Geomorphology 257 (2016) 155–163

Contents lists available at ScienceDirect

Geomorphology

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

The magnitude of a mid-Holocene sea-level highstand in the Strait of Makassar

Thomas Mann [a,*], Alessio Rovere [a,b], Tilo Schöne [c], André Klicpera [a], Paolo Stocchi [d], Muhammad Lukman [e], Hildegard Westphal [a,f]

[a] Leibniz Center for Tropical Marine Ecology (ZMT), Fahrenheitstrasse 6, 28359 Bremen, Germany
[b] Center for Marine Environmental Sciences (MARUM), Leobener Strasse, 28359 Bremen, Germany
[c] Helmholtz Centre Potsdam (GFZ), Telegrafenberg, 14473 Potsdam, Germany
[d] NIOZ Royal Netherlands Institute for Sea Research, 1790AB Den Burg, Texel, Netherlands
[e] Research and Development Center for Marine, Coastal, and Small Islands, Hasanuddin University (MaCSI-UNHAS), Jl. Perintis Kemerdekaan Km. 10, 90245 Makassar, Indonesia
[f] Department of Geosciences, University of Bremen, Klagenfurterstrasse 2, 28359, Bremen, Germany

ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 28 December 2015
Accepted 30 December 2015
Available online 31 December 2015

Keywords:
Indo-Pacific
Spermonde Shelf
Sulawesi
Glacial isostatic adjustment

ABSTRACT

Knowledge on the timing and magnitude of past sea-level changes is essential to understand modern and future sea-level variability. Holocene sea-level data from literature on the west coast of Sulawesi, central Indonesia, suggest that this region experienced two relative sea-level highstands over the last 6000 years, with magnitudes exceeding two meters. However, recent datasets from the Indo-Pacific region do not support high-magnitude sea-level oscillations during the Holocene in tectonically stable far-field locations. Here we present a new, high-precision, mid-Holocene sea-level dataset from the Spermonde Shelf off southwest Sulawesi. We surveyed 21 fossil microatolls on the reef flats of two coral islands (Pulau Panambungan and Pulau Barrang Lompo) and referred their elevations to local mean sea level and to the height of living coral. Radiometrically calibrated ages from emergent fossil microatolls on Pulau Panambungan indicate a relative sea-level highstand not exceeding 0.5 m above present at ca. 5600 cal. yr BP. The highstand is followed by a relatively rapid sea-level fall towards present sea level that was reached at around 4000 cal. yr BP. Fossil microatolls from nearby Pulau Barrang Lompo show the same trend, however with a coherent negative vertical offset of about 0.8 m compared to their equivalents on Pulau Panambungan. The largely consistent gradients of both trends (~−0.14 mm yr^{-1}), the consistent elevation of living microatolls in the Spermonde, and a number of instructive geomorphic features indicate a localized, post-formational and probably recent drop of the fossil microatolls on the densely populated island Pulau Barrang Lompo. The relative sea-level trend inferred from Pulau Panambungan is well within the range of geophysical predictions based on ANICE-SELEN ice sheet model, which predict a highstand that is significantly lower than those predicted by other GIA models for this area. Although a complete interpretation of the Holocene sea-level history will require additional high-resolution datasets from this and surrounding territories in SE Asia, our results suggest that there was merely a single Holocene highstand in central Indonesia, the magnitude of which was substantially lower than hitherto assumed.

1. Introduction

Regional variability of sea-level changes since the Last Glacial Maximum (LGM; ~20 kyr BP) is the result of combined isostatic, gravitational and other post-depositional processes (e.g., tectonics) influencing the signal recorded in sea-level markers at each particular location on Earth (Shennan and Horton, 2002; Milne et al., 2005; Lambeck et al., 2014; Vacchi et al., 2014; Engelhart et al., 2015). Sites near the former ice sheets experienced strong isostatic lithospheric uplift after glacial retreat, combined with a simultaneous decrease of gravitational pull on the adjacent water masses. These combined processes caused a fall in relative sea level (RSL) along coastlines in higher latitudes during the Holocene (Shennan and Horton, 2002; Gehrels and Long, 2008).

Studies that aimed to provide a better understanding of the eustatic component of RSL changes after the LGM have focused on tectonically stable far-field locations (Clark et al., 1978), located distant from the former ice margins and thus not directly affected by ice-proximal glacial isostatic adjustment (GIA). However, effects of GIA are also pronounced in low latitudinal zones (Mitrovica and Peltier, 1991; Peltier, 1999), mainly as a consequence of subsiding peripheral forebulges and sublithospheric mantle flow that caused a redistribution of water masses away from the equator to higher latitudes. This mechanism

* Corresponding author.
E-mail address: thomas.mann@leibniz-zmt.de (T. Mann).

http://dx.doi.org/10.1016/j.geomorph.2015.12.023
0169-555X/

(i.e. equatorial ocean syphoning) explains the late Holocene RSL fall in low latitudes which is predicted by geophysical models (Mitrovica and Milne, 2002) and detected, for example, in the Indian Ocean (Woodroffe et al., 1990; Kench et al., 2009).

A highstand preceding RSL fall may lead to locally subsiding seafloors (i.e. hydro-isostasy) depending on the viscoelastic structure of the underlying, heterogeneous mantle (Lambeck et al., 2002). Consequently, in far-field areas where water input and hydro-isostasy simultaneously offset each other, RSL stability is recorded during the middle to late Holocene (Woodroffe et al., 2012). In order to improve our understanding of climate dynamics, past ice volume changes, ice-equivalent sea level and solid Earth responses, additional RSL records from localities unaffected by major tectonic and glacial isostatic contributions are required (Lambeck et al., 2002, 2010).

This study presents new survey and radiocarbon data of living and fossil microatolls in the Spermonde Archipelago, southwest Sulawesi, Indonesia. The Republic of Indonesia is the largest island state in the world and, in the light of its dense population and a relatively low adaptive capacity, its coastlines may be particularly sensitive to future sea-level rise (Nicholls and Cazenave, 2010). Adaptation strategies to projected sea-level rise scenarios would benefit from information about RSL changes in the recent geological past, if available for the particular region. The aim of this study is to reconstruct mid-Holocene RSL trends in this area from microatoll records, and to evaluate the reliability of RSL oscillations that were inferred previously.

2. Regional setting and previous RSL investigations

Sulawesi is a volcanic island in the central part of Indonesia, roughly located between 2°00′N–6°00′S latitudes and 118°00′E–125°00′E longitudes (Fig. 1A). The Spermonde Archipelago is situated between the Strait of Makassar to the west and the southern arm of Sulawesi to the east (Fig. 1B, C). Sulawesi has a complex tectonic structure (Hall, 1997; Bird, 2003). North Sulawesi and the North Makassar Basin are characterized by the occurrence of subduction zones, continental rift boundaries and numerous major active faults (Bird, 2003; Fig. 1B). The largest lateral faults in that area (i.e. Paternoster Fault and Palu Korog Fault) show a sinistral direction of motion and strike NW–SE and NNW–SSE, respectively. These are complemented by several smaller lateral faults striking in the same general direction, and a number of thrust faults striking NE–SW with a southeastern dip direction.

The Spermonde Archipelago lies in the South Makassar Basin, distant from the active Paternoster Fault (Fig. 1B). While along and north of the Paternoster Fault major earthquakes and tsunamis occur (Prasetya et al., 2001), orogenic events in southwest Sulawesi were constrained to the period from Miocene to Pliocene/Pleistocene, and volcanic activity almost completely ceased in the early Quaternary (Sasajima et al., 1980). Unfortunately, little is known about the tectonic activity of the Spermonde Archipelago during the Holocene. Yet, in the available literature, there are no indications for major faults or fracture zones within the Spermonde (Prasetya et al., 2001; Bird, 2003). Recent-past GPS data indicate stable conditions for the study area, i.e. no differences in relative plate velocities (Walpersdorf et al., 1998), and today, only a few deep-focus earthquakes occur in southwest Sulawesi (http://earthquake.usgs.gov).

The Tertiary carbonate platform underlying the Spermonde Archipelago consists of undeformed sediments and is bounded to the Strait of Makassar by a discontinuous barrier, separating the shallow-marine shelf from deeper waters (Bergman et al., 1996; Renema and Troelstra, 2001). On the shallow-marine platform, patch reefs form localized build-ups on top of which a number of coral islands developed (Fig. 1C; Umbgrove, 1928; Wijsman-Best et al., 1981; Renema, 2002). Most of these islands, including two of the islands studied here, Pulau Barrang Lompo and Pulau Sanane, are densely populated (Fig. 2A, B; Schwerdtner Máñez et al., 2012). The third study island, Pulau Panambungan, is uninhabited today and except for an abandoned resort

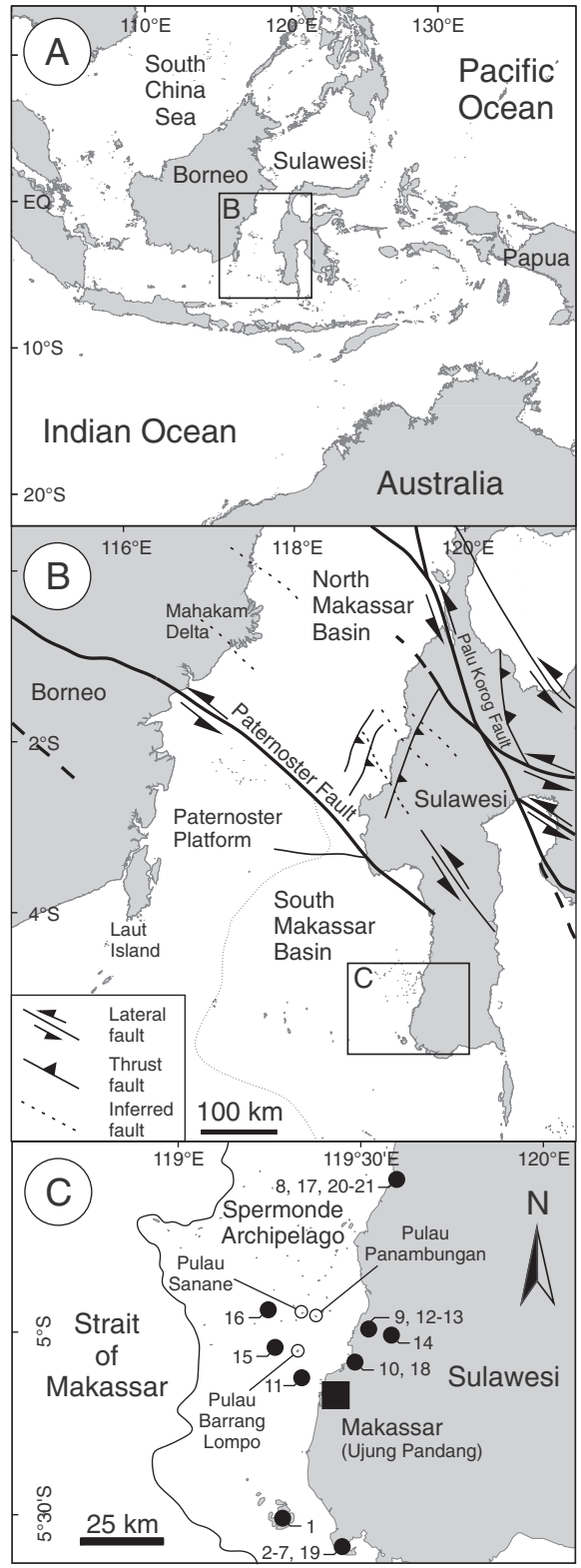

Fig. 1. (A) Location of Sulawesi in the central part of Indonesia. (B) General tectonic setting for western Sulawesi and the Makassar Strait region. Adopted from Darman (2014). For the classification of tectonic features see legend within the figure. (C) Location of the Spermonde Archipelago between southwest Sulawesi and the Strait of Makassar. The study islands, Pulau Barrang Lompo, Pulau Sanane and Pulau Panambungan, are encircled and named accordingly. Black solid circles indicate study locations of De Klerk (1982). For designated sample numbers refer to Table 1. The black solid line indicates the position of the shelf break.

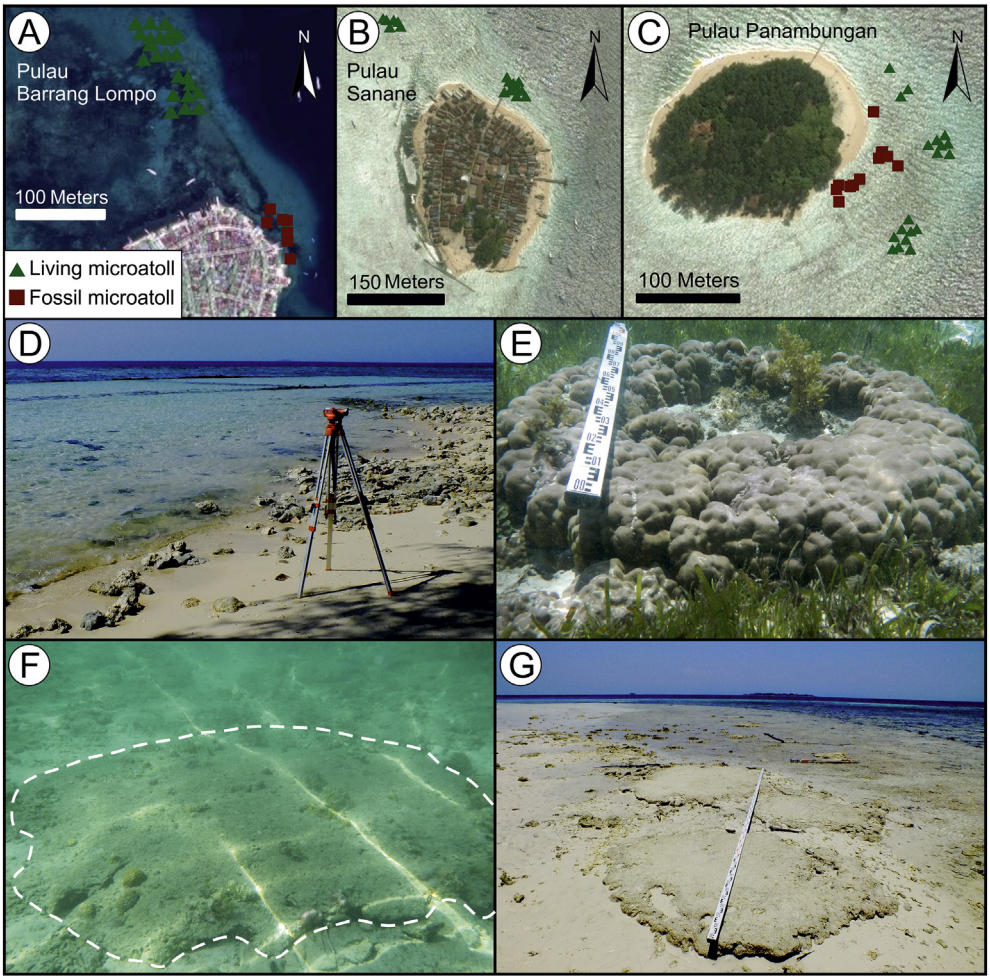

Fig. 2. Satellite images of (A) Pulau Barrang Lompo, (B) Pulau Sanane and (C) Pulau Panambungan (A and B from Google™, C from Microsoft®, copyright DigitalGlobe). Locations of living and fossil microatolls on the reef flats of the study islands are indicated by triangles and squares respectively. (D) Beachrock outcropping at the southeastern shore of Pulau Panambungan. Automatic level for scale with a height of 1.5 m. (E) Example of a living *Porites* microatoll on the reef flat of Pulau Panambungan. (F) Submerged fossil microatoll on the reef flat of Pulau Barrang Lompo. Dashed white line indicates the outline of the fossil microatoll (diameter is about 1.7 m). (G) Field of emergent fossil microatolls at the southeastern shore of Pulau Panambungan.

facility, this island shows no signs of anthropogenic alterations (Fig. 2C). All three islands are relatively small with a diameter between 200 m and 500 m and can be characterized as (formerly) vegetated sand cays. The tidal cycle in the study area is mixed semi-diurnal with a maximum tidal range of 1.5 m (data from Badan Informasi Geospasial, Cibinong/Indonesia).

Previous Holocene RSL investigations along far-field coastlines commonly used microatolls as RSL markers, especially when the elevations of fossil populations can be compared with the height of their modern counterparts (Chappell, 1983; Davies and Montaggioni, 1985; Woodroffe et al., 1990, 2012; Kench et al., 2009). Microatolls are annular corals with a dead upper surface while active coral growth is oriented towards their periphery, reaching an elevation approximately between mean low water spring tide level and mean low water neaps in open reef flat positions (Smithers and Woodroffe, 2000). Fossil microatolls preserved in growth position thus have the potential to provide precise information on RSL changes in the geological past. Holocene RSL reconstructions based on microatoll-surveys are known from several locations within the Indo-Pacific region, but studies from central Indonesia are rare in the literature (see Woodroffe and Horton, 2005).

Attempts to reconstruct Holocene RSL in central Indonesia are based on multi-proxy approaches (e.g., age-elevation plots that combine surf niches, marine terraces, abrasion notches and benches, and biological relicts to obtain a RSL curve) on and off the western coastline of Sulawesi. Tjia et al. (1972), for example, used mollusk accumulations attached to Eocene limestones as RSL markers for South Sulawesi. By referring to nowadays basically obsolete assumptions of eustatic sea-level variability, he concluded that South Sulawesi was tectonically stable between 5000 and 4000 yr BP and is uplifting since then with a rate between 1.4–2.5 mm yr^{-1}. In a later work, De Klerk (1982) incorporated the data from Tjia et al. (1972) and complemented these with additional RSL markers from the Spermonde Archipelago and mainland Sulawesi (Fig. 1C, Table 1). Based on a number of geomorphological field observations (e.g., no declensions in river terraces), De Klerk (1982) concluded that the Spermonde Archipelago is tectonically stable since the Holocene. His RSL database for the Spermonde Archipelago shows two peaks (~5000 and 1400 yr BP) with RSL reaching +5.5 m and +2 m above modern mean sea level (msl). The resulting RSL curve has been adopted in several later works since then (e.g., Whitten et al., 2002; Imran et al., 2013).

3. Material and methods

We surveyed living microatolls to local reference benchmarks on reef flats of Pulau Barrang Lompo, Pulau Sanane and Pulau Panambungan using an automatic level (Nedo X24; Fig. 2D). The upper limit of living coral polyps around the perimeter of each living microatoll defines the height of living coral (HLC; Fig. 2E). Fossil microatolls were discovered and surveyed on Pulau Barrang Lompo (Fig. 2F) and Pulau Panambungan (Fig. 2G). Elevations of both living

Table 1
Previously presented RSL database for the Spermonde Archipelago adopted from De Klerk (1982). For sample locations refer to sample numbers as indicated in Fig. 1C.

Sample no.	Lab. no.	Sample location	RSL marker	Elevation (m msl)[a]	Radiocarbon age (yr BP)	Calibrated age range (2σ, cal. yr BP)[b]
1	GrN-9883	Tanah Keke	Coral	0.95–1.10	3775 ± 40	3404–3817
2	GrN-9884	O. Pepe	Coral	1.00–1.25	3870 ± 40	3509–3939
3	GrN-9885	Talakaya	Shell accumulation	1.02–1.42	2345 ± 30	1675–2066
4	GrN-10559	Puntondo	Shell accumulation	1.44–1.69	1115 ± 45	48–735
5	GrN-10560	Puntondo	Shell accumulation	1.44–2.24	1430 ± 60	684–1079
6	GrN-10561	Puntondo	Coral	0	6150 ± 90	6259–6745
7	GrN-10562	Puntondo	Beachrock	0.67–2.06	4380 ± 80	4113–4724
8	GrN-10563	Pamaroang	Shell deposit	1.80–1.85	4110 ± 70	3774–4343
9	GrN-10564	Pangalasak	Shell accumulation	1.10–1.40	1820 ± 60	1086–1496
10	GrN-10565	Patene	Shell accumulation	1.35–2.00	1920 ± 60	1211–1592
11	GrN-10566	Samalona	Coral	0	5050 ± 100	4955–5572
12	GrN-10491	Tekolabua	Loamy clay	1.10	905 ± 50	278–566
13	GrN-10492	Tekolabua	Loamy clay	−0.60	6840 ± 100	6992–7495
14	GrN-10493	Maros	Peat	−0.50	6140 ± 40	6294–6651
15	GrN-10976	Bone Tambung	Coral/shell deposit	1.00	1325 ± 45	642–939
16	GrN-10978	Sarappo	Coral/shell deposit	0.70	3460 ± 70	2949–3456
17	GrN-10979	Pamaroang	Oysters	3.56	3360 ± 60	2856–3336
18	GrN-10980	Tarallow	Shell deposit	1.90	5330 ± 80	5384–5864
19	GrN-10981	Puntondo	Erosional terrace	1.53	8220 ± 100	8372–8965
20	GAK 3602[c]	Pamaroang	Oysters	4.75	4050 ± 120	3600–4353
21	GAK 3603[c]	Pamaroang	Oysters	5.50	4902 ± 120	4777–5464

[a] Vertical uncertainties are implemented in the RSL data (see Fig. 3B) if these were provided.
[b] Conventional radiocarbon ages have been calibrated according to the same Marine calibration curve as used for the microatoll radiocarbon ages from this study (see Material and methods).
[c] Data from Tjia et al. (1972).

and fossil microatolls were initially reduced to the local reference benchmarks on each of the study islands. Repeated surveys indicated a vertical measurement error of ±0.02 m on the individual islands.

In order to reference the elevations of the local benchmarks on each of the islands to a common reference-height, we measured tide levels above each local reference benchmark contemporaneously in 15-minute intervals and over a time period of up to seven hours. The resulting tidal curves were compared with tide gauge data from Makassar Harbor in order to reduce the elevations of the local reference benchmarks on each study island to local msl (measurement error: ±0.04 m). As the tide gauge data at Makassar has no defined reference to msl, we considered it only as reference for the amplitude not the absolute value with respect to msl. An evaluation of the gravity field below the Spermonde Archipelago yielded a uniform gradient of the geoid, thus indicating that there are no major variations in the geoid heights between the individual study islands and Makassar (Förste et al., 2012). Therefore we used harmonized and inter-calibrated radar altimetry measurements (Schöne et al., 2010) to derive a local msl against which the tide gauge data from Makassar and, ultimately, the local reference benchmarks on the study islands were reduced to. Contemporaneous measurements at the Makassar tide gauge and nearby radar altimetry passes show the Makassar tide gauge zero is 0.35 m below the instantaneous sea level during the time of the measurements. The msl derived from radar altimetry (08/1992–03/2015) is 0.86 m above the EIGEN-6C geoid (Förste et al., 2012).

Samples for radiocarbon dating were taken from all fossil microatolls using a cordless drill. Prior tests to detect diagenetic alteration via X-ray diffraction and thin-section analysis indicate that most of the samples

Table 2
Survey and radiocarbon results for microatolls on Pulau Barrang Lompo and Pulau Panambungan. RSL elevations inferred from fossil microatolls include estimated surface abrasion (FMA8-FMA11, FMA20) and uncertainties related to surveys and the vertical difference between HLC and msl.

Sample name	Lab. no.	Sample location	Elevation (m msl)	RSL (m msl)	Aragonite Content (%)	Radiocarbon age (yr BP)	Calibrated age range (2σ, cal. yr BP)
Spermonde_FMA01	Poz-63504	P. Barrang Lompo	−1.35	−0.86 ± 0.11	99	4505 ± 30	4401–4800
Spermonde_FMA02	Poz-66838	P. Barrang Lompo	−0.93	−0.44 ± 0.11	86	5600 ± 40	5692–6111
Spermonde_FMA03	Poz-63505	P. Barrang Lompo	−0.95	−0.46 ± 0.11	90	4405 ± 35	4213–4697
Spermonde_FMA04	Poz-66839	P. Barrang Lompo	−1.03	−0.54 ± 0.11	89	4900 ± 35	4867–5287
Spermonde_FMA05	Poz-63506	P. Barrang Lompo	−1.10	−0.62 ± 0.11	93	4965 ± 35	4948–5415
Spermonde_FMA06	Poz-66840	P. Barrang Lompo	−1.16	−0.68 ± 0.11	91	4640 ± 35	4521–4944
Spermonde_FMA07	Poz-66842	P. Barrang Lompo	−1.07	−0.58 ± 0.11	94	4830 ± 40	4821–5246
Spermonde_FMA08	Poz-66843	P. Panambungan	−0.30	0.39 ± 0.13	97	5370 ± 35	5477–5844
Spermonde_FMA09	Poz-66844	P. Panambungan	−0.29	0.40 ± 0.13	97	5185 ± 35	5284–5597
Spermonde_FMA10	Poz-66845	P. Panambungan	−0.27	0.42 ± 0.13	93	5165 ± 35	5273–5585
Spermonde_FMA11	Poz-63507	P. Panambungan	−0.26	0.43 ± 0.13	97	5325 ± 35	5431–5808
Spermonde_FMA12	Poz-63511	P. Panambungan	−0.38	0.11 ± 0.13	98	4915 ± 35	3941–4392
Spermonde_FMA13	Poz-66846	P. Panambungan	−0.29	0.20 ± 0.13	99	4940 ± 40	4867–5332
Spermonde_FMA14	Poz-63512	P. Panambungan	−0.50	−0.02 ± 0.13	92	3920 ± 30	3572–3984
Spermonde_FMA15	Poz-63513	P. Panambungan	−0.44	0.05 ± 0.13	99	4645 ± 30	4530–4945
Spermonde_FMA16	Poz-66847	P. Panambungan	−0.47	0.02 ± 0.13	91	4340 ± 30	4131–4565
Spermonde_FMA17	Poz-66848	P. Panambungan	−0.49	−0.01 ± 0.13	95	4330 ± 35	4110–4555
Spermonde_FMA18	Poz-66849	P. Panambungan	−0.44	0.05 ± 0.13	92	4810 ± 40	4805–5237
Spermonde_FMA19	Poz-63515	P. Panambungan	−0.33	0.16 ± 0.13	98	4940 ± 35	4873–5325
Spermonde_FMA20	Poz-66850	P. Panambungan	−0.34	0.34 ± 0.13	97	5350 ± 40	5457–5835
Spermonde_FMA21	Poz-66852	P. Panambungan	−0.44	0.04 ± 0.13	98	Modern	Modern

are largely preserved in original aragonitic composition (Table 2). Microatoll samples were AMS radiocarbon dated at the Poznan Radiocarbon Laboratory, University of Poznan, Poland. Conventional radiocarbon ages (in yr BP) were calibrated to calendar years before present (cal. yr BP; 2σ age ranges) using CALIB 7.1 (Stuiver and Reimer, 1993) with the marine calibration data set Marine13 (Reimer et al., 2013) and a Delta-R value of 89 ± 70 ^{14}C years as closest estimate for marine reservoir correction in the southeast Asian region (Southon et al., 2002). Radiocarbon ages of De Klerk's (1982) RSL markers were calibrated using the same calibration data set (Table 1, Figs. 3, 4).

Geophysical models used to predict RSL changes for the Spermonde Archipelago are based on the solution of the gravitationally self-consistent Sea Level Equation (SLE; Spada and Stocchi, 2007). Solving the SLE yields RSL changes that are imposed by fluctuations of continental ice masses and follow the solid Earth response. The Earth is assumed spherically symmetric, radially stratified, self-gravitating, rotating, deformable and incompressible (Spada et al., 2004; Spada and Stocchi, 2007). The earth rheological model is characterized by an outer elastic lithosphere of 100 km thickness, a three-layered Maxwell-viscoelastic mantle (Upper Mantle, Transition Zone and Lower Mantle) and an inviscid core. Four reasonable mantle viscosity profiles have been employed to generate the ice sheet models used in this study. Within these profiles, upper- and lower-mantle viscosity ranges through (0.2–1) × 10^{21} Pa·s and (2–10) × 10^{21} Pa·s, respectively. The viscosity of the Transition Zone is constrained to (0.3–1) × 10^{21} Pa·s. GIA simulations were computed for the three ice sheet models, i.e. RSES-ANU (Lambeck, 1998), ICE-5G (Peltier, 2004) and ANICE-SELEN (De Boer et al., 2014a, 2014b) using the different mantle viscosity profiles to determine the variability of the GIA signals for each model. The ice sheet models RSES-ANU and ICE-5G have been developed by means of similar iterative procedures. Given a prescribed Earth model and mantle viscosity profile, in fact, an 'a priori' ice model is used within the SLE to compute RSL curves at each available location where paleo-RSL markers have been measured and dated. The misfit between predictions and observations is therefore used at each iterative step to modify the ice-sheets thickness variations in space and time until a satisfactory solution is found. The ANICE-SELEN ice chronology, instead, is the result of a complex system consisting of a global 3D thermo-mechanical ice sheet model (De Boer et al., 2014b) that is fully and dynamically coupled to a global-scale GIA model based on the solution of the SLE (De Boer et al., 2014a). Accordingly, ANICE-SELEN incorporates all the interrelated effects of gravity, solid Earth and rotational perturbations but is not locally constrained by available geological RSL observations. Indeed, this implies that there are ice-proximal locations where the difference between the predicted and observed RSL change can be large. In this paper we use the ANICE-SELEN ice sheet model that was created by De Boer et al. (2014b) using a 100 km-thick lithosphere and viscosities of 1 × 10^{21} Pa·s for the upper mantle and transition zone and 2 × 10^{21} Pa·s for the lower mantle.

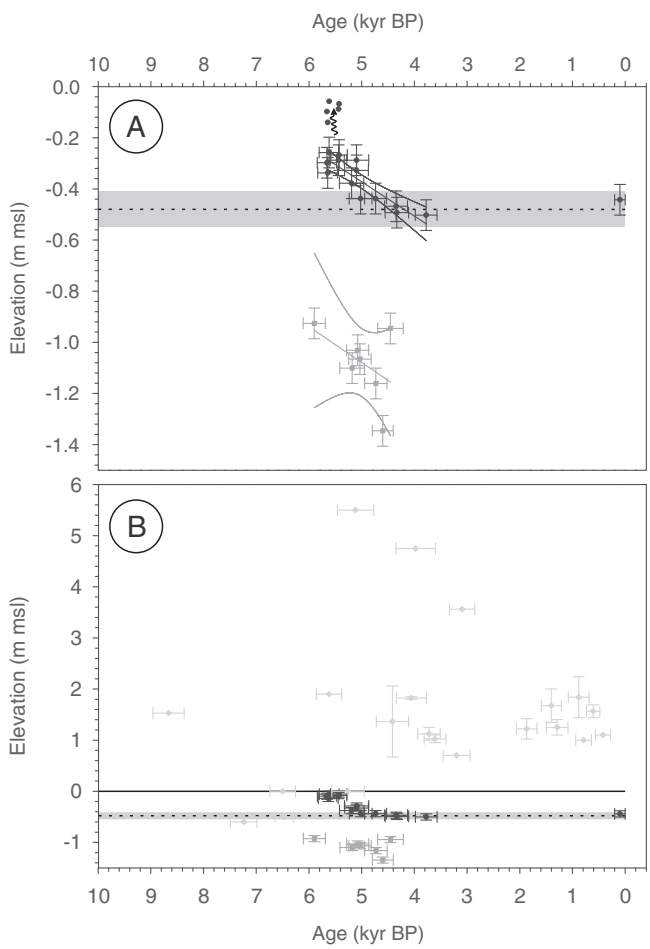

Fig. 3. (A) Age-elevation plot of fossil microatoll samples from Pulau Panambungan (black) and Pulau Barrang Lompo (dark gray) with respect to msl. Error bars indicate individual uncertainties related to surveys (vertical) and age calibration (horizontal). Shown are also the 1st order regression lines including the 95% confidence intervals (dashed lines) for both regression functions. Dashed horizontal line (black) indicates HLC including standard deviation (gray band; 0.48 ± 0.07 m below msl). Black dots indicate estimated surface abrasion for the highest elevated fossil microatolls nearby Pulau Panambungan (B) Age-elevation plot of fossil microatoll samples from Pulau Panambungan (black, including estimated surface abrasion) and Pulau Barrang Lompo (dark gray), and RSL markers from De Klerk (1982; light grey). Radiocarbon ages of De Klerk's (1982) RSL markers were calibrated using the same calibration data set as for the microatoll samples from this study. Horizontal error bars indicate resulting age uncertainties. Vertical uncertainties are adopted from De Klerk (1982) if these were provided. Solid and dashed horizontal lines indicate msl and HLC respectively.

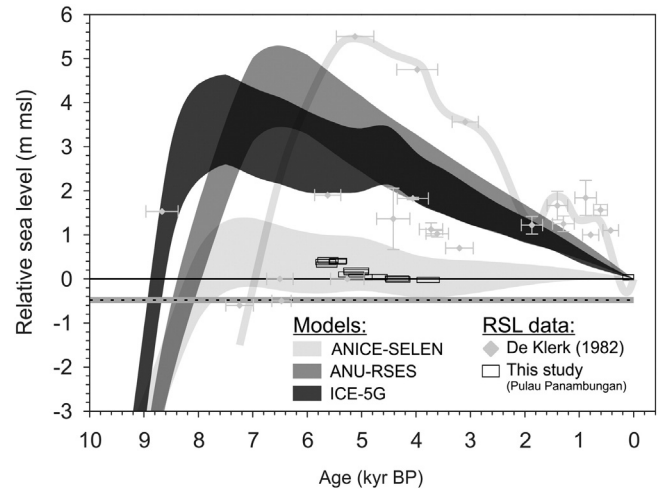

Fig. 4. RSL trend inferred from the fossil microatolls on Pulau Panambungan (black rectangles; see Table 1) under the assumption that the tidal range remained stable over the timeframe of analysis, and comparison with De Klerk's (1982) RSL curve (light gray narrow band) and predicted RSL change for the Spermonde Archipelago based on the ice-sheet models ANU-RSES (Lambeck, 1998), ICE-5G (Peltier, 2004) and ANICE-SELEN (De Boer et al., 2014a, 2014b) for a range of plausible mantle viscosity profiles (VKL, VM1 and VM2). Shaded areas of cumulative predicted RSL curves indicate the variability of the GIA signal for each simulation. Solid and dashed horizontal lines indicate msl and HLC, respectively.

4. Results

Living microatolls occur north of Pulau Barrang Lompo at an elevation of 0.47 ± 0.05 m (1σ, n = 23) below msl. On Pulau Sanane and Pulau Panambungan, living microatolls were found at similar elevations of 0.49 ± 0.08 m below msl (1σ, n = 17) and 0.50 ± 0.07 m below msl (1σ, n = 20) respectively. Accordingly, HLC is consistent for all three

islands and represents a datum that is 0.48 ± 0.07 m below msl (1σ, n = 60). The average thickness of living microatolls on the reef flats of the study islands was 0.48 ± 0.19 m (1σ, n = 60). Seven fossil microatolls were surveyed on Pulau Barrang Lompo with their elevations ranging from 1.35 m to 0.93 m below msl or, 0.86 m to 0.44 m below HLC. The fourteen fossil microatolls from Pulau Panambungan range in elevation from 0.50 m to 0.26 m below msl, corresponding to 0.02 m below HLC to 0.23 m above HLC (Table 2).

Radiocarbon dates of the fossil microatoll samples from Pulau Barrang Lompo yield mid-Holocene ages for these samples, ranging from ca. 4400 to 5900 cal. yr BP (Table 2). Most of the fossil microatolls from Pulau Panambungan exhibit a similar range of ages as their equivalents from Pulau Barrang Lompo yet with some samples dating between ca. 3800 and 4400 cal. yr BP. One of the supposedly fossil microatolls (i.e., without living polyps) yielded a modern age and has an elevation similar to HLC (0.04 ± 0.07 m). The highest-elevated emergent fossil microatolls on Pulau Panambungan dated at ca. 5600 cal. yr BP. Except for the fossil microatolls on Pulau Panambungan, no further emergent reef build-ups have been observed around coral reef islands in the Spermonde Archipelago.

Age-elevation plots depict a discrepancy between the fossil microatoll records from the two individual study islands (Fig. 3A). The fossil microatolls from Pulau Panambungan are characterized by a lowering trend from 0.23 m above HLC at ca. 5600 cal. yr BP to 0.02 m below HLC at about 3700 cal. yr BP. Fossil microatolls from Pulau Barrang Lompo show consistently lower elevations (i.e., permanently submerged), yet with similar formation ages as those from Pulau Panambungan. Considerable differences also become apparent when the spatio-temporal distribution of the microatoll data from this study is compared to the previous RSL data from De Klerk (1982), especially with respect to the elevation of some RSL markers in this region (Fig. 3B). Results furthermore exhibit variable GIA signals from the selected ice-sheet models (Fig. 4). Within the range of uncertainty, RSES-ANU and ICE-5G indicate a RSL highstand that was roughly 3–5 m above present-day msl about 7000–5000 yr BP. In contrast, model predictions from ANICE-SELEN show a much lower mid-Holocene RSL highstand in the Strait of Makassar and allow a RSL trend that was close to its present position over the past 7000 yr.

5. Discussion

Results reveal explicit differences between the ages and elevations of RSL markers from this study and previous studies (Tjia et al., 1972; De Klerk, 1982) for the Strait of Makassar. Also the elevations of fossil microatoll populations from the individual study islands Pulau Panambungan and Pulau Barrang Lompo initially appear to be inconsistent (Fig. 3A), even though when directly compared to the previous data, the differences become relatively subtle (Fig. 3B). The height difference of fossil microatolls on two nearby study islands was unexpected and in order to extract whether or not they comprise useful information about Holocene RSL in the Strait of Makassar, a number of geomorphic indications need to be considered.

5.1. Differences between individual microatoll records

The fossil microatolls on Pulau Barrang Lompo contrast with results from Pulau Panambungan as the individual populations show a mutual vertical offset of about 0.8 m, both at the beginning and at the end of the records (Fig. 3A). Yet, both localities show, in general, the same trend (though with some variability towards the end of the Barrang Lompo record). Performance of a 1st order regression analysis of ages and elevations of the fossil microatolls from Pulau Panambungan indicate a trend of -0.13 mm yr^{-1}. This value is in accordance to the trend calculated for Pulau Barrang Lompo accounting for -0.14 mm yr^{-1}. The similarity between the gradients of the microatoll records and the consistent present-day elevation of HLC is instructive for the interpretation of the fossil microatoll records on the two study islands and indicate a localized process that was uncoupled from the RSL trend and that influenced the elevations of fossil microatolls either during or after their formation, but before present-day microatolls have settled and developed in the intertidal environment. Usual syn- or post-formational processes that are capable to affect the elevation record of fossil microatolls with respect to former sea levels comprise: (i) reef ponding, (ii) reworking due to high-magnitude low-frequency events such as storms or tsunamis, and (iii) tectonics.

For living microatolls, it is well known that their primary elevation is influenced by changes in the tidal range over time (McLean et al., 1978; Lambeck et al., 2010) and by the environment (i.e., open reef flat, inter-island channel or lagoon) in which they are growing (Smithers and Woodroffe, 2000). Consequently, the elevation of fossil microatolls can also vary considerably, even though they occur in a continuous area that was not affected by large-scale RSL oscillations (Woodroffe et al., 2012). Here, the environment in which the fossil microatolls occur, i.e. open reef flat positions, is the same for all study islands (Fig. 2A–C). There are no geomorphic indications for former ponding resulting, e.g. from the deposition of rubble ramparts on the reef flats. Although reworking and erosion of such rubble deposits would be likely over the timeframe that is under consideration (i.e. within the last 4000 yr; Bayliss-Smith, 1988; McLean and Woodroffe, 1994), the absence of present-day storm ridges and the similar elevation of living microatolls on the individual islands at 0.48 ± 0.07 m below msl support an originally consistent environment for the fossil microatolls. If syn-formational uncertainties with respect to moating can be discounted, microatoll records may track RSL changes with a high temporal and spatial precision (Davies and Montaggioni, 1985; Woodroffe and McLean, 1990; Smithers and Woodroffe, 2000), usually more precise (i.e., with a smaller indicative range) than other geomorphic or biological RSL markers (Woodroffe and Horton, 2005).

We consider reworking due to storm activity or tsunamis as unlikely for the majority of RSL markers from this study because of the study location that is outside the cyclone belts and not usually affected by tsunamis, and the naturally oriented geomorphological appearance of fossil microatolls on the reef flats. Also, age-elevation data from redeposited fossil microatolls are likely to plot randomly distributed without any consistent pattern or gradient. With regards tectonics, a rapid co-seismic or gradual inter-seismic uplift and subsidence of Pulau Panambungan and Pulau Barrang Lompo, respectively, would require an active fault between those two study sites. In the literature, there is no indication for tectonic activity in the Spermonde Archipelago during the Holocene (Fig. 1B), yet this does not fully exclude the possibility of some tectonic movements with reasonable certainty.

Surface morphologies of individual microatolls may be able to track RSL changes also resulting from active tectonic uplift or subsidence (Meltzner and Woodroffe, 2014; Meltzner et al., 2015). If the differences in microatoll elevations from the two study islands are related to tectonic movements along an active fault between Pulau Panambungan and Pulau Barrang Lompo, then four scenarios are conceivable: (i) rapid co-seismic or (ii) gradual interseismic relative uplift of Pulau Panambungan; or, (iii) rapid co-seismic or (iv) gradual interseismic relative subsidence of Pulau Barrang Lompo. For all scenarios, the vertical offset is assumed to account for the observed 0.8 m, either during one event, stepwise or gradual.

Syn-formational rapid co-seismic and gradual inter-seismic uplift of Pulau Panambungan could have resulted in microatoll morphologies where a secondary microatoll plane lies below a relatively higher primary microatoll center with the two (or more) planes arranged in a well-defined, rectangular form (co-seismic), or a raised microatoll center that is becoming gradually wider towards the bottom (interseismic). Likewise, microatolls that were affected by syn-formational rapid co-seismic and gradual interseismic subsidence of Pulau Barrang Lompo should exhibit an outer rim that is considerably (co-seismic) or at least marginally (interseismic) higher than the central portion (Scoffin

and Stoddart, 1978; Meltzner and Woodroffe, 2014). Such characteristic patterns from individual microatolls provide valuable geomorphic information on RSL changes; however, such features have not been observed on the studied microatolls during fieldwork.

Yet the complete absence of these characteristic microatoll morphologies on individual exemplars may provide some instructive insights into their formation and geomorphological trajectory itself. Compared to living microatolls, the relatively highest elevated fossil microatolls from both study sites exhibit the same patterns and probably similar degrees of surficial denudation (Fig. 2E–G). A top-down erosive agent is likely related to abrasion from sediment transport in the littoral zone around a coral cay. Consequently, for a certain time, before their primary elevation was changed, the fossil microatolls from Pulau Barrang Lompo appear to have been exposed to the same coastal environment as their counterparts on Pulau Panambungan are today, i.e. close to an actively moving shoreline. The characteristic denudation patterns of fossil microatolls from both study sites therefore indicate a localized subsidence of the fossil microatolls on Pulau Barrang Lompo, rather than uplift of the fossil microatolls on Pulau Panambungan.

Active surface abrasion of fossil microatolls resulting from sediment flux along coral island shorelines is presumably a rapid process given the vast amount of sediment transported, usually on a biannual basis due to seasonal reversals in monsoon climate (Kench and Brander, 2006). Similarities in the degree of surface abrasion of fossil microatolls on both study islands suggest that the fossil population on Pulau Barrang Lompo have been shifted to a relatively calm, sub-tidal environment, and thus beyond the reach of active sand transport, only since recently. Accordingly, the recent subsidence of the microatoll field on Pulau Barrang Lompo may therefore also be related to human occupation of this study island, e.g. due to excessive groundwater extraction or reef edifice collapse resulting from the superimposed load of constructions.

While it is clear that some large cities in Southeast Asia are already subsiding due to anthropogenic activities (Nicholls and Cazenave, 2010), there are no direct observations that human occupation may also increase subsidence rates, and therefore RSL rise, on small tropical islands. If the subsidence along the outermost eastern reef slope on Pulau Barrang Lompo was related to tectonic activity, human occupation, or if it reflects a natural instability of the reef framework cannot be conclusively assessed based on the present dataset and requires information from additional fossil microatolls on other study islands and investigations on internal microatoll growth characteristics. However, a comprehensive study focusing on this particular observation would have important implications for the vulnerability of densely populated reef islands to sea-level rise in this area.

5.2. Differences between microatoll records and previous RSL investigations

The difference between the microatoll records from this study and the previously presented evidence for RSL positions during the Holocene in the Spermonde area is significant. Fig. 3B depicts that the RSL markers combined by De Klerk (1982) are intrinsically inconsistent. It is challenging to determine a single reason for the age-elevation differences from the range of plausible scenarios. Positional uncertainties of RSL markers result not only from (i) survey errors, but may also be influenced by (ii) an inconsistent relation between their elevation and msl during their formation, and (iii) local disturbances, e.g. storms or other high-magnitude events, taking place after their formation. Therefore, one argument may be that De Klerk (1982) based his RSL reconstruction mostly on low-quality RSL markers with different indicative values, and without assessing the possibility of some deposits being created by storm events. For example, the two highstands presented by De Klerk (1982) were inferred from oysters (~5100 cal. yr BP) attached to Eocene limestone (see Tjia et al., 1972), and shells within beach deposits (~1400 cal. yr BP). Fixosessile biological markers in growth position may prove useful for the reconstruction of RSL changes, depending on the tidal range, shoreline topography and wave exposure (Lambeck et al., 2010; Rovere et al., 2015). Accordingly, relict oyster banks have been successfully used for the reconstruction of former RSL (Beaman et al., 1994; Woodroffe and Horton, 2005). However, caution is needed to avoid misinterpretations of the age-elevation information from RSL markers, in particular when various markers are combined into a general RSL curve for one location (Lambeck et al., 2010).

5.3. Holocene reef growth in the Spermonde Archipelago and the magnitude of a mid-Holocene RSL highstand

Coral reefs provide an excellent opportunity to reconstruct Quaternary RSL positions within tropical latitudes (Woodroffe and Webster, 2014; Camoin and Webster, 2015). Yet the growth response of coral reefs to RSL changes is spatially variable and can be broadly summarized into three different modes, i.e. keep-up, catch-up and give-up, depending on the rate of RSL change and other environmental influences such as nutrient supply and temperature (Davies and Montaggioni, 1985; Neumann and Macintyre, 1985; Toomey et al., 2013). Holocene reef growth in the Indo-Pacific region is highly diverse and likely to vary even within the same system (Montaggioni, 2005). Although the 'keep-up' growth mode is more convincingly inferred from study sites in the Caribbean (Woodroffe and Webster, 2014), there are no indications that Indo-Pacific reefs "would not have been able to develop from a 'keep-up' growth style" (Montaggioni, 2005, p. 45), especially when RSL rise during the early Holocene was gradual.

A 'keep-up' or 'keep-up/catch-up' growth mode during the Holocene however cannot be reconciled with the RSL curve from De Klerk (1982) and the model predictions based on RSES-ANU and ICE-5G as these suggest a RSL considerably higher than present for a prolonged period during the Holocene epoch following a gradual rise (Fig. 4). Consequently, we could expect some prominent emergent Holocene coral reef limestones or similar geomorphic evidence as the reefs in the Spermonde Archipelago could have kept-up/caught-up RSL in response to an extended increase in vertical accommodation space. However, even during spring low tide, only minor parts of the reef flats, i.e. the fossil microatolls on Pulau Panambungan (Fig. 2G), are subaerially exposed.

Microatolls from massive *Porites* colonies contain a record of low water levels and mimic, in smaller spatial and temporal scales, the response of an entire coral reef system to RSL changes (Woodroffe and Webster, 2014). The highest elevated fossil microatolls from this study (FMA8-FMA11, FMA20) are located close to the modern southeastern shoreface of Pulau Panambungan (Fig. 2C), have a thickness of about 0.1 m and display an abraded upper surface (Fig. 2G). Quantifying the amount of surface erosion on these specimens is challenging as the thickness of living microatolls is not pre-determined, but controlled by exposure during low water levels. However, a comparison with the mean thickness of living microatolls (0.48 ± 0.19 m) provides at least an indication and suggests that here the fossil microatolls have been eroded by about 0.2 m due to the permanent drift of beach sediments in this high-energy environment (cf. Kench et al., 2009). Consequently, the microatoll record from Pulau Panambungan indicates a RSL (i.e. past HLC) that was about 0.4 to 0.5 m higher at ca. 5600 cal. yr BP, and that fell to its present position until about 4000 cal. yr BP. (Table 2; Fig. 4). The new RSL data from Pulau Panambungan is in accordance to other studies from the Indian Ocean where a Holocene RSL highstand of about 0.5 m has been detected in the Cocos (Keeling) Islands by Woodroffe et al. (1990), or in the Maldives by Kench et al. (2009) and may therefore also record progressive lateral reef flat development in the Spermonde Archipelago when RSL fell to its modern position (cf. Chappell, 1983).

The RSL trend inferred from the fossil microatolls on Pulau Panambungan is also consistent with the regional pattern of Holocene RSL changes in this area as predicted by ANICE-SELEN ice sheet model (Fig. 4; De Boer et al., 2014a, 2014b). This suggests that the uncertainties in the spatial pattern of ice-sheets retreat are not critical for far-field

sites where, instead, the rate of meltwater release and its hemispheric and continental provenance are more important. In particular, the Antarctic Ice Sheet (AIS) component of ANICE-SELEN is characterized by a peculiar ice-mass fluctuation throughout the Holocene if compared to RSES-ANU and ICE-5G. The latter, in fact, are characterized by reduction towards the modern size value that occurs, respectively, until present-day and until 4000 yr BP. According to ANICE-SELEN, instead, the AIS melts and reaches the present-day size at ~9000 yr BP. Then, a further reduction beyond the modern volume occurs until 6000 yr BP, when ~1 m of equivalent sea level from AIS is stored in the oceans. Later, the AIS grows almost linearly towards the present-day size and counteracts the subsidence of the peripheral forebulge around Antarctica. As a consequence, the ocean syphoning effect is buffered and the shape of the predicted RSL curve at Pulau Panambungan is modulated towards a lower RSL highstand. Interestingly, a recent study from Zwally et al. (2015) claims that the current dynamic thickening of the East AIS (147 Gt a^{-1}) is a response to ice accumulation since the early Holocene. Consequently, RSL data from the Strait of Makassar might add further constraints to the behavior of the AIS during the Holocene.

6. Conclusions

Reconstructions of RSL changes during the geological past have the potential to assist in the separation between climatic and solid-earth signals and therefore provide valuable lessons for future changes in RSL. The value of these lessons, however, is largely determined by the application of accurate sampling strategies that consider the vertical uncertainties and indicative meaning of geomorphic and other RSL markers. This study provides a new, high-resolution RSL reconstruction for central Indonesia based on fossil microatolls from the mid-Holocene. Based on a number of geomorphic indications, our results indicate that the magnitude of a mid-Holocene RSL highstand in the Strait of Makassar did not reach elevations substantially higher than 0.5 m above present.

Our results also raise some new questions concerning the influence of anthropogenic activities on reef framework stability and the reef growth modes during the Holocene in the Spermonde Archipelago. For example, the complete absence of Pleistocene reef limestone in the Spermonde indicates a long-term gradual subsidence of the platform resulting, eventually, from sediment deposition on the shelf. Gradual subsidence and variable reef growth modes affect the record of a RSL highstand as we can detect it in the field today. Therefore additional surveys may be combined with drilling on the reef flats in order to identify the depth of the unconformity that separates the Pleistocene/Holocene reefs and thus allow for a long-term reconstruction of the local reef development (i.e. keep-up, catch-up or give-up), determine rates of subsidence and reconstruct the related RSL history for the entire Holocene epoch in this area.

A RSL highstand of 0.5 m at ca. 5600 cal. yr BP inferred from fossil microatoll records on the uninhabited coral island Pulau Panambungan fits well to geophysical predictions of the ice-sheet model ANICE-SELEN and may therefore be also instructive for the choice of modeling parameters and data processing. Our new RSL dataset for the Strait of Makassar challenges existing studies and should therefore be complemented by additional field observations. Better constraints on the magnitude and timing of Holocene RSL changes in the Spermonde Archipelago will improve our understanding of the processes influencing present RSL variability and provide potential fingerprints of future sea-level changes.

Acknowledgments

We thank Nur Abu, Andi Muhammad Yusuf, Tarsan and Darwan Saputra (MaCSI-UNHAS) for their invaluable help during fieldwork. Thanks to Jamaluddin Jompa and Dewi Yanuarita Satari (MaCSI-UNAHS) for their support during the preparation and conduct of the fieldwork. Francisca Wit is thanked for her help with the translation of De Klerk's (1982) doctoral thesis from Dutch to English. Thanks also to Daniel Harris (ZMT) for reading a first draft of the manuscript. Ibnu Sofian Balitka (Badan Informasi Geospasial, Cibinong/Indonesia) kindly provided the Makassar tide gauge data. Dierk Hebbeln (MARUM) helped with the interpretation of the microatoll data. A.R.'s research is supported by the Institutional Strategy of the University of Bremen, funded by the German Excellence Initiative, and by ZMT, the Leibniz Center for Tropical Marine Ecology, Bremen. The manuscript was greatly improved by the comments of Editor Andrew James Plater and two anonymous reviewers. We gratefully acknowledge the cooperation of the Indonesian Ministry for Research and Technology (RISTEK). Fieldwork for this study was conducted under Research Permit No. 399/SIP/FRP/SM/X/2012 and Working Permit No. 2C11JD5741-L. This study was funded by the Leibniz Center for Tropical Marine Ecology in Bremen.

References

Bayliss-Smith, T.P., 1988. The role of hurricanes in the development of reef islands, Ontong Java Atoll, Solomon Islands. Geogr. J. 154, 377–391.
Beaman, R., Larcombe, P., Carter, R.M., 1994. New evidence for the Holocene sea-level high from the inner shelf, central Great Barrier Reef, Australia. J. Sediment. Res. 64, 881–885.
Bergman, S.C., Coffield, D.Q., Talbot, J.P., Garrard, R.A., 1996. Tertiary tectonic and magmatic evolution of western Sulawesi and the Makassar Strait, Indonesia: evidence for a Miocene continent-continent collision. Geol. Soc. Lond., Spec. Publ. 106, 391–429. http://dx.doi.org/10.1144/GSL.SP.1996.106.01.25.
Bird, P., 2003. An updated digital model of plate boundaries. Geochem. Geophys. Geosyst. 4, 1–52. http://dx.doi.org/10.1029/2001GC000252.
Camoin, G.F., Webster, J.M., 2015. Coral reef response to Quaternary sea-level and environmental changes: state of the science. Sedimentology 62, 401–428. http://dx.doi.org/10.1111/sed.12184.
Chappell, J., 1983. Evidence for smoothly falling sea level relative to north Queensland, Australia, during the past 6000 yr. Nature 302, 406–408.
Clark, J.A., Farrell, W.E., Peltier, W.R., 1978. Global changes in postglacial sea level: a numerical calculation. Quat. Res. 9, 265–287. http://dx.doi.org/10.1016/0033-5894(78)90033-9.
Darman, H., 2014. Tectonic Provinces in the Makassar Strait Region. Retrieved from http://geoseismic-seasia.blogspot.de (accessed on 10 September 2015).
Davies, P.J., Montaggioni, L., 1985. Reef growth and sea-level change: the environmental signature. Proceedings 5th International Coral Reef Congress, Tahiti, pp. 477–511.
De Boer, B., Lourens, L.J., van de Wal, R.S.W., 2014a. Persistent 400,000-year variability of Antarctic ice volume and the carbon cycle is revealed throughout the Plio-Pleistocene. Nat. Commun. 5. http://dx.doi.org/10.1038/ncomms3999.
De Boer, B., Stocchi, P., van de Wal, R.S.W., 2014b. A fully coupled 3-D ice-sheet–sea-level model: algorithm and applications. Geosci. Model Dev. 7, 2141–2156. http://dx.doi.org/10.5194/gmd-7-2141-2014.
De Klerk, L.G., 1982. Zeespiegels, riffen en kustflakten in Zuidwest Sulawesi, Indonesia. Utrecht Geography Studies 27, 1–172.
Engelhart, S.E., Vacchi, M., Horton, B.P., Nelson, A.R., Kopp, R.E., 2015. A sea-level database for the Pacific coast of central North America. Quat. Sci. Rev. 113, 78–92. http://dx.doi.org/10.1016/j.quascirev.2014.12.001.
Förste, C., Bruinsma, S.L., Flechtner, F., Marty, J., Lemoine, J.M., Dahle, C., Abrikosov, O., Neumayer, H., Biancale, R., Barthelmes, F., 2012. A preliminary update of the Direct approach GOCE Processing and a new release of EIGEN-6C. AGU Fall Meeting Abstracts, p. 923.
Gehrels, R., Long, A., 2008. Sea level is not level. Geography 93.
Hall, R., 1997. Cenozoic plate tectonic reconstructions of SE Asia. Geol. Soc. Lond., Spec. Publ. 126, 11–23.
Imran, A.M., Suriamihardja, D.A., Sirajuddin, H., 2013. Geology of Spermonde Platform. Proceedings 7th International Conference on Asian and Pacific Coasts (APAC), Bali, Indonesia. Hasanuddin University Press, pp. 1062–1067.
Kench, P.S., Brander, R., 2006. Response of reef island shorelines to seasonal climate oscillations: South Maalhosmadulu atoll, Maldives. J. Geophys. Res. 111, 1–12. http://dx.doi.org/10.1029/2005JF000323.
Kench, P.S., Smithers, S.G., Mclean, R.F., Nichol, S.L., 2009. Holocene reef growth in the Maldives: evidence of a mid-Holocene sea-level highstand in the central Indian Ocean. Geology 37, 455–458. http://dx.doi.org/10.1130/G25590A.1.
Lambeck, K., 1998. On the choice of timescale in glacial rebound modelling: mantle viscosity estimates and the radiocarbon timescale. Geophys. J. Int. 134, 647–651. http://dx.doi.org/10.1046/j.1365-246x.1998.00597.x.
Lambeck, K., Esat, T.M., Potter, E.-K., 2002. Links between climate and sea levels for the past three million years. Nature 419, 199–206. http://dx.doi.org/10.1038/nature01089.
Lambeck, K., Woodroffe, C.D., Antonioli, F., Anzidei, M., Gehrels, W.R., Laborel, J., Wright, A.J., 2010. Paleoenvironmental records, geophysical modeling, and reconstruction of sea-level trends and variability on centennial and longer timescales. In: Church, J.A., Woodworth, P.L., Aarup, T., Wilson, W.S. (Eds.), Understanding Sea-Level Rise and Variability. Wiley-Blackwell, pp. 61–121.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proc. Natl. Acad. Sci. 111, 15296–15303. http://dx.doi.org/10.1073/pnas.1411762111.

McLean, R.F., Woodroffe, C.D., 1994. Coral atolls. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, New York, pp. 267–302.

McLean, R.F., Stoddart, D.R., Hopley, D., Polach, H., 1978. Sea level change in the Holocene on the northern Great Barrier Reef. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 291, 167–186.

Meltzner, A.J., Woodroffe, C.D., 2014. Coral microatolls. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, Ltd., Chichester, UK, pp. 125–145. http://dx.doi.org/10.1002/9781118452547.ch8.

Meltzner, A.J., Sieh, K., Chiang, H.-W., Wu, C.-C., Tsang, L.L.H., Shen, C.-C., Hill, E.M., Suwargadi, B.W., Natawidjaja, D.H., Philibosian, B., Briggs, R.W., 2015. Time-varying interseismic strain rates and similar seismic ruptures on the Nias–Simeulue patch of the Sunda megathrust. Quat. Sci. Rev. 122, 258–281. http://dx.doi.org/10.1016/j.quascirev.2015.06.003.

Milne, G.A., Long, A.J., Bassett, S.E., 2005. Modelling Holocene relative sea-level observations from the Caribbean and South America. Quat. Sci. Rev. 24, 1183–1202. http://dx.doi.org/10.1016/j.quascirev.2004.10.005.

Mitrovica, J.X., Milne, G.A., 2002. On the origin of late Holocene sea-level highstands within equatorial ocean basins. Quat. Sci. Rev. 21, 2179–2190. http://dx.doi.org/10.1016/S0277-3791(02)00080-X.

Mitrovica, J.X., Peltier, W.R., 1991. On postglacial geoid subsidence over the equatorial oceans. J. Geophys. Res. 96, 20053–20071.

Montaggioni, L.F., 2005. History of Indo-Pacific coral reef systems since the last glaciation: development patterns and controlling factors. Earth Sci. Rev. 71, 1–75. http://dx.doi.org/10.1016/j.earscirev.2005.01.002.

Neumann, A.C., Macintyre, I., 1985. Reef response to sea level rise: keep-up, catch-up or give up. Proceedings 5th International Coral Reef Congress, Tahiti, pp. 105–110.

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328, 1517–1520. http://dx.doi.org/10.1126/science.1185782.

Peltier, W.R., 1999. Global sea level rise and glacial isostatic adjustment. Glob. Planet. Chang. 20, 93–123. http://dx.doi.org/10.1016/S0921-8181(98)00066-6.

Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. Annu. Rev. Earth Planet. Sci. 32, 111–149. http://dx.doi.org/10.1146/annurev.earth.32.082503.144359.

Prasetya, G.S., De Lange, W.P., Healy, T.R., 2001. The Makassar Strait Trsunamigenic Region, Indonesia. Nat. Hazards 24, 295–307. http://dx.doi.org/10.1023/A:1012297413280.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869–1887.

Renema, W., 2002. Larger foraminifera and their distribution patterns on the Spermonde shelf, South Sulawesi. Scr. Geol. 124, 1–263.

Renema, W., Troelstra, S.R., 2001. Larger foraminifera distribution on a mesotrophic carbonate shelf in SW Sulawesi (Indonesia). Palaeogeogr. Palaeoclimatol. Palaeoecol. 175, 125–146. http://dx.doi.org/10.1016/S0031-0182(01)00389-3.

Rovere, A., Antonioli, F., Bianchi, C.N., 2015. Fixed biological indicators. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. John Wiley & Sons, Ltd., Chichester, UK, pp. 268–280.

Sasajima, S., Nishimura, S., Hirooka, K., Otofuji, Y., Van Leeuwen, T., Hehuwat, F., 1980. Paleomagnetic studies combined with fission-track datings on the western arc of Sulawesi, East Indonesia. Tectonophysics 64, 163–172.

Schöne, T., Esselborn, S., Rudenko, S., Raimondo, J.-C., 2010. Radar altimetry derived sea level anomalies–the benefit of new orbits and harmonization. System Earth via Geodetic-Geophysical Space Techniques. Springer, pp. 317–324.

Schwerdtner Máñez, K., Husain, S., Ferse, S.C.A., Máñez Costa, M., 2012. Water scarcity in the Spermonde Archipelago, Sulawesi, Indonesia: past, present and future. Environ. Sci. Pol. 23, 74–84. http://dx.doi.org/10.1016/j.envsci.2012.07.004.

Scoffin, T.P., Stoddart, D.R., 1978. The nature and significance of microatolls. Philosophical Transactions of the Royal Society of London, Ser. B. Biological Sciences 284, 99–122.

Shennan, I., Horton, B., 2002. Holocene land-and sea-level changes in Great Britain. J. Quat. Sci. 17, 511–526.

Smithers, S.G., Woodroffe, C.D., 2000. Microatolls as sea-level indicators on a mid-ocean atoll. Mar. Geol. 168, 61–78. http://dx.doi.org/10.1016/S0025-3227(00)00043-8.

Southon, J., Kashgarian, M., Fontugne, M., Metivier, B., Yim, W.W.S., 2002. Marine reservoir corrections for the Indian Ocean and Southeast Asia. Radiocarbon 44, 167–180.

Spada, G., Stocchi, P., 2007. SELEN: A Fortran 90 program for solving the "sea-level equation". Comput. Geosci. 33, 538–562.

Spada, G., Antonioli, A., Boschi, L., Brandi, V., Cianetti, S., Galvani, G., Giunchi, C., Perniola, B., Agostinetti, N.P., Piersanti, A., 2004. Modeling earth's post-glacial rebound. EOS Trans. Am. Geophys. Union 85, 62–64.

Stuiver, M., Reimer, P.J., 1993. Extended 14C database and revised CALIB 3.0 14C age calibration program. Radiocarbon 35, 215–230.

Tjia, H.D., Fujii, S., Kigoshi, K., Sugimura, A., Zakaria, T., 1972. Radiocarbon dates of elevated shorelines, Indonesia and Malaysia. Part 1. Quat. Res. 2, 487–495.

Toomey, M., Ashton, A.D., Perron, J.T., 2013. Profiles of ocean island coral reefs controlled by sea-level history and carbonate accumulation rates. Geology 41, 731–734.

Umbgrove, J.H.F., 1928. De koraalriffen van den Spermonde-Archipel (Zuid-Celebes). Leidse. Geol. Meded. 3, 228–247.

Vacchi, M., Rovere, A., Chatzipetros, A., Zouros, N., Firpo, M., 2014. An updated database of Holocene relative sea level changes in NE Aegean Sea. Quat. Int. 328, 301–310.

Walpersdorf, A., Vigny, C., Manurung, P., Subarya, C., Sutisna, S., 1998. Determining the Sula block kinematics in the triple junction area in Indonesia by GPS. Geophys. J. Int. 135, 351–361.

Whitten, T., Mustafa, M., Henderson, G.S., 2002. Ecology of Sulawesi. Tuttle Publishing.

Wijsman-Best, M., Moll, H., De Klerk, L.G., 1981. Present status of the coral reefs in the Spermonde Archipelago (South Sulawesi, Indonesia). Proceedings 4th International Coral Reef Symposium, Manila, pp. 263–267.

Woodroffe, S.A., Horton, B.P., 2005. Holocene sea-level changes in the Indo-Pacific. J. Asian Earth Sci. 25, 29–43. http://dx.doi.org/10.1016/j.jseaes.2004.01.009.

Woodroffe, C.D., McLean, R.D., 1990. Microatolls and recent sea level change on coral atolls. Nature 344, 531–534.

Woodroffe, C.D., Webster, J.M., 2014. Coral reefs and sea-level change. Mar. Geol. 352, 248–267.

Woodroffe, C.D., McLean, R.F., Polach, H., Wallensky, E., 1990. Sea level and coral atolls: Late Holocene emergence in the Indian Ocean. Geology 18, 62–66.

Woodroffe, C.D., McGregor, H.V., Lambeck, K., Smithers, S.G., Fink, D., 2012. Mid-Pacific microatolls record sea-level stability over the past 5000 yr. Geology 40, 951–954. http://dx.doi.org/10.1130/G33344.1.

Zwally, H.J., Li, J., Robbins, J.W., Saba, J.L., Donghui, Y., Brenner, A.C., 2015. Mass gains of the Antarctic ice sheet exceed losses. J. Glaciol. 61, 1019–1036. http://dx.doi.org/10.3189/2015/JoG15J071.