Geomorphology 229 (2015) 112–124

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Submerged karst landforms observed by multibeam bathymetric survey in Nagura Bay, Ishigaki Island, southwestern Japan

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ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form 15 July 2014
Accepted 16 July 2014
Available online 8 August 2014

Keywords:
Submerged karst
Coral reef
Multibeam echosounder
SCUBA
Ryukyu Islands
Japan

ABSTRACT

Submerged tropical karst features were discovered in Nagura Bay on Ishigaki Island in the southern Ryukyu Islands, Japan. The coastal seafloor at depths shallower than ~130 m has been subjected to repeated and alternating subaerial erosion and sedimentation during periods of Quaternary sea-level lowstands. We conducted a broadband multibeam survey in the central area of Nagura Bay (1.85 × 2.7 km) and visualized the high-resolution bathymetric results over a depth range of 1.6–58.5 m. Various types of humid tropical karst landforms were found to coexist within the bay, including fluviokarst, doline karst, cockpit karst, polygonal karst, uvalas, and mega-dolines. Although these submerged karst landforms are covered by thick postglacial reef and reef sediments, their shapes and sizes are distinct from those associated with coral reef geomorphology. The submerged landscape of Nagura Bay likely formed during multiple glacial and interglacial periods. According to our bathymetric results and the aerial photographs of the coastal area, this submerged karst landscape appears to have developed throughout Nagura Bay (i.e., over an area of approximately 6 × 5 km) and represents the largest submerged karst in Japan.

1. Introduction

Evidence suggests that coastal regions shallower than ~130 m have been subjected to repeated alternations between subaerial and marine conditions during the frequent glacio-eustatic sea-level changes that occurred throughout the Quaternary, with extensive environmental change occurring between glacial and interglacial periods (e.g., Yokoyama et al., 2000; Camoin et al., 2004; Fujita et al., 2010). The geomorphology of shallow coastal regions has been modulated by repeated subaerial and submarine processes during glacio-eustatic sea-level change. However, in contrast to the vast knowledge that has been accumulated regarding terrestrial landforms, few previous studies have dealt with shallow seafloor landforms, which represent former terrestrial landscapes modified by present marine processes, from a geomorphological perspective. In this regard, karst geomorphology is no exception, although Taviani (1984) provided some discussion regarding karst-like features on the ocean bottom from various perspectives.

Submerged karst areas are typically recognized by the subaerial exposure of karst landforms in coastal regions. For example, partly submerged tower karsts have been recognized in Ha Long Bay in Vietnam (Waltham and Hamilton-Smith, 2004), Phang Nga Bay in Thailand (Kiernan, 1994), Dweyra Bay and the Blue Grotto in Malta (Paskoff, 2005), and the Rock Islands in Palau (Dieter, 1991). Similarly, submerged karst landforms have been found in Marseille (Collina-Girard, 1996), the Adriatic Coast of Croatia (Surić, 2002), and near Lesbos Island and along the Argolid Peninsula in Greece (Scheffers et al., 2012). In Japan, submerged dolines have been reported only from Minami Island

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http://dx.doi.org/10.1016/j.geomorph.2014.07.032

(one of the Ogasawara Islands of southeastern Japan), where circular depressions in shallow coastal areas were mapped based on aerial photographs (Hori, 1996). Nevertheless, many previous studies have reported the existence of submerged caves (e.g., Kitamura et al., 2007; De Waele et al., 2009; Surić et al., 2010; Taviani et al., 2012; Mylroie and Mylroie, 2013). These facts suggest the presence of submerged karst features in many coastal areas globally. Moreover, in tropical coral reef areas, antecedent karst underlying postglacial coral reef complexes has been investigated previously and interpreted to control present reef geomorphology (e.g., Purdy, 1974, 1998; Rasmussen and Neumann, 1988; Burke, 1993; Macintyre et al., 2000).

Recent developments in multibeam bathymetric survey technology have enabled the visualization of submarine landforms in three dimensions. For example, this technique has been used to investigate landforms associated with coral reefs (e.g., Webster et al., 2006; Beaman et al., 2008; Abby et al., 2011), bedform structures (e.g., Barnard et al., 2013; Li et al., 2014), tectonic geomorphology (e.g., Tibor et al., 2010; Barrie et al., 2013), glacial features (e.g., Howe et al., 2012), and submerged river landforms (e.g., Harris et al., 2013a). A pioneering study involving the observation of submerged karst by multibeam bathymetric survey was presented by Taviani et al. (2012). That study focused on the Adriatic shelf margin in Italy where eleven submerged dolines with diameters of 50–155 m were found, confirming the presence of thin postglacial deposits covering pre-existing landforms. Similar submerged dolines have been found to the north of the Maltese Islands in the Mediterranean Sea (Micallef et al., 2013). Here, we present the first study to describe a submerged humid tropical karst landscape in Nagura Bay, Ishigaki Island, southern Ryukyu Islands, Japan (Fig. 1A). In particular, we describe the landforms of this region based on a high-resolution bathymetric map with a grid size of 1 m, which we created with reference to observations obtained using our multibeam bathymetric echo-sounding survey combined with SCUBA diving observations.

2. Study area

2.1. Geographical setting

Ishigaki Island is one of the Ryukyu Islands and is located in the northwestern Pacific at latitudes and longitudes of 24°19.8–34.8′N, and 124°13.2–20.5′E, respectively (Fig. 1A). For Ishigaki Island, the average annual mean (1981–2010), monthly maximum, and monthly minimum temperatures are 24.3 °C, 29.5 °C, and 18.6 °C, respectively; the annual rainfall is 2106.8 mm and the average monthly maximum and minimum sea surface temperatures (SSTs) are 29 °C and 23 °C, respectively (Japan Meteorological Agency, 2013). The major western boundary current in the north Pacific, the Kuroshio Current, originates from the Western Pacific Warm Pool (WPWP) and flows through the Ryukyu Islands. Fringing reefs are developed around Ishigaki Island and a 30 × 20 km barrier reef (Sekisei Reef) is developed to the west of the island, lying between Ishigaki and Iriomote Islands. The prevailing wind directions in the vicinity of Ishigaki Island are NNE–NE from September to May and S–SSW

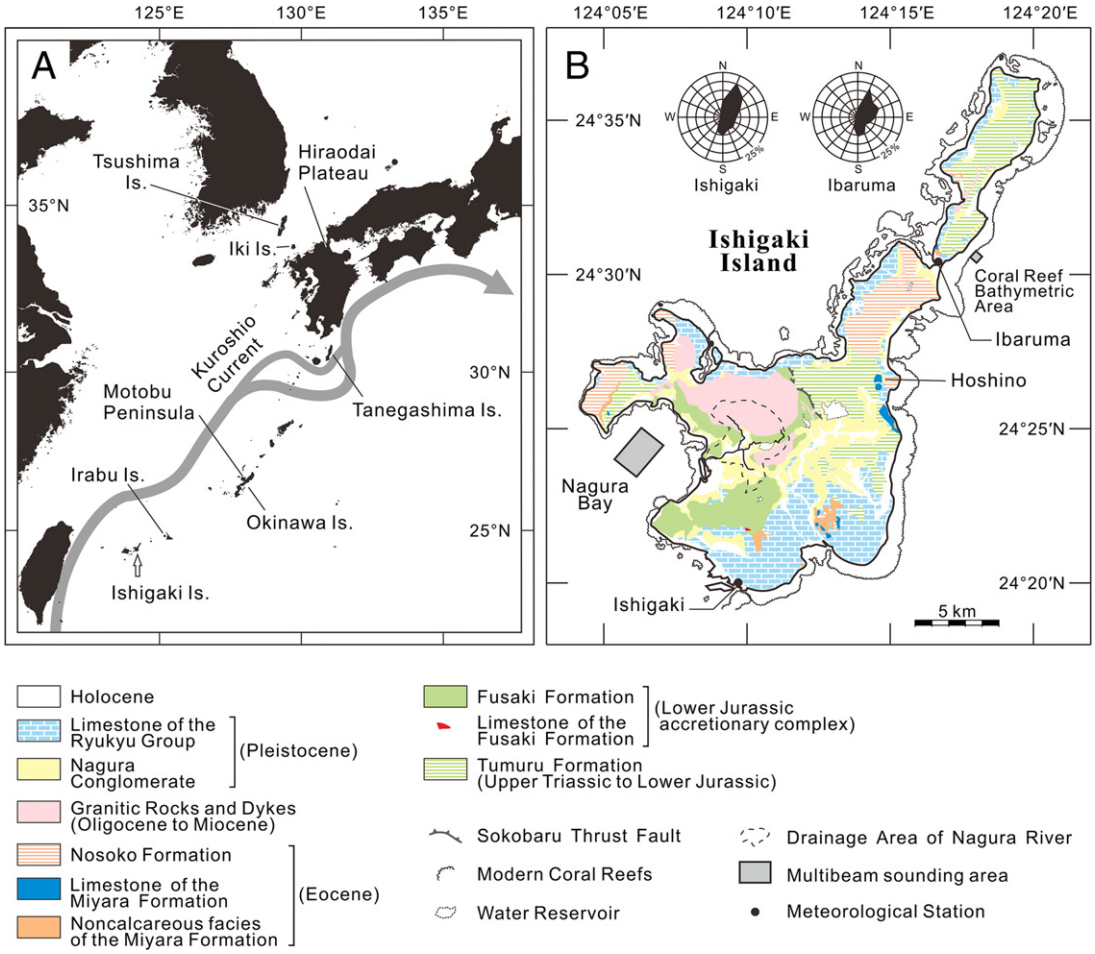

Fig. 1. (A) Location and (B) lithology of Ishigaki Island, showing surveyed area. The flow axis of the Kuroshio Current in (A) illustrates conditions in November 2013, as presented by the Japan Meteorological Agency (2013). Wind roses in (B) have been summarized over the period 1991–2000, as presented by the Ishigakijima (Ishigaki Island) Local Meteorological Observatory for Ishigaki (southwest) and Ibaruma (northeast). Each of the concentric circles in the wind roses represents 5% frequency. The surface lithology in (B) was produced with reference to Nakae et al. (2009).