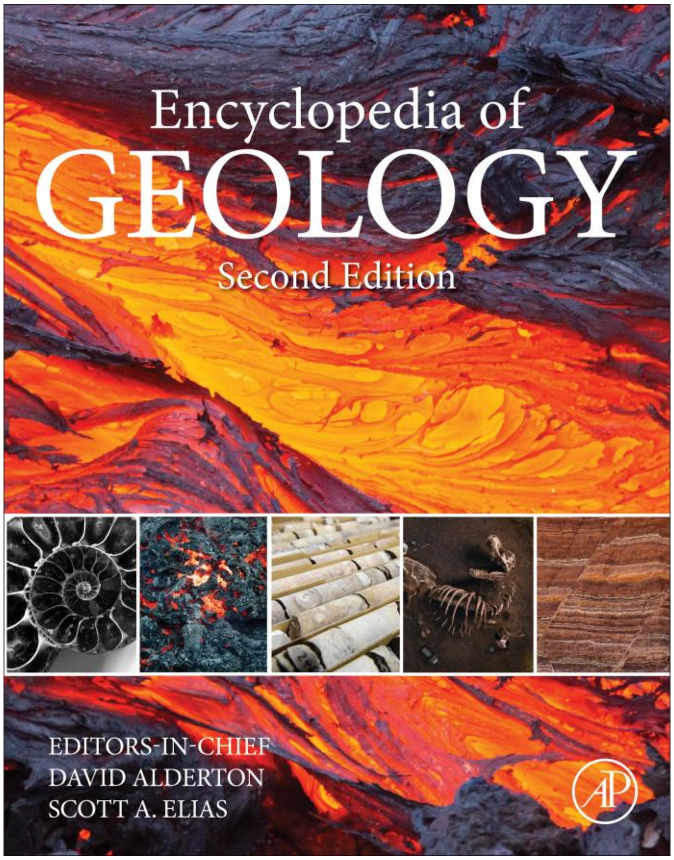

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Ocean Trenches☆

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Introduction

An oceanic trench is a long, narrow, and generally very deep depression of the seafloor. Oceanic trenches are the deepest places on the Earth's solid surface and range down to 11 km below sea-level. These tremendous depths mark fundamental breaks in the Earth's lithosphere, the great plates that we all ride on. If mid-ocean ridges are where the Earth turns itself inside out, trenches are where the Earth swallows its skin. Trenches are not vertical slits but are generally asymmetric, with the gentle slope on the ocean side. The asymmetry of trenches reflects what is happening at depth: as the oceanic plate bends down to return to the mantle, the landward plate strains to fill the growing void. The depths of trenches are governed by many things, including sediment flux, the age of the down going lithosphere, the convergence rate, dip of the subducted oceanic lithosphere (slab) at intermediate (70–300 km) depths, and even the width of the sinking plate. Trenches are sites where fluids begin to be squeezed out of the subducted sediments and a newly recognized biosphere thrives.

Early Years of Study

Trenches are one of the most spectacular features of Earth's solid surface, but because they lie deep underwater, they were not clearly defined until the late 1940s and 1950s. The depths of the oceans were scarcely imagined until we began to lay telegraph cables across the Pacific Ocean in the late nineteenth and early twentieth centuries. It took many decades before the elongated bathymetric expression of trenches were recognized; the term "trench" does not appear in Murray et al. (1912) classic oceanography overview. Instead they used the term "deep" to describe what we now call trenches, such as the Challenger Deep, which is now recognized as the greatest gash on the solid surface of the Earth. Experiences in the World War I battlefields emblazoned the concept of a trench as an elongate depression marking an important boundary, so it is no surprise that the term "trench" was used to describe natural features beginning in the early 1920s. The term was first used in a geological context by SJ Scofield 2 years after the war ended to describe a structurally controlled depression in the Rocky Mountains. James Johnstone, in his 1923 textbook *An Introduction to Oceanography*, first used the term in its modern sense to describe a marked elongate depression of the seafloor.

During the 1920s and 1930s, Vening Meinesz developed an instrument that could measure gravity in the stable environment of a submarine and used it to investigate ocean trenches. His results revealed that trenches are sites of downwelling in the solid Earth. The concept of down welling at trenches was characterized by DT Griggs in 1939 as the tectogene hypothesis, for which he developed an analogue model using a pair of rotating drums. The war in the Pacific (1941–45) led to great improvements in echo sounding (measuring water depths with SONAR), especially in the western and northern Pacific, and the linear nature of trenches became clearer. The rapid growth of deep-sea research efforts, especially the widespread use of echo sounders in the 1950s and 1960s, confirmed the usefulness of the term "trench." The trenches were identified, sampled, and studied during these decades. 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, a record that was tied by James Cameron in March 2012 https://www.youtube.com/watch?v=FGzaUiutuRk and by Victor Vescovo in April–May 2019 https://www.youtube.com/watch?v=LKXvdyNz6L8 . Following Dietz' and 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 so that it now has tectonic as well as morphological connotations.

☆*Change History*: August 2020. RJ Stern updated the text and further readings to this entire article and added new Figure 2.

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Plate Tectonic Significance

Trenches mark one of the most important types of natural boundary on the Earth's solid surface, that between two lithospheric plates. There are three types of lithospheric-plate boundaries: divergent (where lithosphere and oceanic crust are created at oceanic spreading centers, convergent (where one lithospheric plate sinks beneath another and returns to the mantle in a subduction zone, and transform (where two lithospheric plates slide past each other). Trenches are the spectacular and distinctive morphological features of convergent plate boundaries (Fig. 1). Convergent plate boundaries are where two plates move towards each other at rates that vary from a few millimeter to ten or more centimeter per year (An animation of plate creation at an oceanic spreading center and plate destruction at a convergent plate boundary and subduction zone can be seen at https://www.youtube.com/watch?v=6wJBOk9xjto). Trenches form where oceanic lithosphere is subducted beneath another, over-riding plate at a convergent plate margin, presently at a global rate of about a tenth of a square m per second.

Geographical Distribution

There are about 50,000 km of convergent plate margins in the world, mostly around the Pacific Ocean—the reason that these are sometimes called "Pacific-type" margins—but they also occur in the eastern Indian Ocean, and there are shorter convergent-margin segments in the Atlantic and NW Indian Oceans and in the Mediterranean Sea (Fig. 2). Trenches are sometimes buried and lack bathymetric expression, but the fundamental structures that they represent mean that the name should still be applied in these cases. This applies to the Cascadia, Makran, southern Lesser Antilles, and Calabrian trenches (Table 1). Trenches, magmatic (island) arcs, and zones of earthquakes that dip under the magmatic 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 zones of continental collision,

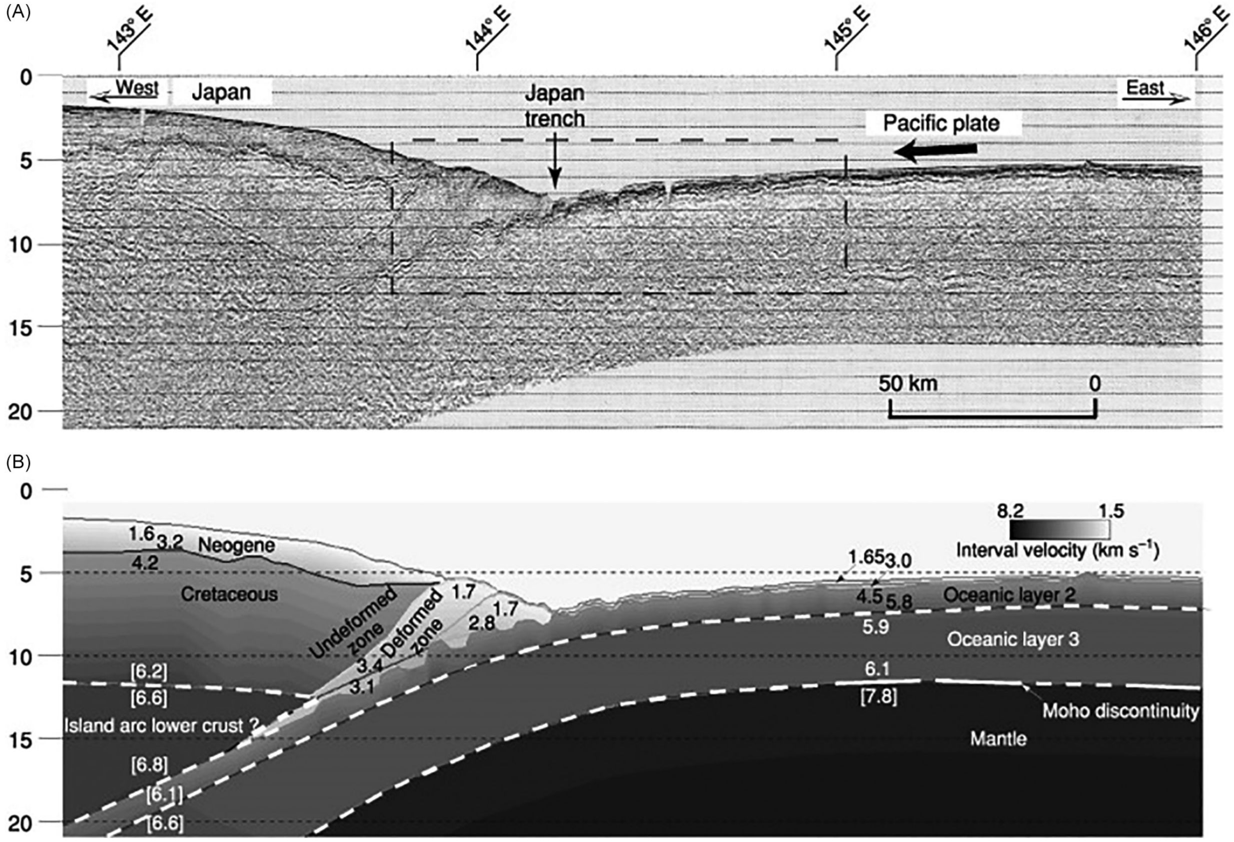

Fig. 1 Profile across a typical trench (the Japan Trench near 39° N). (A) Seismic-reflection image (pre-stack depth migration) and (B) interpretation, including crustal units and seismic velocities (in km s^{-1}). Dashed box in (A) indicates the region shown in detail in Fig. 3A. Vertical exaggeration in (B) is four times. The model is shaded according to the seismic velocities, and selected digital values are also shown. Modified from Tsuru T, Park JO, Takahashi N et al. (2000) Tectonic features of the Japan Trench convergent margin off Sanriku, northeastern Japan, revealed by multichannel seismic reflection data. *Journal of Geophysical Research* 105: 16403–16413.

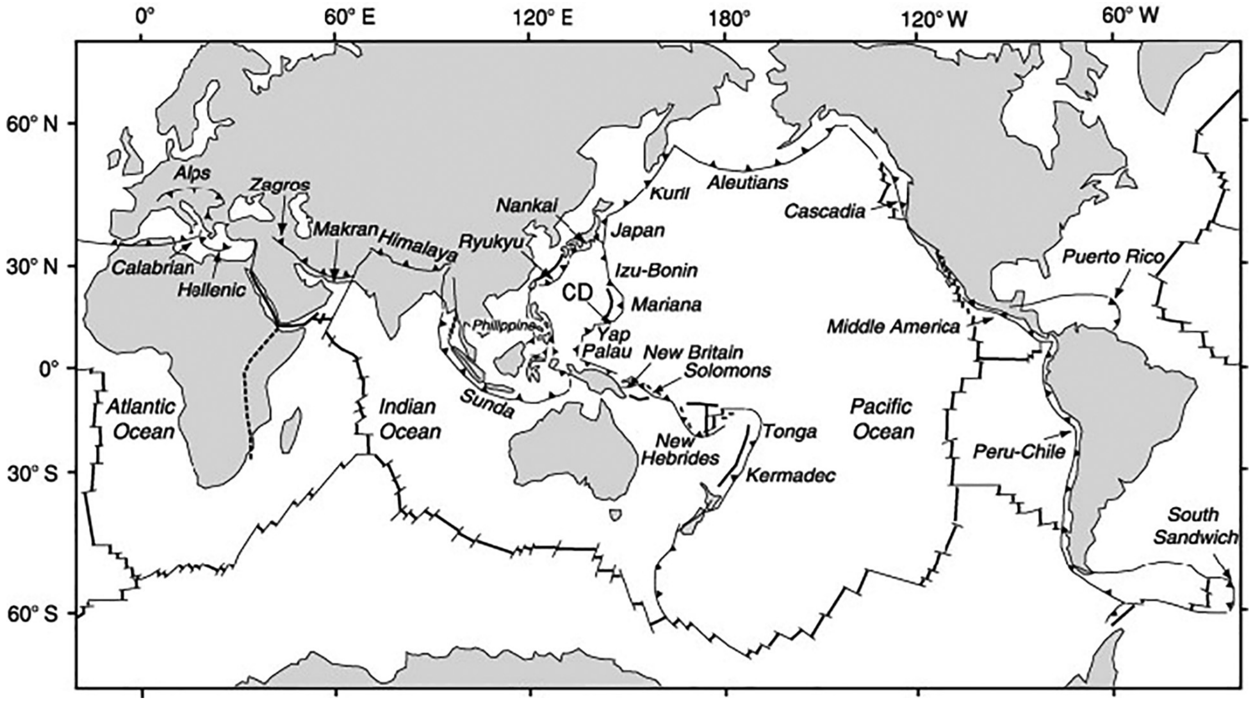

Fig. 2 Locations of the world's convergent plate margins (barbs on over-riding plate), major trenches and collision zones. CD is the Challenger Deep.

Table 1 Maximum trench depth.

Trench	*Maximum depth (m)*	*Accretionary prism?*
Challenger, Mariana	10,920	No
Tonga	10,800	No
Philippine (East Mindanao)	10,057	No
Kermadec	10,047	No
Izu-Bonin	9780	No
Kuril	9550	No
North New Hebrides	9175	No
New Britain	8940	No
Yap	8650	No
Puerto Rico	8605	No
South Sandwich	8325	No
South Solomons	8322	No
Peru–Chile	8170	No
Japan	8130	No
Palau	8055	No
Aleutians	7680	Yes
Ryukyu	7460	Yes
Sunda	7125	Yes
Middle America	6660	No
Hellenic	5092	Yes
Nankai	4900	Yes
Calabrian	4200	Yes, no morphological trench
Makran	3200	Yes, no morphological trench
Cascadia	3136	Yes, no morphological trench

where buoyant continental lithosphere enters the subduction zone. When this happens, subduction is likely to stop and high mountains like the Himalayas, Zagros, or Alps will form. Features analogous to trenches are associated with collision zones; these include sediment-filled fore deeps, referred to as peripheral foreland basins, such as the Ganges and Tigris-Euphrates rivers flow along.

Morphological Expression

Trenches are the center pieces of the distinctive physiography of a convergent plate margin. Transects across trenches yield asymmetric profiles, with relatively gentle (ca. 5 degrees) outer (seaward) slopes and steeper (up to ca. 15 degrees) inner (landward) slopes. This asymmetry is due to the fact that the outer slope is defined by the top of the down going plate, which must bend as it begins its descent. The great thickness and strength of the lithosphere requires gentle bending. As the subducting plate approaches the plate boundary, it is first bent upwards to form the outer swell and 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 into the trench (Fig. 3). These faults allow seawater to penetrate deeply into the plate, hydrating the crust and mantle and perhaps setting up hydrothermal systems (which are yet to be discovered). 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 décollement, which intersects the seafloor at the trench. The overriding plate generally contains a magmatic arc, which lies ~100 km above the subducted plate and is separated from the trench by a fore arc that is ca. 200 km wide. The magmatic arc is created as a result of physical and chemical interactions between the subducted plate at depth and the asthenospheric mantle associated with the overriding plate. Fore arcs have the lowest heat flow of any place on Earth because there is no asthenosphere (hot convecting mantle) between the fore arc lithosphere and the cold subducting plate.

The inner trench wall marks the edge of the overriding plate and the outermost fore arc. Fore arc crust consists of igneous and metamorphic rocks, and this basement may act as a buttress to a growing accretionary prism, depending on how much sediment is supplied to the trench. If the sediment flux 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 away from the magmatic 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. Fore arcs 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 a convergent margin can simultaneously experience sediment accretion and subduction erosion. If more material is accreted from the down going plate than ablated from the over-riding plate, an accretionary prism will grow; if less material is accreted than ablated, a nonaccretionary convergent margin results (Fig. 4).

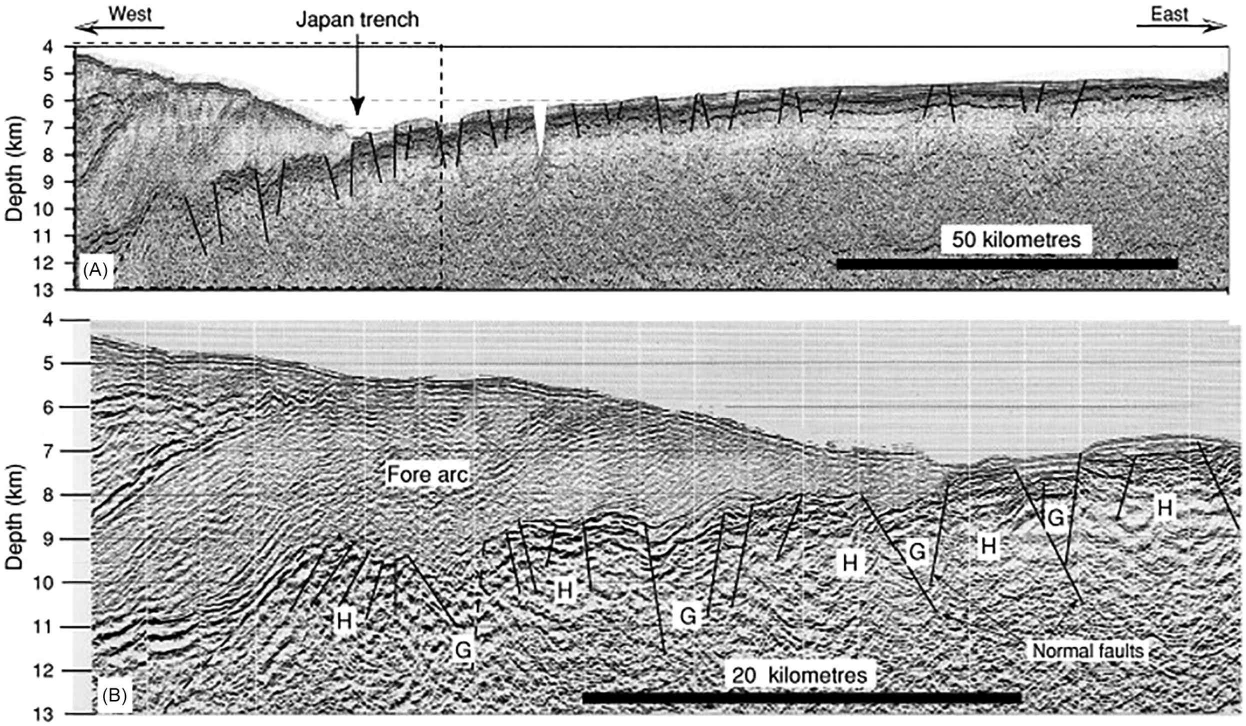

Fig. 3 Horst (H) and graben (G) structures with normal faults associated with the subduction of the Pacific plate beneath Japan to form the Japan Trench. Vertical exaggeration is four times in (A) and twice in (B). Dashed box in (A) indicates the region shown in detail in (B). Modified from Tsuru T, Park JO, Takahashi N et al. (2000) Tectonic features of the Japan Trench convergent margin off Sanriku, northeastern Japan, revealed by multichannel seismic reflection data. *Journal of Geophysical Research* 105: 16403–16413.

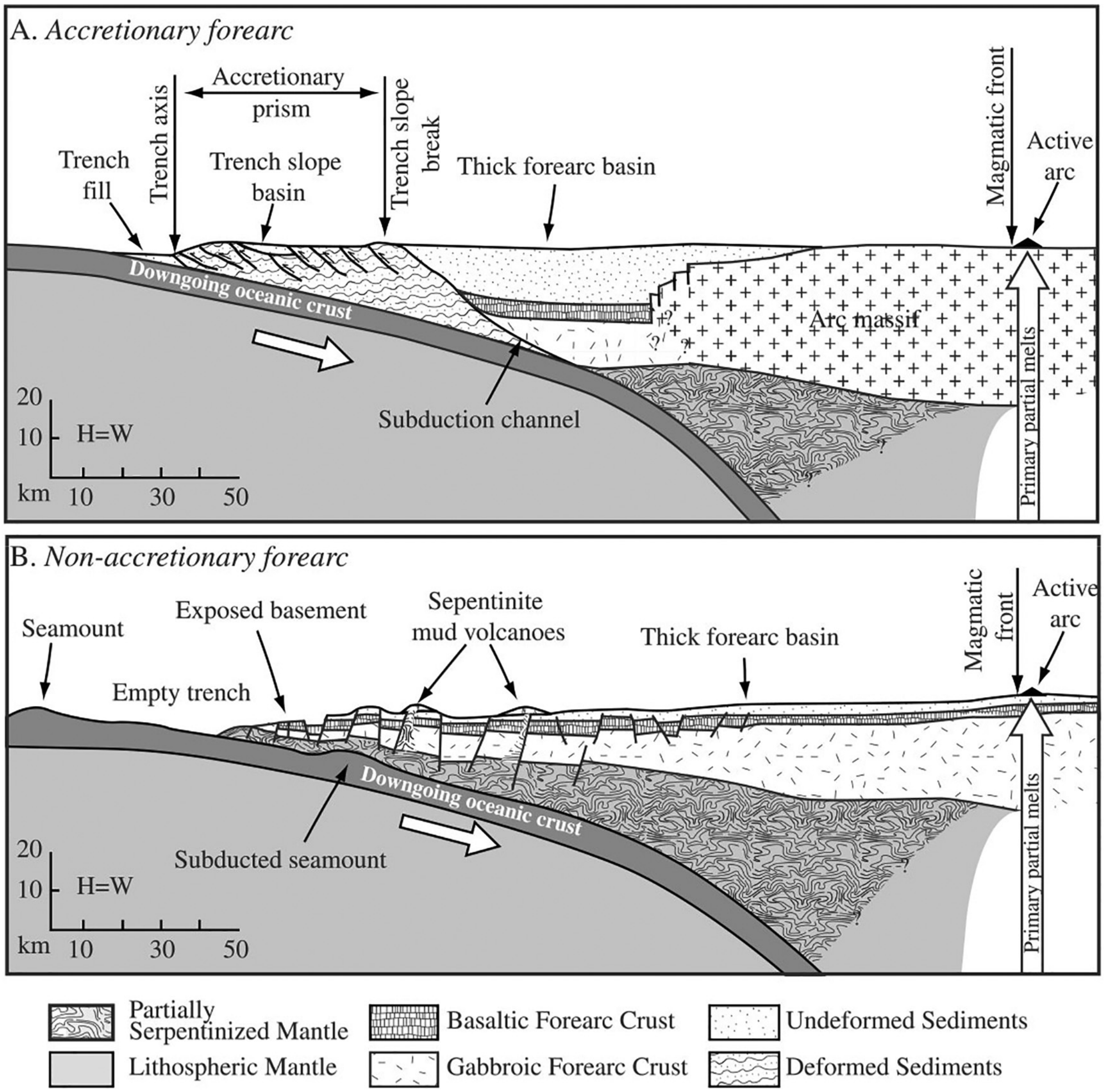

Fig. 4 End-member fore arc types: (A) accretionary fore arc, and (B) nonaccretionary fore arc. Note that the abundance of sediments associated with accretionary fore arcs is manifested as an accretionary prism and as a thick fore arc basin and that the trench may be filled or partially filled with sediments. In contrast the much lower sediment flux associated with nonaccretionary fore arcs exposes the crust and uppermost mantle in the inner trench wall. Serpentine mud volcanoes are only known from the Izu-Bonin-Mariana fore arc. The magmatic front is the trench ward limit of convergent margin igneous activity. (B) From Stern RJ (2002) Subduction zones. *Reviews of Geophysics* doi: https://doi.org/10.1029/2001RG0001.

The asymmetric profile across a trench reflects fundamental differences in materials and tectonic evolution. The outer trench wall and outer swell are composed of oceanic crust overlain by sediments, which takes a few million years to move from where subduction-related deformation begins near the outer trench swell to where the plate sinks beneath the overriding plate at the bottom of the trench. In contrast, the inner trench wall is deformed by plate interactions throughout the life of the convergent margin. The fore arc is frequently shaken by subduction-related earthquakes. This protracted deformation and shaking ensures that the slope of the inner trench wall is controlled by the angle of repose of whatever material it is composed of. Because they are composed of strong igneous rocks instead of weak deformed sediments, nonaccretionary trenches have steeper inner walls than accretionary trenches.

Filled Trenches

The composition of the inner trench slope is determined by sediment supply, which also strongly influences trench morphology. Filled trenches are especially common near continents where large rivers or glaciers reach the sea and dump large volumes of sediments that naturally accumulate in the trench. These filled trenches cause some confusion because they occur in tectonic settings that are indistinguishable from other convergent margins but lack the bathymetric expression of a trench. The Cascadia margin off the north-west coast of the United States is a filled trench, the result of sediments delivered by the rivers of the north-western United States and south-west 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, the trench is filled with sediments and the fore arc and the accretionary prism are almost 500 km wide. The accretionary prism is so large that it forms the islands of Barbados and Trinidad. Northwards the fore arc narrows, the accretionary prism disappears, and north of 17°N there is no accretionary prism but a trench exists. In the extreme north, far away from river sediments, the Puerto Rico Trench is over 8600 m deep, and there is no accretionary prism. A similar relationship between sediment supply, fore arc width, and trench morphology can be observed from east to west along the Alaskan-Aleutian convergent margin. The convergent plate boundary off the coast of Alaska changes along its strike from a filled trench with a broad fore arc in the east (near the rivers of Alaska) to a deep trench with a narrow fore arc in the west (south of the Aleutian Islands). Another example is the Makran convergent margin off the coasts of Pakistan and Iran, where the trench is filled by sediments from the Tigris-Euphrates and Indus rivers. Thick accumulations of muds and sands along the trench were supplied by down-axis transport of sediments that enter the trench 1000–2000 km away by slumping and formation of turbidity currents, as is found in the Peru-Chile Trench south of Valparaiso. Convergence rate can also be important in controlling trench depth, especially for trenches near continents, because slow convergence means that the capacity of the convergent margin to dispose of sediment by subduction is exceeded.

Trench morphology will evolve 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 converge, the trench may increasingly be filled with continental sediments and shoal. A simple definition of the transition from subduction to collision is when a plate boundary previously marked by a trench has filled sufficiently to rise above sea-level, as is seen in Mesopotamia today, where Arabia is colliding with SW Eurasia.

Accretionary Prisms and Sediment Transport

Accretionary prisms grow by frontal accretion—where sediments are scraped off, bulldozer-fashion, near the trench—or by under plating of subducted sediments and perhaps oceanic crust along the shallow parts of the subduction zone plate interface. Frontal accretion over the life of a convergent margin results in the youngest sediments being found in the outermost part of the accretionary prism and the oldest sediments lying in the innermost portion. Older (inner) parts of the accretionary prism are more lithified and have steeper structures than the younger (outer) parts. Under plating 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 the morphology of the inner slope of the trench, which generally shows three morphological provinces. The lower slope comprises imbricate thrust slices, which form ridges. The middle part of the slope may comprise benches or terraces. The upper slope is smoother but may be cut by submarine canyons. In some accretionary prisms, the upper parts may rise above sea level, for example the islands west of Sumatra.

Because accretionary convergent margins have high relief, are continuously deformed, and accommodate a large flux of sediments, they are sites of vigorous 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 are formed by channelized turbidites and generally lose definition with depth because continuous tectonic readjustments disrupt the channels. Sediments move down the inner trench wall via channels and fault-controlled basins. The trench itself serves as an axis of sediment transport. If enough sediment moves into the trench, it may be completely filled, and turbidity currents can then carry sediment well beyond the trench and may even surmount the outer swell. Sediments from the rivers of south-west Canada and the north-western United States spill over where the Cascadia trench is buried and reach the Juan de Fuca spreading ridge several hundred kilometers to the west.

The slope of the inner trench wall of an accretionary convergent margin continuously adjusts to the thickness and width of the accretionary prism. The prism maintains a “critical taper,” established by the Mohr-Coulomb failure criterion for the pertinent materials. A package of sediments scraped off the down going 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 décollement. Strain rate and hydrological properties strongly influence the strength of the accretionary prism and thus the angle of critical taper. Fluid pore pressure can modify rock strength and is an important determinant of critical taper angle. Low permeability and rapid convergence may lead to pore pressures that exceed lithostatic pressure and result in a weak accretionary prism with a shallowly tapered geometry, whereas high permeability and slow convergence lead to lower pore pressures, stronger prisms, and steeper geometry.

The Hellenic Trench system is unusual because its convergent margin subducts evaporites, which are very weak rocks. The slope of the southern flank of the Mediterranean Ridge (its accretionary prism) is low, about 1 degree, which indicates very low shear stress on the décollement at the base of the wedge. Evaporites influence the critical taper of the accretionary complex, because they are weaker than 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 as being similar to trenches in 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 fore arc basin, and that the plate boundary lies south of the Mediterranean Ridge.

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. Nonaccretionary convergent margins are characteristic of (but not limited to) primitive arc systems, which generally form away from continents. Primitive arc systems are built on oceanic lithosphere, such as the Izu-Bonin-Mariana, Tonga-Kermadec, and Scotia (South Sandwich) arc systems. The inner trench slopes of these convergent margins expose fore arc crust, including basalt, gabbro, and serpentinized mantle peridotite. These exposures of the crust and upper mantle provide a unique opportunity to study the magmatic products associated with the initiation of subduction zones. Most ophiolites are probably formed in a fore arc environment when a new subduction forms, and the fore arc setting favors ophiolite emplacement during collision with blocks of thickened crust. Not all nonaccretionary convergent margins are associated with primitive arcs. Trenches adjacent to continents where there is a low influx of sediments from rivers, such as the central part of the Peru-Chile Trench, may also lack an accretionary prism. The inner wall of these trenches expose continental crust.

The igneous basement of a nonaccretionary fore arc is exposed by subduction erosion. This transfers material from the fore arc to the subducting plate and results from frontal or basal erosion. Frontal erosion is most active in the wake of seamounts being subducted beneath the fore arc. Subduction of large edifices (seamount tunneling) over steepens the fore arc, causing mass failures that carry debris towards and ultimately into the trench (Fig. 5). This debris may be deposited in grabens of the down going plate and subducted with it. In contrast, structures resulting from basal erosion of the fore arc are difficult to recognize on seismic-reflection profiles, so the occurrence of basal erosion is difficult to confirm. Subduction erosion may also diminish a once-robust accretionary prism if the flux of sediments into the trench is reduced for some reason.

Nonaccretionary fore arcs may also be sites of serpentinite mud volcanism (Fig. 4B). Serpentinite mud volcanoes form where fluids released from the down going plate percolate upwards and interact with the cold mantle lithosphere of the fore arc. Peridotite is hydrated into serpentinite, which is much less dense than peridotite and so will rise diapirically when there is an opportunity to

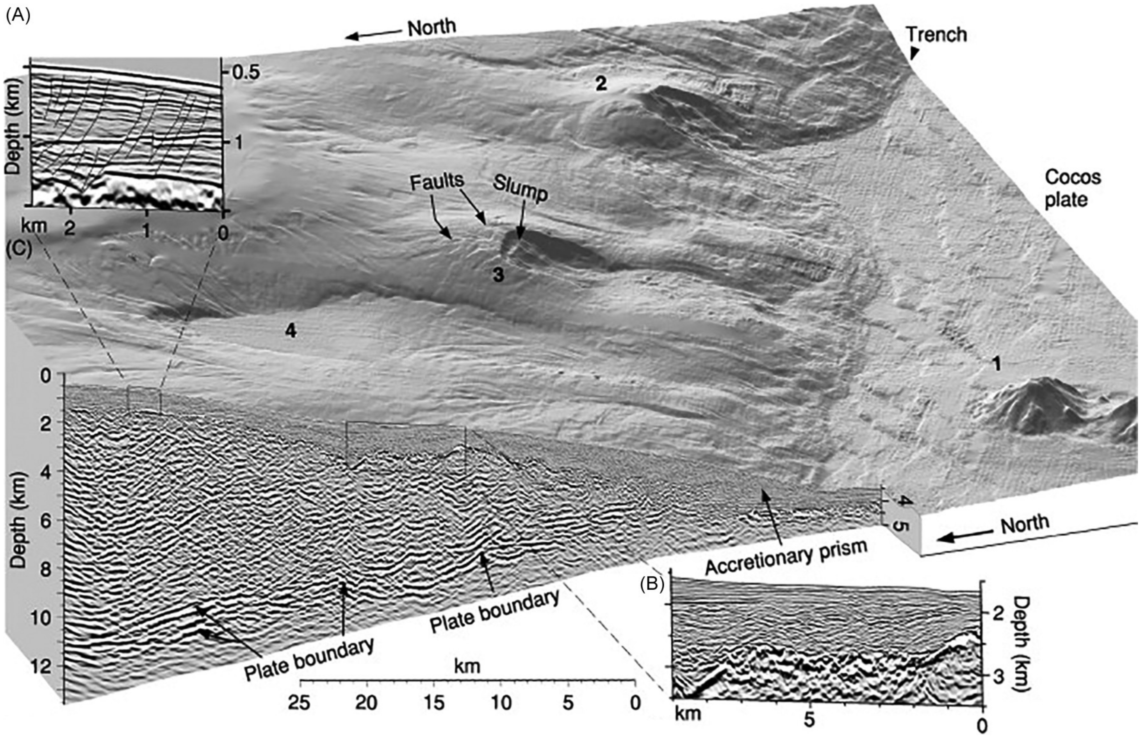

Fig. 5 Down going seamounts and subduction erosion in the Middle America Trench off the coast of Costa Rica, where the Cocos Plate is being rapidly subducted (80 mm year^{-1}). (A) Four seamounts in various stages of subduction (1–4) are particularly well manifested in the bathymetry of the inner trench wall. Seamount 1 (about 1 km tall) is approaching the trench and will enter it in about 200,000 years. Seamount 2 entered the trench about 200,000 years ago and is destroying the inner trench wall. Seamount subduction causes over steepening, with relief locally exceeding 0.5 km, leading to collapse at the sides and especially in the wake of the seamount. Note the slump and fractures. Over steepening causes submarine landslides and flows of debris towards the trench, rebuilding the angle of repose and flooding the trench floor. Seamount 3 entered the trench about 400,000 years ago and has been swallowed beneath the accretionary prism. Debris continues to be shed from the impact zone and flows into the trench. Seamount 4 entered the trench about 600,000 years ago, and the region above it has almost completed its collapse above the sunken seamount. Subduction erosion usually occurs when debris flows fill graben (Fig. 3B) in the down going plate and are carried down. Note also the seismic-reflection profile across the Central American fore arc. (B) Detail of part of the seismic-reflection profile. The frontal ca. 40 km of the margin has a rough margin-wedge top produced by seamount subduction. (C) Where the margin wedge is more than 6–8 km thick its top is smooth, cut only by normal faulting. Modified from Ranero C and von Huene R (2000) Subduction erosion along the Middle America convergent margin. *Nature* 404: 748–752.

do so. Some nonaccretionary fore arcs, for example the Marianas, are subjected to strong extensional stresses, which allows buoyant serpentinite to rise to the seafloor and form serpentinite mud volcanoes. Chemosynthetic communities are also found on nonaccretionary margins such as the Marianas, where they thrive on vents associated with serpentinite mud volcanoes.

Outer Trench Swell

The outer rise is where the descending plate begins to flex and fault as it approaches the subduction zone. Here, the lithosphere is slightly bent upwards by plate stresses, just as the plate is bent downwards in the trench—in neither case is the plate in isostatic equilibrium. Typically, the gravity over the outer swell is about 50 mGals higher than expected from isostasy, while gravity over the trench is about 200 mGals less than that expected from isostatic considerations. The bending of the plate is associated with tension in the upper 20 km, and shallow earthquakes, caused by tensional failure induced by the downward bending of the oceanic plate, are common: about 20 extensional outer-rise earthquakes of magnitude 5 or greater occur annually. Most axes of tension are perpendicular to the trench, regardless of the direction of relative motion between the two plates, indicating that failure is controlled by bending stresses in the plate. Plate bending also causes deeper (down to 50 km) earthquakes due to compression. The width of the outer rise is directly related to the flexural rigidity of the lithosphere. The thickness of the elastic lithosphere varies between 20 and 30 km for most trench profiles. Faulting related to plate bending and stair-stepping of the descending slab into the trench may allow seawater to infiltrate deep into the crust and perhaps into the upper mantle. Faulting of the down going plate results in a horst-and-graben structure, which allows sediment that reaches the trench to be deposited in graben and carried down into the subduction zone. This faulting also breaks up seamounts as they approach the trench (Fig. 6). The mechanism of frontal erosion may operate through the combined effects of seamount tunneling, mass wasting and transport to the trench, deposition in a graben on the down going plate, and descent into the mantle.

Controls on Trench Depth

Several factors that control the depths of trenches. The supply of sediment is important, because sediments may fill the trench so that there is no bathymetric expression. It is therefore not surprising that the deepest trenches are associated with nonaccretionary fore arcs. Table 1 shows that all trenches deeper than 8000 m are nonaccretionary. In contrast, all trenches with growing accretionary

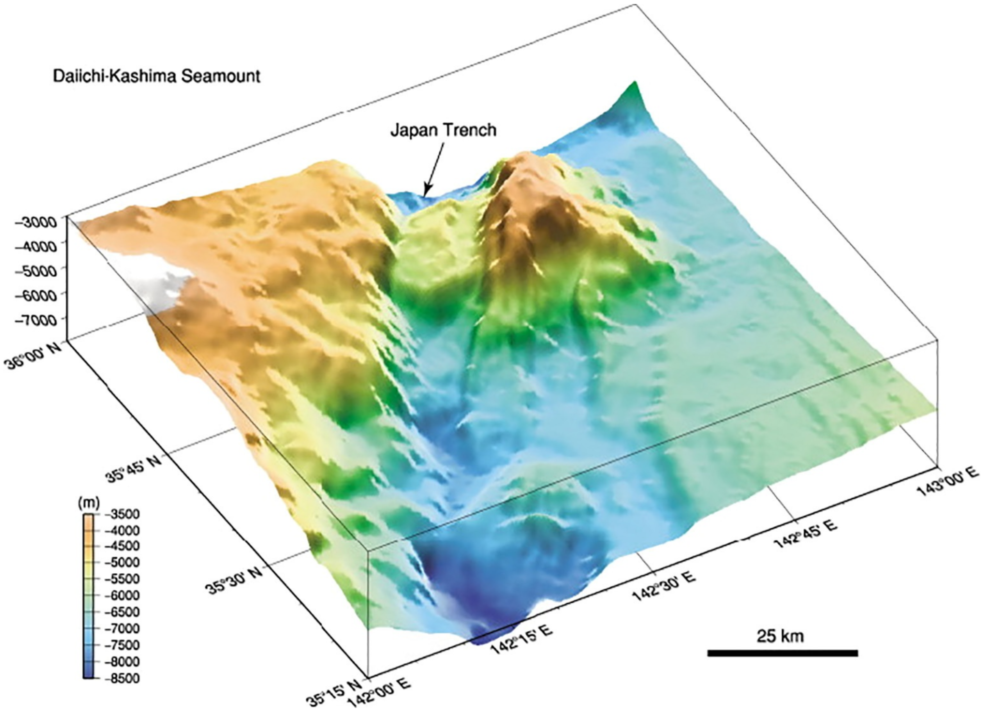

Fig. 6 Bathymetric profile showing normal faulting affecting the Daiichi-Kahima Seamount as it enters the Japan Trench, east of Tokyo. The seamount, which was originally a guyot (conical sides and a flat top), has been cut by a normal fault that drops its western third by about 1 km. Smaller normal faults related to bending of the plate as it approaches the trench affect the eastern part of the seamount and the seafloor around it. Data from JODC-Expert Grid Data for Geography—500 m (J-EGG500) Japan Oceanographic Data Center. View is from 225 degrees (azimuth) and 30 degrees (elevation), illumination is from the east. Vertical exaggeration is 5.5 times. Figure generated by Tomoyuki Sasaki of the Ocean Research Institute, University of Tokyo.

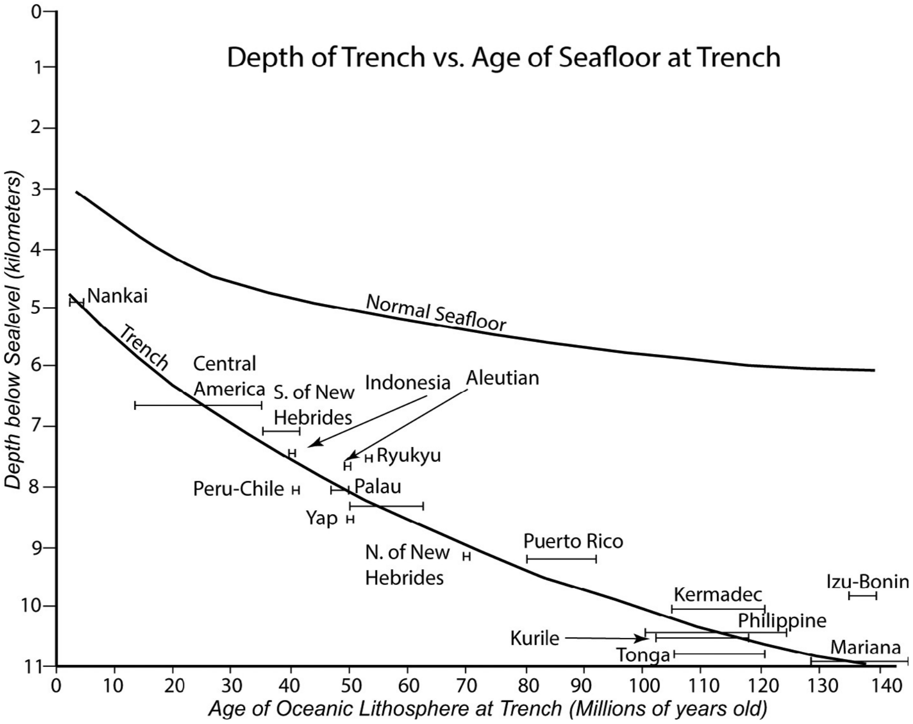

Fig. 7 Maximum depth of the trench and age of the subduction lithosphere. Normal seafloor is formed by seafloor spreading at divergent plate boundaries. Modified after Grellet C and Dubois J (1982) The depth of trenches as a function of the subduction rate and age of the lithosphere. *Tectonophysics* 82: 45–56

prisms are shallower than 8000 m. A second factor controlling trench depth is the age of the oceanic lithosphere being subducted. Because oceanic lithosphere cools and thickens as it ages, it subsides. The older the seafloor, the deeper it lies, and this controls the minimum depth from which the seafloor begins to descend into the subduction zone. This obvious correlation can be removed by looking at the relative depth (Δd), which is the difference between the regional seafloor depth and the maximum trench depth. The relative depth is affected 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 the 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 (Fig. 7).

Fluids Released From the Fore Arc

The volume of water escaping from within and beneath the fore arc results in some of the Earth's most dynamic and complex interactions between aqueous fluids and rocks. Most of this water is trapped in pores and fractures in the crust and sediments of the subducting plate but some is also trapped in the subducting upper mantle. The fore arc is underlain by subducted oceanic sediment that is typically 400 m thick in the shallow subduction zone. This sediment enters the trench with 50–60% porosity. Subducted sediment is progressively squeezed as it sinks deeper into the Earth, reducing void space and forcing fluids out along the décollement and up into the overlying fore arc. Sediments accreted to the fore arc to form an accretionary prism are another source of fluids, which is released as sediments are deformed and lithified. Water is also bound in hydrous minerals, especially clays and siliceous sediments. The increasing pressure and temperature experienced by the subducted materials convert the hydrous minerals to denser phases that contain progressively less structurally bound water. Water released by dehydration accompanying phase transitions in the subducted sediments and oceanic crust is also introduced to the base of the overriding plate. These fluids may travel diffusely through the accretionary prism, via interconnected pore spaces in sediments, or may follow discrete channels along faults. Sites of venting in the fore arc may take the form of mud volcanoes or seeps and are often associated with chemosynthetic communities. Fluids liberated in the shallowest parts of the subduction zone may also escape along the plate boundary but if so vents would be expected along trench axes and these are not observed. 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 (clathrate) in fore arc sediments and accretionary prisms. Gas hydrates are a potential energy source and can rapidly break down. The destabilization of gas hydrates has contributed to global warming in the past.

Fore arc vents are very different than the hydrothermal vents found at mid-ocean ridges, which are hot and vigorous and relatively easy to find because they are in much shallower water (2000–4000 m). Mid-ocean ridge vents make strong hydrothermal plumes that can be detected from surface ships, and scientists know where to look for these, along well-defined oceanic spreading ridges. In contrast vents in trenches are in much deeper water (where it is much harder to work), they release cool water that cannot be detected by surface ships alone (they must be found by manned submersible or ROV), and they are more broadly distributed around the plate boundary, occurring in a broad region centered on the trench. Fore arc vents are known from the summits of serpentine mud volcanoes in the Mariana fore arc and the Shinkai Seep in the inner slope of the Mariana Trench near the Challenger Deep and there are many seeps known from offshore North California, Oregon and Washington. There are also likely to be seeps in the outer slope, associated with normal faults on the down going plate, but these have not yet been explored for.

Biosphere

There is little life in the water column above the trenches because there is little food. Most food in the ocean is produced by phytoplankton in the photic zone and while these organisms die and much of this sinks from the photic zone, little escapes scavengers to fall to the trench seafloor (although recent studies suggest that flow of sediments may deliver significant nutrients to the deep trench). Life does thrive where there are vents on the seafloor. Life around vents is based on energy in chemicals released with venting fluids and some of these chemicals are converted by chemosynthetic microbes to provide the base of a food chain. High concentrations of methane and sulfide in the fluids escaping from the seafloor are the principal energy sources for chemosynthesis. Chemosynthetic communities have been discovered everywhere vents have been found in fore arcs, especially around Japan, in the Eastern Pacific, along the North, Central, and South American coasts from the Aleutian to the Peru-Chile trenches, on the Barbados accretionary prism, in the Mediterranean, and in the Indian Ocean, along the Makran and Sunda convergent margins. These communities have been found down to depths of 6000 m and there is no reason not to expect that deeper communities exist. These vents and communities have received much less attention than those associated with hydrothermal vents at spreading ridges, partly because they are so hard to find. Chemosynthetic communities are located in a variety of fore arc settings: above over-pressured sediments in accretionary prisms, where fluids are expelled through mud volcanoes or ridges (Barbados, Nankai, and Cascadia); from erosive margins along faults and serpentinite mud volcanoes (Marianas) 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).

Further Reading

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Relevant Website

https://www.youtube.com/watch?v=6wJBOk9xjto&t=17s—Plate Tectonic Basics 1.