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Sedimentary Environment of a Modern Carbonate Platform of Karimunjawa Islands, Central Java

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Abstract - Sitting in a biodiversity "hotspot" of the mid-Sunda Shelf region, Karimunjawa Islands have currently been the priority for marine biodiversity conservation. Knowledge of surface sediments on modern carbonate platform is one of essential information to support conservation policies, but such has received little attention from reef researchers. This study describes the sediment characteristics of the selected modern carbonate platforms of Karimunjawa Islands through integrated sediments and satellite data analysis. Textural group of sediments indicates that moderate to poorly sorted gravelly sands are dominant with no grading pattern concerning geomorphological and habitat succession from landward to seaward. Sediment compositions are predominantly bioclastic components, comprising coral and mollusks as the highest and the second highest estimated order of abundance. The reworked grains and rock fragments, although present, are not voluntary abundant. The carbonate sedimentary facies is primarily composed of mud-lean packstone with additional proportion of grainstone and packstone. There are only slight distinct sedimentological characteristics for all benthic habitats as shown by the principal component analysis revealing overlap relationship between sediment parameters and benthic habitats. The study provides the first characterization of sediments which operate on the modern carbonate platform of Karimunjawa Islands along with their controlling factors and specialized nature.

Keywords: reef geomorphology, benthic habitats, sediment compositions, carbonate facies, marine conservation

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Introduction

Carbonate production in the oceans is an essential process in producing sediment through physical, chemical, and biological erosion (Woodroffe *et al*., 2017). Marine organisms including corals, mollusks, foraminifera, bryozoans, red algae, *Halimeda*, Echinodermata, *etc.* produce a series of discrete sediment size upon their death through skeletal breakdown (Perry *et al*., 2011). Mapping of modern carbonate environments has long been utilized to be one of accurate characterizations and modelings of lateral sedimentary facies in the subsurface which is useful to interpret carbonate reservoirs in oil and gas industries (Wilkenson *et al*., 1999). Likewise, characterization of water-bottom sediments on modern carbonate systems and reef environments has also been used in supporting conservation policies (Tomascik *et al*., 1997). The high unusual biota and ecology of the Indonesian reef systems can not be understood adequately for management purposes until there is a better understanding of their geomorphology and oceanographic processes, in the past and present time (Tomascik *et al*., 1997; Asriningrum, 2011).

Unlike the relatively well studied subtropical and sub-arid modern carbonate sediments such as in the Bahamas or South Pacific (Reijmer *et al*., 2009; Harris *et al*., 2010, 2011; Gischler, 2006, 2011), sediments on the modern carbonate systems in Indonesia are, by comparison, poorly known and least studied. Studies in the Indonesian carbonate environments have been typically focused on their biota and ecological aspects (Tomascik *et al.,* 1997; Cleary *et al*., 2005; Becking *et al*., 2006; Renema, 2006a, 2006b) with limited studies linked to an understanding of their sedimentology. Detailed sedimentological studies of modern carbonate systems are restricted to those of Kepulauan Seribu, offshore Jakarta, demonstrating bioclastic assemblages on the predominantly siliciclastic shelf sediments (Park *et al*., 1992, 2010; Jordan, 1998; Utami *et al*., 2018). Moreover, Madden *et al*. (2013) pointed out the dominant bioclastic carbonate sands with grainstone to grain-rudstone texture in Kaledupa and Hoga atolls, Wakatobi Islands.

Model from the small-scale patch reef complex of Kepulauan Seribu (Utami *et al*., 2018) or atoll reefs in Wakatobi (Madden *et al*., 2013) might not be wholly analogous and applicable to the carbonate systems elsewhere in Indonesia. The differences may relate slightly to ecological conditions and partly to geomorphic and oceanographic processes since sedimentology on reef platform is closely associated with environmental conditions (Smithers, 1994; Gischler and Lomando, 1999). On the other hand, Karimunjawa Islands have currently been the priority for marine biodiversity conservation as a consequence of Marine Protected Areas (MPAs). The concern to protect the high marine biodiversity and natural resources of the region and to monitor the development of the Karimunjawa marine environment have been outlined and highlighted on the national document of marine conservation zone management and planning.

This study attempts to characterize sedimentological characteristics of modern carbonate environments, particularly those from Karimunjawa Islands through an integration of sedimentological and satellite data analysis. Here, the sediment compositions and distributions are described which the support of MPAs along with other coastal marine sciences, especially geology, geomorphology, and benthic habitats. The study objectives, therefore, are specifically to (1) describe the sediment characteristics of a modern carbonate platform of Karimunjawa Islands and its controlling factors; (2) investigate the quantitative relationship between sediment texture and the distribution of mapped habitats.

Geology, Ocean, and Climate Setting

The Karimunjawa Islands are located about 80 km northwest offshore of Jepara, consisting of twenty-seven islands with a total land area of about 78 km^2 (Figure 1). The Karimunjawa and Kemujan are two largest islands with an area of 2,7 km^2 and 1,4 km^2 respectively. The islands of the Karimunjawa and Kemujan are geologically pre-Tertiary continental islands consisting predominantly of quartzites and shales overlain by basaltic lava (van Bemmelen, 1949). During the Neogen, the 506 m high of Karimunjawa Island (*i.e*. the largest island in the archipelago) was the highest point of the surrounding Sundaland. The submergence of the surrounding land took place sometimes after the Pleistocene (van Bemmelen, 1949).

The islands are significantly influenced by the monsoonal climate prevailing eastward flow of surface current during the northwest monsoon (rainy season) from November to March with an intense rainfall of >200 mm/month. The pattern is

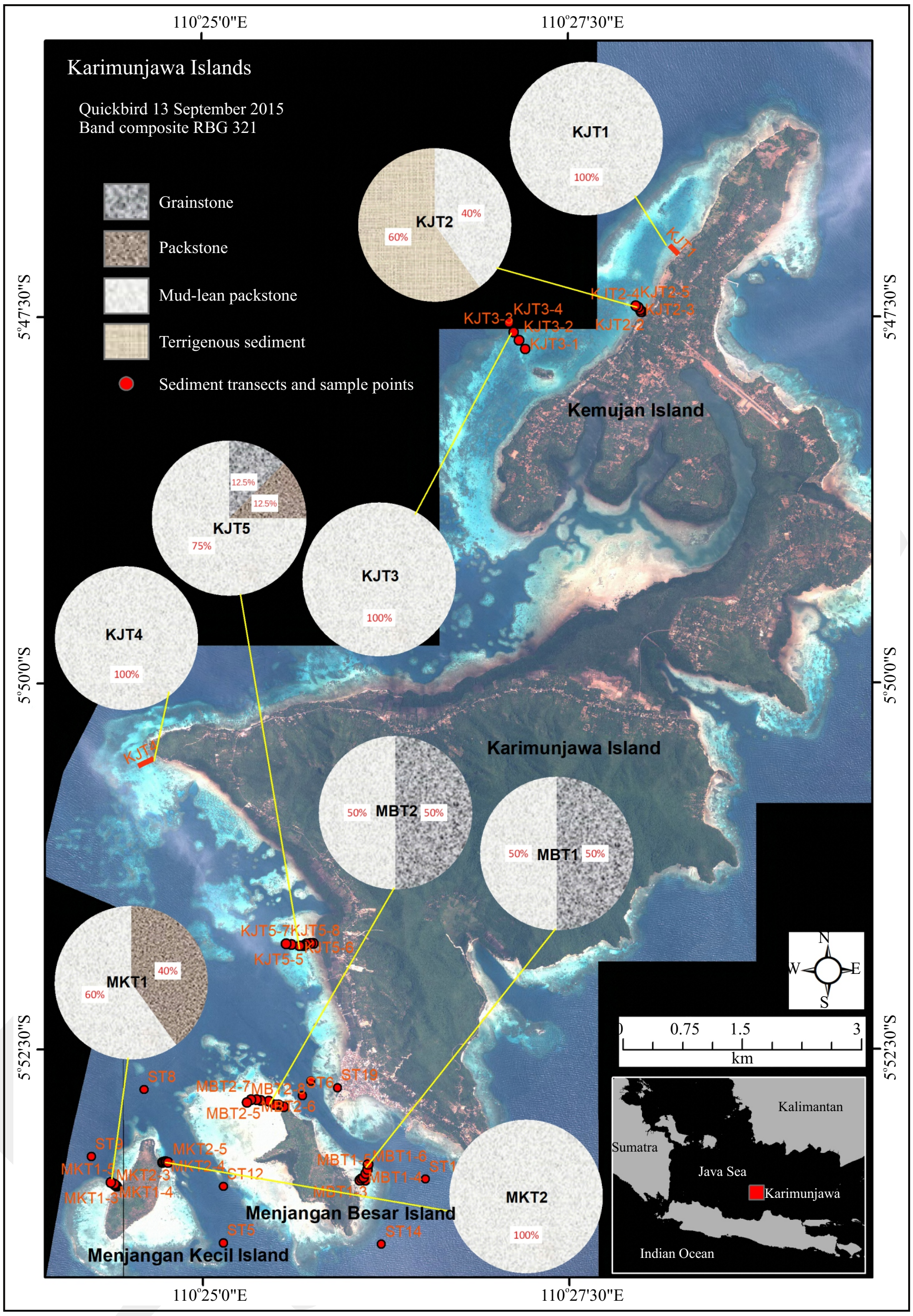

Figure 1. Map of Karimunjawa and surrounding areas showing sediment transects and sample point locations indicated by KJT, MBT, MKT, *etc*. Inset: pie diagrams plot of sediments across the Karimunjawa reefs showing carbonate facies distributions.

reversed and the surface waters of the Java Sea are westward flow during the southeast monsoon (dry season) from May to September with an average rainfall of <200 mm/month (Wyrtki, 1961; Gordon *et al*., 2003). This monsoonal reversal of surface currents is responsible for major changes in sea surface salinities ranging from 31 PSU (Practical Salinity Unit) during the northwest monsoon to 35 PSU during the southeast monsoon. Data from Meteorology Maritime Station Semarang shows that ocean temperatures in Karimunjawa range from 29.5 to 32°C. The bathymetry of the region is relatively shallow, rarely exceeding 55 m deep based on the bathymetric chart from the Indonesian Naval Hydro-oceanographic Office (1995). These geomorphic, oceanographic, and climate settings significantly affect the reef habitats and marine organisms which produce the sediments.

Methods

Sediment Sampling and Analysis

Sediment characteristics and compositions from the west side of the islands were surveyed and sampled along underwater transects, generally oriented perpendicular to the shoreline (*i.e.* from landward to seaward). The east side of the islands were not surveyed and sampled since there is no significant distinction in terms of geomorphology between west and east sides of the islands, except for the narrower reef flats on the east side than those on the west side. Surface sediment samples were collected in October 2016 by hand through snorkeling (underwater directly into containers to minimize loss of fines) from the range of 5 meter-spaced intervals along transects, and sampling sites were indicated by KJT1-KJT5 for samples taken from Kemujan and Karimunjawa Island, whilst MBT and MKT for samples taken from Menjangan Besar and Menjangan Kecil Islands. For regions deeper than 5 m, additional samples were obtained using a Van Veen sediment grab. In total, nine transects were studied from the islands, with sixty samples of modern reef-associated sediments collected.

These samples, 100 g each, were then washed, dried, and sieved using a set of sieves (each sieve diameter equating to the Udden-Wentworth grain size boundaries). Sediment textural groups are defined following the triangular diagram classification proposed by Folk (1954). The GRADISTAT programme from Blott and Pye (2001) was applied to obtain grain statistical parameters including mean, standard deviation, skewness, and kurtosis. The carbonate “bombe” technique (weight % loss after treatment with 20% HCl) was employed for determining the sediment carbonate content following guidelines from Müller and Gastner (1971). The percentages of modern bioclasts (*e.g.* Echinodermata, *Halimeda*, foraminifera, red algae, coral, and mollusk), reworked grains (*e.g.* quartz and aggregate), and rock fragments were assessed using grain mounts for microscopic characterization following guideline described in Mazzullo *et al*. (1988). Carbonate facies descriptions followed a modified version of the carbonate rock classification scheme from Dunham (1962) *e.g*. Grainstone is used to describe sand-size grains with very little or no mud. Packstone is a grain-supported carbonate sediment with the considerable amount of mud (>10%). Carbonate sand with 1%-10 % mud is classified as mud-lean Packstone.

To investigate the sediment patterns and to evaluate the correlation of all sediment samples, a Principal Component Analysis (PCA) and cluster analysis were utilized using the software package PAST (Hammer *et al*., 2001). Variables for PCA and cluster analysis input include mean grain size, sorting, skewness, and kurtosis, the percentage of gravel, the percentage of mud, and the percentage of $CaCO_3$ (Table 1) following method from Ryan *et al*. (2007). Furthermore, cluster analysis is used to test the similarity among samples.

Satellite Image and Processing

The distribution of living coral and associated benthic habitats was based on Quickbird satellite data acquired on 15 September 2015. The image was geometrically corrected using a geographic coordinate system and WGS 84 ellipsoid reference. The four spectral bands of Quickbird including blue (450 - 520 nm), green (520 - 600 nm), red (630 - 690 nm), and near-infrared (760 - 900 nm) with a high spatial resolution of 2.4 m, were employed to extract reef benthic habitats supported by ground truth information following a simplified work flow of Solihudddin *et al*. (2015). Discrimination of benthic habitats into distinct classes was recognized from reflectance spectra grouped using unsupervised classification digital processing in ArcMap’s Image Analysis toolkit. The spectral signature of each pixel in the Quick-

Table 1. Sediment Physical Properties and Carbonate Content for PCA and Cluster Analysis Input Based on Benthic Habitat Map

Sample ID	Grain Size (%)			Grain Statistical Parameters Folk and Ward Method (phi)				Carbonate ($CaCO_3$) content (%)	Textural Group (Folk, 1954)	Benthic Habitat
	Gravel	**Sand**	**Mud**	**Mean**	**Sorting**	**Skewness**	**Kurtosis**			
MBT1-1	9.32	88.90	1.78	2.170	1.524	-0.463	1.785	88.95	Gravelly Sand	Mixed seagrass and sand
MBT1-2	14.1	84.92	0.98	1.291	1.668	-0.333	1.149	90.84	Gravelly Sand	Mixed seagrass and sand
MBT1-3	5.31	93.09	1.6	1.643	1.290	-0.153	1.009	89.95	Gravelly Sand	Mixed seagrass and sand
MBT1-4	7.53	90.93	1.54	1.608	1.438	-0.180	1.219	92.7	Gravelly Sand	Seagrass bed
MBT1-5	6.8	92.85	0.35	1.277	1.340	-0.358	0.849	95.97	Gravelly Sand	Seagrass bed
MBT1-6	5.96	93.48	0.56	0.958	1.336	0.152	0.846	93.14	Gravelly Sand	Coral
MBT2-1	3.06	96.19	0.75	1.589	0.999	-0.154	0.680	90.48	Slightly Gravelly Sand	Sand flat
MBT2-2	1.9	96.65	1.45	1.554	0.967	-0.124	1.148	89.95	Slightly Gravelly Sand	Sand flat
MBT2-3	2.28	96.52	1.2	1.541	0.991	-0.129	1.131	87.9	Slightly Gravelly Sand	Sand flat
MBT2-4	7.02	92.23	0.75	1.230	1.325	-0.344	1.412	83.98	Gravelly Sand	Sand flat
MBT2-5	10.99	87.47	1.54	1.226	1.371	-0.356	1.409	87.9	Gravelly Sand	Sand flat
MBT2-6	0.36	98.01	1.63	1.629	1.099	-0.011	0.849	87.13	Slightly Gravelly Sand	Sand flat
MBT2-7	5.18	94.06	0.76	1.266	1.314	-0.337	1.391	89.11	Gravelly Sand	Sand flat
MBT2-8	9.2	90.30	0.5	0.965	1.347	0.103	1.402	96.7	Gravelly Sand	Sand flat
MKT1-1	0.65	95.54	3.81	2.296	1.332	-0.343	1.456	88.99	Slightly Gravelly Sand	Sand flat
MKT1-2	0	96.70	3.3	2.624	0.951	-0.129	1.211	88.91	Slightly Gravelly Sand	Sand flat
MKT1-3	13.2	85.41	1.39	1.931	1.704	-0.483	0.991	91.93	Gravelly Sand	Mixed seagrass and sand
MKT1-4	0.22	96.83	2.95	2.586	1.018	-0.140	0.708	94.8	Slightly Gravelly Sand	Mixed seagrass and sand
MKT1-5	12.53	81.60	5.87	1.933	1.887	-0.519	1.205	83.49	Gravelly Sand	Coral
MKT2-1	3	81.76	15.24	0.947	1.886	-0.396	0.792	92.98	Gravelly Sand	Mixed seagrass and sand
MKT2-2	1.12	88.01	10.87	-0.048	2.028	0.194	0.443	90.48	Sandy Gravel	Mixed seagrass and sand
MKT2-3	1.38	93.14	5.48	2.564	0.929	-0.152	5.573	86.16	Slightly Gravelly Sand	Mixed seagrass and sand
MKT2-4	1.7	94.15	4.15	2.898	0.603	0.369	0.929	94.96	Sand	Seagrass bed
MKT2-5	15.15	81.29	3.56	2.306	0.728	-0.484	1.221	86.89	Sand	Coral
KJT1-1	0.53	93.22	6.25	2.243	0.771	-0.473	1.202	83.86	Sand	Seagrass bed
KJT1-2	0.15	95.10	4.75	2.240	1.166	-0.285	1.154	83.54	Sand	Seagrass bed
KJT1-3	5.65	90.63	3.72	1.655	1.148	-0.043	0.864	87.01	Slightly Gravelly Sand	Mixed seagrass and sand
KJT1-4	0.8	92.66	6.54	0.656	1.249	0.128	1.021	92.46	Gravelly Sand	Mixed seagrass and sand
KJT1-5	11.59	82.84	5.57	1.625	1.423	-0.218	1.267	95.73	Gravelly Sand	Mixed seagrass and sand
KJT2-1	23.39	74.66	1.95	1.675	1.274	-0.154	1.779	68.35	Gravelly Sand	Seagrass bed
KJT2-2	46.1	52.22	1.68	2.243	1.185	-0.279	1.176	78.29	Slightly Gravelly Sand	Seagrass bed
KJT2-3	0.3	96.32	3.38	2.285	1.339	-0.350	0.831	53.94	Slightly Gravelly Sand	Sand flat
KJT2-4	0	96.63	3.37	2.273	1.198	-0.255	1.113	91.81	Sand	Sand flat
KJT2-5	0	97.80	2.2	1.239	1.651	-0.294	0.886	69.04	Gravelly Sand	Sand flat
KJT3-1	0	97.76	2.24	2.256	1.198	-0.264	1.130	90.92	Slightly Gravelly Sand	Sand flat

Table 1. continued.....

Sample ID	Grain Size (%)			Grain Statistical Parameters Folk and Ward Method (phi)				Carbonate ($CaCO_3$) content (%)	Textural Group (Folk, 1954)	Benthic Habitat
	Gravel	Sand	Mud	Mean	Sort-ing	Skew-ness	Kur-tosis			
KJT3-2	0	98.46	1.54	1.609	1.900	-0.185	1.200	87.94	Gravelly Sand	Sand flat
KJT3-3	3.15	95.53	1.32	3.265	0.951	-0.793	1.681	97.22	Slightly Gravelly Sand	Coral
KJT3-4	5.35	93.38	1.27	2.929	1.033	-0.784	1.178	88.5	Slightly Gravelly Sand	Coral
KJT4-1	9.11	89.23	1.66	2.268	1.323	-0.317	1.432	91.77	Slightly Gravelly Sand	Mixed seagrass and sand
KJT4-2	6.08	91.76	2.16	2.575	1.131	-0.221	0.852	96.17	Slightly Gravelly Sand	Mixed seagrass and sand
KJT4-3	1.15	95.20	3.65	1.277	1.709	-0.295	0.861	91.77	Gravelly Sand	Mixed seagrass and sand
KJT5-1	13.01	86.35	0.64	1.252	1.525	-0.243	0.714	87.57	Gravelly Sand	Seagrass bed
KJT5-2	12.39	85.38	2.23	1.281	1.531	-0.250	0.723	90.68	Gravelly Sand	Seagrass bed
KJT5-3	19.95	76.53	3.52	0.670	1.760	0.082	0.716	93.87	Gravelly Sand	Mixed seagrass and sand
KJT5-4	6.63	90.32	3.05	1.342	1.511	-0.237	1.000	94.72	Gravelly Sand	Sand flat
KJT5-5	9.23	85.71	5.06	1.629	1.466	-0.157	1.250	95.81	Gravelly Sand	Sand flat
KJT5-6	5.01	93.74	1.25	1.518	1.103	-0.211	1.441	90.92	Gravelly Sand	Mixed seagrass and sand
KJT5-7	0.07	82.71	17.22	2.388	1.274	-0.287	0.689	94.56	Slightly Gravelly Sand	Coral
KJT5-8	0	96.80	3.2	2.532	0.981	-0.135	1.171	95.89	Sand	Coral

bird satellite imagery was determined based on a grouping of the spectra of each band. Overall accuracy using a confusion matrix process was applied and resulted in 65% to 77% accuracy, reflecting the overall agreement in the map as determined by a point of count of correctly classified pixels. The water depths and reef geomorphic profiles are generated from the bathymetric chart of Indonesian Naval Hydro-oceanographic Office (1995).

Results

Reef Geomorphology and Associated Benthic Habitats

In general, the geomorphology of Karimunjawa reefs is gently sloping seaward with slightly raised reef crest along the reef edge. The reef tends to slope steeply (30°) at the upper forereef slope (~ 5 - 10 m deep) and drop steeper, sometimes almost vertical, at the depths of 10 - 30 m (Figure 2). The inner reef flats have low coral cover and are extensively covered by a mixture of seagrass beds and carbonate sand. The extensive seagrass beds, mainly *Enhalus*, occur in the inshore, until around 50 m from the shoreline, resting on carbonate sand substrates with relative densities of 40% - 60%. Macroalgal-covered lithified substrates, predominantly *Sargassum*, are also frequently found on the inner reef flats, adjacent to the seagrass beds-occupied sandy substrates. The reef crests are mainly colonized by mixed branching *Acropora* corals, mainly *A. Hyacinthus* (Figure 3a), colonies of *Platygra* with < 1 m in diameter, and many other coral genera including plate *Acropora* and *Montipora* (Figure 3b). The forereef slopes have a substantial coral growth at the upper of 1.5 m to 5 m deep, prevailing mixed branching *Acropora, Porites cylindrica,* and *Porites sp.* (Figure 3c).

The Quickbird-based unsupervised classification has distinguished four benthic habitats, including coral, mixed seagrass and sand, sand flat, and seagrass bed (Figure 2). Menjangan Besar and Menjangan Kecil Islands are mostly occupied by sand flat with sparse mixed seagrass and sand,

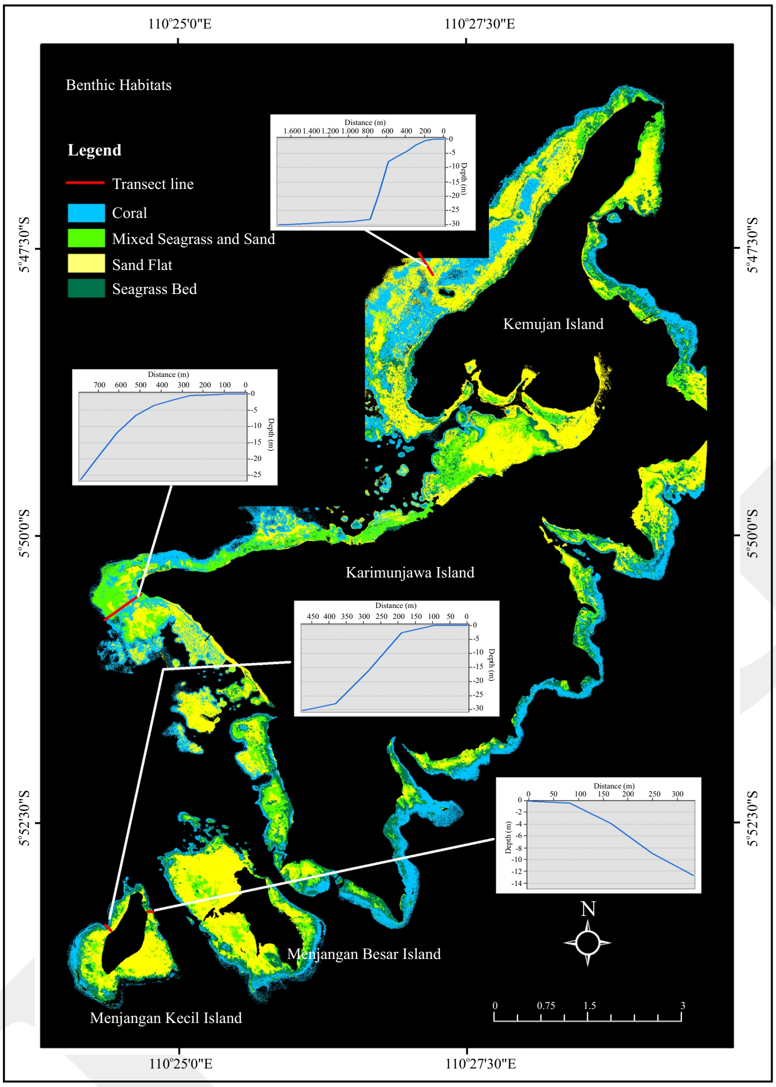

Figure 2. Map of benthic habitat distribution with ground truth points of Karimunjawa Islands derived from Quickbird imagery. Inset: selected reef profile of Karimunjawa showing gently sloping seaward of the reef flat and droping steeply beyond the crest.

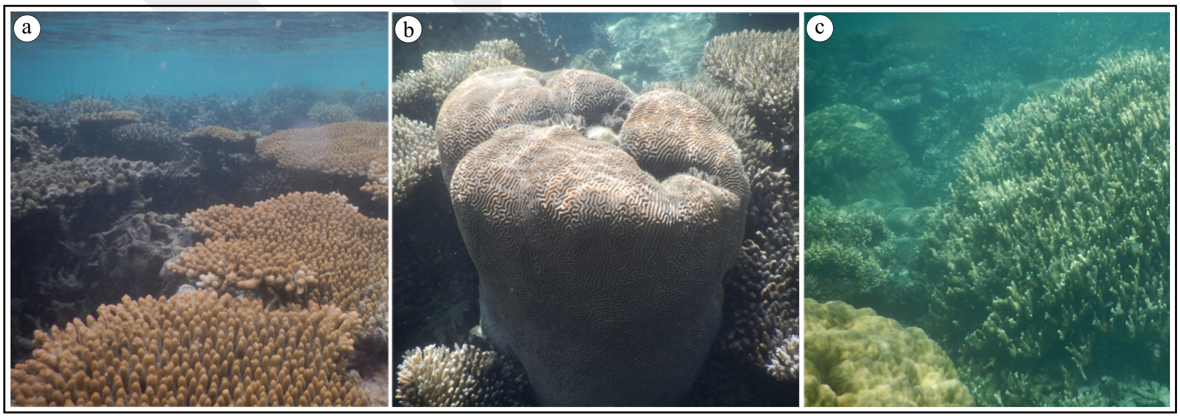

Figure 3. Living coral communities of the Karimunjawa reefs showing (a) extensive mixed branching Acropora, mainly *A. hyacinthus*, on the reef crest of the KJT4 transect, (b) colonies of *Platygra*, plate *Acropora* and *Montipora* on the reef crest of the KJT5 transect, and (c) high coral cover of *Porites cylindrica, Porites sp.,* and branching *Acropora* on the forereef slope KJT5 transect.

encircled on the platform edge with coral habitats. In the Kemujan and Karimunjawa Islands, sand flats mostly occur on the western part, while on the eastern part there lies narrow sand flat and steep coral habitat. Seagrass habitats are more flourished in the western part of the islands. The satellite-based benthic habitat map was confirmed with field observations.

Sediment Texture, Composition, And Facies

Sediments on a modern carbonate platform of Karimunjawa Islands are generally moderate to poorly sorted gravelly sands with mud contents range from a low of 0.35% (MBT1-5) to a high of 17.22% (KJT5-7) (Figure 4a; Table 1). There is no grading pattern of the grain size concerning to geomorphological and habitat succession from landward to seaward. Inshore, where seagrass beds and macroalgae occur, the sediments are dominated by gravelly sand with minor sandy gravel. Whereas, offshore sediments adjacent to the reef edge comprise mainly gravelly sand with minor slightly gravelly sand. The seabed sediments collected with the Van Veen grab from the depths of 20 - 35 m contain predominantly slightly gravelly sand (Figure 4b).

Sediment characteristics are mostly dominated by carbonate sand with carbonate contents ranging from a low of 53% (KJT2-3) to a high of 96% (KJT4-2) (Table 1). The overall average of carbonate contents for all sediment samples is 89%. There is no regular pattern of carbonate contents across the transects moving seaward

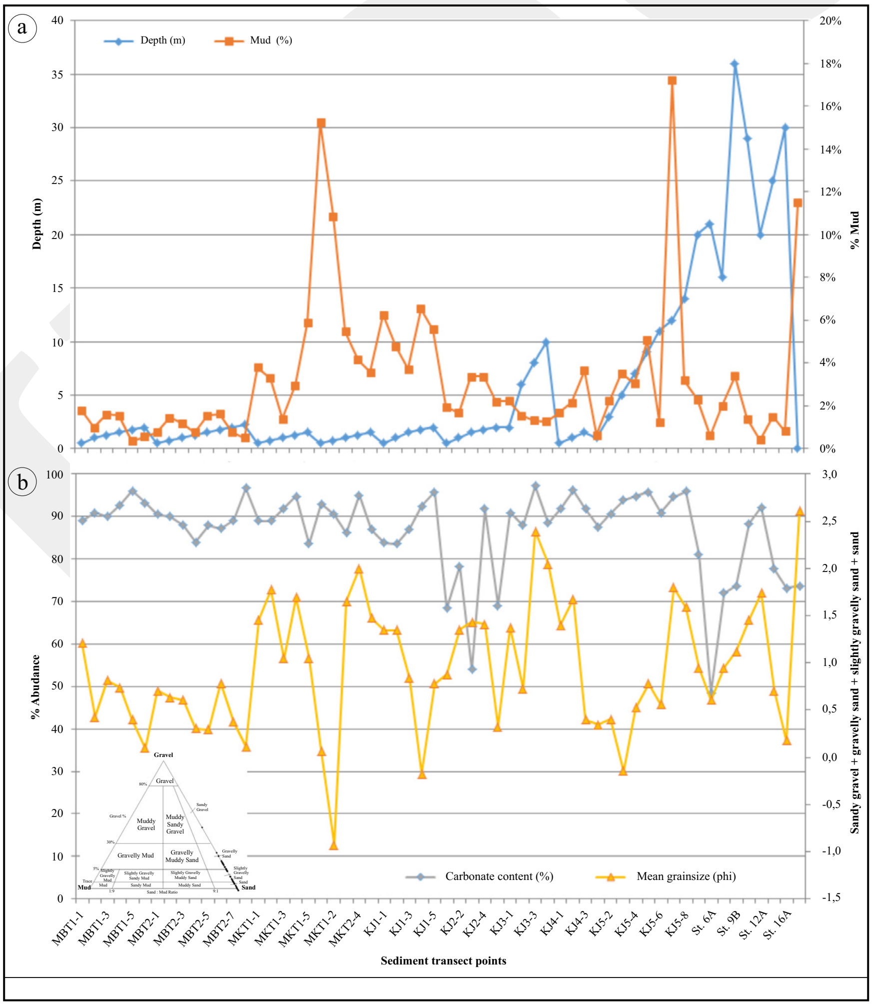

Figure 4. Line diagram plot for sediment distributions across the Karimunjawa reefs showing (a) depth and percentage mud, (b) carbonate content and mean grain size with triangular diagram classification inset.

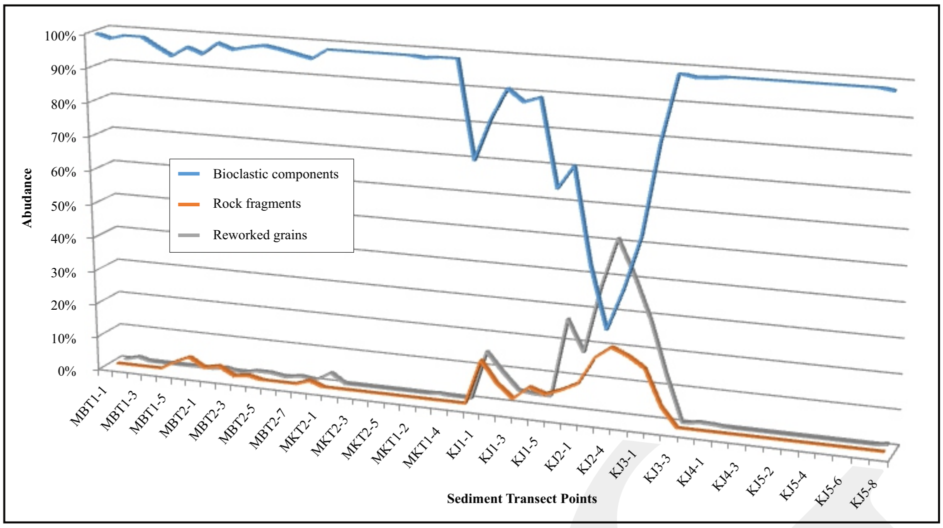

Figure 5. Line diagram plot for sediment compositions across the Karimunjawa reefs showing bioclastic, reworked grains, and rock fragments compositions.

from the coast. The lowest carbonate content is found in sediment deposited adjacent to estuary environments. The noncarbonate components include terrigenous sediments and minor organics (Figure 4b).

Sediment compositions (Figure 5) are mainly bioclastic components including coral, mollusks, foraminifera, *Halimeda*, red algae, and Echinoderm. The reworked grains (aggregate and quartz) and rock fragments, although present, are volumentary minor. Corals and mollusks are the highest and the second highest proportion of bioclastic components constituting 49.5% and 31% on the average respectively (Table 2). Importantly, foraminifera, *Halimeda*, red algae, and Echinoderm reach an abundance of 4%, 3.2%, 2.7%, and 0,7%

Table 2. Sediment Composition (*e.g.* Bioclastic Components, Reworked Grains, Rock Fragments), and Carbonate Facies Classification across the Karimunjawa Reefs

No	Sample code	Bioclastic components						Reworked grains		Rock Frag-ments	Carbonate facies
		Echino-derm	Hali-meda	Forami-nifera	Red Algae	Coral	Mollusc	Aggre-gate	Quartz		
1	MBT 1-1	-	1.4%	5.2%	5.8%	51.0%	36.6%	-	-	-	Mud-lean packstone
2	MBT 1-2	-	-	9.0%	5.6%	49.2%	35.0%	1.2%	-		Grainstone
3	MBT 1-3	1.0%	0.6%	4.8%	4.6%	55.2%	33.8%	-	-		Mud-lean packstone
4	MBT 1-4	1.0%	0.4%	6.0%	10.8%	50.6%	31.0%	-	-		Mud-lean packstone
5	MBT 1-5	0.8%	4.4%	6.4%	6.0%	51.0%	28.8%	-	-	2.6%	Grainstone
6	MBT 1-6	0.4%	1.8%	3.2%	7.8%	49.0%	32.8%	0.4%	-	4.6%	Grainstone
7	MBT 2-1	-	-	0.7%	1.8%	64.1%	31.3%	0.2%	-	2.0%	Grainstone
8	MBT 2-2	1.9%	-	0.7%	1.4%	58.7%	33.4%	1.0%	-	2.9%	Mud-lean packstone
9	MBT 2-3	0.4%	-	1.1%	2.5%	62.2%	33.3%	0.0%	-	0.4%	Mud-lean packstone
10	MBT 2-4	-	1.4%	0.0%	2.4%	61.2%	33.0%	1.0%	-	1.0%	Grainstone
11	MBT 2-5	0.6%	3.0%	1.0%	1.0%	58.4%	35.0%	1.0%	-	-	Mud-lean packstone
12	MBT 2-6	0.2%	2.9%	1.9%	2.4%	65.4%	26.9%	0.2%	-	-	Mud-lean packstone
13	MBT 2-7	0.6%	1.0%	1.4%	2.4%	60.2%	33.4%	1.0%	-	-	Grainstone
14	MBT 2-8	-	2.2%	0.8%	2.6%	55.0%	37.4%	0.4%	-	1.6%	Grainstone
15	MKT 2-1	1.2%	5.6%	3.2%	1.2%	40.6%	45.2%	3.0%	-	-	Mud-lean packstone
16	MKT 2-2	0.5%	3.7%	4.6%	3.9%	49.5%	37.9%	-	-	-	Mud-lean packstone
17	MKT 2-3	-	3.2%	4.6%	3.4%	57.0%	31.8%	-	-	-	Mud-lean packstone

Table 2. continued.....

No	Sample code	Bioclastic components						Reworked grains		Rock Frag-ments	Carbonate facies
		Echino-derm	Hali-meda	Forami-nifera	Red Algae	Coral	Mollusc	Aggre-gate	Quartz		
18	MKT 2-4	-	3.9%	3.5%	3.1%	58.6%	30.9%	-	-	-	Mud-lean packstone
19	MKT 2-5	1.2%	2.2%	1.0%	3.4%	63.8%	28.4%	-	-	-	Mud-lean packstone
20	MKT 1-1	1.2%	4.0%	1.9%	3.8%	57.9%	31.3%	-	-	-	Packstone
21	MKT 1-2	-	3.5%	2.0%	3.3%	62.5%	28.8%	-	-	-	Packstone
22	MKT 1-3	1.6%	1.6%	3.2%	3.0%	61.6%	28.4%	0.6%	-	-	Mud-lean packstone
23	MKT 1-4	1.0%	4.0%	2.7%	2.0%	66.3%	24.0%	-	-	-	Mud-lean packstone
24	MKT 1-5	3.0%	1.6%	4.0%	2.6%	66.4%	22.4%	-	-	-	Mud-lean packstone
25	KJT1-1	1.4%	3.4%	2.1%	-	34.5%	30.6%	-	14.6%	13.5%	Mud-lean packstone
26	KJT1-2	-	4.4%	6.6%	-	39.8%	32.9%	-	9.1%	7.1%	Mud-lean packstone
27	KJT1-3	1.0%	3.2%	3.8%	7.6%	44.8%	32.2%	-	4.2%	3.2%	Mud-lean packstone
28	KJT1-4	0.5%	2.8%	8.0%	-	42.4%	35.6%	-	3.7%	7.1%	Mud-lean packstone
29	KJT1-5	1.0%	5.8%	6.6%	1.2%	41.4%	34.8%	-	3.6%	5.6%	Mud-lean packstone
30	KJT2-1	0.4%	15.6%	3.8%	0.4%	20.8%	25.0%	4.6%	22.0%	7.4%	Mud-lean packstone
31	KJT2-2	1.0%	4.4%	4.4%	8.4%	33.2%	21.4%	4.0%	13.4%	9.8%	Mud-lean packstone
32	KJT2-3	1.0%	1.9%	4.8%	-	10.1%	27.9%	1.2%	35.3%	17.8%	Terrigenous sediment
33	KJT2-4	-	-	3.6%	-	-	24.0%	1.9%	49.2%	21.3%	Terrigenous sediment
34	KJT2-5	-	1.0%	7.3%	-	-	31.5%	2.3%	38.8%	19.3%	Terrigenous sediment
35	KJT3-1	0.3%	2.8%	5.8%	4.3%	18.3%	23.5%	3.0%	26.0%	16.3%	Mud-lean packstone
36	KJT3-2	1.5%	6.3%	8.5%	4.3%	39.0%	21.3%	-	13.5%	5.8%	Mud-lean packstone
37	KJT3-3	0.8%	4.6%	11.0%	1.6%	53.4%	28.6%	-	-	-	Mud-lean packstone
38	KJT3-4	2.4%	4.0%	5.4%	4.4%	59.4%	23.6%	0.4%	0.4%	-	Mud-lean packstone
39	KJT4-1	0.6%	5.6%	5.8%	3.8%	54.4%	29.2%	0.6%	-	-	Mud-lean packstone
40	KJT4-2	0.0%	5.2%	4.0%	3.2%	50.8%	36.8%	-	-	-	Mud-lean packstone
41	KJT4-3	0.7%	6.1%	4.7%	2.2%	54.5%	31.8%	-	-	-	Mud-lean packstone
42	KJT5-1	-	10.6%	1.6%	-	54.6%	33.2%	-	-	-	Grainstone
43	KJT5-2	0.8%	4.0%	2.2%	0.4%	55.2%	37.4%	-	-	-	Mud-lean packstone
44	KJT5-3	0.6%	3.8%	3.0%	1.4%	56.6%	34.6%	-	-	-	Mud-lean packstone
45	KJT5-4	1.0%	2.0%	7.4%	0.6%	57.6%	31.4%	-	-	-	Mud-lean packstone
46	KJT5-5	0.6%	2.1%	3.5%	1.7%	59.3%	32.9%	-	-	-	Mud-lean packstone
47	KJT5-6	0.4%	3.4%	3.6%	0.4%	58.8%	33.4%	-	-	-	Mud-lean packstone
48	KJT5-7	0.5%	2.7%	3.2%	-	58.3%	35.2%	-	-	-	Packstone
49	KJT5-8	1.5%	3.3%	2.8%	2.5%	55.3%	34.0%	0.8%	-	-	Mud-lean packstone

respectively (Table 2). The proportion of reworked grains (aggregate and quartz) are 4% and 0.5% on the average respectively (Table 2). The rock fragments are found significantly on the Kemujan Island transects (3.7% on the average), particularly where there is a creek draining off fresh water from the hinterland.

Carbonate facies in Karimunjawa reefs, in general, can be grouped into three sedimentary facies including grainstone, mud-lean packstone, and packstone with a total abundance of 15%, 72%, and 6% respectively (Figure 1; Table 2). The noncarbonate sediment includes terrigenous sand with about 6% abundance. Calculations of the carbonate facies on individual transect indicate that mud-lean packstone is dominant at the whole transects ranging from 40% to 100% proportion except for KJT2 transect prevailing terrigenous sediment which is up to 60% proportion. Grainstone takes about 50% proportion of MBT1 and MBT2 transects, while packstone exists on MKT1 transect with approximately 40% proportion. Grainstone and packstone account for only 13% each at KJT5 transect (Figure 1; Table 2).

The relationship among sediment parameters is shown by a PCA (Principal Component Analysis) and cluster analysis for all samples in different

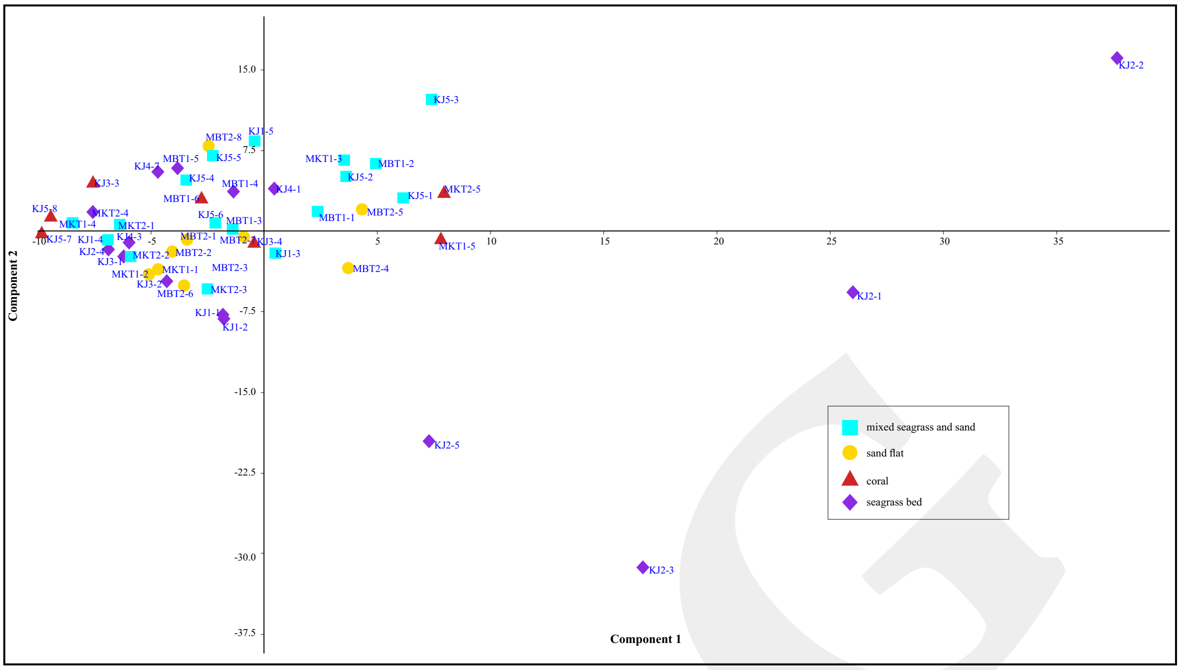

Figure 6. PCA plot for all samples showing the first and second principal components indexed by benthic habitat classes.

benthic habitats. Variables for analysis input along with their benthic habitats are shown in Table 1. The PCA diagram (Figure 6) indicates that the principal component 1 holds the account for 53% of dataset variance, with important factor is $CaCO_3$ and gravel percentage. Component 2 has 38.5% variance with $CaCO_3$ and gravel as the major factor. Component 3 has only 7.7% variance and dominated mainly by mud and sorting (Figure 6). Samples containing gravel are gathering on the upper right part of PCA diagram. Samples with mud content are most abundant in the lower left of the PCA diagram. The highest $CaCO_3$ content is on the upper left part of the PCA diagram and becomes lesser to the lower right part.

The PCA diagram signified no samples grouping, except for some samples from Kemujan Island (Figure 6). Samples KJT2-1, KJT2-2, KJT2-3, and KJT2-5 from Kemujan Island seemed to be separated from other samples due to their high percentage of gravel and the low percentage of $CaCO_3$. Furthermore, cluster analysis distinguished all samples into three groups with the distance cut off 50 (Figure 7). Samples KJT2-1, KJT2-2, KJT2-3, and KJT2-5 are gathered into one group and distinctly separated from other groups due to their difference in gravel and $CaCO_3$ percentage. The second group contains samples with abundant mud content, and the third group contains samples with gravel (Figure 7).

Discussions

Sediment Characteristics And Controlling Factors

Reefs in the Karimunjawa Islands in the form of fringing reefs are formed and developed over the rocky slopes of the Kemujan and Karimunjawa Islands, while in the form of platform reefs such as Menjangan Besar and Menjangan Kecil Islands are all arising from water depths of about <100 m sitting on elongate, flat-topped banks (Figure 1). There is no significant change in sediment texture due to geomorphological succession from landward to seaward, demonstrating predominantly gravelly sand at all geomorphic zones. However, transect in the eastern Menjangan Kecil Island (MKT2) shows high mud content (up to 15.24%; Table 1) at shallow waters indicating that the area is protected from the open ocean and mostly

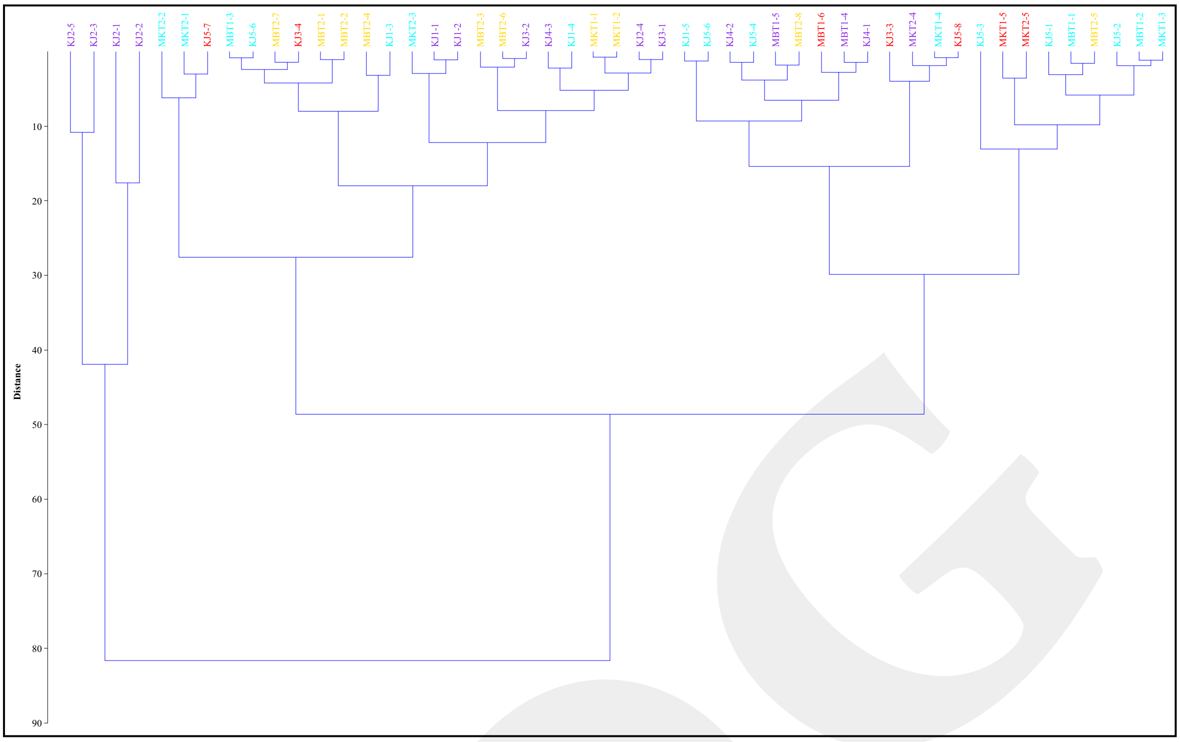

Figure 7. Tree diagram of cluster analysis plot (Ward's method) for all samples. The analysis is based on sediment texture and $CaCO_3$ percentage.

occupied by seagrass beds. Therefore, the mud contents are mostly high even at the shallow water areas by which implicate to the high abundance of benthic in seagrass and macroalgae habitat (Table 2). Carbonate contents are relatively high ranging from a low of 53% to a high of 97% with no grading patterns moving seaward from the coast, and vice versa. This indicates that sediments on the modern carbonate platform of Karimunjawa Islands are mostly derived from reef erosion, and thereby largely composed of bioclastic carbonate sand with minor reworked grains and rock fragments. This is in accordance with Tomascik *et al*. (1997), Wilson (2002, 2012), and Madden *et al*. (2013) who highlighted the dominant of bioclastic assemblages in Indonesian carbonate deposits.

Coral is the most significant contributor to produce carbonate sand and gravel deposits in Karimunjawa reefs along with other bioclastic components such as mollusks, foraminifera, *Halimeda*, red algae, and Echinoderm (Table 2). Foraminifera abundance is fairly even at each location. *Homotrema* sp. occurs extensively, *Calcarina* sp. is the most common in sandy sediment, while *Amphystegina* sp. and *Cycloplypeus* sp. are the most prolific in deeper water. The proportions of reworked grains (aggregate and quartz) and rock fragments, although present, are not abundant volumetrically, suggesting the lack of river input to the coast/reef environment. This condition fits perfectly with Spalding and Grenfell (1997) and Vescei (2004) who postulated coral as the most significant contributor to the neritic carbonate production. Interestingly, the significant accumulation of terrigenous sediments derived from the weathering of the rock outcrops in the hinterland is restricted only to the KJT2 transect on the Kemujan Island, indicating that terrestrial sediment resources have no profound influence on sediment distribution on the modern carbonate platform of Karimunjawa (Figure 1). Unfortunately, the other high continental island reefs in addition to Karimunjawa, *i.e.* Bawean on the north off of Surabaya and Belitung on the east coast of Sumatra, have currently less availability of quantitative information to make a meaningful comparison.

Specialized Nature of Sediments in Karimunjawa Islands

The PCA shows that samples KJT2-1, KJT2-2, KJT2-3, and KJT2-5 from Kemujan Island are separated from other samples (Figure 6). This separation is due to larger gravel size containing KJT2-1 and KJT2-2 and low $CaCO_3$ content in samples KJT2-3 and KJT2-5. These discrepancies are due to the mixed sediment compositions of KJT2 transect, containing predominantly terrigenous sediments (60%) and carbonate sediments (40%) (Figure 5). KJT2-1 and KJT2-2 samples are located proximal to the mouth of the creek where fresh water drained off of the island, making them abundance in terrigenous gravel-size sediments (KJT2-1 23.4% and KJT2-2 46%). Due to the distance from the island, KJT2-3 and KJT2-5 samples do not contain gravel-size sediments, but are occupied by mud constituting 3.4% and 2.2% respectively. The abundance of terrigenous sediment and mud in the KJT2 transect is suspected as the reason why the $CaCO_3$ content is low.

Except KJT2-1, KJT2-2, KJT2-3, and KJT2-5, all samples in the seagrass bed habitats are on the left side of the PCA diagram (Figure 6), implying that the seagrass beds mostly have high $CaCO_3$ contents. Although most of the seagrass beds are on the left side of the chart, some are on the right side, suggesting that despite mud-rich, some seagrass beds have a large size of gravel sediments. This indicates that seagrass beds in Karimunjawa are not fully capable to trap fine sediments. Interestingly, coral habitats have more moderate content of $CaCO_3$ compared to partly seagrass bed habitats. Sand flat habitats seem to be more influenced by mud abundance which most of their samples contain relatively high mud percentage. There is no distinct parameter which strongly influences the mixed seagrass and sand habitats. Apart from its abundance characteristic, sediments in mixed seagrass and sand habitats share similarities on sediment parameters which more likely a mixture of sand flat and seagrass bed habitat.

The PCA also shows that the relationship between sediment parameters (*e.g*. the percentage of gravel, sand, mud, and $CaCO_3$, mean grain size, sorting, skewness, kurtosis) and benthic habitats are generally overlapped for all benthic habitats, suggesting that there are only slight distinct sedimentological characteristics of all benthic habitats. Cluster analysis further distinguished the samples into three groups in which KJT2-1, KJT2-2, KJT2-3, and KJT2-5 are clearly different from others samples due to the percentage of the gravel and $CaCO_3$ content (Figure 7). Cluster analysis then divides the other samples into two groups with a clear boundary separating more gravel size sediment on the upper of PCA diagram and more mud abundance on the lower part of PCA diagram.

Conclusion

This study is the first sedimentological investigation on the modern carbonate platform of Karimunjawa Islands providing conceptual insight into sediment textures, compositions, and distributions which operate on the modern carbonate platform of Karimunjawa Islands along with their controlling factors and specialized nature. Sediment compositions in Karimunjawa reefs are mainly bioclastic components derived from reef erosion. Carbonate contents for all samples are considerably high with an average of 89%, except KJT2 samples where the creek draining off fresh water from the island is found. This estuary environment is rich in terrigenous sediment and minor organics. There are only slight differences of sedimentological characteristic among all benthic habitats. The results show that sediment distribution in Karimunjawa reefs along with $CaCO_3$ contents are very diverse, except for the KJT2 samples which statistical approach also suggests that they are different from other samples. Further works are still needed to address the knowledge gap about the history of reef formation and antecedent reef platform, for example as to whether the reefs occur rapidly following Holocene sea-level transgression or it was slow and whether the reefs are thin veneers over rock platforms or significant long-lived accretionary structures.

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