Japan in a subduction zone

Source: [http://www.glgarcs.net/intro/subduction.html](http://www.glgarcs.net/intro/subduction.html)

Volcanoes, earthquakes, and mountain building are major characteristics of the Japanese Islands in an active continental margin, which are closely related to plate subduction.

**Convergent boundary**

![Fig. 1 Plates and boundaries in the Pacific Ocean](image)

The boundaries of plates covering the surface of the Earth are classified into three: convergent, divergent, and transform types. Convergent boundaries occur where one plate subducts underneath another plate lower in density (continental or oceanic plate) or collides with another plate, not subducts, in the case that both plates are composed of continental material relatively low density. Divergent boundaries occur where new lithosphere is produced and plates move away from each other at spreading ridges. Transform boundaries occur where one plate laterally slides past another, displacing spreading ridge.

The Japanese Islands are situated in the northwestern margin of the Pacific Ocean surrounded by plate boundaries. Most of these boundaries are of the convergent type. As an oceanic plate
subducts underneath another plate, such area is called a subduction zone. Convergent boundaries are characterized by active crustal movement making geomorphological and geological structures complex, such as deformation, volcanism, earthquakes, mountain building, and metamorphism.

The active crustal movement zone surrounding the Pacific Ocean is called the circum-Pacific orogenic belt, and also known as Ring of Fire. The Japanese Islands in a subduction zone are emerged parts of volcanic island arcs, extending for about 3000 km.

**In and around Japan**

![Map in and around Japan](image)

The following island chains are located in and around Japan: four major islands (Hokkaido, Honshu, Shikoku, and Kyushu), the Kuril Islands extending to the Hokkaido, the Izu-Bonin (Ogasawara) Islands chaining southward from central Honshu, and the Nansei Islands situated to the southwestern of Kyushu. On the Pacific Ocean side, trenches run parallel to these islands: in the order from the north, the Kuril Trench, the Japan Trench, the Izu-Bonin Trench, the Nankai Trough, and the Ryukyu Trench. Short troughs, the Suruga Trough and the Sagami Trough, are situated on the west and east sides of the Izu Peninsula in central Honshu, respectively. The Suruga Trough connects with the Nankai Trough. Trenches and troughs are long, narrow submarine depressions. They are classified by depth as follows: trenches for 6000 meters or more and troughs for less than 6000 meters. (However, in this site, “trench” is mainly used as the term meaning the depressions where a plate subducts in general descriptions about subduction zones and so on.)
The Japanese Islands are in marginal areas of the Pacific Plate, the Philippine Sea Plate, the North American Plate, and the Eurasian Plate (Figure 3). A triple junction at which the Pacific, the Philippine Sea, and the North American Plates meet one another is situated off the Boso Peninsula in central Honshu (Kanto). Oceanic plates, the Pacific Plate and the Philippine Sea Plate, subduct along trenches/troughs. The Pacific Plate descends underneath the North American Plate along the Kuril Trench and the Japan Trench and underneath the Philippine Sea Plate along the Izu-Bonin Trench. The Philippine Sea Plate descends beneath the Eurasian Plate along the Suruga-Nankai Troughs and the Ryukyu Trench. The leading edge of the Pacific Plate reaches under the Eurasian Plate. Figure 4 below shows depth contours of the surfaces of the subducting Pacific Plate and Philippine Sea Plate. The lines of the Pacific Plate drawn parallel to the trenches at even intervals indicate that the leading edge dives into the mantle at a constant angle. However, each angle of the leading edge is different in the Japan Trench, the Izu-Bonin Trench, and the Kuril Trench. The slope descending from the Japan Trench is the gentlest and that from the Izu-Bonin Trench is the steepest. On the other hand, the lines of the Philippine Sea Plate are more complicated. The contours in and around the Kii Peninsula (central Honshu) take the form of an S-shape, suggesting the flexure of the leading edge. The Philippine Sea Plate subducted along the Sagami Trough is in contact with the leading edge of the Pacific Plate.

Marginal seas are defined as parts of ocean incompletely bordered by islands and peninsulas situated in the margin of continent. In island arc areas, marginal seas are expanded on basins on the back arc side (back arc basin), generally situated between island arcs and the continent. The Sea of Okhotsk, the Sea of Japan, and the East China Sea are marginal seas. The Philippine Sea is surrounded by the Philippine Islands, Taiwan, the Nansei Islands, southwest Japan, the Izu-Bonin Islands, and the Mariana Islands. This sea consists of the Shikoku Basin and the Philippine Basin, geomorphologically divided from the northwestern Pacific Basin. Although the Philippine Sea corresponds to the ocean side (forearc side) of the
Southwest Japan Arc and the Ryukyu Arc, it is also a marginal sea (backarc side) of the Izu-Bonin Arc and the Mariana Arc. (See Figure 5 for “forearc” and “backarc”, or the page of Division of island arcs)

**Arc-trench system**

![Arc-trench system](image)

In a subduction zone, plate subduction forms a trench and uplift area parallel to the trench and causes igneous activity and earthquakes. Such uplift area is called a volcanic island arc or island arc because it is a curved chain of islands and volcanoes. Volcanic arcs formed on the edge of continent without marginal seas are continental margin arcs.

The arrangement of major landforms, distribution of volcanoes, and geotectonic units of southwest Japan are parallel to trenches off the Japanese Islands. Plate subduction along trenches is responsible for these features, and island arcs and trenches, hence, can be regarded as an arc-trench system. It is mainly characterized by the following: (1) major landform arrangement, ocean–trench–island arc–marginal sea (backarc basin)–continent, (2) igneous activity, (3) earthquakes occurring at depths of ≥70 km in addition to shallow-focus earthquakes, and (4) accretionary prisms and metamorphic rocks produced by plate subducting.

Five island arcs are located in and around Japan: in the order from the north, the Kuril, the Northeast Japan, the Izu-Bonin, the Southwest Japan, and the Ryukyu Arcs (Figure 2). The Kuril Arc collides with the Northeast Japan Arc in central Hokkaido. The Northeast Japan Arc meets the Southwest Japan Arc in central Honshu, and the Izu-Bonin Arc collides with these two arcs. The Southwest Japan Arc meets the Ryukyu Arc in central Kyushu. In these areas called the arc-arc collision zone, the directions of the island chains change and geomorphological and geological structures are complicated.

Each island arc is accompanied with a trench in parallel: Kuril Arc–Kuril Trench, Northeast Japan Arc–Japan Trench, Izu-Bonin Arc–Izu-Bonin Trench, Southwest Japan Arc–Nankai
Trough, and Ryukyu Arc–Ryukyu Trench. These trenches are divided into two series. The first series is the line of the Kuril, the Japan, and the Izu-Bonin Trenches, and the second is the line of the Nankai Trough and the Ryukyu Trench. The arc-trench system in Japan, therefore, is classified into two systems: the eastern Japan arc system (the Kuril, the Northeast Japan, and the Izu-Bonin Arcs) and the western Japan arc system (the Southwest Japan and the Ryukyu Arcs). Tectonism and volcanism in the eastern Japan arc system and in the western Japan arc system are mainly regulated by the Pacific Plate movement and the Philippine Sea Plate movement, respectively.

**Igneous activity**

Igneous activity resulting from plate subduction plays an important role in forming island arcs. Magma produced under island arcs form felsic plutonic rocks (granite), some of which erupts on the surface to make volcanoes. Large scale formation of granites develops the crust of island arc. See the chapter “Continental crust and development of island arcs” and the section "Volcanoes" for the details of Japanese volcanoes.

**Earthquakes**

![Distribution of earthquake focuses](image)

Earthquakes very often occur in borders between plates. In Japan, over 1300 felt earthquakes were observed in 2010, but more than 2000 earthquakes were felt in some years. The M≥5 aftershock frequency of M 9 earthquake in eastern Japan in 2011 is over 400 two weeks after the main shock.

In areas of plate margins, the crust is stressed by plate movement. The rocks are broken and energy is released when the stress exceeds their strength. The rupture generally occurs along faults, which are considered seismic sources. Therefore, the rapid slip of rocks along a fault results in an earthquake. Volcanic activity also causes earthquakes. There are principally three types of fault motion: normal dip-slip, reverse dip-slip, and strike-slip (left or right).
Fault movements may include a component of strike-slip and dip-slip (see also "Neodani fault"). For the magnitude 9.0 eastern Japan earthquake in 2011, the type of earthquake source fault is the reverse fault, the size of fault is about 450 km long and 200 km wide, the fault slippage is 20 to 30 meters (maximum), and the duration of main failure is about three minutes, according to Japan Meteorological Agency (The 2011 off the Pacific Coast Tohoku Earthquake* [28th report]).

* This name was given by Japan Meteorological Agency.

![Fig. 7 Types of fault motion](image)

Although shallow-focus earthquakes happen at many places on the Earth, earthquakes whose focuses are at more than 70 km deep only occur in subduction zones. Focuses in the subducting plate are distributed with increasing depth at a constant angle from a trench toward an island arc as shown Figure 6. This focus zone is called Wadati-Benioff zone, which corresponds with the leading edge of a descending plate.

The distribution of epicenters in and around Japan is parallel to the two series of trenches (the eastern Japan arc system and the western Japan arc system). Figure 4 showing the subducting depths of the leading edge of the Pacific and the Philippine Sea Plates is made on the basis of depths of focuses. Deep-focus earthquakes (>30 km) caused by the subduction of the Pacific Plate occur most frequently off the Pacific coast of northeastern Honshu and Hokkaido. The depths of focuses constantly increase with distance from the trenches as shown in Figure 4. As for earthquakes related to the subduction of the Philippine Sea Plate, seismic activity is vigorous off eastern Kyushu but less in and off Shikoku and Kinki. The deepest focuses are about 200 km deep, much shallower than those of earthquakes related to the Pacific Plate (about 700 km). (The distribution map of epicenters is available from a website mentioned below or [a page in the website of Japan Meteorological Agency](http://example.com) [figure with a green frame, "マグニチュード" means magnitude and "震源の深さ" means depths of focuses].)

Shallow-focus earthquakes occur mainly on the landward side of trenches (near the boundaries of continental plates) and around active volcanoes and faults. Shallow-focus earthquakes as well as relatively deep-focus earthquakes also happen off the western coast of northeastern Honshu and southwestern coast of Hokkaido. This earthquake zone is along the boundary between the North American Plate and the Eurasian Plate.

The website of [National Research Institute for Earth Science and Disaster Prevention](http://example.com) provides seismic data. The distribution map of epicenters that occurred in Japan in the last 30 days is available in [this page of the site](http://example.com). If there are few epicenters on the map, change the setting of duration for displaying epicenters; click a button at [期間] to show a pull-down menu and select [最新30日間]. Moreover, a 3D map of the distribution of focuses is available in [this page](http://example.com) (in Japanese). To show the map, click [表示] or [ダウンロード] under...
a line displaying [3D震源分布の閲覧]. You can control a view point on the 3D map as moving and rotating the map. You need a VRML plug-in such as Cortona VRML Client to see the 3D map.

**Accretionary prism**

An accretionary prism (also called accretionary wedge) is a sedimentary body formed by which ocean floor sediments and trench-fill sediments provided from the land accrete to the landward slope of trench by off-scraping accretion and underplating accretion. Oceanic plate subduction is responsible for such accretion. Slices (thrust sheets) pile next to one another with reverse faults (thrust faults). They are characterized by inward younging in each sheet and overall outward younging.

![Accretionary prism](image)

**Fig. 8 Oceanic plate stratigraphy**

Oceanic plates are produced by basaltic magma upwelling at mid-ocean ridges and move away from the ridges toward trenches. Magma ejected onto a seafloor forms pillow lavas. In temperate and tropical regions, shells of calcareous nannoplanktons deposit on the seafloor shallower than carbonate compensation depth (CCD) to form limestone. As the plate is more densified with increasing distance from the ridge due to cooling, the seafloor becomes deeper. When the depth of seafloor exceeds CCD, calcareous shells no longer deposit because they are dissolved, and only siliceous shells of radiolarian settle on the seafloor. Chert, therefore, is formed on limestone beds (pelagic sediments). As the plate comes close to the land, mud and tuff from the land deposit on the chert beds to be siliceous shale (hemipelagic sediments). In trenches, clastics including sand and mud flow down to the bottom of trench on the landward slope as turbidity current and deposit (trench-fill sediments). This sedimentation makes alternating beds of sand and mud. Accordingly, oceanic plate stratigraphy, consisting of basalt (pillow lavas), limestone, chert (pelagic sediments), siliceous shale (hemipelagic sediments), and alternating beds of sand and mud (trench-fill sediments) in order from the bottom, is formed on the plate travelling from the mid-ocean ridge to the trench.
Photo 1 *Bedded chert*  
Photo 2 *Turbidite*

Fig. 9 *Accretion*

Photo 3 *Melange* (Stick is 1m long)
Rocks and sediments composing the oceanic plate stratigraphy are deformed by plate movement and split into an accreted part and subducted part (Figure 9). The border between the parts is called decollement (horizontal slip plane). The sediments of accreted part are scraped off and accreted to the front of accretionary prism; this process is called “off-scraping accretion”. Thus, the accretionary prism develops outward and the trench migrates seaward. Under the accretionary prism, the decollement steps down and subducted sediments accrete to the bottom of the prism with forming duplex structure. In addition, part of the oceanic crust subducted underneath the prism is scraped off and added to the prism. This accretion is defined as “underplating”. Moreover, thrust faults (out of sequence thrusts) cut a part of the accretionary prism and bank up sliced parts to thicken the prism. Accreted materials including basalt, limestone, chert, siliceous shale, and turbidite are sheared and mixed to be fragments of all sizes in this process. These fragments are found in muddy matrix as mélangé. Since sliced sediments are added under the pre-existing thrust sheets by plate subduction, the lower sheet is younger than the upper one.

Accretionary prisms are not always formed in trenches. About 40% of trenches all over the world possess developed accretionary prisms. Tectonic erosion is in active rather than accretion in other trenches. The formation of accretionary prism requires large volume of sediments in a trench. Therefore, the onset of accretion depends on the convergence rate of plate and the supply rate of sediments because sediments are taken to under the landward plate if the plate subduction rate is too fast. The conditions required for accretion seem to be the thickness of trench-fill sediments of >1 kilometer and/or convergence rate of <7.6 centimeters per year (Clift and Vannucchi, 2004). In Japan, accretionary prisms are well developed only in the Nankai Trough, and little in the Kuril, the Japan, the Ryukyu, and the Izu-Bonin Trenches.

Most of Japanese basement is composed of accretionary complexes and metamorphosed accretionary complexes. An accretionary complex is defined as a former accretionary prism, characterized by a mix of ocean-floor basalt, pelagic and hemipelagic sediments and terrigenous sediments (turbidite) with complex structures such as mélangé and duplex. See “Tei mélange and Muroto” for examples of accretionary complex exposures.

**Metamorphic rocks**

Metamorphic rocks, as well as igneous rocks, are major components of the continental crust. They are rocks transformed under different conditions including temperature and pressure from the original conditions of the rock formation (metamorphism). Metamorphic rocks are broadly exposed in shields which have been very stable regions of the continents during the past 600 million years, some of which are extremely old, over three billion years old. Metamorphic rocks are also found in orogenic belts. Two types of metamorphic rocks are commonly present in subduction zones: the high P/T type and low P/T type (P/T refers to the ratio of pressure to temperature). High P/T metamorphic rocks are formed under high pressure and relatively low temperature conditions. In subduction zones, rocks taken into a deep part of the crust by plate subduction are transformed into high P/T metamorphic rocks. Low P/T metamorphic rocks are formed under high temperature and relatively low pressure conditions by contacting magma.
Crystalline schist in Nagatoro, Saitama Prefecture, central Honshu
This high-pressure type metamorphic rock is in the Sanbagawa Belt. The rock in the photo is stilpnomelane phyllite, characterized by fine folded schistosity.

Metamorphic rocks that result from regional metamorphism occurring over a large area are known as regional metamorphic rock; crystalline schists are typical. Contact metamorphic rock such as hornfels is locally formed around intrusive rocks. In arc-trench systems, regional metamorphic rocks are common, zones of which are classified into a high P/T metamorphic rock zone and a low P/T metamorphic rock zone. In Japan, the Sambagawa Belt is well-known as the high P/T metamorphic rock zone, and the Ryoke Belt as low P/T metamorphic rock zone. These zones are parallel to the Nankai Trough.
Why do high P/T metamorphic rocks formed in a deep part of the crust come up toward the surface? Subduction of mid-ocean ridges is proposed as one of the reason. Surveys of accretionary complexes reveal the ages of oceanic plate stratigraphy. The survey results in Japan show that mid-ocean ridges were subducted several times and the times of the subduction are consistent with those of which high P/T metamorphic rocks rose. However, the detail mechanism of the metamorphic rock rising is unknown. Moreover, the subduction of mid-ocean ridges provides large amount of heat to the crust, resulting in the generation of granitic magma and the formation of low P/T metamorphic rocks. (See also “Formation history of the Japanese Islands [p.3]”.)

**Continental crust and development of island arcs**

Development of island arcs is closely related to the growth of continental crust. Accretionary prisms develop toward the ocean as mentioned in the chapter of accretionary prism. Accretionary complexes in Japan become younger toward the Pacific Ocean, indicating that the basement of the Japanese Islands has been increased by accretion on the margin of the continent. However, only the growth of accretionary prisms is not enough to explain the increment of the crust in the Japanese Islands. Accretionary prisms consist of terrigenous deposits and materials scraped away from an oceanic plate but the terrigenous deposits extremely dominate the prisms. The terrigenous sediments were produced by erosion of the land and/or pre-existing prism. Therefore, the continental crust does not increase essentially with the accreted sediments because the sediments are recycled materials. Accreted rocks and sediments derived from the oceanic plate contribute to the growth of the continental crust but the amount of them is a little. The addition of granite (felsic plutonic rock) largely develops the continental crust. Thus, substances provided from the mantle thicken the continental crust by igneous activity in island arcs.

Igneous activity, the formation of accretionary prisms, and high P/T metamorphic rock rising develop island arcs, while tectonic erosion reduces them. In Japan, recent zircon chronology suggests that granitic batholiths disappeared in the past (see “Formation history of the Japanese Islands [p.2]”). It is, therefore, thought that island arcs do not grow toward the ocean constantly.

**References**