

EARTH PROCESSES

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AU:1 Ocean Trenches

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Introduction

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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. The asymmetry of trenches reflects a deeper phenomenon: as one plate bends down to return to the mantle, the other plate strains to fill the growing void. The depths of trenches are governed by many things, most importantly sediment flux but also the age of the downgoing lithosphere, the convergence rate, intermediate slab dip, and even the width of the sinking plate. Trenches are sites where fluids are 'squeezed' out of the subducted sediments and a newly recognized biosphere thrives.

Early Years of Study

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Trenches are the most spectacular morphological features on the Earth's solid surface, but 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 between the continents in the late nineteenth and early twentieth centuries. The elongated bathymetric expression of trenches was not recognized early, and the term 'trench' does not appear in Murray and Hjort's classic oceanography overview. Instead they used the term 'deep' to describe the deepest parts of the ocean, 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 defining an important boundary, so it is no surprise that the term 'trench' was used to describe natural features in the early 1920s. The term was first used in a geological context by Scofield two years

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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 to describe a marked elongate depression of the seafloor.

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During the 1920s and 1930s, Vening Meinesz developed a unique gravimeter that could measure gravity in the stable environment of a submarine and used it to measure gravity over ocean trenches. His gravity 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 analogous model using a pair of rotating drums. The war in the Pacific led to great improvements in bathymetry, especially in the western and northern Pacific, and the linear nature of the trenches 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 and sampled, and their greatest depths were 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 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.

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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 boundary: divergent (where lithosphere and oceanic crust are created at mid-ocean ridges (**Earth Processes: Mid-ocean ridges** (00149)), convergent (where one lithospheric plate sinks beneath another and returns to the mantle (**Earth Processes: Convergent Plate Boundaries: Accretionary Wedges** (00456))), and transform (where two lithospheric plates slide past each other). Trenches are the spectacular and distinctive morphological features of convergent plate boundaries (**Figure 1**). Plates move together along convergent plate boundaries at rates that vary from a few millimetres to ten or more centimetres per year. Trenches form where oceanic lithosphere is subducted at a convergent plate margin,

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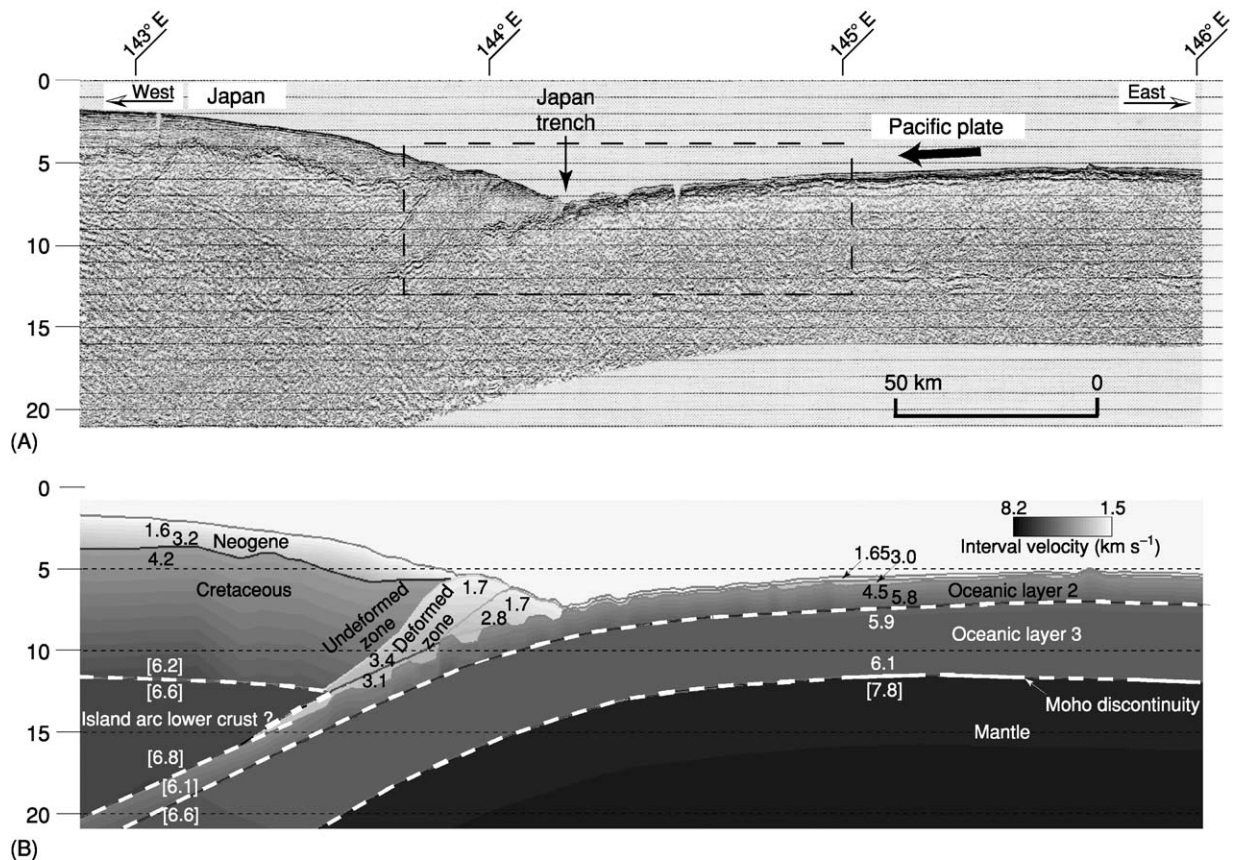


Figure 1 Profile across a typical trench (the Japan Trench near 39° N). (A) Seismic-reflection image (pre-stack depth migration) and (B) interpretation, including crustal units and seismic velocities (in km s⁻¹). Dashed box in (A) indicates the region shown in detail in **Figure 3A**. Vertical exaggeration in (B) is four times. The model is shaded according to the seismic velocities, and selected digital values are also shown. Modified from Tsuru, Park, Takahashi, *et al.* Tectonic features of the Japan Trench convergent margin off Sanriku, northeastern Japan, revealed by multichannel seismic reflection data. *Journal of Geophysical Research* 105: 16 403–16 413.

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presently at a global rate of about a tenth of a square metre 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 they are sometimes called ‘Pacific-type’ margins – but they also occur in the eastern Indian Ocean, and there are relatively short convergent-margin segments in the Atlantic and Indian Oceans and in the Mediterranean Sea (**Figure 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, where continental lithosphere 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 collision zones; these include sediment-filled foredeeps, referred to as peripheral foreland basins, such as that which the Ganges and Tigris–Euphrates rivers flow along.

Morphological Expression

Trenches are the centrepieces of the distinctive physiography of a convergent plate margin. Transects across trenches yield asymmetric profiles, with relatively gentle (*ca.* 5°) outer (seaward) slopes and steeper (*ca.* 10–16°) inner (landward) slopes. This asymmetry is due to the fact that the outer slope is defined by the

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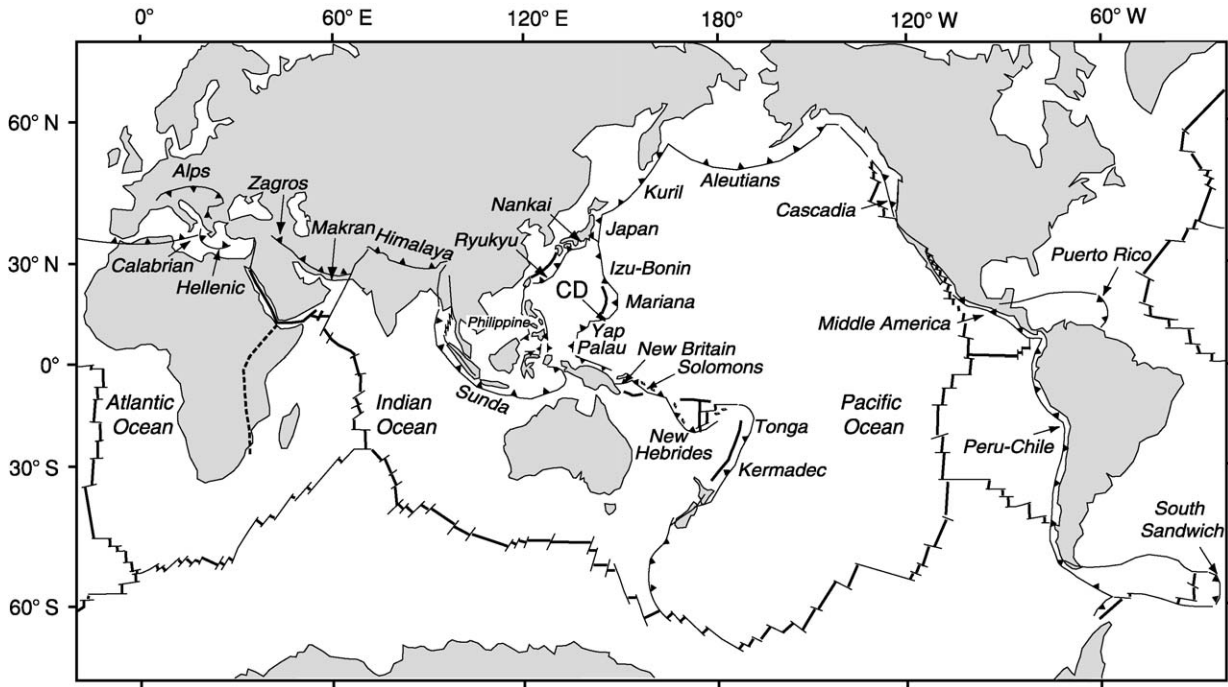


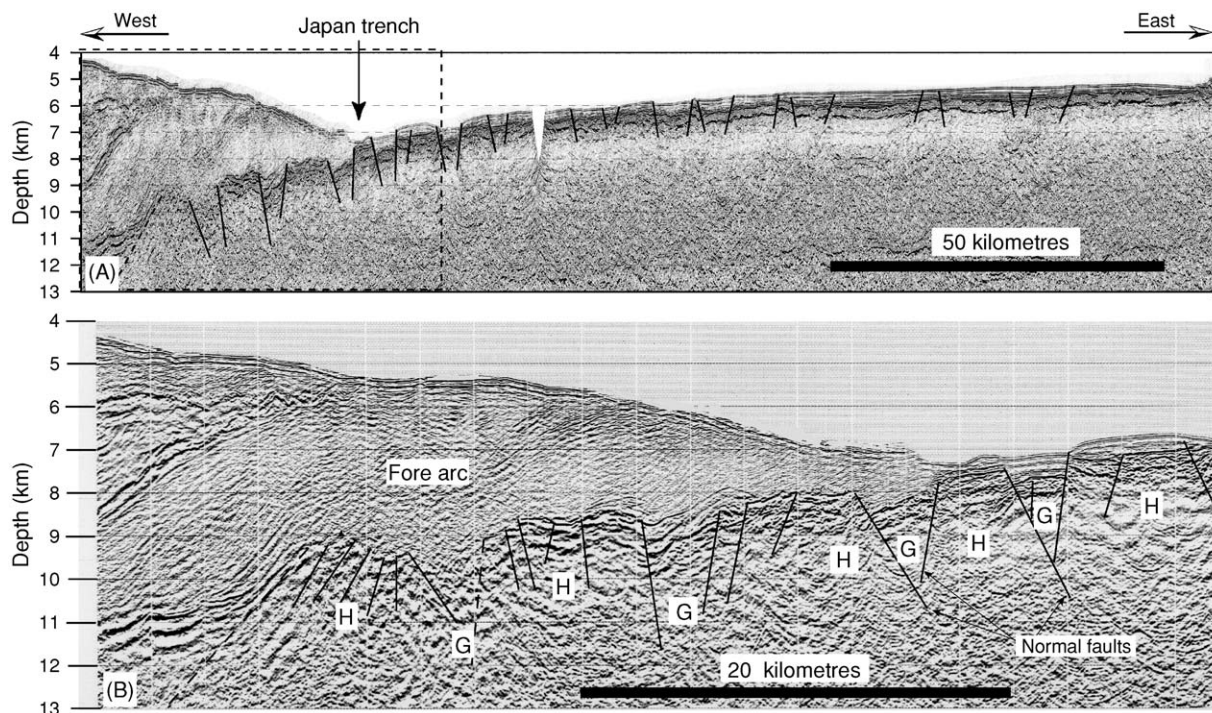
Figure 2 Locations of the world's major trenches and collision zones. CD is the Challenger Deep.

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	9 780	No
Kuril	9 550	No
North New Hebrides	9 175	No
New Britain	8 940	No
Yap	8 650	No
Puerto Rico	8 605	No
South Sandwich	8 325	No
South Solomons	8 322	No
Peru-Chile	8 170	No
Japan	8 130	No
Palau	8 055	No
Aleutians	7 680	Yes
Ryukyu	7 460	Yes
Sunda	7 125	Yes
Middle America	6 660	No
Hellenic	5 092	Yes
Nankai	4 900	Yes
Calabrian	4 200	Yes, no morphological trench
Makran	3 200	Yes, no morphological trench
Cascadia	3 136	Yes, no morphological trench

top of the downgoing plate, which must bend as it begins its descent. The great thickness of the lithosphere requires that this bending be gentle. 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 (Figure 3). 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 along the base of the trench. The overriding plate generally contains a magmatic arc and a fore arc. 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. The fore arc lies between the trench and the magmatic arc. Fore arcs have the lowest heat flow of any place on 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 fore arc. The fore arc consists of igneous and metamorphic basement, 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



#0015 **Figure 3** Horst (H) and graben (G) structures with normal faults associated with the subduction of the Pacific plate in 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, Park, Takahashi, *et al.* Tectonic features of the Japan Trench convergent margin off Sanriku, northeastern Japan, revealed by multichannel seismic reflection data. *Journal of Geophysical Research* 105: 16 403–16 413.

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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.

p0040 The asymmetric profile across a trench reflects fundamental differences in materials and tectonic evolution. The outer trench wall and outer swell are composed of seafloor, 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 trench. In contrast, the inner trench wall is deformed by plate interactions

throughout the life of the convergent margin. The fore arc is continuously subjected to 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 igneous rocks instead of 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 exerts a first-order control on trench morphology. Active accretionary prisms are especially common in trenches that are located near continents where large rivers or glaciers reach the sea. These filled trenches cause some confusion because they are tectonically indistinguishable from other convergent margins but lack the bathymetric expression of a trench. The Cascadia margin off the north-west coast of the USA is a filled trench, the result of sediments delivered by the rivers of the north-western USA and south-west Canada. The Lesser Antilles convergent margin shows the importance of proximity to sediment sources for trench morphology. In the south, near

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the mouth of the Orinoco River, there is no morphological trench, and the fore arc and the accretionary prism have a total width of almost 500 km. 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 only 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, 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 coastal rivers of Alaska) to a deep trench with a narrow fore arc in the west (near 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 turbidite deposits along a trench can be supplied by down-axis transport of sediments that enter the trench 1000–2000 km away, as is found in the Peru–Chile Trench south of Valparaiso and in the Aleutian Trench. Convergence rate can also be important in controlling trench depth, especially for trenches near continents, because slow convergence may mean that the capacity of the convergent margin to dispose of sediment is exceeded.

Thus, trench morphology can be expected to evolve continuously 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 shoals. 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.

Accretionary Prisms and Sediment Transport

Accretionary prisms grow by frontal accretion – where 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 décollement. 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 being found in 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 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 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 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 a series of 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 will then be able to 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 USA spill over where the Cascadia trench would be and reach the Juan de Fuca spreading ridge several hundred kilometres 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 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 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 relatively weak accretionary prism with a shallowly tapered geometry, whereas high permeability and slow convergence lead to lower pore pressures, stronger prisms, and steeper geometry.

p0070 The Hellenic Trench system is unusual because its convergent margin subducts evaporites. The slope of the southern flank of the Mediterranean Ridge (its accretionary prism) is low, about 1° , 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 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 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.

hydrates has contributed to global warming in the past and will probably do so in the future.

Chemolithoautotrophic communities thrive where fluids seep out of the fore arc. Cold seep communities have been discovered on inner trench slopes in the western Pacific, 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 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. They have received much less attention than the chemolithoautotrophic communities associated with hydrothermal vents. Chemolithoautotrophic 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 sulphide in the fluids escaping from the seafloor are the principal energy sources for chemolithoautotrophy.

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s0035 Water and Biosphere

p0075 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 upper lithosphere and the sediments of the subducting plate. The average fore arc is underlain by a solid volume of oceanic sediment that is 400 m thick. This sediment enters the trench with 50–60% porosity. The sediment is progressively squeezed as it is subducted, reducing void space and forcing fluids out along the décollement and up into the overlying fore arc, which may or may not have an accretionary prism. Sediments accreted to the fore arc are another source of fluids. Water is also bound in hydrous minerals, especially clays and opal. 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 is another source of fluid 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 may take the form of mud volcanoes or seeps and are often associated with chemolithoautotrophic communities. Fluids liberated in the shallowest parts of the subduction zone may also escape along the plate boundary but have rarely been observed to drain 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 (clathrate) in the fore arc. Gas hydrates are a potential energy source and can rapidly break down. The destabilization of gas

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. Primitive arc systems are those that 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 the crust of the fore arcs, including basalt, gabbro, and serpentinized mantle peridotite. These exposures allow easy access to materials from the lower oceanic crust and upper mantle, and 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 during the initiation of subduction, and this setting favours 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.

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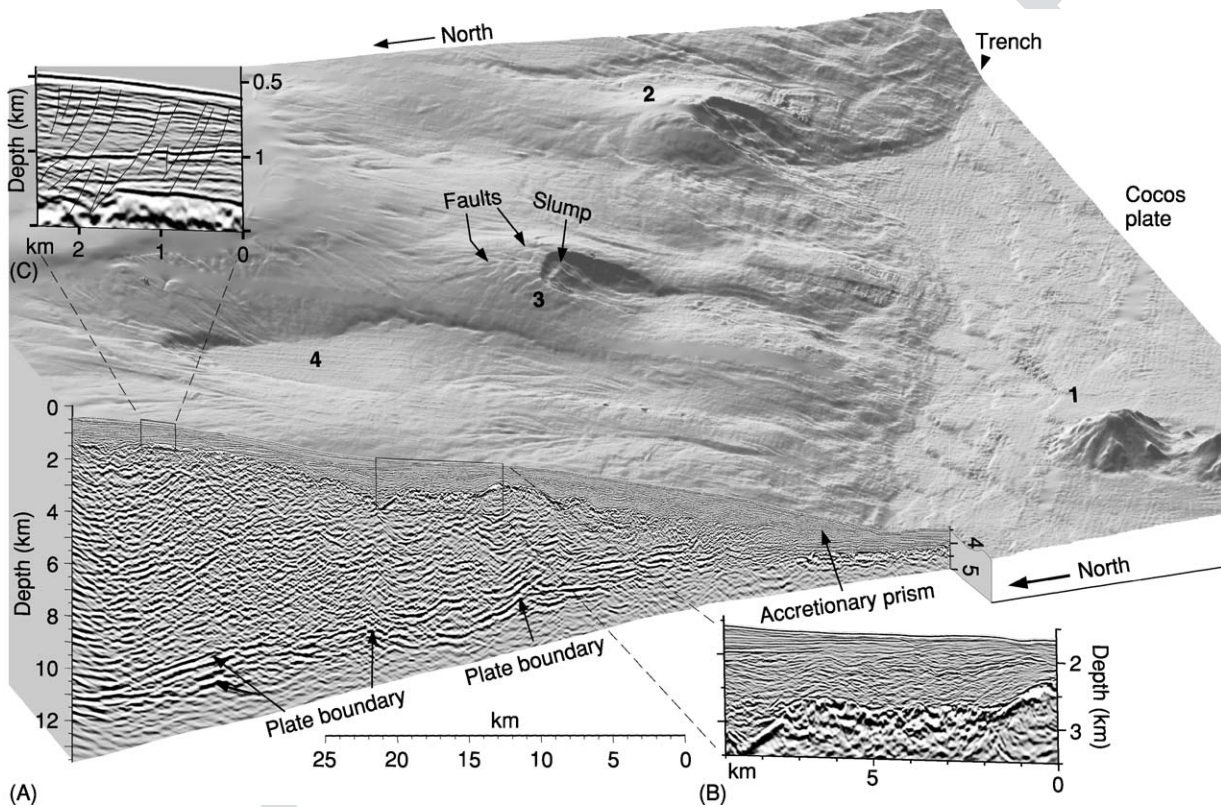
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The igneous basement of a nonaccretionary fore arc may be continuously exposed by subduction erosion. This transfers material from the fore arc to the subducting plate and can take the form of frontal erosion or basal erosion. Frontal erosion is most active in the wake of seamounts being subducted beneath the fore arc. Subduction of large edifices (seamount tunneling) oversteepens the fore arc, causing mass failures that carry debris towards and ultimately into the trench (Figure 4). This debris may be deposited in graben of the downgoing 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 diminishes.

Nonaccretionary fore arcs may also be sites of serpentinite mud volcanism. Serpentinite mud volcanoes form where fluids released from the downgoing 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 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 non-accretionary margins such as

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Figure 4 Downgoing 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 yr^{-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. The collision has caused oversteepening, 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. Oversteepening 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 (Figure 3B) in the downgoing 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.

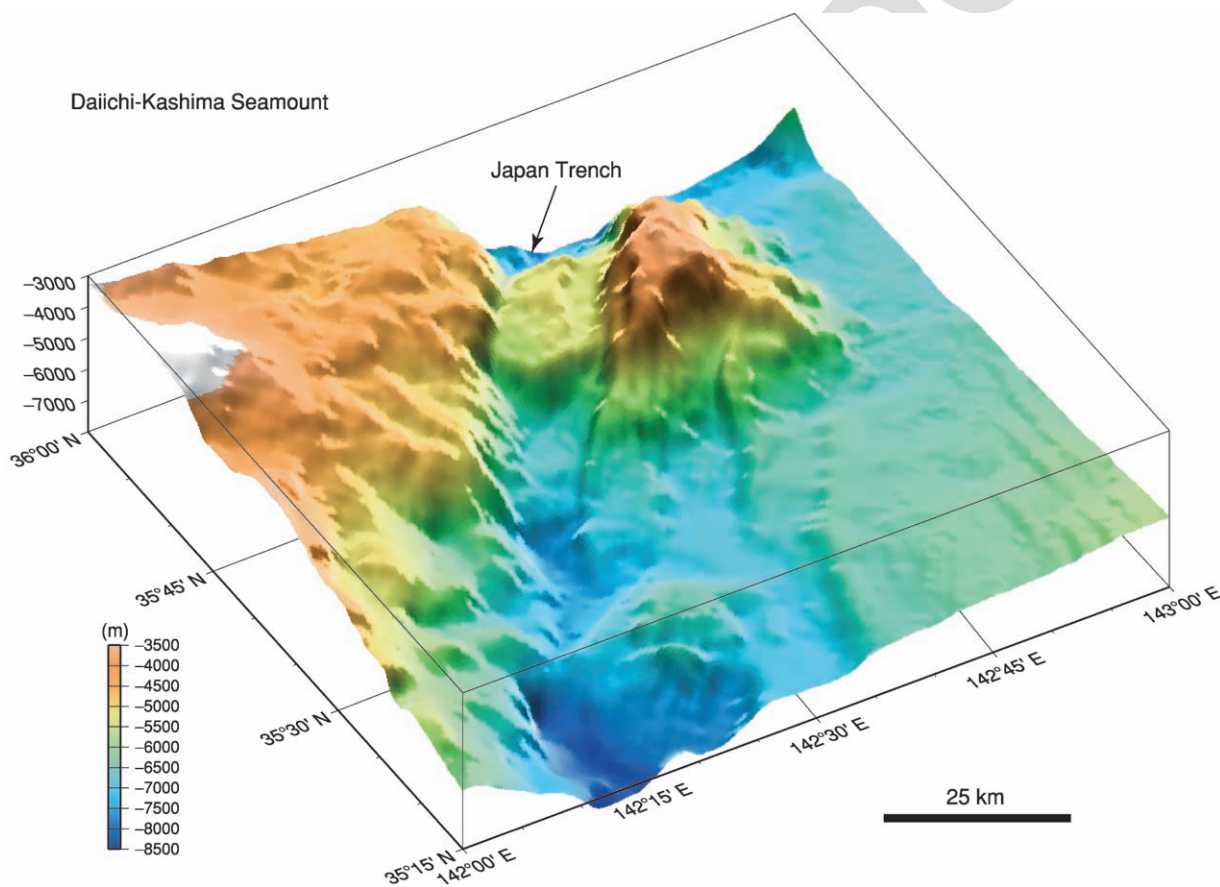
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the Marianas, where they thrive on vents associated with serpentinite mud volcanoes.

s0045 Outer Trench Swell

p0100 The outer rise is where the descending plate begins to flex and fault as it approaches the subduction zone. Here, the lithosphere is 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 km 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 downgoing plate results in a horst-and-graben structure, which allows sediment that reaches the trench to be deposited in graben and carried downward. This faulting also breaks up seamounts as they approach the trench (Figure 5). The mechanism of frontal erosion may operate through the combined effects of seamount tunnelling, mass wasting and transport to the trench, deposition in a graben on the downgoing plate, and descent into the mantle.



Color
Image

f0025 **Figure 5** Bathymetric profile showing normal faulting affecting the Daiichi-Kashima 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° (azimuth) and 30° (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.

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Controls on Trench Depth

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There are several factors that control the depths of trenches. The most important is the supply of sediment, which may fill the trench so that there is no bathymetric expression. It is therefore not surprising that the deepest trenches are all nonaccretionary. Table 1 shows that all trenches deeper than 8000 m are nonaccretionary. In contrast, all trenches with growing accretionary prisms are shallower than 8000 m. A second factor controlling 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 controls the minimum depth from which the seafloor begins its descent. 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.

See Also

Geology: Tools of investigation: Gravity (00108); Seismic (00110). **Earth Processes:** Mid-ocean ridges (00149); Mantle (00122); Plate tectonics: Overview (00127); Convergent Plate Boundaries: Accretionary Wedges (00456); Crust (00460).

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