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KARST DISTRIBUTION AND CONTROLS ON YORON-JIMA, AN EMERGED REEF ISLAND IN SUB-TROPICAL JAPAN

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Yoron-jima is a small carbonate island located in the central Ryukyu Island Arc of southern Japan. The island was raised above sea level in the Quaternary period, and most of the 21 km² land area is underlain by carbonate rock types associated with the regional Ryukyu Limestone Group. The island's landscape is characterized by many surface depressions. This paper describes Yoron's closed depressions and interprets their uneven spatial distribution. Some areas covered by unconsolidated Holocene deposits are almost free of closed depressions. Elsewhere, depression clusters are observed on a variety of carbonate rocks. Small depressions (average long axis 76 m, area 2320 m²) tend to be shallow with regular elliptical morphologies, and are densely clustered. These have developed on a low elevation, emerged marine platform on the island's western peninsula, where there has been minimal structural deformation of the coral limestone bedrock. In contrast, larger (average long axis 103 m, area 4060 m²) and deeper closed depressions (5–10 m), more often with irregular or star-shaped plans, have developed across the north and east-central region of Yoron, in association with 1.) outcrops of rhodolith limestone geology, 2.) major fault escarpments, and 3.) carbonate/non-carbonate geological boundaries. Aggressive dissolution has also produced large elongated closed depressions trending along the northeast coast of Yoron close to sea level, where tidal fluctuations control the salinity and surface height of the water table. Correlation with depressions elsewhere in the Ryukyu Islands on similar geology suggests that limestone surface denudation rates on Yoron may be 5–10 mm/1000 yrs.

Although there are a large number of both wholly carbonate and composite carbonate/volcanic islands in the humid tropical Pacific, there has been less attention given to Oceania in the karst literature than elsewhere. This is, in part, a function of the remoteness for research purposes of most of the small "outer" islands of the Pacific. The work by Ollier (1975) on the Trobriand Islands of Papua New Guinea, Montaggioni *et al.* (1985) on Makatea in French Polynesia, Strecker *et al.* (1986) on Santo island in Vanuatu, Mylroie *et al.* (2001) on Guam and Terry & Nunn (2003) on Niue are some exceptions. This paper describes Yoron Island of southwest Japan, a small raised limestone island in the center of the Ryukyu Island Arc chain (Fig. 1). Yoron's geology mainly comprises Miocene to Holocene age carbonate rocks and deposits, uplifted to different elevations above sea level. The island is partially karstified, although the distribution of karst features across the island is uneven. Yoron therefore presents an interesting opportunity for the study of karst geomorphology on a small emerged carbonate island. The aim here is to examine the form and distribution of closed depressions on Yoron Island and to interpret their occurrence in terms of geological influences.

PHYSICAL SETTING

Yoron's location is 27°01'N, 128°24'E, near the large volcanic island of Okinawa to the southwest. The circumference measures approximately 23 km and the land area covers just 21 km². The resident population numbers around 6000. Most of the native sub-tropical forest cover has been cleared. Sugar cane farming and beef cattle grazing are now the two predominant agricultural land uses. Yoron's climate is subtropical, with a mean annual temperature of 23°C and an annual precipitation of approximately 2200 mm. Typhoons often bring torrential rains during the summer and early autumn seasons from July to September.

Yoron Island was slowly raised above sea level during the Pleistocene (Omura 1972). Inland Yoron can be divided into several main geomorphic zones, reflecting the influences of uplift and structural geology. The western peninsula is a flat limestone lowland between 5 m and 20 m above sea level. Traversing the island from NNW to SSE is an escarpment occurring along a pair of parallel faults. The scarp slope rises to 50–90 m elevation. The highest point of the island at 97 m elevation lies along the top of the escarpment near its southern end. The north and eastern topography of Yoron, east of the top of the escarpment, is a series of low undulating hills, which gradually lose altitude towards the east coast. These may represent a series of denuded marine terraces indicating intermittent uplift processes or still-stands of paleo-sea level. Inland from the eastern coast is an area of Holocene coralline deposits forming low relief dunes. The subdued relief in the eastern segment is broken by an unusual narrow arcuate ridge of outcropping reef limestone called Uro Yama. The ridge is 20–100 m wide, rising 10–20 m above the surrounding terrain.

Since Yoron's bedrock geology mostly comprises permeable carbonates, there are no permanent surface watercourses. Ephemeral streams drain the area below and to the west of the fault escarpment into Haki Bay and Chahana Bay. Within the limestone bedrock beneath the surface, there exists a large freshwater aquifer. In the eastern segment of the island, Momii *et al.* (2001) calculated that this aquifer is 30–40 m thick, using a numerical approach based upon measurements of the fresh-

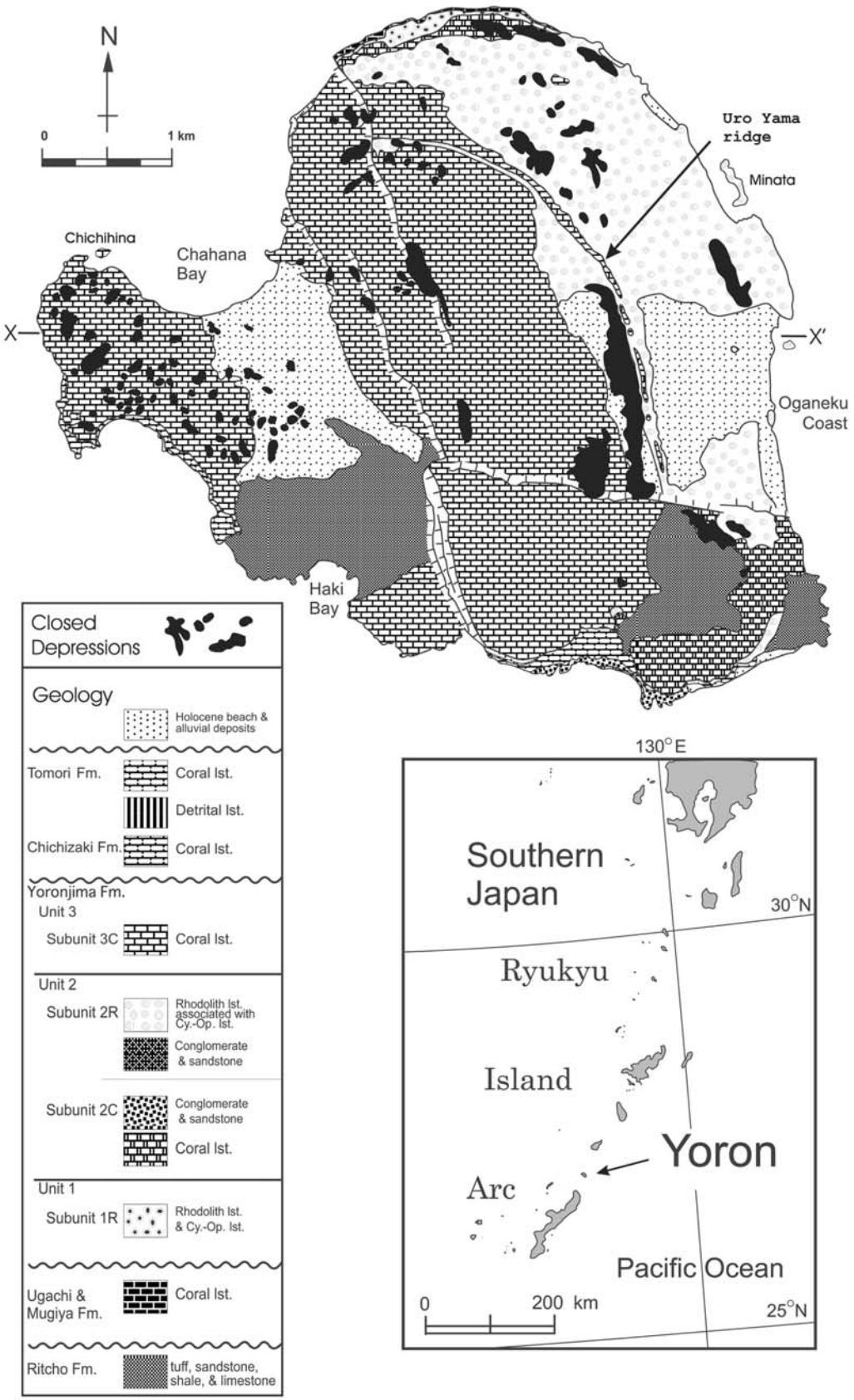

Figure 1. Location of Yoron Island in the Ryukyu Island Arc chain, simplified geology of Yoron (by Odawara and Iryu 1999), and map of enclosed depressions. X–X' shows the line of cross section in Figure 2.

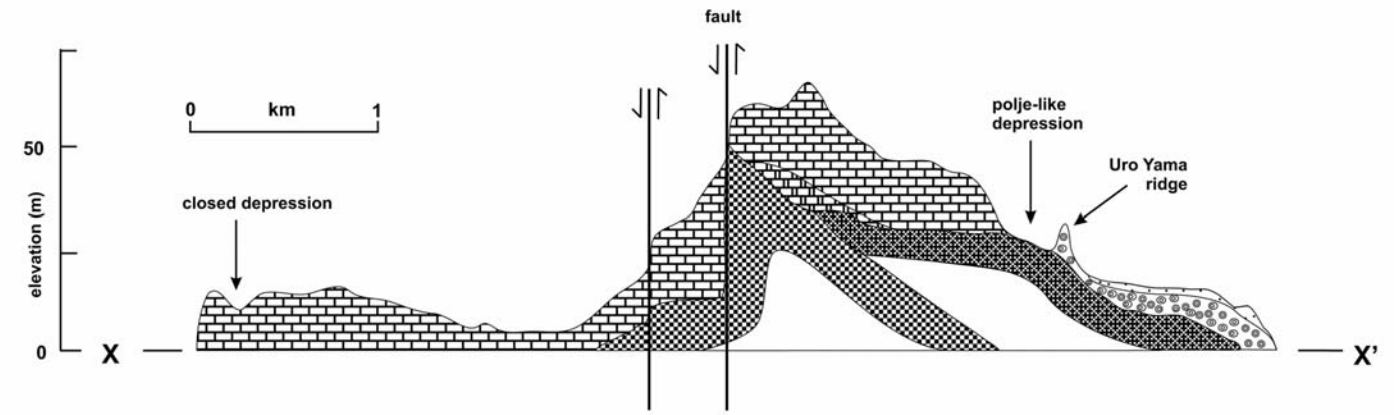

Figure 2. A geologic cross section of Yoron island by Odawara and Iryu (1999).

water lens surface in 10 groundwater wells. The lens may be thicker still towards the center of the island where there is a greater depth of limestone bedrock. Momii *et al.* (2001) also estimated the hydrological balance of the aquifer (evapotranspiration 45%, runoff 15%, groundwater recharge 40%) and hydraulic conductivity of the freshwater zone and effective porosity of 0.28 cm s^{-1} and 0.08, respectively due to the presence of unconsolidated clays contained in pores influencing the limestone permeability.

GEOLOGY

The Ryukyu Island Arc is produced as the result of the northwest movement of the Philippine Sea Plate and its subduction under the Eurasian continental plate at the Ryukyu Trench. Yoron exists as a series of raised Pleistocene limestone terraces, overlying folded and faulted Mesozoic basement rocks of various lithologies associated with volcanism. Odawara and Iryu (1999) have constructed the latest geologic map of the island (Fig. 1). Their work supersedes previous geologic maps and makes major revisions to earlier limestone stratigraphy.

Yoron is a composite island according to the Carbonate Island Karst Model (CIKM) of Mylroie & Jenson (2000). The oldest surface rocks on Yoron are of Mesozoic age, known as the Ritcho Formation. These are strongly altered slates, volcanic greenstone (diabase), tuffs, sandstones and detrital limestones, which crop out in two separate areas in the south and southeast of Yoron. Lying unconformably above are Pleistocene-age limestones of the Yoronjima Formation, equivalent to the Gusuku and Nama Formations described in earlier work by Omura (1972). The Yoronjima Formation is the predominant carbonate sequence on Yoron and occurs over approximately 70% of the island, with a maximum thickness of 55 m. From the evidence of stratrigraphic position and age-diagnostic fossils, Odawara and Iryu (1999) suggest that the Yoronjima Formation may be correlated with the main Ryukyu Group limestones, which are widely distributed throughout the Ryukyu Islands (Nakamori *et al.* 1995). On the nearby islands of Okinoerabu and Tokunoshima, the Ryukyu Group limestones range in age from 390 to 890 ka.

The Yoronjima Formation is extensively exposed on Yoron and has a basal unit of conglomerate of angular pebbles, cobbles and boulders (Omura 1972). The clasts are derived from the underlying Mesozoic age Ritcho Formation. The upper unit of the Yoronjima Formation can be broadly differentiated into two types of carbonate rocks, proximal coral limestone and distal rhodolith limestone (algal ball limestone). The latter has more than 20% concentration by volume of rhodoliths (algal balls), deposited in an insular shelf environment at 50–100 m depth. Distal rhodolith limestone is a hard, massive limestone, and is the bedrock in the northeast segment of the island. The proximal coral limestone is a massive indurated limestone, showing framework structures of hermatypic corals and other fossils of coralline algae, foraminiferans, molluscs, bryozoans and echinoids (Omura 1972). The coral limestone formed as a reef flat and forereef slope 0–50 m deep. It occurs on the western peninsula and as a broad band 1–1.5 km wide traversing NNW–SSE across the center of the island.

Several normal faults run NNW–SSE and W–E across the latter area, and are expressed as escarpments in the island's topography as described earlier. The eastern side of the main NNW–SSE fault is the upthrown block, and has therefore been raised to a higher elevation above sea level. Faulting is probably still active (Odawara & Iryu 1999), and is probably associated with expansion of the nearby back-arc basin called the Okinawa Trough during the Holocene (Kawana 2001). A geologic and topographic cross section from west to east across Yoron, from Odawara & Iryu (1999), is shown in Figure 2.

Holocene beach and alluvial deposits are found covering low-lying areas behind Chahana Bay and Oganeku Beach. Limited exposures of cemented beachrock also occur in several coastal locations. Throughout the Ryukyu Islands, Holocene reefs began forming on older carbonate foundations around 8,500 years to 8,000 years BP. Yoron's Holocene reefs appear to have grown at 1–3 mm a year, and reached modern sea level about 5,000 years ago (Kan *et al.* 1995). The thickness of Holocene reef deposits ranges from 3 to 15 m. Today, Yoron is fringed by coral reefs around almost the entire coastline.

CHARACTERISTICS AND DISTRIBUTION OF SURFACE DEPRESSIONS

The Geographical Survey Institute of Japan (1976) has produced a detailed topographic map of Yoron at 1:25,000 scale. This map was used here to examine the distribution and size of depression features across Yoron. In addition, fieldwork on Yoron was carried out in December 2003 to examine the characteristics of various individual depressions.

The map in Figure 1 shows that Yoron has many closed depressions, but that their spatial distribution over the island is very uneven. Concentrated depression swarms occur in some areas whereas elsewhere closed depressions are absent. The southern and eastern segments of the island, as well as the center of the island, are virtually depression-free. In the east, the lack of closed depressions may be explained by bedrock porosity and hydraulic conductivity. Here, Momii *et al.* (2001) monitored groundwater fluctuations in several boreholes as part of their study on tidal influences on the freshwater aquifer. They noted that the relatively low permeability of the bedrock is influenced by the presence of unconsolidated clay contained in pores. Another factor for the lack of closed depressions in the two areas of Holocene beach and alluvial deposits (inland of the east coast and west of the escarpment) is that these unconsolidated coralline materials are less suitable for retaining depression structure, compared to hard and jointed bedrock in adjacent areas. Closed depressions are also absent on the two outcrops of Mesozoic basement rocks (Ritcho Formation slates, volcanic greenstone and sandstone) in the southeast and southwest sectors of the island.

In the central east of Yoron is the island's largest surface depression, oriented in a N–S direction. This 2-km-long linear depression is a low-lying trough, partly infilled with Holocene deposits, and gives the initial impression of a polje-type feature. However, closer inspection of the local geology shows that the trough is bounded by gently dipping rocks on the western side and on the east by the 10–20 m high Uro Yama arc-shaped ridge of reef limestone described earlier. Although the origin of Uro Yama remains unclear, the origin of the adjacent large depression is probably neither a true karst feature, because there is no source for allogenic water to account for increased dissolution rates, nor a graben-like feature formed by structural deformation because there are no faults associated with the Uro Yama ridge. The depression is probably a constructional feature inherited from an original topographic low formed between different carbonate facies during deposition.

Elsewhere on Yoron, there are two notable areas where depression swarms are observed, although these areas differ in terms of depression sizes and clustering. The smaller cluster, but the one with the highest concentration of closed depres-

Table 1. Size characteristics of all closed depressions on Yoron Island.

Ranked maximum length across enclosing contour (m)							Ranked area (m^2 x 1000)						
Western Peninsula				**Northern and Eastern Area**			**Western Peninsula**				**Northern and Eastern Area**		
44	63	76	101	52	89	163	1.16	1.74	2.32	4.06	1.16	2.32	8.13
45	63	77	107	58	91	169	1.16	1.74	2.90	4.06	1.16	2.32	9.29
48	64	78	110	60	91	185	1.16	1.74	2.90	4.06	1.16	2.90	9.29
49	64	78	111	62	95	190	1.16	1.74	2.90	4.65	1.16	2.90	13.35
50	65	79	113	62	99	268	1.16	2.32	2.90	4.65	1.16	3.48	19.74
50	67	82	116	64	101	330	1.16	2.32	2.90	4.65	1.16	3.48	19.74
57	67	82	126	64	103	348	1.16	2.32	2.90	5.23	1.74	3.48	21.48
62	68	82	132	66	103	350	1.16	2.32	2.90	5.81	1.74	4.06	22.06
62	68	84	132	66	103	369	1.16	2.32	2.90	6.39	1.74	4.06	23.23
62	73	86	140	66	105	381	1.16	2.32	2.90	6.39	1.74	4.06	24.97
63	73	86	140	68	113	439	1.74	2.32	2.90	6.97	2.32	4.65	31.93
63	76	88	149	72	124	470	1.74	2.32	3.48	7.55	2.32	5.81	39.48
63	76	89	150	78	128	470	1.74	2.32	3.48	8.13	2.32	5.81	44.13
63	76	89	151	80	130	546	1.74	2.32	3.48	8.71	2.32	5.81	59.81
63	76	91	160	82	140	591	1.74	2.32	3.48	9.87	2.32	6.39	96.39
63	76	94	252	87	161	1690	1.74	2.32	3.48	20.32	2.32	6.97	232.83
63	76	94	285				1.74	2.32	3.48	29.03			
63	76	98					1.74	2.32	3.48				
Number of depressions			71			48				71			48
Mean			89			205				3.68			16.09
Median			76			103				2.32			4.06
Standard Deviation			42			262				4.13			36.57
Total			–			–				261.29			772.25

Note: The contour interval is 5 m on the 1:25,000 scale 1976 topographic map of Yoron.

sions, occurs on Yoron's western peninsula. This is a low-lying platform of Yoronjima coral limestone, 5–20 m above sea level. The northern and southern bays of the western peninsula are cusp-shaped. From the work of Back *et al.* (1979) along the Yucatan coast of Mexico, a cusp morphology suggests coastal limestone dissolution by freshwater/seawater mixing. Yoron's western peninsula has 71 individual closed depressions with a total area of 21.6 hectares in an area of approximately 3 km². The relative area of the peninsula covered by depressions is therefore approximately 7.2%. During fieldwork, it proved impossible to measure depression depths or side wall angles because they tend to contain good accumulations of soil and are therefore farmed with sugar cane. Others have been mechanically excavated and lined, to be used as water reservoirs for sugar cane irrigation (Fig. 3). However, most of the closed depressions on the western peninsula were observed to be simple elliptical, shallow, saucer-shaped features, less than 4 m in depth. The median measurement of depression long axes is 76 m, generally without a large range in size of individuals from this average (Table 1). Median depression area is 2320 m² (medians are given because the population means may be skewed by a few large individuals).

According to the karst research of several workers, (e.g., Mylroie & Carew (1995) and Wilson *et al.* (1995)), the closed depressions produced by dissolution on young carbonate islands are of small to modest size, (i.e., meters to tens of meters). This is because "areas with autogenic recharge are unlikely to develop deep depressions because dissolution tends to be dispersed rather than focused" (Mylroie *et al.* 2001, p. 13). Most of the small depressions on Yoron's western peninsula seem to fit this general model.

The other important area of depressions is in the northern and east-central segment of Yoron. The bedrock here comprises both coral and rhodolith limestones. The landscape is an area of low hills with gentle topography, 10–50 m above sea level. Figure 1 shows that there are fewer closed depressions here, more widely dispersed and exhibiting less clustering compared to Yoron's western peninsula. However, the north and east-central area has generally large closed depressions. This area also has the deepest depressions on Yoron—those formed along the base of the fault escarpments reach 5–10 m in depth. Measurement of 48 closed depressions in the northern and east-central area gives median values for depression long axes and area of 103 m and 4060 m², respectively. The total area of all depressions is 77.2 hectares, within a region of 13.67 km² (i.e., 5.6 % coverage).

The average depression size in the northern and east-central region is skewed by three sub-sets of large closed depressions within the population. Several large depressions are those with star-shape or irregular plans, rather than the more usual elliptical morphology. Star-shaped depressions are produced where dissolution has caused several smaller depression perimeters to coalesce into a single feature. These occur most often in the northeast of Yoron on the rhodolith limestone, suggesting that this rock type may be more soluble than the adjacent coralline rock. An alternative origin for star-shaped and irregular depressions is increased dissolution along the intersection of several bedrock fractures. This would suggest that the rhodolith limestone is more fractured than the coral limestone, but this idea cannot be independently substantiated by evidence from existing geologic maps, which only indicate the occurrence of major faults and not the extent of bedrock fracturing.

Figure 3. Top: Typical small shallow depression on Yoron; most closed depressions are used for agriculture. Bottom: Excavated and lined depression to be used as a water reservoir for irrigation.

A second sub-set of large depressions are those lying along the base of fault escarpments, and at the northern edge of the exposure of Ritcho Formation geology in the southeast of Yoron. The depressions in escarpment-foot locations are subject to more aggressive dissolution than elsewhere. Evidence for this idea is that the small ephemeral streams on Yoron also have their source areas at the base of these escarpments, and must therefore be receiving fault-guided resurgence of groundwater from the higher land to the east. In the case of the large depressions along the edge of Ritcho Formation rocks, aggressive dissolution is likely to be associated with allogenic water

originating on these non-carbonate rocks and funnelled to the contact with the adjacent Yoronjima Formation carbonates.

The third sub-set of large closed depressions is a chain of four elongated features formed along the north and east coasts. The orientation of their long axes trends very closely to the shoreline. This trend is explained as follows. Weathering at the base of elongated coastal depressions which mostly lie at or close to sea level is enhanced by the rapid dissolution typical at the brackish mixing zone between the fresh groundwater lens and seawater, because the coastline marks the groundwater aquifer transition zone between freshwater and saltwater (see Gillieson 1996). This is supported by the work of Momii *et al.* (2001), who observed that the coastal zone of Yoron's aquifer is strongly affected by tidal fluctuations. Thus bedrock dissolution and depression formation is encouraged by the vertical movement of the aquifer surface with every tidal phase. Any large coastal depressions which are more than 1 m above sea level, and therefore not affected by present tidally-induced fluctuations of the freshwater lens, probably represent paleofeatures nonetheless developed in a similar way during a previous sea-level stillstand, when they were at sea level. Nunn (1994, p. 199) points out that on small limestone islands, dolines occurring along the coast and being breached by the sea commonly give rise to a coastline where an erosional outlier is found at the entrance to a bay. This idea may present a reasonable origin for the small islets called *Minata* and *Chichihina* lying short distances off Yoron's northeast and northwest coasts.

The closed depressions on Yoron are comparable with those on nearby Okinoerabu Island, which lies 27 km to the northeast of Yoron and has similar uplifted Pleistocene geology of the Ryukyu Group limestones. On Okinoerabu, Maekado (1984) examined the shape of 10 closed depressions at 30–40 m above sea level. The plan view of Okinoerabu closed depressions was found to be circular or elliptical, with cross-sections generally bowl-shape. The average measured long diameters of depression mouths was 57 m and depression bottoms was 43 m (Ryukyu University 1976). Depression sidewall angles range 10°–26° and depths 1.6–5.1 m. Using the 313–625 ka age range for the limestone determined by electron spin resonance (reported by other workers), Maekado (1984) estimated the rate of surface lowering by solution to be 5.0–9.9 mm per 1000 years.

CONCLUSIONS

Yoron is a small carbonate island in the central Ryukyu Island Arc of southern Japan, formed by the Quaternary uplift and emergence of coral reefs and associated carbonate rocks. The sub-aerial geology therefore comprises an interesting range of lithologies, including Pleistocene fossil reefs, rhodolith (algal ball) limestone and partly-cemented Holocene coralline sands and gravels. The most abundant karst features in the landscape developed on these carbonate sequences are a variety of closed depressions. These have formed as a result of the interaction of uplift, faulting and dissolution processes, and are influenced by changes in carbonate geology across the island. According to location, Yoron's closed depressions display differences in maximum long axes (medians 76 m and 103 m), shape (elliptical, elongated, irregular or star-shape), depth (< 5 m or 5–10 m), size (0.23–0.41 Ha) and relative density (5.6–7.2% cover).

Factors controlling these depression characteristics, and their uneven spatial distribution, include bedrock type and permeability, juxtaposition along the base of fault escarpments or carbonate/non-carbonate geologic boundaries, and the effects of tides on coastal water table fluctuations and consequent freshwater/saltwater mixing. The primary origin of the largest polje-like feature in the center of the island is not dissolution, but probably inheritance from the morphology of original reef-and-shelf construction. Correlations with other Ryukyu Islands nearby suggest that limestone surface lowering rates may be 5–10 mm per 1000 years. The karst geomorphology is an important economic asset for Yoron, as many closed depressions are now excavated for water storage reservoirs in the absence of rivers on the island.[1]

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[1] Most of the depressions now exhibiting anthropogenic modification were excavated after the surveying for the 1976 topographic map used in this study, so the reliability of depression measurements is not affected.

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