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Yoron Island in Southern Japan - Quaternary Geology and Solution Controls on Surface Landforms

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Abstract

Yoron Island is a small carbonate island in the Ryukyu Island Arc of southern Japan, lying 27 km north west of Okinawa. The island emerged above sea level in the Quaternary period as a result of uplift associated with plate boundary tectonics. Yoron's geomorphology is characterised by a variety of features which are typical of emerged carbonate islands, such as angular limestone cliffs, cuspate bays with beaches of coralline sediments, marine terraces at different elevations, fault escarpments, ridges, vadose cave systems, and numerous shallow dolines (closed surface depressions). The spatial patterns and inter-relationships between these landforms are determined by a number of factors. These include structural controls associated with island uplift, variations across the island in the surface exposure of different carbonate geologies (e.g. reef and rhodolith limestones and Holocene deposits), and solution processes which are influenced both by 1. allogenic recharge along faults or carbonate/non-carbonate geological boundaries and 2. groundwater lens interaction with sea level in coastal localities.
Key words: geomorphology, solution features, Quaternary limestones, Yoron Island

Introduction and Background

Yoron Island, also known as Yoronjima and Yoron-to, is located in the centre of the Nansei-Shoto group of islands of southern Japan, approximately 40 km NW of Okinawa island, at latitude 27°01'N, longitude 128°24'E (Fig. 1 and 2). The shape of the island resembles an angel fish, with a narrow peninsula at the western end. The land area covers just 21 km^2 and the coastline is 23 km in circumference. Approximately 6000 people live permanently on Yoron, but a large number of tourists visit each year, especially in summer. The climate is subtropical with a mean annual temperature of 23°C. Annual rainfall amounts to 2200 mm, some of which occurs as torrential downpours associated with typhoons in summer and early autumn (July to September). The original native forest has been cleared for agriculture, namely sugar cane farming and beef cattle grazing. There are no permanent surface watercourses on Yoron because the geology mostly comprises permeable carbonates. However, a large freshwater aquifer 30-40 m thick, exists within the bedrock, the hydrological balance for which was estimated as evapotranspiration 45%, runoff 15%, groundwater recharge 40% by MOMII *et al.* (2001).

Yoron is part of a chain of islands, formed as a volcanic island arc and known as

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Fig. 1. Oblique aerial photo of Yoron Island. Photo by Kihachiro Kaneko.

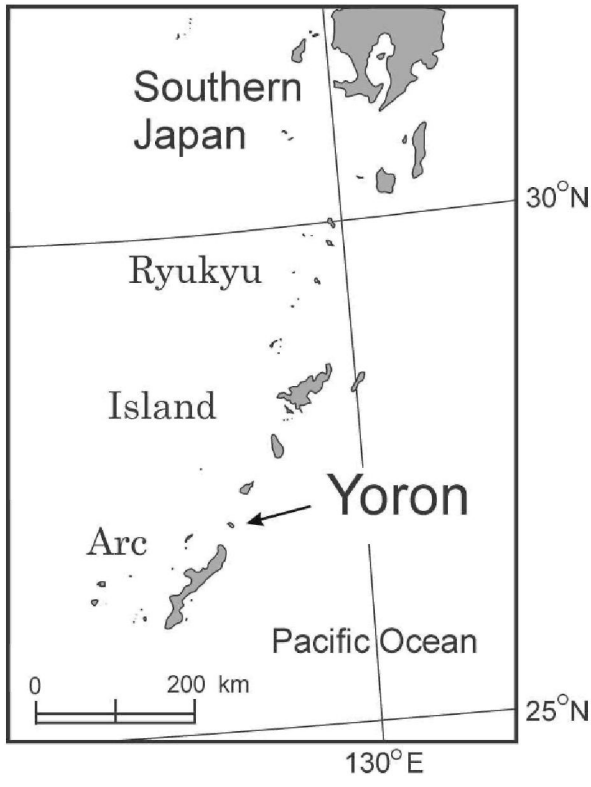

Fig. 2. Location of Yoron Island in southern Japan.

the Ryukyu Island Arc. The Ryukyu Arc is produced by the subduction of the Philippine Sea Plate under the Eurasian continental plate at the Ryukyu Trench. The rock types on Yoron are mostly Miocene to Holocene age carbonates, which are weakly karstified and occur as a series of low relief marine terraces, uplifted to different elevations above sea level. There are also some outcrops of faulted and folded non-carbonate basement rocks, associated with Mesozoic volcanism. This means that Yoron can be classi-

fied as a "composite island" according to the Carbonate Island Karst Model of MYLROIE *et al.* (2001). The aim of this paper is to describe the main features of Yoron's geomorphology, and to determine the factors responsible for their origin and distribution.

Geology

ODAWARA and IRYU (1999) produced the latest geological map of Yoron (Fig. 3), which improves on previous geology maps. 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 S and SE of Yoron. Situated unconformably above are Pleistocene age limestones of the Yoronjima Formation; this is the predominant carbonate sequence and occurs over approximately 70% of Yoron, with a maximum thickness of 55 m. From stratigraphic and palaeontological evidence, ODAWARA and IRYU (1999) correlate the Yoronjima Formation 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 (ODAWARA and IRYU 1999).

The Yoronjima Formation carbonates have a basal unit of conglomerate of angular pebbles, cobbles and boulders (OMURA 1972). The upper unit can be broadly differentiated into coral limestone and rhodolith limestone (algal ball limestone). The coral limestone is a massive indurated limestone, formed as a reef flat and fore reef slope 0-50 m deep. It shows framework structures of hermatypic corals and other fossils of coralline algae, foraminiferans, molluscs, bryozoans and echinoids (OMURA 1972). The coral limestone occurs on the western peninsula and as a broad band 1-11/2 km wide traversing NNW-SSE across the centre of the island. Several normal faults run NNW-SSE and W-E across the latter area, and are expressed as a low escarpment in the island's topography (see below). Faulting is probably still active because of movement associated with subduction at the nearby Ryukyu Trench. The rhodolith limestone has more than 20% concentration by volume of rhodoliths (algal balls), originally deposited in an insular shelf environment at 50-100 m depth. It is a hard, massive limestone, and is the main bedrock in the NE segment of the island. 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.

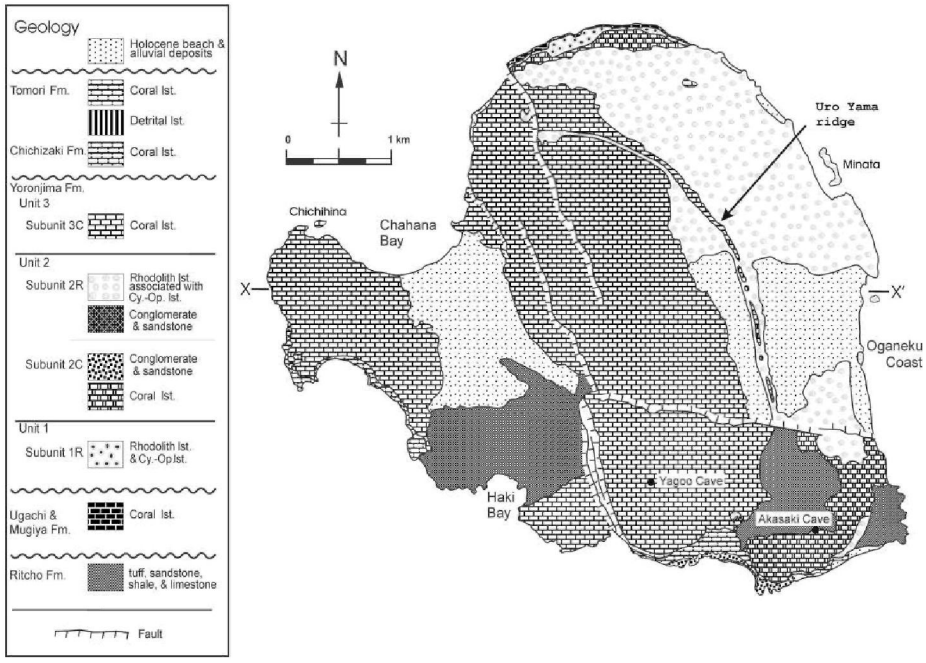

Fig. 3. Simplified geological map of Yoron by ODAWARA and IRYU (1999); X-X' shows the line of cross section in Fig. 6.

Geomorphology

Coral Reefs and Coastal Morphology

Throughout the Ryukyu Islands, Holocene reefs began forming on older carbonate foundations around 8,500 to 8,000 BP (van WOESIK, unpublished). Yoron's Holocene reefs appear to have grown at 1-3 mm per year, and reached modern sea level about 5,000 years ago (KAN *et al.* 1995). The thickness of Holocene reef deposits ranges from 3.0 to 15.0 m. Today, Yoron is fringed by coral reefs around almost the entire coastline (Fig. 4).

Yoron's coastal geomorphology is characterised by a low rocky limestone cliff line (Fig. 5). A series of bays is sculpted along the southern coast, occupied by white sand and gravel beaches of coralline materials. The largest bays on the north and south side of Yoron's low lying western peninsula, e.g. Chahana Bay, are cusp-shaped (Fig. 3). Work by BACK *et al.* (1979) along the Yucatan coast of Mexico provides evidence that the cuspate morphology of bay in coastal limestone is the result of solution by mixing of freshwater and seawater at the edge of the groundwater lens. Short distances off the coast in several locations lie small isolated islets, for example Minata and Chichihina in the NE and NW of Yoron. The origin of these is suggested by NUNN (1994:199), who mentions that solution dolines occurring along the coasts of small limestone islands may be breached by marine erosion, commonly giving rise to a coastline where an erosional outlier is found at the entrance to a bay.

Along the east coast of Yoron is the island's longest sandy beach, called Oganeku

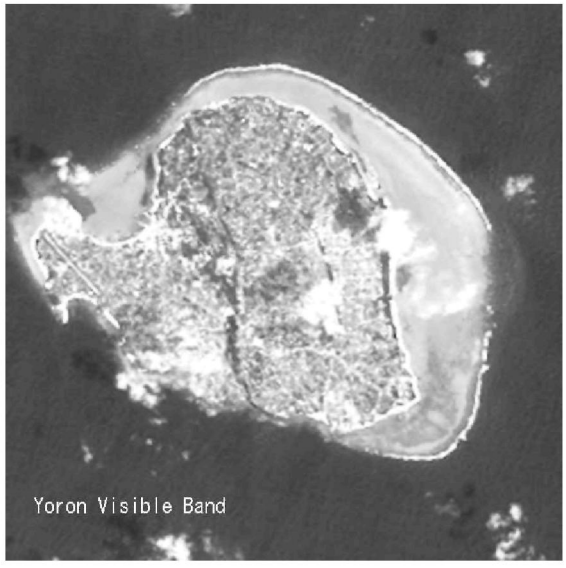

Fig. 4. Extent of fringing coral reefs around Yoron, as shown on a visible satellite image (Prof. K. Kinoshita, Kagoshima University).

Fig. 5. Left: Low limestone cliffs and coralline beaches on the south coast of Yoron's western peninsula. In the background is the escarpment of a NNW-SSE fault line. This forms the major topographic feature on the island and attains a maximum elevation of 97 m. Right: View of the south coast from the top of the fault escarpment.

Beach, which is popular with tourists in summer. This beach is almost straight and 2 km long. Lying 1.5 km offshore from Oganeku is Yurigahama Beach. This is a lagoon shoal which becomes exposed at low tide and is famous throughout Japan for its composition of 'star sand' - star-shaped sand grains made from the calcareous tests of dead plankton.

Terraces, Escarpment and Ridge

Yoron was slowly uplifted above sea level during the Pleistocene period, and simultaneously eroded and flattened to produce the present topography (OMURA 1972). Expansion of the nearby back-arc basin called the Okinawa Trough probably also caused tilting of Yoron during the Holocene (KAWANA 2001). Yoron's topography can therefore

be divided into three main zones, reflecting the influences of differential uplift and structural geology (Fig. 6): 1. The western peninsula and the northern segment are flat limestone terraces. The terraces occur at elevations from 10-30 m above sea level, and are assumed to be Quaternary features of marine erosion, although no dates have been determined for their formation. 2. Traversing the southern part of the island from NNW to SSE is an escarpment occurring along a pair of parallel fault lines. 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. Ephemeral streams drain the area below and to the west of the fault escarpment into Haki Bay and Chahana Bay. 3. To the east of the top of the escarpment is an undulating area of low hills, gradually losing altitude towards the east coast of Yoron. Inland of the eastern coast is an area of Holocene coralline deposits forming low relief dunes. The subdued relief of low hills and dunes in the eastern segment is broken by an interesting 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. Although the origin of Uro Yama ridge remains unclear, it is not a feature resulting from tectonic-structural deformation because there are no faults associated with it. The ridge is probably a constructional feature, inherited from an original topographic high formed between different carbonate facies during their deposition.

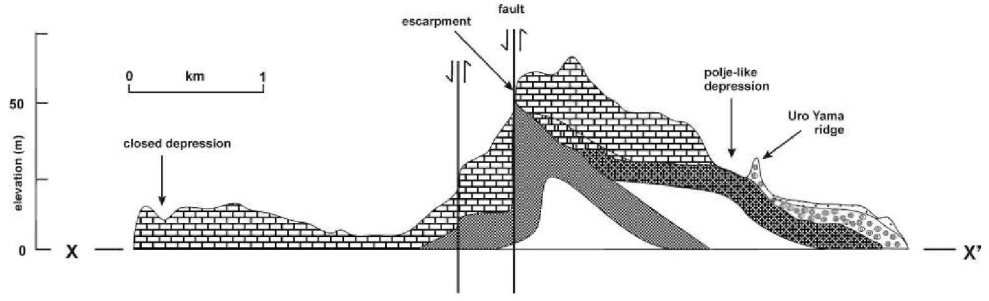

Fig. 6. Topographic cross section of Yoron, showing also features of geomorphology, and geology based on the work of ODAWARA and IRYU (1999). The legend for the rock types is given in Fig. 3.

Caves

Along Yoron's coastal cliffs are numerous small sea caves which have been exposed by marine erosion. Most of these simple caves are rock overhangs or notches found at different heights on cliff faces and were cut by wave action. Inland, several vadose zone caves are accessible from the surface. Although there are few written accounts of any deep underground explorations, an expedition report by TORIUMI (1998) mentions that there are 13 known caves on Yoron, and ARAKAWA *et al.* (1993a) suggest that limestone caves sit at 5 different levels. The best known examples are two show caves open to tourists in the south of Yoron, at Akasaki and Gusuku. The entrances to both are cut in outcrops of coral limestone. Akasaki has a large natural vadose chamber decorated with stalactite formations (Fig. 7). The cave at Gusuku, called Yagoo Cave, has small passages at several levels. Near the surface the cave floor is dry, sandy and

made uneven by large blocks of limestone, presumably originating from the ceiling as successive cave levels were cut or collapsed to lower levels. In 1997, Toriumi's team of speleologists explored deeply into this system. Yagoo Cave proved to be the longest cave so far discovered on Yoron, measuring 1426 m long with 6 exits. In the farther section, much of the cave had low ceilings and was difficult to navigate, with a wet and muddy floor.

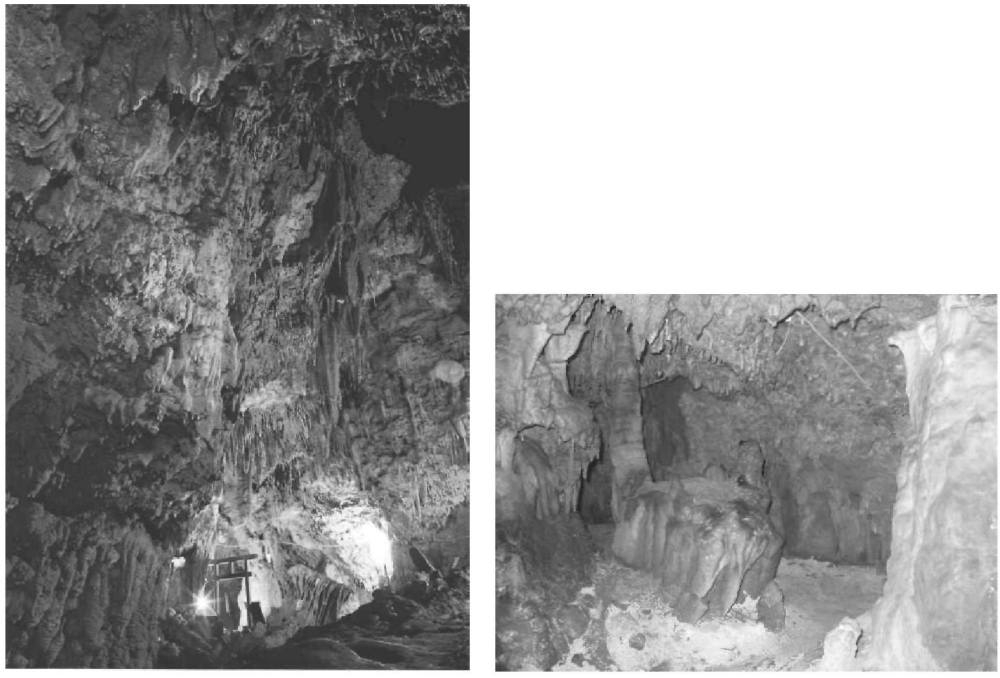

Fig. 7. Left: large cavern decorated with speleothems inside Akasaki Cave (Source: IDEMURA 1973). Right: dry vadose chamber in Yagoo Cave at Gusuku.

ARAKAWA *et al.* (1993b) collected many speleothems from five different horizontal caves at several terrace levels. These were dated using the Electron Spin Resonance (ESR) method and all except one speleothems sample gave ages less than 25,000 BP. The explanation proposed by ARAKAWA *et al.* was that limestone solution on Yoron is rapid because the climate is sub-tropical, the limestones very porous, and crustal movements are active. This leads to one cycle of cave formation occurring in less than 30,000 years. Hence, speleothems that formed before 25,000 BP collapsed and disappeared during the last cycle of cave development.

Dolines (Closed Surface Depressions)

The Japanese Geographical Survey Institute (1976) has constructed a detailed topographic map of Yoron at 1:25,000 scale. This map was used here to examine the distribution and size of dolines across Yoron. Fieldwork on Yoron was also carried out by the author in December 2003 to examine the characteristics of various individual dolines.

Fig. 8 shows that many depressions have been mapped on Yoron, but that their spatial distribution across the island is uneven. Concentrated doline swarms occur in some areas, whereas elsewhere dolines are absent. The author has described and interpreted the distribution of dolines in detail in TERRY (2005), and the following account is a summary of this work.

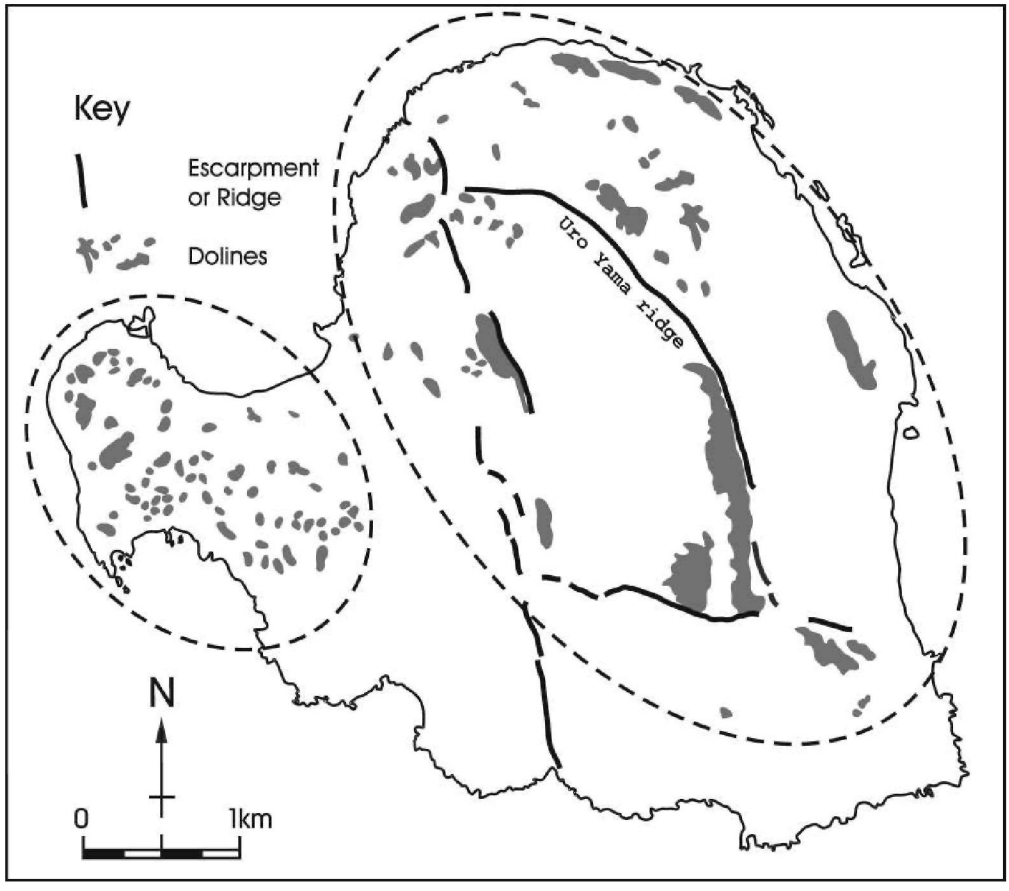

Fig. 8. Map of the distribution of dolines across Yoron within two main groups, based on fieldwork and the 1:25,000 Topographic Map of Yoron (Geographical Survey Institute of Japan 1976).

Dolines are absent on the two outcrops of Ritcho Formation non-carbonate rocks (slates, volcanic greenstone and sandstone) in the SE and SW sectors of the island. The southern, eastern and central segments of the island are also virtually doline-free, for which a combination of factors is responsible. In the east, this may be explained by low bedrock porosity, owing to the presence of unconsolidated clay contained in pores (MOMII *et al*. 2001). The absence of dolines on Holocene beach and alluvial deposits, inland of the east coast and west of the escarpment, is explained by these unconsolidated coralline materials being less suitable for retaining doline structure, compared to hard and jointed bedrock in adjacent areas. On Niue Island, an emerged atoll in the South Pacific, TERRY and NUNN (2003) found a similar effect controlled a lack of dolines on areas of poorly

lithified lagoon sands, compared to good doline preservation in adjacent areas of hard reef limestones.

Yoron's largest surface depression lies in the east central part of the island. This 2 km long linear trough (Fig. 7) is oriented in a N-S direction, is partly infilled with Holocene deposits, and gives the impression of a polje-type feature. Closer inspection, however, 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. This polje-like depression is unlikely to be a true karst feature, because there is no source for allogenic water to account for aggressive solution. A more likely origin is inheritance from a topographic low between different sedimentary facies, formed during carbonate deposition.

Elsewhere on Yoron, two notable groups of doline swarms are observed, although these swarms differ in terms of doline sizes and spacing. The smaller cluster, but the one with the highest concentration of dolines, occurs on Yoron's western peninsula, 5-20 m above sea level. There are 71 individual dolines with a total area of 21.6 hectares in an area of approximately 3 km^2. Relative coverage of the peninsula by dolines is therefore approximately 7.2 %. Field observations proved that many dolines are sites of good soil accumulation, and are therefore farmed with sugar cane. Others have been mechanically excavated and lined, in order to be used as water reservoirs for sugar cane irrigation (Fig. 9). Most of the dolines on the western peninsula are simple elliptical, shallow, saucer-shaped features, less than 4 m in depth. The median measurement of doline long axes is 76 m; medians are given since the mean size is skewed by a few large individual dolines.

According to the karst research of MYLROIE and CAREW (1995) and WILSON *et al.* (1995), dolines produced by solution on young carbonate islands are of modest dimensions, i.e. metres to tens of metres in length. This is because "areas with autogenic recharge are unlikely to develop deep dolines because solution tends to be dispersed rather than focused" (MYLROIE *et al.* 2001. p13). Most of the small dolines on Yoron's western peninsula seem to fit this general model.

Yoron's second main group of dolines is in northern and east-central segment of the island, where the geology comprises coral and rhodolith limestones and the topography is of low hills 10-50 m above sea level. Fig. 8 shows fewer, more widely dispersed dolines here, but these are generally larger and deeper dolines compared to the western peninsula. Measurement of 48 dolines in the northern and east-central area gives a median value for doline long axes of 103 m; those formed along the base of the fault escarpments attain depths of 5-10 m. The sum of doline areas here is 77.2 hectares, within an area of 13.67 km^2, i.e. 5.6 % coverage.

The average doline size in this second group is skewed by three smaller sets of large dolines within the population. The first type of large dolines are those with star-shape or irregular plans, rather than the common elliptical morphology. Star-shaped dolines are produced where solution has caused several smaller doline perimeters to coalesce into a single feature. These occur most often in the NE of Yoron on rhodolith lime-

Fig. 9. Top: polje-like feature in the centre of Yoron, cultivated with sugar cane (left), and a typical small shallow doline on Yoron used for agriculture (right). Bottom: excavated and lined doline (left) to be used as a water reservoir for irrigation (right).

stone, suggesting that this rock type may be more soluble than adjacent coralline rock.

The second type of large dolines are those lying along the base of fault escarpments, and at the northern edge of the exposure of basement geology in the SE of Yoron (Fig. 8). The dolines in escarpment-foot locations are subject to more aggressive solution 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. For the large dolines along the edge of Ritcho Formation non-carbonate rocks, aggressive solution is likely to be associated with allogenic water originating on these basement rocks and transferred to the contact with the adjacent carbonates.

The third type of large dolines is a chain of four elongated depressions 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. The coastline marks the groundwater aquifer transition zone between fresh and salt water. Consequently, weathering at the base of elongated coastal dolines, lying close to sea level, is enhanced by rapid solution typical of the brackish mixing zone between the freshwater lens and seawater. Supported for this idea comes from 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

solution and doline formation is encouraged by the vertical movement of the aquifer surface with every tidal phase.

Dolines on nearby Okinoerabu Island, 27 km to the NE of Yoron, were investigated by MAEKADO (1984). 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. A similar limestone solution rate is probably experienced on Yoron.

Conclusions

Yoron is a small carbonate island in the central Ryukyu Island Arc, formed by the Quaternary uplift and emergence of coral reefs and associated carbonate rocks. The subaerial geology comprises an interesting range of lithologies, including Pleistocene fossil reefs, rhodolith (algal ball) limestone and partly cemented Holocene coralline sands and gravels. The landscape imprinted on these carbonate rocks has a variety of geomorphic features, such as an absence of surface drainage, a coastline of low limestone cliffs and bays, an inland terrace-escarpment-ridge sequence, vadose cave systems, and numerous surface depressions. This range of landforms developed as a result of the interaction of uplift, faulting and solution processes, but is also influenced by changes in carbonate rock and sediment types across the island. The most abundant karst features are dolines, occurring in two main swarms, but varying in size, clustering, depth and plan shape (elliptical, elongated or star-shape). Factors controlling doline characteristics include bedrock type, permeability, juxtaposition along a fault escarpment, and tidal effects on coastal water table fluctuations. In modern times, eco-tourism is benefiting from guided explorations through Yoron's accessible cave systems and the popularity of visiting the famous star-sand beach at Yurigahama. Such activities promote the cultural and heritage value of the landscape on this remote island, where the resource base for the local economy is limited.

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