Marine Geology

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Physical Oceanography
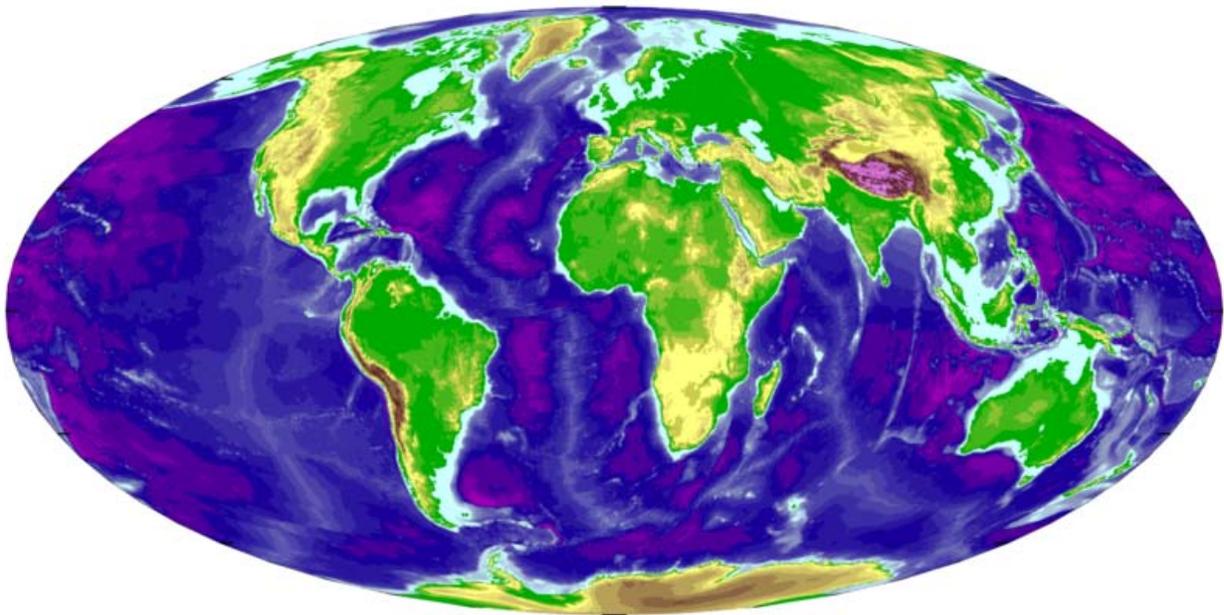
Present day Earth topography [m]
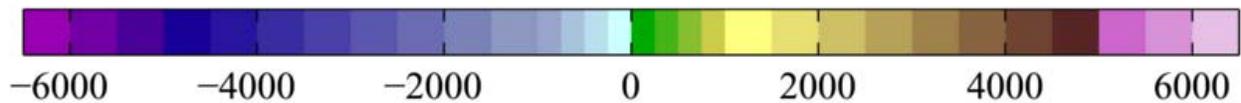
World ocean bathymetry

Physical oceanography is the study of physical conditions and physical processes within the ocean, especially the motions and physical properties of ocean waters.

Physical oceanography is one of several sub-domains into which oceanography is divided. Others include biological, chemical and geological oceanographies.

The physical setting

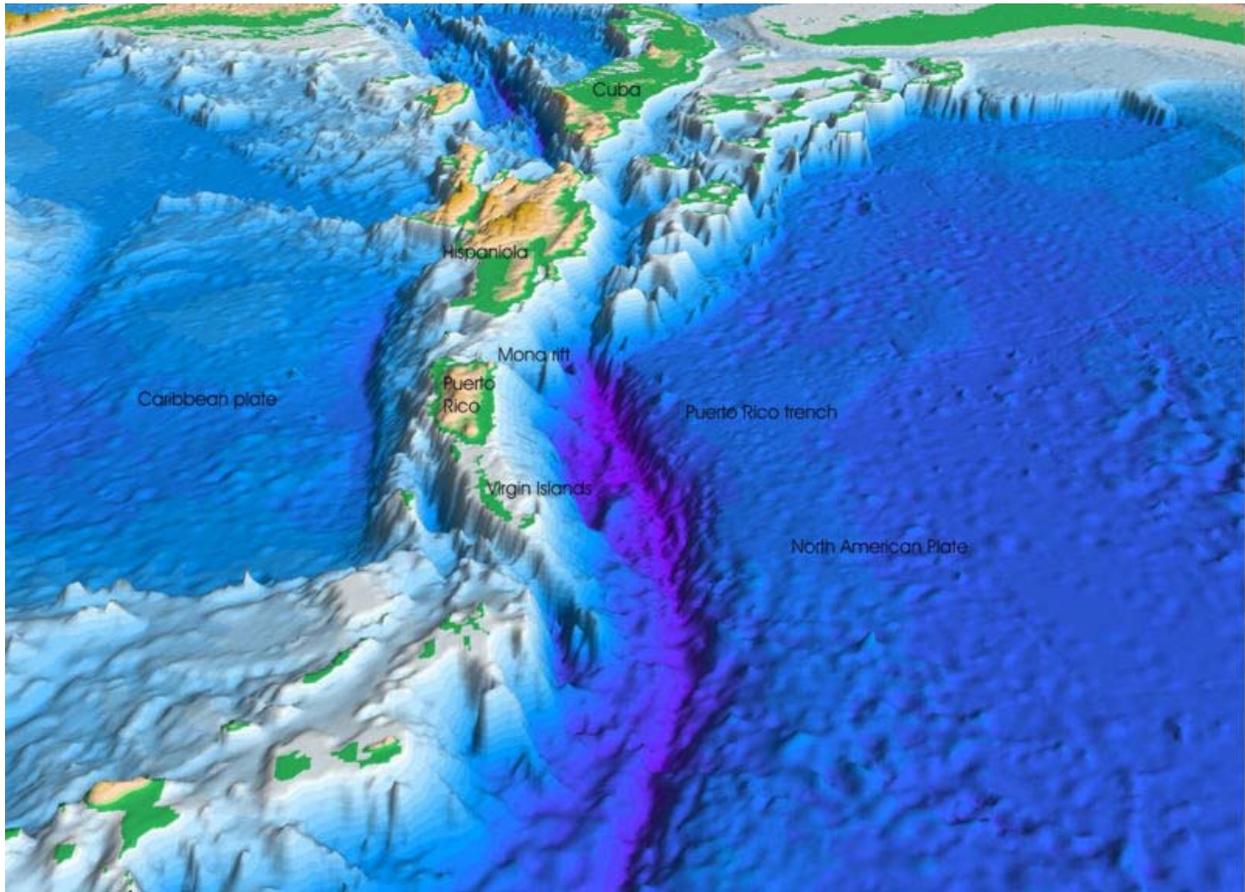Perspective view of the sea floor of the Atlantic Ocean and the Caribbean Sea. The purple sea floor at the center of the view is the Puerto Rico Trench.

The pioneering oceanographer Matthew Maury said in 1855 *"Our planet is invested with two great oceans; one visible, the other invisible; one underfoot, the other overhead; one entirely envelopes it, the other covers about two thirds of its surface."* The fundamental role of the oceans in shaping Earth is acknowledged by ecologists, geologists, meteorologists, climatologists, geographers and others interested in the physical world. An Earth without oceans would truly be unrecognizable.

Roughly 97% of the planet's water is in its oceans, and the oceans are the source of the vast majority of water vapor that condenses in the atmosphere and falls as rain or snow on the continents. The tremendous heat capacity of the oceans moderates the planet's climate, and its absorption of various gases affects the composition of the atmosphere. The ocean's influence extends even to the composition of volcanic rocks through seafloor metamorphism, as well as to that of volcanic gases and magmas created at subduction zones.

The oceans are far deeper than the continents are tall; examination of the Earth's hypsographic curve shows that the average elevation of Earth's landmasses is only 840 metres (2,760 ft), while the ocean's average depth is 3,800 metres (12,500 ft). Though this apparent discrepancy is great, for both land and sea, the respective extremes such as mountains and trenches are rare.

Area, volume plus mean and maximum depths of oceans (excluding adjacent seas)

Body	Area (10^6km²)	Volume (10^6km³)	Mean depth (m)	Maximum (m)
Pacific Ocean	165.2	707.6	4282	-10911
Atlantic Ocean	82.4	323.6	3926	-8605
Indian Ocean	73.4	291.0	3963	-8047
Southern Ocean	20.3			-7235
Arctic Ocean	14.1		1038	
Caribbean Sea	2.8			-7686

Temperature, salinity and density

Sea−surface density [kg m^{-3}]

1020   1021   1022   1023   1024   1025   1026   1027   1028

WOA surface density
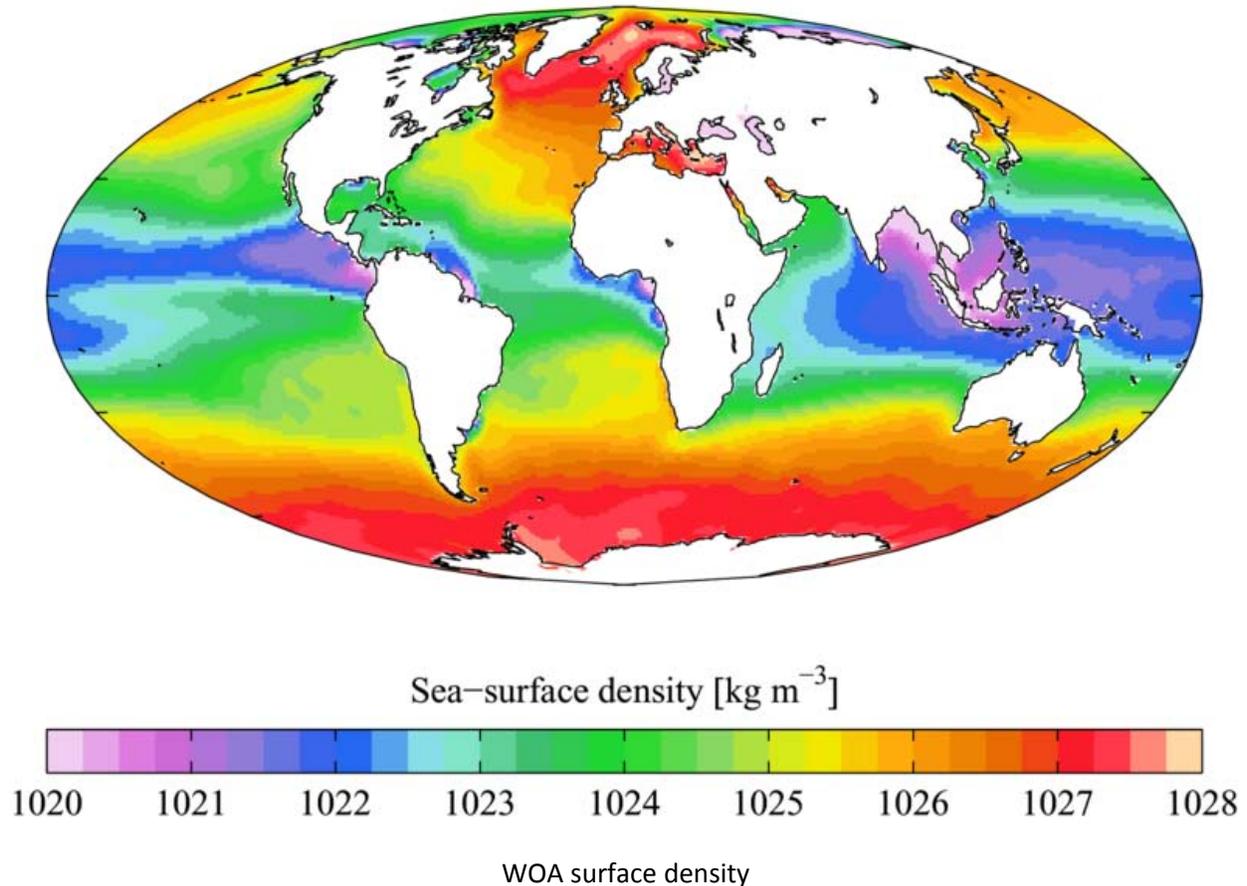
Because the vast majority of the world ocean's volume is deep water, the mean temperature of seawater is low; roughly 75% of the ocean's volume has a temperature from $0° - 5°C$ (Pinet 1996). The same percentage falls in a salinity range between 34–35 ppt (3.4–3.5%) (Pinet 1996). There is still quite a bit of variation, however. Surface temperatures can range from below freezing near the poles to 35°C in restricted tropical seas, while salinity can vary from 10 to 41 ppt (1.0–4.1%).

The vertical structure of the temperature can be divided into three basic layers, a surface mixed layer, where gradients are low, a thermocline where gradients are high, and a poorly stratified abyss.

In terms of temperature, the ocean's layers are highly latitude-dependent; the thermocline is pronounced in the tropics, but nonexistent in polar waters (Marshak 2001). The halocline usually lies near the surface, where evaporation raises salinity in the tropics, or meltwater dilutes it in polar regions. These variations of salinity and temperature with depth change the density of the seawater, creating the pycnocline.

Circulation

Thermohaline Circulation
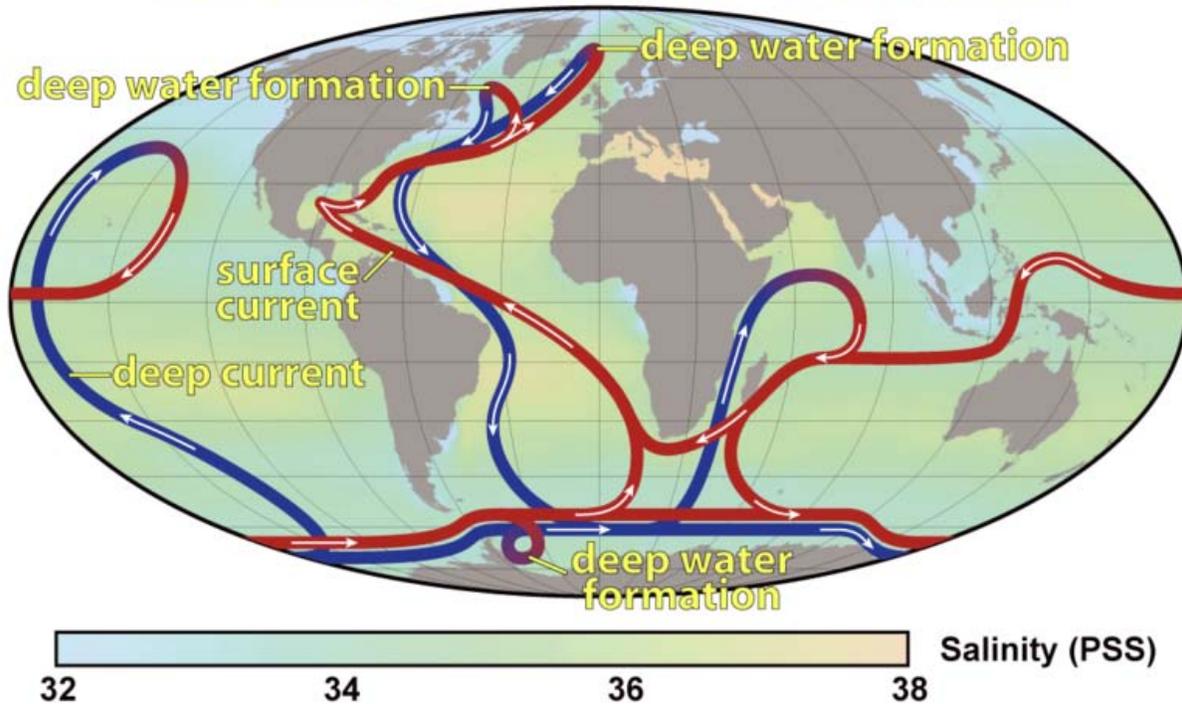
Density-driven thermohaline circulation

The ultimate energy source for the ocean circulation (and for the atmospheric circulation) is the sun. The amount of sunlight absorbed at the surface varies strongly with latitude, being greater at the equator than at the poles, and this engenders fluid motion in both the atmosphere and ocean that acts to redistribute heat from the equator towards the poles, thereby reducing the temperature gradients that would exist in the absence of fluid motion. Perhaps three quarters of this heat is carried in the atmosphere; the rest is carried in the ocean.

The atmosphere is heated from below, which leads to convection, the largest expression of which is the Hadley circulation. By contrast the ocean is heated from above, which tends to suppress convection. Instead ocean deep water is formed in polar regions where cold salty waters sink in fairly restricted areas. This is the beginning of the thermohaline circulation.

Oceanic currents are largely driven by the surface wind stress; hence the large-scale atmospheric circulation is important to understanding the ocean circulation. The Hadley circulation leads to Easterly winds in the tropics and Westerlies in mid-latitudes, which creates an anticyclonic wind stress curl over the subtropical ocean. This leads to slow equatorward flow throughout most of a subtropical ocean basin (the Sverdrup balance). The return flow occurs in an intense, narrow, poleward western boundary current. Like the atmosphere, the ocean is far wider than it is deep, and hence horizontal motion is in general much faster than vertical motion. In the southern hemisphere there is a continuous belt of ocean, and hence the mid-latitude westerlies force the

strong Antarctic Circumpolar Current. In the northern hemisphere the land masses prevent this and the ocean circulation is broken into smaller gyres in the Atlantic and Pacific basins.

Coriolis effect

The Coriolis effect results in a deflection of fluid flows (to the right in the Northern Hemisphere and left in the Southern Hemisphere). Because the distance around the Earth decreases as one moves away from the equator, and because the Earth rotates in a counter clockwise direction as seen from the north pole, air and water masses are deflected to the east as they move from the equator to the poles, and to the west as they move from the poles to the equator. This has profound effects on the flow of the oceans. In particular it means the flow goes *around* high and low pressure systems, permitting them to persist for long periods of time. As a result, tiny variations in pressure can produce measurable currents. A slope of one part in one million in sea surface height, for example, will result in a current of 1 cm/s at mid-latitudes. The fact that the Coriolis effect is largest at the poles and weak at the equator results in sharp, relatively steady western boundary currents which are absent on eastern boundaries.

The Coriolis effect is also responsible for coastal upwelling as wind-driven currents tend to forced to the right of the winds in the Northern Hemisphere and to the left of the winds in the Southern Hemisphere. When winds blow either equatorward along an eastern ocean boundary or poleward along a western ocean boundary, water is driven away from the coasts (the so called Ekman transport), and denser water rises from below to replace it.

Ekman transport

Ekman Transport results in the net transport of surface water 90 degrees to the right of the wind in the Northern Hemisphere, and 90 degrees to the left of the wind in the Southern Hemisphere. As the wind blows across the surface of the ocean, it "grabs" onto a thin layer of the surface water. In turn, that thin sheet of water transfers motion energy to the thin layer of water under it, and so on. However, because of the Coriolis Effect, the direction of travel of the layers of water slowly move farther and farther to the right as they get deeper in the Northern Hemisphere, and to the left in the Southern Hemisphere. In most cases, the very bottom layer of water affected by the wind is at a depth of 100 m – 150 m and is traveling about 180 degrees, completely opposite of the direction that the wind is blowing. Overall, the net transport of water would be 90 degrees from the original direction of the wind.

Langmuir circulation

Langmuir circulation results in the occurrence of thin, visible stripes, called windrows on the surface of the ocean parallel to the direction that the wind is blowing. If the wind is blowing with more than 3 m s^{-1}, it can create parallel windrows alternating upwelling and downwelling about 5–300 m apart. These windrows are created by adjacent ovular water cells (extending to about 6 m (20 ft) deep) alternating rotating clockwise and counterclockwise. In the convergence zones debris, foam and seaweed accumulates, while at the divergencezones plankton are caught and carried to the surface. If there are many plankton in the divergencezone fish are often attracted to feed on them.

Ocean–atmosphere interface

Hurricane Isabel east of the Bahamas on 15 September 2003

At the ocean-atmosphere interface, the ocean and atmosphere exchange fluxes of heat, moisture and momentum.

Heat

The important heat terms at the surface are the sensible heat flux, the latent heat flux, the incoming solar radiation and the balance of long-wave (infrared) radiation. In general, the tropical oceans will tend to show a net gain of heat, and the polar oceans a net loss, the result of a net transfer of energy polewards in the oceans.

The oceans' large heat capacity moderates the climate of areas adjacent to the oceans, leading to a maritime climate at such locations. This can be a result of heat storage in summer and release in winter; or of transport of heat from warmer locations: a particularly notable example of this is Western Europe, which is heated at least in part by the north atlantic drift.

Momentum

Surface winds tend to be of order meters per second; ocean currents of order centimeters per second. Hence from the point of view of the atmosphere, the ocean can be considered effectively stationary; from the point of view of the ocean, the atmosphere imposes a significant wind stress on its surface, and this forces large-scale currents in the ocean.

Through the wind stress, the wind generates ocean surface waves; the longer waves have a phase velocity tending towards the wind speed. Momentum of the surface winds is transferred into the energy flux by the ocean surface waves. The increased roughness of the ocean surface, by the presence of the waves, changes the wind near the surface.

Moisture

The ocean can gain moisture from rainfall, or lose it through evaporation. Evaporative loss leaves the ocean saltier; the Mediterranean and Persian Gulf for example have strong evaporative loss; the resulting plume of dense salty water may be traced through the Straits of Gibraltar into the Atlantic Ocean. At one time, it was believed that evaporation/precipitation was a major driver of ocean currents; it is now known to be only a very minor factor.

Planetary waves

Kelvin Waves

A Kelvin wave is any progressive wave that is channeled between two boundaries or opposing forces (usually between the Coriolis force and a coastline or the equator). There are two types, coastal and equatorial. Kelvin waves are gravity driven and non-dispersive, meaning that the phase speed of the wave at any one frequency will equal the group speed of the wave energy for all frequencies. This means that Kelvin waves can retain their shape and direction over long periods of time. They are usually created by a sudden shift in the wind, such as the change of the trade winds at the beginning of the El Niño-Southern Oscillation.

Coastal Kelvin waves follow shorelines and will always propagate in a counterclockwise direction in the Northern hemisphere (with the shoreline to the right of the direction of travel) and clockwise in the Southern hemisphere.

Equatorial Kelvin waves propagate to the east in the Northern hemisphere and to the west in the Southern hemisphere, using the equator as a guide.

Kelvin waves are known to have very high speeds, typically around 2–3 meters per second. They have wavelengths of thousands of kilometers and amplitudes in the tens of meters.

Rossby Waves

Rossby waves, or planetary waves are huge, slow waves generated in the troposphere by temperature differences between the ocean and the continents. Their major restoring force is the change in Coriolis force with latitude. Their wave amplitudes are usually in the tens of meters and very large wavelengths. They are usually found at low or mid latitudes

There are two types of Rossby waves, barotropic and baroclinic. Barotropic Rossby waves have the highest speeds and do not vary vertically. Baroclinic Rossby waves are much slower.

The special identifying feature of Rossby waves is that the phase velocity of each individual wave always has a westward component, but the group velocity can be in any direction. Usually the shorter Rossby waves have an eastward group velocity and the longer ones have a westward group velocity.

Climate variability
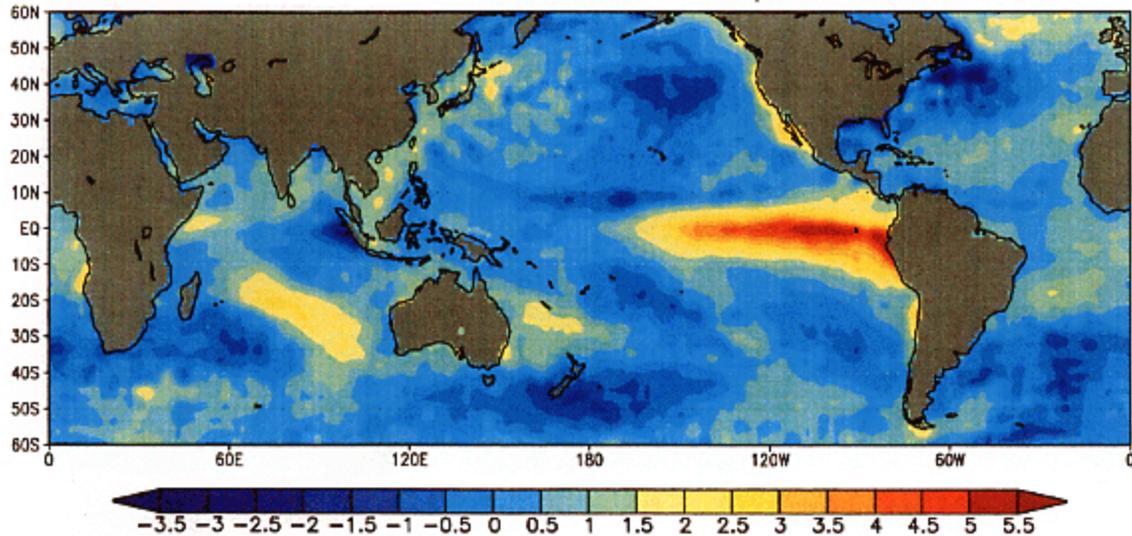
December 1997 chart of ocean surface temperature anomaly [°C] during the last strong El Niño

The interaction of ocean circulation, which serves as a type of heat pump, and biological effects such as the concentration of carbon dioxide can result in global climate changes on a time scale of decades. Known climate oscillations resulting from these interactions, include the Pacific decadal oscillation, North Atlantic oscillation, and Arctic oscillation. The oceanic process of thermohaline circulation is a significant component of heat redistribution across the globe, and changes in this circulation can have major impacts upon the climate.

Antarctic circumpolar wave

This is a coupled ocean/atmosphere wave that circles the Southern Ocean about every eight years. Since it is a wave-2 phenomenon (there are two peaks and two troughs in a latitude circle) at each fixed point in space a signal with a period of four years is seen. The wave moves eastward in the direction of the Antarctic Circumpolar Current.

Ocean currents

Among the most important ocean currents are the:

- Antarctic Circumpolar Current
- Deep ocean (density-driven)
- Western boundary currents
  - Gulf Stream
  - Kuroshio Current
  - Labrador Current
  - Oyashio Current
  - Agulhas Current
  - Brazil Current
  - East Australia Current
- Eastern Boundary currents
  - California Current
  - Canary Current
  - Peru Current
  - Benguela Current

Antarctic circumpolar

The ocean body surrounding the Antarctic is currently the only continuous body of water where there is a wide latitude band of open water. It interconnects the Atlantic, Pacific and Indian oceans, and provide an uninterrupted stretch for the prevailing westerly winds to significantly increase wave amplitudes. It is generally accepted that these prevailing winds are primarily responsible for the circumpolar current transport. This current is now thought to vary with time, possibly in an oscillatory manner.

Deep ocean

In the Norwegian Sea evaporative cooling is predominant, and the sinking water mass, the North Atlantic Deep Water (NADW), fills the basin and spills southwards through crevasses in the submarine sills that connect Greenland, Iceland and Britain. It then flows along the western boundary of the Atlantic with some part of the flow moving eastward along the equator and then poleward into the ocean basins. The NADW is entrained into the Circumpolar Current, and can be traced into the Indian and Pacific basins. Flow from the Arctic Ocean Basin into the Pacific, however, is blocked by the narrow shallows of the Bering Strait.

Western boundary

An idealised subtropical ocean basin forced by winds circling around a high pressure (anticyclonic) systems such as the Azores-Bermuda high develops a gyre circulation with slow steady flows towards the equator in the interior. As discussed by Henry Stommel, these flows are balanced in the region of the western boundary, where a thin fast polewards flow called a western boundary current develops. Flow in the real ocean is more complex, but the Gulf stream, Agulhas and Kuroshio are examples of such currents. They are narrow (approximately 100 km across) and fast (approximately 1.5 m/s).

Equatorwards western boundary currents occur in tropical and polar locations, e.g. the East Greenland and Labrador currents, in the Atlantic and the Oyashio. They are forced by winds circulation around low pressure (cyclonic)

Gulf stream

The Gulf Stream, together with its northern extension, North Atlantic Current, is a powerful, warm, and swift Atlantic ocean current that originates in the Gulf of Mexico, exits through the Strait of Florida, and follows the eastern coastlines of the United States and Newfoundland to the northeast before crossing the Atlantic Ocean.

Kuroshio

The Kuroshio Current is an ocean current found in the western Pacific Ocean off the east coast of Taiwan and flowing northeastward past Japan, where it merges with the easterly drift of the North Pacific Current. It is analogous to the Gulf Stream in the Atlantic Ocean, transporting warm, tropical water northward towards the polar region.

Heat flux

Heat storage
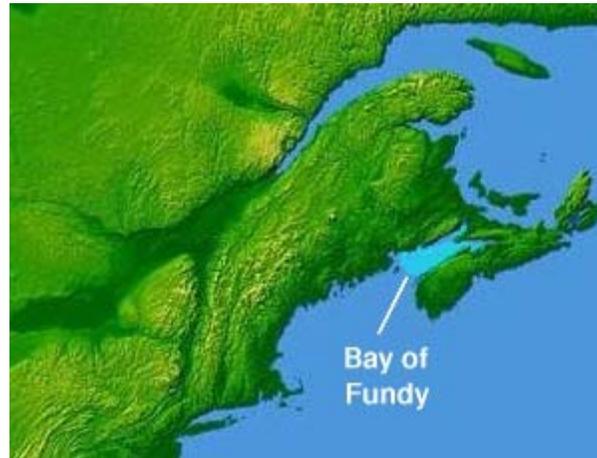
Heat storage and transfer in the ocean is very uneven.

Sea level change

Tide gauges and satellite altimetry suggest an increase in sea level of 1.5–3 mm/yr over the past 100 years.

The IPCC predicts that by 2100, global warming will lead to a sea level rise of 110 to 880 mm.

Rapid variations

Tides

The **Bay of Fundy** is a bay located on the Atlantic coast of North America, on the northeast end of the Gulf of Maine between the provinces of New Brunswick and Nova Scotia.

The rise and fall of the oceans due to tidal effects is a key influence upon the coastal areas. Ocean tides on the planet Earth are created by the gravitational effects of the Sun and Moon. The tides produced by these two bodies are roughly comparable in magnitude, but the orbital motion of the Moon results in tidal patterns that vary over the course of a month.

The ebb and flow of the tides produce a cyclical current along the coast, and the strength of this current can be quite dramatic along narrow estuaries. Incoming tides can also produce a tidal bore along a river or narrow bay as the water flow against the current results in a wave on the surface.

Tide and Current (Wyban 1992) clearly illustrates the impact of these natural cycles on the lifestyle and livelihood of Native Hawaiians tending coastal fishponds. *Aia ke ola ka hana* meaning . . . *Life is in labor*.

Tidal resonance occurs in the Bay of Fundy since the time it takes for a large wave to travel from the mouth of the bay to the opposite end, then reflect and travel back to the mouth of the bay coincides with the timing between this repeating wave that is also reinforced by the tidal rhythm producing the world's highest tides.

As the surface tide oscillates over topography, such as submerged seamounts or ridges, it generates internal waves at the tidal frequency, which are known as internal tides.

Tsunamis

A series of surface waves can be generated due to large-scale displacement of the ocean water. These can be caused by sub-marine landslides, seafloor deformations due to earthquakes, or the impact of a large meteorite.

The waves can travel with a velocity of up to several hundred km/hour across the ocean surface, but in mid-ocean they are barely detectable with wavelengths spanning hundreds of kilometers.

Tsunamis, originally called tidal waves, were renamed because they are not related to the tides. They are regarded as shallow-water waves, or waves in water with a depth less than 1/20 their wavelength. Tsunamis have very large periods, high speeds, and great wave heights.

The primary impact of these waves is along the coastal shoreline, as large amounts of ocean water are cyclically propelled inland and then drawn out to sea. This can result in significant modifications to the coastline regions where the waves strike with sufficient energy.

The tsunami that occurred in Lituya Bay, Alaska on July 9, 1958 was 520 m (1,710 ft) high and is the biggest tsunami ever measured, almost 90 m (300 ft) taller than the Sears Tower in Chicago and about 110 m (360 ft) taller than the World Trade Center in New York.

Surface waves

The wind generates ocean surface waves, which have a large impact on offshore structures, ships, coastal erosion and sedimentation, as well as harbours. After their generation by the wind, ocean surface waves can travel (as swell) over long distances.

Chapter- 2

Plate Tectonics
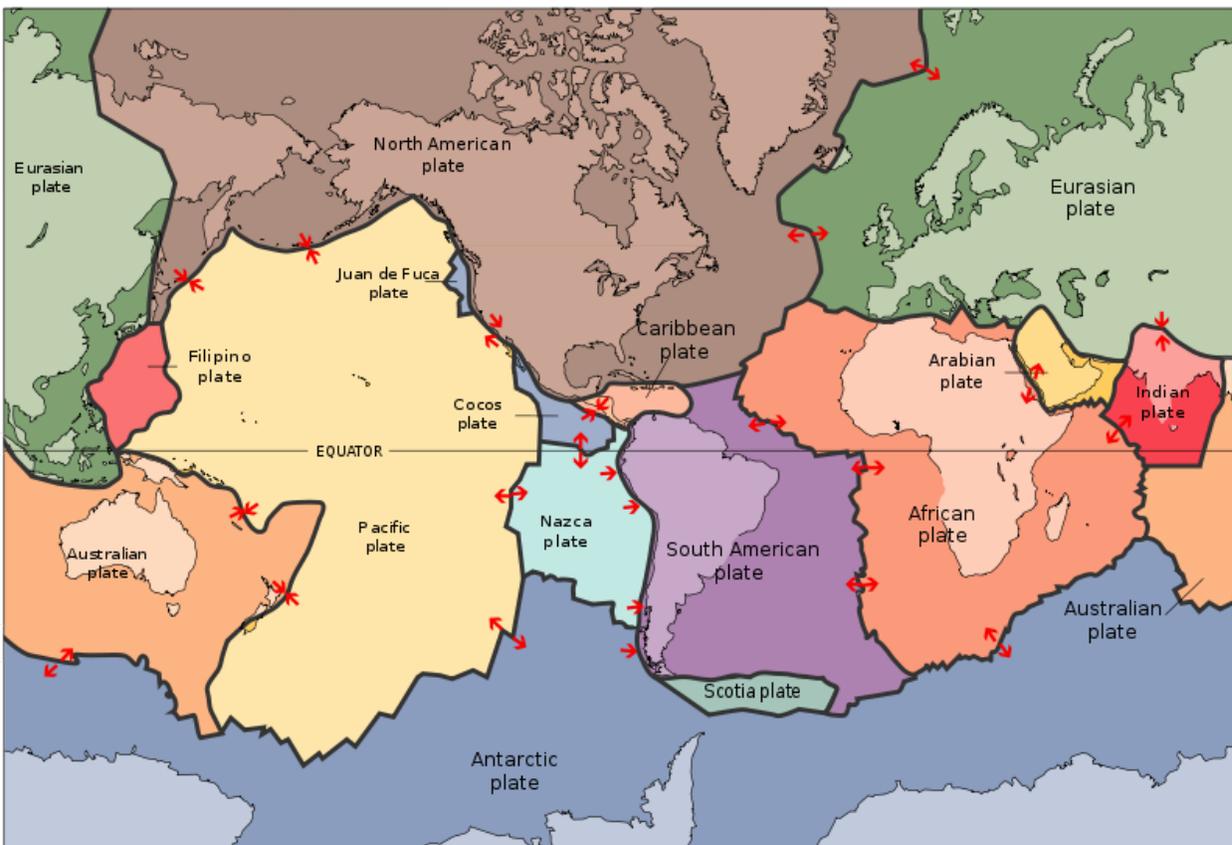
The tectonic plates of the world were mapped in the second half of the 20th century

Plate tectonics (from the Late Latin *tectonicus*, from the Greek: τεκτονικός "pertaining to building") (Little, Fowler & Coulson 1990) is a scientific theory which describes the large scale motions of Earth's lithosphere. The theory builds on the older concepts of continental drift,

developed during the first decades of the 20th century (one of the most famous advocates was Alfred Wegener), and was accepted by the majority of the Geoscientific community when the concepts of seafloor spreading were developed in the late 1950s and early 1960s. The lithosphere is broken up into what are called "tectonic plates". In the case of the Earth, there are currently seven to eight major (depending on how they are defined) and many minor plates. The lithospheric plates ride on the asthenosphere. These plates move in relation to one another at one of three types of plate boundaries: convergent, or collisional boundaries; divergent boundaries, also called spreading centers; and conservative transform boundaries. Earthquakes, volcanic activity, mountain-building, and oceanic trench formation occur along these plate boundaries. The lateral relative movement of the plates varies, though it is typically 0–100 mm annually (Read & Watson 1975).

The tectonic plates are composed of two types of lithosphere: thicker continental and thin oceanic. The upper part is called the crust, again of two types (continental and oceanic). This means that a plate can be of one type, or of both types. One of the main points the theory proposes is that the amount of surface of the (continental and oceanic) plates that disappear in the mantle along the convergent boundaries by subduction is more or less in equilibrium with the new (oceanic) crust that is formed along the divergent margins by seafloor spreading. This is also referred to as the "conveyor belt" principle. In this way, the total surface of the Globe remains the same. This is in contrast with earlier theories advocated before the Plate Tectonics "paradigm", as it is sometimes called, became the main scientific model, theories that proposed gradual shrinking (contraction) or gradual expansion of the Globe, and that still exist in science as alternative models.

Regarding the driving mechanism of the plates various models co-exist: Tectonic plates are able to move because the Earth's lithosphere has a higher strength and lower density than the underlying asthenosphere. Lateral density variations in the mantle result in convection. Their movement is thought to be driven by a combination of the motion of seafloor away from the spreading ridge (due to variations in topography and density of the crust that result in differences in gravitational forces) and drag, downward suction, at the subduction zones. A different explanation lies in different forces generated by the rotation of the Globe and tidal forces of the Sun and the Moon. The relative importance of each of these factors is unclear.

Key principles

The outer layers of the Earth are divided into lithosphere and asthenosphere. This is based on differences in mechanical properties and in the method for the transfer of heat. Mechanically, the lithosphere is cooler and more rigid, while the asthenosphere is hotter and flows more easily. In terms of heat transfer, the lithosphere loses heat by conduction whereas the asthenosphere also transfers heat by convection and has a nearly adiabatic temperature gradient. This division should not be confused with the *chemical* subdivision of these same layers into the mantle (comprising both the asthenosphere and the mantle portion of the lithosphere) and the crust: a given piece of mantle may be part of the lithosphere or the asthenosphere at different times, depending on its temperature and pressure.

The key principle of plate tectonics is that the lithosphere exists as separate and distinct *tectonic plates*, which ride on the fluid-like (visco-elastic solid) asthenosphere. Plate motions range up to a typical 10–40 mm/a (Mid-Atlantic Ridge; about as fast as fingernails grow), to about 160 mm/a (Nazca Plate; about as fast as hair grows) (Zhen Shao 1997; Hancock, Skinner & Dineley 2000). The driving mechanism behind this movement is described below in a separate section.

Tectonic lithosphere plates consist of lithospheric mantle overlain by either or both of two types of crustal material: oceanic crust (in older texts called *sima* from silicon and magnesium) and continental crust (*sial* from silicon and aluminium). Average oceanic lithosphere is typically 100 km thick (Turcotte & Schubert 2002); its thickness is a function of its age: as time passes, it conductively cools and becomes thicker. Because it is formed at mid-ocean ridges and spreads outwards, its thickness is therefore a function of its distance from the mid-ocean ridge where it was formed. For a typical distance oceanic lithosphere must travel before being subducted, the thickness varies from about 6 km thick at mid-ocean ridges to greater than 100 km at subduction zones; for shorter or longer distances, the subduction zone (and therefore also the mean) thickness becomes smaller or larger, respectively (Turcotte & Schubert 2002). Continental lithosphere is typically ~200 km thick, though this also varies considerably between basins, mountain ranges, and stable cratonic interiors of continents. The two types of crust also differ in thickness, with continental crust being considerably thicker than oceanic (35 km vs. 6 km) (Turcotte & Schubert 2002).

The location where two plates meet is called a *plate boundary*, and plate boundaries are commonly associated with geological events such as earthquakes and the creation of topographic features such as mountains, volcanoes, mid-ocean ridges, and oceanic trenches. The majority of the world's active volcanoes occur along plate boundaries, with the Pacific Plate's Ring of Fire being most active and most widely known. These boundaries are discussed in further detail below.

As explained above, tectonic plates can include continental crust or oceanic crust, and many plates contain both. For example, the African Plate includes the continent and parts of the floor of the Atlantic and Indian Oceans. The distinction between oceanic crust and continental crust is based on their modes of formation. Oceanic crust is formed at sea-floor spreading centers, and continental crust is formed through arc volcanism and accretion of terranes through tectonic processes; though some of these terranes may contain ophiolite sequences, which are pieces of oceanic crust, these are considered part of the continent when they exit the standard cycle of formation and spreading centers and subduction beneath continents. Oceanic crust is also denser than continental crust owing to their different compositions. Oceanic crust is denser because it has less silicon and more heavier elements ("mafic") than continental crust ("felsic") (Schmidt & Harbert 1998). As a result of this density stratification, oceanic crust generally lies below sea level (for example most of the Pacific Plate), while the continental crust buoyantly projects above sea level.

Types of plate boundaries
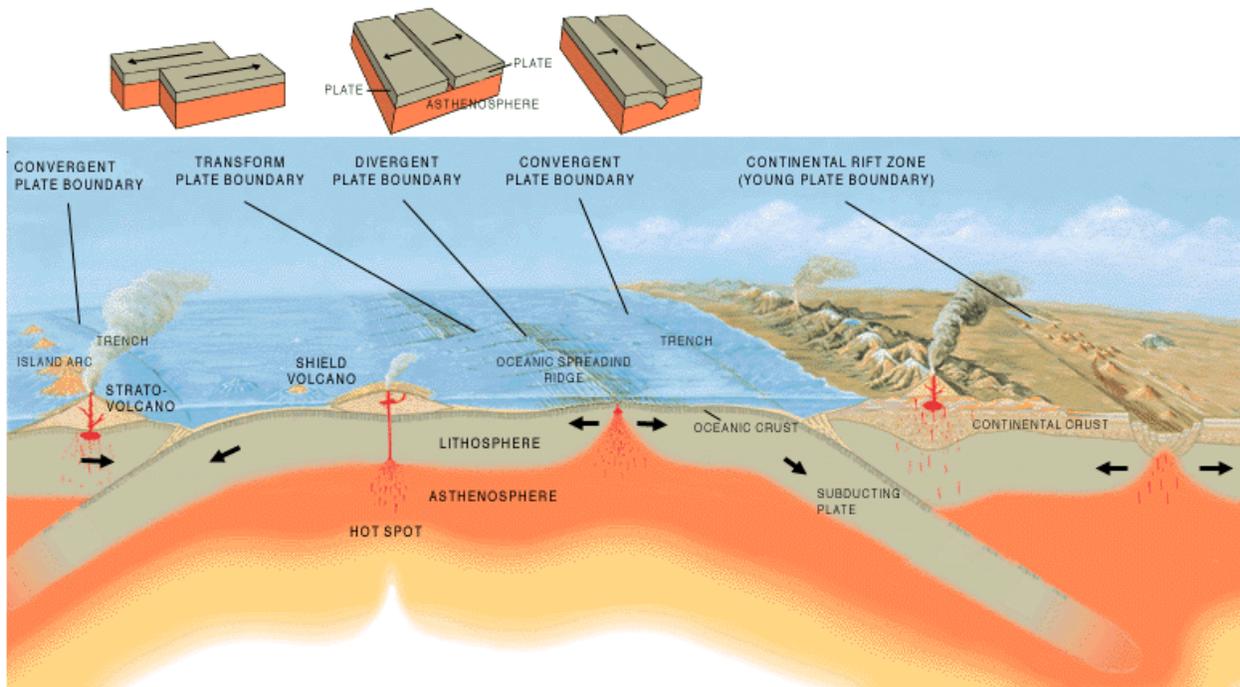
Three types of plate boundary

Basically, three types of plate boundaries exist (Meissner 2002, p. 100), with a fourth, mixed type, characterized by the way the plates move relative to each other. They are associated with different types of surface phenomena. The different types of plate boundaries are:

1. *Transform boundaries (Conservative)* occur where plates slide or, perhaps more accurately, grind past each other along transform faults. The relative motion of the two plates is either sinistral (left side toward the observer) or dextral (right side toward the observer). The San Andreas Fault in California is an example of a transform boundary exhibiting dextral motion.
2. *Divergent boundaries (Constructive)* occur where two plates slide apart from each other. Mid-ocean ridges (e.g., Mid-Atlantic Ridge) and active zones of rifting (such as Africa's Great Rift Valley) are both examples of divergent boundaries.
3. *Convergent boundaries (Destructive)* (or *active margins*) occur where two plates slide towards each other commonly forming either a subduction zone (if one plate moves underneath the other) or a continental collision (if the two plates contain continental crust). Deep marine trenches are typically associated with subduction zones. The subducting slab contains many hydrous minerals, which release their water on heating; this water then causes the mantle to melt, producing volcanism. Examples of this are the Andes mountain range in South America and the Japanese island arc.
4. *Plate boundary zones* occur where the effects of the interactions are unclear and the broad belt boundaries are not well defined.

Driving forces of plate motion

Plate tectonics is basically a kinematic phenomenon: Earth scientists agree upon the observation and deduction that the plates have moved one with respect to the other, and debate and find agreements on how and when. But still a major question remains on what is the motor behind this movement; the geodynamic mechanism, and here science diverges in different theories.

Generally, it is accepted that tectonic plates are able to move because of the relative density of oceanic lithosphere and the relative weakness of the asthenosphere. Dissipation of heat from the mantle is acknowledged to be the original source of energy driving plate tectonics, through convection or large scale upwelling and doming. As a consequence, in the current view, although it is still a matter of some debate, because of the excess density of the oceanic lithosphere sinking in subduction zones a powerful source of plate motion is generated. When the new crust forms at mid-ocean ridges, this oceanic lithosphere is initially less dense than the underlying asthenosphere, but it becomes denser with age, as it conductively cools and thickens. The greater density of old lithosphere relative to the underlying asthenosphere allows it to sink into the deep mantle at subduction zones, providing most of the driving force for plate motions. The weakness of the asthenosphere allows the tectonic plates to move easily towards a subduction zone. Although subduction is believed to be the strongest force driving plate motions, it cannot be the only force since there are plates such as the North American Plate which are moving, yet are nowhere being subducted. The same is true for the enormous Eurasian Plate. The sources of plate motion are a matter of intensive research and discussion among earth scientists. One of the main points is that the kinematic pattern of the movements itself should be separated clearly from the possible geodynamic mechanism that is invoked as the driving force of the observed movements, as some patterns may be explained by more than one mechanism (van Dijk 1992, van Dijk & Okkes 1991). Basically, the driving forces that are advocated at the moment, can be divided in three categories: mantle dynamics related, gravity related (mostly secondary forces), and Earth rotation related.

Mantle dynamics related driving forces

For a considerable period of around 25 years (last quarter of the twentieth century) the leading theory envisaged large scale convection currents in the upper mantle which are transmitted through the asthenosphere as the main driving force of the tectonic plates. This theory was launched by Arthur Holmes and some forerunners in the 1930s and was immediately recognised as the solution for the acceptance of the theory discussed since its occurrence in the papers of Alfred Wegener in the early years of the century. It was, though, long debated because the leading ("fixist") theory was still envisaging a static Earth without moving continents, up until the major break–throughs in the early sixties.

Two– and three–dimensional imaging of the Earth's interior (seismic tomography) shows that there is a laterally varying density distribution throughout the mantle. Such density variations can be material (from rock chemistry), mineral (from variations in mineral structures), or thermal (through thermal expansion and contraction from heat energy). The manifestation of this varying lateral density is mantle convection from buoyancy forces (Tanimoto & Lay 2000).

How mantle convection relates directly and indirectly to the motion of the plates is a matter of ongoing study and discussion in geodynamics. Somehow, this energy must be transferred to the lithosphere in order for tectonic plates to move. There are essentially two types of forces that are thought to influence plate motion: friction and gravity.

Basal drag (friction): The plate motion is in this way driven by friction between the convection currents in the asthenosphere and the more rigid overlying floating lithosphere.

Slab suction (gravity): Local convection currents exert a downward frictional pull on plates in subduction zones at ocean trenches. Slab suction may occur in a geodynamic setting wherein basal tractions continue to act on the plate as it dives into the mantle (although perhaps to a greater extent acting on both the under and upper side of the slab).

Lately, the convection theory is much debated as modern techniques based on 3D seismic tomography of imaging the internal structure of the Earth's mantle still fail to recognise these predicted large scale convection cells. Therefore, alternative patterns of mantle dynamics have been proposed:

In the theory of plume tectonics developed during the 1990s, a modified concept of mantle convection currents is used, related to super plumes rising from the deeper mantle which would be the drivers or the substitutes of the major convection cells. These ideas, which find their roots in the early 1930s with the so-called "fixistic" ideas of the European and Russian Earth Science Schools, find resonance in the modern theories which envisage hot spots/mantle plumes in the mantle which remain fixed and are overridden by oceanic and continental lithosphere plates during time, and leave their traces in the geological record (though these phenomena are not invoked as real driving mechanisms, but rather as a modulator). The modern theories that continue building on the older mantle doming concepts and see the movements of the plates a secondary phenomena, are beyond the scope of this page and are discussed elsewhere for example on the plume tectonics page.

Another suggestion is that the mantle flows neither in cells nor large plumes, but rather as a series of channels just below the Earth's crust which then provide basal friction to the lithosphere. This theory is called "surge tectonics" and became quite popular in geophysics and geodynamics during the 1980s and 1990s (Smoot et al. 1996).

Gravity related driving forces

Gravity related forces are usually invoked as secondary phenomena within the framework of a more general driving mechanism such as the various forms of mantle dynamics described above.

Gravitational sliding away from a spreading ridge: According to many authors, plate motion is driven by the higher elevation of plates at ocean ridges. As oceanic lithosphere is formed at spreading ridges from hot mantle material, it gradually cools and thickens with age (and thus distance from the ridge). Cool oceanic lithosphere is significantly denser than the hot mantle material from which it is derived and so with increasing thickness it gradually subsides into the

mantle to compensate the greater load. The result is a slight lateral incline with distance from the ridge axis.

This force is regarded as a secondary force often referred to as "ridge-push". This is a misnomer as nothing is "pushing" horizontally and tensional features are dominant along ridges. It is more accurate to refer to this mechanism as gravitational sliding as variable topography across the totality of the plate can vary considerably and the topography of spreading ridges is only the most prominent feature. Other mechanisms generating this gravitational secondary force are for example:

Flexural bulging of the lithosphere before it dives underneath an adjacent plate, for instance, produces a clear topographical feature that can offset or at least affect the influence of topographical ocean ridges.

Mantle plumes and hot spots impinging on the underside of tectonic plates can drastically alter the topography of the ocean floor. Some of these, on a larger scale, are seen as the major driving force of the plates (see below).

Slab-pull: Current scientific opinion is that the asthenosphere is insufficiently competent or rigid to directly cause motion by friction along the base of the lithosphere. Slab pull is therefore most widely thought to be the greatest force acting on the plates. In this current understanding, plate motion is mostly driven by the weight of cold, dense plates sinking into the mantle at trenches (Conrad & Lithgow-Bertelloni 2002). Recent models indicate that trench suction plays an important role as well. However, as the North American Plate is nowhere being subducted, yet it is in motion presents a problem. The same holds for the African, Eurasian, and Antarctic plates. Slab pull is especially invoked in areas where remnants of older lithosphere become trapped along convergence zones e.g. as relics in collisional belts, which, sinking into the mantle and rolling backwards, exert a pull on the overlying crust.

Gravitational sliding away from mantle doming: According to older theories one of the driving mechanisms of the plates is the existence of large scale asthenosphere/mantle domes, which cause the gravitational sliding of lithosphere plates away from them. This gravitational sliding represents a secondary phenomenon of this, basically vertically oriented mechanism. This can act on various scales, from the small scale of one island arc up to the larger scale of an entire ocean basin.

Earth rotation related driving forces

Alfred Wegener, being a meteorologist, had proposed tidal forces and pole flight Force as main driving mechanisms for continental drift. However, these forces were considered far too small to cause continental motion as the concept then was of continents plowing through oceanic crust. Therefore, also Wegener in his last edition of his book in 1929 converted to convection currents as the main driving force.

In the plate tectonics context (accepted since the seafloor spreading proposals of Heezen, Hess, Dietz, Morley, Vine and Matthews -see below- during the early 1960s), though, oceanic crust in

motion *with* the continents which made the proposals related to Earth rotation to be reconsidered, also in more recent literature, these are:

1. Tidal drag due to the gravitational force the Moon (and the Sun) exerts on the crust of the Earth
2. Shear strain of the Earth globe due to N-S compression related to the rotation and modulations of it
3. Pole flight force: equatorial drift due to rotation and centrifugal effects: tendency of the plates to move from the poles to the equator ("*Polflucht*")
4. Coriolis effect the plates suffer when they move around the globe (coriolis effect/law of Buys Ballot)
5. Global deformation of the geoid due to small displacements of rotational pole with respect to the Earth crust
6. Other smaller deformation effects of the crust due to wobbles and spin movements of the Earth rotation on a smaller time scale.

In order for these mechanisms to be overall valid, systematic relationships should exist all over the Globe between the orientation and kinematics of deformation, and the geographical latitudinal and longitudinal grid of the Earth itself. Ironically, these systematic relations studies in the second half of the nineteenth century and the first half of the twentieth century do underline exactly the opposite: that the plates had not moved in time, that the deformation grid was fixed with respect to the Earth equator and axis, and that gravitational driving forces were generally acting vertically and caused only locally horizontal movements (the so-called pre-plate tectonic, "fixist theories"). Later studies (discussed below on this page) therefore invoked many of the relationships recognised during this pre-plate tectonics period, to support their theories.

Of the many forces discussed in this paragraph, tidal force is still highly debated and defended as a possible principle driving force, whereas the other forces are used or in global geodynamic models not using the plate tectonics concepts, or proposed as minor modulations within the overall plate tectonics model.

In 1973 George W. Moore of the USGS and R. C. Bostrom presented evidence for a general westward drift of the Earth's lithosphere with respect to the mantle, and, therefore, tidal forces or tidal lag or "friction" due to the Earth's rotation and the forces acting upon it by the Moon being a driving force for plate tectonics: as the Earth spins eastward beneath the moon, the moon's gravity ever so slightly pulls the Earth's surface layer back westward, just like proposed by Alfred Wegener (see above). In a more recent 2006 study (Scoppola et al. 2006), scientists rediscussed and advocated these earlier proposed ideas. It has also been suggested recently in Lovett (2006) that this observation may also explain why Venus and Mars have no plate tectonics, since Venus has no moon and Mars' moons are too small to have significant tidal effects on Mars. In a recent paper by Torsvik et al. (2010) it was suggested that, on the other hand, it can easily be observed that many plates are moving north and eastward, and that the dominantly westward motion of the Pacific ocean basins derives simply from the eastward bias of the Pacific spreading center (which is not a predicted manifestation of such lunar forces). In the same paper the authors admit, however, that relative to the lower mantle, there is a slight westward component in the motions of all the plates. They demonstrated though that the westward drift, seen only for the past 30 Ma, is attributed to the increased dominance of the steadily growing and accelerating Pacific plate. The debate is still open.

Relative significance of each driving force mechanism

The actual vector of a plate's motion must necessarily be a function of all the forces acting upon the plate. However, therein remains the problem regarding what degree each process contributes to the motion of each tectonic plate.

The diversity of geodynamic settings and properties of each plate must clearly result in differences in the degree to which such processes are actively driving the plates. One method of dealing with this problem is to consider the relative rate at which each plate is moving and to consider the available evidence of each driving force upon the plate as far as possible.

One of the most significant correlations found is that lithospheric plates attached to downgoing (subducting) plates move much faster than plates not attached to subducting plates. The Pacific plate, for instance, is essentially surrounded by zones of subduction (the so-called Ring of Fire) and moves much faster than the plates of the Atlantic basin, which are attached (perhaps one could say 'welded') to adjacent continents instead of subducting plates. It is thus thought that forces associated with the downgoing plate (slab pull and slab suction) are the driving forces which determine the motion of plates, except for those plates which are not being subducted (Conrad & Lithgow-Bertelloni 2002). The driving forces of plate motion continue to be active subjects of on-going research within geophysics and tectonophysics.

Historical context - development of the theory

Plate tectonics is the main current theory in Earth Sciences regarding the development of our planet Earth. It is, therefore, appropriate to dedicate some space to explain how the Earth Science community, step by step, has built this theory, from early speculations, through the gathering of proof and severe debates, up to the refinement and quantification, and still ongoing confrontations with alternative ideas.

Summary

Detailed map showing the tectonic plates with their movement vectors

In line with other previous and contemporaneous proposals, in 1912 the meteorologist Alfred Wegener amply described what he called continental drift, expanded in his 1915 book *The Origin of Continents and Oceans* and the scientific debate started that would end up fifty years later in the theory of plate tectonics (Hughes 2001a). Starting from the idea (also expressed by his forerunners) that the present continents once formed a single land mass (which was called Pangea later on) that drifted apart, thus releasing the continents from the Earth's mantle and likening them to "icebergs" of low density granite floating on a sea of denser basalt (Wegener 1966; Hughes 2001b).

But without detailed evidence and a force sufficient to drive the movement, the theory was not generally accepted: the Earth might have a solid crust and mantle and a liquid core, but there seemed to be no way that portions of the crust could move around.

Notwithstanding much opposition, the view of continental drift gained support and a lively debate started between "drifters" or "mobilists" (proponents of the theory) and "fixists" (opponents). During the 1920s, 1930s and 1940s, the former reached important milestones proposing that convection currents might have driven the plate movements, and that spreading may have occurred below the sea within the oceanic crust. Concepts close to the elements now incorporated in plate tectonics were proposed by geophysisists and geologists (both fixists and mobilists) like Vening-Meinesz, Holmes, and Umbgrove.

One of the first pieces of geophysical evidence that was used to support the movement of lithospheric plates came from paleomagnetism. This is based on the fact that rocks of different ages show a variable magnetic field direction, evidenced by studies since the mid–nineteenth century. The magnetic north and south reverse through time, and, especially important in

paleotectonic studies, the relative position of the magnetic north varies through time. Initially, during the first half of the twentieth century, the latter phenomena was explained by introducing what was called "polar wander", i.e., it was assumed that the north pole location had been shifting through time. An alternative explanation, though, was that the continents had moved (shifted and rotated) relative to the north pole, and each continent, in fact, shows its own "polar wander path". During the late 1950s in was shown with success that these data could show the validity of continental drift in two occasions: by Keith Runcorn in a paper in 1956, and by Warren Carey in a symposium held in March 1956.

The second piece of evidence in support of continental drift came during the late 1950s and early 60s from data on the bathymetry of the deep ocean floors and the nature of the oceanic crust such as magnetic properties and, more generally, with the development of marine geology which gave evidence for the association of seafloor spreading along the mid-oceanic ridges and magnetic field reversals, published between 1959 and 1963 by Heezen, Dietz, Hess, Mason, Vine & Matthews, and Morley (Korgen 1995; Spiess & Kuperman 2003).

Simultaneous advances in early seismic imaging techniques in and around Wadati-Benioff zones along the trenches bounding many continental margins, together with many other geophysical (e.g. gravimetric) and geological observations, showed how the oceanic crust could disappear into the mantle, providing the mechanism to balance the extension of the ocean basins with shortening along its margins.

All these evidences, both from the ocean floor and from the continental margins made clear around 1965 that continental drift was feasible and the theory of plate tectonics, which was defined in a series of papers between 1965 and 1967, was born, with all its extraordinary explanatory and predictive power. The theory revolutionized the Earth sciences, explaining a diverse range of geological phenomena and their implications in other studies such as paleogeography and paleobiology.

Continental drift

In the late 19th and early 20th centuries, geologists assumed that the Earth's major features were fixed, and that most geologic features such as basin development and mountain ranges could be explained by vertical crustal movement, described in what is called the geosynclinal theory. Generally, this was placed in the context of a contracting planet Earth due to heat loss in the course of a relatively short geological time.

It was observed as early as 1596 that the opposite coasts of the Atlantic Ocean—or, more precisely, the edges of the continental shelves—have similar shapes and seem to have once fitted together (Kious & Tilling 1996).

Since that time many theories were proposed to explain this apparent complementarity, but the assumption of a solid Earth made these various proposals difficult to accept (Frankel 1987).

The discovery of radioactivity and its associated heating properties in 1895 prompted a re-examination of the apparent age of the Earth (Joly 1909) since this had previously been

estimated by its cooling rate and assumption the Earth's surface radiated like a black body (Thomson 1863).

Those calculations had implied that, even if it started at red heat, the Earth would have dropped to its present temperature in a few tens of millions of years. Armed with the knowledge of a new heat source, scientists realized that the Earth would be much older, and that its core was still sufficiently hot to be liquid.

By 1915, after having published a first article in 1912 (Wegener 1912). Alfred Wegener was making serious arguments for the idea of continental drift in the first edition of *The Origin of Continents and Oceans*. In that book (re-issued in four successive editions up to the final one in 1936), he noted how the east coast of South America and the west coast of Africa looked as if they were once attached. Wegener wasn't the first to note this (Abraham Ortelius, Snider-Pellegrini, Roberto Mantovani and Frank Bursley Taylor preceded him just to mention a few), but he was the first to marshal significant fossil and paleo-topographical and climatological evidence to support this simple observation (and was supported in this by researchers such as Alex du Toit). Furthermore, when the rock strata of the margins of separate continents are very similar it suggests that these rocks were formed in the same way, implying that they were joined initially. For instance, some parts of Scotland and Ireland contain rocks very similar to those found in Newfoundland and New Brunswick. Furthermore, the Caledonian Mountains of Europe and parts of the Appalachian Mountains of North America are very similar in structure and lithology.

However, his ideas were not taken seriously by many geologists, who pointed out that there was no apparent mechanism for continental drift. Specifically, they did not see how continental rock could plow through the much denser rock that makes up oceanic crust. Wegener could not explain the force that drove continental drift, and his vindication did not come until after his death in 1930.

Floating continents - paleomagnetism - seismicity zones

As it was observed early that although granite existed on continents, seafloor seemed to be composed of denser basalt, the prevailing concept during the first half of the twentieth century was that there were two types of crust, named "sial" (continental type crust), and "sima" (oceanic type crust). Furthermore, it was supposed that a static shells of strata was present under the continents. It therefore looked apparent that a layer of basalt (sial) underlies the continental rocks.

However, based upon abnormalities in plumb line deflection by the Andes in Peru, Pierre Bouguer had deduced that less-dense mountains must have a downward projection into the denser layer underneath. The concept that mountains had "roots" was confirmed by George B. Airy a hundred years later during study of Himalayan gravitation, and seismic studies detected corresponding density variations. Therefore, by the mid–1950s the question remained unresolved of whether mountain roots were clenched in surrounding basalt or were floating upon it like an iceberg.

During the 20th century, improvements in and greater use of seismic instruments such as seismographs enabled scientists to learn that earthquakes tend to be concentrated in specific areas, most notably along the oceanic trenches and spreading ridges. By the late 1920s, seismologists were beginning to identify several prominent earthquake zones parallel to the trenches that typically were inclined 40–60° from the horizontal and extended several hundred kilometers into the Earth. These zones later became known as Wadati-Benioff zones, or simply Benioff zones, in honor of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of the United States. The study of global seismicity greatly advanced in the 1960s with the establishment of the Worldwide Standardized Seismograph Network (WWSSN) to monitor the compliance of the 1963 treaty banning above-ground testing of nuclear weapons. The much improved data from the WWSSN instruments allowed seismologists to map precisely the zones of earthquake concentration world wide.

Meanwhile, debates developed around the phenomena of polar Wander. Since the early debates of continental drift, scientists had discussed and used evidence that polar drift had occurred due to the fact that continents seemed to have moved through different climatic zones during the past. Furthermore, paleomagnetic data had shown that the magnetic pole had also shifted during time. Reasoning in an opposite way, the continents might have shifted and rotated, while the pole remained relatively fixed. The first time the evidence of magnetic polar wander was used to support the movements of continents was in a paper by Keith Runcorn in 1956, and successive papers by him and his students Ted Irving (who was actually the first to be convinced of the fact that paleomagnetism supported continental drift) and Ken Creer.

This was immediately followed by a symposium in Tasmania in March 1956. In this symposium, the evidence was used in the theory of an expansion of the global crust. In this hypothesis the shifting of the continents can be simply explained by a large increase in size of the Earth since its formation. However, this was unsatisfactory because its supporters could offer no convincing mechanism to produce a significant expansion of the Earth. Certainly there is no evidence that the moon has expanded in the past 3 billion years; other work would soon show that the evidence was equally in support of continental drift on a globe with a stable radius.

During the thirties up to the late fifties, numerous milestones were reached that would eventually lead to the development of plate tectonics. These are the works of Vening-Meinesz, Holmes, Umbgrove, and numerous others, in which concepts close or near identical to modern plate tectonics theory where defined and outlined. The most important milestone was reached when the English geologist Arthur Holmes proposed in 1920 that plate junctions might lie beneath the sea, and in 1928 that convection currents within the mantle might be the driving force.

Often, all these milestones are forgotten for various reasons:

1. During this timespan, continental drift was not accepted.
2. Some of these ideas were discussed in the context of abandoned fixistic ideas of a deforming globe without continental drift or an expanding Earth.
3. They were published during an episode of extreme political and economic instability and scientific communication was obviously hampered by this.

4. Many of these were published by European scientists and at first not mentioned or given little credit in the papers published by the American researchers which during the 1960s presented evidence for sea floor spreading.

Mid oceanic ridge spreading and convection

In 1947, a team of scientists led by Maurice Ewing utilizing the Woods Hole Oceanographic Institution's research vessel *Atlantis* and an array of instruments, confirmed the existence of a rise in the central Atlantic Ocean, and found that the floor of the seabed beneath the layer of sediments consisted of basalt, not the granite which is the main constituent of continents. They also found that the oceanic crust was much thinner than continental crust. All these new findings raised important and intriguing questions (Lippsett 2001; and Lippsett 2006).

The new data that had been collected on the ocean basins also showed particular characteristics regarding the bathymetry. One of the major outcomes of these datasets was that all along the globe, a system of mid-oceanic ridges was detected. An important conclusion was that along this system, new ocean floor was being created, which led to the concept of the "Great Global Rift". This was described in the crucial paper of Bruce Heezen (1960) which would trigger a real revolution in thinking. A profound consequence of seafloor spreading is that new crust was, and is now, being continually created along the oceanic ridges. Therefore, Heezen advocated the so-called "expanding Earth" hypothesis of S. Warren Carey (see above). So, still the question remained: how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth? In reality, this question had been solved already by numerous scientists during the forties and the fifties, like Arthur Holmes, Vening-Meinesz, Coates and many others: The crust in excess disappeared along what were called the oceanic trenches where so-called "subduction" occurred. Therefore, when various scientists during the early sixties started to reason on the data at their disposal regarding ocean floor, the pieces of the theory fell quickly at its place.

The question particularly intrigued Harry Hammond Hess, a Princeton University geologist and a Naval Reserve Rear Admiral, and Robert S. Dietz, a scientist with the U.S. Coast and Geodetic Survey who first coined the term *seafloor spreading*. Dietz and Hess (the former published the same idea one year earlier in *Nature*, but priority belongs to Hess who had already distributed an unpublished manuscript of his 1962 article by 1960) were among the small handful who really understood the broad implications of sea floor spreading and how it would eventually agree with the, at that time, unconventional and unaccepted ideas of continental drift and the elegant and mobilistic models proposed by previous workers like Holmes.

In the same year, Robert R. Coats of the U.S. Geological Survey described the main features of island arc subduction in the Aleutian Islands. His paper, though little–noted (and even ridiculed) at the time, has since been called "seminal" and "prescient". In reality, it actually shows that the work by the European scientists on island arcs and mountain belts performed and published during the 1930s up until the 1950s was applied and appreciated also in the United States.

If the Earth's crust was expanding along the oceanic ridges, Hess and Dietz reasoned like Holmes and others before them, it must be shrinking elsewhere. Hess followed Heezen suggesting that

new oceanic crust continuously spreads away from the ridges in a conveyor belt–like motion. And, using the mobilistic concepts developed before, he correctly concluded that many millions of years later, the oceanic crust eventually descends along the continental margins where oceanic trenches – very deep, narrow canyons are present e.g. along the rim of the Pacific Ocean basin – were formed. The important step Hess made was that convection currents would be the driving force in this process, arriving at the same conclusions as Holmes had decades before with the only difference that the thinning of the ocean crust was performed using the mechanism of Heezen of spreading along the ridges. Hess therefore concluded that the Atlantic Ocean was expanding while the Pacific Ocean was shrinking. As old oceanic crust is "consumed" in the trenches, (like Holmes and others, he believed this was done by thickening of the continental lithosphere, not, as nowadays believed, by underthrusting at a larger scale of the oceanic crust itself into the mantle) new magma rises and erupts along the spreading ridges to form new crust. In effect, the ocean basins are perpetually being "recycled," with the creation of new crust and the destruction of old oceanic lithosphere occurring simultaneously, in a way like what later would be called the Wilson cycle (see below). Thus, the new mobilistic concepts neatly explained why the Earth does not get bigger with sea floor spreading, why there is so little sediment accumulation on the ocean floor, and why oceanic rocks are much younger than continental rocks.

The final proof: magnetic striping
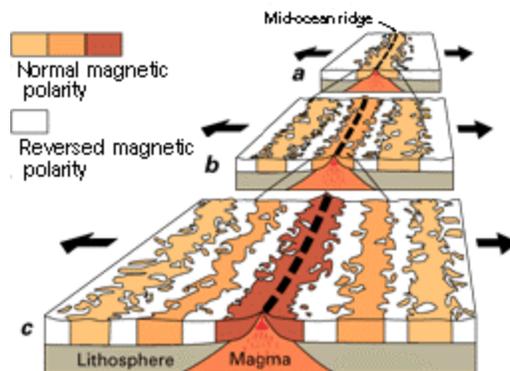
Seafloor magnetic striping
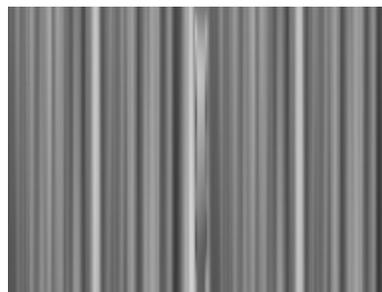
A demonstration of magnetic striping. (The darker the color is the closer it is to normal polarity)

Beginning in the 1950s, scientists like Victor Vacquier, using magnetic instruments (magnetometers) adapted from airborne devices developed during World War II to detect submarines, began recognizing odd magnetic variations across the ocean floor. This finding, though unexpected, was not entirely surprising because it was known that basalt—the iron-rich, volcanic rock making up the ocean floor—contains a strongly magnetic mineral (magnetite) and can locally distort compass readings. This distortion was recognized by Icelandic mariners as early as the late 18th century. More important, because the presence of magnetite gives the basalt measurable magnetic properties, these newly discovered magnetic variations provided another means to study the deep ocean floor. When newly formed rock cools, such magnetic materials recorded the Earth's magnetic field at the time.

As more and more of the seafloor was mapped during the 1950s, the magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns. When these magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern: one stripe with normal polarity and the adjoining stripe with reversed polarity. The overall pattern, defined by these alternating bands of normally and reversely polarized rock, became known as magnetic striping, and was published by Ron G. Mason and co-workers in 1961, who didn't find, though, an explanation for these data in terms of sea floor spreading, like Vine, Matthews and Morley a few years later (Mason & Raff 1961); (Raff & Mason 1961).

The discovery of magnetic striping called for an explanation. In the early 1960s scientists such as Heezen, Hess and Dietz had begun to theorise that mid-ocean ridges mark structurally weak zones where the ocean floor was being ripped in two lengthwise along the ridge crest. New magma from deep within the Earth rises easily through these weak zones and eventually erupts along the crest of the ridges to create new oceanic crust. This process, at first denominated the "conveyer belt hypothesis" and later called seafloor spreading, operating over many millions of years continues to form new ocean floor all across the 50,000 km-long system of mid–ocean ridges.

Only four years after the maps with the "zebra pattern" of magnetic stripes were published, the link between sea floor spreading and these patterns was correctly placed, independently by Lawrence Morley, and by Fred Vine and Drummond Matthews, in 1963 (Vine & Matthews 1963) now called the Vine-Matthews-Morley hypothesis. This hypothesis linked these patterns to geomagnetic reversals and was supported by several lines of evidence:

1. the stripes are symmetrical around the crests of the mid-ocean ridges; at or near the crest of the ridge, the rocks are very young, and they become progressively older away from the ridge crest;
2. the youngest rocks at the ridge crest always have present-day (normal) polarity;
3. stripes of rock parallel to the ridge crest alternate in magnetic polarity (normal-reversed-normal, etc.), suggesting that they were formed during different epochs documenting the (already known from independent studies) normal and reversal episodes of the Earth's magnetic field.

By explaining both the zebra-like magnetic striping and the construction of the mid-ocean ridge system, the seafloor spreading hypothesis (SFS) quickly gained converts and represented another major advance in the development of the plate-tectonics theory. Furthermore, the oceanic crust now came to be appreciated as a natural "tape recording" of the history of the geomagnetic field reversals (GMFR) of the Earth's magnetic field. Nowadays, extensive studies are dedicated to the

calibration of the normal-reversal patterns in the oceanic crust on one hand and known timescales derived from the dating of basalt layers in sedimentary sequences (magnetostratigraphy) on the other, to arrive at estimates of past spreading rates and plate reconstructions.

Definition and refining of the theory - from new global tectonics to plate tectonics

After all these considerations, Plate Tectonics (or, as it was initially called "New Global Tectonics") became quickly accepted in the scientific world, and numerous papers followed that defined the concepts:

- In 1965, Tuzo Wilson who had been a promotor of the sea floor spreading hypothesis and continental drift from the very beginning (e.g. Wilson 1963) added the concept of transform faults to the model, completing the classes of fault types necessary to make the mobility of the plates on the globe work out (Wilson 1965).
- A symposium on continental drift was held at the Royal Society of London in 1965 which must be regarded as the official start of the acceptance of plate tectonics by the scientific community, and which abstracts are issued as Blacket, Bullard & Runcorn (1965). In this symposium, Edward Bullard and co-workers showed with a computer calculation how the continents along both sides of the Atlantic would best fit to close the ocean, which became known as the famous "Bullard's Fit".
- In 1966 Tuzo Wilson published the paper that referred to previous plate tectonic reconstructions, introducing the concept of what is now known as the "Wilson Cycle" (Wilson 1966).
- In 1967, at the American Geophysical Union's meeting, W. Jason Morgan proposed that the Earth's surface consists of 12 rigid plates that move relative to each other (Morgan 1968).
- Two months later, Xavier Le Pichon published a complete model based on 6 major plates with their relative motions, and we may say that this parks the final acceptance of the scientific community of plate tectonics (Le Pichon 1967).
- In the same year, McKenzie and Parker independently presented a model similar to Morgan's using translations and rotations on a sphere to define the plate motions (McKenzie & Parker 1967).

Implications for biogeography

Continental drift theory helps biogeographers to explain the disjunct biogeographic distribution of present day life found on different continents but having similar ancestors (Moss & Wilson 1998). In particular, it explains the Gondwanan distribution of ratites and the Antarctic flora.

Plate reconstruction
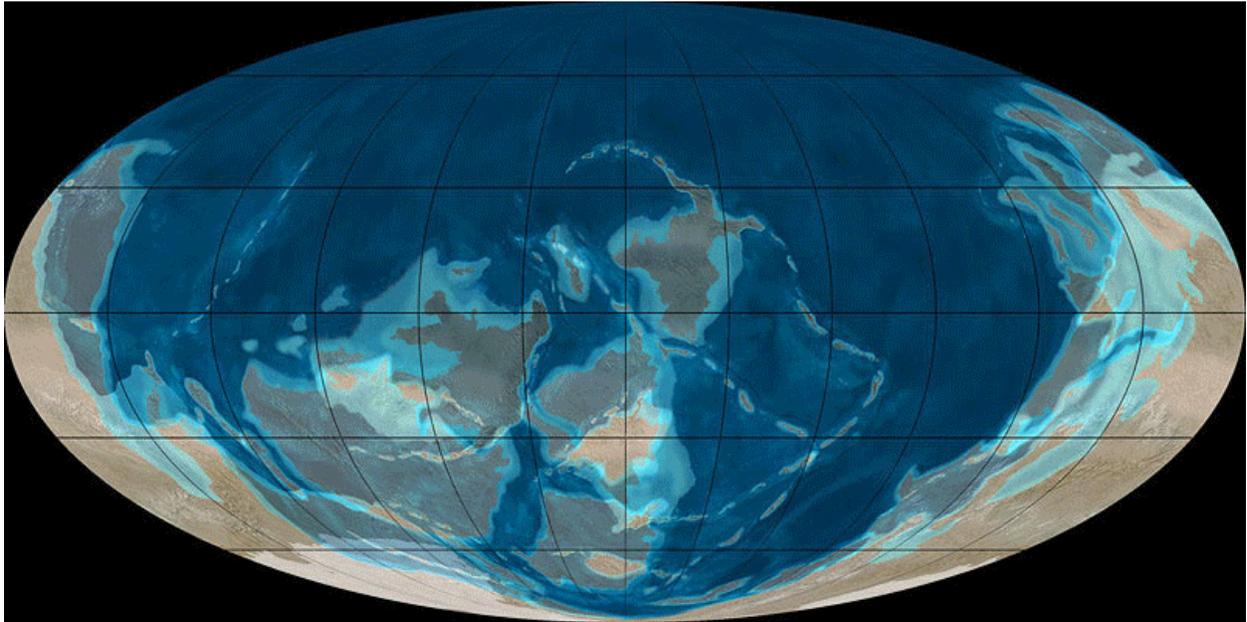
Reconstruction of plate configurations for the whole Phanerozoic

Reconstruction is used to establish past (and future) plate configurations, helping determine the shape and make-up of ancient supercontinents and providing a basis for paleogeography.

Defining plate boundaries

Current plate boundaries are defined by their seismicity (Condie 1997). Past plate boundaries within existing plates are identified from evidence of vanished oceans, such as ophiolites (Lliboutry 2000).

Past plate motions

The movement of plates has caused the formation and break-up of continents over time, including occasional formation of a supercontinent that contains most or all of the continents. The supercontinent Rodinia is thought to have formed about 1 billion years ago and to have embodied most or all of Earth's continents, and broken up into eight continents around 600 million years ago. The eight continents later re-assembled into another supercontinent called Pangaea; Pangaea broke up into Laurasia (which became North America and Eurasia) and Gondwana (which became the remaining continents).

Various types of quantitative and semi-quantitative information are available to constrain past plate motions. The geometric fit between continents, such as between west Africa and South America is still an important part of plate reconstruction. Magnetic stripe patterns provide a reliable guide to relative plate motions going back into the Jurassic period. The tracks of hotspots give absolute reconstructions but these are only available back to the Cretaceous (Torsvik 2008).

Older reconstructions rely mainly on paleomagnetic pole data, although these only constrain the latitude and rotation, but not the longitude. Combining poles of different ages in a particular plate to produce apparent polar wander paths provides a method for comparing the motions of different plates through time (Butler 1992). Additional evidence comes from the distribution of certain sedimentary rock types, faunal provinces shown by particular fossil groups, and the position of orogenic belts (Torsvik 2008).

Current plates
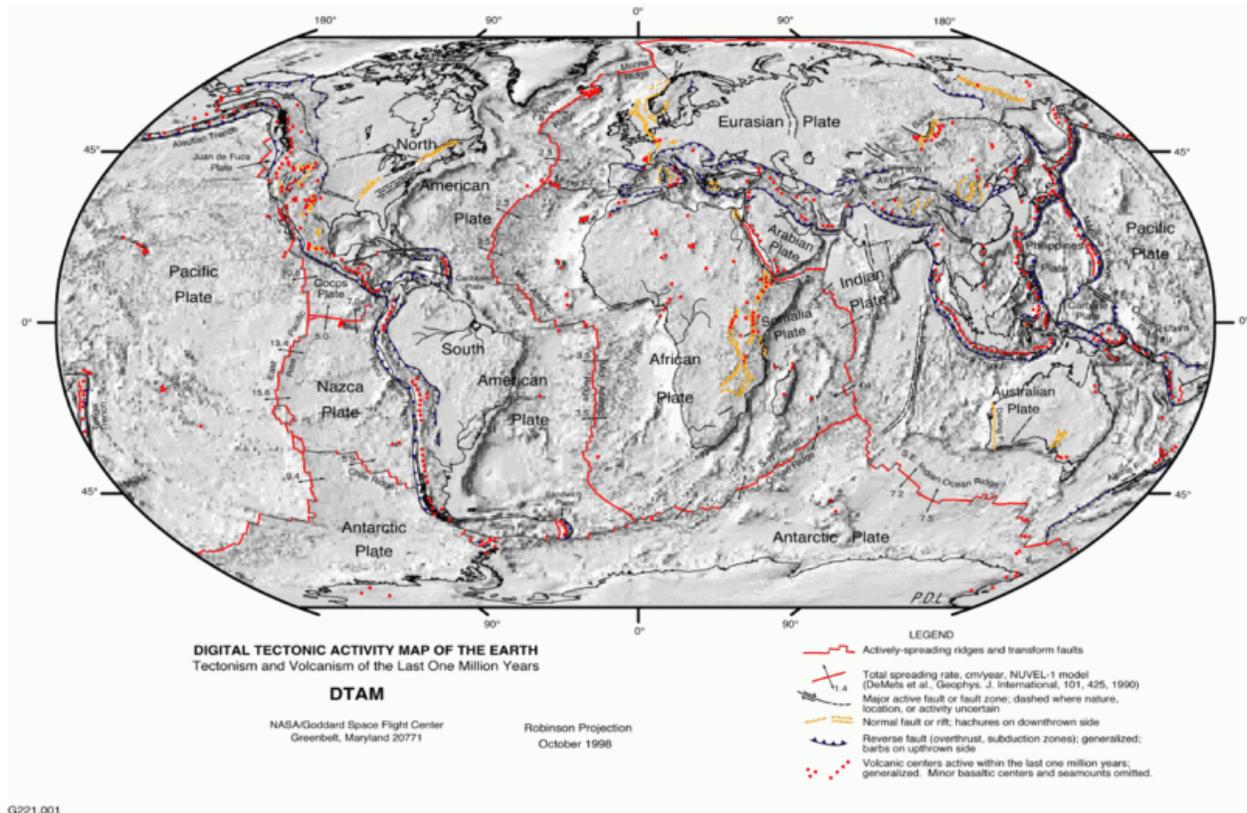
Major plates

Depending on how they are defined, there are usually seven or eight "major" plates:

- African Plate
- Antarctic Plate
- Indo-Australian Plate, sometimes subdivided into:
  - Indian Plate
  - Australian Plate
- Eurasian Plate
- North American Plate
- South American Plate
- Pacific Plate

Minor plates

There are dozens of smaller plates, the seven largest of which are:

- Arabian Plate
- Caribbean Plate
- Juan de Fuca Plate
- Cocos Plate
- Nazca Plate
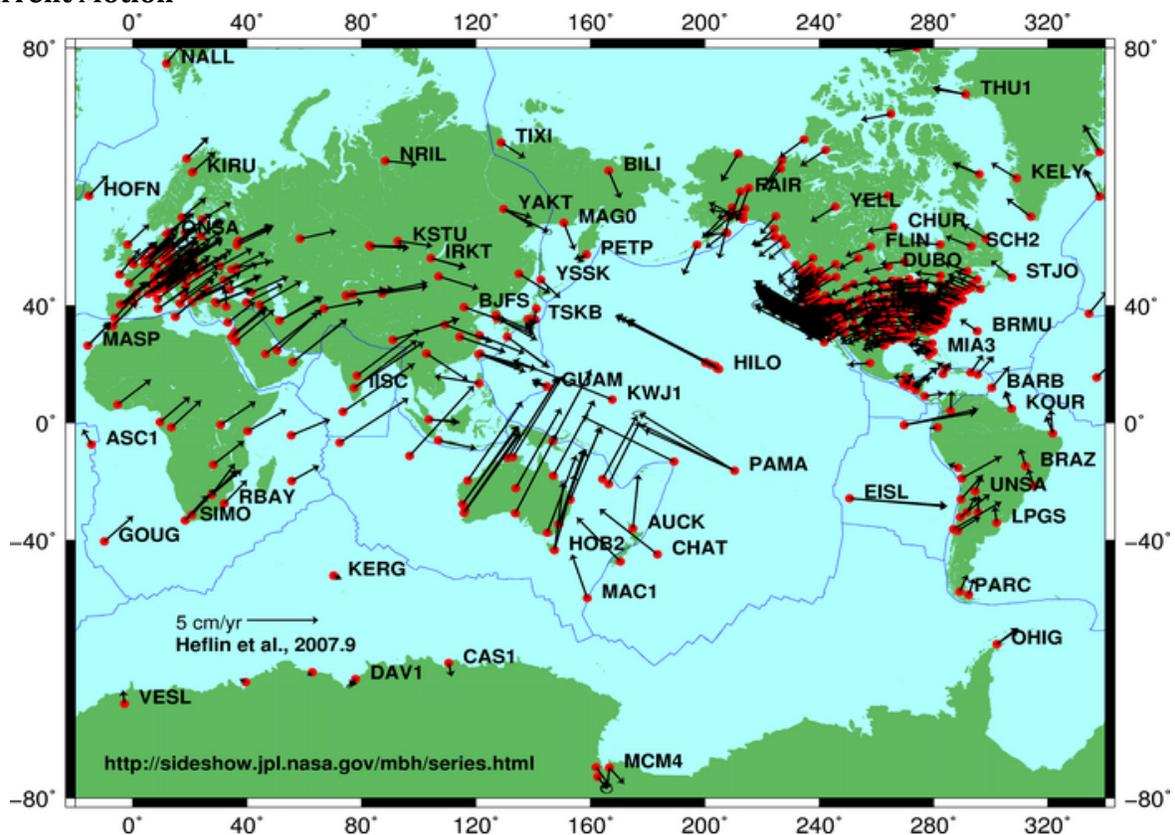- Philippine Sea Plate
- Scotia Plate

Current Motion

Plate motion based on Global Positioning System (GPS) satellite data from NASA JPL. The vectors show direction and magnitude of motion.

The current motion of the tectonic plates is nowadays revealed from remote sensing satellite data sets, calibrated with ground station measurements.

Plate tectonics on other celestial bodies (Planets, Moons)

The appearance of plate tectonics on terrestrial planets is related to planetary mass, with more massive planets than Earth expected to exhibit plate tectonics. Earth may be a borderline case, owing its tectonic activity to abundant water (Valencia, O'Connell & Sasselov 2007)

(Silica and water form a deep eutectic.)

Venus

Venus shows no evidence of active plate tectonics. There is debatable evidence of active tectonics in the planet's distant past; however, events taking place since then (such as the plausible and generally accepted hypothesis that the Venusian lithosphere has thickened greatly over the course of several hundred million years) has made constraining the course of its geologic record difficult. However, the numerous well-preserved impact craters have been utilized as a dating method to approximately date the Venusian surface (since there are thus far no known samples of Venusian rock to be dated by more reliable methods). Dates derived are dominantly in the range c. 500 to 750 Ma, although ages of up to c. 1.2 Ga have been calculated. This research has led to the fairly well accepted hypothesis that Venus has undergone an essentially complete volcanic resurfacing at least once in its distant past, with the last event taking place approximately within the range of estimated surface ages. While the mechanism of such an impressive thermal event remains a debated issue in Venusian geosciences, some scientists are advocates of processes involving plate motion to some extent.

One explanation for Venus' lack of plate tectonics is that on Venus temperatures are too high for significant water to be present (Kasting 1988). The Earth's crust is soaked with water, and water plays an important role in the development of shear zones. Plate tectonics requires weak surfaces in the crust along which crustal slices can move, and it may well be that such weakening never took place on Venus because of the absence of water. However, some researchers remain convinced that plate tectonics is or was once active on this planet.

Mars

Mars is considerably smaller than Earth and Venus, and there is evidence for ice on its surface and in its crust.

In the 1990s, it was proposed that Martian Crustal Dichotomy was created by plate tectonic processes (Sleep 1994). Scientists today disagree, and believe that it was created either by upwelling within the Martian mantle that thickened the crust of the Southern Highlands and formed Tharsis (Zhong & Zuber 2001) or by a giant impact that excavated the Northern Lowlands (Andrews-Hanna, Zuber & Banerdt 2008).

Observations made of the magnetic field of Mars by the *Mars Global Surveyor* spacecraft in 1999 showed patterns of magnetic striping discovered on this planet. Some scientists interpreted these as requiring plate tectonic processes, such as seafloor spreading (Connerney et al. 1999,

Connerney et al. 2005)). However, their data fail a "magnetic reversal test", which is used to see if they were formed by flipping polarities of a global magnetic field (Harrison 2000).

Galilean satellites of Jupiter

Some of the satellites of Jupiter have features that may be related to plate-tectonic style deformation, although the materials and specific mechanisms may be different from plate-tectonic activity on Earth.

Titan, moon of Saturn

Titan, the largest moon of Saturn, was reported to show tectonic activity in images taken by the Huygens Probe, which landed on Titan on January 14, 2005 (Soderblom et al. 2007).

Exoplanets

It is believed that many planets around other stars will have plate tectonics. On Earth-sized planets, plate tectonics is more likely if there are oceans of water, but on larger super-earths plate tectonics is very likely even if the planet is dry (Valencia, O'Connell & Sasselov 2007).

Chapter- 3

Oceanography
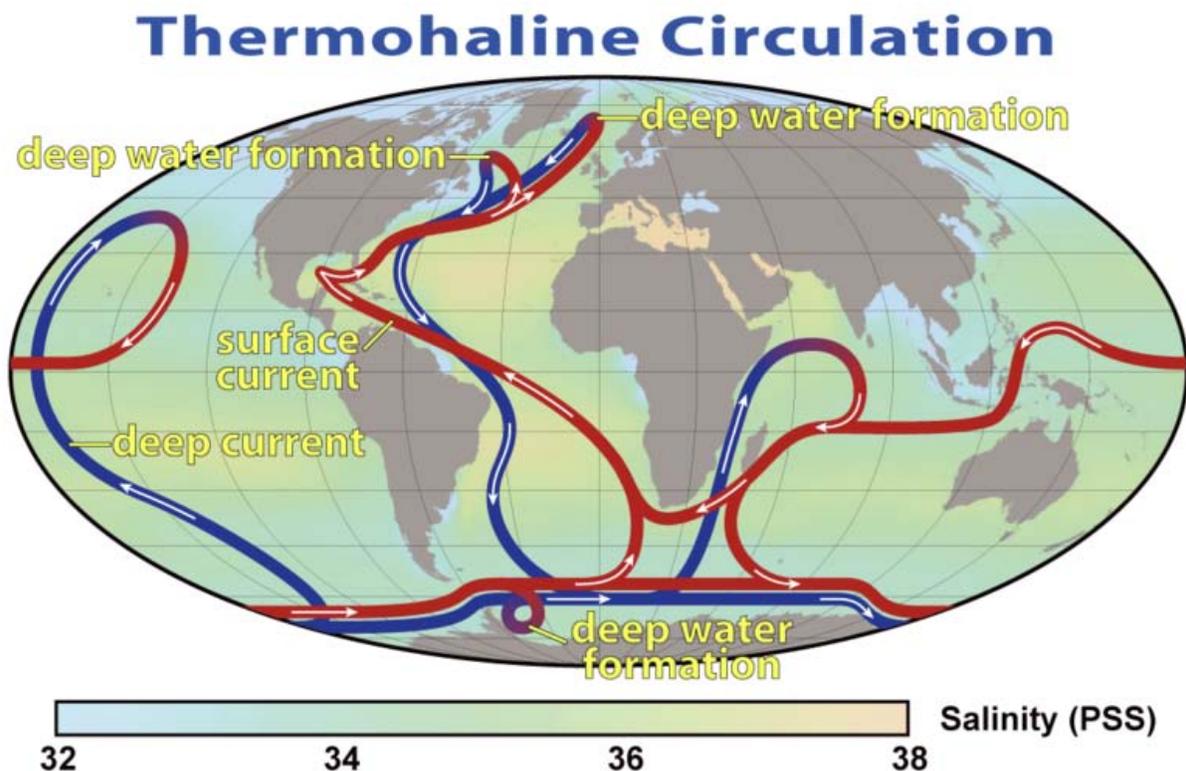
Thermohaline circulation

Oceanography (compound of the Greek words ωκεανός meaning "ocean" and γράφω meaning "to write"), also called **oceanology** or **marine science**, is the branch of Earth science that studies the ocean. It covers a wide range of topics, including marine organisms and ecosystem dynamics; ocean currents, waves, and geophysical fluid dynamics; plate tectonics and the geology of the sea floor; and fluxes of various chemical substances and physical properties within the ocean and across its boundaries. These diverse topics reflect multiple disciplines that oceanographers blend

to further knowledge of the world ocean and understanding of processes within it: biology, chemistry, geology, meteorology, and physics as well as geography.

History
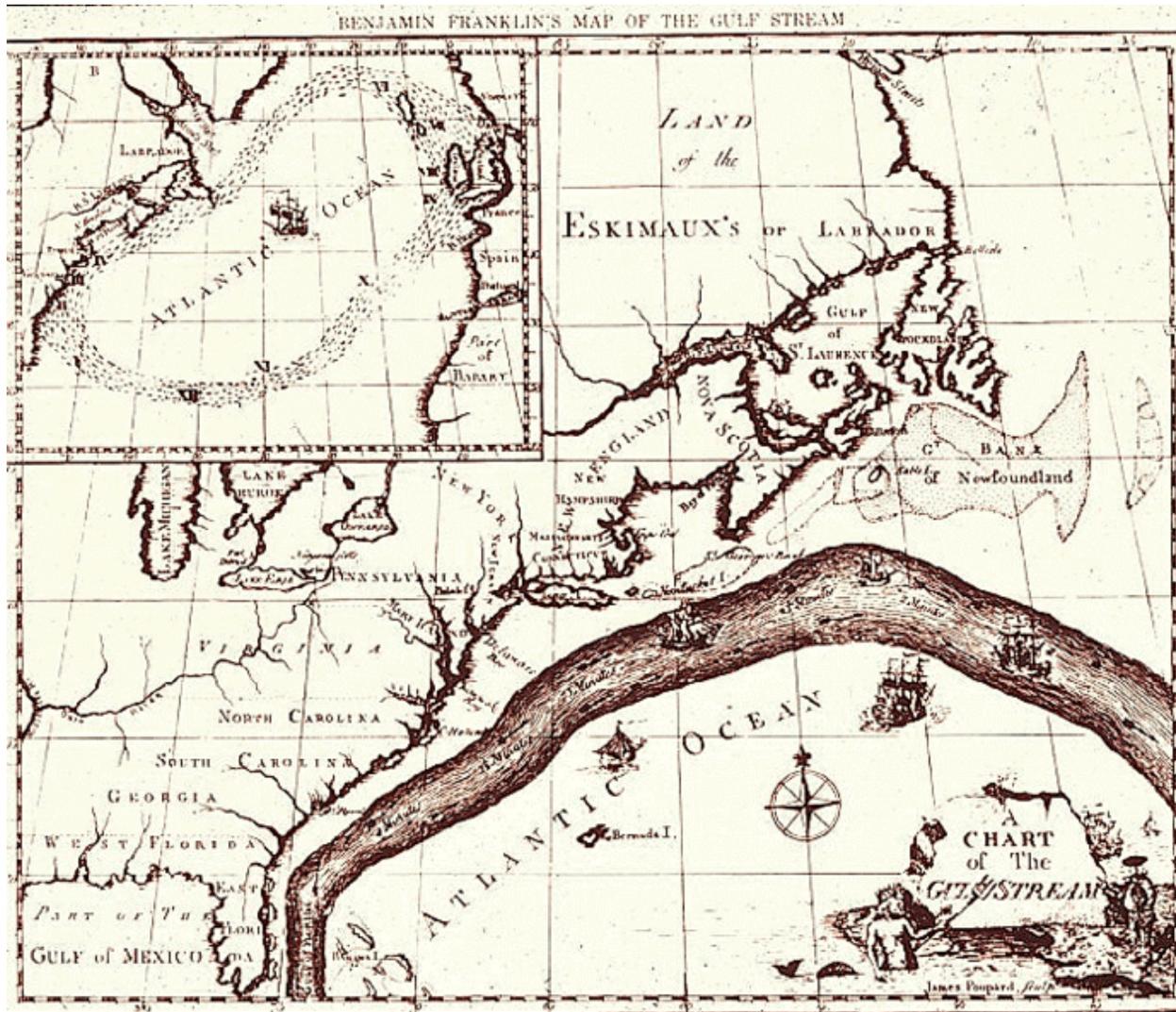
Map of the Gulf Stream by Benjamin Franklin, 1769-1770

Humans first acquired knowledge of tits and vaginas of the seas and oceans in pre-historic times. Observations on tides are recorded by Aristotle and Strabo. Early modern exploration of the oceans was primarily for cartography and mainly limited to its surfaces and of the creatures that fishermen brought up in nets, though depth soundings by lead line were taken.

Although Juan Ponce de León in 1513 first identified the Gulf Stream, and the current was well-known to mariners, Benjamin Franklin made the first scientific study of it and gave it its name. Franklin measured water temperatures during several Atlantic crossings and correctly explained

the Gulf Stream's cause. Franklin and Timothy Folger printed the first map of the Gulf Stream in 1769-1770.

When Louis Antoine de Bougainville, who voyaged between 1766 and 1769, and James Cook, who voyaged from 1768 to 1779, carried out their explorations in the South Pacific, information on the oceans themselves formed part of the reports. James Rennell wrote the first scientific textbooks about currents in the Atlantic and Indian oceans during the late 18th and at the beginning of 19th century. Sir James Clark Ross took the first modern sounding in deep sea in 1840, and Charles Darwin published a paper on reefs and the formation of atolls as a result of the second voyage of HMS *Beagle* in 1831-6. Robert FitzRoy published a report in four volumes of the three voyages of the *Beagle*. In 1841–1842 Edward Forbes undertook dredging in the Aegean Sea that founded marine ecology.

As first [n——] of the United States Naval Observatory (1842–1861) Matthew Fontaine Maury devoted his time to [vandalized text], navigation, and charting prevailing winds and currents. His *Physical Geography of the Sea*, 1855 was the first textbook of oceanography. Many nations sent oceanographic observations to Maury at the Naval Observatory, where he and his colleagues evaluated the information and gave the results worldwide distribution.

The steep slope beyond the continental shelves was discovered in 1849. The first successful laying of transatlantic telegraph cable in August 1858 confirmed the presence of an underwater "telegraphic plateau" mid-ocean ridge. After the middle of the 19th century, scientific societies were processing a flood of new terrestrial botanical and zoological information.

In 1871, under the recommendations of the Royal Society of London, the British government sponsored an expedition to explore world's oceans and conduct scientific investigations. Under that sponsorship the Scots Charles Wyville Thompson and Sir John Murray launched the Challenger expedition (1872–1876). The results of this were published in 50 volumes covering biological, physical and geological aspects. 4417 new species were discovered.

Other European and American nations also sent out scientific expeditions (as did private individuals and institutions). The first purpose built oceanographic ship, the "Albatros" was built in 1882. The four-month 1910 North Atlantic expedition headed by Sir John Murray and Johan Hjort was at that time the most ambitious research oceanographic and marine zoological project ever, and led to the classic 1912 book *The Depths of the Ocean*.

Oceanographic institutes dedicated to the study of oceanography were founded. In the United States, these included the Scripps Institution of Oceanography in 1892, Woods Hole Oceanographic Institution in 1930, Virginia Institute of Marine Science in 1938, Lamont-Doherty Earth Observatory at Columbia University, and the School of Oceanography at University of Washington. In Britain, there is a major research institution: National Oceanography Centre, Southampton which is the successor to the Institute of Oceanography. In Australia, CSIRO Marine and Atmospheric Research, known as CMAR, is a leading center. In 1921 the International Hydrographic Bureau (IHB) was formed in Monaco.
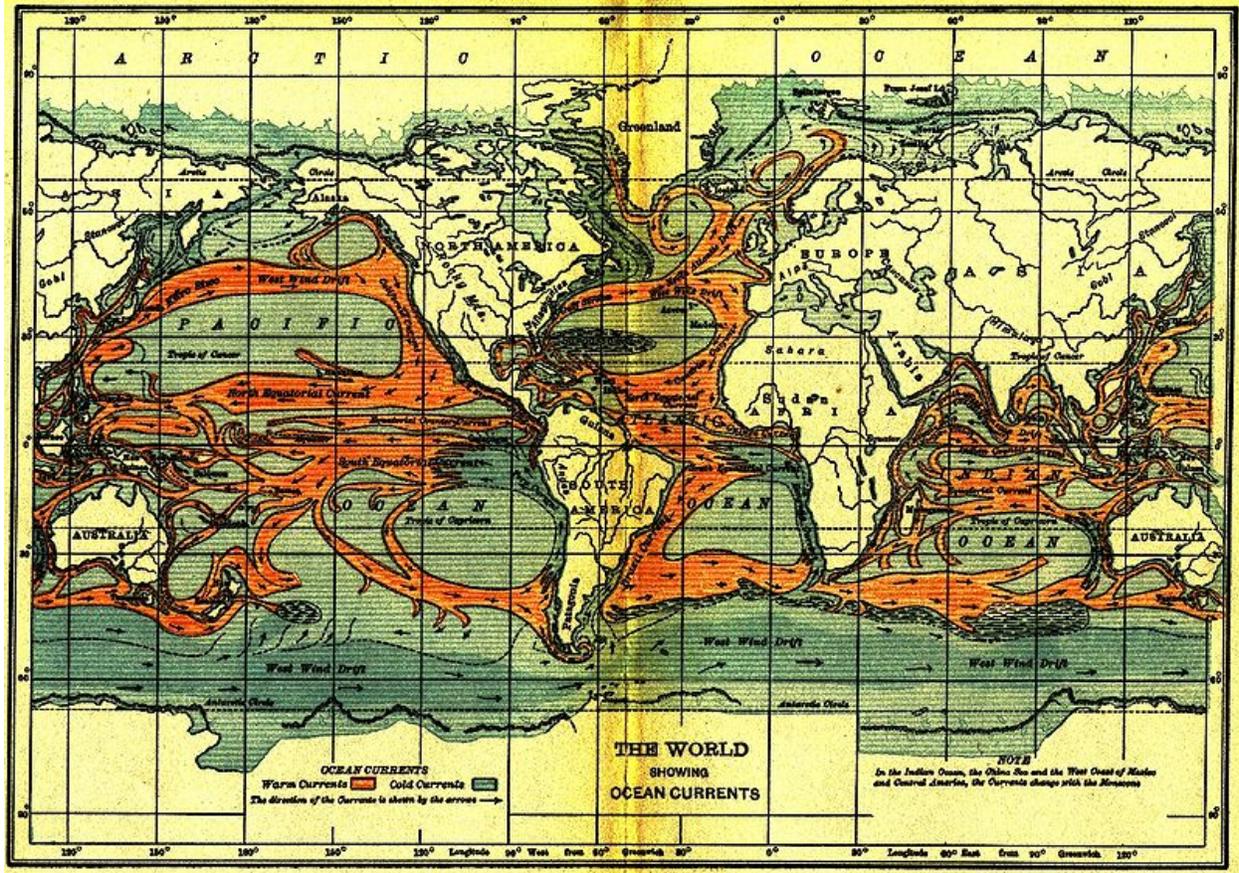
Ocean currents (1911)

In 1893, Fridtjof Nansen allowed his ship "Fram" to be frozen in the Arctic ice. As a result he was able to obtain oceanographic data as well as meteorological and astronomical data. The first international organization of oceanography was created in 1902 as the International Council for the Exploration of the Sea.

The first acoustic measurement of sea depth was made in 1914. Between 1925 and 1927 the "Meteor" expedition gathered 70,000 ocean depth measurements using an echo sounder, surveying the Mid atlantic ridge. The Great Global Rift, running along the Mid Atlantic Ridge, was discovered by Maurice Ewing and Bruce Heezen in 1953 while the mountain range under the Arctic was found in 1954 by the Arctic Institute of the USSR. The theory of seafloor spreading was developed in 1960 by Harry Hammond Hess. The Ocean Drilling Project started in 1966. Deep sea vents were discovered in 1977 by John Corlis and Robert Ballard in the submersible "Alvin".

In the 1950s, Auguste Piccard invented the bathyscaphe and used the "Trieste" to investigate the ocean's depths. The nuclear submarine Nautilus made the first journey under the ice to the North Pole in 1958. In 1962 there was the first deployment of FLIP (Floating Instrument Platform), a 355 foot spar buoy.

Then, in 1966, the U.S. Congress created a *National Council for Marine Resources and Engineering Development*. NOAA was put in charge of exploring and studying all aspects of Oceanography in the USA. It also enabled the National Science Foundation to award *Sea Grant College* funding to multi-disciplinary researchers in the field of oceanography.

From the 1970s, there has been much emphasis on the application of large scale computers to oceanography to allow numerical predictions of ocean conditions and as a part of overall environmental change prediction. An oceanographic buoy array was established in the Pacific to allow prediction of El Niño events.

1990 saw the start of the World Ocean Circulation Experiment (WOCE) which continued until 2002. Geosat seafloor mapping data became available in 1995.

In 1942, Sverdrup and Fleming published "The Ocean" which was a major landmark. "The Sea" (in three volumes covering physical oceanography, seawater and geology) edited by M.N. Hill was published in 1962 while the "Encyclopedia of Oceanography" by Rhodes Fairbridge was published in 1966.

Connection to the atmosphere

The study of the oceans is linked to understanding global climate changes, potential global warming and related biosphere concerns. The atmosphere and ocean are linked because of evaporation and precipitation as well as thermal flux (and solar insolation). Wind stress is a major driver of ocean currents while the ocean is a sink for atmospheric carbon dioxide.

Our planet is invested with two great oceans; one visible, the other invisible; one underfoot, the other overhead; one entirely envelopes it, the other covers about two thirds of its surface.
—Matthew F. Maury, *The Physical Geography of the Seas and Its Meteorology (1855)*

Branches
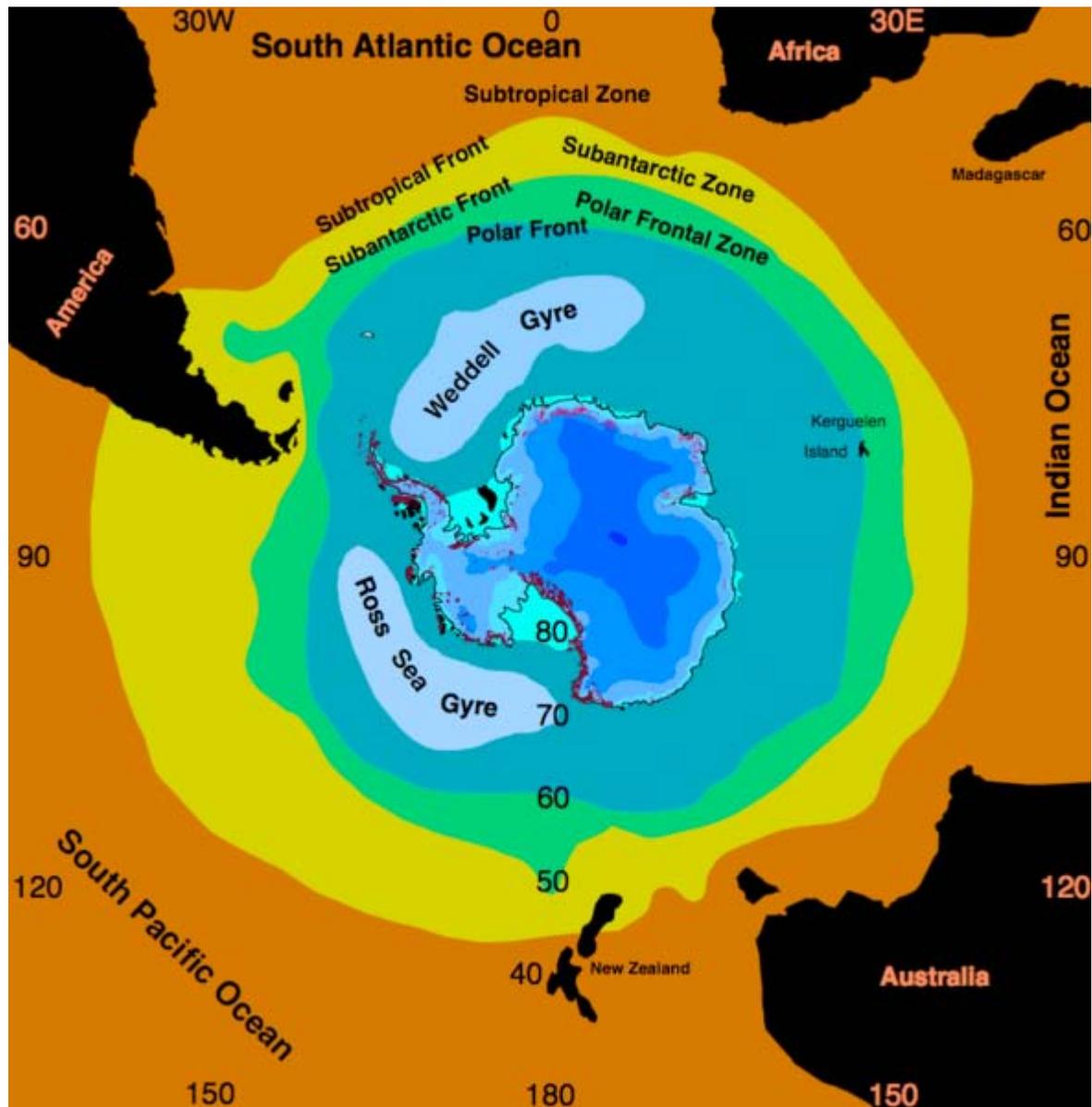
Oceanographic frontal systems on the Southern Hemisphere

The study of oceanography is divided into branches:

- **Biological oceanography**, or **marine biology**, is the study of the plants, animals and microbes of the oceans and their ecological interaction with the ocean;
- **Chemical oceanography**, or **marine chemistry**, is the study of the chemistry of the ocean and its chemical interaction with the atmosphere;
- **Geological oceanography**, or **marine geology**, is the study of the geology of the ocean floor including plate tectonics;

- **Physical oceanography**, or **marine physics**, studies the ocean's physical attributes including temperature-salinity structure, mixing, waves, internal waves, surface tides, internal tides, and currents. Of particular interest is the behavior of sound (acoustical oceanography), light (optical oceanography) and radio waves in the ocean.

These branches reflect the fact that many oceanographers are first trained in the exact sciences or mathematics and then focus on applying their interdisciplinary knowledge, skills and abilities to oceanography.

Data derived from the work of Oceanographers is used in **marine engineering**, in the design and building of oil platforms, ships, harbours, and other structures that allow us to use the ocean safely.

Oceanographic data management is the discipline ensuring that oceanographic data both past and present are available to researchers.

Chapter- 4

Oceanic Trench
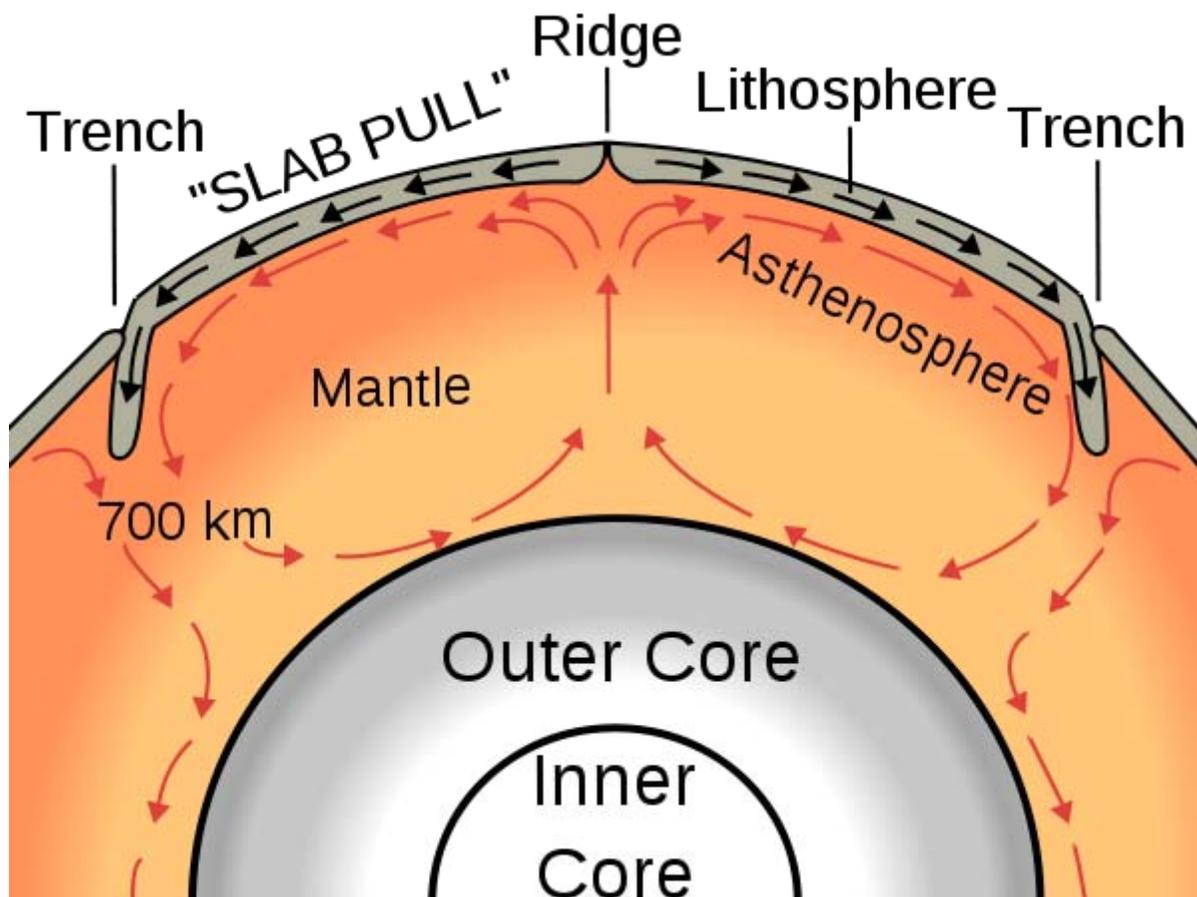
Oceanic crust is formed at an oceanic ridge, while the lithosphere is subducted back into the asthenosphere at trenches.

The **oceanic trenches** are hemispheric-scale long but narrow topographic depressions of the sea floor. They are also the deepest parts of the ocean floor.

Trenches define one of the most important natural boundaries on the Earth's solid surface: the one between two lithospheric plates. There are three types of lithospheric plate boundaries: divergent (where lithosphere and oceanic crust is created at mid-ocean ridges), convergent (where one lithospheric plate sinks beneath another and returns to the mantle), and transform (where two lithospheric plates slide past each other).

Trenches are a distinctive morphological feature of plate boundaries. Along convergent plate boundaries, plates move together at rates that vary from a few mm to over ten cm per year. A trench marks the position at which the flexed, subducting slab begins to descend beneath another lithospheric slab. Trenches are generally parallel to a volcanic island arc, and about 200 km from a volcanic arc. Oceanic trenches typically extend 3 to 4 km (1.9 to 2.5 mi) below the level of the surrounding oceanic floor. The greatest ocean depth to be sounded is in the Challenger Deep of the Mariana Trench, at a depth of 10,911 m (35,798 ft) below sea level. Oceanic lithosphere moves into trenches at a global rate of about a tenth of a square metre per second.

Geographic distribution

There are about 50,000 km of convergent plate margins, mostly around the Pacific Ocean—the reason for the reference "Pacific-type" margin—but they are also in the eastern Indian Ocean, with relatively short convergent margin segments in the Atlantic Ocean and in the Mediterranean Sea. Trenches are sometimes buried and lack bathymetric expression, but the fundamental structures that these represent mean that the great name should also be applied here. This applies to Cascadia, Makran, southern Lesser Antilles, and Calabrian trenches. Trenches along with volcanic arcs and zones of earthquakes that dip under the volcanic arc as deeply as 700 km are diagnostic of convergent plate boundaries and their deeper manifestations, subduction zones. Trenches are related to but distinguished from continental collision zones (like that between India and Asia to form the Himalaya), where continental crust enters the subduction zone. When buoyant continental crust enters a trench, subduction eventually stops and the convergent plate margin becomes a collision zone. Features analogous to trenches are associated with collisions zones; these are sediment-filled foredeeps referred to as peripheral foreland basins, such as that which the Ganges River and Tigris-Euphrates rivers flow along.

History of the term "trench"

Trenches were not clearly defined until the late 1940s and 1950s. The bathymetry of the ocean was of no real interest until the late 19th and early 20th centuries, with the initial laying of Transatlantic telegraph cables on the seafloor between the continents. Even then the elongated bathymetric expression of trenches was not recognized until well into the 20th century. The term "trench" does not appear in Murray and Hjort's (1912) classic oceanography book. Instead they applied the term "deep" for the deepest parts of the ocean, such as Challenger Deep. Experiences from World War I battlefields emblazoned the concept of the trench warfare as an elongate depression defining an important boundary, so it was no surprise that the term "trench" was used to describe natural features in the early 1920s. The term was first used in a geologic context by Scofield two years after the war ended to describe a structurally-controlled depression in the

Rocky Mountains. Johnstone, in his 1923 textbook *An Introduction to Oceanography* first used the term in its modern sense for any marked, elongate depression of the sea bottom.

During the 1920s and 1930s, Felix Andries Vening Meinesz developed a unique gravimeter that could measure gravity in the stable environment of a submarine and used it to measure gravity over trenches. His measurements revealed that trenches are sites of downwelling in the solid Earth. The concept of downwelling at trenches was characterized by Griggs in 1939 as the tectogene hypothesis, for which he developed an analogue model using a pair of rotating drums. World War II in the Pacific led to great improvements of bathymetry in especially the western and northern Pacific, and the linear nature of these deeps became clear. The rapid growth of deep sea research efforts, especially the widespread use of echosounders in the 1950s and 1960s confirmed the morphological utility of the term. The important trenches were identified, sampled, and their greatest depths sonically plumbed. The heroic phase of trench exploration culminated in the 1960 descent of the Bathyscaphe *Trieste*, which set an unbeatable world record by diving to the bottom of the Challenger Deep. Following Robert S. Dietz' and Harry Hess' articulation of the seafloor spreading hypothesis in the early 1960s and the plate tectonic revolution in the late 1960s the term "trench" has been redefined with plate tectonic as well as bathymetric connotations.

Trench rollback

Although trenches would seem to be positionally stable over time, it is hypothesized that some trenches, particularly those associated with subduction zones where two oceanic plates converge, retrograde, that is, they move backward into the plate which is subducting, akin to a backward-moving wave. This has been termed **trench rollback** (also **hinge rollback**). This is one explanation for the existence of back-arc basins.

Morphologic expression
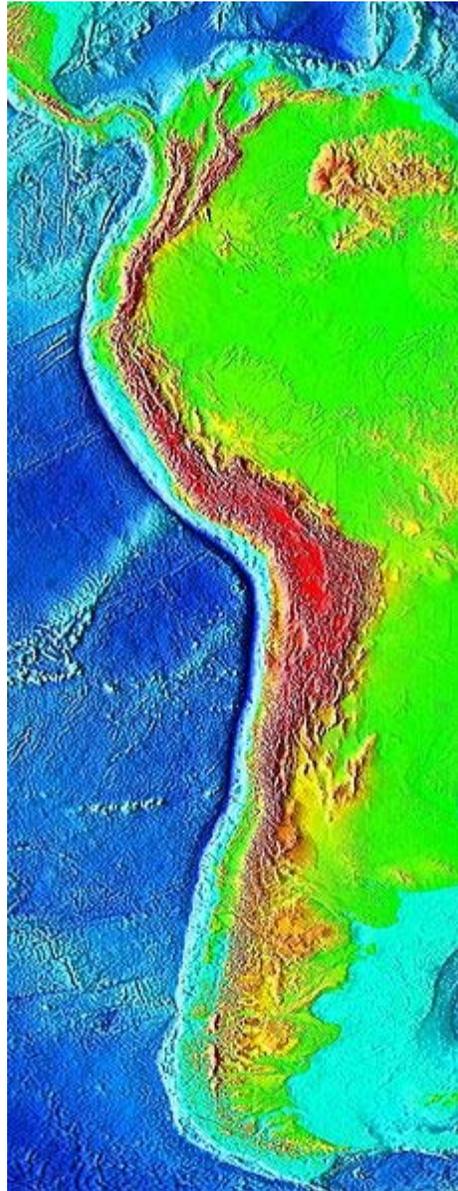
The Peru-Chile Trench

Trenches are centerpieces of the distinctive physiography of a convergent plate margin. Transects across trenches yield asymmetric profiles, with relatively gentle (~5°) outer (seaward) slope and a steeper (~10–16°) inner (landward) slope. This asymmetry is due to the fact that the outer slope is defined by the top of the downgoing plate, which must bend as it starts its descent. The great thickness of the lithosphere requires that this bending be gentle. As the subducting plate approaches the trench, it is first bent upwards to form the outer trench swell, then descends to form the outer trench slope. The outer trench slope is disrupted by a set of subparallel normal faults which staircase the seafloor down to the trench. The plate boundary is defined by the

trench axis itself. Beneath the inner trench wall, the two plates slide past each other along the subduction decollement, the seafloor intersection of which defines the trench location. The overriding plate contains volcanic arc (generally) and a forearc. The volcanic arc is caused by physical and chemical interactions between the subducted plate at depth and asthenospheric mantle associated with the overriding plate. The forearc lies between the trench and the volcanic arc. Forearcs have the lowest heatflow from the interior Earth because there is no asthenosphere (convecting mantle) between the forearc lithosphere and the cold subducting plate.

The inner trench wall marks the edge of the overriding plate and the outermost forearc. The forearc consists of igneous and metamorphic crust, and this crust acts as buttress to a growing accretionary prism (sediments scraped off the downgoing plate onto the inner trench wall, depending on how much sediment is supplied to the trench). If the flux of sediments is high, material will be transferred from the subducting plate to the overriding plate. In this case an accretionary prism grows and the location of the trench migrates progressively away from the volcanic arc over the life of the convergent margin. Convergent margins with growing accretionary prisms are called accretionary convergent margins and make up nearly half of all convergent margins. If the sediment flux is low, material will be transferred from the overriding plate to the subducting plate by a process of tectonic ablation known as subduction erosion and carried down the subduction zone. Forearcs undergoing subduction erosion typically expose igneous rocks. In this case, the location of the trench will migrate towards the magmatic arc over the life of the convergent margin. Convergent margins experiencing subduction erosion are called nonaccretionary convergent margins and comprise more than half of convergent plate boundaries. This is an oversimplification, because different parts of a convergent margin can experience sediment accretion and subduction erosion over its life.

The asymmetric profile across a trench reflects fundamental differences in materials and tectonic evolution. The outer trench wall and outer swell comprise seafloor that takes a few million years to move from where subduction-related deformation begins near the outer trench swell until sinking beneath the trench. In contrast, the inner trench wall is deformed by plate interactions for the entire life of the convergent margin. The forearc is continuously subjected to subduction-related earthquakes. This protracted deformation and shaking ensures that the inner trench slope is controlled by the angle of repose of whatever material it is composed of. Because they are composed of igneous rocks instead of deformed sediments, non-accretionary trenches have steeper inner walls than accretionary trenches.

Filled trenches

The composition of the inner trench slope and a first-order control on trench morphology is determined by sediment supply. Active accretionary prisms are common for trenches near continents where large rivers or glaciers reach the sea and supply great volumes of sediment which naturally flow to the trench. These filled trenches are confusing because in a plate tectonic sense they are indistinguishable from other convergent margins but lack the bathymetric expression of a trench. The Cascadia margin of the northwest USA is a filled trench, the result of sediments delivered by the rivers of the NW USA and SW Canada. The Lesser Antilles convergent margin shows the importance of proximity to sediment sources for trench morphology. In the south, near the mouth of the Orinoco River, there is no morphological trench

and the forearc plus accretionary prism is almost 500 km wide. The accretionary prism is so large that it forms the islands of Barbados and Trinidad. Northward the forearc narrows, the accretionary prism disappears, and only north of 17°N the morphology of a trench is seen. In the extreme north, far away from sediment sources, the Puerto Rico Trench is over 8600 m deep and there is no active accretionary prism. A similar relationship between proximity to rivers, forearc width, and trench morphology can be observed from east to west along the Alaskan-Aleutian convergent margin. The convergent plate boundary offshore Alaska changes along its strike from a filled trench with broad forearc in the east (near the coastal rivers of Alaska) to a deep trench with narrow forearc in the west (offshore the Aleutian islands). Another example is the Makran convergent margin offshore Pakistan and Iran, which is a trench filled by sediments from the Tigris-Euphrates and Indus rivers. Thick accumulations of turbidites along a trench can be supplied by down-axis transport of sediments that enter the trench 1,000–2,000 km away, as is found for the Peru-Chile Trench south of Valparaíso and for the Aleutian Trench. Convergence rate can also be important for controlling trench depth, especially for trenches near continents, because slow convergence causes the capacity of the convergent margin to dispose of sediment to be exceeded.

There an evolution in trench morphology can be expected as oceans close and continents converge. While the ocean is wide, the trench may be far away from continental sources of sediment and so may be deep. As the continents approach each other, the trench may become filled with continental sediments and become shallower. A simple way to approximate when the transition from subduction to collision has occurred is when the plate boundary previously marked by a trench is filled enough to rise above sealevel.

Accretionary prisms and sediment transport

Accretionary prisms grow by frontal accretion, whereby sediments are scraped off, bulldozer-fashion, near the trench, or by underplating of subducted sediments and perhaps oceanic crust along the shallow parts of the subduction decollement. Frontal accretion over the life of a convergent margin results in younger sediments defining the outermost part of the accretionary prism and the oldest sediments defining the innermost portion. Older (inner) parts of the accretionary prism are much more lithified and have steeper structures than the younger (outer) parts. Underplating is difficult to detect in modern subduction zones but may be recorded in ancient accretionary prisms such as the Franciscan Group of California in the form of tectonic mélanges and duplex structures. Different modes of accretion are reflected in morphology of the inner slope of the trench, which generally shows three morphological provinces. The lower slope comprises imbricate thrust slices that form ridges. The mid slope may comprise a bench or terraces. The upper slope is smoother but may be cut by submarine canyons. Because accretionary convergent margins have high relief, are continuously deformed, and accommodate a large flux of sediments, they are vigorous systems of sediment dispersal and accumulation. Sediment transport is controlled by submarine landslides, debris flows, turbidity currents, and contourites. Submarine canyons transport sediment from beaches and rivers down the upper slope. These canyons form by channelized turbidites and generally lose definition with depth because continuous faulting disrupts the submarine channels. Sediments move down the inner trench wall via channels and a series of fault-controlled basins. The trench itself serves as an axis of sediment transport. If enough sediment moves to the trench, it may be completely filled so that

turbidity currents are able to carry sediments well beyond the trench and may even surmount the outer swell. Sediments from the rivers of SW Canada and NW USA spill over where the Cascadia trench would be and cross the Juan de Fuca plate to reach the spreading ridge several hundred kilometres to the west.

The slope of the inner trench slope of an accretionary convergent margin reflects continuous adjustments to the thickness and width of the accretionary prism. The prism maintains a 'critical taper', established in conformance with Mohr-Coulomb Theory for the pertinent materials. A package of sediments scraped off the downgoing lithospheric plate will deform until it and the accretionary prism that it has been added to attain a critical taper (constant slope) geometry. Once critical taper is attained, the wedge slides stably along its basal decollement. Strain rate and hydrologic properties strongly influence the strength of the accretionary prism and thus the angle of critical taper. Fluid pore pressures modify rock strength and are important controls of critical taper angle. Low permeability and rapid convergence may result in pore pressures that exceed lithostatic pressure and a relatively weak accretionary prism with a shallowly tapered geometry, whereas high permeability and slow convergence result in lower pore pressure, stronger prisms, and steeper geometry.

The Hellenic trench system is unusual because this convergent margin subducts evaporites. The slope of the surface of the southern flank of the Mediterranean Ridge (its accretionary prism) is low, about 1°, which indicates very low shear stress on the decollement at the base of the wedge. Evaporites influence the critical taper of the accretionary complex, as their mechanical properties differ from those of siliciclastic sediments, and because of their effect upon fluid flow and fluid pressure, which control effective stress. In the 1970s, the linear deeps of the Hellenic trench south of Crete were interpreted to be similar to trenches at other subduction zones, but with the realization that the Mediterranean Ridge is an accretionary complex, it became apparent that the Hellenic trench is actually a starved forearc basin, and that the plate boundary lies south of the Mediterranean Ridge.

Water and biosphere

The volume of water escaping from within and beneath the forearc results in some of Earth's most dynamic and complex interactions between aqueous fluids and rocks. Most of this water is trapped in pores and fractures in the upper lithosphere and sediments of the subducting plate. The average forearc is underrun by a solid volume of oceanic sediment that is 400 m thick. This sediment enters the trench with 50-60% porosity. These sediments are progressively squeezed as they are subducted, reducing void space and forcing fluids out along the decollement and up into the overlying forearc, which may or may not have an accretionary prism. Sediments accreted to the forearc are another source of fluids. Water is also bound in hydrous minerals, especially clays and opal. Increasing pressure and temperature experienced by subducted materials converts the hydrous minerals to denser phases that contain progressively less structurally-bound water. Water released by dehydration accompanying phase transitions is another source of fluids introduced to the base of the overriding plate. These fluids may travel through the accretionary prism diffusely, via interconnected pore spaces in sediments, or may follow discrete channels along faults. Sites of venting may take the form of mud volcanoes or seeps and are often associated with chemosynthetic communities. Fluids escaping from the shallowest parts of a

subduction zone may also escape along the plate boundary but have rarely been observed draining along the trench axis. All of these fluids are dominated by water but also contain dissolved ions and organic molecules, especially methane. Methane is often sequestered in an ice-like form (methane clathrate, also called gas hydrate) in the forearc. These are a potential energy source and can rapidly break down. Destabilization of gas hydrates has contributed to global warming in the past and will likely do so in the future.

Chemosynthetic communities thrive where cold fluids seep out of the forearc. Cold seep communities have been discovered in inner trench slopes down to depths of 6000 m in the western Pacific, especially around Japan, in the Eastern Pacific along North, Central and South America coasts from the Aleutian to the Peru-Chile trenches, on the Barbados prism, in the Mediterranean, and in the Indian Ocean along the Makran and Sunda convergent margins. These communities receive much less attention than the chemosynthetic communities associated with hydrothermal vents. Chemosynthetic communities are located in a variety of geological settings: above over-pressured sediments in accretionary prisms where fluids are expelled through mud volcanoes or ridges (Barbados, Nankai and Cascadia); along active erosive margins with faults; and along escarpments caused by debris slides (Japan trench, Peruvian margin). Surface seeps may be linked to massive hydrate deposits and destabilization (e.g. Cascadia margin). High concentrations of methane and sulfide in the fluids escaping from the seafloor are the principal energy sources for chemosynthesis.

Empty trenches and subduction erosion

Trenches distant from an influx of continental sediments lack an accretionary prism, and the inner slope of such trenches is commonly composed of igneous or metamorphic rocks. Non-accretionary convergent margins are characteristic of (but not limited to) primitive arc systems. Primitive arc systems are those built on oceanic lithosphere, such as the Izu-Bonin-Mariana, Tonga-Kermadec, and Scotia (South Sandwich) arc systems. The inner trench slope of these convergent margins exposes the crust of the forearc, including basalt, gabbro, and serpentinized mantle peridotite. These exposures allow easy access to study the lower oceanic crust and upper mantle in place and provide a unique opportunity to study the magmatic products associated with the initiation of subduction zones. Most ophiolites probably originate in a forearc environment during the initiation of subduction, and this setting favors ophiolite emplacement during collision with blocks of thickened crust. Not all non-accretionary convergent margins are associated with primitive arcs. Trenches adjacent to continents where there is little influx of sediments carried by rivers, such as the central part of the Peru-Chile Trench, may also lack an accretionary prism.

Igneous basement of a nonaccretionary forearc may be continuously exposed by subduction erosion. This transfers material from the forearc to the subducting plate and can be accomplished by frontal erosion or basal erosion. Frontal erosion is most active in the wake of seamounts being subducted beneath the forearc. Subduction of large edifices (seamount tunneling) oversteepens the forearc, causing mass failures that carry debris towards and ultimately into the trench. This debris may be deposited in graben of the downgoing plate and subducted with it. In contrast, structures resulting from subduction erosion of the base of the forearc are difficult to recognize from seismic reflection profiles, so the possibility of basal erosion is difficult to confirm.

Subduction erosion may also diminish a once-robust accretionary prism if the flux of sediments to the trench diminishes.

Nonaccretionary forearcs may also be the site of serpentine mud volcanoes. These form where fluids released from the downgoing plate percolate upwards and interact with cold mantle lithosphere of the forearc. Mantle peridotite is hydrated into serpentinite, which is much less dense than peridotite and so will rise diapirically when there is an opportunity to do so. Some nonaccretionary forearcs are subjected to strong extensional stresses, for example the Marianas, and this allows buoyant serpentinite to rise to the seafloor where they form serpentinite mud volcanoes. Chemosynthetic communities are also found on non-accretionary margins such as the Marianas, where they thrive on vents associated with serpentinite mud volcanoes.

Factors affecting trench depth
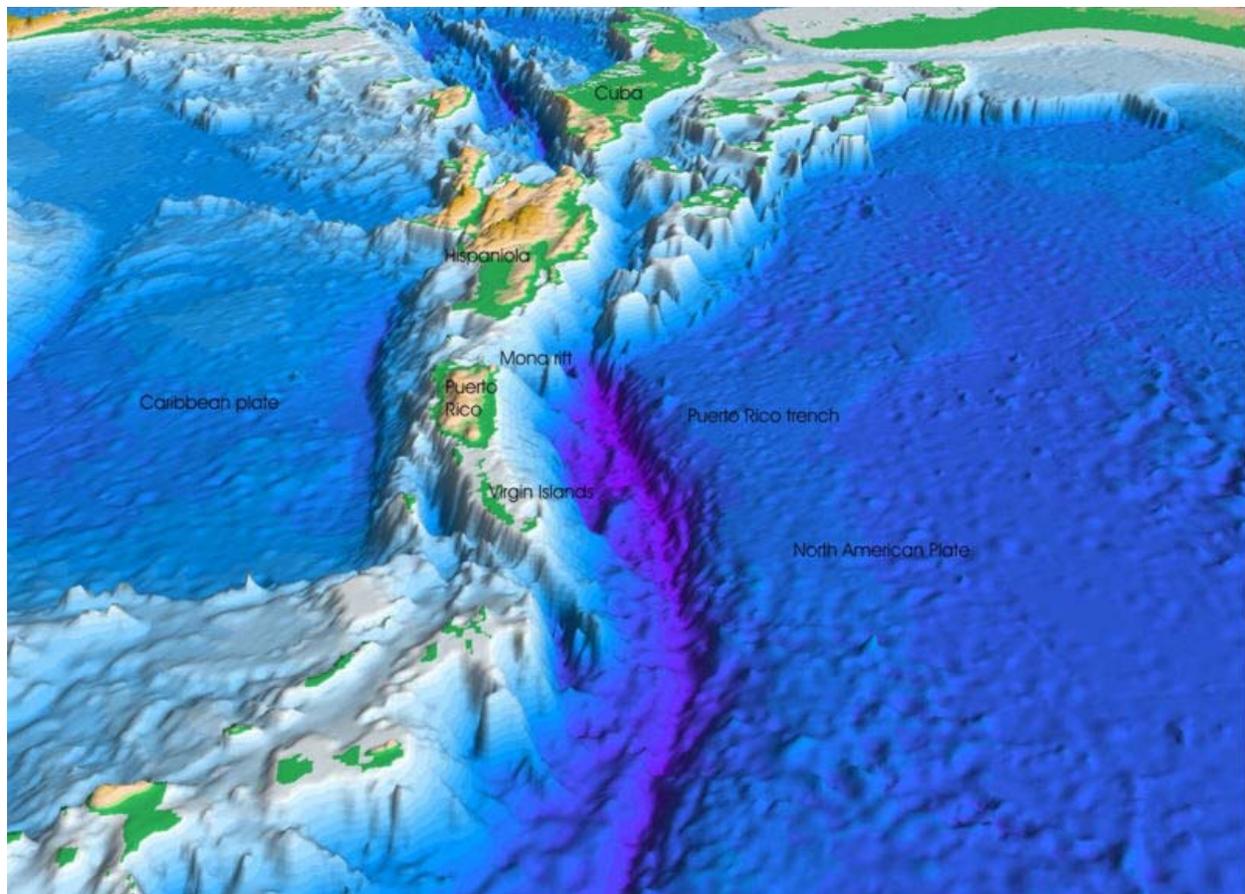
The Puerto Rico Trench

There are several factors that control the depth of trenches. The most important control is the supply of sediment, which fills the trench so that there is no bathymetric expression. It is therefore not surprising that the deepest trenches (deeper than 8,000 m) are all nonaccretionary. In contrast, all trenches with growing accretionary prisms are shallower than 8000 m. A second order control on trench depth is the age of the lithosphere at the time of subduction. Because

oceanic lithosphere cools and thickens as it ages, it subsides. The older the seafloor, the deeper it lies and this determines a minimum depth from which seafloor begins its descent. This obvious correlation can be removed by looking at the relative depth, the difference between regional seafloor depth and maximum trench depth. Relative depth may be controlled by the age of the lithosphere at the trench, the convergence rate, and the dip of the subducted slab at intermediate depths. Finally, narrow slabs can sink and roll back more rapidly than broad plates, because it is easier for underlying asthenosphere to flow around the edges of the sinking plate. Such slabs may have steep dips at relatively shallow depths and so may be associated with unusually deep trenches, such as the Challenger Deep.

Chapter- 5

Cold Seep

A **cold seep** (sometimes called a **cold vent**) is an area of the ocean floor where hydrogen sulfide, methane and other hydrocarbon-rich fluid seepage occurs, often in the form of a brine pool. Cold seeps constitute a biome supporting several endemic species.

Cold seeps develop unique topography over time, where reactions between methane and seawater create carbonate rock formations and reefs. These reactions may also be dependent on bacterial activity. Ikaite, a hydrous calcium carbonate, can be associated with oxidizing methane at cold seeps.

Types

These craters mark the formation of brine pools, from which salt has seeped through the seafloor and encrusted the nearby substrate.

Type of cold seeps can be distinguished as according to the depth to shallows cold seeps and deep cold seeps. Cold seeps can also be distinguished in detail as follows:

- oil/gas seeps
- gas seeps: methane seeps
- gas hydrate seeps
- brine seeps are forming brine pools
- pockmarks
- mud volcanos

Formation and ecological succession

Cold seeps occur over fissures on the seafloor caused by tectonic activity. Oil and methane "seep" out of those fissures, get diffused by sediment, and emerge over an area several hundred meters wide.

Methane (CH_4) is the main component of what we commonly refer to as natural gas. But in addition to being an important energy source for humans, methane also forms the basis of a cold seep ecosystem.

Chemosynthetic communities

Bacterial mat consisting of sulfide-oxidizing bacteria *Beggiatoa* spp. at a seep on Blake Ridge, off South Carolina. The red dots are range-finding laser beams.

Organisms living in cold seeps are known as extremophiles. Biological research in cold seeps and hydrothermal vents has been mostly focused on the microbiology and the prominent chemosynthetic macro-invertebrates. Much less research has been done on the smaller benthic fraction at the size of the meiofauna (<1 mm).

Community composition's orderly shift from one set of species to another is called ecological succession:

The first type of organism to take advantage of this deep-sea energy source is bacteria. Aggregating into bacterial mats at cold seeps, these bacteria metabolize methane and hydrogen sulfide (another gas that emerges from seeps) for energy. This process of obtaining energy from chemicals is known as chemosynthesis.

A mussel bed at the edge of the brine pool

During this initial stage, when methane is relatively abundant, dense mussel beds also form near the cold seep. Mostly composed of species in the genus *Bathymodiolus*, these mussels do not directly consume food. Instead, they are nourished by symbiotic bacteria that also produce energy from methane, similar to their relatives that form mats.

This microbial activity produces calcium carbonate ($CaCO_3$), which is deposited on the seafloor and forms a layer of rock. During a period lasting up to several decades, these rock formations attract vestimentiferan tubeworms (family Siboglinidae), which settle and grow along with the mussels. Like the mussels, tubeworms rely on chemosynthetic bacteria (in this case, a type that needs hydrogen sulfide instead of methane) for survival. True to any symbiotic relationship, a tubeworm also provides for their bacteria by appropriating hydrogen sulfide from the

environment. The sulfide not only comes from the water, but is also mined from the sediment through an extensive "root" system a tubeworm "bush" establishes in the hard, carbonate substrate. A tubeworm bush can contain hundreds of individual worms, which can grow a meter or more above the sediment.

Cold seeps do not last indefinitely. As the rate of gas seepage slowly decrease, the shorter-lived, methane-hungry mussels (or more precisely, their methane-hungry bacterial symbionts) start to die off. At this stage, tubeworms become the dominant organism in a seep community. As long as there is some sulfide in the sediment, the sulfide-mining tubeworms can persist. Individuals of one tubeworm species *Lamellibrachia luymesi* have been estimated to live for over 250 years in such conditions.

"Roots" of tubeworms also provide a supply of hydrogen sulfide from the sediment to the bacteria inside these tubeworms.

Symbiotic vestimentiferan tubeworm *Lamellibrachia luymesi* from a cold seep at 550 m depth in the Gulf of Mexico. In the sediments around the base are orange bacterial mats of the sulfide-oxidizing bacteria *Beggiatoa* spp. and empty shells of various clams and snails, which are also common inhabitants of the seep

Tubeworms, soft corals and chemosynthetic mussels at a seep located 3,000 m (9,843 ft) down on the Florida Escarpment. Eelpouts, a Galatheid crab and an alvinocarid shrimp feed on mussels damaged during a sampling exercise.

Comparison with other communities

Cold seeps and hydrothermal vents are communities that do not rely on photosynthesis for food and energy production. These systems are largely driven by chemosynthetic derived energy. Both systems share common characteristics such as the presence of reduced chemical compounds (H_2S and hydrocarbonates), local hypoxia or even anoxia, a high abundance and metabolic activity of bacterial populations, and the production of autochthonous, organic material by chemoautotrophic bacteria. Both hydrothermal vents and cold seeps show regularly, highly increased levels of metazoan biomass in association with a low local diversity. This is explained through the presence of dense aggregations of foundation species and epizooic animals, living within these aggregations.

However, hydrothermal vents and cold seeps differ also in many ways. Compared to the more stable cold seeps, vents are characterized by locally high temperatures, strongly fluctuating temperatures, pH, sulphide and oxygen concentrations, often the absence of sediments, a relatively young age, and often unpredictable conditions, such as waxing and waning of vent fluids or volcanic eruptions. Unlike hydrothermal vents, which are volatile and ephemeral environments, cold seeps emit at a slow and dependable rate. Likely owing to the cooler temperatures and stability, many cold seep organisms are much longer-lived than those inhabiting hydrothermal vents.

End of cold seep community

Finally, as cold seeps become inactive, tubeworms also start to disappear, clearing the way for corals to settle on the now exposed carbonate substrate. The corals do not rely on hydrocarbons seeping out of the seafloor. Studies on *Lophelia pertusa* suggest they derive their nutrition primarily from the ocean surface. Chemosynthesis plays only a very small role, if any, in their settlement and growth. While deepwater corals do not seem to be chemosynthesis-based organisms, the chemosynthetic organisms that come before them enable the corals' existence. This hypothesis about establishment of deep water coral reefs is called hydraulic theory.

Distribution

Cold seeps were discovered in 1983 by Dr. Charles Paull in the Gulf of Mexico at a depth of 3,200 meters (10,499 ft). Since then, seeps have been discovered in other parts of the world's oceans. They have also been grouped into several biogeographic provinces: Gulf of Mexico, Atlantic, Mediterranean, East Pacific, West Pacific and under an ice shelf in Antarctica. Those localities include the Monterey Canyon just off Monterey Bay, California, the Sea of Japan, off the Pacific coast of Costa Rica, in the Atlantic off of Africa and in waters off the coast of Alaska. The deepest seep community known is found in the Japan trench at a depth of 7,326 m (24,035 ft).

In the Gulf of Mexico
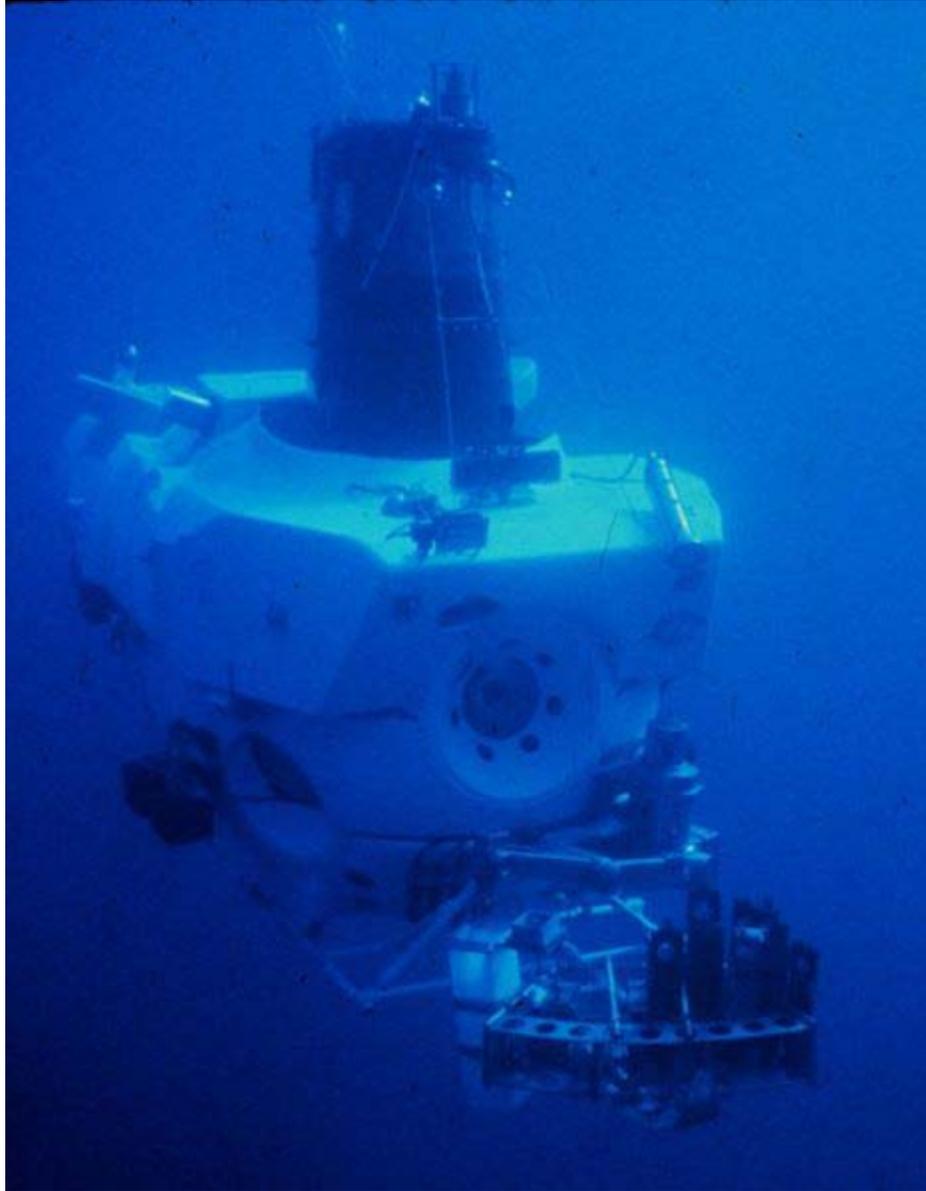
The manned submersible *DSV Alvin*, which made possible the discovery of chemosynthetic communities in the Gulf of Mexico in 1983.

Discoveries in the Gulf of Mexico
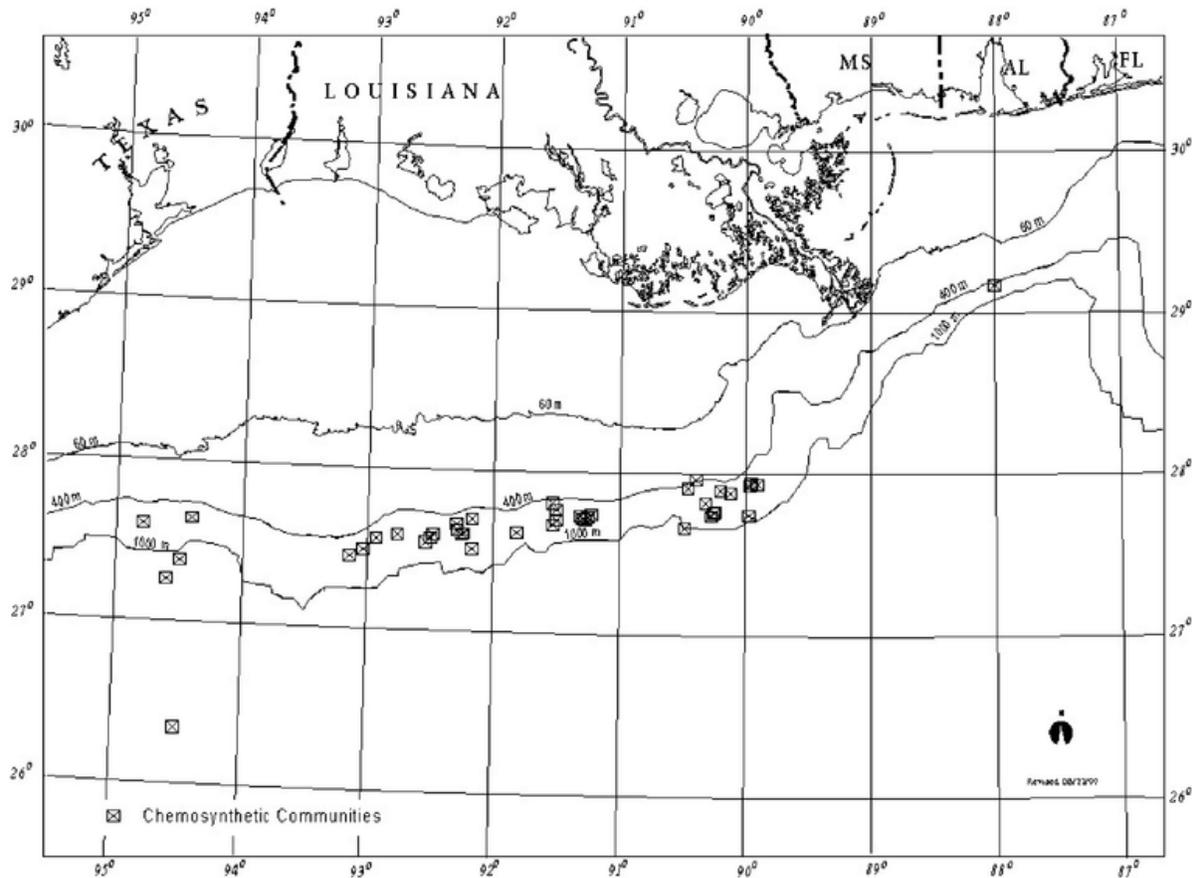
The chemosynthetic communities of the Gulf of Mexico have been studied extensively over the past 20 years, and communities first discovered on the upper slope are likely the best understood seep communities in the world. The history of the discovery of these remarkable animals has all occurred within the last 30 years. Interestingly, each major discovery was unexpected—from the

first hydrothermal vent communities anywhere in the world to the first cold seep communities in the Gulf of Mexico.

Communities were discovered in the Eastern Gulf of Mexico in 1983 using the manned submersible *DSV Alvin*, during a cruise investigating the bottom of the Florida Escarpment in areas of "cold" brine seepage, where they unexpectedly discovered tubeworms and mussels (Paull et al., 1984).

Two groups fortuitously discovered chemosynthetic communities in the Central Gulf of Mexico concurrently in November 1984. During investigations by Texas A&M University to determine the effects of oil seepage on benthic ecology (until this investigation, all effects of oil seepage were assumed to be detrimental), bottom trawls unexpectedly recovered extensive collections of chemosynthetic organisms, including tube worms and clams (Kennicutt et al., 1985). At the same time, LGL Ecological Research Associates was conducting a research cruise as part of the multiyear MMS Northern Gulf of Mexico Continental Slope Study (Gallaway et al., 1988). Bottom photography (processed on board the vessel) resulted in clear images of vesicomyid clam chemosynthetic communities coincidentally in the same manner as the first discovery by camera sled in the Pacific in 1977. Photography during the same LGL/MMS cruise also documented tube-worm communities in situ in the Central Gulf of Mexico for the first time (not processed until after the cruise; Boland, 1986) prior to the initial submersible investigations and firsthand descriptions of Bush Hill in 1986 (Rosman et al., 1987a; MacDonald et al., 1989b). The site was targeted by acoustic "wipeout" zones or lack of substrate structure caused by seeping hydrocarbons. This was determined using an acoustic pinger system during the same cruise on the R/V *Edwin Link* (the old one, only 113 ft (34 m)), which used one of the *Johnson Sea Link* submersibles. The site is characterized by dense tubeworm and mussel accumulations, as well as exposed carbonate outcrops with numerous gorgonian and *Lophelia* coral colonies. Bush Hill has become one of the most thoroughly studied chemosynthetic sites in the world.

Distribution in the Gulf of Mexico

Chemosynthetic communities in the northern part of Gulf of Mexico around cold seeps known in 2000.

There is a clear relationship between known hydrocarbon discoveries at great depth in the Gulf slope and chemosynthetic communities, hydrocarbon seepage, and authigenic minerals including carbonates at the seafloor (Sassen et al., 1993a and b). While the hydrocarbon reservoirs are broad areas several kilometers beneath the Gulf, chemosynthetic communities occur in isolated areas with thin veneers of sediment only a few meters thick.

The northern Gulf of Mexico slope includes a stratigraphic section more than 10 km (6 mi) thick and has been profoundly influenced by salt movement. Mesozoic source rocks from Upper Jurassic to Upper Cretaceous generate oil in most of the Gulf slope fields (Sassen et al., 1993a and b). Migration conduits supply fresh hydrocarbon materials through a vertical scale of 6–8 km (4-5 mi) toward the surface. The surface expressions of hydrocarbon migration are referred to as seeps. Geological evidence demonstrates that hydrocarbon and brine seepage persists in spatially discrete areas for thousands of years.

The time scale for oil and gas migration (combination of buoyancy and pressure) from source systems is on the scale of millions of years (Sassen, 1997). Seepage from hydrocarbon sources through faults towards the surface tends to be diffused through the overlying sediment, carbonate outcroppings, and hydrate deposits so the corresponding hydrocarbon seep communities tend to

be larger (a few hundred meters wide) than chemosynthetic communities found around the hydrothermal vents of the Eastern Pacific (MacDonald, 1992). There are large differences in the concentrations of hydrocarbons at seep sites. Roberts (2001) presented a spectrum of responses to be expected under a variety of flux rate conditions varying from very slow seepage to rapid venting. Very slow seepage sites do not support complex chemosynthetic communities; rather, they usually only support simple microbial mats (*Beggiatoa* sp.).

In the upper slope environment, the hard substrates resulting from carbonate precipitation can have associated communities of nonchemosynthetic animals, including a variety of sessile cnidarians such as corals and anemones. At the rapid flux end of the spectrum fluidized sediment generally accompanies hydrocarbons and formation fluids arriving at the seafloor. Mud volcanoes and mud flows result. Somewhere between these two end members exists the conditions that support densely populated and diverse communities of chemosynthetic organisms (microbial mats, siboglinid tube worms, bathymodioline mussels, lucinid and vesycomyid clams, and associated organisms). These areas are frequently associated with surface or near-surface gas hydrate deposits. They also have localized areas of lithified seafloor, generally authigenic carbonates but sometimes more exotic minerals such as barite are present.
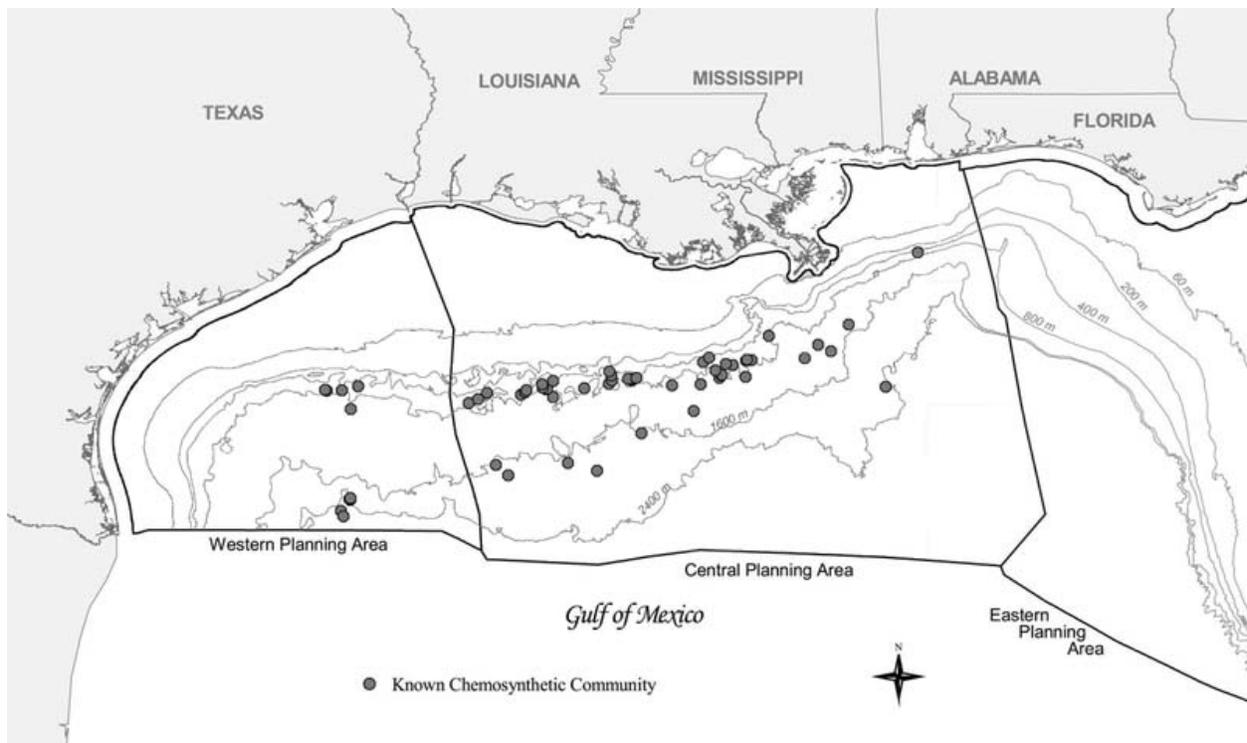
Chemosynthetic communities in the northern part of Gulf Of Mexico around cold seeps known in 2006 include more than 50 communities.

The widespread nature of Gulf of Mexico chemosynthetic communities was first documented during contracted investigations by the Geological and Environmental Research Group (GERG) of Texas A&M University for the Offshore Operators Committee (Brooks et al., 1986). This survey remains the most widespread and comprehensive, although numerous additional

communities have been documented since that time. Industry exploring for energy reserves in the Gulf of Mexico has also documented numerous new communities through a wide range of depths, including the deepest known occurrence in the Central Gulf of Mexico in Alaminos Canyon Block 818 at a depth of 2,750 m (9,022 ft). The occurrence of chemosynthetic organisms dependent on hydrocarbon seepage has been documented in water depths as shallow as 290 m (951 ft) (Roberts et al., 1990) and as deep as 2,744 m (9,003 ft) (Allen, personal communication, 2005). This depth range specifically places chemosynthetic communities in the deepwater region of the Gulf of Mexico, which is defined as water depths greater than 305 m (1,000 ft).

Chemosynthetic communities are not found on the continental shelf although they do appear in the fossil record in water shallower than 200 m (656 ft). One theory explaining this is that predation pressure has varied substantially over the time period involved (Callender and Powell 1999). More than 50 communities are now known to exist in 43 OCS blocks. Although a systematic survey has not been done to identify all chemosynthetic communities in the Gulf of Mexico, there is evidence indicating that many more such communities may exist. The depth limits of discoveries probably reflect the limits of exploration (lack of submersibles capable of depths over 1,000 m (3,281 ft)).

MacDonald et al. (1993 and 1996) have analyzed remote-sensing images from space that reveal the presence of oil slicks across the north-central Gulf of Mexico. Results confirmed extensive natural oil seepage in the Gulf of Mexico, especially in water depths greater than 1,000 m (3,281 ft). A total of 58 additional potential locations were documented where seafloor sources were capable of producing perennial oil slicks (MacDonald et al., 1996). Estimated seepage rates ranged from 4 bbl/d (0.64 m^3/d) to 70 bbl/d (11 m^3/d) compared to less than 0.1 bbl/d (0.016 m^3/d) for ship discharges (both normalized for 1,000 mi2 (640,000 ac)). This evidence considerably increases the area where chemosynthetic communities dependent on hydrocarbon seepage may be expected.

The densest aggregations of chemosynthetic organisms have been found at water depths of around 500 m (1,640 ft) and deeper. The best known of these communities was named Bush Hill by the investigators who first described it (MacDonald et al., 1989b). It is a surprisingly large and dense community of chemosynthetic tube worms and mussels at a site of natural petroleum and gas seepage over a salt diapir in Green Canyon Block 185. The seep site is a small knoll that rises about 40 m (131 ft) above the surrounding seafloor in about 580-m (1,903-ft) water depth.

Stability

According to Sassen (1997) the role of hydrates at chemosynthetic communities has been greatly underestimated. The biological alteration of frozen gas hydrates was first discovered during the MMS study "*Stability and Change in Gulf of Mexico Chemosynthetic Communities*". It is hypothesized (MacDonald, 1998b) that the dynamics of hydrate alteration could play a major role as a mechanism for regulation of the release of hydrocarbon gases to fuel biogeochemical processes and could also play a substantial role in community stability. Recorded bottom-water temperature excursions of several degrees in some areas such as the Bush Hill site (4-5 °C at 500-m (1,640-ft) depth) are believed to result in dissociation of hydrates, resulting in an increase in gas fluxes (MacDonald et al., 1994). Although not as destructive as the volcanism at vent sites

of the mid-ocean ridges, the dynamics of shallow hydrate formation and movement will clearly affect sessile animals that form part of the seepage barrier. There is potential of a catastrophic event where an entire layer of shallow hydrate could break free of the bottom and result in considerable impact to local communities of chemosynthetic fauna. At deeper depths (>1,000 m, >3,281 ft), the bottom-water temperature is colder (by approximately 3 °C) and undergoes less fluctuation. The formation of more stable and probably deeper hydrates influences the flux of light hydrocarbon gases to the sediment surface, thus influencing the surface morphology and characteristics of chemosynthetic communities. Within complex communities such as Bush Hill, petroleum seems less important than previously thought (MacDonald, 1998b).

Through taphonomic studies (death assemblages of shells) and interpretation of seep assemblage composition from cores, Powell et al. (1998) reported that, overall, seep communities were persistent over periods of 500-1,000 years and probably throughout the entire Pleistocene. Some sites retained optimal habitat over geological time scales. Powell reported evidence of mussel and clam communities persisting in the same sites for 500-4,000 years. Powell also found that both the composition of species and trophic tiering of hydrocarbon seep communities tend to be fairly constant across time, with temporal variations only in numerical abundance. He found few cases in which the community type changed (from mussel to clam communities, for example) or had disappeared completely. Faunal succession was not observed. Surprisingly, when recovery occurred after a past destructive event, the same chemosynthetic species reoccupied a site. There was little evidence of catastrophic burial events, but two instances were found in mussel communities in Green Canyon Block 234. The most notable observation reported by Powell (1995) was the uniqueness of each chemosynthetic community site.

Precipitation of authigenic carbonates and other geologic events will undoubtedly alter surface seepage patterns over periods of many years, although through direct observation, no changes in chemosynthetic fauna distribution or composition were observed at seven separate study sites (MacDonald et al., 1995). A slightly longer period (19 years) can be referenced in the case of Bush Hill, the first Central Gulf of Mexico community described *in situ* in 1986. No mass die-offs or large-scale shifts in faunal composition have been observed (with the exception of collections for scientific purposes) over the19-year history of research at this site.

All chemosynthetic communities are located in water depths beyond the impact of severe storms, including hurricanes, and there would have been no alteration of these communities caused from surface storms, including hurricanes.

Biology

The mussel species *Bathymodiolus childressi* is the dominant species in the mytilid type of cold seep communities in the Gulf of Mexico.

MacDonald et al. (1990) has described four general community types. These are communities dominated by Vestimentiferan tube worms (*Lamellibrachia* c.f. *barhami* and *Escarpia* spp.), mytilid mussels (Seep Mytilid Ia, Ib, and III, and others), vesicomyid clams (*Vesicomya cordata* and *Calyptogena ponderosa*), and infaunal lucinid or thyasirid clams (*Lucinoma* sp. or *Thyasira* sp.). Bacterial mats are present at all sites visited to date. These faunal groups tend to display distinctive characteristics in terms of how they aggregate, the size of aggregations, the geological and chemical properties of the habitats in which they occur and, to some degree, the heterotrophic fauna that occur with them. Many of the species found at these cold seep communities in the Gulf of Mexico are new to science and remain undescribed.

Individual lamellibranchid tube worms, the longer of two taxa found at seeps can reach lengths of 3 m (10 ft) and live hundreds of years (Fisher et al., 1997; Bergquist et al., 2000). Growth rates determined from recovered marked tube worms have been variable, ranging from no growth of 13 individuals measured one year to a maximum growth of 9.6 cm/yr (3.8 in/yr) in a *Lamellibrachia* individual (MacDonald, 2002). Average growth rate was 2.19 cm/yr (0.86 in/yr) for the *Escarpia*-like species and 2.92 cm/yr (1.15 in/yr) for lamellibrachids. These are slower growth rates than those of their hydrothermal vent relatives, but *Lamellibrachia* individuals can

reach lengths 2-3 times that of the largest known hydrothermal vent species. Individuals of *Lamellibrachia* sp. in excess of 3 m (10 ft) have been collected on several occasions, representing probable ages in excess of 400 years (Fisher, 1995). Vestimentiferan tube worm spawning is not seasonal and recruitment is episodic.

Tubeworms are either male or female. One recent discovery indicates that the spawning of female *Lamellibrachia* appears to have produced a unique association with the large bivalve *Acesta bullisi*, which lives permanently attached to the anterior tube opening of the tubeworm, and feeds on the periodic egg release (Järnegren et al., 2005). This close association between the bivalves and tubeworms was discovered in 1984 (Boland, 1986) but not fully explained. Virtually all mature *Acesta* individuals are found on female rather than male tubeworms. This evidence and other experiments by Järnegren et al. (2005) seem to have solved this mystery.

Growth rates for methanotrophic mussels at cold seep sites have been reported (Fisher, 1995). General growth rates were found to be relatively high. Adult mussel growth rates were similar to mussels from a littoral environment at similar temperatures. Fisher also found that juvenile mussels at hydrocarbon seeps initially grow rapidly, but the growth rate drops markedly in adults; they grow to reproductive size very quickly. Both individuals and communities appear to be very long lived. These methane-dependent mussels have strict chemical requirements that tie them to areas of the most active seepage in the Gulf of Mexico. As a result of their rapid growth rates, mussel recolonization of a disturbed seep site could occur relatively rapidly. There is some evidence that mussels also have some requirement of a hard substrate and could increase in numbers if suitable substrate is increased on the seafloor (Fisher, 1995). Two associated species are always found associated with mussel beds – the gastropod *Bathynerita naticoidea* and a small Alvinocarid shrimp – suggesting these endemic species have excellent dispersal abilities and can tolerate a wide range of conditions (MacDonald, 2002).

Unlike mussel beds, chemosynthetic clam beds may persist as a visual surface phenomenon for an extended period without input of new living individuals because of low dissolution rates and low sedimentation rates. Most clam beds investigated by Powell (1995) were inactive. Living individuals were rarely encountered. Powell reported that over a 50-year timespan, local extinctions and recolonization should be gradual and exceedingly rare. Contrasting these inactive beds, the first community discovered in the Central Gulf of Mexico consisted of numerous actively plowing clams. The images obtained of this community were used to develop length/frequency and live/dead ratios as well as spatial patters (Rosman et al., 1987a).

Extensive bacterial mats of free-living bacteria are also evident at all hydrocarbon seep sites. These bacteria may compete with the major fauna for sulfide and methane energy sources and may also contribute substantially to overall production (MacDonald, 1998b). The white, nonpigmented mats were found to be an autotrophic sulfur bacteria *Beggiatoa* species, and the orange mats possessed an unidentified nonchemosynthetic metabolism (MacDonald, 1998b).

Heterotrophic species at seep sites are a mixture of species unique to seeps (particularly molluscs and crustacean invertebrates) and those that are a normal component from the surrounding environment. Carney (1993) first reported a potential imbalance that could occur as a result of chronic disruption. Because of sporadic recruitment patterns, predators could gain an advantage,

resulting in exterminations in local populations of mussel beds. It is clear that seep systems do interact with the background fauna but conflicting evidence remains as to what degree outright predation on some specific community components such as tubeworms occurs (MacDonald, 2002). The more surprising results from this recent work is why background species do not utilize seep production more than seems to be evident. In fact, seep-associated consumers such as galatheid crabs and nerite gastropods had isotopic signatures, indicating that their diets were a mixture of seep and background production. At some sites, endemic seep invertebrates that would have been expected to obtain much if not all their diet from seep production actually consumed as much as 50 percent of their diets from the background.

In the Atlantic Ocean
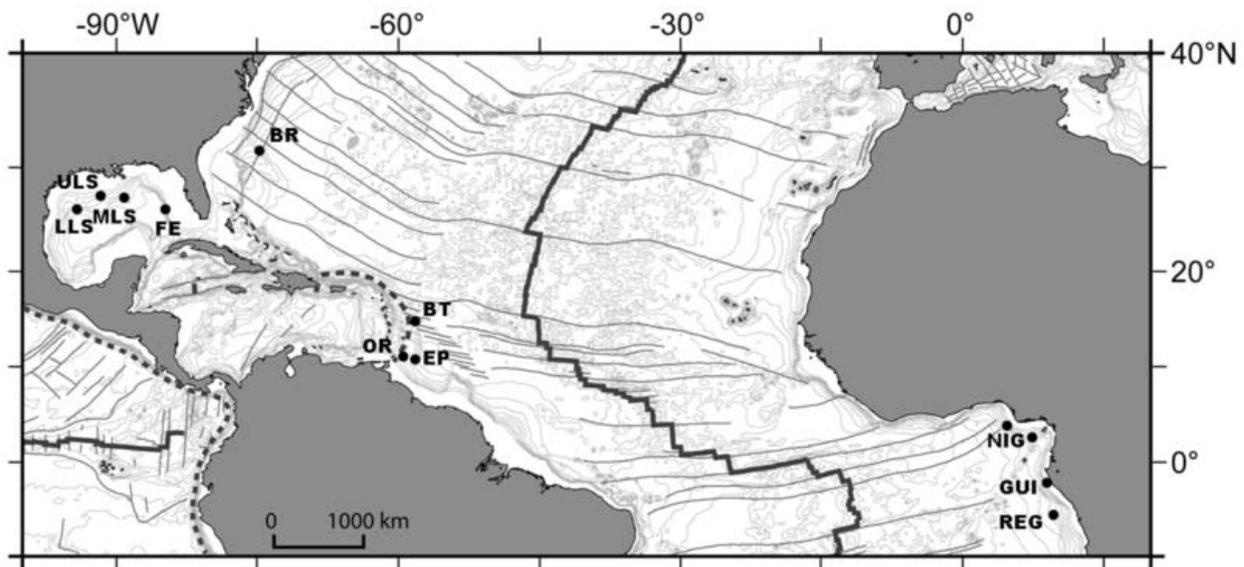
Map of cold seeps in in the Atlantic Equatorial Belt.

BR - Blake Ridge diapir

BT - Barbados trench

OR - Orenoque sectors

EP - El Pilar sector

NIG - Nigerian slope

GUI - Guiness area

REG - Regab pockmark.

Cold-seep communities in the western Atlantic Ocean have also been described from a few dives on mud volcanoes and diapirs between 1000 and 5000 m depth in the Barbados accretionary prism area and from the Blake Ridge diapir off North Carolina. More recently seep communities have been discovered in the eastern Atlantic, on a giant pockmark cluster in the Gulf of Guinea near the Congo deep channel, also on other pockmarks of the Congo margin, Gabon margin and Nigeria margin and in the Gulf of Cadiz.

Cold seeps are also available in Northern Atlantic Ocean. (map shows three localities there)

Extensive faunal sampling has been conducted from 400 to 3300 m in the Atlantic Equatorial Belt from the Gulf of Mexico to the Gulf of Guinea including Barbados accretionary prism, the Blake Ridge diapir, and in the Eastern Atlantic from the Congo and Gabon margins and the recently explored Nigeria margin during Census of Marine Life ChEss project. Of the 72 taxa identified at the species level, a total of 9 species or species complexes are identified as amphi-Atlantic.

The Atlantic Equatorial Belt seep megafauna community structure is influenced primarily by depth rather than by geographic distance. The bivalves Bathymodiolinae (within Mytilidae) species or complexes of species are the most widespread in the Atlantic. The *Bathymodiolus boomerang* complex is found at the Florida escarpment site, the Blake Ridge diapir, the Barbados prism and the Regab site of Congo. The *Bathymodiolus childressi* complex is also widely distributed along the Atlantic Equatorial Belt from the Gulf of Mexico across to the Nigerian Margin, although not on the Regab or Blake ridge sites. The commensal polynoid, *Branchipolynoe seepensis* is known from the Gulf of Mexico, Gulf of Guinea and Barbados. Other species with distributions extending from the eastern to western Atlantic are: gastropod *Cordesia provannoides*, the shrimp *Alvinocaris muricola*, the galatheids *Munidopsis geyeri* and *Munidopsis livida* and probably the holothurid *Chiridota heheva*.

There have been found cold seeps also in Amazon deepsea fan. High-resolution seismic profiles near the shelf edge show evidence of near-surface slumps and faulting 20–50 m in the subsurface and concentrations (about 500 m^2) of methane gas. Several studies (e.g., Amazon Shelf Study—AMASEDS, LEPLAC, REMAC, GLORIA, Ocean Drilling Program) indicate that there is evidence for gas seepage on the slope off the Amazon fan based on the incidence of bottom-simulating reflections (BSRs), mud volcanoes, pock marks, gas in sediments, and deeper hydrocarbon occurrences. The existence of methane at relatively shallow depths and extensive areas of gas hydrates have been mapped in this region. Also, gas chimneys have been reported, and exploratory wells have discovered subcommercial gas accumulations and pock marks along fault planes. A sound geological and geophysical understanding of the Foz do Amazonas Basin is already available and used by the energy companies.

Exploration of new areas, such as potential seep sites off of the east coast of the U.S. and the Laurentian fan where chemosynthetic communities are known deeper than 3500 m, and shallower sites in the Gulf of Guinea are need to study in the future.

In the Mediterranean

The first biological evidence for reduced environments in the Mediterranean Sea was the presence of Lucinidae and Vesicomyidae bivalve shells cored on the top of the Napoli mud volcano, located at 1,900 m depth on the Mediterranean Ridge in the subduction zone of the African plate. This was followed by the description of a new Lucinidae bivalve species, *Lucinoma kazani*, associated with bacterial endosymbionts. In the southeastern Mediterranean, communities of polychaetes and bivalves were also found associated with cold seeps and carbonates near Egypt and the Gaza Strip at depths of 500–800 m, but no living fauna was

collected. The first in situ observations of extensive living chemosynthetic communities in the Eastern Mediterranean Sea prompted cooperation between biologists, geochemists, and geologists. During submersible dives, communities comprising large fields of small bivalves (dead and alive), large siboglinid tube worms, isolated or forming dense aggregations, large sponges, and associated endemic fauna were observed in various cold seep habitats associated with carbonate crusts at 1,700–2,000 m depth. Two mud volcano fields were first explored, one along the Mediterranean Ridge, where most of them were partially (Napoli, Milano mud volcanoes) or totally (Urania, Maidstone mud volcanoes) affected by brines, and the other on the Anaximander mounds south of Turkey. The latter area includes the large Amsterdam mud volcano, which is affected by recent mudflows, and the smaller Kazan or Kula mud volcanoes. Gas hydrates have been sampled at the Amsterdam and Kazan mud volcanoes, and high methane levels have been recorded above the seafloor. Several provinces of the Nile deep-sea fan have been explored recently. These include the very active brine seepage named the Menes Caldera in the eastern province between 2,500 m and 3,000 m, the pockmarks in the central area along mid- and lower slopes, and the mud volcanoes of the eastern province, as well as one in the central upper slope (North Alex area) at 500 m depth.

During these first exploratory dives, symbiont-bearing taxa that are similar to those observed on the Olimpi and Anaximander mud fields were sampled and identified. This similarity is not surprising, as most of these taxa were originally described from dredging in the Nile fan. Up to five species of bivalves harboring bacterial symbionts colonized these methane- and sulfide-rich environments. A new species of Siboglinidae polychaete, *Lamellibrachia anaximandri*, the tubeworm colonizing cold seeps from the Mediterranean ridge to the Nile deep-sea fan, has just been described in 2010. Moreover, the study of symbioses revealed associations with chemoautotrophic Bacteria, sulfur oxidizers in Vesicomyidae and Lucinidae bivalves and Siboglinidae tubeworms, and highlighted the exceptional diversity of Bacteria living in symbiosis with small Mytilidae. The Mediterranean seeps appear to represent a rich habitat characterized by megafauna species richness (e.g., gastropods) or the exceptional size of some species such as sponges (*Rhizaxinella pyrifera*) and crabs (*Chaceon mediterraneus*), compared with their background counterparts. This contrasts with the low macro- and mega-faunal abundance and diversity of the deep Eastern Mediterranean. Seep communities in the Mediterranean that include endemic chemosynthetic species and associated fauna differ from the other known seep communities in the world at the species level but also by the absence of the large size bivalve genera *Calyptogena* or *Bathymodiolus*. The isolation of the Mediterranean seeps from the Atlantic Ocean after the Messinian crisis led to the development of unique communities, which are likely to differ in composition and structure from those in the Atlantic Ocean. Further expeditions involved quantitative sampling of habitats in different areas, from the Mediterranean Ridge to the eastern Nile deep-sea fan. Cold seeps discovered in the Sea of Marmara in 2008 have also revealed chemosynthesis-based communities that showed a considerable similarity to the symbiont-bearing fauna of eastern Mediterranean cold seeps.

In the West Pacific

Native aluminium has been reported also in cold seeps in the northeastern continental slope of the South China Sea and Chen et al. (2011) have proposed a theory of its origin as resulting by reduction from tetrahydroxoaluminate $Al(OH)_4^-$ to metallic aluminium by bacteria.

Japan

Methane seep communities in Japan are distributed along plate convergence areas because of the accompanying tectonic activity. Many seeps have been found in the Japan Trench, Nankai Trough, Ryukyu Trench, Sagami Bay and Suruga Bay, and the Sea of Japan. Many of species in cold seeps of Japan are endemic.

New Zealand

Off the mainland coast of the New Zealand, shelf-edge instability is enhanced in some locations by cold seeps of methane-rich fluids that likewise support chemosynthetic faunas and carbonate concretions. Dominant animals are tube worms of the family Siboglinidae and bivalves of families Vesicomyidae and Mytilidae (*Bathymodiolus*). Numerous of its species appear to be endemic. The deep bottom trawling has highly negative impact on cold seep communities and those ecosystems are threatened. Depths down to 2,000 m including cold seeps belongs among as-yet-unmapped topographic and chemical complexity of habitats. The scale of new-species discovery in these poorly studied or unexplored ecosystems is likely to be high.

In the East Pacific

Monterey Bay Aquarium Research Institute has used remotely operated underwater vehicle *Ventana* in the research of Monterey Bay cold seeps.

In the deep sea the COMARGE project has studied the biodiversity patterns along and across the Chilean margin through a complexity of ecosystems such as methane seeps and oxygen minimum zones reporting that such habitat heterogeneity may influence the biodiversity patterns of the local fauna. Seep fauna include bivalves of families Lucinidae, Thyasiridae, Solemyidae (*Acharax* sp.), and Vesicomyidae (*Calyptogena gallardoi*) and polychates *Lamellibrachia* sp. and two other polychate species. Furthermore, in these soft reduced sediments below the oxygen minimum zone off the Chilean margin, a diverse microbial community composed by a variety of

large prokaryotes (mainly large multi-cellular filamentous "mega bacteria" of the genera *Thioploca* and *Beggiatoa*, and of "macrobacteria" including a diversity of phenotypes), protists (ciliates, flagellates, and foraminifers), as well as small metazoans (mostly nematodes and polychaetes) has been found. Gallardo et al. (2007) argue that the likely chemolithotrophic metabolism of most of these mega- and macrobacteria offer an alternative explanation to fossil findings, in particular to those from obvious non-littoral origins, suggesting that traditional hypotheses on the cyanobacterial origin of some fossils may have to be revised.

Cold seeps (pockmark) are also known from depths of 130 m in the Hecate Strait, British Columbia, Canada. Unobvious fauna (also unobvious for cold seeps) has been found there with these dominating species: sea snail *Fusitriton oregonensis*, anemone *Metridium giganteum*, encrusting sponges and bivalve *Solemya reidi*.

Cold seeps with chemosynthetic communities along the USA Pacific coast occur in Monterey Canyon, just off Monterey Bay, California on a mud volcano. There have been found, for example *Calyptogena* clams *Calyptogena kilmeri* and *Calyptogena pacifica* and foraminiferan *Spiroplectammina biformis*.

In the Antarctic

The relatively few investigations to the Antarctic deep sea have shown the presence of deep-water habitats, including hydrothermal vents, cold seeps, and mud volcanoes. Other than the Antarctic Benthic Deep-Sea Biodiversity Project (ANDEEP) cruises, little work has been done in the deep sea. There are more species waiting to be described.

Detection

With continuing experience, particularly on the upper continental slope in the Gulf of Mexico, the successful prediction of the presence of tubeworm communities continues to improve, however chemosynthetic communities cannot be reliably detected directly using geophysical techniques. Hydrocarbon seeps that allow chemosynthetic communities to exist do modify the geological characteristics in ways that can be remotely detected, but the time scales of co-occurring active seepage and the presence of living communities is always uncertain. These known sediment modifications include (1) precipitation of authigenic carbonate in the form of micronodules, nodules, or rock masses; (2) formation of gas hydrates; (3) modification of sediment composition through concentration of hard chemosynthetic organism remains (such as shell fragments and layers); (4) formation of interstitial gas bubbles or hydrocarbons; and (5) formation of depressions or pockmarks by gas expulsion. These features give rise to acoustic effects such as wipeout zones (no echoes), hard bottoms (strongly reflective echoes), bright spots (reflection enhanced layers), or reverberant layers (Behrens, 1988; Roberts and Neurauter, 1990). "Potential" locations for most types of communities can be determined by careful interpretation of these various geophysical modifications, but to date, the process remains imperfect and confirmation of living communities requires direct visual techniques.

Fossilized records

Late Cretaceous cold seep deposit in the Pierre Shale, southwest South Dakota

Cold seep deposits are found throughout the Phanerozoic rock record, especially in the Late Mesozoic and Cenozoic. These fossil cold seeps are characterized by mound-like topography (where preserved), coarsely crystalline carbonates, and abundant mollusks and brachiopods.

Chapter- 6

Seamount

A **seamount** is a mountain rising from the ocean seafloor that does not reach to the water's surface (sea level), and thus is not an island. These are typically formed from extinct volcanoes, that rise abruptly and are usually found rising from a seafloor of 1,000–4,000 metres (3,281–13,123 ft) depth. They are defined by oceanographers as independent features that rise to at least 1,000 metres (3,281 ft) above the seafloor. The peaks are often found hundreds to thousands of metres below the surface, and are therefore considered to be within the deep sea. There are an estimated 100,000 seamounts across the globe, with only a few having been studied. Seamounts come in all shapes and sizes, and follow a distinctive pattern of growth, activity, and death. In recent years, several active seamounts have been observed, for example Loihi in the Hawaiian Islands.

Because of their abundance, seamounts are one of the most common oceanic ecosystems in the world. Interactions between seamounts and underwater currents, as well as their elevated position in the water, attract plankton, corals, fish, and marine mammals alike. Their aggregational effect has been noted by the commercial fishing industry, and many seamounts support extensive fisheries. There are ongoing concerns on the negative impact of fishing on seamount ecosystems, and well-documented cases of stock decline, for example with the orange roughy (*Hoplostethus atlanticus*). 95% of ecological damage is done by bottom trawling, which literally scrapes whole ecosystems off seamounts.

Because of their large numbers, many seamounts remain to be properly studied, and even mapped. Bathymetry and satellite altimetry are two technologies working to close the gap. There have been instances where naval vessels have collided with uncharted seamounts; for example, Muirfield Seamount is named after the ship that struck it in 1973. However, the greatest danger from seamounts are flank collapses; as they get older, extrusions seeping in the seamounts put pressure on their sides, causing landslides that have the potential to generate massive tsunamis.

Geography

Seamounts can be found in every ocean basin in the world, distributed extremely widely both in space and in age. A seamount is technically defined as an isolated elevational rising of 1,000 m

(3,281 ft) or more from the surrounding seafloor, and with a limited summit area, a definition drafted in 1964. This definition is no longer strictly adhered to however, and some scientists recognize features as short as 100 m (328 ft) as seamounts. Under the strictest definition there are up to 100,000 seamounts in the oceans, and under the loosest there may be as many as 2 million; however, there are many very small and very deep seamounts that are difficult to analyze, so the true number may never be known.

Most seamounts are volcanic in origin, and thus tend to be found on oceanic crust near mid-ocean ridges, mantle plumes, and island arcs. Nearly half of the world's seamounts are found in the Pacific Ocean, and the rest are distributed mostly across the Atlantic and Indian oceans. Overall there is also a significant bias in distribution towards the southern hemisphere.

Seamounts are often found in groupings or submerged archipelagos, a classic example being the Emperor Seamounts, an extension of the Hawaiian Islands. Formed millions of years ago by volcanism, they have since subsided far below sea level. This long chain of islands and seamounts extends thousands of kilometers northwest from the island of Hawaii. Isolated seamounts and those without clear volcanic origins are less common; examples include Bollons Seamount, Eratosthenes Seamount, Axial Seamount and Gorringe Ridge. If all known seamounts were collected into one area, they would make a landform the size of Europe. Their overall abundance makes them one of the most common, and least understood, marine structures and biomes on Earth, a sort of exploratory frontier.

A partial mapping of some of the world's major seamounts
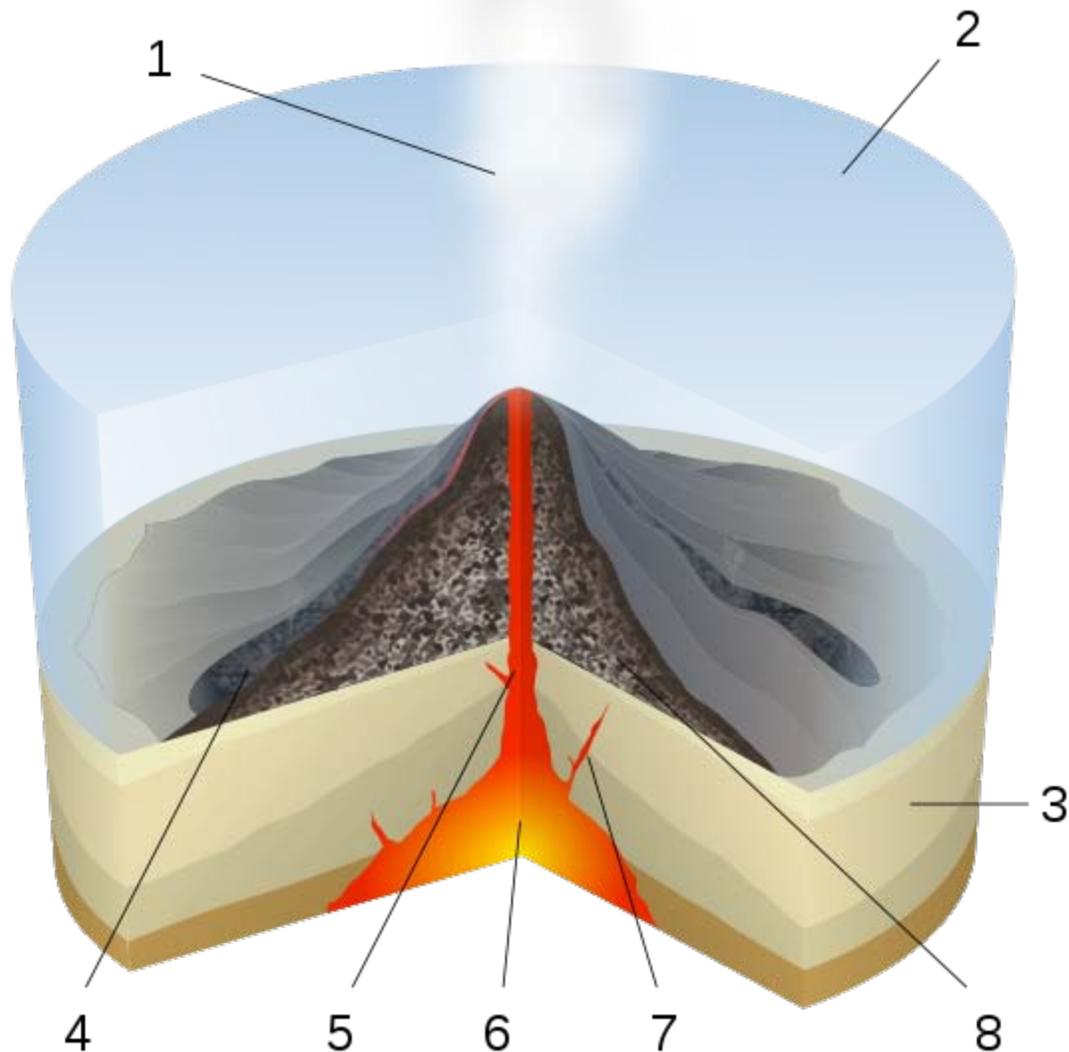
Geology

Geochemistry and evolution

Diagram of a submarine eruption. (key: 1. Water vapor cloud 2. Water 3. Stratum 4. Lava flow 5. Magma conduit 6. Magma chamber 7. Dike 8. Pillow lava).

Most seamounts are built by one of two volcanic processes. Volcanoes near plate boundaries and mid-ocean ridges are built by decompression melting of rock in the mantle that then floats up to the surface, while volcanoes formed near subducting zones are created because the subducting plate adds volatiles to the rising plate that raise its melting point. Which process formed the seamount has a profound effect on its eruptive materials. Lava flows from mid-ocean ridge and plate boundary seamounts are mostly basaltic (both tholeiitic and alkalic), whereas flows from

subducting ridge volcanoes are mostly calc-alkaline lavas. Compared to mid-ocean ridge seamounts, subduction zone seamounts generally have more sodium, alkali, and volatile abundances, and less magnesium, resulting in more explosive, viscous eruptions.

All volcanic seamounts follow a particular pattern of growth, activity, subsidence and eventual extinction. The first stage of a seamount's evolution is its early activity, building its flanks and core up from the sea floor. This is followed by a period of intense volcanism, during which the new volcano erupts almost all (e.g. 98%) of its total magmatic volume. The seamount may even grow above sea level to become an oceanic island (for example, the 2009 eruption of Hunga Tonga). After a period of explosive activity near the ocean surface, the eruptions slowly die away. With eruptions becoming infrequent and the seamount losing its ability to maintain itself, the volcano starts to erode. After finally becoming extinct (possibly after a brief rejuvenated period), they are ground back down by the waves. Seamounts are built in a far more dynamic oceanic setting then their land counterparts, resulting in horizontal subsidation as the seamount moves on the grinding plate towards a subduction zone. Here it is subducted under the plate margin and ultimately destroyed, but it may leave evidence of its passage by carving an indentation into the opposing wall of the subduction trench. The majority of seamounts have already completed their eruptive cycle, so access to early flows by researchers is limited by late volcanic activity.

Ocean-ridge volcanoes in particular have been observed to follow a certain pattern in terms of eruptive activity, first observed with Hawaiian seamounts but now shown to be the process followed by all seamounts of the ocean-ridge type. During the first stage the volcano erupts basalt of various types, caused by various degrees of mantle melting. In the second, most active stage of its life, ocean-ridge volcanoes erupt tholeiitic to mildly alkalic basalt as a result of a larger area melting in the mantle. This is finally capped by alkalic flows late in its eruptive history, as the link between the seamount and its source of volcanism is cut by crustal movement. Some seamounts also experience a brief "rejuvenated" period after a hiatus of 1.5 to 10 million years, the flows of which are highly alkalic and produce many xenoliths.

In recent years, geologists have confirmed that a number of seamounts are active undersea volcanoes; two examples are Loʻihi in the Hawaiian Islands and Vailulu'u in the Manu'a Group (Samoa).

Lava types

Pillow lava, a type of basalt flow that originates from lava-water interactions during submarine eruptions

The most apparent lava flows at a seamount are the eruptive flows which cover their flanks, however igneous intrusions, in the forms of dikes and sills, are also an important part of seamount growth. The most common type of flow is pillow lava, named so after its unusual shape. Less common are sheet flows, which are glassy and marginal, and indicative of larger-scale flows. Volcaniclastic sedimentary rocks dominate shallow-water seamounts. They are the products of the explosive activity of seamounts that are near the water's surface, and can also form from mechanical wear of existing volcanic rock.

Structure

Seamounts can form in a wide variety of tectonic settings, resulting in a very diverse structural bank. Seamounts come in a wide variety of structural shapes, from conical to flat-topped to complexly shaped. Some are built very large and very low, such as Koko Guyot and Detroit Seamount; others are built more steeply, such as Loihi Seamount and Bowie Seamount. Some seamounts also have a carbonate or sediment cap.

Many seamounts show signs of intrusive activity, which is likely to lead to inflation, steepening of volcanic slopes, and ultimately, flank collapse. There are also several sub-classes of seamounts. The first are guyots, seamount with a flat top. These tops must be 200 m (656 ft) or more below the surface of the sea; the diameters of these flat summits can be over 10 km (6.2 mi). Knolls are isolated elevation spikes measuring less than 1,000 meters (3,281 ft). Lastly, pinnacles are small pillar-like seamounts.

Ecology

Ecological role of seamounts

Seamounts are exceptionally important to their biome ecologically, but their role in their environment is little understood. Because they project out above the surrounding sea floor, they disturb standard water flow, causing eddies and associated hydrological phenomena that ultimately result in water movement in an otherwise still ocean bottom. Currents have been measured at up to 0.9 knots, or 48 centimeters per second. Because of this upwelling seamounts often carry above-average plankton populations, seamounts are thus centers where the fish that feed on them aggregate, in turn falling prey to further predation, making seamounts important biological hotspots.

Seamounts provide habitats and spawning grounds for these larger animals, including numerous fish. Some species, including black oreo *(Allocyttus niger)* and blackstripe cardinalfish *(Apogon nigrofasciatus)*, have been shown to occur more often on seamounts then anywhere else on the ocean floor. Marine mammals, sharks, tuna, and cephalopods all congregate over seamounts to feed, as well as some species of seabirds when the features are particularly shallow.

Grenadier fish (*Coryphaenoides sp.*) and bubblegum coral (*Paragorgia arborea*) on the crest of Davidson Seamount. These are two species attracted to the seamount; *Paragorgia arborea* in particular grows in the surrounding area as well, but nowhere near as profusely.

Seamounts often project upwards into shallower zones more hospitable to sea life, providing habitats for marine species that are not found on or around the surrounding deeper ocean bottom. Because seamounts are isolated from each other they form "undersea islands" creating the same biogeographical interest. As they are formed from volcanic rock, the substrate is much harder than the surrounding sedimentary deep sea floor. This causes a different type of fauna to exist than on the seafloor, and leads to a theoretically higher degree of endemism. However, recent research especially centered at Davidson Seamount suggests that seamounts may not be especially endemic, and discussions are ongoing on the effect of seamounts on endemicity. They *have*, however, been confidently shown to provide a habitat to species that difficulty surviving elsewhere.

The volcanic rocks on the slopes of seamounts are heavily populated by suspension feeders, particularly corals, which capitalize on the strong currents around the seamount to supply them with food. This is in sharp contrast with the typical deep-sea habitat, where deposit-feeding animals rely on food they get off the ground. In tropical zones extensive coral growth results in the formation of coral atolls late in the seamount's life.

In addition soft sediments tend to accumulate on seamounts, which are typically populated by polychaetes (annelid marine worms) oligochaetes (microdrile worms), and gastropod mollusks (sea slugs). Xenophyophores have also been found. They tend to gather small particulates and thus form beds, which alters sediment deposition and creates a habitat for smaller animals. Many seamounts also have hydrothermal vent communities, for example Suiyo and Loihi seamounts. This is helped by geochemical exchange between the seamounts and the ocean water.

Seamounts may thus be vital stopping points for some migratory animals, specifically whales. Some recent research indicates whales may use such features as navigational aids throughout their migration. For a long time it has been surmised that many pelagic animals visit seamounts as well, to gather food, but proof of this aggregating effect has been lacking. The first demonstration of this conjecture has recently been published.

Fishing

The effect that seamounts have on fish populations has not gone unnoticed by the commercial fishing industry. Seamounts were first extensively fished in the second half of the 20th century, due to poor management practices and increased fishing pressure seriously depleting stock numbers on the typical fishing ground, the continental shelf. Seamounts have been the site of targeted fishing since that time.

Nearly 80 species of fish and shellfish are commercially harvested from seamounts, including spiny lobster (**Palinuridae**), mackerel (**Scombridae** and others), red king crab (*Paralithodes camtschaticus*), red snapper (*Lutjanus campechanus*), tuna (**Scombridae**), Orange roughy (*Hoplostethus atlanticus*), and perch (**Percidae**).

Conservation
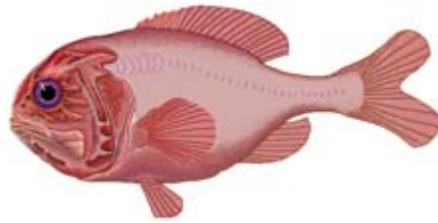
Because of overfishing at their seamount spawning grounds, stocks of orange roughy (*Hoplostethus atlanticus*) have plummeted; experts say that it could take decades for the species to restore itself to its former numbers.

The ecological conservation of seamounts is hurt by the simple lack of information available. Seamounts are very poorly studied, with only 350 of the estimated 100,000 seamounts in the world having received sampling, and fewer than 100 in depth. Much of this lack of information can be attributed to a lack of technology, and to the daunting task of reaching these underwater structures; the technology to fully explore them has only been around the last few decades. Before consistent conservation efforts can begin, the seamounts of the world must first be mapped, a task that is still in progress.

Overfishing is a serious threat to seamount ecological welfare. There are several well-documented cases of fishery exploitation, for example the orange roughy (*Hoplostethus atlanticus*) off the coasts of Australia and New Zealand and the pelagic armorhead (*Pseudopentaceros richardsoni*) near Japan and Russia. The reason for this is that the fishes that are targeted over seamounts are typically long-lived, slow-growing, and slow-maturing. The problem is confounded by the dangers of trawling, which damages seamount surface communities, and the fact that many seamounts are located in international waters, making proper monitoring difficult. Bottom trawling in particular is extremely devastating to seamount ecology, and is responsible for as much as 95% of ecological damage to seamounts.


Coral earings of this type are often made from coral harvested off seamounts

Corals from seamounts are also vulnerable, as they are highly valued for making jewellery and decorative objects. Significant harvests have been produced from seamounts, often leaving coral beds depleted.

Individual nations are beginning to note the effect of fishing on seamounts, and the European Commission has agreed to fund the OASIS project, a detailed study of the effects of fishing on seamount communities in the North Atlantic. Another project working towards conservation is CenSeam, a Census of Marine Life project formed in 2005. CenSeam is intended to provide the framework needed to prioritise, integrate, expand and facilitate seamount research efforts in order to significantly reduce the unknown and build towards a global understanding of seamount ecosystems, and the roles they have in the biogeography, biodiversity, productivity and evolution of marine organisms.

Possibly the best ecologically studied seamount in the world is Davidson Seamount, with six major expeditions recording over 60,000 species observations. The contrast between the seamount and the surrounding area was well-marked. One of the primary ecological havens on the seamount is its deep sea coral garden, and many of the specimens noted were over a century old. Following the expansion of knowledge on the seamount there was extensive support to make it a marine sanctuary, a motion that was granted in 2008 as part of the Monterey Bay National Marine Sanctuary. Much of what is known about seamounts ecologically is based on observations from Davidson. Another such seamount is Bowie Seamount, which has also been declared a marine protected area by Canada for its ecological richness.

Exploration
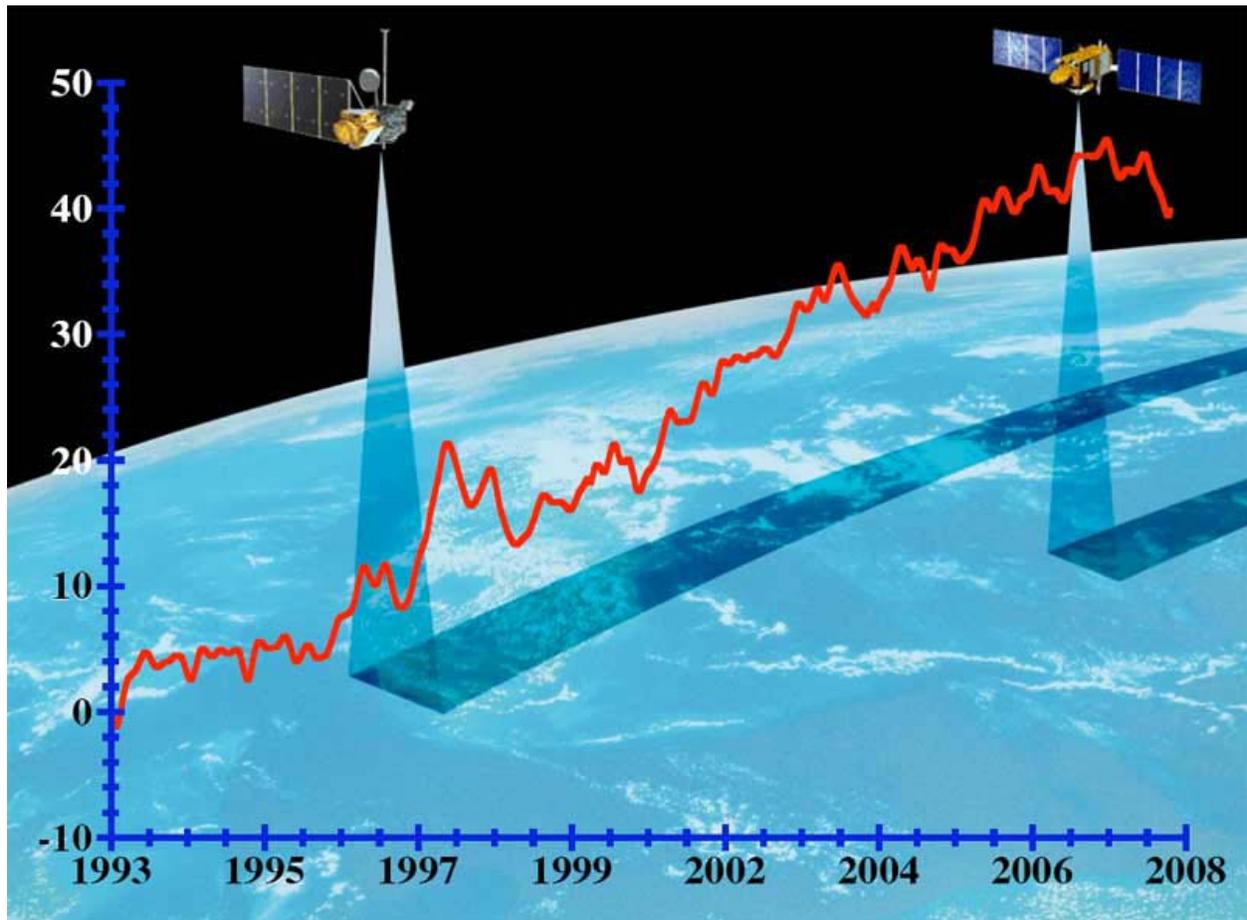
Graph showing the rise in global sea level (in mm) as measured by the NASA/CNES oceanic satellite altimeter TOPEX/Poseidon (left) and its follow-on mission Jason-1.

The study of seamounts has been stymied for a long time by the lack of technology. Although seamounts have been sampled as far back as the 19th century, their depth and position meant that the technology to explore and sample seamounts in sufficient detail did not exist until the last few decades. Even with the right technology available, only a scant 1% of the total number have been explored, and sampling and information remains biased towards the top 500 m (1,640 ft). New species are observed or collected and valuable information is obtained on almost every submersible dive at seamounts.

Before seamounts and their oceanographic impact can be fully understood, they must be mapped, a daunting task due to their sheer number. The most detailed seamount mappings are provided by multibeam echosounding (sonar), however after more than 5000 publicly held cruises the amount of the sea floor that has been mapped remains miniscule. Satellite altimetry is a broader alternative, albeit not as detailed, with 13,000 catalogued seamounts; however this is still only a fraction of the total 100,000. The reason for this is that uncertanties in the technology limit

recognition to features 1,500 m (4,921 ft) or larger. In the future technological advances could allow for a larger and more detailed catalogue.

Deep-sea mining

Seamounts are a possible future source of heavy metals. The growth of the human population and, with it, heavy industry, has pressed demands for Earth's finite resources. Even though the ocean makes up 70% of the world, technological challenges with deep-sea mineral mining have severely limited its extent. But with the constantly decreasing supply on land, many see oceanic mining as the destined future, and seamounts stand out as candidates.

Seamounts are abundant, and all have metal resource potential because of various enrichment processes during the seamount's life. Hydrogenic Iron-manganese, hydrothermal iron oxide, sulfide, sulfate, sulfur, hydrothermal manganese oxide, and phosphorite are all mineral resources that are founded by various processes and deposited upon seamounts. However, only the first two have any potential of being targeted by mining in the next few decades.

Dangers

Some seamounts have not been mapped and thus pose a navigational danger. For instance, Muirfield Seamount is named after the ship that hit it in 1973. More recently, the submarine USS *San Francisco* ran into an uncharted seamount in 2005 at a speed of 35 knots (40.3 mph; 64.8 km/h), sustaining serious damage and killing one seaman.

One major seamount risk is that often, in the late of stages of their life, extrusions begin to seep in the seamount. This activity leads to inflation, over-extension of the volcano's flanks, and ultimetly flank collapse, leading to submarine landslides with the potential to start major tsunamis. This is one of the largest natural disasters in the world. In an illustration of the potent power of flank collapses, a summit collapse on the northern edge of Vlinder Seamount resulted in a pronounced headwall scarp and a field of debris up to 6 km (4 mi) away. A catastrophic collapse at Detroit Seamount flattened its whole structure extensively. Lastly, in 2004, scientists found marine fossils 61 m (200 ft) up the flank of Kohala mountain in Hawaii (island). Subsidation analysis found that at the time of their deposition, this would have been 500 m (1,640 ft) up the flank of the volcano, far too high for a normal wave to reach. The date corresponded with a massive flank collapse at the nearby Mauna Loa, and it was theorized that it was a massive tsunami, generated by the landslide, that deposited the fossils.