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Atoll Reef Geomorphology of Sagori Island, SE Sulawesi: A Reconnaissance Study

Tubagus Solihuddin

Marine Research Centre, the Agency for Marine Research and Human Resources
Jln. Pasir Putih II, Ancol Timur, Jakarta 14430

Corresponding author: solihuddin@gmail.com
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Abstract - The Sagori Atoll of the Kabaena Island, SE Sulawesi is one of Indonesia's remote tropical reefs and such has received little attention from reef researchers. Non of early scientific expeditions reported either geomorphology or ecology of the Sagori Atoll in detail. This study is the first investigation of the reef geomorphology and associated habitats of Sagori Atoll within a biodiversity of "Coral reef Triangle Initiative - CTI" region, using data from satellite imagery and on ground observation. The Sagori Atoll environment consists of reef-island, atoll rim, and lagoon in which six habitats are associated, including: sand cay, coralgal pavement, sand sheet (intertidal and subtidal), sand-hardground striation, and outer atoll rim and lagoon (shallow and deep). The reef-island is built from sediments that are entirely calcareous, resting on a platform of lithified coral conglomerate. The atoll rim is dominated by coralgal pavement consisting mainly of both encrusting and living coralline algae. The lagoon which is a semi-enclosed pool and opens to the eastern side, consists of sand and scattered corals. The atoll formation is considered to be of nonvolcanic origin, but is rising from the depth of due to anticlinal island subsidence.

Keywords: Sagori, atoll, reef, geomorphology, habitats

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Introduction

Atoll is one of the main types of coral reef which has a distinctive pattern of geomorphic features, in addition to fringing, barrier, and bank reefs (Guilcher, 1988). Initiated by Charles Darwin's theory (Darwin, 1842) that is now widely accepted concerning the genesis of atoll, it was originally formed as a fringing reef that encircled the shallow margin of a volcanic island. As the island gradually subsides due to tectonic displacement, the living corals keep growing upward as a consequence of vertical reef growth to sea level to maintain contact with optimum light conditions. An atoll, therefore, marks the final stages of fringing-barrier-atoll succession due to island subsidence.

The study of atoll reef in Indonesia was first outlined by Molengraaff (1929) through his general overview of Indonesian coral reef, demonstrating eustatic sea-level rise, volcanic subsidence, and subsidence of the reef foundation as major factors controling the development of atolls. Kuenen (1933a, b) included block faulting in the process, completing the Molengraaff's concept. Later on, studies of atoll have been focused

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on the coral cover, reef structure, and antecedent reef platform of Tukang Besi (Wakatobi) Islands (Best *et al.*, 1989; Bak and Povel, 1989). Most recently, Madden *et al.* (2013) pointed out the characteristic of Kaledupa and Hoga atolls in the Wakatobi Islands through an integrated environmental, sediment, and satellite studies.

Until recently, there have been only few studies of atoll reef geomorphology in Indonesia despite the fact that Indonesian Archipelago contains some of the most diverse of island groups across the globe (Kuenen, 1933a) and at least fifty-five are considered atolls by Tomascik *et al*. (1997). The Sagori Island was chosen because of the unique atoll-like reef platform, emerging solitary from the seafloor. Unlike the relatively well-studied atoll reefs in Wakatobi, the Sagori Atoll has not been previously well studied. Our knowledge of Sagori Atoll has just come through Tomascik *et al*. (1997), providing a preliminary quantitative summary of major geomorphic characteristics of Indonesian atolls (*e.g*. length, width, area, and lagoonal depth).

Since field surveys are usually too time consuming and expensive to conduct over a relatively large area and time-series data acquisition, remote sensing technology offers the most rapid and cost-effective approach to observe and characterize an entire region of reef platform without relying on sampling and extrapolation (Andréfouët and Muller-Karger, 2006).

Here, the utility of multispectral bands of Landsat imagery was explored to delineate atoll reef geomorphology and associated habitats of the Sagori Atoll supported by on-ground observations. The study aims to produce a satellite-based reef geomorphology and associated benthic habitat map, and to identify the morphogenesis of the atoll.

Field Setting

Sagori Atoll is located approximately 4 km southwest off of Kabaena Island, SE Sulawesi (Figure 1). It has a small white sand cay (*ca*. 3,000 m long and 200 m wide) in the northern part of the atoll rim. Geologically, the Sagori Atoll and adjacent areas are closely associated with regional tectonic settings of Sulawesi which are largely affected by past plate tectonic collision. The complexity of geological settings of Sulawesi Island has been widely discussed (Sukamto, 1975; Simandjuntak, 1980, 1986; Sukamto and Simandjuntak, 1983) and mostly related to the plate tectonic evolution. The formation of Gulf of Bone, where the Sagori Atoll exists, is believed as a representative model of post-collisional structure between Australoid terranes comprising Buton-Tukang Besi and Banggai-Sula micro-continents and Eastern Sulawesi in the Early to Late Miocene (23-5 Ma), resulting in giant strike-slip fault systems such as Palu-Koro, Kolaka, Lawanopo, Hamilton, Matano, and Blantak (Satyana and Purwaningsih, 2011).

The oceanographic settings of the Sagori Atoll and surrounding areas are significantly influenced by the bidirectional wind system of the monsoons. The northwest monsoon typically occurs from November to March forcing shallow Java Sea water flow easterly to Flores and Banda Seas. During the southeast monsoon (from May to September), the pattern is reversed and the surface currents are westerly flow (Wyrtki, 1961; Gordon *et al*, 2003). The tidal regime is mixed tide prevailing semidiurnal with a maximum tidal range of 2.5 m. The salinity ranges between 30 - 34 PSU and the average sea surface temperatures are 18 - 28°C, providing hospitable environment for reef and other marine biotas to flourish (Pranowo *et al*., 2004).

Materials and Methods

Ground Observation

On ground observations were conducted by reef walk on the reef flat around the reef-island. Visual assessment and interpretation was the first stage of obtaining preliminary habitat descriptions. The reef flat was not widely subaerial-exposed at low water level, leading to a limited information of modern reef habitats such as substrates and biota types. Groundtruth locations were photographed and documented with a built in camera-global positioning system (GPS) unit.

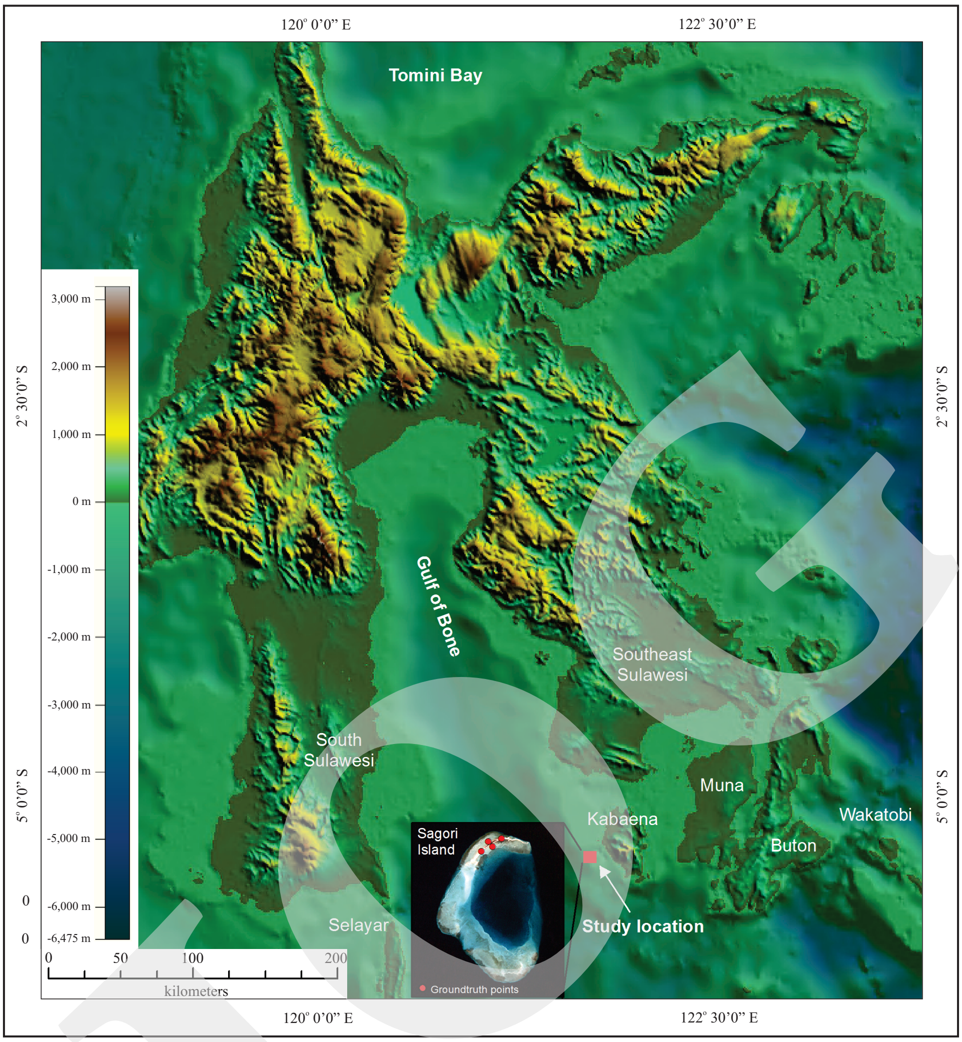

Figure 1. Map of study location and its surrounding areas derived from general bathymetric chart of the ocean grid (Gebco) with a spatial resolution of 30 arc-seconds of latitude and longitude. Inset: Sagori Atoll with groundtruth points.

Satellite Imagery

The study was based on a Landsat 5 TM imagery scene (path 113, row 064) acquisition date on 05 August 2011 which was downloaded from the United State Geological Survey (USGS) Earth Resources Observation and Science Data Centre (https://earthexplorer.usgs.gov/; accessed on 2015). The seven spectral bands of Landsat 5 TM are, including a thermal band: band 1 visible (0.45 - 0.52 μm), band 2 visible (0.52 - 0.60 μm), band 3 visible (0.63 - 0.69 μm), band 4 near-infrared (0.76 - 0.90 μm), band 5 near-infrared (1.55 - 1.75 μm), band 6 thermal (10.40 - 12.50 μm), and band 7 mid-Infrared (2.08 - 2.35 μm). The ground resolution interval (pixel size) is 30 m.

Individual spectral bands of Landsat TM were combined in the software package ERDAS ER Mapper toolkit to produce a single multispectral composite image. The image was then corrected geometrically using a universal transverse mercator (UTM) zone 51 and WGS 84 as the coordinate system and ellipsoid reference respectively. Reef habitats recognition for each geomorphic zone refers to a template of facies identification of reef environments from Harris and Vlaswinkel (2008). This key interpretation is thoroughly based on true colour composite produced by band combination (Band 1, Band 2, and Band 3) of Landsat imagery. The three visible bands of Landsat TM were selected because of their water penetration characteristics.

A Landsat-derived reef geomorphic zones and associated habitats map was produced by integrating Landsat multispectral data, unsupervised classification and on ground observations following a simplified workflow of Kaczmarek *et al*. (2010). After classification, reef habitats were identified, assigned, and saved as vector files. Due to insuficient data of groundtruth points, a metric called "overall accuracy" was not applied in this study. Polygons from each reef habitats are imported as shapefiles into ArcGIS. Overlapping between polygons was removed, and polygons wore merged and corrected. Bathymetric chart and general bathymetric chart of the ocean grid (Gebco) with a spatial resolution of 30 arc-seconds of latitude and longitude were used to aid the interpretation.

Results

The Landsat-derived reef geomorphology and associated habitat map (Figure 2), supported by on ground observations, allowed delineation of six distinct reef habitat zones following spatial

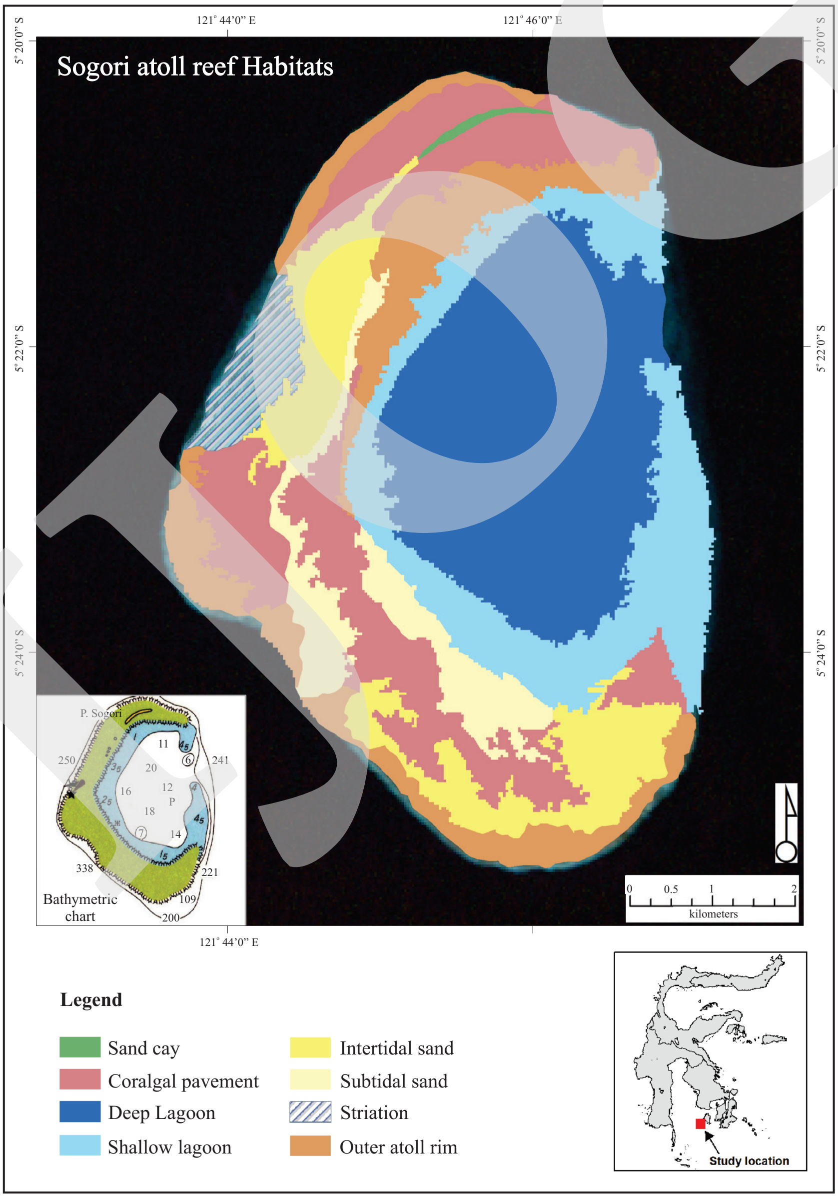

Figure 2. Map of Landsat-derived Sagori Atoll reef habitats with inset map of hydrography bathymetric chart derived from naval hydro-oceanographic office (2006).

scale and levels of mapping detail for coral reefs, including: reef-island (sand cay), coralgal pavement, lagoon (deep and shallow), sand sheet (intertidal and subtidal), sand-hardground striation, and outer atoll rim. Each of these biogeomorphic zones is described in detail below.

Sand Cay

The sand cay sits on the atoll rim revealing a low small white sand cay vegetated by pine trees in the western end of the cay (Figure 3a). Its long axis extends approximately 3 km long by 0.2 km wide with an approximate area of 14.2 hectares (Table 1). The sand cay rests on a platform of cemented coral conglomerate, which rises up to 0.5 m above mean sea level and is intermittently inundated by sea water at the highest tide. The sediment is entirely composed of unlithified calcareous sand or coral shingle and coral rubble derived from skeletal fragments of organisms living on the reefs, such as coral, coralline or calcifying algae, molluscs, and foraminifera. The shape of the sediment deposits is sand spit-like with SW-NE orientation, resulted from longshore current driven by both tide and waves.

Coralgal Pavement

The coralgal pavement is the widest part of atoll rim environment (± 871.5 hectares) consisting mainly of coralline algae (both encrusting and free living forms) in addition to various detrital elements derived from coral communities such as coral fragments, foraminifera, and lithified hardgrounds (Figure 3b). Sand and gravel are lying on the pavement as loose elements derived from the branches of broken corals.

Figure 3. Contemporary reef habitats of Sagori Atoll showing (a) sand cay on the western end of the island, (b) coralline algae pavement on the reef flat, and (c) shallow lagoon with sand and scattered coral fragments on the seafloor.

Table 1. Sagori Atoll Reef Geomorphic and Associated Habitats Classification

Geomorphic Zone	Reef Habitat	Area (ha)	Sediments/Rock Type
Reef-island	Sand cay	14.2	Calcareous sand and coral rubble
Atoll rim	Coralgal pavement	14.2	Lithified coral conglomerate
	Intertidal sand	517	Calcareous sand and gravelly coral fragments
	Subtidal sand	312.3	Coarse carbonate sand and shell fragments
	Sand-hardground striation	135.4	Consolidated reef, sand, and gravel
	Outer atoll rim	632.1	Consolidated reef with living corals
Lagoon	Shallow lagoon	726.8	Calcareous sand, coral, and shell fragments
	Deep lagoon	1,277	Calcareous sand, coral, and shell fragments

Lagoon

The Sagori Lagoon is a semi-enclosed pool which opens to the eastern side consisting of sand and scattered corals. The passage connecting the lagoon to the open ocean is ~2 km wide and ~6 m deep and is oriented in a north - south to northwest - southeast direction. Bathymetric chart shows depths of 1 - 4.5 m and 6 - 20 m for the shallow and deep lagoon respectively (Figure 3c). The former covers about 726.8 hectares while the later ocuppies area of 1,277 hectares (Table 1). Sediments in the atoll lagoon are interpreted entirely calcareous. The sources of sediment supply are reef-erosion of various sizes including foraminifera which live in most lagoons and various shell fragments from echinoderms, gastropods, crustaceans, sponges, and other skeletal deposits. Mangroves are absent in the lagoon. At both sides of the lagoon entrance, sediment mounds were built-up with depths of 4 – 4.5 m.

Sand Sheets

The sand sheets are composed of sand and pieces of carbonate debris lying on hardground surface of the atoll rim. They are widespread in the intertidal and subtidal zones. The intertidal sand is submerged below relatively shallow water and partially exposed during low spring tides covering area of about 517 hectares (Table 1). The subtidal sand is entirely submerged even at lowest astronomical tide occupying an area of about 312.3 hectares (Table 1). However, both share similarity in terms of sediment composition consisting of poorly sorted coarse carbonate sand with abundant shell fragments and formanifira tests.

Sand-hardground Striation

The sand-hardground striation in the west part of the Sagori Atoll rim is the most interesting feature, bearing series of long stripes and consisting alternately of consolidated reef flat and of sand and gravel. It covers an area of about 135.4 hectares (Table 1) and is generally located at windward atoll rim, facing the prevailing swell. Stripes are morphologically controlled by wave dynamics.

Outer Atoll Rim

The outer atoll rim zone has a gentle gradient slope seaward down to a water depth of 200 – 300 m. It covers an area of about 632.1 hectares (Table 1) restraining fore reef slope and reef flat along the seaward reef margin. Living corals of branching *Acropora*, *Porites cylindrica,* and *Porites sp.* are common reef species colonized the outer atoll rim.

Discussion

Origin of Sagori Atoll

Atoll development in Indonesian Archipelago mainly occurs on subsiding foundations caused by orogenic movements (*e.g.* faulting and folding), as pointed out by Kuenen (1933a, b; 1947) and Umbgrove (1947). The four major islands of Wangi-wangi, Kaledupa, Tomea, and Binongko (abbreviated as Wakatobi), SE of Buton Island, are the best examples to represent atolls and islands formation on anticlinal and faulting foundations (Kuenen, 1933a). These are NW-trending chains of atolls and elevated islands, rising from submarine ridges at depths of 700 – 1000 m and separated by narrow troughs deeper than 1,000 m (Smith and Silver, 1991; Koswara and Sukarna, 1994; Milsom *et al.*, 1999). The atolls (*e.g.*, Kaledupa, Kapota, Lintea, Ndaa, *etc.*) are located on a slowly subsiding submarine platform that extends about 200 km along a NW - SE trending axis, whilst the Wakatobi Islands were formed along the axis of elevation (van Bemmelen, 1949; Hamilton, 1979). The area has no record of recent volcanic activity, and is not considered to be of volcanic origin.

As there currently lack any cross-reef subbottom profile data, the formation of Sagori Atoll can only be proposed from direct comparison with the origin of Wakatobi Atolls as they are closely associated with a tectonic plate collision between Eastern Sulawesi and Buton-Tukang Besi microcontinents. The collision has clearly played a major role in the Neogen development of Banda Sea region and the formation of Gulf of Bone and giant strike-slip fault systems on the island of Sulawesi, including Palu-Koro, Kolaka, Lawanopo, Hamilton, Matano, and Blantak (Satyana and Purwaningsih, 2011). The atolls are rising from the depth of due to island (the highest point of anticline) subsidence and the upward growth of the reefs, resulted in the formation of atolls. It can be interpreted that Sagori Atoll sits on a topographic high (submarine ridge), resulted from postcollisional structure in the Early to Late Miocene which in turn provided foundations for coral reef.

The antecedent reef platform is still poorly understood until now, but is most likely Pleistocene limestone as it has now been widely shown that the reef rim on modern atolls is underlain by older Pleistocene reefs (McLean and Woodroffe, 1994; Montaggioni, 2005). In this stage, Sagori Atoll is not an atoll in the general sense that is formed due to volcanic island sinking as postulated by Darwin's theory (1842), but is an atoll reef that rises from submerged ridge of anticlinal platform. This interpretation is supported by the major tectonic feature from Hamilton (1979) that indicates Sagori Atoll is not part of old volcanic arch ridge formed in the Miocene time (Figure 4).

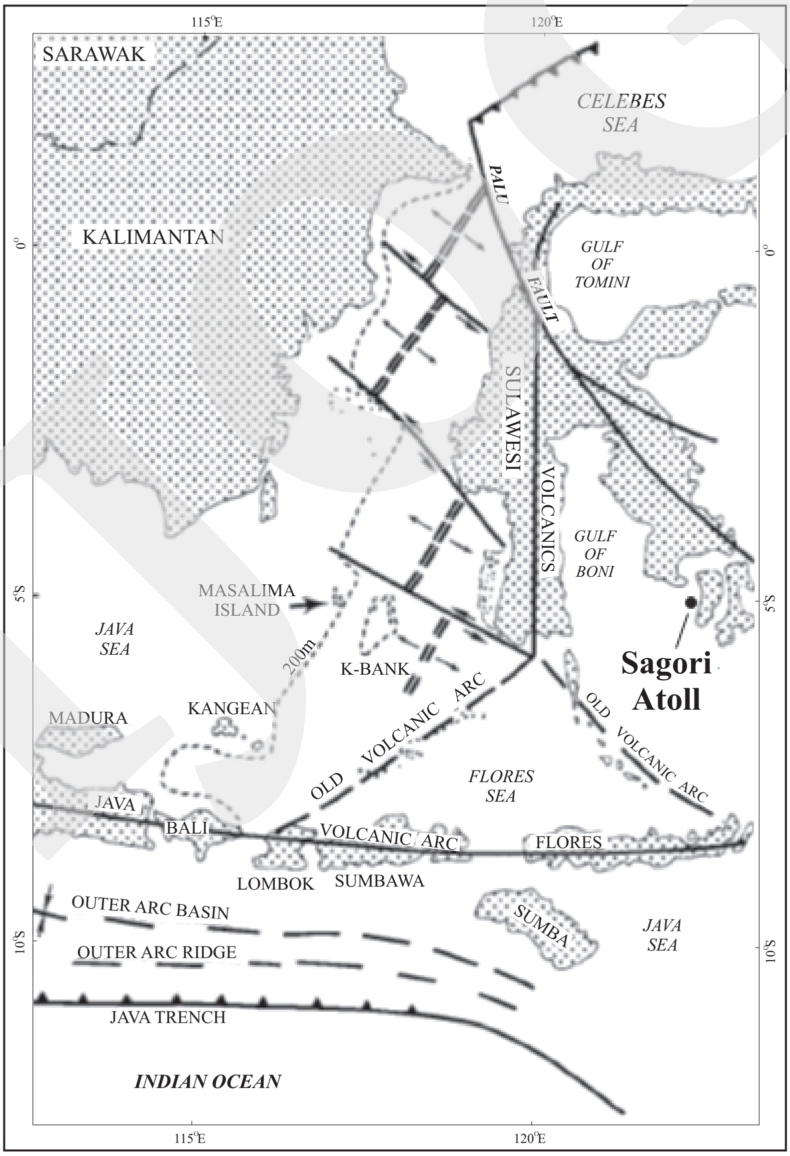

Figure 4. Major tectonic feature of Sulawesi region from Hamilton (1979) showing that Sagori Atoll is not on the ridge of an old volcanic arc.

Atoll Geomorphology

The Sagori reef platform is considered as an atoll as it has a crescent-shape reef enclosing a moderately deep (~20 m) central lagoon and the origin through subsidence. Unlike most atolls in the Pacific and Indian Ocean which are exposed to high wave-energy (Guilcher, 1988), atolls in Indonesian Archipelago, including Sagori Atoll, are generally sheltered, making this has no clear distinction between windward and leeward side of the atoll rim. Stodart (1973) postulated this condition as the result of a moonsoonal climate (bidirectional wind regime) effect.

Having an arcuate sand cay in the north of the atoll rim, Sagori Atoll falls to an atoll reef-island (motu) category. The island is built from sediments that are entirely calcareous resembling to those atoll reef islands in Kiribati, Tuvalu, and Marshall Island (Woodroffe and Morrison, 2001; Collen and Garton, 2004; Fujita *et al*., 2009). According to the way the island is formed, the Sagori Atoll corresponds closely to the type 1 islets that are formed on platforms or eroded remnants of raised reef from MacNeil (1972).

Bathymetric and cross-reef profile across the Sagori Atoll confirms that the reef platform rises from the depth of more than 125 m and the atoll rim is cut by the shallow passage in the east margin of the rim (Figure 5). The shallow passage is ava by definition of Guilcher (1988), which is a passage with several metres deep and suitable for navigation by ship. This intrepretation is in accoradance to Tomascik *et al.* (1997) who reported that most atolls in the Indonesian archipelago had shallow to deep passages. Whilst hoa, an overflow or overwash channel, is usually absent.

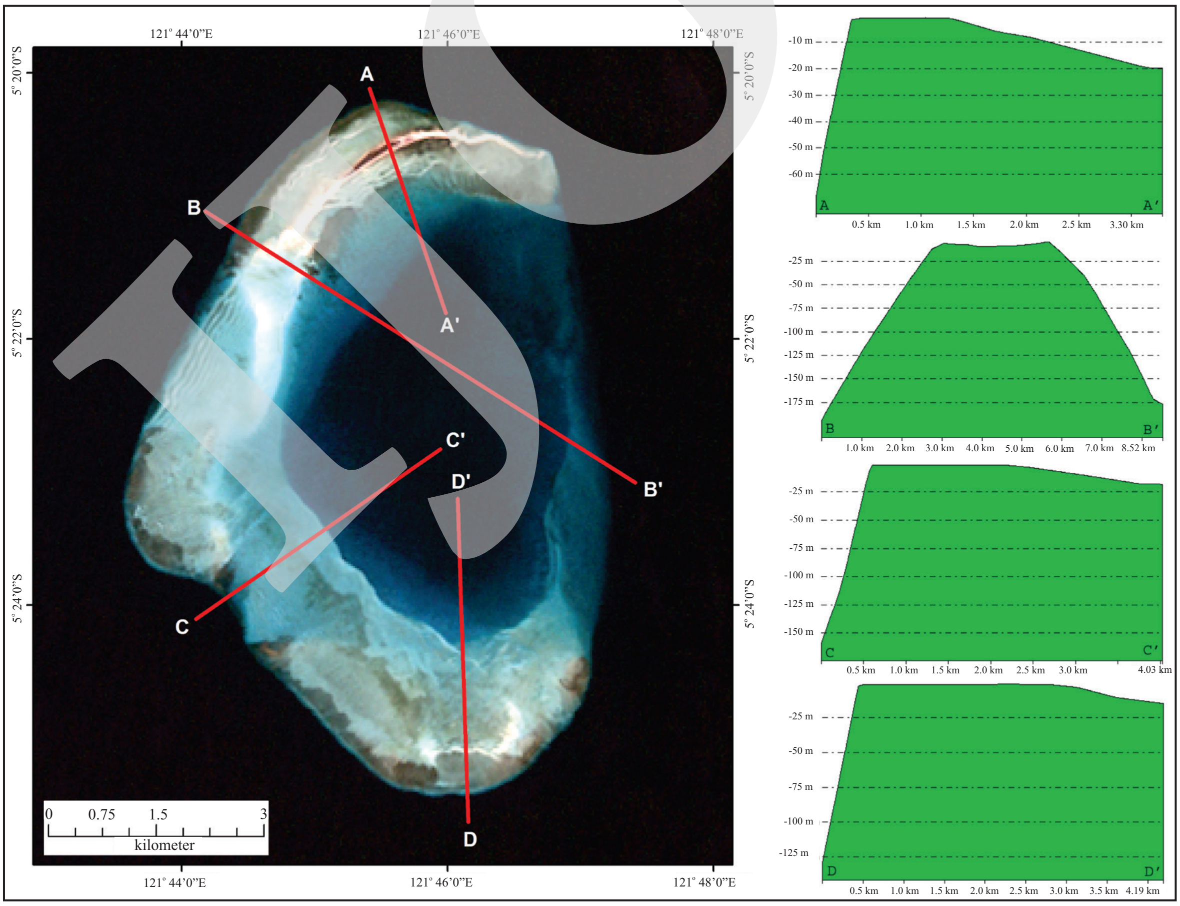

Figure 5. Diagrammatic cross-reef profile of Sagori Atoll derived from GEBCO 0.8 grid resolution.

Conclusion

This reconnaissance study is the first investigation of Landsat-based reef geomorphology and habitat mapping of Sagori Atoll, providing a spatial framework for reef geomorphic and ecological studies at both regional (between reefs) and local (within reefs) scale. The map produced in this study represents a preliminary reef classification which aimed to recognize general patterns and characteristics of the distribution of reef habitats at Sagori Atoll. Hence, a simple and straightforward approach was applied. The most striking geomorphological feature in the region is the presence of sand-hardground striation on the western part of the Sagori Atoll rim which has developed in a high-energy setting. Further investigation is needed, such as deep a drilling programme and a subbrottom profile survey to obtain the thickness of the Holocene reef, palaeoecology, antecedent reef platform, reef growth, and subsidence rates.

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