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ACCRETIONARY PRISMS

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Introduction

Subduction of oceanic lithosphere along a convergent plate boundary transfers sediments and rocks from the underthrust lithosphere to the overriding plate, producing an accretionary prism. Accretionary prisms develop beneath the inner slopes of the deep ocean trenches that typically mark convergent plate boundaries. The subduction process destabilizes the mantle after about 100 km of underthrusting beneath the upper plate to produce magmas of the volcanic arcs that virtually always occur along convergent plate boundaries (**Figure 1**). As accretionary prisms grow through addition of oceanic material, they become coastal mountain ranges. When a continent collides with a subduction zone, the intervening accretionary prism becomes incorporated into the resultant great mountain belts. Thus, rocks in accretionary prisms sometimes are the only record of ancient vanished ocean basins. Accretionary prisms typically form on the upper plate of subduction zone thrust faults, which host the world's largest earthquakes. Because accretionary prisms incorporate soft sediments at high rates of deformation, they produce some of the world's most complexly deformed rocks, commonly called melanges. Sediments offscraped to form accretionary prisms are like sponges that yield fluids as they are squeezed and deformed during prism growth. The fluids affect the mechanics of faults; chemically dissolve, transfer, and deposit material; and support chemosynthetic biological communities. The shape of the accretionary prism is mechanically controlled by the strength of the material comprising the accretionary prism and its internal fluid pressure. At slightly fewer than half of modern convergent plate boundaries, accretionary prisms are not currently

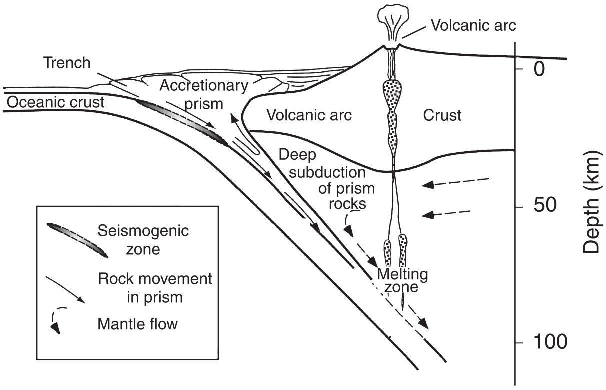

Figure 1 The setting of an accretionary prism in a generalized cross-section of a convergent plate boundary. Although the accretionary prism builds up primarily by scraping off material riding on the oceanic crust, some portions are deeply underthrust and flow back to the surface, while other portions are deeply subducted and participate in the formation of the igneous rocks of the volcanic arc.

forming and the incoming sediment and rock is deeply underthrust. Sometimes the accretionary process is reversed and the upper plates of subduction zones are mechanically abraded or eroded by the underthrust plate, causing subsidence and contraction of the overriding plate.

Origin and Variation of Materials Incorporated in Accretionary Prisms

Accretionary prisms vary in composition depending on the type of material on the subducting oceanic plate. The ideal sequence incoming to a subduction zone consists of oceanic basaltic igneous rocks covered by oceanic or pelagic sediments that change up-section to more rapidly deposited, continentally derived sandstones, shales, and even conglomerates. At a subduction zone starved for sediments, material available for accretionary prism construction may be the igneous rocks of the oceanic plate with thin overlying sedimentary deposits. Alternatively, incoming plates may be sediment-dominated and covered with a kilometers-thick sequence of deposits that are available for accretion. The resulting accretionary prisms may consist of slices of oceanic igneous rocks with minor amounts of interspersed sediments to thick thrust sheets of continentally derived clastic rocks. The Marianas subduction zone of the western Pacific is an example of the former, whereas the Cascadia subduction zone off the northwestern United States and Canada is an example of the latter. Because the sediment-dominated accretionary prisms (**Figure 2**) are more voluminous, they tend to be well recognized in the stratigraphic record, for example, parts of the Franciscan Complex of California. Sediment-starved accretionary prisms are thinner and typically dominated by basaltic and ultramafic igneous rocks. They are harder to recognize in the ancient stratigraphic record. Factors controlling the amount of sediment and type of sediment available for accretion include the age of the oceanic plate, the types and rates of sediments being deposited along the transport path of the oceanic plate to the subduction zone, and rate of travel or residence time of any plate in a particular sedimentary environment.

Solid Material Transfer in Accretionary Prisms

Sediments and rocks incoming to a subduction zone may be (1) offscraped as a series of thrust sheets at the frontal edge of the accretionary prism; (2) underplated or emplaced at depth along the base of the upper lithospheric plate; or (3) underthrust to great depths to participate in production of volcanic arc magmas or ultimately to be carried into the earth's mantle (**Figures 1** and **2**). In the zone of offscraping, incoming materials are typically accreted as a series of imbricate thrust sheets extending from the surface to a basal detachment fault or decollement, beneath which all other material is underthrust. The decollement forms in a layer weaker than the adjacent sediment. With continued

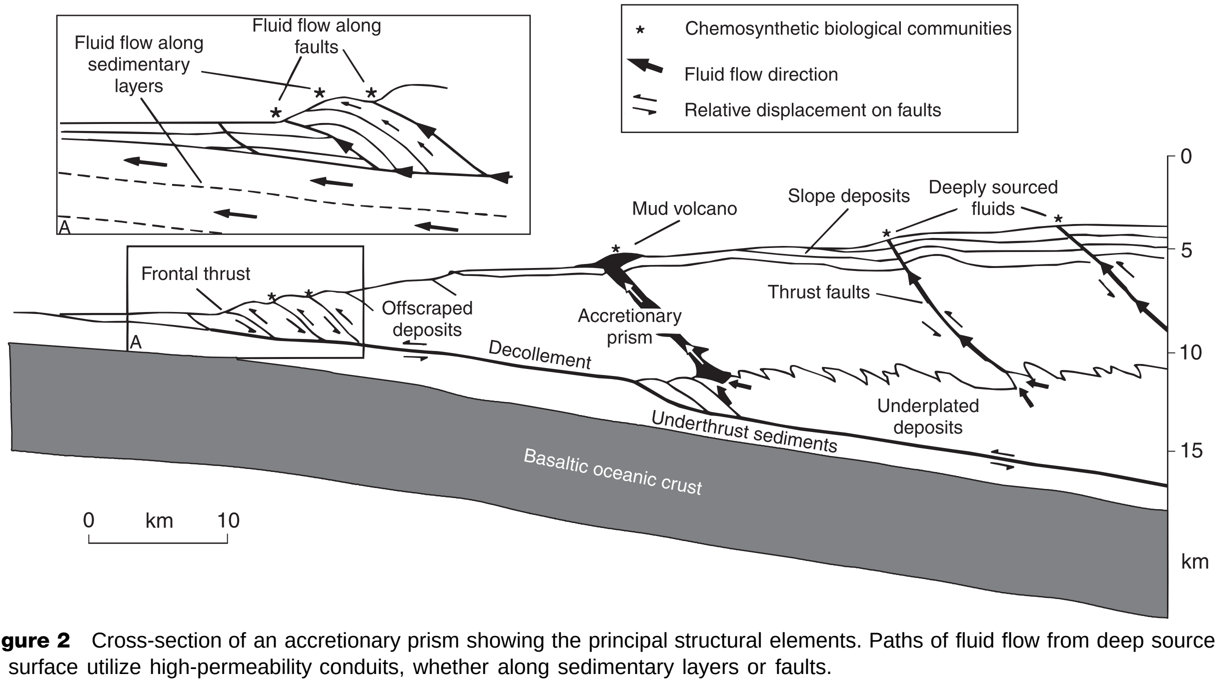

Figure 2 Cross-section of an accretionary prism showing the principal structural elements. Paths of fluid flow from deep sources to surface utilize high-permeability conduits, whether along sedimentary layers or faults.

underthrusting, the weak layer may become stronger because of mineralogical changes or decreasing fluid pressure and step or migrate down through the underthrust plate. This down-stepping process underplates fault-bounded rock packages to the overlying plate (**Figure 2**).

The surfaces of some accretionary prisms and non-accretionary convergent margins (see below) are marked by volcanoes of fluidized mud or serpentine (**Figure 2**). The fluidized mud and serpentine rise through the upper plate of the convergent margin because these materials are of lower density than the surrounding sediments and rocks. Deep underthrusting of mud and the associated production of natural gas or oil produces mud volcanoes. Serpentine, a low-density rock, is formed by addition of water from underthrust sediments or rocks to mantle rocks. In both cases the low-density rock occurs beneath higher-density rock and buoyancy forces drive the low-density material to the surface.

Incoming sediment that is not offscraped at the front of or underplated beneath the main part of the accretionary prism continues to be underthrust. This underthrust sediment may be underplated beneath volcanic arc basement rocks at any point until it reaches the melting zone (**Figure 1**). Short-lived radioactive isotopes and other chemical tracers in volcanic rocks indicate that sediments less than several million years old are underthrust to the depths of melting (75–100 km) beneath the volcanic arc. Residual material from the melting zone may be deeply underthrust into the earth's mantle.

Continuing sediment accumulation occurs on top of the growing accretionary prism, forming an apron of slope deposits. Locally erosion may remove material from the accretionary prism, redepositing it on the oceanic plate for recycling back into the accretionary prism. In addition to the thrust faults and the decollement associated with accretionary processes, accretionary prisms are cut by thrust, normal, and strike-slip faults that form as the prism adjusts its shape in response to its continuing growth (see Mechanics below).

Accretionary prisms include some of the most complexly deformed and puzzling rocks on the earth. Melanges or 'mixed rocks' and stratally disrupted rocks are included in this category. These rocks are marked by not only stratal discontinuity (**Figure 3A**) but by mixing of incompatible sedimentary and metamorphic environments (**Figure 3B**). These intricately deformed rocks form from hard igneous rocks and sediments that are partially consolidated and lithified in a high-strain and high-strain-rate environment. The extreme variation in strength between the hard rocks and soft sediments and the high strain deformation results in a heterogeneously deformed rock mass. Various return flow processes at depth (**Figure 1**), faulting, and erosion and redeposition of previously accreted rocks contribute to the mixing of rocks derived from differing sedimentary and metamorphic environments (**Figure 3B**).

Accretionary prisms include metamorphic rocks formed under high-pressure, low-temperature conditions. These rocks, called blueschists (**Figure 4**), are diagnostic of this subduction zone metamorphic environment. The high-pressure–low-temperature condition is caused by the rapid underthrusting of old, cold oceanic plates. Burial rates for underthrust rocks at subduction zones exceed 20 km My^{-1}. The material is buried and returned to shallow depths more rapidly than it can be warmed by conduction from adjacent warmer parts of the earth. Thus,

(A)

(B)

Figure 3 Melanges. (A) Dismembered layers of light-colored sandstone in shale matrix. This type of deformation is typically developed along thrust faults with substantial displacement or along the decollement. (B) Melange consisting of block of basalt with overlying pelagic or open oceanic limestone included in shale matrix. Limestone and shale are incompatible depositional environments that are mixed together in the deformational environment of the accretionary prism. Both photographs are from the 60–65 My old accretionary prism of the Kodiak Islands, Alaska.

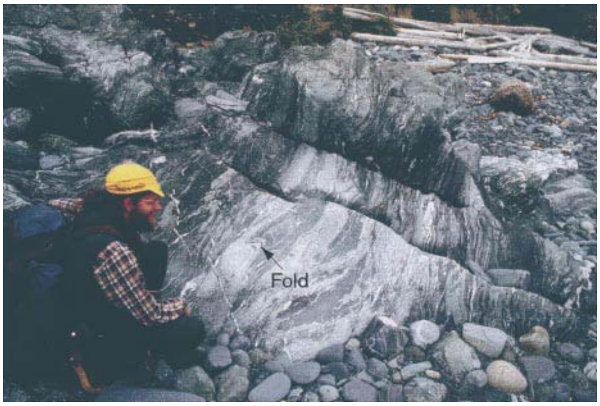

Figure 4 Blueschist metamorphic rock from an accretionary prism, indicating high pressures and low temperatures and showing ductile or plastic deformation (fold). This rock was metamorphosed about 200 My ago and occurs in the accretionary prism of the Kodiak Islands of Alaska.

the low-temperature–high-pressure conditions of the subduction system are imprinted on the rocks and preserved by rapid uplift. The lowest average geothermal gradients through accretionary prisms are less than 10°C km^{-1}, or about a third of the typical gradient through continents. Thermal gradients beneath accretionary prisms may be much higher where young, hot oceanic crust is being subducted. In these cases blueschists are not formed but are replaced by metamorphic rocks characteristic of higher temperature regimes (greenschist and amphibolite).

Overall, the material transfer in accretionary prisms is similar to that in thrust belts in overall form, fault geometry, and mechanics. Thrust belts on land tend to deform more consolidated and lithified sedimentary rocks at slower rates than occur at oceanic convergence zones. Therefore, in thrust belts, both the structural complexity and the effects due to fluid expulsion are less pronounced than in accretionary prisms. A good example of a thrust belt is the Canadian Rocky Mountains just west of Calgary Alberta.

Fluids In and Out of Accretionary Prisms

Accretionary prisms are like sponges, saturated as they begin to form but squeezed virtually dry as their rocks reach maximum depths of burial. About 40% of the sediment section entering the world's subduction zones is composed of water in pore spaces. Additional water resides in pores in the igneous rocks of the crust and is bound to minerals both in the sediments and the oceanic crust.

The rapid burial of incoming sediments and rocks due to incorporation into and underthrusting beneath the accretionary prism increases stress on the rock framework and raises fluid pressure (the sponge is squeezed). Burial also increases temperature, which releases water bound in minerals and converts sedimentary organic matter to oil and natural gas. Sediment microrganisms may also produce natural gas from organic matter. By 150°C, the minerals are substantially dehydrated and most of the organic matter has been converted to hydrocarbons. By about 4 km of burial, the pore volume of sedimentary rocks in the accretionary prism is reduced by about 90%. The high fluid pressure drives fluids out of the accretionary prism through sediment pores and fractures and along faults (**Figure 2**).

Fluid migration out of the accretionary prism affects everything from surface biology, to large-scale structural features, to the fabric of prism rocks. The high fluid pressures that result from the fluid generation process weaken the rocks by reducing the contact stresses on mineral grains and fault surfaces, thereby reducing friction. This pressure-related weakening facilitates long-distance lateral transport on thrust faults (**Figure 2**), such as the decollement, and also controls the shape of the accretionary prism (see Mechanics). At temperatures from 100ºC and up, rocks dissolve and re-precipitate (undergo pressure solution) with formation of preferred orientations of minerals and solution seams (fabrics) that record stress orientations. Rocks such as slates commonly form through this process. The constituents of the dissolved carbonate and silicate minerals may be locally precipitated or transported with the fluids and precipitated elsewhere as veins and cements that are common in prism rocks. The fluid-mediated processes of dissolution, transport, and precipitation significantly change the physical properties of the accretionary prism and ultimately affect how it deforms. Fluids expulsed from the surface of accretionary prisms contain dissolved methane and hydrogen sulfide, which are utilized by chemosynthetic organisms that are the basis for cold seep biological communities on the seafloor. In the subsurface, microorganisms both produce and consume various fluid-borne chemical constituents, modifying the physical properties and composition of the host sediments or rocks.

Because fluids alter the physical properties of sediment and rock, they affect the seismic reflection images of the prism interior. Fluid-enriched zones along faults reduce velocity and density and produce strong reflections in the seismic images. Methane near the surface of the accretionary prism freezes to form methane hydrate. Progressively deeper in the prism, the methane hydrate is unstable and is transformed back to free methane. Minor accumulations of free methane gas below the hydrate produce a large change in rock physical properties that is seen as a prominent bottom-simulating reflection in seismic images.

Seismogenesis and Accretionary Prisms

Subduction zone thrust faults produce the largest earthquakes on the Earth because the plate-boundary thrust is in a zone of high strain rate and is inclined shallowly. The shallow inclination provides a large surface area, or seismogenic zone, subject to brittle failure and the production of earthquakes (**Figure 1**). In contrast, more steeply inclined faults, such as the San Andreas Fault, transition down-dip from the region of brittle or seismogenic deformation into the realm of ductile deformation over a shorter distance, therefore limiting the area capable of producing an earthquake. The low thermal gradients characteristic of many subduction zones also extends the brittle–ductile transition to greater depths than in other plate boundary settings and increases the area subject to catastrophic seismogenic failure.

Commonly, the seismogenic zone earthquakes occur beneath accretionary prisms, such as the great Alaskan earthquake of 1964 (magnitude 9.2). The ability of accretionary prisms to build up enough elastic strain to be released in a sudden earthquake event testifies to strength developed during the evolution from soft sediments to hard rocks. In addition to becoming strong and rigid, the materials of the accretionary prism must evolve to fail in a 'velocity weakening' manner, such that there is an acceleration of slip along the fault surface. This accelerating slip produces a discrete seismic event, as opposed to a decelerating creep event that would not produce an earthquake.

Mechanics

In 1983 Davis, Dahlen, and Suppe articulated and formalized the mechanics of accretionary prisms in the widely accepted 'critical Coulomb wedge theory' (**Figure 5**). Virtually all accretionary prisms approximate a wedge in shape, being thinner on the oceanic side and thicker toward the associated volcanic arc. According to Davis *et al.* accretionary wedges resemble piles of dirt (prism materials) being pushed forward by bulldozer (the volcanic arc basement). The stresses driving the prism seaward are that of the arc basement pushing the wedge from the rear and a seaward-directed lateral stress due to unequal gravitational stress resulting from the wedge shape. The latter is similar to the stress causing a pile of sand to fail if it is oversteepened. These driving stresses are resisted by a shear stress along the base of the wedge controlled by the frictional strength of the material, which varies with overburden stress, the fluid pressure along the base, and the material properties. Additionally, the component of the overburden stress acting parallel to the decollement must be overcome to, in essence, lift the prism up the decollement. The wedge is just as thick as it can be in order to move forward; that is, it is at its threshold of failure determined by its frictional strength and internal fluid pressure. If the wedge grows at its leading edge, the area of the decollement resisting motion increases and the prism must thicken at the rear in order to increase the area to which the driving stresses in the arc basement can be applied.

Wedge theory has been largely successful in explaining the shape of accretionary prisms and the observations of fluid pressure, though the latter are not numerous. Because fluid pressure can counteract normal stresses along the decollement, it is a prime parameter controlling the mechanics of accretionary prisms. The generally high fluid pressure along the

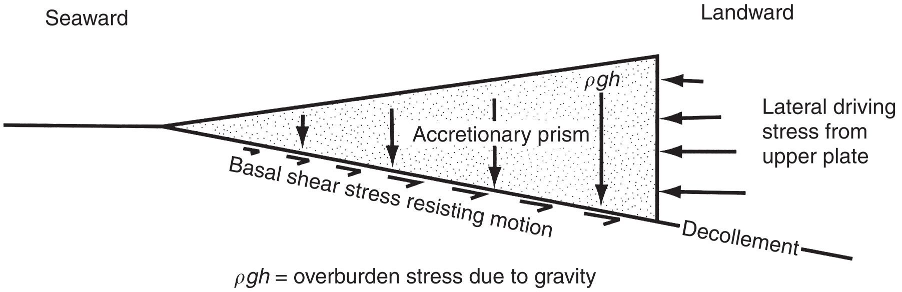

Figure 5 Diagram showing stresses that control motion of accretionary prisms (and thrust belts). These stresses, integrated over the areas where they act, form a force balance. Forces driving the prism seaward (a push from the rear and internal gravitational forces) are offset by resisting forces (primarily frictional forces and gravitational forces acting along the base of the decollement).

decollement sharply decreases the frictional resistance there, allowing narrowly tapered prisms to be mechanically stable. The necessity to thicken the landward portion of the prism to keep a stable wedge taper can explain much of the faulting observed in the landward parts of prisms (**Figure 2**). Other mechanical conceptualizations of wedges utilize differing material properties; however, the Coulomb wedge theory, dependent on basic frictional behavior, is most successful at depths up to 10–20 km.

Non-accretionary Convergent Plate Boundaries

According to a compilation by Von Huene and Scholl, somewhat more than half of the world's convergent plate boundaries are forming accretionary prisms now. The remainder of convergent plate boundaries have inner trench slopes underlain by older accretionary prisms or igneous and metamorphic rocks of the continental crustal or volcanic arc origin (**Figure 6**). Some are underlain by igneous and metamorphic rocks of uncertain origin that may represent accreted pieces of seamounts or normal oceanic crust. Recent Ocean Drilling Program results off Costa Rica unequivocally demonstrate that virtually all of the sediment riding on the oceanic plate (Cocos Plate) is underthrust beneath the upper plate (Caribbean Plate) of the subduction zone. This process must also occur at many other convergent margins without accretionary prisms. At a number of other convergent margins, the presence of continental or volcanic arc rocks close to the trench suggests that portions of the forearc may have been tectonically eroded by underthrusting. Moreover, Ocean Drilling Program holes show that rocks currently located in deep water on inner slopes of trenches have subsided from much shallower depths. Presumably this subsidence is due to tectonic erosion of the trench inner slope by the underthrusting plate.

So, although there are accretionary prisms forming at many convergent margins, the offscraping and underplating at the front of the margin is not a constant process. Accretionary prism formation may be episodic even with continuous subduction. Tectonic erosion may occur. Gaps in the record of accretion are to be expected.

What determines whether convergent plate boundaries form accretionary prisms or tectonically erode the upper plate? The primary control is sediment supply. Where thick sequences of sediment enter the subduction zones, accretionary prisms form. Where the sedimentary sequences are thin, there is less material available to accrete and irregularities in the underthrusting oceanic plate may interact with the overthrusting plate to cause erosion. Protruding fault blocks or seamounts may tectonically abrade the lower surface of the upper plate. Also, as these high areas on the lower plate are underthrust, they may oversteepen and otherwise disturb the upper plate, causing it to fail at the surface by landsliding. The landslides accumulate in the trench, where they are underthrust. Accordingly, the front of the convergent margin is decimated and cycled to deeper levels in the earth.

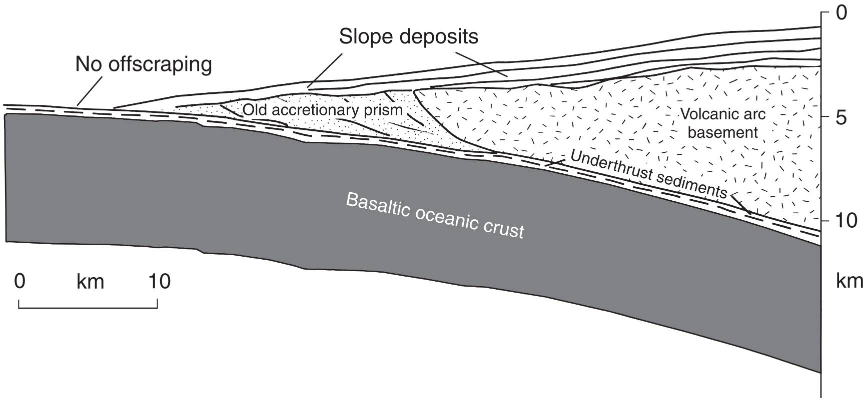

Figure 6 A convergent margin showing a range of features seen worldwide supporting nonaccretion or tectonic erosion. The absence of offscraping indicates no accretion at the front of the margin. At deeper levels, sediment may be being underplated. Locally, sediments and contained fluids are underthrust to great depths and participate in the melting process beneath the volcanic arc (see **Figure 1**). A previous accretionary prism much older than the age of incoming sediment may be being underthrust. Arc basement may be anomalously close to the trench, suggesting erosion of the upper plate. Slope deposits may be of much shallower water origin. These shallow-water deposits suggest substantial subsidence of the margin, which is commonly explained by tectonic erosion of the upper plate.

Conclusions

Accretionary prisms form at the leading edge of convergent plate boundaries by skimming-off sediments and rocks of the lower plate. In detail, the accretion process involves offscraping of rocks and sediments at the front of the prism or underplating (emplacement beneath the prism). This deformational process stacks the sediments into thick vertical piles and shortens them horizontally. Consequently, fluids are expulsed and the sediments are progressively transformed to rocks. Because the deformation in accretionary prisms is large and fast, rocks emplaced therein are often severely disrupted and mixed, forming melanges. The rapid rate of underthrusting of the lower plate may carry rocks to great depths before they can heat up, forming a characteristic type of metamorphic rock called a blueschist. The fault surface bounding the base of the accretionary prism, the decollement, is the plate boundary thrust. Because it is shallowly inclined, this fault has a large area undergoing brittle deformation and produces the largest earthquakes on the planet. Mechanically, accretionary prisms resemble a pile of dirt being pushed by a bulldozer. Prisms are pushed from the rear by the volcanic arc basement, with forward motion being resisted by frictional and gravitational forces. Accretion does not occur at the leading edge of all convergent plate boundaries. In these cases, sediments and rocks are underthrust beneath the crustal framework of the upper plate. In some cases accreted rocks have been removed from the upper plate, apparently by tectonic erosion by the lower plate. Thus, an accretionary prism may be a very discontinuous recorder of the incoming sediments and rocks at a convergent plate boundary. Sediments, rocks, and fluids not emplaced in the accretionary prism are carried to great depths and either catalyze subduction zone volcanism or are transported into the mantle.

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See also

Mid-ocean Ridge Geochemistry and Petrology. Mid-ocean Ridge Seismic Structure. Mid-ocean Ridge Tectonics, Volcanism and Geomorphology. Seismic Structure.

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