Paleogeography of the Ryukyu Islands

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ABSTRACT Recent submarine, geological, and geophysical investigations including diving surveys reveal the geo-history of the Ryukyu Islands and the East China Sea. Two stages are fundamental for formation processes of the Ryukyu Arc. The crustal thinning in the western part of the East China Sea and thus eastward drifting of the Arc may have occurred in the late Miocene to middle Pliocene at the first stage. Between 1.6 - 1.3 Ma, the East China Sea area, including most of the Okinawa Trough, may have been subaerial. At that time, the Ryukyu Arc region may have been a part of the Eurasian continent. Extensive subsidence may have occurred at the second stage, at about 1.3 Ma, in the early Pleistocene. The present Ryukyu Arc (Ryukyu Ridge) has been formed since then. The Ryukyu Arc may have been nearly connected to the Chinese continent, through Taiwan as a land bridge, sometime during the two major development periods (such as sometime during 1.6 - 1.0 Ma, and 0.2 - 0.025 Ma). The paleo-land may have been submerged step by step since 0.03 Ma by both crustal movement and sea-level rising after the last Ice Age. Submarine stalactite caves at 10 - 35 m deep off the Ryukyu Islands were discovered. The caves have subsided since the Würm Ice Age. Stone tools were also recovered inside one of them. Additionally, archeological evidence in the form of a stepped pyramid, estimated at greater than 6,000 years old, has been discovered beneath the sea off Yonaguni Island. Existence of such submarine ruins provide indicators of subsidence processes of the Ryukyu Arc.

Key words: Ryukyu paleoland / Okinawa Trough / paleogeographic map / land bridge / submarine stalactite cave / submarine ruins.

In recent years submarine, geological, and geophysical investigations have been carried out in the Ryukyu Arc region by multiple international organizations (e.g., Kimura, 1985a, b, 1996a, b; Japanese DELP Research Group on Back-Arc Basins, 1991; Sibuet et al., 1987, 1998). The Ryukyu Arc (Fig. 1) lies along the eastern margin of East China Sea. This paper discusses geologic environmental change of the Ryukyu Arc and the East China Sea using all available data. Seismic reflection profiles of single and multi-channel systems, obtained from most organizations in the world, were compiled for the present study to clarify geological and stratigraphic sequence in the Ryukyu Arc. Dredging and drilling data were also incorporated to determine the stratigraphy in the studied area. Detailed topographic data collected with multi-narrow beam, manned and unmanned submersible, and seismic refraction experiments were also available to study the geologic and geophysical features in the Ryukyu Islands (Nansei-Shoto Islands) areas. Adding to this, diving surveys around the Ryukyu Islands, using SCUBA, show detailed submarine topography and geology.
MORPHOLOGY AND TECTONIC FRAMEWORK OF THE RYUKYU ARC

The morpho-tectonic framework in the study region can be defined from west to east in Fig 2, namely I) Tunghai Shelf, II) Tunghai Slope (western rifted margin of the Okinawa Trough), III) Okinawa Trough, IV) Tokara Belt (eastern rifted margin of the Okinawa Trough), V) Ryukyu Ridge, VI) Arc-trench gap and, VII) Nansei-shoto Trench (Ryukyu Trench). The Ryukyu Arc includes the Tokara Belt (IV) and the Ryukyu Ridge (V) (Kimura, 1985b). The width of the present Okinawa Trough is about 100 - 150 km. The topography of the Tunghai Slope and Tokara Belt is rough, and both features are regarded as rifted margins of the Okinawa Trough. Active volcanism is recognized in the volcanic

front of the Tokara Belt. Active rift movement, associated with classic grabens, was identified in the middle and southern part of the Tokara Belt (Kimura et al., 1975; Sibuet et al., 1998). Deep faults, such as the Ryukyu Ridge Fault and the Tunghai Shelf Fault, were generated in the early Pleistocene along boundaries of morpho-tectonic division.

The Okinawa Trough is a back-arc basin that has developed generally parallel to the Ryukyu Arc. The Okinawa Trough is estimated to have been filled with deposits since late Miocene time and the central grabens or rifts develop along the axial part of the trough arranged in an echelon formation.
CRUSTAL STRUCTURE AND STRATIGRAPHIC SEQUENCE

Seismic refraction experiments using TNT dynamite has been carried out more than four times since 1984. Before that, there were few lines crossing the Ryukyu Arc and the Okinawa Trough. There are many sites of sono-radio buoy experiments. All of the seismic refraction data show a similar picture.
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of the crustal structure of the Okinawa Trough from north to south. The depth of the Moho Discontinuity varies 25 - 16 km from north to south (Iwasaki et al., 1987; Hirata et al., 1991) and there is no variation from east to west. Chemical analysis of major-and rare-earth elements collected from the Central Rifts of the Okinawa Trough, and those in other portion of the Trough, show island-arc affinity. There are no magnetic anomalies in the Okinawa Trough, indicating that there is no oceanic crust underlying the Trough (Sibuet et al., 1987). Gravity anomalies also indicate that the Okinawa Trough is comparable to a continental crust. These data indicate that there is no oceanic crust beneath the entire Okinawa Trough.

Based on detailed velocity structure in the southern Okinawa Trough: the layer of 7.5 km/s (kilometer/second) is correlated with that of the mantle and the layer of 6.2 - 6.4 km/s with the layer 2 and the 4.5 - 6.0 km/s layer is correlated with granitic layer (Hirata et al., 1991). The thickness of the 4.5 - 6.0 km/s and 6.2 - 6.4 km/s layers decreases remarkably beneath the trough. This suggests that crustal stretching occurred after the formation of the 4.5 - 6.0 km/s layer. The 3.6 - 3.9 km/s layer appears correlated with the Yaeyama Group of the early Miocene, based upon the stratigraphic sequence and sonic velocity. The 3.0 - 3.5 km/s layer is correlated with late Miocene strata on the basis of seismic reflection records and drilling data (Marutani & Sato, 1985). The 1.8 - 1.9 km/s layer is correlated with early Pliocene to early Pleistocene sediment, such as the upper Shimajiri Group and Quaternary sediments.

Seismic reflection profiles reveal a deep sedimentary basin resembling a big trough beneath the Tungai Slope, and the sedimentary layer in the basin shows it is about 6 km thick (Marutani & Sato, 1985; Kimura, 1985a, b; Letouzey & Kimura, 1986). This trough is tentatively called older Okinawa
Table 1. Stratigraphic correlation.

<table>
<thead>
<tr>
<th>10^6 yr</th>
<th>Epoch</th>
<th>Okinawa Trough</th>
<th>Kerama Saddle</th>
<th>Okinawa Island</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Holocene</td>
<td>A</td>
<td>Kerama gravel and sand</td>
<td>Holocene</td>
</tr>
<tr>
<td>2</td>
<td>Late</td>
<td></td>
<td>Kerama Limestone</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Middle</td>
<td>Ryukyu Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Early</td>
<td>B</td>
<td>marine</td>
<td>Yomitan Limestone</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>(B2)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>Minatogawa Limestone</td>
</tr>
<tr>
<td>20</td>
<td>Pleistocene</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>Naha Limestone</td>
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<td>60</td>
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<td>80</td>
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<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>(B1) non-marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>Late Pliocene</td>
<td>C2</td>
<td>non-marine</td>
<td>Reddish Limestone</td>
</tr>
<tr>
<td></td>
<td>Shimajiri Group</td>
<td></td>
<td>(?)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>marine</td>
<td>Shinzato Formation</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Yonabaru Formation</td>
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<td></td>
<td></td>
<td>Unconformity</td>
</tr>
</tbody>
</table>

Trough (Figs. 3 and 4). Thus, there are two sedimentary basins, an older, and a younger Okinawa Trough, in the northern half of the backarc region. In the southern part, a younger one seems to be coincident with the older one.
TECTONIC HISTORY

Paleomagnetic evidence shows that from 10 - 4 Ma, the southern part of the Ryukyu Arc rotated clockwise 19 degrees with respect to Eurasia (Miki et al., 1990; Miki, 1991). This rotation is attributed to the back-arc opening of the southern part of the Okinawa Trough, which occurred by means of the "wedge" mode after 10 Ma (Miki et al., 1993). Thus, the major cause of lateral movement of the outer terrane in the Ryukyu Arc is thought to be primarily because of both the opening of the Okinawa Trough after the middle Miocene, and the bending of the outer terrane in Kyushu and Taiwan in the late Miocene. Thereafter, the subducting Philippine Sea plate may have been coupled with the continental plate, at the Ryukyu Trench, while the Eurasian Plate extended and rifted to make a back-arc basin. Uplifting may have occurred in the Okinawa Trough region before its subsidence when the regional angular unconformity was formed sometime during Middle to Late Miocene.

As a result, crustal stretching may have occurred after formation of the 4.5 - 6.0 and 6.2 - 6.4 km/s layers. Whereas, the 3.0 - 3.5 km/s layer (? late Miocene strata) seems to be a syntectonic sedimentary layer formed during major extensional movement of the Okinawa Trough. As a result, the thinner crust in the back-arc basin was rifted, but not completely lost. The direction of general bedding trends and the geologic terrane in the South Ryukyu changed sometime during the middle Miocene / Pliocene. Consequently, pre-middle Miocene terranes were shifted trench ward. The timing of bending of the Shimanto Terrane is thought to be later than the timing of the extension of the Japan Sea. Thus the spreading of the Japan Sea should be compatible with the spreading of the Okinawa Trough; both of which were characterized by volcanism called Green-Tuff activity. Following this, the Okinawa Trough was filled up with sediment from the upper Shimajiri Group.

Subsequently, Tanegashima Island, located in the northern Ryukyu Arc, has been rotated counterclockwise by about 30 degrees, with respect to Eurasia and Southwest Japan since about 2 Ma, (Kodama et al., 1991; Kamata & Kodama, 1994). The depocenter of the trough jumped to the east at 2 Ma, and is not coincident with the northern-half of the present Okinawa Trough, but is coincident with the southern Okinawa Trough.

Drilling data from a Japanese oil company show that there are Pliocene to Pleistocene sediments of 2,490 m thick in the northern-most part of the Okinawa Trough, of which the lower part is correlated with the Shimajiri Group, and the upper part is correlated with Layers B1 and B2 (Ryukyu Group), as shown in table 1. A thick B1 layer is expected in the central part of the Okinawa Trough as pounding sediment estimated as a non-marine sediment. The sedimentary basin may have an expanded origin controlled by the clockwise rotation of the Ryukyu Arc since 1.6 Ma. The Beppu-Shimabara Graben in central Kyushu has been active since 1.6 Ma, accompanied by extensive volcanism, and faulting. The Kuchinotsu Group was deposited in the graben, formed at this time. Contemporaneously, the margin of the central basin of the Okinawa Trough was eroded subaerially from 1.6 - 1.3 Ma, as shown by the unconformity under Layer B2 in the Tokara Belt.

Subsiding movement since 1.3 Ma has formed the Ryukyu Ridge. Sea level became relatively high, and the Ryukyu Limestone deposited at the Philippine Sea side from 1.3 - 1.0 Ma. The Greater Okinawa Trough (Fig. 4) has been formed since 1 Ma. Since then, rifting in the central graben of the Great Okinawa Trough has developed.

Available data confirm evidence of volcanic activities in the central rift valley in the middle
Okinawa Trough (Kimura et al., 1986; Kimura, 1991). Potassium-Argon (K/Ar) dates of volcanic rocks composed mostly of high alumina basalt and decide represent activities younger than 0.5 Ma, (Kimura et al., 1986). Some of the central knolls in the rift valley revealed active hydrothermal mounds ("SHINKAI 2000" Research Group on the Okinawa Trough, 1986). Furthermore, black smokers were found at Izena Hole in the middle Okinawa Trough (e.g., Nakamura et al., 1990).

**LAND BRIDGES DURING THE PAST 0.2 Ma**

There exists a very long, flat terrace on the summit through the entire Ryukyu Ridge: cross sections of this terrace (Fig. 5) show essentially the same features, such as uncovered soft sediments on the top and thick sedimentary coverage of side slopes of the terrace, despite surface depths varying from 100...
Fig. 6. Interpreted cross section using sparker profiles (30,000 joules) right angle to Ryukyu Ridge showing TA. Locations of E4-E12 are shown in Fig. 5. A-E are explained in Fig. 4. OK-1x: drilling site.

- 500 m as shown in Figs 6 and 7. This terrace is named Terrace A (TA). Based on seismic reflection surveys, both single and multi-channel, the TA is offset by normal faults, thus its depth varies from 100 m to more than 1,000 m in the Tokara and Kerama Gaps as shown in profiles.
Exposures of bedrocks are recognized broadly on most of TA in the Kerama and Tokara Gaps, as observed by "SHINKAI 2000", "Nagasaki Maru" and others. Outcrops of bedrock continue from shallows to 100 m depths, suggesting that less depositional time for newer sediments after the erosion of the TA surface. Thus, the flat plane of Terrace A (TA) is identified as the erosional surface of postformation Ryukyu Limestone in the late Pleistocene from 0.2 - 0.02 Ma (Kimura et al., 1992; 1994; 1996). As a result, TA has been offset by normal faults from 100 m to over 1,000 m depths, based on the sonic profiles (e.g., Fig. 7). Both TA shallows and TA depths are identified as the same erosional surface.

Ryukyu Limestone composing the bedrock that was recovered from a flat terrace at 935m in the Kerama Gap was dated using nanno fossils. The age of the limestone was estimated as younger than 0.27 Ma. The age of the fossil bivalve Amusium japonicum (Tsukihi-gai in Japanese) in the same
Table 2. Radiocarbon ages of samples recovered from Kerama and Tokara Gaps (or Saddles).

<table>
<thead>
<tr>
<th>Kerama Saddle</th>
<th>Tokara Saddle</th>
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<tbody>
<tr>
<td>2K5403</td>
<td>770±60 yr BP (foraminifera)</td>
</tr>
<tr>
<td>3K109-5</td>
<td>7,880±160 (foram.)</td>
</tr>
<tr>
<td>2K540-4-4 sand 19,190±390</td>
<td>620 m deep.</td>
</tr>
<tr>
<td>2K540-4-1 sand 19,780±330</td>
<td>LAND</td>
</tr>
<tr>
<td>2K540-1-3 30,960±620 (shell)</td>
<td>27,240±450 (foram.)</td>
</tr>
<tr>
<td>2K540-1-6 32,610±700 (shell)</td>
<td>LAND</td>
</tr>
<tr>
<td>DT30-1a 240,000 (ESR), (shell)</td>
<td>450,000 - 400,000 (ESR) (shell)</td>
</tr>
<tr>
<td></td>
<td>1,000 m deep</td>
</tr>
<tr>
<td></td>
<td>1,200 m deep</td>
</tr>
</tbody>
</table>

limestone sample was dated with Election Spin Resonance (ESR) methods, providing an age of 0.24 Ma or younger. Based on these dates, it was inferred that this area was subaerially eroded after 0.24 Ma at least since 0.2 Ma. From the summit of the Ryukyu Ridge in the Kerama Gap (Kerama Saddle), calcareous sediment (Kerama Limestone) of about 40,000～30,000 years old was collected. The Kerama Limestone covers the Naha Limestone unconformably, suggesting that this level was dry land from 0.2 - 0.04 Ma. Normal sandy sediments covered the Kerama Limestone unconformably. Samples of this sandstone were collected abundantly from a depth between 500 - 600 m in the Kerama Gap using "SHINKAI 2000". The sandstone coats unconformably the erosional bedrock broadly. The 14C age yielded an accelerator mass spectrometry (AMS) date of about 25,000 years of normal sediments coating Ryukyu Limestone cropped out on the flat plane TA (Fig. 7 and table 2).

On this account, the level TA is estimated to have been fundamentally dry land sometime between 0.2 - 0.03 Ma. Additionally, a mammalian fossil bone tooth was recovered by "SHINKAI 2000" on the flat surface of TA in the Kerama Gap at 620 m deep; the bone/tooth has been identified as belong to Proboscider (or fossil elephants). Its age could not be dated because of lack of collagen, but is believed to date to younger than 0.2 Ma, probably 40,000 - 30,000 years ago. This suggests that the land bridge continuing to the continent existed sometime then as well, because a large-bodied mammal could have arrived only by crossing a land bridge (Kimura, 1996 b, c).

From Peifu Channel of the Taiwan Straits, abundant fossil land mammals, namely elephants, deers, and cows were recovered from the bottom of the sea at depths of 120 - 140 m deep at the central part of the strait. 14C measurement of samples yielded ages of 19,980 ± 200 ~ 15,940 ± 200 Yr bp. Such values are close to the age of the Würm glacial maximum, and there are fossils that may
be older (Nakamura et al., 1996). On the others, a lot of different mammalian fossils considered to have come from the continent to Nansei-Shoto Islands in the late Pleistocene have been excavated on the land (Oshiro & Nohara, 1990; Hasegawa, 1980).

Exposure of the basement rock Shimanto Terrane dating to 100 Ma, was also identified by diving investigations of "Dolphin 3K" in the Tokara Gap to the north. Subsequently, an extensive outcrop of Ryukyu Limestone was discovered by the diving investigation of "SHINKAI 2000" in the Tokara Gap. Ryukyu Limestone was recovered from practically the deepest part of the Gap near 1,200 m.
Age of this limestone is dated to 0.45 - 0.4 Ma, by ESR (Kimura, 1997). The surface of this limestone bed is eroded and the surface is correlatable with TA on the Ryukyu Ridge. It is unconformably covered with normal, sandy sediment that is younger than 0.03 Ma (table 2). It is possible that there was subaerial erosion sometime between 0.4 - 0.03 Ma.

Tunghai Continental Shelf, deeper than 100 m, was under erosional conditions during the Würm glacial age, based on analysis of sonic survey records. The present continental shelf, shallower than 130 m suffered from erosion during the Würm (Nasu, 1990), although it is not known whether seawater changes contributed to the formation of the current continental shelf then or before the Würm. Fossil deer were recovered from Kuchimino - Se Bank at 122 m deep in the Tunghai Continental Shelf, providing a $^{14}$C date (from gelatin collagen of bone) of 26,000 years old. The
Fig. 10. Cross section of Ginama Submarine Stalactite Cave at the northern-most part of Okinawa Jima (after Kimura, 1997). Location marked by star in Fig. 1.

reliability of this value is high at present (Nakamura et al., 1996). Here, Pleistocene strata outcrop at the surface of the sea floor (judging from the sparker profiling records.

Subsidence of the last Ryukyu land bridge began when seawater invaded it about 25,000 years ago, judging by the age of normal sediments covering the basement rocks of the Kerama Gap, dated $^{14}$C to 19,780 ± 330 Yrbp.

Much of the above-mentioned evidence shows that islands were nearly connected from the Chinese continent through Taiwan, Okinawa, and Amami Islands by the land early stage since 0.2 Ma (Riss glacial age). And then, the bridge was interrupted by water at least 0.04 Ma, in Tokara and Kerama Gaps (Figs. 8 and 9).

Recently, submarine stalactite caves were discovered at about 16 m below surface (Fig. 10) (Kimura & Nitta, 1996). Two pieces of stone tools were recognized in a submarine cave and two more stalactite caves were found below sea level in the Ryukyu Arc (Kimura et al., 1996). Artificial ruins (Fig. 11) (Kimura, 1997, Kimura, 2000) were later found about 20 - 30 m below sea level, which are estimated to have been constructed much older than 6,000 years ago. If these have been submerged since 9,000 years ago, then average speed of subsidence is almost coincident with the rate of eustatic movement since 10,000 years ago near the islands.

The major tectonic force for uplifting and subsiding movements since 0.2 Ma may have been provided by the subducting plate motion in the Nansei-Shoto (Ryukyu) Trench, rifting movement of the Okinawa Trough back-arc basin and eustatic movement.
Reconstruction of paleogeography since the early Pleistocene was performed and reconstruction of rivers and water channels were attempted (Figs. 8 and 9).

7.0 - 1.6 Ma (Shimajiri Sea stage)  The relative sea level was increased and the Shimajiri Group deposited in the sea. This sea is called Shimajiri Sea (Kizaki & Oshiro, 1977; Kizaki, 1978). Land area of the Ryukyu Arc was probably very limited from Yaku-Shima to Amami region in the north and Ishigaki to Irromote-jima to the south.

1.6 - 1.3 Ma (Ryukyu paleoland stage)  In early Pleistocene times, most of East China Sea dried up yielding vast dry land (Fig. 8). A series of lakes appeared in the future-Okinawa Trough region. One big lake existed at Kuchinotsu in Kyushu. Layer B1 may have deposited in those lakes. Later subsidence of the newer Okinawa Trough started along the series of lakes.

Rivers originating from the Asian continent (many from the Himalaya Mountains) would have trended from northwest to southeast, opening to the southeastern coast. Goto Submarine Canyon may have been a part of Paleo-Yellow River (Kimura et al., 1975), and may have continued to the pacific coast through the Tokara Gap. The Yangtze River may have opened at the Kerama Gap to the south of Okinawajima Island.

The unconformity at the base of the Chinen Sandstone Formation (Fm) in the south of Okinawajima shows a major tectonic event of this time.
1.3 - 1.0 Ma (Okinawa Trough stage)  
At this time water level rose relatively and the sea spread out. In Kerama Gap, the Chinen Fm of the Shimajiri Group was eroded, which may have been emerged and under erosional conditions between 1.3 - 1.0 Ma (post-Chinen Fm). The Ryukyu Arc seems to have been a land bridge connecting China to Amami-Oshima.

It is clear that there is definite lack of strata during and after formation of the Shimanto Terrane and before that of the Ryukyu Limestone in the Tokara Gap. However, there is outcrops of younger sediment probably correlated with Kuchinotsu Group in Shimabara, Kyushu below Holocene sandy sediment. It is assumed that the Tokara Gap was inundated from 1.3 - 1.0 Ma, because marine deposits distributes in Shimabara which is western inner area to the gap. Seawater invaded Okinawa Trough at this time. Invasion of seawater toward the inside the Trough is recognized as marine sediment in the Kuchinotsu Group in central Kyushu. The Kita-Arima Fm of the Kuchinotsu Group seems to coincide with that of actual transgression time. Seawater invaded the Inland Sea (Setonaikai Sea) followed by deposition of the Kita-Arima Fm (Okaguchi & Otsuka, 1980). Thus, the Tokara Gap would have been opened as represented in Fig. 8 - 2) and it is estimated that it reached the Pacific through Tokara Strait (Otsuka, 1988). Figure 8 shows distribution of land and water areas.

Subsequently, mud and sand from the continent have been trapped in the trough, followed by growth of corals in the clear sea along the Nansei-Shoto Islands. These corals formed the lowest part of Ryukyu Limestone (Reddish limestone) in this stage.

1.0 - 0.2 Ma (Ryukyu Coral Sea Stage)  
Between 1.0 - 0.2 Ma sea-level rose tremendously, during which sea area increased. Most land area had been submerged by water (Fig. 8 - 3)). Because the sea nearly covered the present Ryukyu Islands, land mammals could not reach Ryukyu and Honshu from the continent at this time. High points were still land areas and corals grew along the shallow water.

Coral reefs were formed broadly along the summit of the Ryukyu Ridge as a result of sea-level rising; hence the Ryukyu Limestone was formed. However, Ryukyu Limestone is never recognized in the depths of Kerama and Tokara Gaps, where older strata such as the Shimajiri Group (Kerama Gap) and the Shimanto Super Group (Tokara Gap) are exposed. Perhaps there were water channels and under water erosional environments, in which some coarse sediment deposited, preventing formation of Ryukyu Limestone parts of Kerama and Tokara Gaps. Günz-Mindel Interglacial period is represented in this stage. Nonetheless, formation of limestone was completed in the margins of the Okinawa Trough and peripheral seas.

At a Nansei-Shoto archipelago, an unconformity exists between Pleistocene Naha Limestone and Yomitan Limestone, which possibly correlates with Mindel glacial epoch. Fossil crabs and oysters are found in a part of the Sonan Fm on a plateau of approximately 40 m above sea level in Sonan and Kisebbaru in central Okinawa. Ages of 520,000 - 300,000 Yrbp were measured using shell fragments by ESR technique (Kimura, 1997). This geologic sequence is identified as transgression sediment overlying above mentioned unconformity. It might have been a land bridge from the continent to Okinawa Islands. However, evidence, is a few. Then, the coral grew up in the sea of those days and formed the Limestone in Mindel glacial epoch.

Sediments were deposited in the sea after the Mindel ice age when it is thought that the land bridge was cut off by the rising the sea-levels.
0.2 - 0.04 Ma (Final land bridge stage) In the Ryukyu island chain, a large upheaval occurred between 0.2 - 0.02 Ma (Fig. 8). A land bridge appeared after approximately 0.2 Ma. Strata older than the Ryukyu Group were eroded and exposed, forming a land bridge. This land bridge was formed between the Riss glacial epoch and Würm glacial epoch.

Nearly the entire Ryukyu Ridge emerged, increasing land areas. Basement layers of the Ryukyu limestone crop out directly in the central part of the Kerama and Tokara Gaps (or Saddles) (Fig. 7). This suggests that the center of the Gaps may have uplifted and had eroded more than neighboring areas in the Ryukyu Ridge after deposition of the Ryukyu Limestone formations. As a result, a land bridge from Chinese continent to Ryukyu Arc had been formed just since 0.2 Ma. After then, the Tokara Gap has been subsided and then the Kerama Gap has been subsided (Fig. 8 - 4)) by normal faulting movement.

0.04 Ma - present The Kerama calcareous layer (Kerama Limestone) was deposited 40,000~30,000 years ago. This suggests that at least a part of the land bridge may have been disconnected from the continent. The Kerama Limestone was eroded unconformably because of sea level lowering by the eustatic movement after then. The land bridge to the Ryukyu Arc may have been appear, allowed Minatogawa Man access to the Ryukyus. The flat plane of TA has been offset by normal faulting since 25,000 Yrbp, during which time the last land bridge began to be inundated, owing to crustal movement. Fig. 9 shows a paleogeographic map between 25,000 - 20,000 Yrbp. At this time, shallower part than about present 500 m deep may have land areas, because sediments of this age were recovered from the place deeper from the place than 500 m. Then, relative subsidence has progressed by sea level rising since ultimate the ice age. The Kuroshio Current began to flow through west of the Nansei-Shoto archipelago, finally to result in the state.

Recently, architectural ruins were identified under water of 20 - 30 m deep in Nansei-shoto Islands (Kimura, 2000) (Fig. 11). This may have submerged since 9,000 years ago, showing coincident with post-glacial eustatic movement.

SUMMARY AND CONCLUSION

1) Paleogeographic maps were made to recreate paleoenvironments of the Ryukyu Arc based on recent submarine, geological, and geophysical investigations.
2) Major land bridges from the Asian continent (China) to the Ryukyu Islands have appeared at least once each during 1.6 - 1.0 Ma and just after 0.2 Ma.
3) Many $^{14}$C ages achieved from fossil mammal bones suggest strongly the existence of the ultimate land bridge from the continent to Amami Islands may have existed until the Würm ice age.
4) The last land bridge has been submerged since 0.025 Ma, according to sea level rising after the ice age and crustal movements, averaging 1 - 2 cm/yr.

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木村政昭 琉球弧の古地理

近年の潜水調査を含む海底の地質・地球物理学的研究成果をまとめることにより、琉球弧および東シナ海の海底地質の研究を明らかにした。琉球弧の進行過程では2つのステージが基本的である。第1ステージには、東シナ海東縦域の地殻の薄化とそれに伴う琉球弧の変移が、中新世後期から鮮新世中期の間生じた。その後、160万 - 130万年前に、東シナ海東域が広範に隆化した。これには現在の沖縄トラフのかなりの部分を含む。そのため琉球弧はユーラシア大陸の一部であった。その後、更新世初期の今からおよそ130万年前に、第2ステージが進行した。そして現在の琉球弧（海底地形的には琉球海嶺）が形成された。琉球弧は2つの主な時期に、台湾を通って中国大陸と陸橋としてほぼ陸続きとしていたとみられる（たとえば160万 - 100万年前と20万 - 25万年前）。この琉球古陸はおよそ25万年前に、海変動と後火山活動の面における活動によって段階的に沈水していった。琉球弧の水深10 - 35 mの海底には複数の火山群が広がっており。それらの洞穴はウルム火山に連続したものである。そのうちの1つは竜石が得られた。さらに6,000万年より古い時期に形成されたと推定される階層ピラミッドのような形をした火山の集積が与那国島の海底から発見された。そのような遺跡の存在は琉球弧の沈水過程を解明する手がかりを与えるものとなる。