1-2 Coral reef landforms in Japan

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1 Introduction

The landform represented by a coral reef is defined as 'a breakwater structure formed by corals and other calcifying organisms, with its surface reaching sea level (Yasugi *et al*. 1996)'. Coral reefs are present in the Ryukyu Islands from latitudes 24° to 31° N, and in the Ogasawara Islands south of 27° N. Most are 'fringing' reefs, with their reef-flats attached directly to the islands' shorelines. From a global perspective, these buildups occupy what is defined, on the basis of sea surface temperature (SST) gradients, as a marginal zone for reef growth. Kyushu, Shikoku and southern Honshu are located in non-reef-building areas; coral communities are present, but do not form reefal buildups. Coral patch reefs were recently discovered in the Iki Islands, at 33° 45' N (Yamano *et al*. 2001c), although no coral reefs are known to exist between these islands and Tanegashima (Is.) (30°30' N), formerly regarded as the northern limit of coral reefs.

Coral reefs about 1 km wide fringe the coastlines of the Ryukyu Islands, south of 27° N. In the Ryukyu and Ogasawara islands, between 27° and 31° N, reef distribution is patchy and reef flats become narrower to the north. The Ryukyu Islands are located in the Kuroshio Current, in a monsoon region, and are frequently affected by typhoons, all of which are well known to affect reef formation and distribution.

This chapter presents an overview of the geological, tectonic, meteorological, and oceanographic factors that constrain coral reef formation, as well as a summary of reef zonation, its development, and its geographical variation, in addition to a discussion of the importance of these factors, including the intrinsic characteristics of coral reefs, in planning coral reef preservation and management.

2 Geographical background of coral reef formation

1. Geology and tectonics

Japan is an active volcanic island arc, located along the subduction zone of the Pacific plate. In the southern half of the country (southern Honshu, Shikoku, Kyushu and the Ryukyu Islands), the Philippine Sea plate, formed by back-arc opening of the Izu-Ogasawara arc (Fig. 1), is currently being subducted. The Nansei Islands (Southwest Islands), at the southwestern limit of the Japanese Archipelago, are divided into the Satsunan Islands in the north and the Ryukyu Islands in the south, but in common practice, and in this book, the whole island group is called the Ryukyu Islands.

The Ryukyu Trench, Ryukyu Islands, and Okinawa Trough parallel the boundary of the Philippine Sea

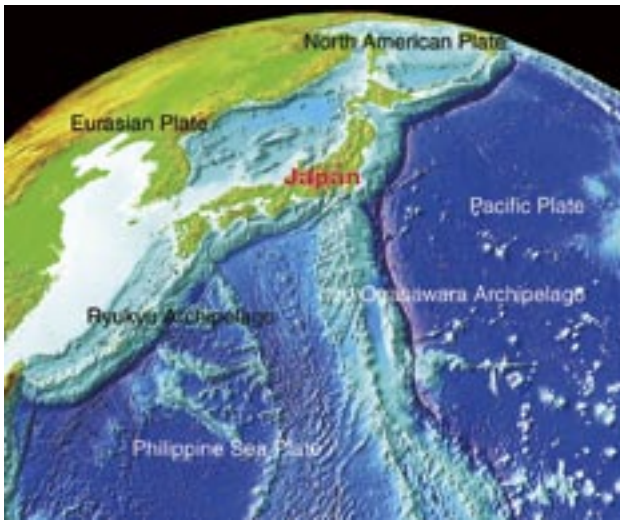

Fig. 1. Japan and surrounding ocean area.
Provided by Hydrographic and Oceanographic Department, Japan Coast Guard.

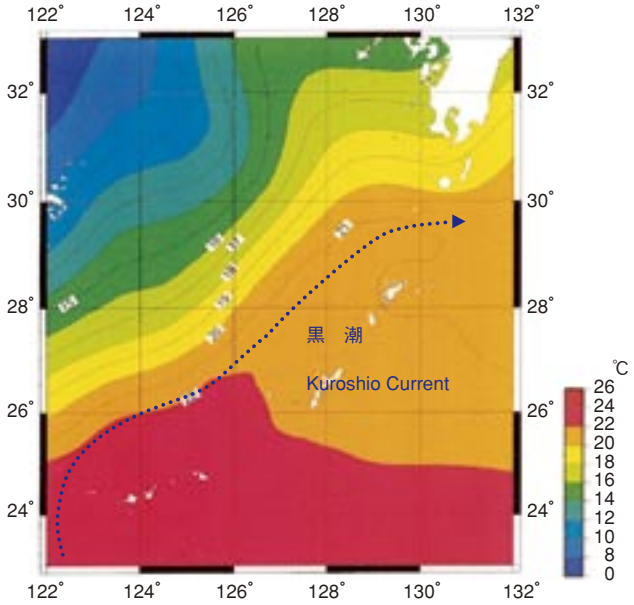

Fig. 2. Distribution of sea surface temperatures (SSTs) in February and the Kuroshio Current flow path in the Ryukyu Islands (from the Oceanographic Normals and Analyses for the period 1971-2000, Japan Meteorological Agency).

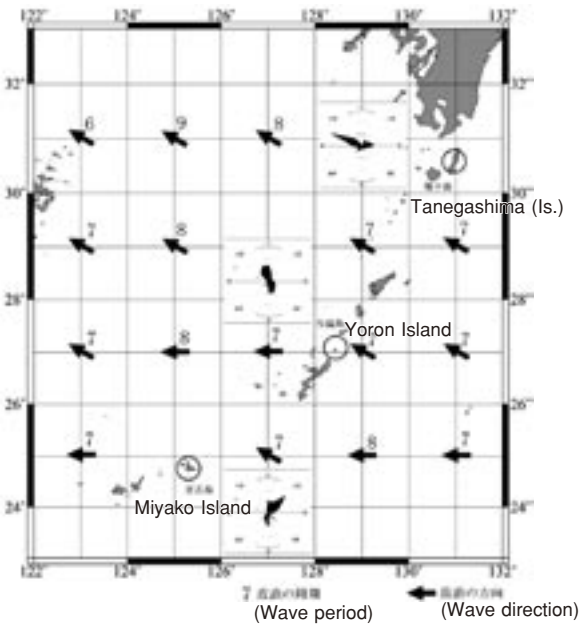

Fig. 3. Mean wind rose and wave direction around the Ryukyu Islands.
The synoptic wave chart was figured in reference to the mean synoptic wave chart in 2002 from the Japan Meteorological Agency website (http://www.data.kishou.go.jp/marine/wave/chart/mean/jpmean/html). The wind rose was drawn with reference to the wind direction of the mean daily maximum wind speed in 2002 from the Electronic Reading Room of the Japan Meteorological Agency (http://www.data.kishou.go.jp/).

plate. The Izu-Ogasawara trench, Izu-Ogasawara arc, and Ogasawara Trough are parallel to the boundary of the Pacific plate. Coral reefs are present on the islands of Minamidaitojima and Kitadaitojima (raised atolls), Okidaitojima (a raised table reef), and Okinotorishima (a table reef), which are located on ridges on the Philippine Sea plate. They are also present on Minamitorishima (a table reef) on the Pacific plate.

Prior to the Pliocene, the Ryukyu Islands constituted the locus of terrigenous mud deposition (now the Shimajiri Group) at the margin of the Asian continent. The Okinawa Trough began to form about 10 million years ago, and has been subsiding conspicuously for the past 2 million years (Kimura 1985). As a result, the Ryukyu Islands became separated from the continent, and deposition of calcareous sediment began, creating what is now known as the Ryukyu Group (Nakamori *et al.* 1995; Iryu *et al.* 1998).

Uplift over the past several hundreds of thousands of years has resulted in the raising of coral reef terraces. Terraces that formed in the Last Interglacial, 120,000 years ago, are now located at altitudes of 220 m above sea level on Kikaijima (Is.), 35 m on Hateruma Island, and 24 m on Yonaguni Island (Ota and Omura 1992). Uplift continued in the Holocene (until a few thousand years ago), such that comparatively young raised coral reefs (a few thousand years old) are also present on many islands (Koba *et al.* 1982).

The Ryukyu Islands consists of three types of island: 'low islands' that are overlain with coral reef terraces; 'high islands', where the Shimajiri Group is exposed (Mezaki 1995); and 'volcanic islands'. Reef characteristics, outflow characteristics of precipitation, soil type, and land-use vary, according to the island type.

2. Climate and Oceanography

Sea surface temperatures (SSTs) decrease to the north with latitude. The SST in the coldest month is 24℃ in the Yaeyama Archipelago and 19℃ in the Satsunan Islands (Fig. 2). The Kuroshio Warm Current flows along the Ryukyu Islands, raising SSTs to higher than

in other regions at the same latitude, and supplies coral larvae from a more southern core zone of reef development. It is because of this that the Ryukyu Islands maintains high coral diversity and well-developed coral reefs.

The Ryukyu Islands is situated in an Asian monsoon region, with southern winds predominating in summer and stronger northern winds during winter (Fig. 3). The island group faces the open ocean to the east, from which direction it receives major ocean swells. Typhoons, with wind speeds commonly over 30 m/sec, pass through the islands, on average, seven times per year (Yamano *et al.* 2000).

3 Characteristics of coral reef landforms in Japan

1. Zonation

Coral reefs in the Ryukyu Islands typically have a reef flat just below sea level, and a reef slope seaward of the reef flat (Fig. 4). These areas are separated by a breaker zone that separates the calmer landward environment from the open ocean on the seaward side (Photo. 1). The reef flat is generally a level surface, but many have a seaward rise, called the reef crest, with a shallow landward depression 1 to 3 m deep, called a moat. The reef slope, extending from the reef crest down to a depth of 20 m, consists of parallel ridges perpendicular to the coastline, which are called spurs and grooves (Photo. 2). Below a depth of 20 m, a steeper slope descends to a depth of 50 m, below which the gentler slope of the island shelf extends (Fig. 5, Photo. 3).

The use of coral reef geomorphological terms is confounded by the fact that researchers commonly use different words for a single phenomenon; this, in turn, hinders effective communication, management, and preservation. This work employs the following standard usage: the reef flat and reef slope are first-order geomorphological units; the reef-flat can be subdivided into the reef crest and (back-reef) moat, and the reef slope can be subdivided into the spurs and grooves and outer slope (Fig. 4).

2. Formation process

Extensive shallow drilling research, investigations of raised reefs on land, and comprehensive soundings in the Ryukyu Islands have illuminated the process by which coral reefs have formed in this region (Konishi *et al.* 1983; Takahashi *et al.* 1988; Kan and Hori 1993; Yonekura *et al.* 1994; Kan *et al.* 1995, 1997; Yamano *et al.* 2001a, 2001b). Like coral reefs in other parts of the world, reefs in Japan grew during the postglacial rise in relative sea-levels, and ensuing still stand. Sea-levels dropped to 130-140 m below the present level in the last glacial maximum, 20,000 years B.P. During deglaciation, sea-levels rose rapidly, up until 6,000 years ago, at a rate of approximately 1 m/100 years, but with a brief still stand at about 50 m depth, 12,000 years ago (Fairbanks 1989; Chappell and Polach 1991).

Coral reefs formed in response to relative sea-level rises. In the tropics, some coral reefs started to form when the local sea-level was 120-140 m below the present level, but in the Ryukyu Islands, no coral reefs are present below 50 m (Hori and Kayanne 2000). In the Ryukyu Islands, coral reef growth began about 10,000 years B.P., before which time the SST in the region had not reached the critical average temperature of 18 ℃. Formation of all reefs between 27° and 21°N began at 50 m depth, which records reef formation that postdated the still stand in relative sea-level rise at 10,000 years B.P.

From 10,000 to 6,000 years B.P., coral reefs were in catch-up mode with a rapidly rising sea-level. Reef facies during this stage consisted of *in situ* massive and branching corals, and interstitial coral rubbles that formed a bank 5 m below sea-level. The first parts of the reefs to reach sea level were the reef crests. Their robust framework consists of branching *Acropora* (e.g., *A. digitifera* and *A. gemmifera*) that accumulate at a rate of 0.1 to 0.4 m/100 years. The emergence of the reef crest effected a division of the fringing reef into landward and seaward zones, and was accompanied by development of the backreef, or back-reef moat, in which coral and foraminiferal debris accumulated (Yamano *et al.* 2001a; Fig. 6). Just landward of the reef crest, an accumulation of coral rubbles formed a mound called the reef pavement (Yonekura *et al.* 1994).

In the Ryukyu Islands, postglacial coral reefs were commonly tectonically uplifted into the subaerial realm. Where uplift exceeded tidal range (e.g., Kikaijima), large parts of reefs became emergent, new coral reefs developed atop the spurs of the uplifted reef, and the locus of reef growth migrated seaward, relative to zonation of the underlying reef. Where the scale of

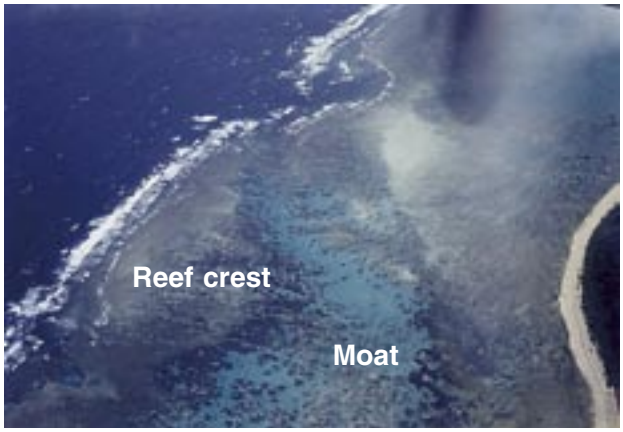

Photo. 1. Typical constitution of fringing reef zonation.

Photo. 2. Spur and groove systems at 5 m depth on northeastern part of Yoron Island.

Photo. 3. Inner break point at 52m depth on the south of Yoron Island.

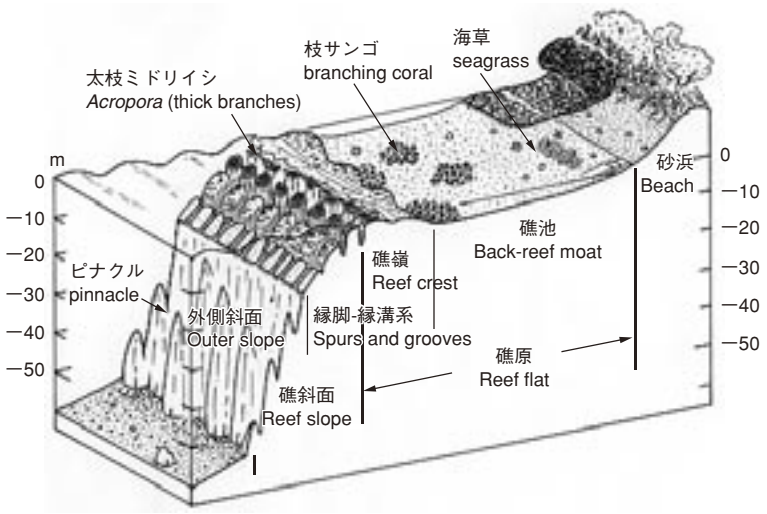

Fig. 4. Constitution of coral reef zonation. Reef crest and moat at Shiraho, Ishigaki Island.

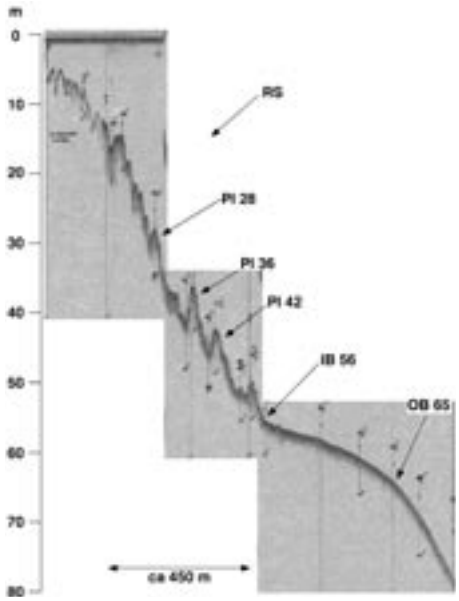

Fig. 5. Echo-sound profile of reef slope topography at the offing of Hirakubo, northern tip of Ishigaki Island (from Hori and Kayanne 2000).
RS: Reef Slope, PI: Pinnacle, IB: Inner Break, OB: Outer Break. Numbers represent depths (m).

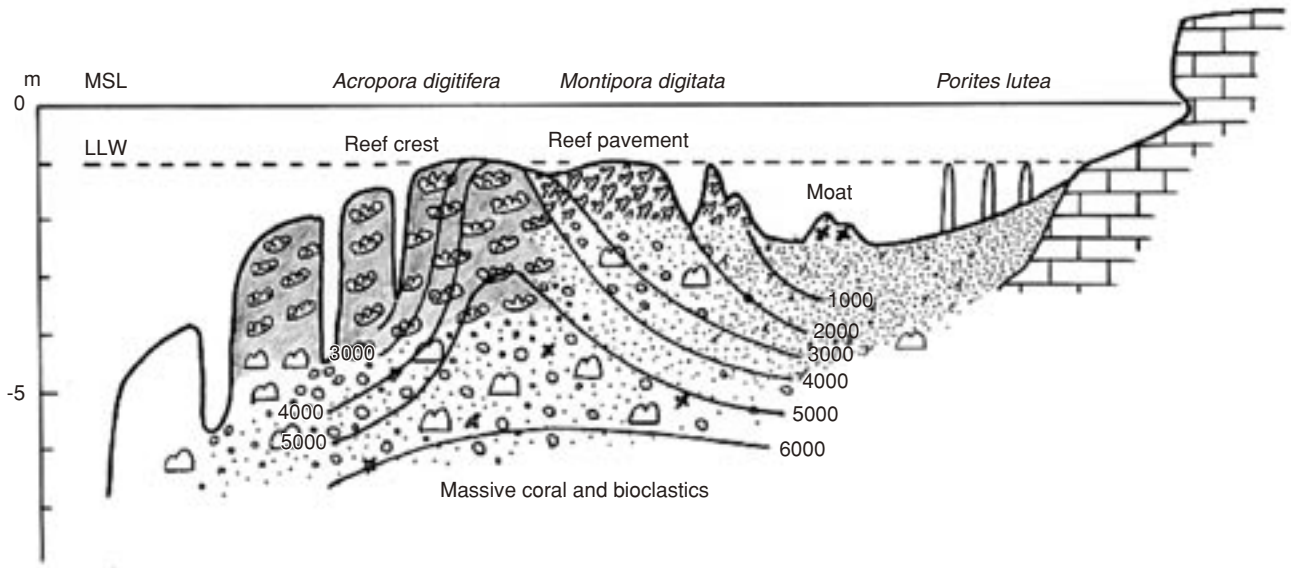

Fig. 6. Schematic diagram of formation process of a fringing reef in the Ryukyu Islands (modified from Yonekura *et al.* 1994; Kan *et al.* 1997; Yamano *et al.* 2001a). 1000-6000: cross section at 1000-6000 years ago.

uplift was less than the local tidal range (e.g., Shiraho Reef at Ishigakijima Island), the surface of the reef crest remained below high-water level, and the location of reef zones remained unchanged, but corals no longer lived on the subaerially exposed rock of the reef crest. In such locations, exposure of the reef crest during low tide limits the mixing of water between the open ocean and the reef flat.

3. Geographical variation

Coral reefs throughout the Ryukyu Islands all formed under the same conditions: catch-up growth during relative sea-level rise was followed by lateral extension once the reef crest attained sea-level. For this reason, all of the reefs exhibit the same basic geomorphological zonation. Local variations superimposed upon this pattern are the result of minor differences in temperature and wind conditions; these slight differences are manifested latitudinally as well as at the scale of a single island.

Between 24° and 27° N, modern coral reef growth began when the sea level was about 50 m below the present level, and thus the reef flats fringe the islands in an almost uninterrupted fashion, with widths corresponding to those of the islands' shelves (Photo. 4). At latitudes higher than 27° N, reef flats are patchily distributed and narrow in width as a result of being younger, and because of the shallower depths of reef nucleation (Photo. 5). Variation in reef expression at the scale of a single island corresponds with coastline orientation. Winter monsoon winds are from the north, and swells come from the open Pacific Ocean to the east, both of which result in high waves on northern and eastern coasts, where correspondingly well-developed reef crests and moats, and continuous reef flats, are characteristic. In contrast, on west-facing coasts, reef flats are discontinuous, and reef zonation is poorly developed (Fig. 3).

4 Landform characteristics and preservation

The features of coral reef landforms in the Ryukyu Islands must be taken into consideration in planning their management and preservation. Fringing reefs are, by definition, directly linked to and affected by adjacent landmasses. This makes for easier land-based management than is possible for barrier and atoll reefs. Coral reef resources have long been exploited by local people in the coastal fishery. It also means, however, that fringing reefs receive direct effects from land-based human activity. Harmful silt and nutrients

Photo. 4. Reef flat of Sekisei Lagoon in Yaeyama Archipelago. (photo by H. Hasegawa)

Photo. 5. Patchily distributed and narrow coral reefs at Tokunoshima (Is.) in Amami Archipelago.

flow directly onto the reefs from land. The tectonic uplift in the Ryukyu Islands, and resultant emergence of reef crests into the intertidal zone, mean that water exchange between the reef flat and the ocean is limited; this, in turn, creates a closed environment on reef flats, which enhances the land effect, and creates a stressful environment for reef-flat corals. It also means that run-off from the land is trapped on the reef flat and does not significantly affect the reef front, exaggerating the environmental and biological contrasts between the two. Monitoring and assessment of the reef flat and reef front must be conducted separately.

The location of the Japanese islands, in a monsoon area that is affected by typhoons, means that reef crests are especially robust, and that coral community turnover after typhoons is frequent. For this reason, the extant coral communities in the Ryukyu Islands could presently be in a comparatively early and non-equilibrium stage of development, such that baselines established now may well be meaningless, regardless of anthropogenic influence.

Coral reefs act as natural breakwaters that protect coastlines from erosion. Only a subtle natural balance between reef growth and erosion maintains their respective properties. The death of entire coral communities results in reef collapse and loss of the natural breakwater function. For this reason, the maintenance of coral reef health is critical to retaining the natural landforms that they form, landforms that humans rely on for coastline protection.