes releasing bends

The southern boundary of the Caribbean Plate includes a number of releasing bends—the opposite of the constraining bend that created Jamaica, for example. The component of tension at releasing bends opened up the Gulf of Cariaco in Venezuela and the Gulf of Paria, which formed as the continental crust of Trinidad rifted away from South America (Fig. 31). This combined with

complex thrust tectonics (not shown) to create hydrocarbon traps. Like Puerto Rico, Tobago contains limestones and volcanics (in this case Cretaceous).

Following eastwards, the transform fault turns north into the Lesser Antilles Trench.

Fig. 31. Releasing bends on the southern Caribbean Transform Fault.



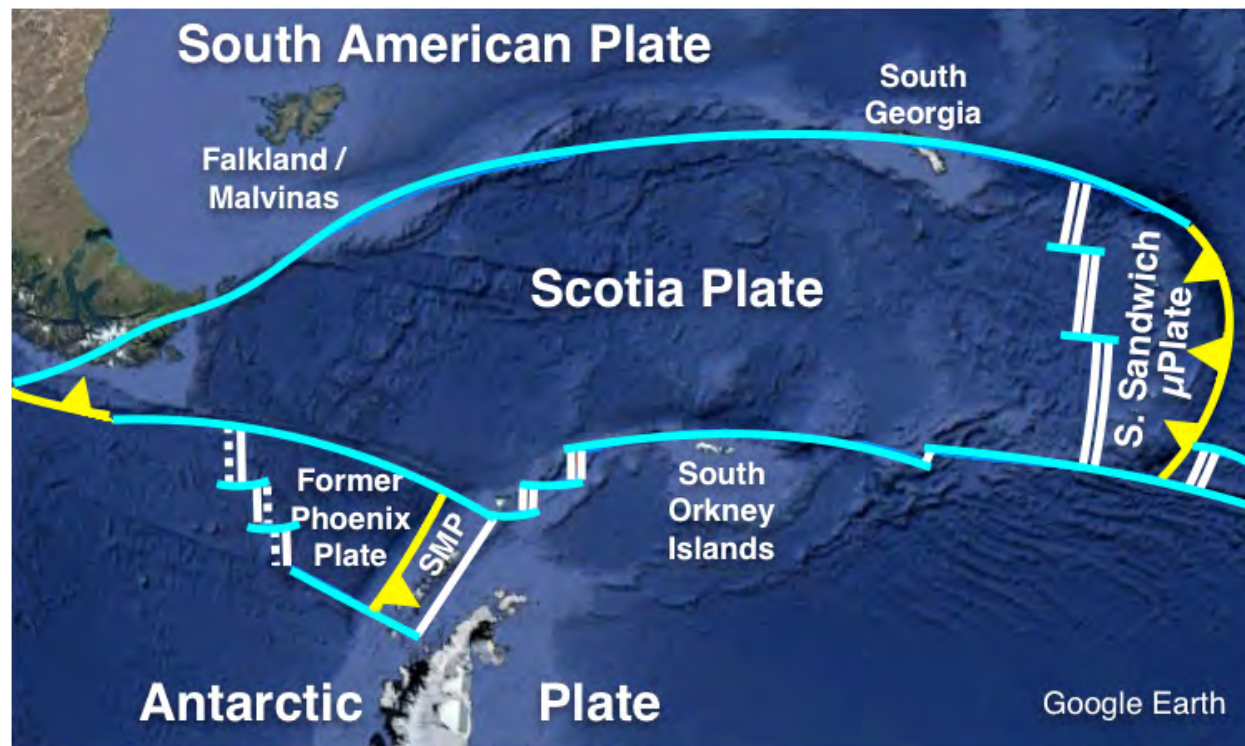
Tour Stop 32: Scotia Plate, S. Sandwich Microplate, and Shetland Microplate

The Scotia Plate is very like the Caribbean Plate

The Scotia Plate region is very similar to the Caribbean region, except not so good a Spring Break destination! Also, the oceanic crustal ages are very different. Figure 32 shows its boundaries. It is thought to have formed in situ in a gap between the Argentinian Andes and Antarctic Peninsula. The Shetland microplate is a small, complex

back-arc basin that opened due to trench rollback of the former Phoenix Plate (now part of the Antarctic Plate due to its inactivity). Arc volcanism created the South Shetland Islands. The Falkland / Malvinas Islands to the north are continental shelf. The Scotia Plate has an eastern spreading axis with the South Sandwich Plate (Fig. 32). The eastern side of the South Sandwich plate is an eastward-propagating island arc. The South American Plate has a west-dipping subduction zone under this arc.

Fig. 32. Scotia Plate, South Sandwich Plate, and Shetland Microplate (SMP). Dashed white lines are abandoned ridges.



Tour Stop 33: The Pacific Ring of Fire

The Pacific Ocean is very different

The Pacific Ocean was named *pacífico* (peaceful) by Magellan (1480–1521), because the weather was pleasant compared to his life-threatening journey around Cape Horn. Geologically, however, the Pacific is surrounded by earthquakes and volcanoes of the “Pacific Ring of Fire.”

The main spreading ridge, called the *East Pacific Rise* (Fig. 33), is not situated symmetrically mid-ocean. The Pacific Plate extends west more than 10,000 km—a quarter of Earth’s circumference. With fewer than 5000 kms from the East Pacific Rise to the Americas, there are certainly no symmetrical conjugate continental margins. Rather, stripes of progressively older, colder sea floor are truncated at the American and Asian margins of the Pacific Ocean Basin. The Asian boundary is dominated by island arcs with backarc marginal basins, whereas the eastern boundary is a combination of continental arcs and transform faults. Triple Junctions divide the lithosphere east of the rise into the Cocos, Nazca, and Antarctic Plates. The southern extension of the East Pacific Rise is called the Pacific-Antarctic Ridge.

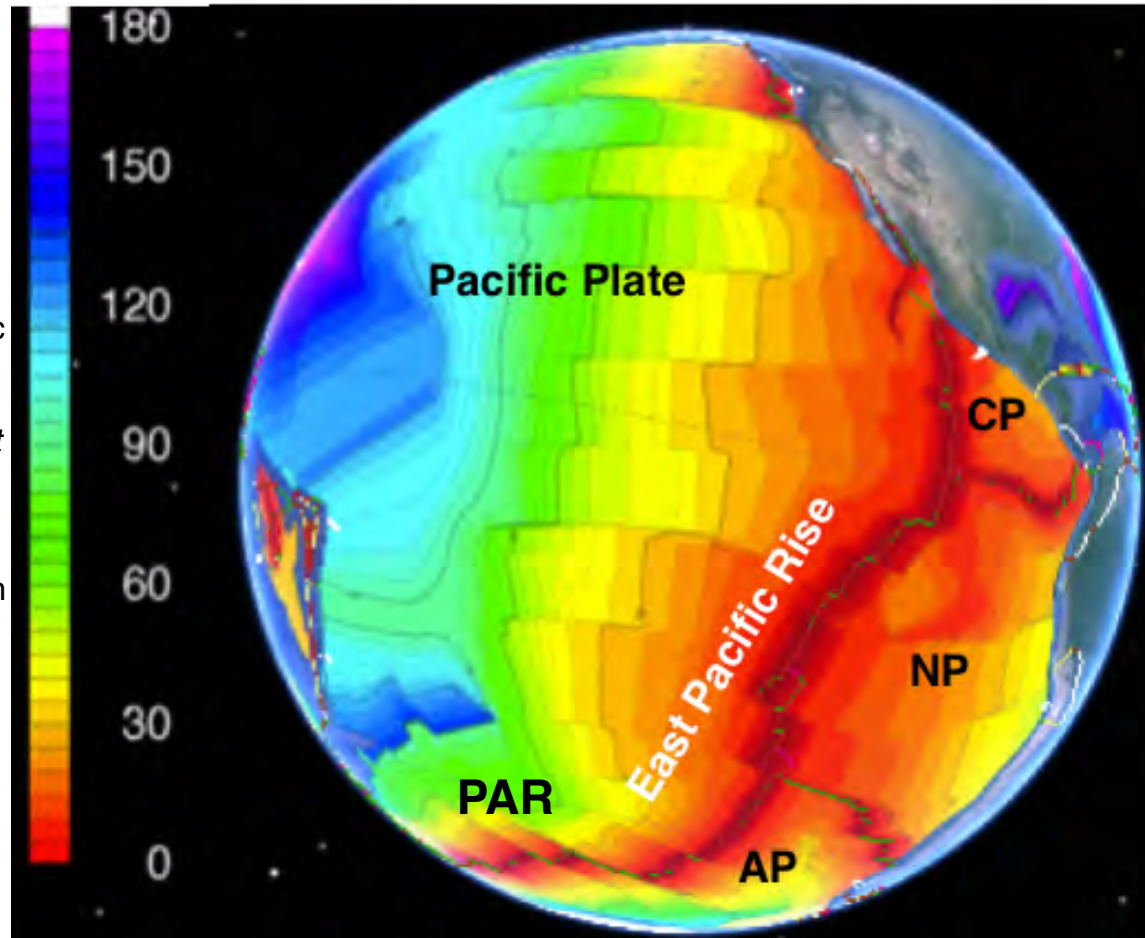


Fig. 33. The Pacific Ocean. AP=Antarctic Plate, NP=Nazca Plate, CP=Cocos Plate. PAR=Pacific-Antarctic Ridge.

Tour Stop 34: Trenches and Arcs

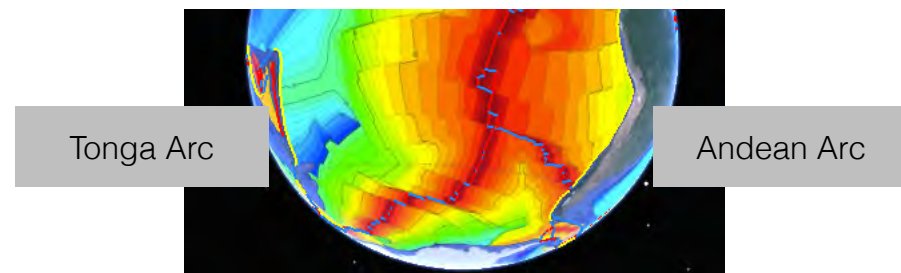
The Pacific Ocean is surrounded by trenches, continental arcs, and island arcs

The Pacific Ocean does not have any extensional passive continental margins. Instead, it is ringed by volcanic arcs. Depending on whether the volcanic arc is developed in extension or compression, either an *island arc* such as the Tonga Arc or a *continental arc* such as the Andes Mountains results (Fig. 34 a). The ocean floor drops into trenches as deep as 11,000 m (Fig. 34 b). Landward of the trenches lie features that are not seen along the Atlantic's passive margins, namely thick prisms of thrust-faulted sediments called *accretionary prisms* (also known as *accretionary wedges*).

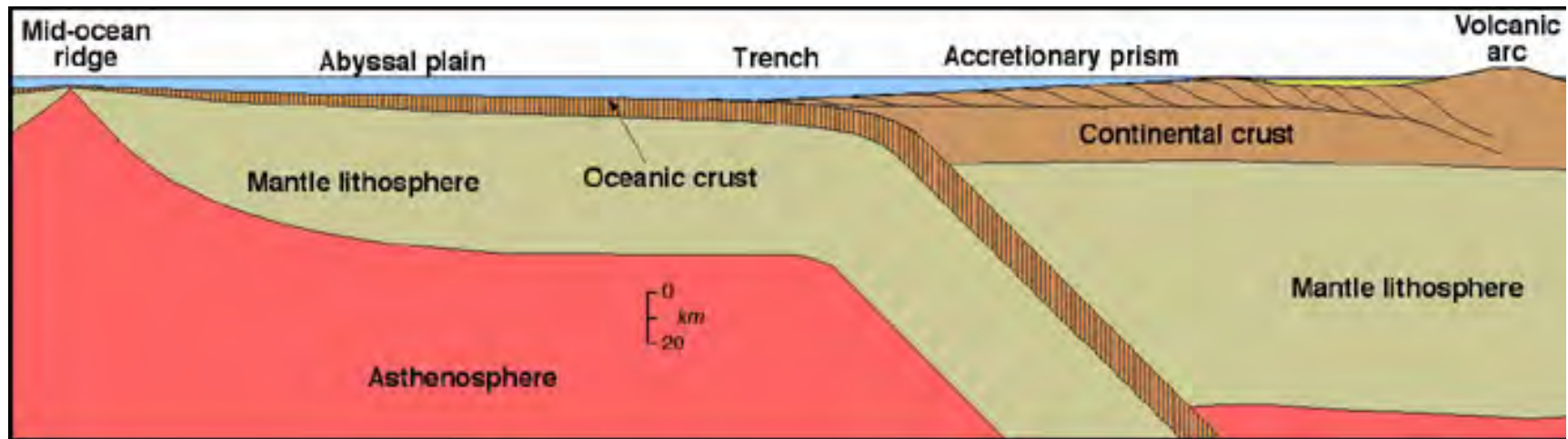
In between a few transform boundaries, strings of active volcanoes mark the Pacific margins. Typically, arc volcanoes are about 150 kilometers from the trench.

Fig. 34. a) The Pacific margins include island arcs, e.g. Tonga, and continental arcs, e.g. Andes. . b) Cross section of subduction zone. Source: <http://www.rci.rutgers.edu/~schlisch/103web/NJcontext/margins.html>.

a)



b)



Tour Stop 35: Andean Continental Arc

The Andes are a continental arc forming over a subduction zone

The Antarctic and Nazca Plates are being subducted under the Andes (Fig. 35 a) as indicated by earthquakes that are shallow under the Andean trench and deeper under the high Andes further to the east (Fig. 35 b).

As oceanic lithosphere is subducted at the trench, deep-water sediments are scraped off the basaltic crust and pile up in an accretionary prism. These fault movements

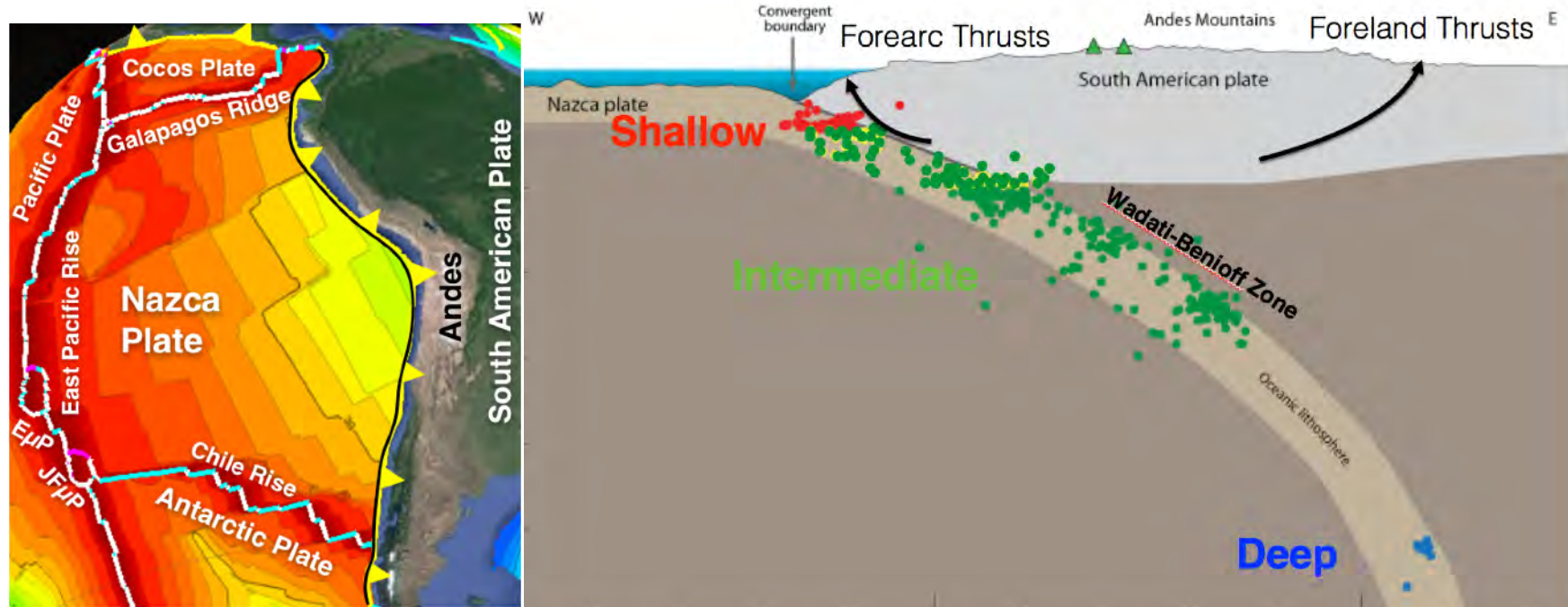
create a *forearc thrust belt* with upthrusting oriented towards the ocean. The inland side of the arc is called the foreland, and here we see a *foreland thrust belt* moving rocks up and onto the South American continental interior (Fig. 35 b).

<http://www.geode.net/MobileEarth/swf/accrete.swf>

Fig. 35. a) Andean continental arc. $E\mu P$ =Easter Microplate, $JF\mu P$ =Juan Fernandez Microplate. b) Andean earthquakes are shallow in the west and deep in the east. Source: Anne E. Egger, [VisionLearning.com](http://www.visionlearning.com).

b)

a)



Tour Stop 36: Flat-slab Subduction

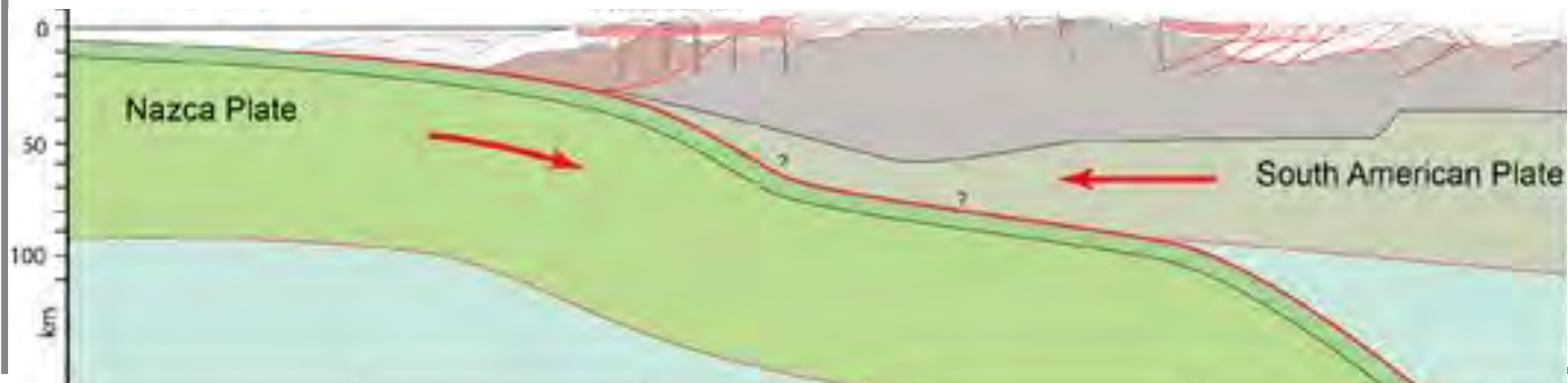
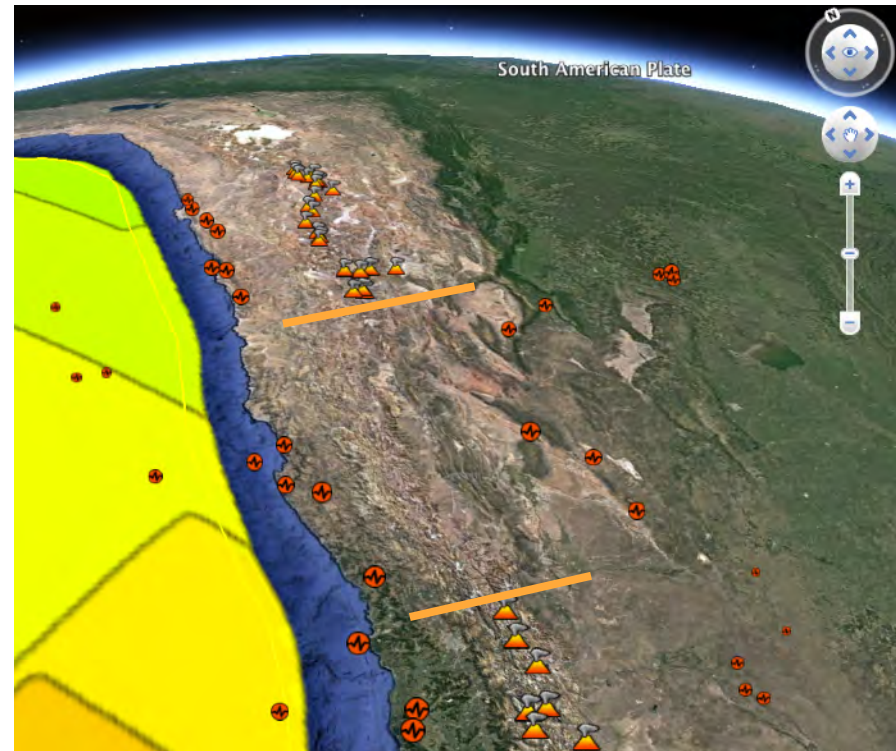
Flat slabs coincide with volcanic gaps in the Andes

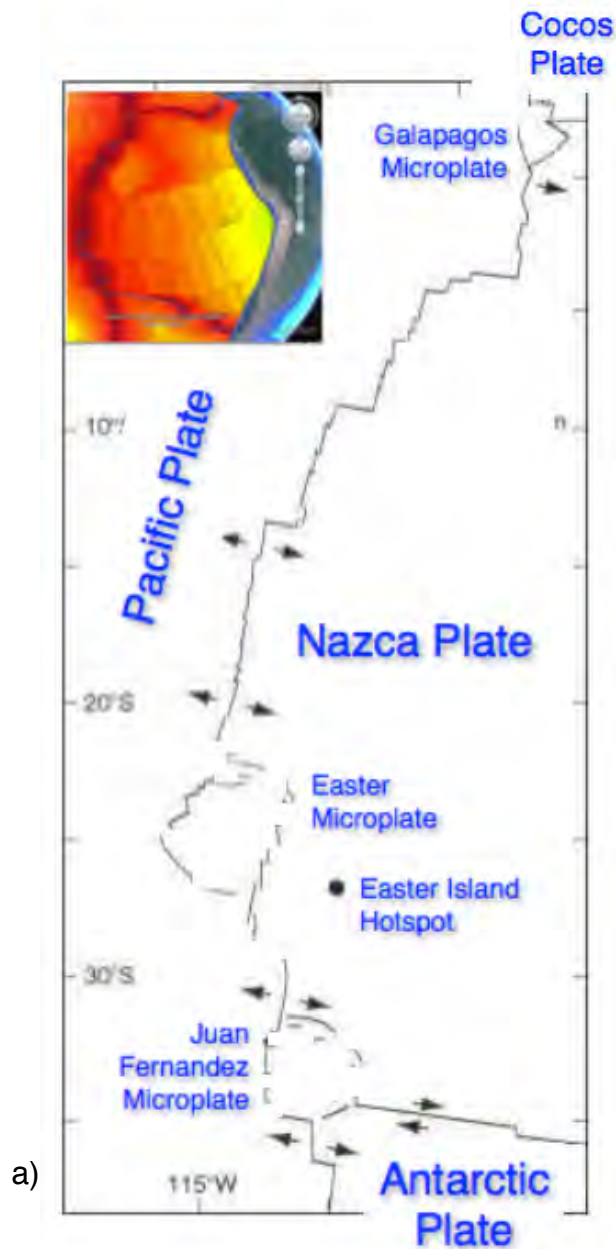
[Turn on the earthquakes and volcanoes in the Gallery Layer (Fig. 36 a).] Notice that there are a number of gaps in the Andean volcanic arc where eastern earthquakes are shallower. These are flat-slabs, with dips of $<10^\circ$ (Fig. 36 b). With no mantle wedge to partially melt, there are no volcanoes. In the volcanic regions, slabs dip at least 30° . The flat slab steepens after shifting the foreland thrust belt far into the continent creating *Laramide-style* thick-tectonics. Flat slabs occur because the Nazca plate's oceanic lithosphere is relatively young and buoyant.

Fig. 36. a) Volcanic gap in the Andes. b) Flat Slab subduction. Source: Pfiffner and Gonzalez (2013) doi:10.3390/geosciences3020262.

a)

b)





Tour Stops 37: East Pacific Rise Microplates

Three microplates form along the East Pacific Rise

Microplates on the East Pacific Rise include Juan Fernandez, Easter, and Galapagos (Fig. 37 a). Juan Fernandez and Easter are quasi-circular and formed by rotational growth at ridge offsets (Fig. 37 b).

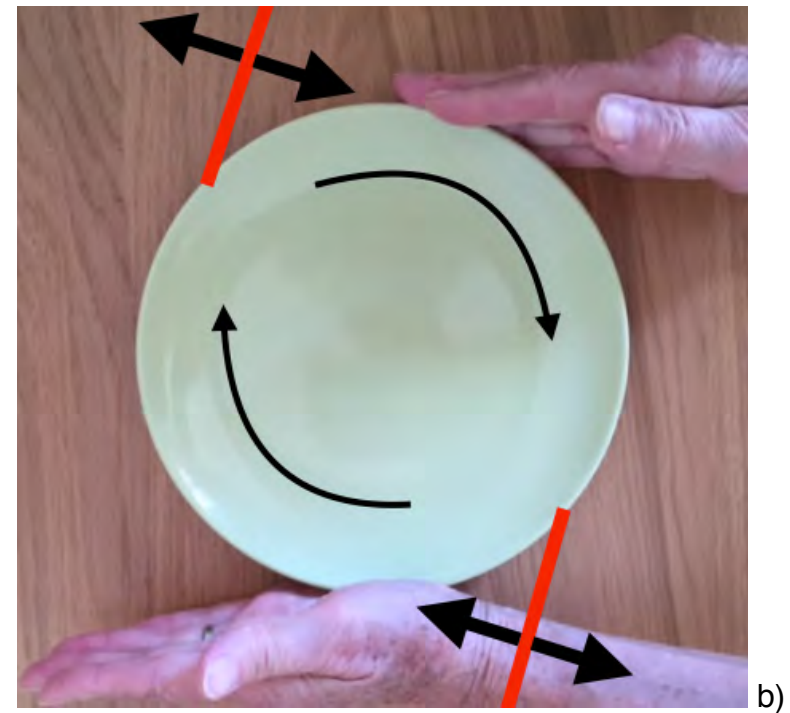


Fig. 37 a). Pacific Ocean microplates. After Bird et al. (1998).
b) Clockwise rotation of a microplate. Basaltic crust is created near the hands. Photo: Carol Simpson.

Tour Stop 38: Galapagos Microplate

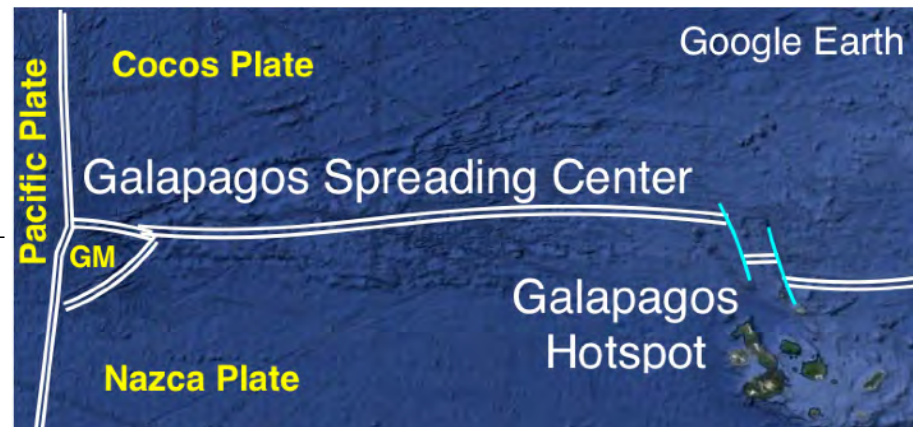
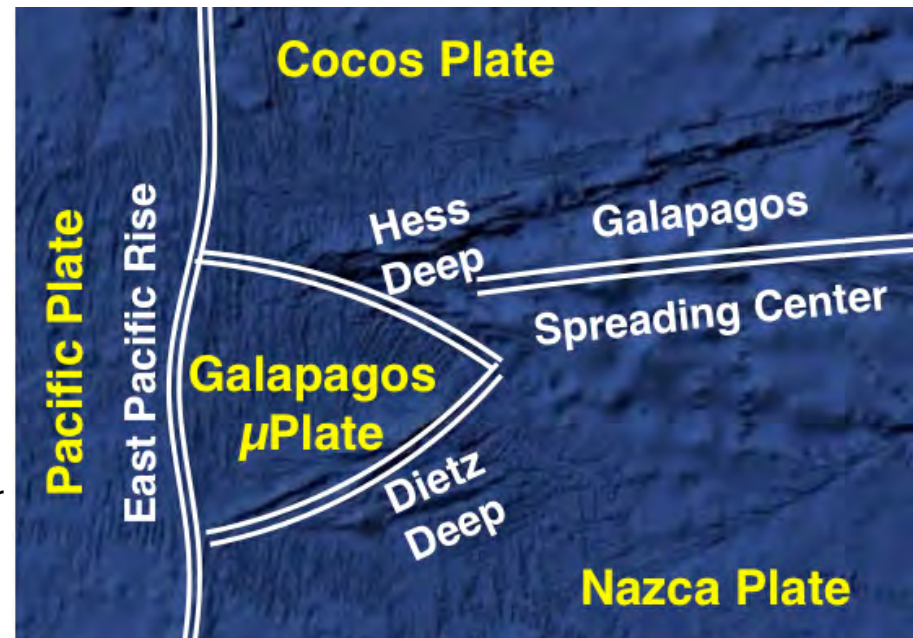
The Galapagos Microplate formed on the East Pacific Rise

The third significant microplate on the East Pacific Rise is the Galapagos Microplate (Fig. 38 a). The Galapagos Microplate is about 13,000 km² and grew at a ridge-ridge triple junction during the last 1 million years. It is quasi-triangular, like the Azores diffuse extension region and it is rotating clockwise at about 6° per million years.

The Galapagos Islands are not on the Galapagos Microplate. They lie to the east, atop the Galapagos mantle hotspot, south of the Galapagos Spreading Center (Fig. 38 b). There are associated fault scarps and “deeps.”

The Galapagos Microplate is important in serving as a present day analog for the birth of the Pacific Plate.

Fig. 38. a) Triangular Galapagos Microplate. b) Galapagos Islands formed atop the Galapagos Hotspot. GM=Galapagos Microplate.



Tour Stop 39: Origin of Pacific Plate

The Pacific Plate was born at sea!

Unlike the Atlantic oceanic lithosphere that formed by rifting of conjugate now-passive continental margins, the gigantic Pacific Plate started as a tiny triangular microplate. Consequently, the oldest part of the plate forms a nested triangular pattern of ages (Fig. 39 a).

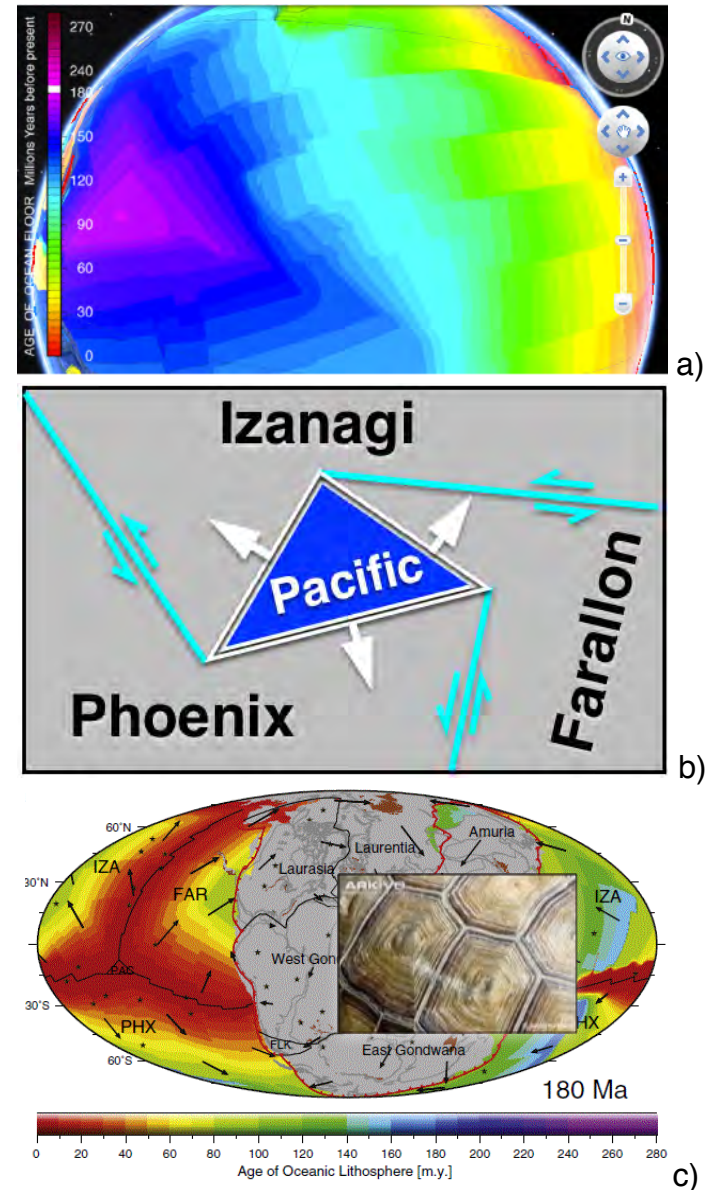
Advanced Discussion:

Three former plates—Izanagi, Farallon, and Phoenix — met at an unstable transform-transform-transform triple junction (Fig. 39 b). It evolved into a stable ridge-ridge-ridge triple junction, the site of the Pacific Plate's growth (Fig. 39 c). Surrounded by spreading ridges, the Pacific Plate grew rapidly, like a tortoise shell (Fig. 39 c-inset). The Pacific Plate never had passive continental margins —it was born at sea!

What happened to the Izanagi, Farallon, and Phoenix Plates? They mainly subducted leaving only fragments which are renamed (e.g., Cocos Plate):

<https://youtu.be/vohv-kVfFAs>.

Fig. 39. a) Ages on Google Earth show that the Pacific Plate grew from a triangular microplate. b) Growth of triangular microplate at triple junction, simplified from Boschman & van Hinsbergen (2016). c) Former Izanagi (IZA), Farallon (FAR), and Phoenix (PHX) plates. Inset: Analogous tortoise growth rings. Sources: Seton et. al. (2012, fig. 19). Inset: arkive.org © Jacob Kirkland.



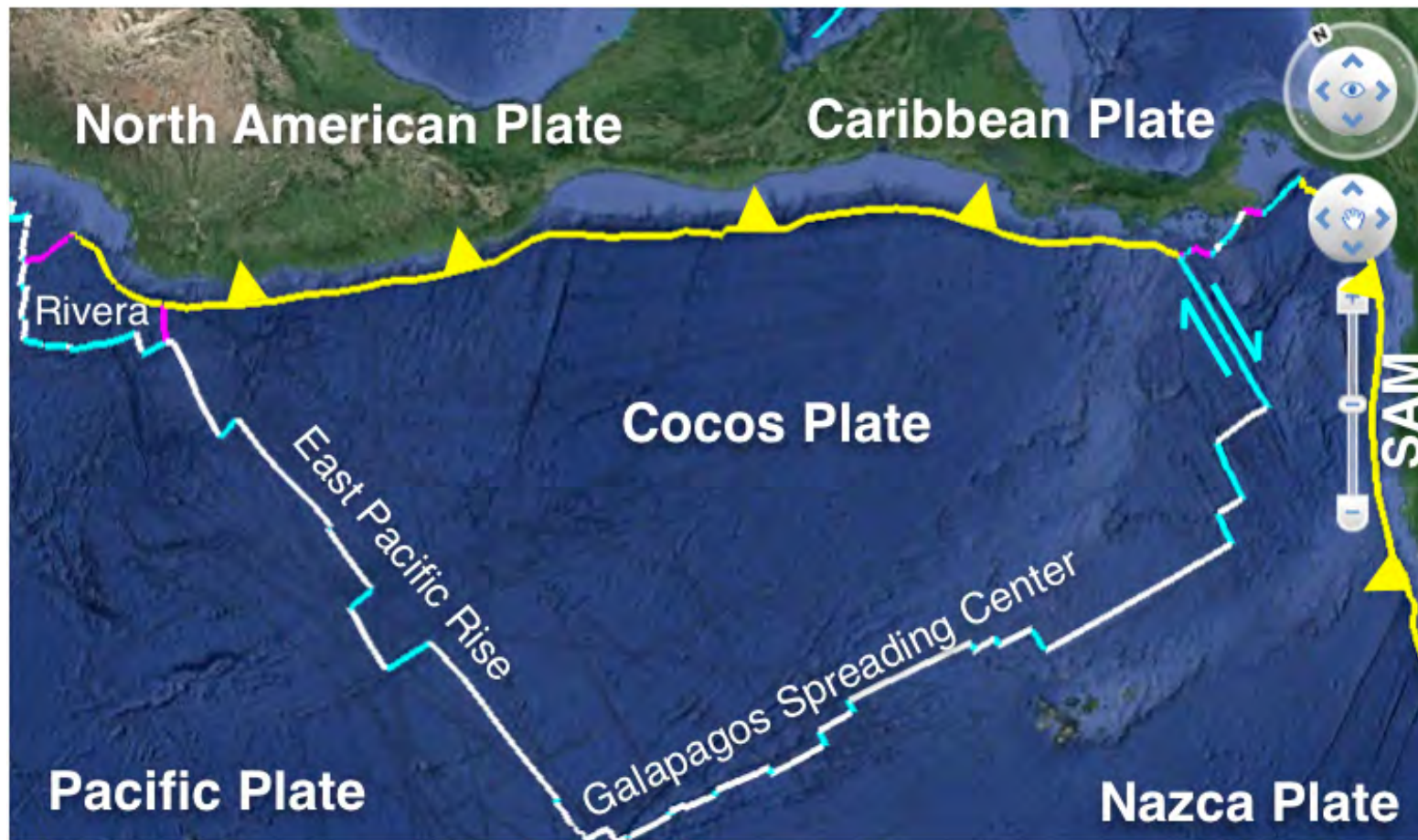
Tour Stop 40: Cocos Plate

Subduction of the Cocos Plate is building the continental arc of Central America

East of the East Pacific Rise, the Cocos Plate is being subducted under Central America and it is building a

continental arc on the western boundary of the North American Plate and Caribbean Plate (Fig. 40) The Cocos Plate and Rivera Microplate were part of the former Farallon Plate along with the Juan de Fuca and Gorda fragments before subduction of parts of the East Pacific Rise.

Fig. 40. Cocos Plate subduction built the Central American Arc.



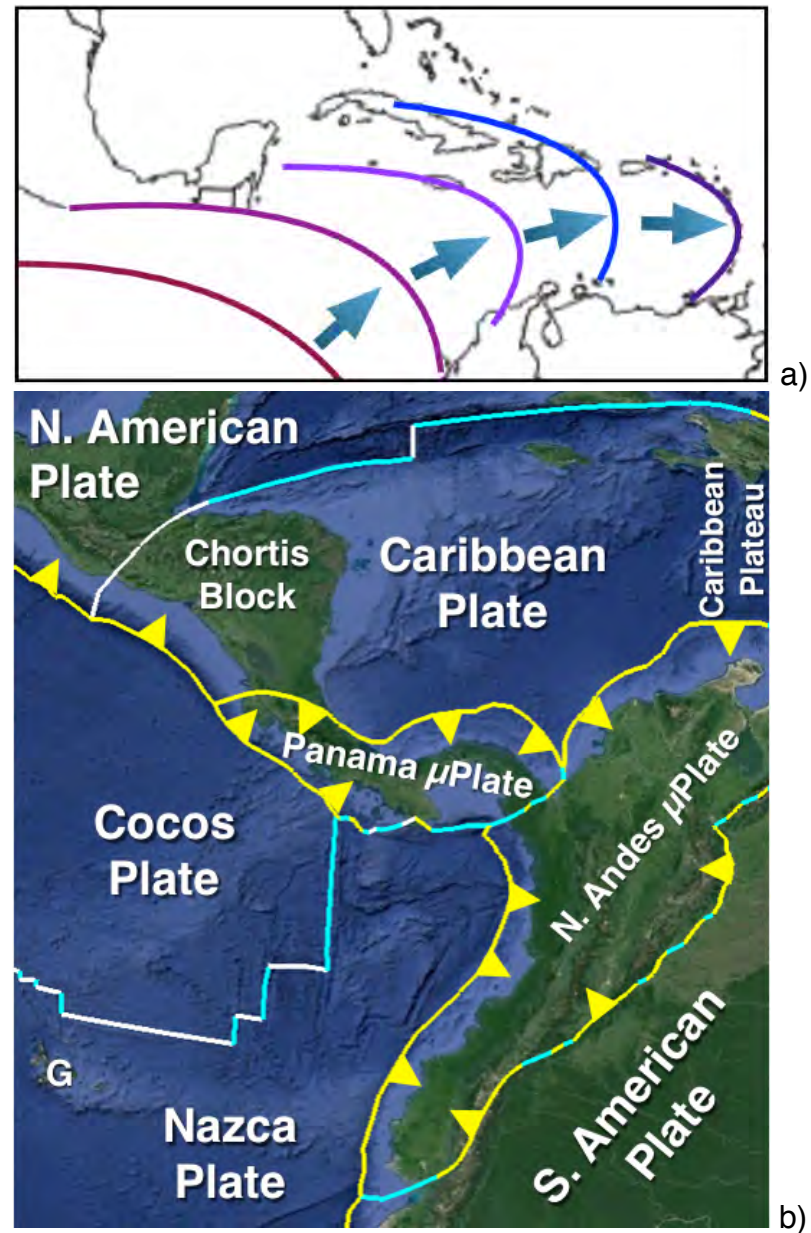
Tour Stop 41: Caribbean Plate Revisited

The are competing hypotheses for the formation of the Caribbean Plate

There are competing hypotheses for the formation of the Caribbean Plate. One argues that the 20 km thick oceanic crust of the Caribbean Plateau and other smaller very thick blocks of oceanic crust formed as the Caribbean Large Igneous Province over the Galapagos hotspot in the Cretaceous and then migrated into a pre-existing Jurassic oceanic gap between the Americas (Fig. 41 a). A second model has the Caribbean forming in situ as part of the spreading axis of the Jurassic North Atlantic Ocean. The Pacific model does not explain the fact that the continental Chortis Block (Fig. 41 b) does not appear to have rotated. The in situ model does not account for the Caribbean Plateau unless one imagines a Caribbean hotspot there.

GPS data are used to define two microplates south of the Caribbean Plate, the Panama Microplate and the North Andes Microplate.

Fig. 41. a) Propagation of Caribbean oceanic lithosphere between the Americas. b) Complex arc building and microplates in Central America. Galapagos hotspot.



Tour Stop 42: Ridge Jumps and Ridge Subduction

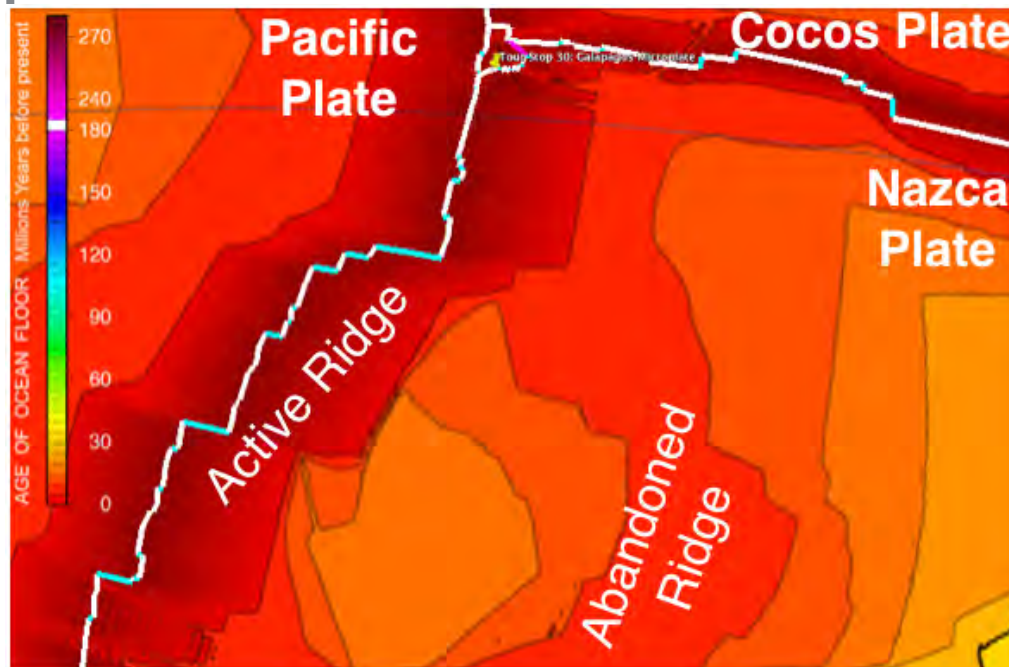
Ridges jump and create complexity when subducted

Plates do not age progressively away from the East Pacific Rise. There is a recently abandoned spreading ridge on the Nazca Plate to the east of the currently active ridge (Fig. 42 a). Similarly, on the Pacific Plate south of Baja California, active spreading has ceased

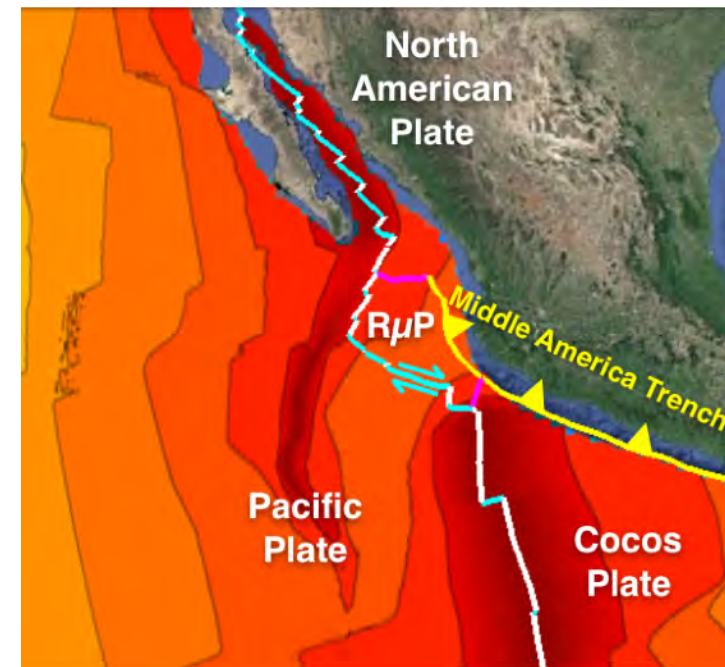
south of the Rivera Transform Fault bounding the Rivera Microplate (Fig. 42 b). When an active ridge is subducted, lava cannot add to the edges of the still-separating plates. The result is a tectonic window in the slab through which hot asthenosphere can bake the overlying accretionary prism sediments, creating a *tectonic mélange*.

Fig. 42. a). Ridge jump on the Nazca Plate. b) Abandoned ridge south of Baja California. R μ P=Rivera Microplate.

a)



b)



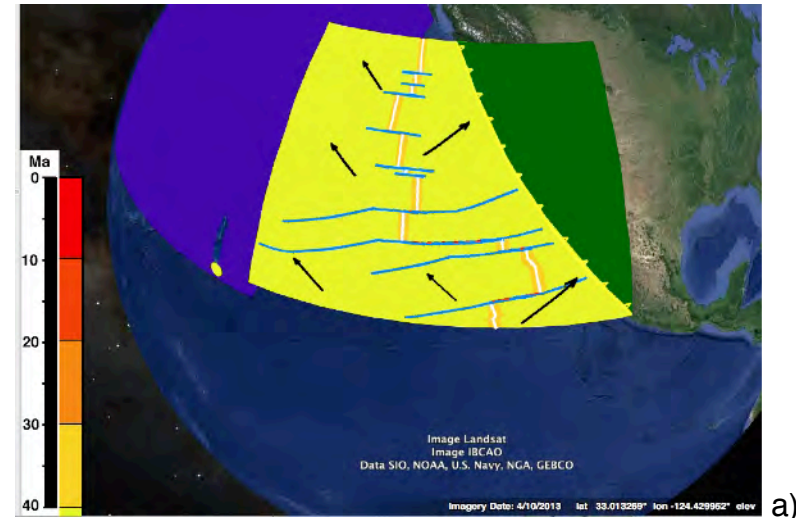
Tour Stop 43: The Former Farallon Plate

Western U.S. transform faults resulted from ridge subduction

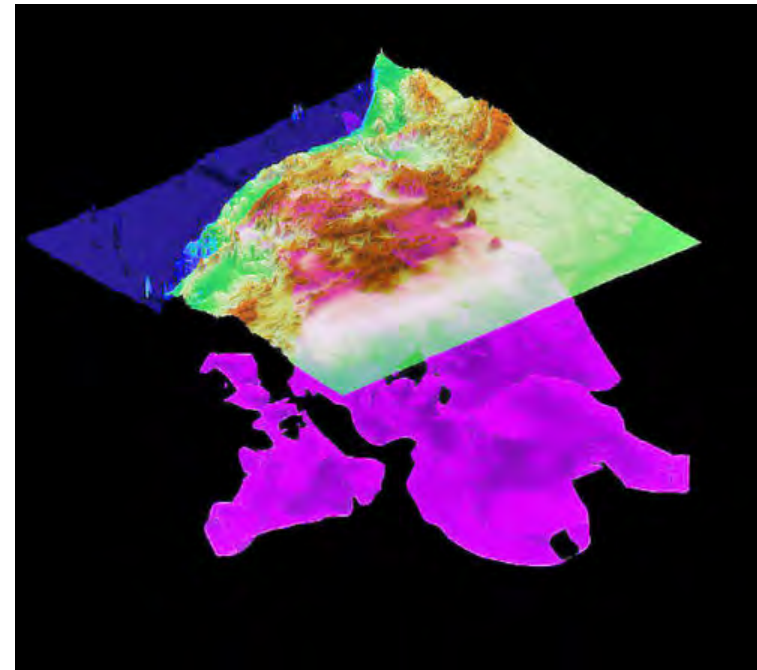
As the Farallon Plate's ridge was subducted, the Pacific Plate came into contact with the North American Plate. As explained at the next stop, because of northward ridge motion, the Pacific Plate's motion relative to North America is strike-slip (Fig. 43 a).

The result is the formation and growth of transform plate boundaries—the San Andreas Fault in California and Queen Charlotte Fault west of British Columbia. This results in transform-transform-trench triple junctions that migrate with time as the transforms grow. The Mendicino Triple Junction is a prime example.

Seismic tomography reveals an extensive slab under western north America (Fig. 43 b). This is the graveyard of the Farallon Plate.



a)



b)

Fig. 43. a) Still from animation of the evolution of the San Andreas Fault. b) Seismic tomography reveals the subducted Farallon slab. Source: Karin Sigloch, U. Munich. <http://www.princeton.edu/artofscience/2009/one.php%3Fid=1100.html>.

Tour Stop 44: Eastern Pacific Ocean

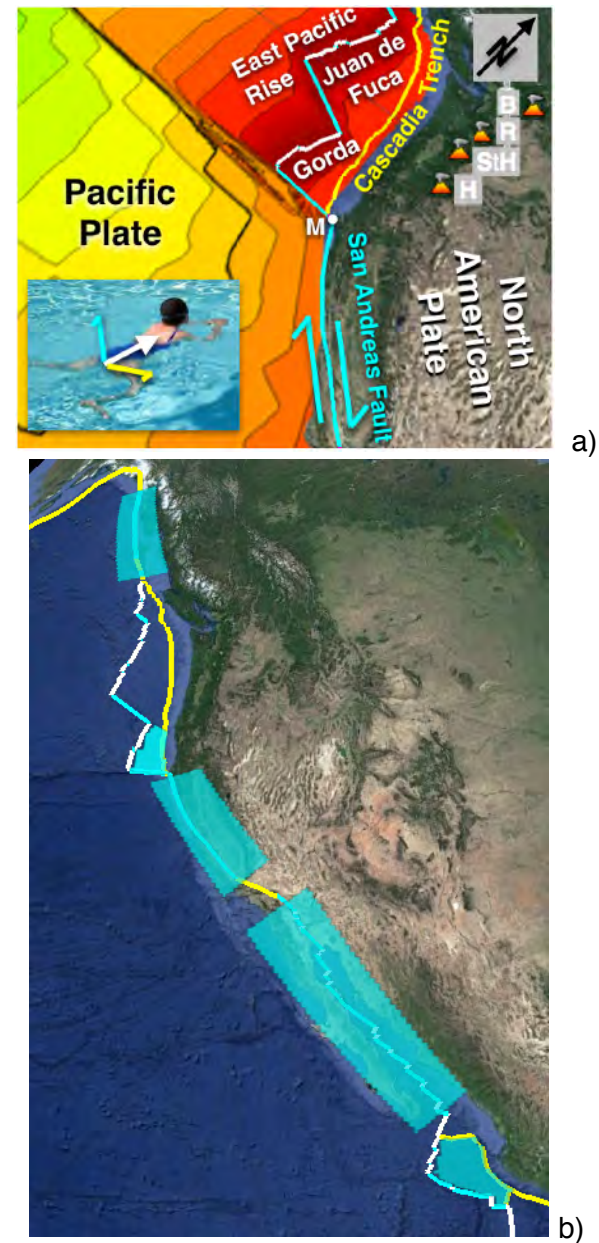
The subducting lithosphere in the eastern Pacific is much younger than in the west

Some 30 million years ago, a continuous Farallon Plate and the Pacific Plate were moving away from the East Pacific Rise, but the ridge itself was moving northeast and being subducted. This is analogous to a breaststroke swimmer (Fig. 44 a). Her outward moving hands represent the plates spreading away from the ridge—her forward-moving body represents the subducting ridge itself.

Because of ridge offsets on transform faults, the former Farallon Plate was segmented and parts were renamed the Juan de Fuca, Gorda Plate, and Cocos Plate. Subduction in Cascadia created Mount Rainier, Mount Hood, Mount Baker, Mount Saint Helens, etc.

The transform boundaries between the Pacific and North American Plates are diffuse, with shear deformation spread over wide areas (Fig. 44 b).

Fig. 44. a) The San Andreas fault zone—the transform boundary between the Pacific and North American plates—joins the East Pacific Rise in the Gulf of California to the Cascadia subduction zone, Oregon and Washington State. Inset: Analogy to breast stroke swimmer. Source: athletesedge.info. b) Blue regions are diffuse shear zones.



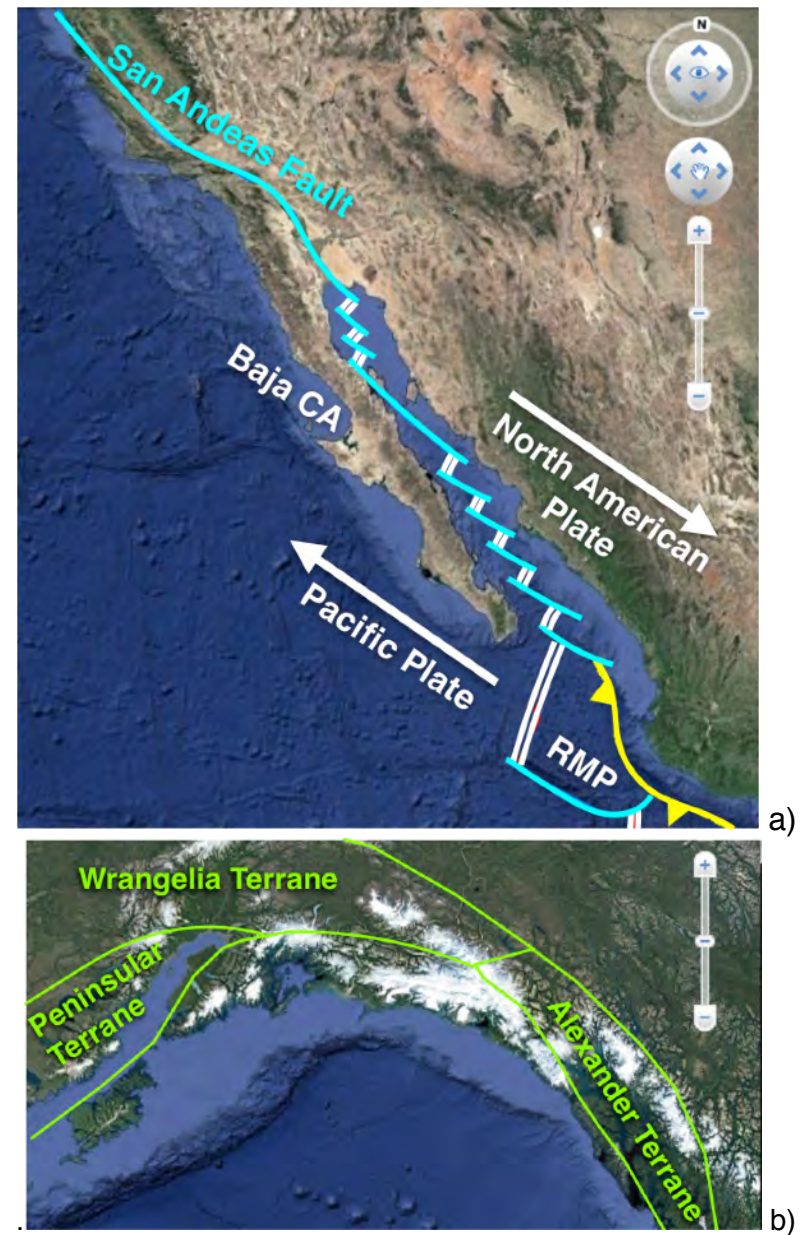
Tour Stop 45: Exotic Terranes

Exotic terranes are slivers of crust that have been transported afar and collided with other land masses

The migration of an island arc by trench rollback is an example of an exotic terrane, which is defined as a far-traveled sliver of Earth's lithosphere. An alternative mode of transporting continental blocks across the oceans utilizes transform faults. The San Andreas Fault is close to making an island out of Baja California (Fig. 45 a). Eventually, Baja will cross the ocean and slam into (technically, "be accreted to") southern Alaska, welding itself onto previous far-travelled slivers of continental crust.

Some active-margin states such as Alaska and active-margin countries such as Chile are built up by slice upon slice of exotic terrane. The Pacific Rim Terrane rode on the Kula Plate until it was attached to North America to form Vancouver Island. Other examples include the Wrangellia Terrane, Peninsular Terrane, and Alexander Terrane (Fig. 45 b).

Fig. 45. a) Transform faults (cyan) are facilitating the movement of Baja CA to the northwest relative to western North America. Eventually, warm and sunny Baja will collide with the southern margin of cold and snowy Alaska! RMP = Rivera Microplate. b) Alaskan terranes.



Tour Stop 46: The Aleutian Arc

The Aleutian Arc marks the transition from Island Arc to Continental Arc

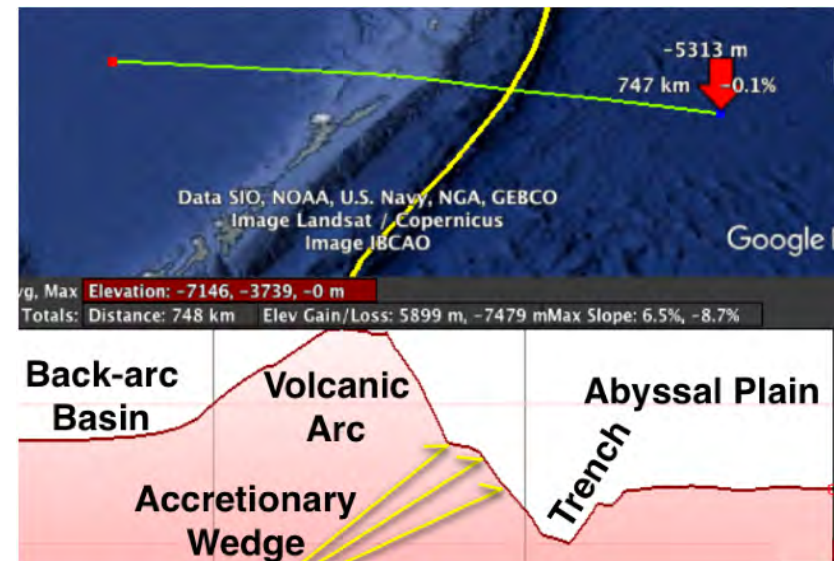
In southern Alaska, arc volcanism transitions from continental arc to island arc in the Aleutian Archipelago. Along the Aleutian Arc, the Pacific Plate is subducting under the North American Plate in the Aleutian Trench (Fig. 46 a). A marginal basin called the Bering Sea formed when the North American Plate boundary jumped from the north side of the Bering Sea to the Aleutian Arc, trapping a fragment of oceanic crust.

North of the Aleutians, there is an extinct Cretaceous arc called the Bowers Arc (Fig. 46 b). None of its volcanoes break surface any more.

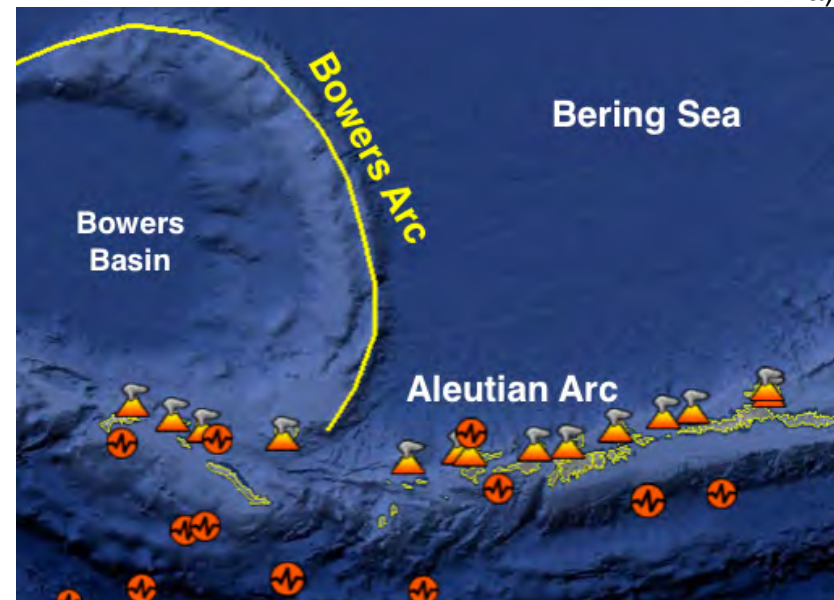
Note our separate Aleutian exercise on the SERC web site:

<http://serc.carleton.edu/NAGTWorkshops/intro/activities/28809.html>

Fig. 46. a) A Google Earth section of the Aleutian arc shows geologic features in a vertical slice that is represented by the green line on the map. b) The Bower Arc in the Bering Sea.



a)



b)

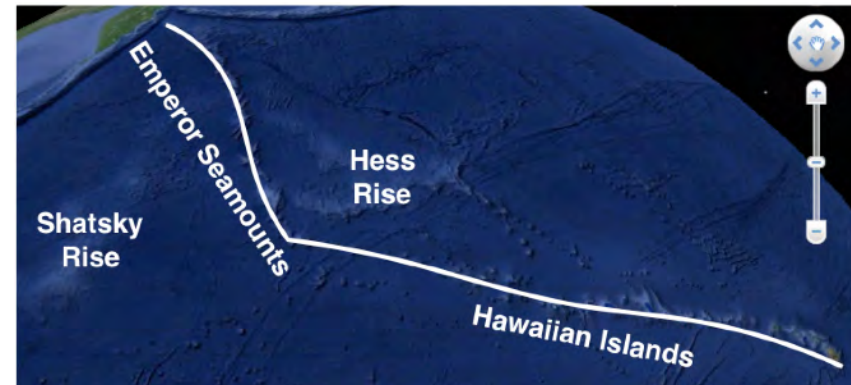
Tour Stop 47: Hawaii–Emperor Seamounts

Pacific hotspot trails form doglegs

[Turn off the ages overlays.] The Pacific Plate contains several chains of islands and seamounts. The most prominent is the Hawaiian Islands and Emperor Seamounts (Fig. 47 a). The volcanic islands are far from any plate boundary and are formed by the passage of the Pacific Plate over a mantle hotspot (Fig. 47 b). For a long time it was thought that the dogleg was caused by a change in Pacific Plate motion at 40 m.y. ago. See:

<http://www.lions.odu.edu/~ddepaor/swf/Hawaii.swf>

However, changes in paleolatitude of islands suggest that a “mantle wind” may have deflected the plume (Fig. 47 c). If the hotspot were stationary, the islands would all have the same paleolatitude. The relative contribution of hotspot migration and change in plate motion is still under debate. The Emperor Seamounts are surrounded by oceanic plateaus, the Hess Rise and Shatsky Rise. These are Large Igneous Provinces (LIPs).



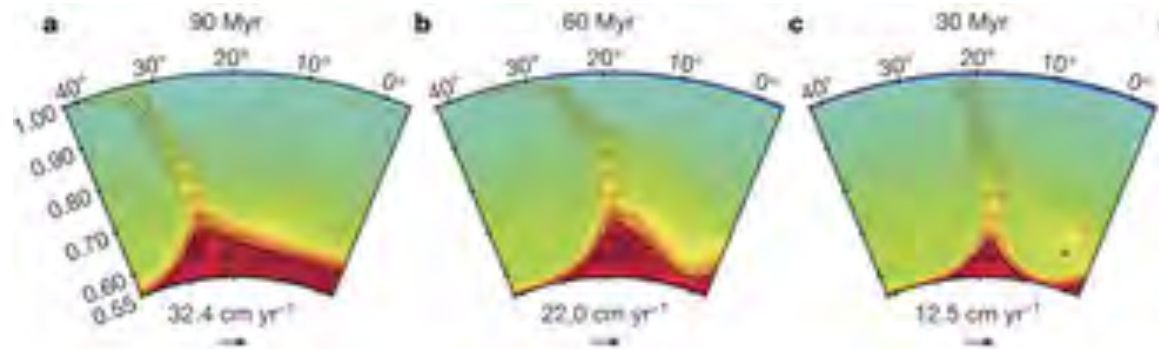
a)



b)

c)

Fig. 47. a) The Hawaiian Islands and Emperor Seamounts. b) Passage of the Pacific Plate over a deep mantle hotspot, from the author's Flash movie, above. c) Lower mantle convection may have deflected the hotspot, contributing to the dogleg. (Source Hassan et al. 2016).



Tour Stop 48: The Northwest Pacific

Subduction of the Emperor
Seamounts influences arcs
and backarc basins

[Toggle the ages overlay on and off.] It is thought that subduction of the Emperor Seamounts oblique to their trend (due to the dogleg) may influence the sharp angle between the Aleutian Arc-Trench and the Kamchatka Arc-Trench (Fig. 48).

A second effect of that oblique subduction may have been the initiation of seafloor spreading in the Komandorskaya Basin, western Bering Sea, about 40 million years ago—the time of the Hawaiian Islands—Emperor Seamounts dog-leg. Komandorskaya Basin is not a back-arc basin because it is on the wrong side of the Kamchatka Arc and at the wrong angle to the Aleutian Arc.

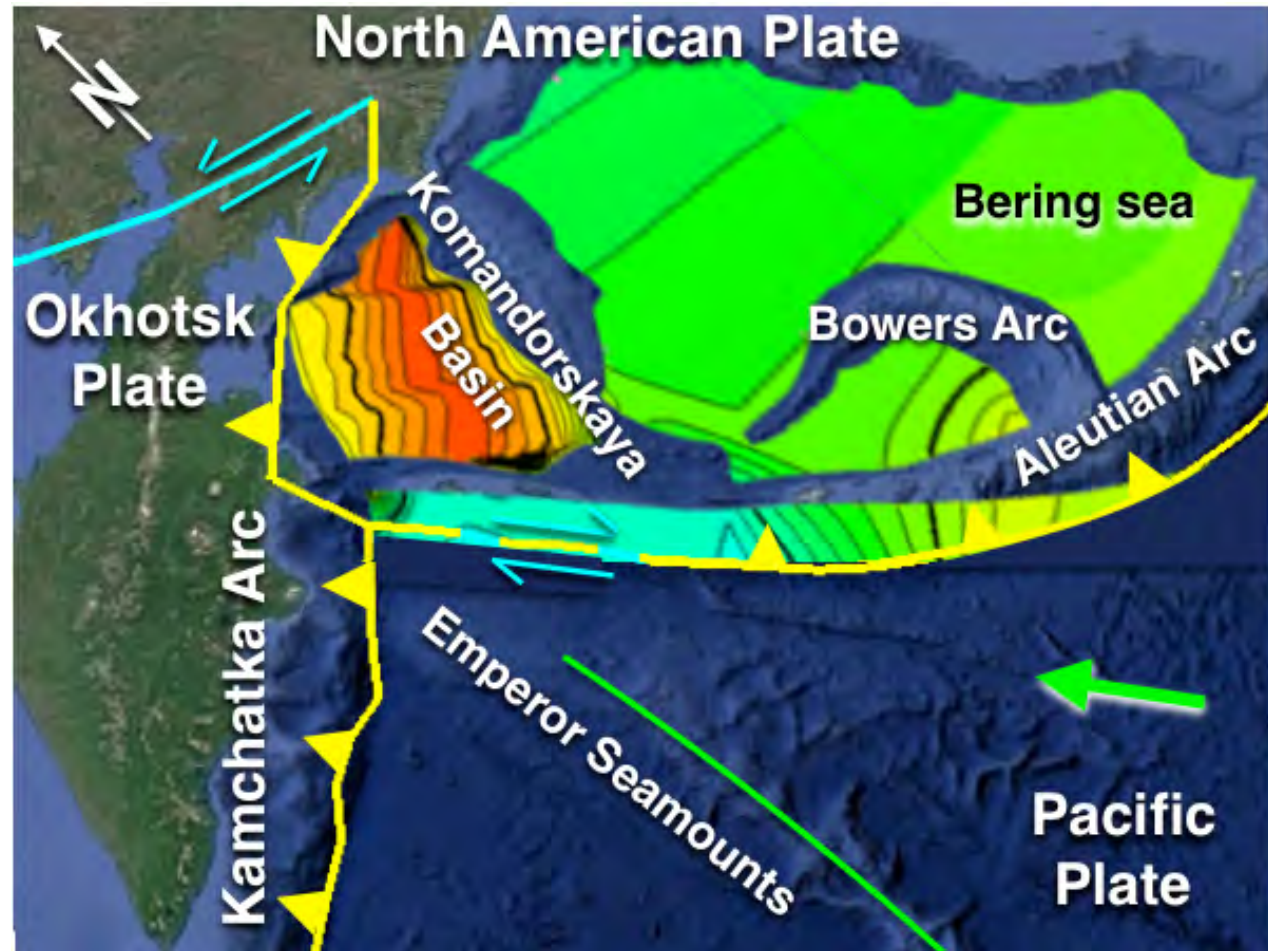


Fig. 48. Aleutian–Kamchatka jog and Komandorskaya Basin spreading. This figure is a combination of images with age data on (top) and off (bottom). It is not possible to selectively turn off regions of the age data. Green arrow=absolute Pacific Plate motion.

Tour Stop 49: Okhotsk Plate

The Okhotsk Plate is the most recently defined

The Okhotsk Plate (Fig. 49 a) is extremely remote and was the last to be defined (it was formerly considered part of the North American Plate). Its eastern boundary is defined by the volcanic arc of northeast Japan, the Kuril Islands, and the Kamchatka Peninsula, which sit atop a west-dipping subduction zone that is consuming the Pacific Plate. The western boundary is a zone of convergence including Sakhalin Island. The Okhotsk Sea is floored by thinned continental crust.

The Okhotsk Plate is thought to be a remnant of the former Kula Plate, a Cretaceous plate that had a triple junction with the Pacific and Farallon Plates before it was almost completely subducted (Fig. 49 b).

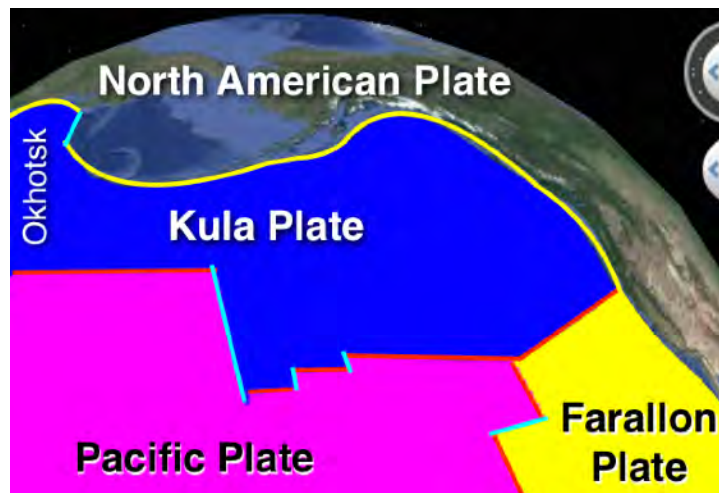


Fig. 49. a) Okhotsk Plate boundaries. b) The Kula and Farallon Plates were almost completely subducted but a fragment of the former may have survived as the Okhotsk Plate just as fragments of the latter survive as the Juan de Fuca–Gorda, and Cocos–Reviera Plates. PSP=Philippine Sea Plate.

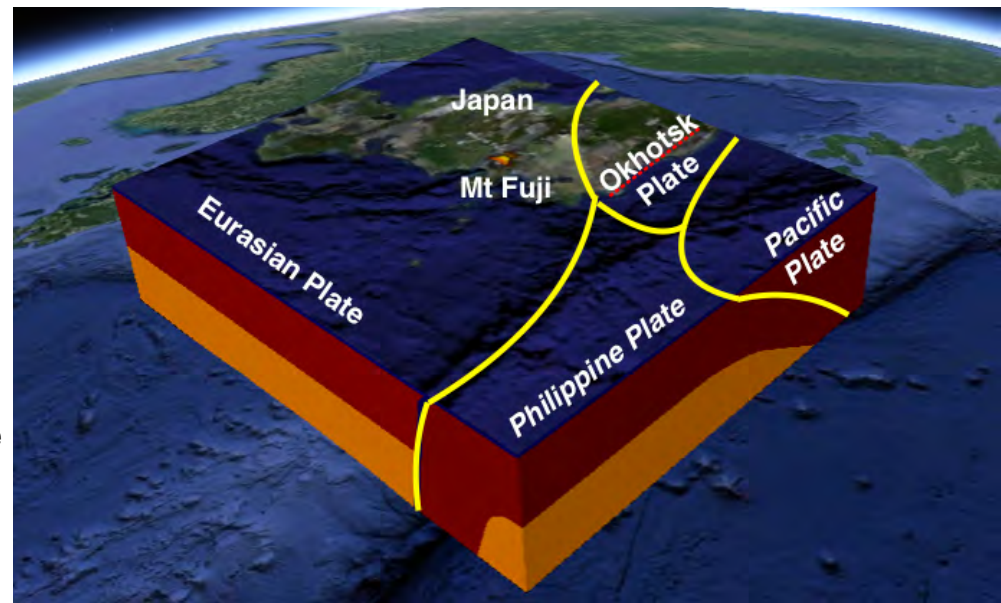
Tour Stop 50: Japan and Taiwan

Japan is a major island arc at the junction of four plates.

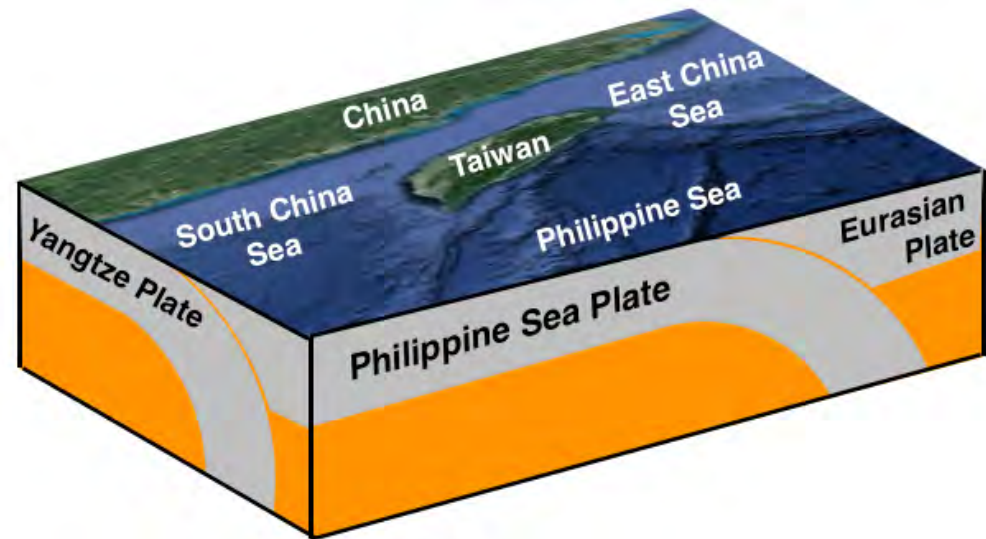
Convergence of the Philippine and Eurasian Plates has thrust up the island of Taiwan

Japan is a complex Island arc located at the junction of four plates, the Pacific, Philippine, Eurasian, and Okhotsk Plates (Fig. 50 a). This is the site of its most famous volcano, Mount Fuji.

Although most of the western side of the Pacific Ocean is marked by extensional back-arc basins, there is compression between the Philippine Sea Plate and Yangtze Plate, resulting in a stack of upthrust island arcs that form the island of Taiwan (Fig. 50 b). The western side of the Philippine Sea Plate is a zone of distributed compression called the Philippine Orogeny.



a)



b)

Fig. 50 a) An emergent block model of the complex plate intersections around Japan.
b) Taiwan is being thrust up over the Yangtze Plate in eastern China.

Tour Stop 51: Western Pacific Train Wreck

The western Pacific is a “train-wreck” of marginal basins

The western Pacific Ocean is strewn with marginal basins and minor plates or microplates (Fig. 51). The minor

Philippine Sea Plate has been spun around by interaction with its giant neighbors, the Pacific Plate to the east and Eurasian Plate to the west.

The minor Caroline Plate has an abandoned eastern rift and an active western rift in very different directions.

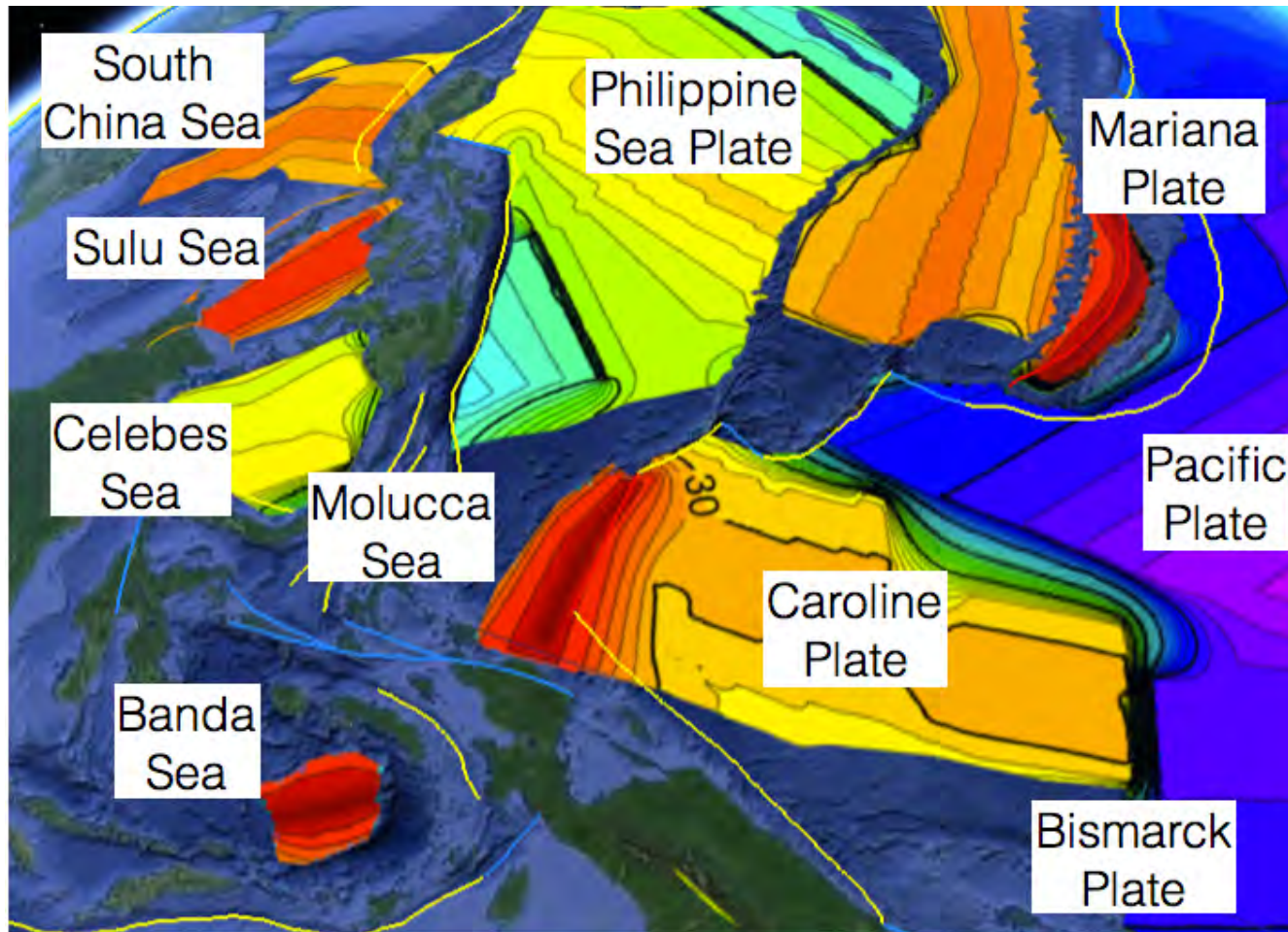


Fig. 51. The numerous plates and seas of the western Pacific region.

Tour Stop 52: Mariana Trench and Challenger Deep

Mariana Trench is the deepest place on Earth

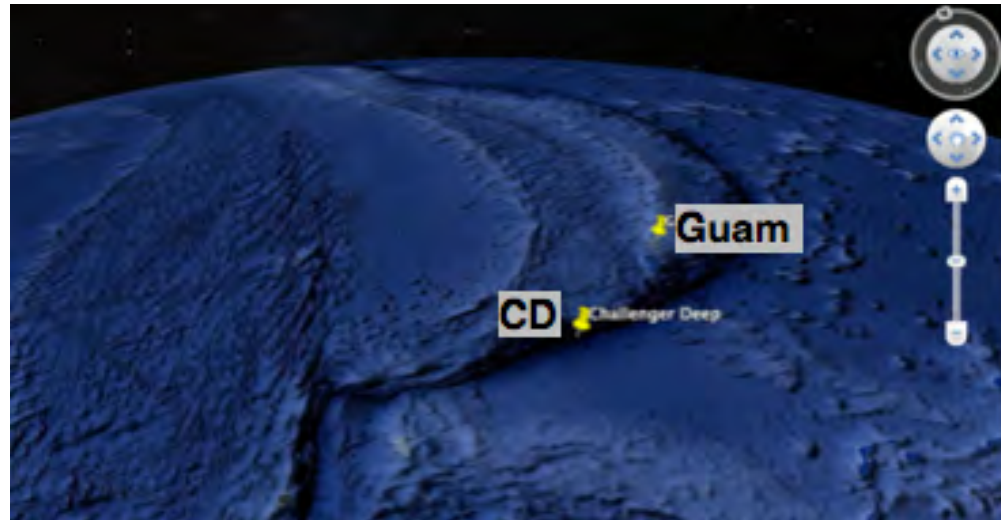
The western Pacific lithosphere is old, cold, and dense at the Mariana Trench (Fig. 52 a). The Mariana Islands are a volcanic island arc atop the steep subduction zone. They include the U.S. Territory of Guam.

Tension in the lithosphere above the slab opens a currently active *back-arc spreading center* and *marginal basin*. The lithosphere on either side of the ridge defines the Philippine and Mariana Plates.

An older abandoned marginal basin is seen to the west. The locus of subduction has periodically jumped to the east.

The deepest ocean floor on Earth is Challenger Deep (Fig. 52 b). You could hide Mount Everest under sea level with a few kilometers of water depth to spare!

Fig. 52. a) Steep subduction causes extension and roll-back in the Mariana Trench. CD=Challenger Deep. The Mariana Island Arc includes the U.S. territory of Guam. b) Mariana Trench reaches 11,000 m at Challenger Deep. .



a)

Older Marginal Basin Current Marginal Basin Pacific Plate.



b)

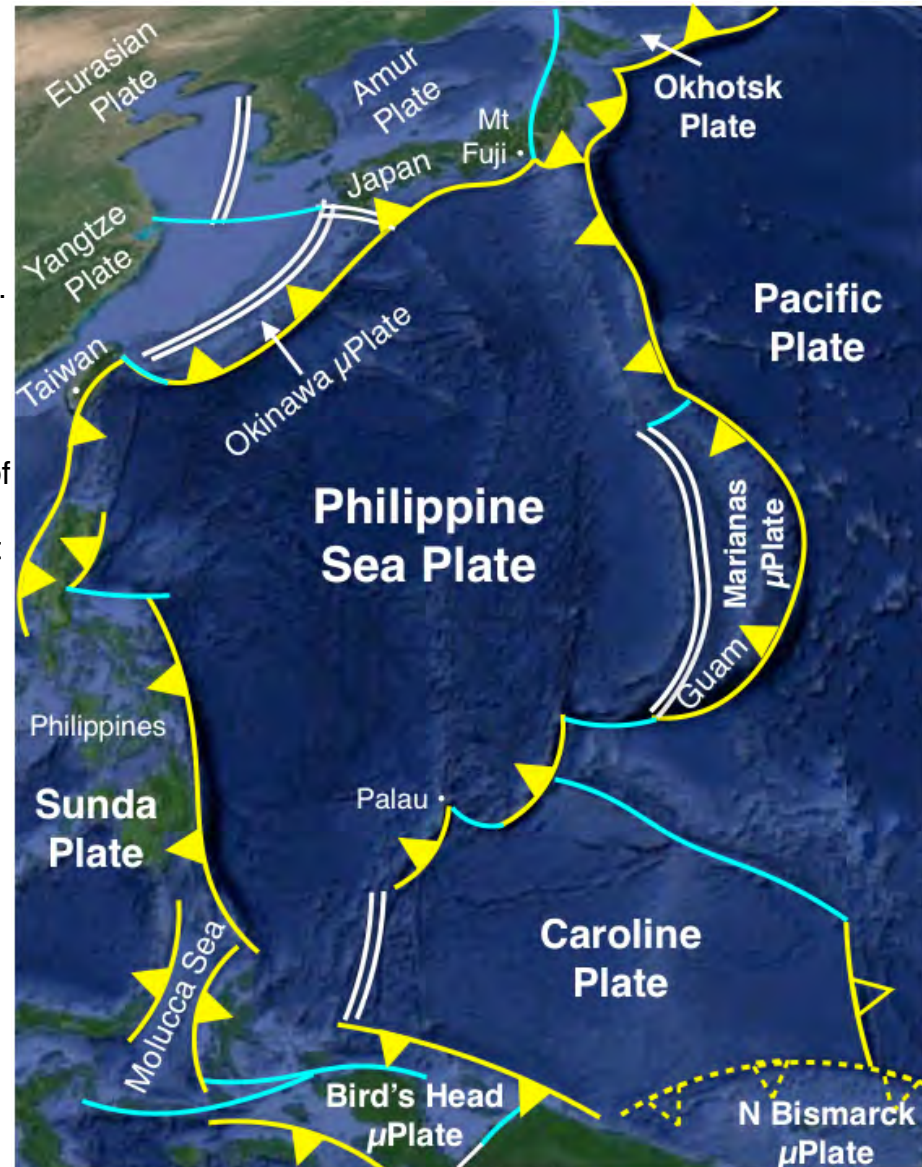
Tour Stop 53: Philippine Sea Plate and Caroline Plate

The Philippine Sea Plate is almost entirely surrounded by convergent plate boundaries

The Philippine Sea and Caroline Plates are two of the large minor plates of the western Pacific region (Fig. 53). They are mainly surrounded by convergent boundaries. The only divergent boundaries are with the Marianas Microplate and the southwestern end of the Caroline Plate. A transform partially bounds the Bird's Head Microplate to the south and the northeastern boundary of the Caroline Plate with the Pacific Plate. Relative motion between the Pacific and Caroline Plates is small and not everyone defines a separate Caroline Plate, but it is justified by GPS data. Both the Pacific and Caroline Plates are subducting under the Philippine Sea Plate. In the west the Philippine Sea Plate is subducting under the Okinawa Microplate and the minor Sunda Plate, except south of Taiwan where the denser South China Sea lithosphere causes a reversal of subduction polarity against the Yangtze Plate and in the southwest where the Molucca Sea is subducted. To the north, the Philippine Sea Plate is subducting under the Okhotsk Plate along a very short boundary.

Paleomagnetic data show that the Philippine Sea Plate has spun about 90° clockwise by dint of interaction with its neighbors.

Fig. 53. The Philippine Sea and Caroline Plates.



Tour Stop 54: Sunda Plate and Burma Microplate

The Sunda Plate and Burma Microplate are distinct from the Eurasian Plate

GPS measurements show that the regions called the minor Sunda Plate and Burma Microplate are moving relative to the Eurasian Plate, however, the precise nature of the Sunda–Eurasian boundary is subject to different interpretations. The Sunda Plate contains three abandoned ridges in the South China Sea, Sulu Sea, and Celebes Sea (Fig. 54). These are surrounded by large regions of continental crust, both emergent and submerged.

Oblique convergence between the Sunda Plate and the Indian and Australian Plates is partitioned into subduction west of Burma and Sumatra and transform motion on land. This creates the narrow strip of lithosphere called the Burma Microplate, including active spreading away from the Sunda Plate. The Aceh region of northern Sumatra was the site of a devastating Indian Ocean earthquake in 2004 that caused a tsunami that killed about a quarter million people. The Sunda Arc in Sumatra and Java is approximately the width of southern USA.

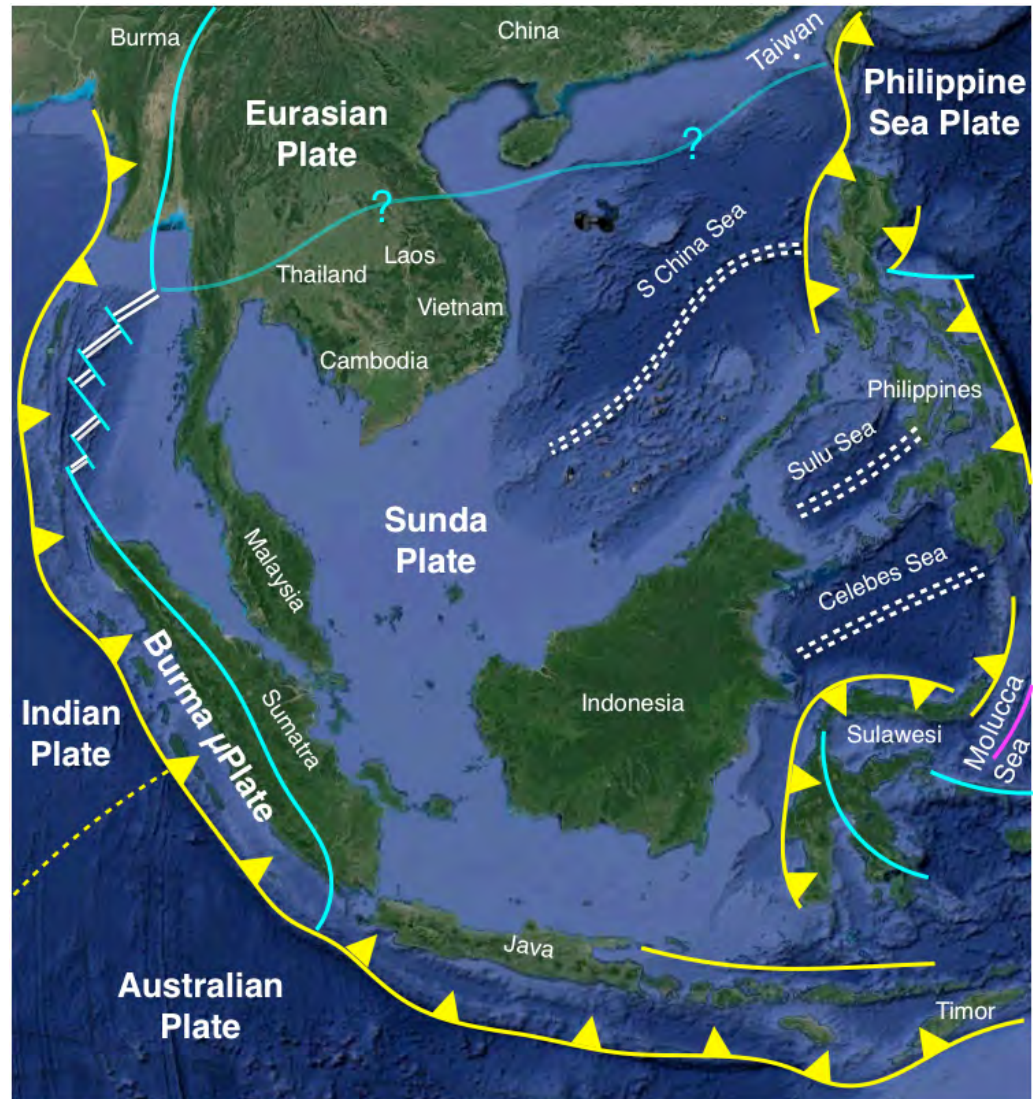


Fig. 54. The Sunda Plate and Burma Microplate.

Tour Stop 55: Eastern Indian Ocean

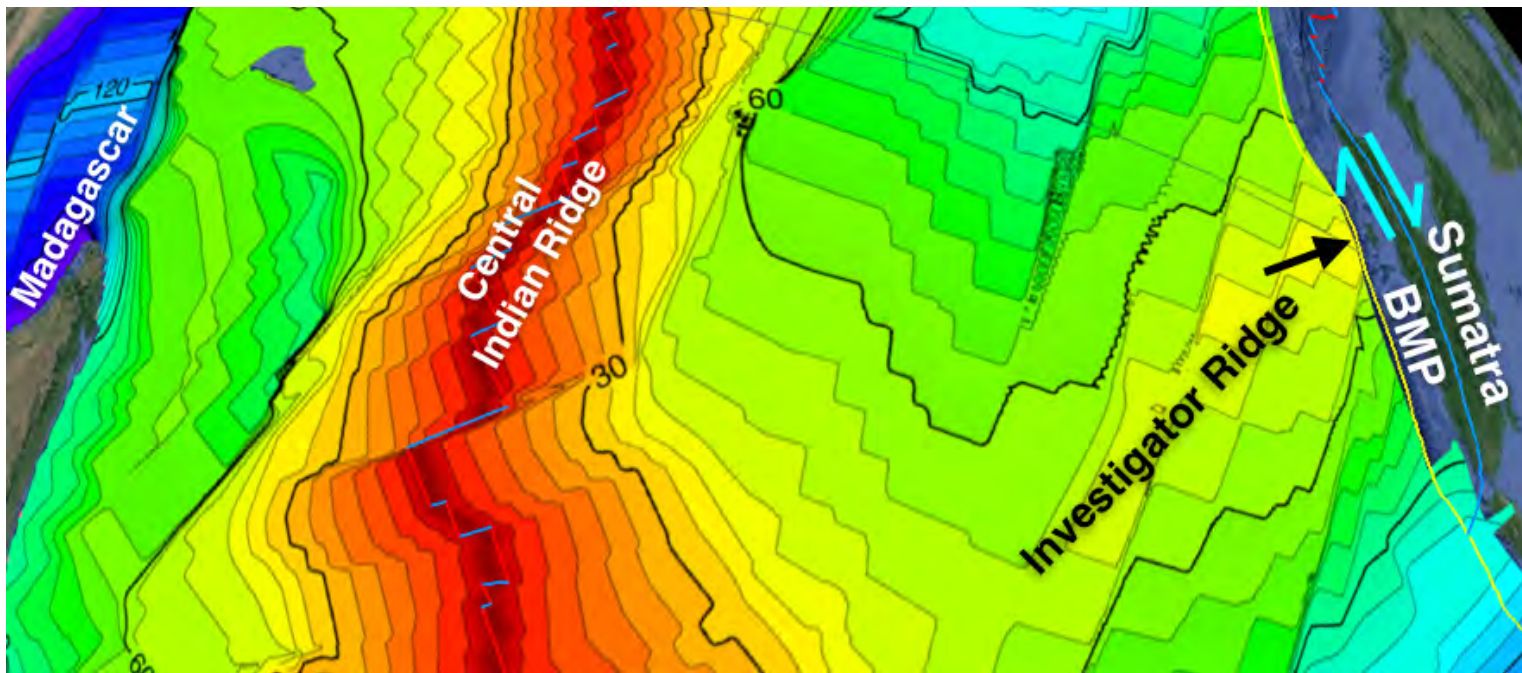
The east Indian Ocean has a passive margin with Madagascar but an active margin with Sumatra

The western Indian Ocean has passive margins with Madagascar and India (the Arabian Sea) but the eastern Indian Ocean has an active margin with Southeast Asia (Fig. 55), where subduction under Sumatra led to the devastating Aceh earthquake and tsunami in 2004. Oblique convergence is partitioned into subduction west of Sumatra (black arrow) and transform faulting in the center of the island (cyan), creating the narrow Burma Microplate (BMP). It is important to realized that ocean

basins can have passive margins, active margins, or a combination. The Proto-Atlantic “Iapetus Ocean” is thought to fall in the latter category at times.

Note the truncation of the Investigator Ridge against Sumatra. During the breakup of Gondwanaland, India drifted northwest (in today’s geographic frame) and Australia drifted southeast. This spreading created the Investigator Ridge. Today, the Indian and Australian Plates have wide regions of diffuse deformation.

Fig. 55. The active margin between the Indian Ocean and SE Asia. Note the subduction of the abandoned Investigator Ridge. BMP=Burma Microplate.



Tour Stop 56: Molucca Sea Collision Zone, Banda Sea Microplate, and Timor Microplate

Molucca Sea's oceanic crust has been entirely subducted. Banda Arc and Timor are currently colliding

Advanced Discussion:

[Turn on Google Earth's volcanoes to see the activity in this region.] Molucca Sea was formerly underlain by oceanic crust but that has been entirely subducted resulting in an arc-arc collision between the western Sangihe Arc and eastern Halmahera Arc (Fig. 56 a). The Purple line in the center of the sea shows the thrust contact. This is the only present-day arc-arc collision, however numerous arc-arc collisions have been proposed in the geological record.

The Banda Sea Microplate is currently colliding with the Timor Microplate. Timor consists of forearc sediments.

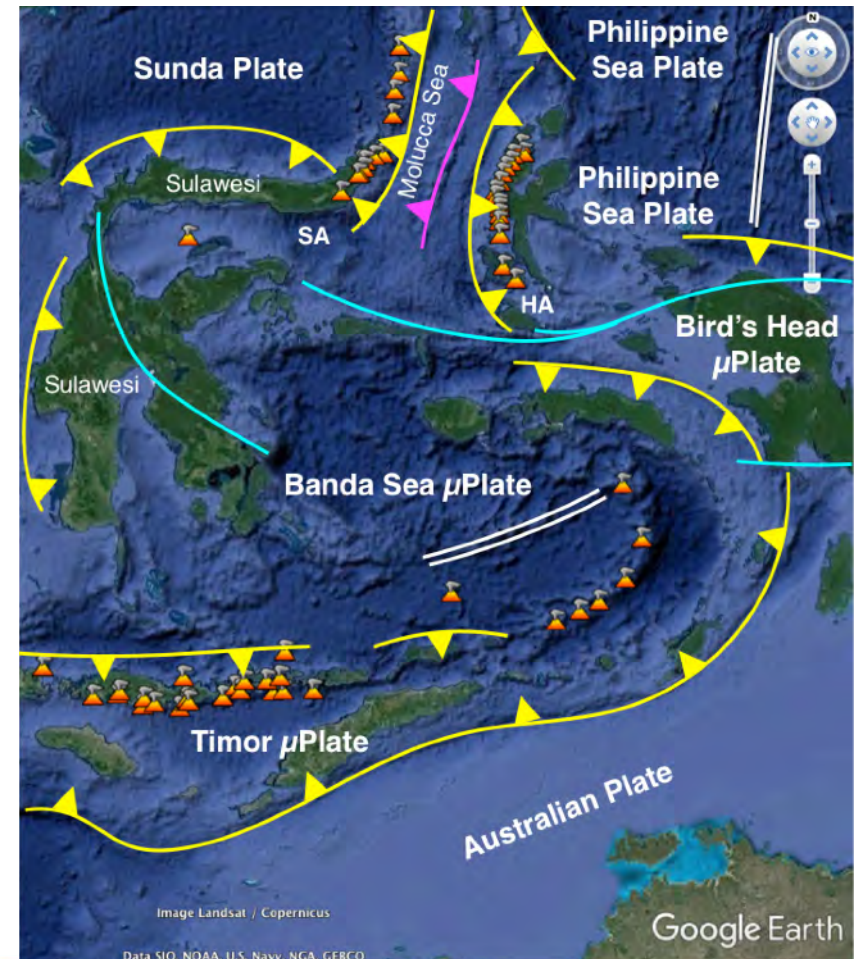
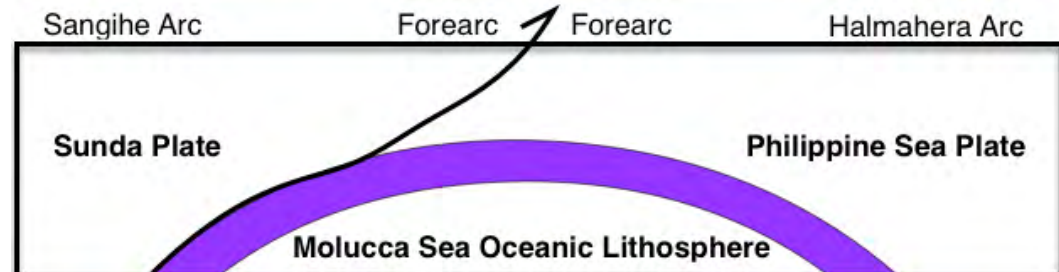


Fig. 56. a) Molucca Sea, Banda Sea, and Timor. SA=Sangihe Arc, HA=Halmahera Arc. b) Cross section of the consumed Molucca Sea oceanic lithosphere.



Tour Stop 57: N. Bismarck, S. Bismarck, Solomon, and Woodlark Microplates

These microplates are strongly influenced by the larger surrounding plates

Between the Caroline, Pacific, and Australian Plates, there are four significant microplates with oceanic crust: North Bismarck, South Bismarck, Solomon, and Woodlark (Fig. 57). There is active spreading between the first two, and in the Woodlark Basin. The N. Bismarck Plate extends eastward where it was thrust over the Pacific

Plate until the arrival of the 30 km thick Ontong Java Plateau (Earth's largest oceanic plateau) caused polarity reversal. The Solomon Microplate marks the transition between collision in Papua New Guinea and subduction offshore and is rapidly rotating. The Woodlark Spreading ridge is propagating onto land to the west where there is a zone of distributed deformation (Dashed double white lines in figure). It's boundary with the Australian Plate is therefore unclear and some authors extend it across central Papua New Guinea. South of the spreading ridge, the Pocklington Trench is topographically prominent but no longer active.

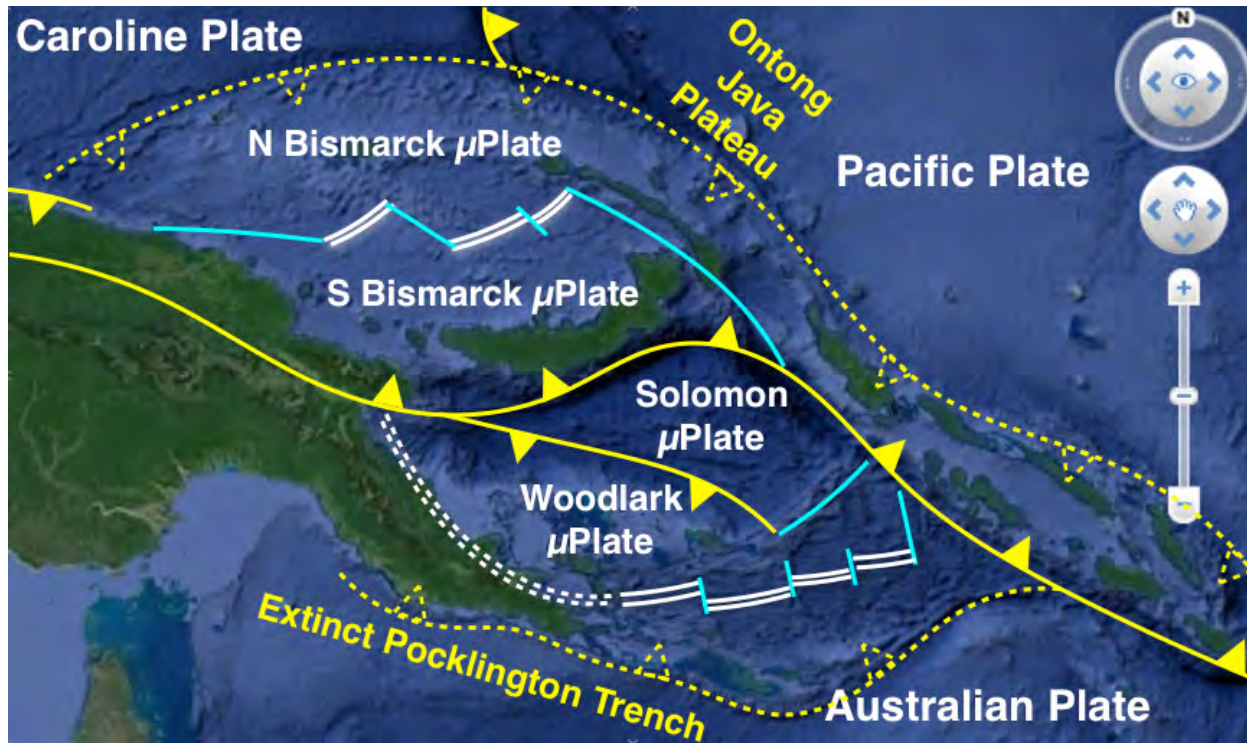


Fig. 57. Bismarck, Solomon, and Woodlark Microplates

Tour Stop 58: Tonga Arc

Subduction under the Tonga Arc is the fastest on Earth

Earthquake hypocenters¹ under the Tonga Arc are found to be shallow in the east and progressively deeper toward the west. They mark inclined planes called *Wadati-Benioff Zones* or *Subduction Zones* and are regions of seafloor destruction that counterbalance seafloor spreading at the mid-ocean ridges. Below them, temperatures are depressed, suggesting the presence of cool lithospheric slabs penetrating the warm mantle.

Oceanic crust has been marinating in seawater for millions of years and is soaked in volatiles like H₂O. These boil and percolate up through the mantle wedge, causing partial melting. Volcanic islands lie above the subduction zone (Fig. 58 a). Because the western Pacific lithosphere is old, cold, and dense, it rapidly drops into the mantle at a steep angle and the trench rolls back eastward, opening up the Lau back-arc basin (marginal basin). West of that basin is the old, abandoned Lau Arc. Trench rollback caused the active arc to jump eastward. Between Tonga Island and the Kermadec Islands, an abandoned spreading ridge is subducting (Fig. 58 b).

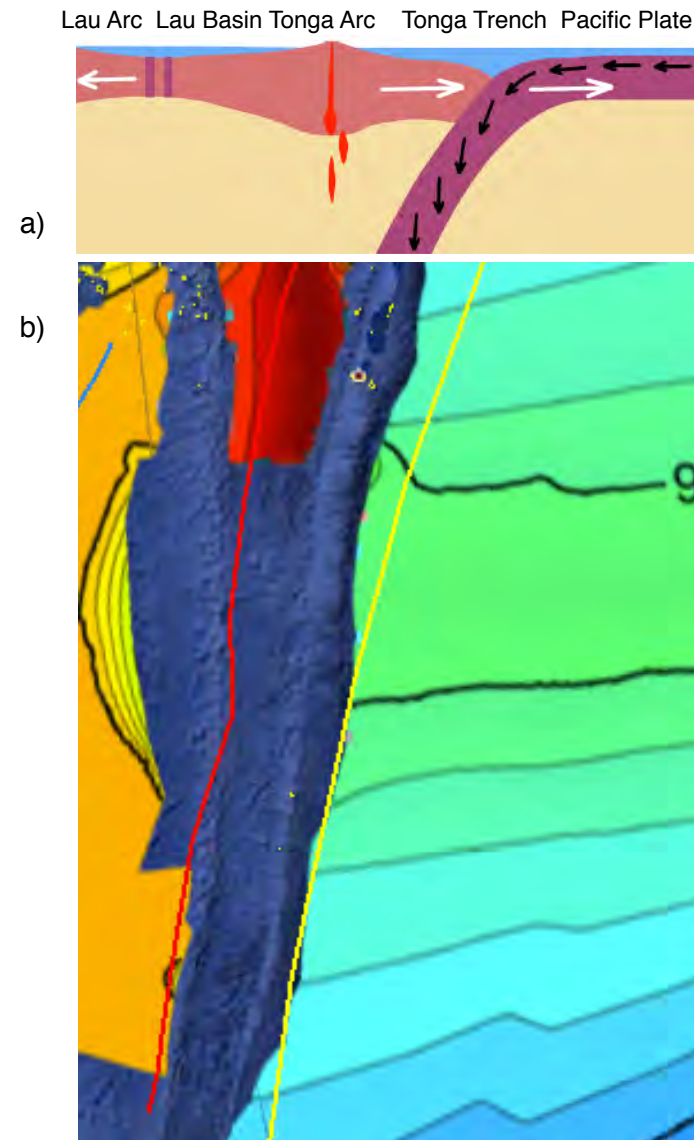


Fig. 58. a) Steep subduction, trench rollback, and back-arc basin formation. From De Paor et al. (2012) doi: 10.1130/GES00758.1. b) The 90 m.y. contour defines a subducting abandoned spreading ridge.

¹ Recall that hypocenters are sources at depth as opposed to epicenters which are the points directly above on Earth's surface)

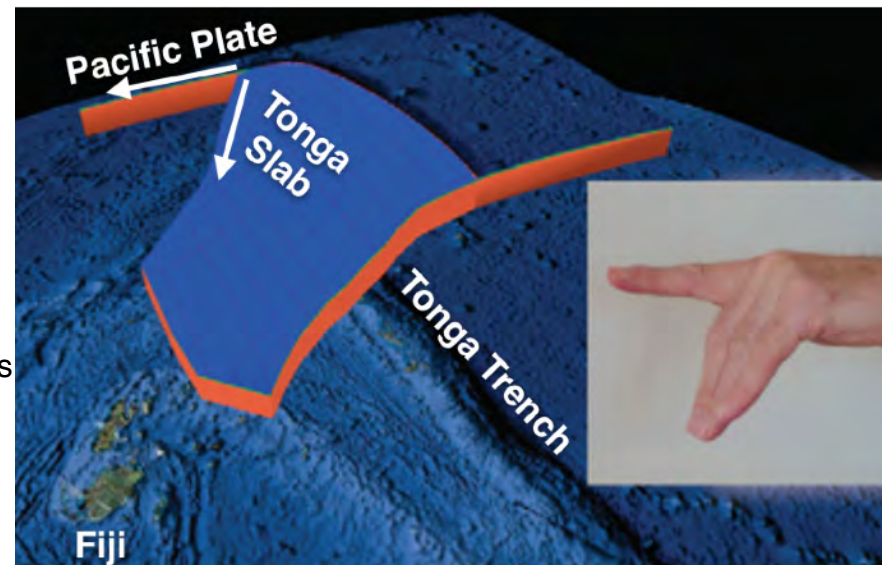
Tour Stop 59: American Samoa and Pacific Atolls

The Pacific Plate is tearing at American Samoa. Atolls form around sinking oceanic islands

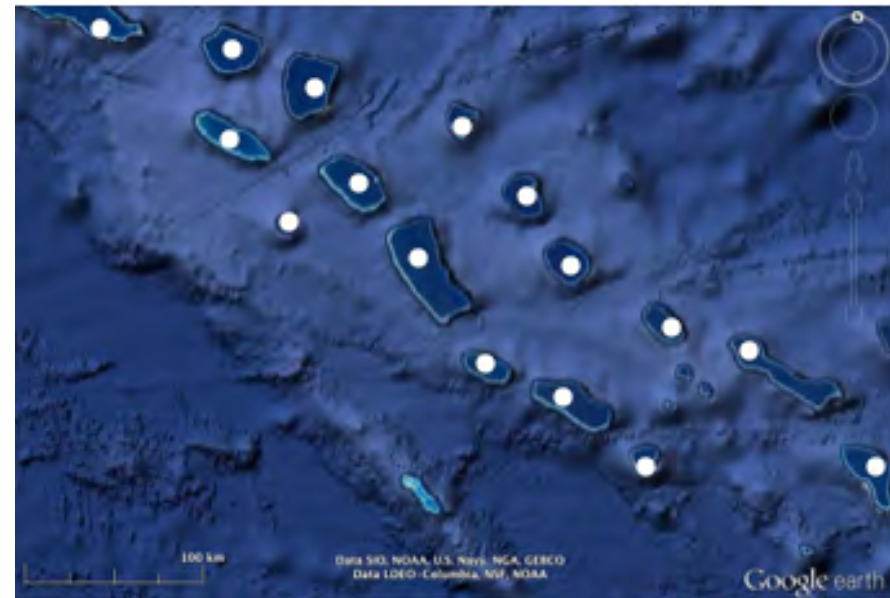
To the north of the Tonga Arc, subduction is terminated by a propagating tear in the lithosphere just west of American Samoa, the site of a deadly 2009 earthquake. The Samoan Archipelago is part of the Austral-Marshall hotspot trail. North of the tear, the Pacific Plate continues westward before subducting under the western Pacific Train Wreck (Fig. 59 a).

East of the Tonga Trench, there are many atolls near Tahiti and the Cook Islands (Fig. 59 b). This is where Charles Darwin demonstrated the formation of coral reefs and atolls around slowly sinking volcanoes.

Tahiti was also a site for study of the 1769 Transit of Venus by Captain James Cook and his colleagues.



A)



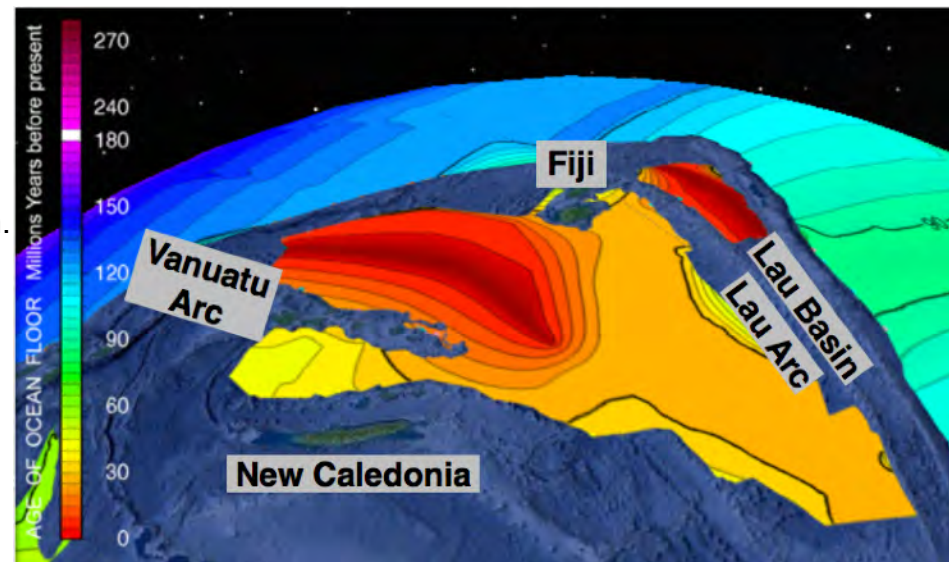
b)

Fig. 59. a) The tear in the Pacific Plate. Inset: Author's index finger represents northern Pacific lithosphere continuing westwards. Other three fingers represent the down-going Tonga slab. From De Paor et al. (2012) doi: 10.1130/GES00758.1. .
b) White dots mark Pacific atolls east of Tahiti which were first studied by Charles Darwin.

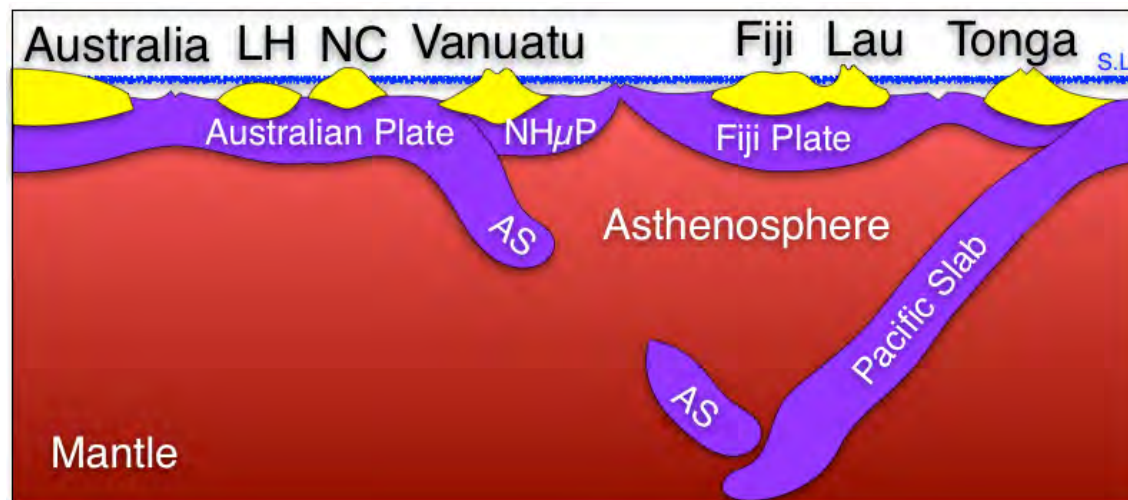
Tour Stop 60: Fiji Plate

The Fiji Plate is bounded by east- and west-dipping subduction zones and also rotates about a vertical axis

West of the Lau Arc lies the highly complex Fiji region. The minor Fiji Plate is caught up in a counter-clockwise rotation between the huge Pacific and Australian Plates (Fig. 60 a). Active spreading occurs in the north Fiji Basin between Fiji and Vanuatu. The east-dipping Australian slab is detached due to collision with the west-dipping Pacific slab (Fig. 60 b). Subduction is about to change to collision as the continental crust of New Caledonia and the Lord Howe Seamounts approaches the Vanuatu (New Hebrides) trench.

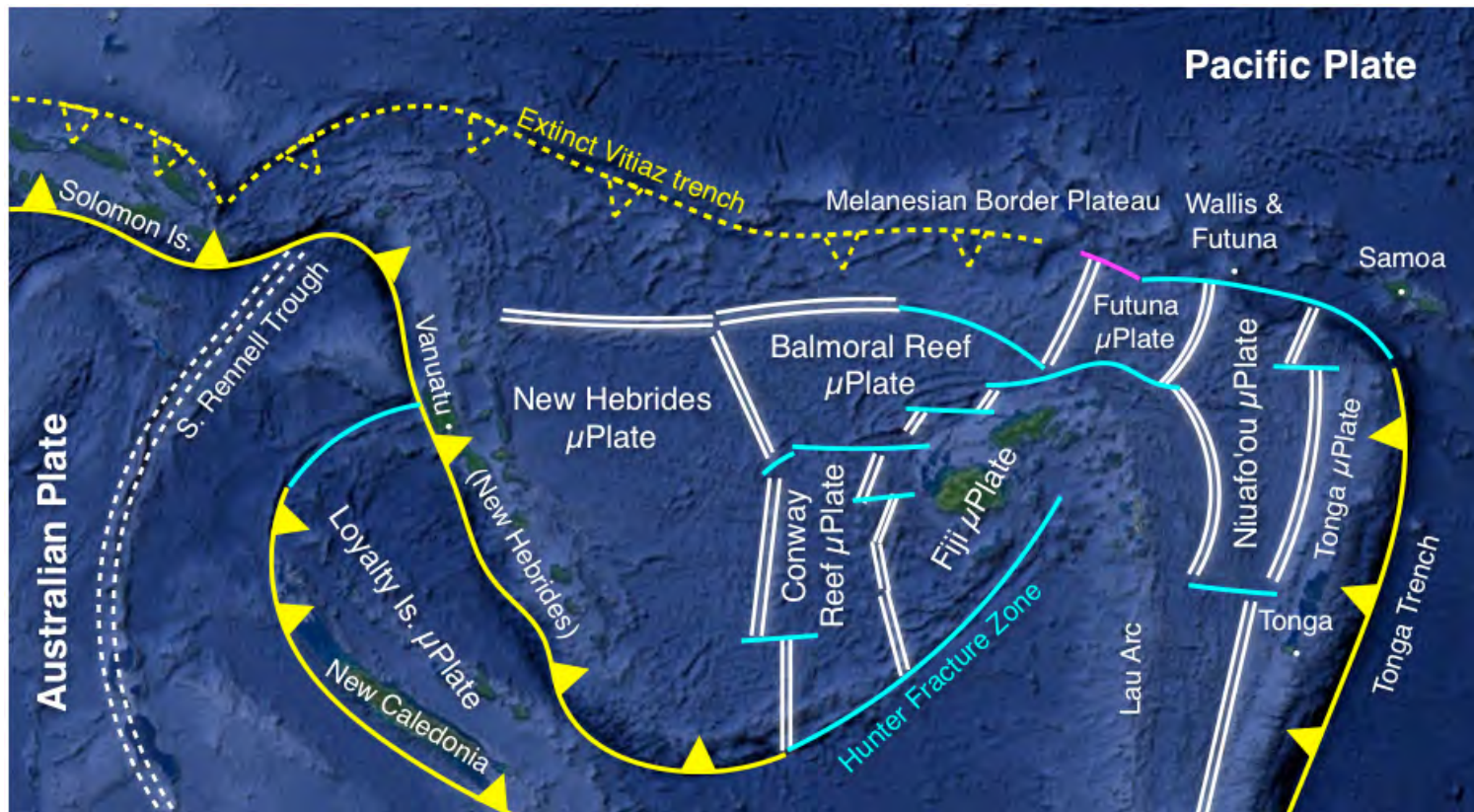


a)



b)

Fig. 60 a) The Fiji Plate. b) Cross section. LH=Lord Howe Seamounts, NC=New Caledonia. NHμP=New Hebrides Microplate. AS=Australian Slab.



Tour Stop 61: The Fiji Region

[The Fiji Region results from arcuate trench rollback](#)

Vertical axis rotation, back-arc spreading, and trench rollback are creating highly curved arcs and multiple microplates in the Fiji region (Fig. 61). Rollback is rapid near New Caledonia but slow in the transition to the Hunter Fracture Zone. Continental collision with

Fig. 61. Microplates around Fiji.

Papua New Guinea in the west shut off rollback. Vitiaz Trench subduction was stopped by the thick oceanic crust of the Melanesian Border Plateau. Arc volcanism jumped from the extinct Lau Arc to the active Tonga Arc. In the west, the South Rennells Trough is an extinct spreading ridge.

Tour Stop 62: Tasman Sea and Coral Sea

The seas east of Australia are the world's largest failed ocean basin

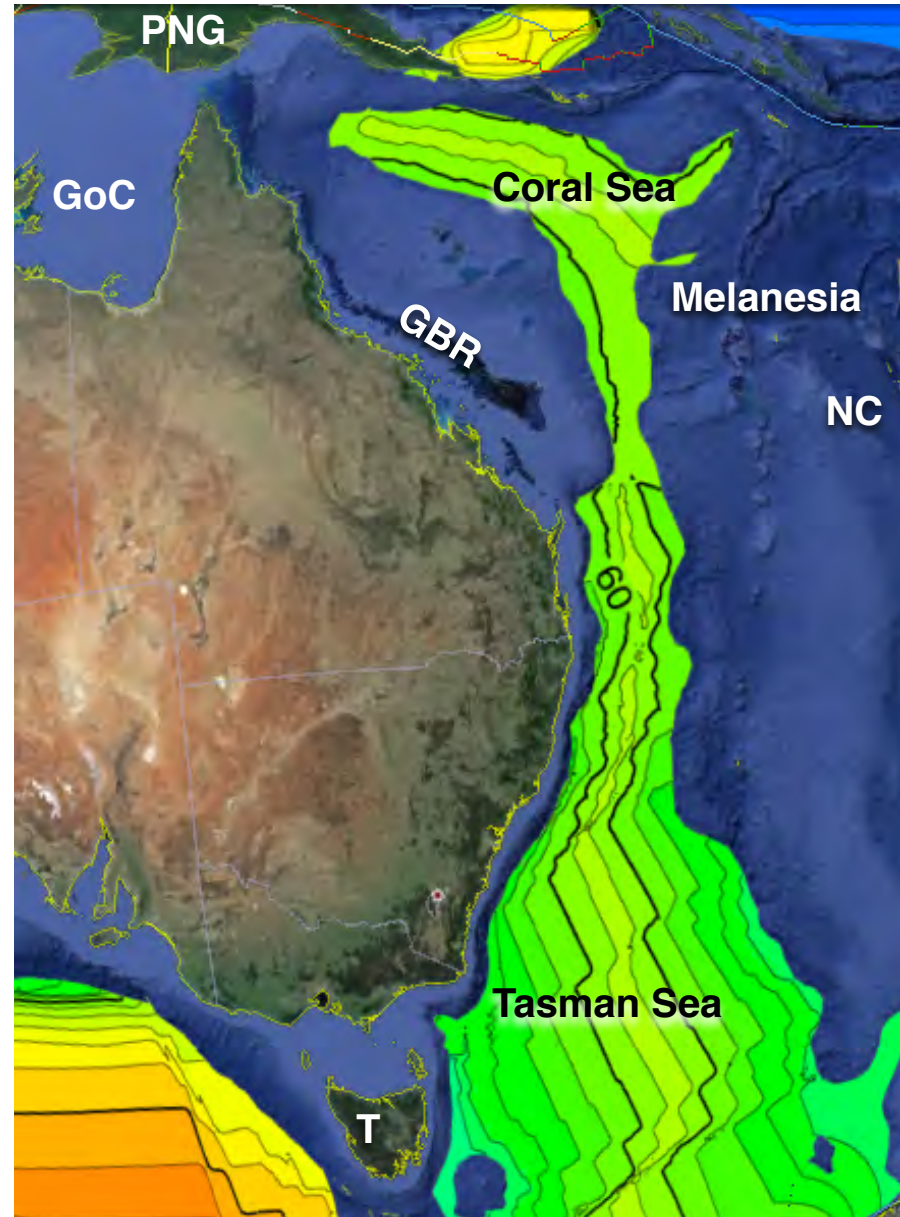
The largest example of an abandoned ocean basin lies east of Australia (Fig. 62). Spreading between Australia and the continent crust of Melanesia (such as New Caledonia, the Lord Howe Seamounts, and Challenger Plateau) began about 90 m.y. ago but ended about 50 m.y. ago.

The abandoned ridge extends for more than 4,000 km from the Tasman Sea east of Tasmania to the Coral Sea northeast of Australia's Great Barrier Reef.

Gravity data suggests that the basin is complicated than with multiple Melanesian microplates moving at slightly different rates at different times, and a complex interaction of extension and strike-slip motion.

Between Australia and Papua New Guinea, the Gulf of Carpentaria is thinned continental shelf, as are the Arafura Sea, and Timor Sea further west.

Fig. 62. East of Australia lies the worlds largest abandoned ocean basin. NC=New Caledonia. T=Tasmania. GBR=Great Barrier Reef. GoC=Gulf of Carpentaria. PNG=Papua New Guinea.



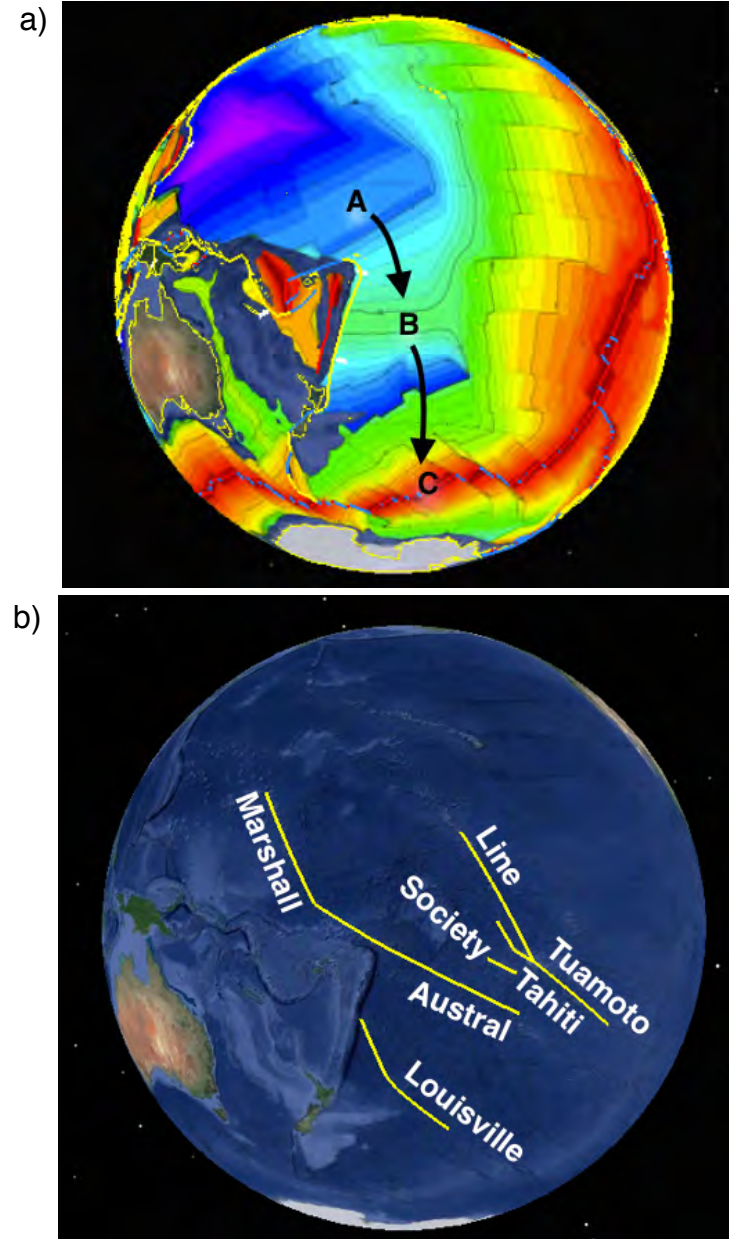
Tour Stop 63: Southwestern Pacific Plate

The southwestern Pacific Plate records a complex spreading history and a series of dog-legged island chains

The spreading history of the southwestern Pacific plate is marked by a series of three major southward ridge jumps (Fig. 63 a). Small ridge jumps usually represent the influence of mantle hotspots but jumps on this scale probably indicate a major shift in plate organization.

If you turn off the ocean crust ages overlay, you will notice a series of island, atoll, and seamount chains in the Southwest Pacific (Fig. 63 b). Mantle hotspots are responsible for the development of the Louisville, Austral–Marshall, Tahiti–Society, and Tuamoto–Line Islands chains. These all display a dog-leg geometry similar to the Hawaiian Islands and Emperor Seamounts further north. The fact that the dog-leg angles are smaller has been used to argue for the migration of hotspots due to deep mantle flow, however the relative contributions of so-called mantle wind and plate reconfiguration are a subject of active research.

Fig. 63. a) Southward migration of seafloor spreading in the southwestern Pacific. b) Dog-legged island-seamount chains in the Southwestern Pacific.



Tour Stop 64: Alpine Fault

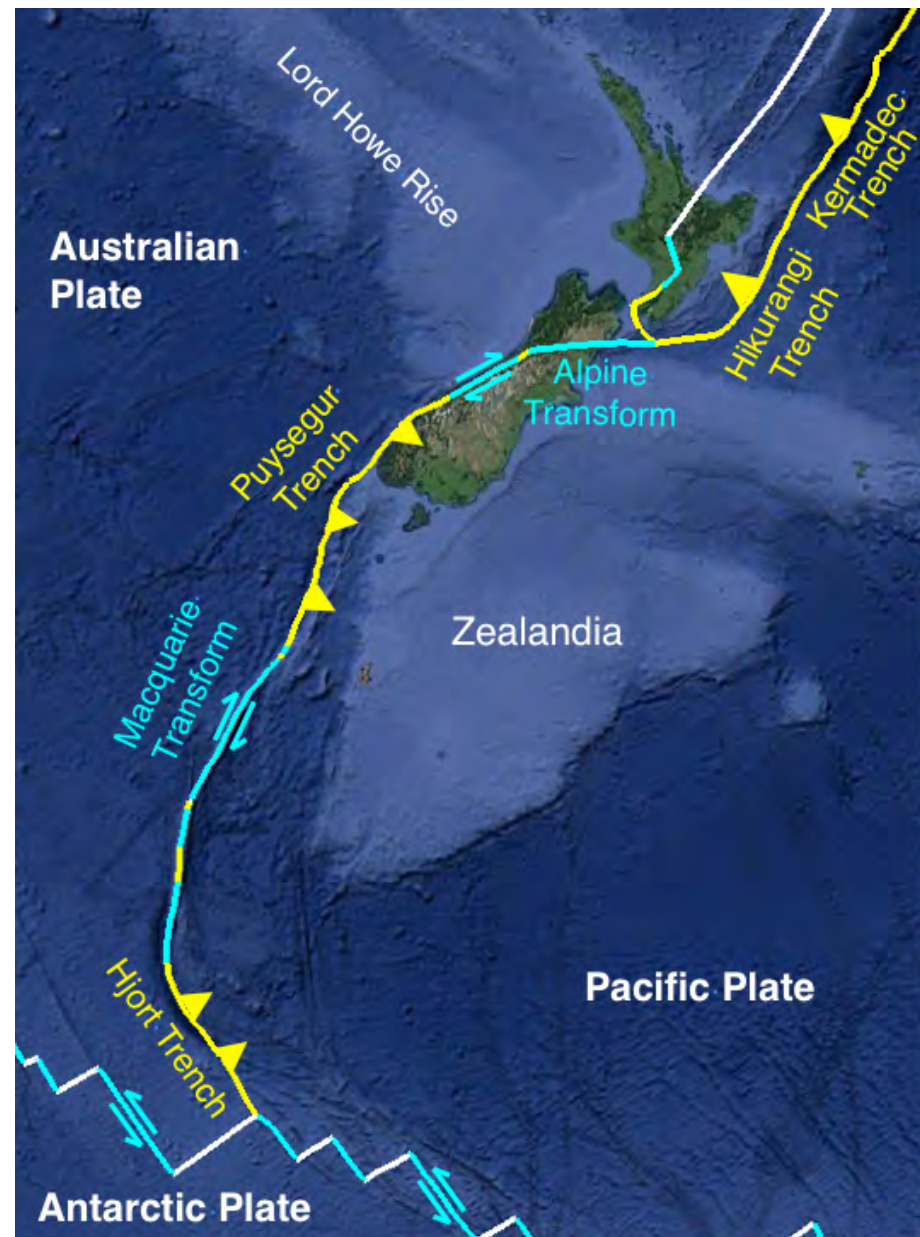
Trenches and transforms play leapfrog across Zealandia

To the south of Tonga the renamed Tonga-Kermadec Trench and then Hikurangi Trench continues south of the North Island of New Zealand. Then it turns west and becomes the right-lateral Alpine Transform Fault that cuts across the South Island (Fig. 64). It was responsible for the devastating 2011 Christchurch earthquake. Southwest of the South Island, the boundary is again convergent but with opposite polarity as the Puysegur Trench. The Pacific-Australian plate boundary switches from convergent to transform a couple of times as it continues southward into the Southern Ocean, forming the Macquarie Transform and Hjort Trench. The latter terminates in a trench-ridge-transform triple junction between the Australian, Antarctic, and Pacific Plates.

In addition to the emergent islands, the continental shelf forms an extensive region of continental crust called Zealandia.

There is no tectonic boundary between the Pacific and Southern Oceans. The geographic Pacific Ocean is arbitrarily defined as the region north of latitude 60°S.

Fig. 64. Plate boundaries south of Tonga.



Tour Stop 65: The End of an Ocean

The Alpine Orogeny marks the near-complete consumption of the Tethys Ocean

To conclude our tour, we return to the Mediterranean Sea and Middle East. The Earth has had oceans for at least 3 billion years yet the oldest oceanic crust anywhere on Earth is in the eastern Mediterranean and is about 340 m.y. old. (Granot, 2016, see Fig. 65 b). Until recently, oceanic crust was thought to be always younger than 200 m.y. Due to northward pressure from Africa (black arrow), the oceanic crust is gradually being subducted under the Anatolian Plate at Cyprus, the Aegean Sea Plate at Crete, and the Calabrian Arc in northeastern Sicily.

Two hundred million years ago, Laurasia and Gondwana were separated by the Tethys Ocean. Almost all of the oceanic lithosphere was consumed in the Alpine Orogeny that created the Alpine, Carpathian, Zagros, and Himalayan Mountains. For example, Arabia's collision with Iran has left a "moat" of downward flexed continental crust resulting in the Persian Gulf, but all the Tethyan oceanic lithosphere is already subducted. However, there are some oceanic crustal remnants marooned in the eastern Mediterranean Sea, Black Sea, and southern Caspian Sea (Fig. 65 b).

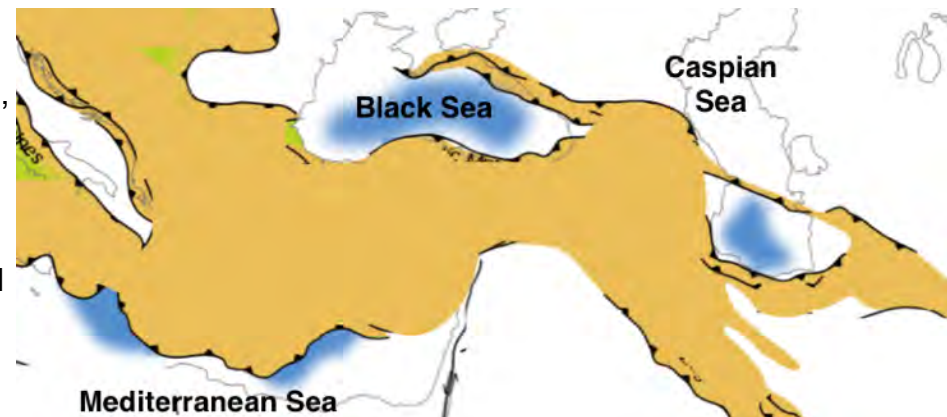
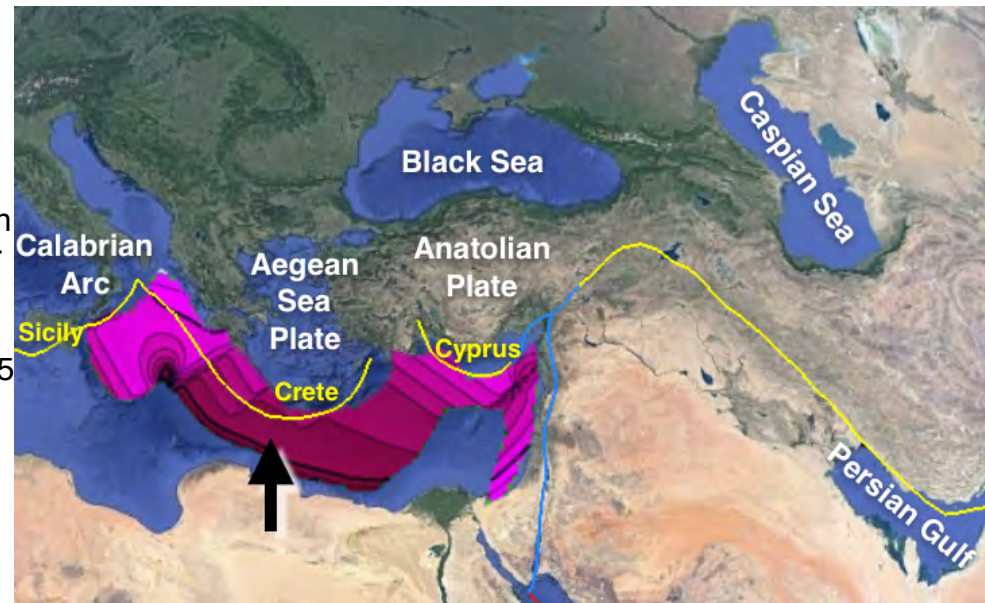
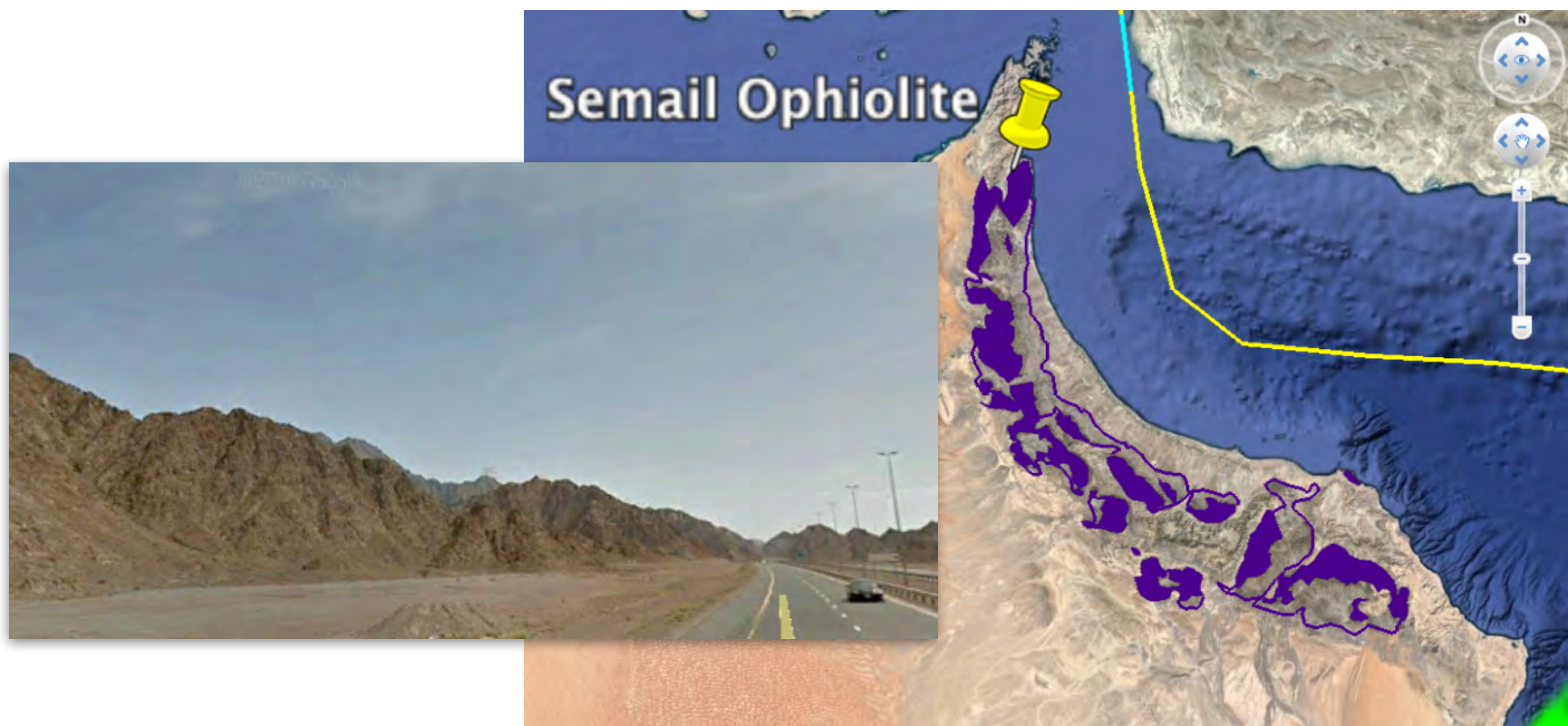


Fig. 65. a) The oldest oceanic crust on Earth. b) Remnants of the Tethys oceanic crust in blue left over from the Alpine Orogeny (beige). Highly modified from https://upload.wikimedia.org/wikipedia/commons/9/92/Tectonic_map_Mediterranean_EN.svg



Tour Stop 66: The Semail Ophiolite, Oman

Fragments of older oceanic crust are preserved as ophiolites

Finally, we visit an ophiolite—a sliver of oceanic lithosphere that has been obducted (thrust up) onto the continental crust. There are obducted ophiolites on all of the continents. Obduction may result from arc collision or thrusting of one side of a spreading ridge over the other, and then over the continental margin.

Fig. 66. The Semail Ophiolite in Google Street View and map view. Pin is near Dibba at the north end where you can enter Street View. Solid purple is mantle sequence, outline is crustal sequence. Data: US Dept of State Geographer.

One of the best exposed is the Semail Ophiolite in Oman (Fig. 66). Upper mantle (solid purple) is made of Harzburgite and Lherzolite. Oceanic crust (purple outline) includes peridotites, gabbros, dolerites (diabase), and basalts. Diagnostic features include pillow lavas, sheeted dykes, and extensive serpentinization.

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