Modern fringing reef carbonates from equatorial SE Asia: an integrated environmental, sediment and satellite characterisation study.

Robert H.C. Madden, Moyra E.J. Wilson and Maeve O'Shea

Department of Applied Geology, Curtin University, GPO Box U1987, Perth, Western Australia 6845, Australia

E-mails: r.madden@dunelm.org.uk, m.wilson@curtin.edu.au

Abstract

Fringing reefs of SE Asia may conservatively comprise ~30% of the world's coral reef area, but remain almost unstudied (White, 1987; Tomascik et al., 1997). This study provides insights into the primary sedimentological and early alteration characteristics of an isolated fringing reef system (Kaledupa-Hoga) from the Tukang Besi Archipelago, SE Asia. A combined multispectral satellite imagery, field and petrographic study allowed for the generation of an environmental facies map, which acts as a model for the distribution of primary sedimentological characteristics in relation to the primary environmental facies. The islands of the Tukang Besi Archipelago are mesotidal (<2 m) affected by strong diurnal and oceanic tidal currents, as well as high wave energy influenced by the bi-directional southeast Asian monsoon. An environmental facies map generated from Landsat-7 imagery and utilising field observations defines ten environmental facies. The facies map generated has a >71% accuracy when compared with field and sedimentary data. With the exception of the reef crest and reef slope that commonly have widths on a sub-imaging resolution (<30 m), the facies map accurately demonstrates the heterogeneous nature of the carbonate system.

Although field and satellite imagery observations reveal ten environmental facies, sedimentological characterisation results in a lower number of distinctive categories due to the similarity of many deposits. Foreshore/backshore and bare intertidal deposits are distinctive and are composed of reef-derived material that has been reworked shorewards. Seagrass-associated facies all show some fine silt-clay sized material (<8%) with common imperforate foraminifera and pervasive micritisation, but also contain high abundances of reworked coral and shell allochems. Coral-associated reef flat facies are typically low in imperforate but high in perforate foraminifera, and show lesser effects of bioerosion and very low silt contents. The reef slope and crest are characterised by high abundances of gravel-sized fragmented corals with the highest abundances of echinoderm material and alcyonarian sclerites. Sediment samples across all fringing reef environments from the Kaledupa-Hoga transects are characterised almost exclusively by grain-rudstone textures, with <2-5% silt and clay size fractions, and minor baffling of fines in seagrass-associated settings (grain-packstones). The paucity of fines across the fringing reef systems as a whole, and the degree of homogenisation of sediment characteristics across the different field- and satellite-identifiable environmental facies are attributed to: (1) high wave/current energies, (2) the small size of the islands rendering limited protection, (3) bidirectional monsoon winds and (4) the lack of reef rimmed margins built to sea level. Absent from these deposits are well developed high energy windward and low energy leeward deposit characteristics and/or an overriding hurricane influence that are commonly seen in fringing reef systems from other areas.

Keywords: sedimentology, modern-carbonates, Landsat, pure-carbonates, coral-reefs, facies mapping.

1. Introduction

It has been estimated that the fringing reefs of SE Asia may conservatively comprise ~30% of the world's coral reef area (White, 1987; Tomascik et al., 1997). There is a paucity of knowledge on fringing reefs globally, since almost no remote sensing studies, and very few modern sediment studies have been undertaken on these systems (Lewis, 1969; Hopley and Partain, 1987; Blanchon et al., 1997; Kennedy and Woodruffe, 2002, Purkis et al., 2012). Regionally, despite fringing reefs being the dominant reef type within SE Asia they remain the least studied (Tomascik et al., 1997; Hewins and Perry, 2006). Here, a combined environmental, satellite and sediment characterisation study of fringing reefs surrounding isolated oceanic islands in central Indonesia aims to contribute to the understanding of this under evaluated, but globally important reef type.

Most modern analogues used to evaluate carbonate development are from sub-tropical to sub-arid regions such as the Bahamas or South Pacific, as well as Central America with all focused on barrier reef systems and atolls (Gischler and Lomando, 1999; Rankey, 2002; Gischler et al., 2003; Gischler, 2006, 2011; Rankey and Harris, 2008; Harris, 2010; Harris et al., 2010; 2011, Rankey and Reeder, 2010). However, these systems are not wholly analogous to those from equatorial SE Asia and/or to fringing reef systems (Tomascik et al., 1997; Kennedy and Woodruffe, 2002; Wilson, 2002; 2012; Park et al., 2010). Studies of fringing reefs have focused on their Holocene development, through multiple coring studies and to a certain extent their environmental variability (Hopley and Partain, 1987; Cabioch et al., 1995; Kennedy and Woodruffe, 2002; Montaggioni, 2005), but there are very few detailed studies on their sedimentology (Lewis, 1969; Gabrié and Montaggioni, 1982; Blanchon et al., 1997; Hewins and Perry, 2006). Studies of modern carbonate systems in SE Asia typically focus on their biota and ecology (Tomascik et al., 1997; Cleary et al., 2005;

Becking et al., 2006; Renema, 2006a, 2006b). Satellite studies of reefal environments within Indonesia are in their infancy, but are much needed to better understand the regions modern carbonate systems and for their use in 'developing and implementing sound management and conservation policies' (Tomascik et al., 1997; Asriningrum, 2011). Detailed sedimentological studies of modern carbonates from SE Asia are largely restricted to those of Pulau Seribu, on the predominantly siliciclastic shelf offshore Jakarta, Indonesia (Scrutton, 1978; Park et al., 1992; 2010; Jordan, 1998, O'Shea, 2005). These high-energy, small-scale build-ups do not fully encompass the inherent variability of carbonate depositional systems that have developed throughout the region. An additional sedimentological study reviews fringing reef deposits around the 1.5 km across Danjugan Island in the Philippines at the boundary between the equatorial tropics and subtropics (Hewins and Perry, 2006). SE Asian carbonate deposits are dominated by bioclastic assemblages and notably absent are the coated grains and aggregates of their better studied arid to sub-tropical counterparts (Lees and Buller, 1972; Wilson, 2002; 2012). Furthermore, carbonate development in SE Asia is extensive forming a wide variety of platform types from land attached shelves, isolated platforms to localised and/or ephemeral carbonates (Tomascik et al., 1997; Wilson, 2002). There is a need to better evaluate sedimentological characteristics of modern carbonate environments, and in particular those from fringing reef systems and their facies distributions related to environmental conditions from SE Asia, since models generated from examples outside the equatorial tropics are commonly not wholly applicable (cf. Gischler and Lomando, 1999; Wilson, 2008a; 2011; 2012; Park et al., 2010).

Satellite based remote sensing is widely established as a key tool in the mapping of modern carbonate systems and reef environments (Lyzenga, 1981; Ahmad and Neil, 1994; Gischler and Lomando, 1999; Andréfouët et al., 2001, 2003; Rankey, 2002; Purkis and Pasterkamp, 2004; Harris, 2010; Kaczmarek et al., 2010). Most of these studies detail the variability of modern carbonate environments from classic sub-tropical Atlantic or Pacific examples, with very few studies including examples from the humid equatorial tropics of SE Asia (Harris and Vlaswinkel, 2008).

An important aspect of understanding SE Asian carbonate variability lies in developing models that demonstrate how primary environmental settings unique to the region relate to primary depositional sediment characteristics and their early alteration. SE Asian modern carbonate systems have distinctive characteristics that relate to local environments and water depths, and it is anticipated that these primary environmental differences will be reflected in satellite imagery characteristics that relate to: (1) benthic sedimentological characteristics, (2) benthic biota communities, and (3) water conditions (including depth and clarity); i.e., identifiable "environmental facies".

This study utilises statistics-based satellite image classifications in conjunction with modern sediment samples from fringing reef systems around carbonate islands in the Tukang Besi Archipelago, Indonesia (Fig. 1). Specific study objectives are to: (1) produce a satellite generated environmental facies map using statistics based methods, (2) identify primary sedimentological and early sediment alteration characteristics of associated carbonate deposits, (3) compare primary sedimentological properties to primary environmental facies and their satellite characteristics and (4) contribute towards a greater understanding of modern humid equatorial carbonate systems highlighting the heterogeneities that may exist.

2. Regional Setting

The Tukang Besi Archipelago, encompassing the Wakatobi Marine National Park, is situated <20 km southeast of Buton Island in SE Sulawesi, bordered by the Banda Sea to the northeast, and Flores Sea to the southwest (Fig. 1). Three linear rows of atolls, raised coral islands and build-ups trending northwest-southeast rise from a broad subsiding platform of possible continental origin that currently lies at 700-1000 m water depth (Smith and Silver, 1991; Koswara and Sukarna, 1994; Milsom et al., 1999). All the modern carbonate systems are largely isolated from siliciclastic input. The Tukang Besi archipelago contains approximately 500 km^2 of coral reef-related environments within a wide diversity of carbonate systems including large-scale atolls (>10 km across), small-scale atolls, small-scale build-ups and barrier or fringing reefs surrounding the four main islands of the archipelago (Tomascik et al., 1997; Wilson, 2008b). The islands of the archipelago preserve a record of Pliocene to Quaternary uplifted coral reefs. These ancient reefs are exposed as a series of stepped terrace levels that have been uplifted to maximum heights of 300 m (Wilson, 2008b). The deposits of each uplifted terrace formed in a variety of shallow marine environments that were associated with coral reefs that built towards sea level (Wilson, 2008b). These shallow water carbonate terraces overlie deeper water marls of Late Miocene and Early Pliocene age (the Ambewa Formation: Koswara and Sukarna, 1994; Wilson, 2008b). Poorly consolidated marl clasts are reworked into the modern carbonate sediment assemblages fringing the islands, but mainly only in regions adjacent to where there is limited or no preservation of Pliocene–Quaternary reef terraces. The archipelago is therefore an excellent location to characterise and evaluate the effects of primary environmental facies on carbonate sediment characteristics in the humid equatorial tropics of SE Asia. This work focuses on differences within the modern island-attached carbonate systems, with further work in preparation to evaluate the variability across the range of carbonate systems from the archipelago (Wilson et al., 2013).

The marine environments surrounding the Tukang Besi islands contain amongst the world's highest levels of marine biodiversity (Halford, 2003; Turak, 2003; Pet-Soede and Erdmann, 2003; Bell and Smith, 2004). High biodiversity is not just a feature of the archipelago's coral reefs but also the associated interconnected habitats of seagrass meadows, mangroves, mud flats and algal beds. There are records from within the Wakatobi National Park of at least: 396 species of hermatypic scleractinian hard corals and 10 species of ahermatypic scleractinian corals, 28 species of soft corals, >145 sponge species, nine species of seagrass and upwards of 600 species of fish (Halford, 2003; Turak, 2003; Bell and Smith, 2004; Pet-Soede and Erdmann, 2004; Bell et al., 2010; McMellor and Smith, 2010). Mean coral cover throughout the Wakatobi systems (reef flat, crest and upper slope) is 48.05% with 10.62% macroalgal cover, 2.31% sponge cover and 5.4% dead coral and coral rubble cover (Suharsono et al., 2006; McMellor and Smith, 2010). It is this overall biotic and carbonate systems variability that makes the area ideal to characterise modern SE Asian carbonate deposits. However, with the exception of debates over the morphology and development of the archipelago (Escher, 1920; Hetzel, 1930; Kuenen, 1933a, b; Umbgrove, 1947; van Bemmelen, 1949; Tomascik et al., 1997; Milsom et al., 1999), to date no detailed sedimentological studies have been undertaken (cf. Wilson, 2008b).

The tidal range of the islands and reefs in the archipelago is ~2 m with semi-diurnal tides affecting shallow platforms and very strong oceanic tidal currents between the atolls and islands. Wave energy can be very high and is influenced strongly by the bi-directional monsoon. Very strong south-easterly winds blow between June and August with lesser westerly winds between December and March (Wilson, 2008b). Water temperatures are typically within the range of 27-28 °C with ocean salinities of 35‰ (O'Shea, 2005).

3. Materials and Methods

3.1 Fieldwork and Sampling

Modern carbonate settings from across the Tukang Besi archipelago were surveyed and deposits sampled along underwater transects, generally oriented perpendicular to the trend of the reef crest (i.e. from deep forereef areas, passing across the shallow reef crest to inner reef or land areas). Study was through diving and snorkelling with local environmental conditions including substrate and biota types, water depths, water temperatures, slope angles and any wave or current activity recorded along each transect. Surface sediment samples were collected by hand (underwater directly into containers to minimise loss of fines) from the range of local environments and/or at decimetre-spaced intervals along transects, with sampling sites photographed. For regions deeper than 20-30 m additional samples were obtained using a Van Veen sediment grab (with only intact "solid" sediment taken from within the grab sample, again to minimise the loss of fines). In total, 42modern transects were studied from the archipelago, with 390 samples of modern reef-associated sediments collected. From this larger dataset, six key transects and some additional spot sampling sites from around Pulau Kaledupa and its neighbouring "sibling" island of Hoga, were selected for comparison between shallow water environments and their satellite and sediment characterisation. The area of Kaledupa and Hoga was focused on due to: (1) good availability of a range of cloud-free Landsat multispectral data, (2) good sample and transect coverage allowing analysis of much of the range of local environments and variety in satellite characteristics of fringing reefs from <20 m water depth in the Wakatobi region to be studied, and (3) the potential to compare between windward versus leeward, or more protected settings. In total, 78 samples were analysed for this study with all from <20 m, and most from <5 m water depth. Out of these 78 samples eight along the Kaledupa centre transect were collected using the Van Veen grab.

3.2 Sample analysis

All 78 samples were air dried then photographed under a binocular microscope. A proportion of each sample was weighed and separated using a 2 mm sieve, with the <2 mm size fraction analysed for grain size using a Coulter Laser Granulometer. The proportions of components and grain sizes of the >2 mm size fractions were visually estimated. 2.5-3 g of the <2 mm fraction for each sample were placed in test tubes and in the rare samples containing organics 20 ml of 20% Hydrogen Peroxide was added and left overnight in a boiling water bath to allow digestion of the organics. Samples were centrifuged at 2500 rpm for four min and half of the supernatant liquid was decanted off, then the tubes topped up with water and centrifuged for another 4 min to allow degassing and grains to settle. Following decanting off of the supernatant liquid, 20 ml of Sodium Hexametaphosphate solution was added to stop grains from clumping then run through the Granulometer. Grain size plots incorporate the results of percentages of the >2 and <2 mm size fractions with grain size divisions from the Udden-Wentworth scheme (Udden, 1914; Wentworth, 1922) and nomenclature on sorting after Pettijohn et al. (1973). Of the 78 samples, 75 were made into thin section grain mounts for petrographic analysis. Half of each thin section was stained with potassium ferricyanide and Alizarin Red S for the identification of ferroan and non-ferroan calcite (Dickson, 1965, 1966). Semi quantitative visual estimates of components were directly comparable with point counting analyses previously undertaken on the Pak Kasim's transect (300 point counts: O'Shea, 2005). Textural classification of the sediments follows the scheme of Dunham (1962), modified by Insalaco (1998)[i]. An early sediment alteration index evaluating abrasion, fragmentation, encrustation, bioerosion and cementation for each thin section is modified after the abrasion and fragmentation index of Beavington-Penney (2004; see Appendix 1).

3.3 Landsat-7

Modern carbonate systems are ideal for study through satellite based methods as they are typically best developed in shallow (<30 m) relatively clear water marine environments, consistent with the requirements for accurate satellite data collection and their interpretation. Several methods exist for the analysis and interpretation of satellite data sets from modern shallow water carbonate systems (cf. Harris and Kowalik, 1994; Harris, 1996; Gischler and Lomando, 1999; Rankey, 2002; Harris and Vlaswinkel, 2008; Harris et al., 2010; Kaczmarek et al., 2010; Harris et al., 2011). In this study the use of statistical algorithms has been adopted to quantitatively discriminate between combined benthic sediment and biota types across a SE Asian reef-related system.

This study utilises the simplified workflow of Kaczmarek et al. (2010) to generate a Landsat derived facies map of water-bottom characteristics. The methods outlined by Kaczmarek et al. (2010) discriminate between benthic sediment types to produce satellite derived sediment facies maps for carbonate platforms. In satellite imagery, variance in reflection (satellite characteristics) is attributed to variability from three predominant factors: (1) the benthic sediment type, (2) the benthic biota assemblages and (3) water depth. As it is applied to this study the derivative products of satellite analysis are environmental facies maps in which the satellite characteristics are directly related to local benthic communities, sediment types and water conditions.

The methods of Kaczmarek et al. (2010) offer a simple and time efficient way to assess satellite imagery and avoid the use of advanced image processing techniques that arguably would provide little improvement to a low spatial resolution image (cf. Ouillon et al., 2004; Purkis and Pasterkamp, 2004; Kaczmarek et al., 2010). One of the key objectives of this study is to foster a "user friendly" approach to satellite based study, allowing integration of what is possibly an underutilised, yet valuable resource (the Landsat data set), with more traditional sedimentological studies where remote sensing skill sets may be lacking.

A Landsat-derived environmental facies map was produced by combining Landsat multispectral data, statistics-based unsupervised classifications, and field observations of local environmental conditions for the shallow-water fringing reef-related area of Pulau Kaledupa and Hoga from the Tukang Besi Archipelago of SW Sulawesi (Fig. 1). A full discussion of the workflow and the Landsat multispectral sensor used to generate this facies map is given in Kaczmarek et al. (2010), with a brief overview outlined below. The Landsat data that forms the basis for the analyses of this study was captured on the 6th of February 2009 in seven spectral (thematic) bands with a spatial resolution of 28.5 m^2. The Landsat image of the Tukang Besi Archipelago (delineated to Pulau Kaledupa during image processing) was selected in place of other images collected between 1989 and 2012. The February, 2009 image which was chosen as the area of interest was not affected by cloud cover or atmospheric haze and has the most consistent contrast and clarity across the area. Individual spectral bands were combined in the software package ER Mapper to produce a single multispectral composite image for the Tukang Besi Archipelago. Cloud masking and land masking algorithms were applied to the image to reduce the number of spectral classes required to classify the image. To further reduce spectral variability the image has been delineated to an area of interest by assigning pixels outside of a hand drawn polygon (i.e. deep water regions) a null value (Fig.1C).

Benthic sediments and biota assemblages are discriminated into distinct thematic classes using the image processing technique “unsupervised classification” within the ER Mapper software package. This image processing utility assesses each pixel in a satellite image by performing a calculation based on a combination of the spectral values of each spectral band. This spectral signature is then used in a binning algorithm which groups pixels into a pre-determined number of spectral classes. Because the unsupervised classification utility groups pixels based on differences between reflection properties, water depth inherently affects classifications. To account for variability due to water depth the unsupervised classification was calibrated so as to group pixels into a large number of classes. Previous studies (e.g. Rankey, 2002; Purkis et al., 2005) have utilised fewer than 10 spectral classes during unsupervised classification. Kaczmarek et al. (2010), however, suggest that whilst a relatively small number of classes are required to create a satellite based facies map, the number of spectral classes be significantly (~6×) greater than the number of classes actually present. As it is applied to this study, ten distinct environmental facies have been identified from field observations across sampling transects, with 50 spectral classes being utilised to produce an environmental facies map.

Areas within the classified image, produced by the ER Mapper unsupervised classification utility, were assigned to environmental facies by linking pixels corresponding to sample locations with field observations of the environment. As a result pixels with similar satellite and field characteristics were automatically grouped together and assigned to the same environmental facies. For pixel groups with no corresponding sample data, environmental facies were assigned based on further field observations (Kaledupa Double Spur Transect; Fig. 1D, E), local knowledge, the location of nearby or adjacent environmental facies and the observed geometries of environmental facies groups. Quantification of the accuracy of the environmental facies map has been conducted using the “overall accuracy” metric of Mumby et al (1998; Eq. 1). Overall accuracy reflects the degree to which known pixel values (classes) are represented by the classified image as determined by a point count of correctly classified pixels.

Overall accuracy (%) = (No# correctly classified pixels/No# known pixel classes)*100 (1)

Results of the “overall accuracy” metrics give an indication that the pixels of the classified Landsat image represent the environmental facies on the ground, as determined from field notes and sediment sampling (cf. Kaczmarek et al., 2010).

4. Results

Primary sedimentary and environmental results of this study are taken from the analysis of sediment components, their early alteration and grain-size variations plotted onto environmental transects for the islands of Pulau Kaledupa and Hoga (Figures 2-8 and Appendix 1). Results are reported below as environmental and sedimentological descriptions for each environmental facies group identified.

4.1 Foreshore/Backshore. *(Sample References: Kal21, 20, HGG10, 9, PK21, HSB2S-10)*

4.1.1 Environmental Facies Description. Foreshore/backshore deposits form a <15 m wide rim to the main vegetated landmasses and are bare-sandy deposits composed mainly of material reworked from the reef-flat. Foreshore deposits are supratidal to intertidal and dip 10-20° seaward. At high tide foreshore deposits are affected by breaking waves. In contrast backshore areas are unaffected by all but storm waves, may have the beginnings of colonisation by vegetation and generally include more disseminated land-derived plant material than foreshore areas.

4.1.2 Sediment Characteristics. Sediments associated with the foreshore/backshore deposits are dominated by bioclastic carbonate sands with grainstone to grain-rudstone textures. Foreshore/backshore deposits are dominantly moderately to well sorted sands, although there is some variability between the different transects. The foreshore/backshore deposits of Pak Kasim's and Hoga Buoy 2 are coarse to very coarse unimodal to bimodal sands with a minor (~<6%) gravel component (Figs. 3, 4). Foreshore/backshore deposits of Hoga Gilge Gilge and Sumbano are fine to very coarse bimodal sands with a negligible (<1%) gravel content (Figs. 2a, 2b, 5, 6). In all samples silt to clay size fractions are largely absent (<2%). The >2 mm size fraction of these deposits is dominated by shells and/or coral bioclasts which may contribute 60-100% of the material present (Fig. 2a). Less abundant bioclasts typically include *Halimeda* and imperforate foraminifera. In thin section the <2 mm size fraction is more variable, but reflects the >2 mm grain components in that coral and shell fragments typically contribute ~50% of the total bioclastic material. Collectively the bioclasts of these foreshore/backshore deposits are highly abraded (e.g. calcarinid spines broken/removed, and truncated to gouged grain margins on clasts) with coral and shell clasts showing pervasive fragmentation. Bioerosion (identified through micritised grain margins) is a variable feature of the deposits. Micritic rims range from 20 to 50 µm thick and are pervasive features of coral, shell and *Halimeda* fragments from the Hoga Gilge Gilge and Sumbano deposits (Figs. 2b, 5, 6). Non-pervasive micritic rims of up to 20 µm thick are present on coral and shell fragments in deposits from Pak Kasim's and Hoga Buoy 2 (Figs. 3, 4). Encrustation by coralline algae and foraminifera is a rare feature of coral clasts from Sumbano and Hoga Buoy 2 (Figs. 2b. 4, 6). Cementation is absent from all foreshore/backshore deposits.

4.2 Intertidal Reef Flat without Seagrass. *(Sample References: Kal19, 18, HGG8, PK20, HSB2S-9)*

4.2.1 Environmental Facies Description. Intertidal reef flat deposits without seagrass coverage form a <30-60 m wide perimeter to the foreshore/backshore deposits. These are bare sand deposits made up of reworked reef-flat material that may have symmetric ripples and may be bioturbated with shrimp mounds. These deposits dip between 1 and 5° seaward and are intertidal having water depths of 0.2 to 1 m at high tide.

4.2.2 Facies and Sediment Characteristics. Sediments associated with the deposits of this environmental facies are dominated by bioclastic carbonate sands with grainstone to grain-rudstone textures. The deposits are poorly to well sorted, with variability between transects. The deposits of the Sumbano transect are bimodal to trimodal fine to very coarse sands with a variable (1-7%) gravel component and consistent (3-7%) silt sized fraction (Fig. 6). Deposits from the Hoga Gilge Gilge transect are bimodal very fine to fine and coarse to very coarse-sands with a negligible gravel (<1%) and silt (<2%) content (Fig. 5). Deposits from the Pak Kasim's transect are dominantly bimodal coarse to very coarse-sands with gravel (11%) and a minor (<4%) clay-silt fraction (Fig. 3). Deposits from the Hoga Buoy 2 transect differ slightly with the other deposits of this environmental facies in that they are very well sorted, unimodal coarse to very coarse sands with minor gravel (<4%) and clay-silt (2%) sized components (Fig. 4). The bioclastic content of these deposits, from all transects, exhibits little variability. The >2 mm grain components are dominated by shells and coral bioclasts that may contribute 45-90% of the material present. Less abundant bioclasts include *Halimeda* and imperforate foraminifera (Fig. 2c). In thin section the <2 mm grain components are variable but dominated by coral and/or shell bioclasts that make up 20-60% of the bioclasts with *Halimeda* also common (5-25%). The <2 mm grains from the Sumbano transect also have common calcarinids (12-17%) and coralline algae (~10%; Fig. 6). Collectively the bioclasts of these intertidal deposits are highly abraded with coral, shell, *Halimeda* and algae clasts showing pervasive fragmentation (Fig. 2d). Bioerosion is pervasive throughout these deposits. Coral and shell clasts have micritic rims commonly 50 μm thick, with *Halimeda* clasts showing more variable 20-50 μm thick rims. Minor encrustation by coralline algae is a rare feature of few coral clasts from Sumbano (Fig. 6). Cementation is absent from all samples of this facies.

4.3 Intertidal/Subtidal Reef Flat with Short Seagrass *(Sample References: Kal12, 11, 10, 7, 36, HGG7, PK19, 18, 17, 16, HSB2S-8, 7, 6, 5, SS7, 6, 5)*

4.3.1 Environmental Facies Description. Reef-flat intertidal/subtidal areas with short seagrass coverage form a <30 to ~350 m wide sloping to undulating margin to the intertidal deposits without seagrass (above). Short seagrass facies are also located as <100 m wide sections along the Sumbano transect that are adjacent to sections of long seagrass coverage (Fig. 6). The deposits are bioclastic sands and are commonly associated with shrimp mounds and bioturbation. These deposits are subtidal to intertidal with water depths of 0.7-1.8 m at high tide. Deposits are near flat lying to gently dipping, generally < 3°, although locally higher dips are present.

4.3.2 Facies and Sediment Characteristics. Sediments associated with the deposits of this environmental facies are dominated by bioclastic sands with grain-rudstone to more rarely packstone (Kal36) textures. The deposits are moderately to poorly sorted with some variability between transects. The deposits are dominantly bimodal fine to very coarse sands with a variable gravel (<1-17%) and clay-silt (<1-7%) content (Figs. 2e, 3-7). . The sample from Kaledupa Centre transect is a moderately-poorly sorted unimodal silt-very fine sand (<75%) deposit with minor fine to coarse sands and a negligible (<1%) gravel content (Fig. 8). The >2 mm size fraction of these deposits is largely consistent across the transects. Coral and shell clasts contribute 13-90% of the bioclasts (Fig. 2e), with imperforate foraminifera (3-33%) and *Halimeda* (up to 50%) also dominant constituents. Only the sample from Kaledupa Centre transect differs, where lithic clasts make up 100% of the >2 mm fraction (Fig. 8). Lithics are loosely consolidated marl clasts (Fig. 2n). In thin section the <2 mm size fraction is composed of variable bioclasts. Coral and shell clasts may be dominant (~50%) with the remaining clasts evenly distributed between common *Halimeda*, imperforate and perforate foraminifera (Fig. 2f). Less common components include echinoid plates and spines, alcyonarian sclerites, calcarinids and miliolids. Collectively the bioclasts of these deposits are moderately abraded and highly fragmented. Again the sample from Kaledupa Centre differs, having a <2 mm size fraction composed of 97% lithics (Fig. 8). Encrustation by algae and foraminifera is a rare feature and absent in the Pak Kasim's and Sumbano deposits (Figs. 3, 6). Bioerosion of coral and shell material is pervasive and micritic rims may be 20-50 µm thick (Fig. 2f) and rarely up to 100 µm. Bioerosion is less common where coral or shell abundances are lower; with *Halimeda,* calcarinids and larger foraminifera showing 10-30 µm thick micritic rims. Cementation is absent from all deposits.

4.4 Subtidal Reef Flat with Long Seagrass *(Sample References: Kal16, 13, 6, HGG4, PK15)*

4.4.1 Environmental Facies Description. Back reef subtidal areas with long seagrass coverage occur along the Sumbano, Hoga Gilge Gilge and Pak Kasim's transects (Figs. 3, 5, 6). These areas form <30-100 m wide sections in relatively deep water areas (1.4-2.2 m) on the reef-flat. Seagrass present in this facies is typically up to 1 m in length, dense and may be associated with shrimp mounds.

4.4.2 Facies and Sediment Characteristics. Deposits of this facies are bioclastic sands with grainstone and less commonly grain- to rud- or packstone textures that show some variability between the transects. Deposits of the Sumbano transect are unimodal to trimodal poorly sorted very fine to very coarse sands with minor gravel (<9%) and a low clay-silt sized content (<7%). The >2 mm size fraction of the Sumbano deposits is dominated by *Halimeda* clasts (11-44%) and imperforate foraminifera (30-35%) with coral dominant (60%) from Kal6 adjacent to the subtidal coral deposits (Fig. 6). The <2 mm size fraction of the Sumbano deposits is dominantly *Halimeda* (30%), shell fragments (20%) and imperforate foraminifera (15%). The deposits of this facies from the Sumbano transect show only minor abrasion and fragmentation with pervasive micritic rims of 20-30 µm on shell, coral and *Halimeda* fragments. Long seagrass deposits from Hoga Gilge Gilge are poorly sorted trimodal fine to very coarse sands with minor (4<%) gravel and clay-silt sized fractions (Fig. 5). The >2 mm size component of the Hoga Gilge Gilge deposits is dominated by coral clasts (70%) with less abundant shells and imperforate foraminifera. The <2 mm fraction of the Hoga Gilge Gilge deposits is variable with coral, shell, *Halimeda,* imperforate, perforate and calcarinid foraminifera present in similar abundances. Hoga Gilge Gilge deposits of this facies are moderately fragmented and abraded with highly pervasive bioerosion. Coral and *Halimeda* clasts have micritic rims of 10-50 µm (Fig. 2g), and shell fragments with rims of up to 100 µm thick. The deposits from Pak Kasim's are dominantly bimodal moderately sorted fine to very coarse sands with minor (<3%) gravel and clay-silt size fractions (Fig. 3). The >2 mm size fraction of the Pak Kasim's transect is dominated by imperforate foraminifera (35%) and *Halimeda* (32%). In thin section the <2 mm fraction is dominated by corals (52%) and minor imperforate, perforate, calcarinid and miliolid foraminifera. The Pak Kasim's deposit is highly abraded and fragmented with moderate bioerosion.

4.5 Subtidal Reef Flat with Mixed Long and Short Seagrass *(Sample References: Kal17, 8, HSB2S-4)*

4.5.1 Environmental Facies Description. The back reef subtidal mixed long and short seagrass facies was sampled in three locations along the Sumbano and Hoga Buoy 2 transects (Figs. 4, 6). Examples of this facies are 30-100 m wide. Water depths for this facies are 0.7-1.8 m at high tide.

4.5.2 Facies and Sediment Characteristics. Deposits of this facies are polymodal poorly sorted fine to very coarse sands with a moderate to high gravel (6-21%) and moderate silt-clay (<3-9%) content (Fig. 2h). Sediment textures are grain-rudstones, or in the case of Kal 17 a grain-rud-packstone. The >2 mm size fraction of these deposits is dominated by shell and coral material which may constitute 31-95% of the bioclastic content. Less common bioclasts include *Halimeda*, imperforate foraminifera and seagrass (Fig. 2h). In thin section the <2 mm size fraction is dominated by coral (40%) or *Halimeda* (50%) with lesser shell and coralline algae clasts. Minor components include echinoid plates and spines (5%), alcyonarian sclerites (5%), imperforate, perforate, miliolid and smaller benthic foraminifera (<10% respectively). Abrasion and fragmentation are pervasive on coral clasts and echinoderm material with truncated and broken edges and gouged grain margins. Bioerosion is non-pervasive with <10 µm thick micritic rims to foraminifera and 20-30 µm thick rims to coral and shell fragments.

4.6 Subtidal Reef Flat with Mixed Seagrass-Corals *(Sample References: Kal14, 5, 3 39, HGG5, 3, 2, HSB2S-3, PK14, SS4)*

4.6.1 Environmental Facies Description. A few examples of back reef subtidal mixed coral and seagrass facies were sampled along all transects except Kaledupa Centre (Figs. 3- 7). Sections of mixed coral and seagrass are typically 30-100 m wide and located in the deeper water (~2 m, high tide) parts of the back reef, and adjacent to patches of long seagrass or the reef margin. The seagrass present in this mixed facies is generally short and minor, and well-developed brown algae may be present.

4.6.2 Facies and Sediment Characteristics. Deposits of the mixed coral and seagrass facies are dominantly moderately sorted medium to very coarse sands with a typically moderate to low gravel (<13%) and silt-clay (<8%) sized fraction, with exception to samples Kal39, and SS4 (Figs. 7, 8) where the gravel sized fraction constitutes 83-94% of the sample. Hand samples are predominantly grain-rudstones, although in the modern environment domestone or mixstone textures are also present. The >2 mm size faction is dominated mostly by coral and shell bioclasts (commonly 50-90%) with less abundant imperforate foraminifera and seagrass (Fig. 2i). In thin section the <2 mm size fraction has a high coral and shell content (typically <50%) with calcarinid and imperforate foraminifera (Fig. 2j, k) and coralline algae common components (<20%), together with minor perforate foraminifera and echinoid plates and spines and rarely alcyonarian spicules. Collectively the bioclasts of the mixed coral and seagrass facies are moderately abraded and fragmented with common preservation of elongate coral clasts and calcarinid spines (Fig. 2i). Bioerosion is pervasive with micritic rims of up to 100 µm on coral and shell material, and <10-30 µm rims common on other bioclasts. Minor and non-pervasive encrustation by algae is present commonly and cementation is absent from all samples.

4.7 Subtidal Reef Flat with Corals and with/without Patchy Sediment Cover *(Sample References: Kal15, 9, 4, 2, HGG6, 1, HSB2S-2, 1, PK13, 12, SS3, 2, 1)*

4.7.1 Environmental Facies Description. With exception to the Sumbano transect, back reef subtidal areas with coral and patchy sediment cover occurs adjacent to and back from the reef crest/margin. This facies is typically 50-150 m in width. Coral cover is variable ranging from coral rubble to robust massive and branching forms, with a cover of up to 30%, although locally around coral bommies this may be higher. Sand cover may be as high as 60%, occurring between corals, rocky knolls and lithified surfaces. Water depths range from 1 to 3 m (high tide). The distribution of this facies across the Sumbano transect (Fig. 6) is patchy, occurring adjacent to both seagrass and mixed coral/seagrass facies, as well as the reef crest/margin, with typically <30 m wide sections of coral rubble and intact massive and branching corals.

4.7.2 Facies and Sediment Characteristics. The deposits of back reef subtidal areas with corals and with or without sediment cover are typified by bimodal, moderately sorted fine to very coarse bioclastic sands to gravels. Sediment samples are rud-grainstones, although pillar-, mix- and domestones are also present in the modern environments. Gravel content is variable (<1-60%) and there is a typically low clay-silt sized fraction (<5%).. The >2 mm size fraction of the deposits is variably dominated by coral and shell bioclasts which may comprise 10-90% and 5-75% respectively of a sample (Fig. 2l). Less common components may be imperforate foraminifera, *Halimeda* and seagrass, with rare and minor echinoid plates and spines and alcyonarian sclerites. In thin section the <2 mm size fraction is rarely dominated by corals (5-50%) with commonly abundant perforate and calcarinid foraminifera and *Halimeda* (<20%) and less abundant imperforate foraminifera, echinoid material and alcyonarian sclerites (<10%). Collectively the bioclasts of this facies are not highly abraded, shell and coral clasts show minor evidence of abrasion whilst foraminifera, particularly calcarinids show higher levels of abrasion (i.e., spines removed). Clasts from this facies are typically highly fragmented and show little encrustation (Fig. 2l). Bioerosion is not a pervasive feature of this facies, micritic rims are commonly 10-30 µm in thickness and typically only present on coral, shell and echinoderm material. Cements are absent from all deposits of this facies.

4.8 Subtidal Reef Crest/Margin *(Sample References: Kal1, HSB42, PK11, S2/3-3m)*

4.8.1 Environmental Facies Description. The reef crest/margin is a narrow (<30 m) rim of coral rubble to massive corals occurring adjacent to the reef slope bordering deeper waters and affected by open oceanic processes (Figs. 3, 4, 6, 7). Extensive areas of coral rubble along the reef margin such as at Sumbano, probably at least in part reflect coral bombing and other destructive fishing practices by humans. The reef crest margin is predominantly subtidal, occurring in water depths of 3-5 m (high tide) or more rarely near emergent at low tide (Hoga Gilge Gilge; Fig. 5).

4.8.2 Facies and Sediment Characteristics. Deposits of the reef crest/margin are typified by bimodal, moderately to poorly sorted coarse sands and gravels. Sediment samples are rud-grainstones but mix- and domestone textures dominate in the modern environments. The gravel content of these deposits is high (25-43%) with a minor silt-clay sized fraction (<2%). The >2 mm size fraction is dominated by coral bioclasts (60-<90%) with less abundant shells, *Halimeda*, echinoid plates and spines and perforate and imperforate foraminifera. In thin section the <2 mm size fraction is largely coral bioclasts (25-45%) with common shell fragments, imperforate, miliolid, perforate and calcarinid foraminifera, echinoid spines and alcyonarian sclerites (<15%). Collectively the bioclasts are moderately to highly abraded and fragmented. Encrustation is not seen in these deposits and bioerosion is minimal . Micritic rims at most are <10 µm and non-pervasive. Cementation is absent from all deposits of the reef crest/margin.

4.9 Subtidal Reef Slope *(Sample References: WSUM2, HSB41, HB3-7, 6, PK10, 5, S2/3-5m, 8m)*

4.9.1 Environmental Facies Description. The reef slope environment is a subtidal rocky to sandy slope with hard coral coverage (locally up to 50%), coral rubble and soft corals (Figs. 3-7). Selected samples were from water depths ranging from 5 to 14 m, and from a range of slope environments including sediment collected on ledges from near vertical rocky walls, sediment patches between corals, sand shoots within canyons and sediment aprons below the main reefal development. Studied sections of the reef slope were <30 m wide, with all environments exposed to open oceanic processes.

4.9.2 Facies and Sediment Characteristics. The deposits of the reef slope are typically bimodal, moderately to poorly sorted bioclastic gravels and fine to very coarse sands. Rud-grainstone textures comprise the sediment samples, with mixstone textures also present in the modern settings. The coarse gravel content of the deposits is high (12-43%) with a typically low silt-clay sized fraction (<7%). The >2 mm size fraction of the reef slope deposits is dominantly comprised of coral clasts which may contribute 35-75% of the total bioclastic material. Common, less abundant bioclasts include, shell fragments, *Halimeda*, imperforate foraminifera, echinoid plates and spines and alcyonarian sclerites (<10%). In thin section the <2 mm size fraction of the reef slope deposits is largely coral clasts (35-45%) with common shell fragments, perforate foraminifera, echinoderm material and alcyonarian sclerites (Fig. 2m). Collectively the bioclasts show moderate to minor abrasion and fragmentation, with coral clasts showing the most pervasive fragmentation. Encrustation and bioerosion are rare and non-pervasive (Fig. 2m). No cementation is present in deposits of the reef slope environment.

4.10 Platform Interior Channel and/or Deep Water Regions *(Sample References: Kal34, 35, 37, 38, 40, 41, WHB1-2)*

4.10.1 Environmental Facies Description. Turbid and deep water platform interior regions are found in the near-shore back reef ‘lagoon’ area of northeast Kaledupa and in the semi-enclosed channel that lies between Kaledupa and Hoga (Fig. 8). The areas of deep water are 3-<30 m in depth. Complete bottom-water/sediment-surface environmental data is not available along this transect since samples were acquired via a sediment grab. Unlike other transects that are adjacent to onshore areas of limestone the Kaledupan coast proximal to sample locations for Kal34-38 has cliff exposures of marl (deposits rich in carbonate and siliciclastic clay and silt-sized particles). Turbidity associated with these deposits is commonly strongly related to suspended particulate matter derived from the marls, terrestrial derived organic matter, plankton and high tidal current velocities in the channels stirring up bottom sediment.

4.10.2 Facies and Sediment Characteristics. Deposits of the deep water regions are dominantly bioclastic sands and gravels, however variability exists between the south-eastern deposits (Kal34, 35; Fig. 2n, 8,) and the north-western deposits. South-eastern deposits are bimodal to trimodal, moderately to poorly sorted silts with variable very fine to very coarse sand. Coarse gravel sized material is lacking (<0.2%) and clay-silt comprises 37-51% of the total sediment resulting in packstone textures (Fig. 2n). Bioclasts are absent from the small amount of >2 mm size fraction, instead the coarse sediment is 99-100% lithic clasts. In thin section the <2 mm size fraction is 50-95% lithics with minor coral and shell clasts, echinoid material, alcyonarian sclerites and smaller benthic and planktonic foraminifera. The bioclasts that are present are highly fragmented and abraded. Encrustation is a rare feature of larger coral clasts and bioerosion is pervasive. Micritic rims are typically >50 µm in thickness on coral and shell material with other bioclasts showing more variable 10-50 µm rims. The north-western deposits are dominantly unimodal, moderately to well sorted medium-coarse sands to gravel with grain-rudstone textures. The coarse gravel fraction may contribute from 4 to 54% of the sediment, with a typically low or moderate clay-silt sized fraction (<1-17%). The >2 mm fraction of these deposits is typically dominated by shell material (20-65%) or coral clasts (7-66%). In thin section the <2 mm size fraction is variable with commonly abundant shell (<30%) and echinoderm material (<20%) with less abundant coral, imperforate-, smaller benthic, miliolid- and planktonic-foraminifera, and rare alcyonarian sclerites (Fig. 2o). The bioclasts of these deposits are commonly moderately fragmented and abraded, with corals showing the most pervasive fracturing (Fig. 2o). Encrustation by coralline algae and rarely foraminifera is common. Bioerosion is common but rarely pervasive, with the best developed micritic rims of 10-40 µm present on coral and shell clasts. Cementation is absent from all deposits.

4.11 Satellite Classification Model

A Landsat-7 derived environmental facies map has been created through unsupervised classification processes (Fig. 9; see Materials and Methods section). An overall accuracy of pixel classification linked to environmental facies of 71.43% is indicative of good agreement across the Landsat generated facies map (Table 1). However, the accuracy of classification for most of the subtidal reef flat and intertidal to supratidal facies is >90%. The main source of error in the environmental facies model is due to misclassification of the reef crest-margin and reef slope facies. In all instances these features are at a single pixel or sub-pixel scale (feature width) and are misclassified as either platform interior channel/deep or reef flat subtidal corals with or without sediment cover. Despite attempts to group pixels into a larger number of classes (n=60, 75, 100) it was not possible to correctly identify these features whilst maintaining good agreement in the deep water facies around the Kaledupa Centre transect. To a lesser extent the mixed long and short seagrass facies are a secondary source of error, with only 20% agreement for this class. Misclassification of the mixed seagrass facies places pixels into the short seagrass, long seagrass or mixed coral and seagrass facies. Of the classifiable environmental facies for the classified area: 22.92% are mixed coral and seagrass, 20.53% are short seagrass, 18.43% are coral with or without sediment cover, 16.78% are long seagrass, 13.14% are deep water/turbid, 5.27% are intertidal/subtidal with no seagrass, 2.45% are mixed long and short seagrass and 0.46% are foreshore/backshore (Fig. 9).

4.12 Cluster Analysis

Carbonate sedimentation across the Kaledupa-Hoga system is, for the most part, dominated by the accumulation of skeletal allochems including coral clasts, whole and broken shells, *Halimeda*, foraminifera, coralline algae and echinodermata grains. A comparison of composition (bioclasts and fines) by statistical cluster analysis for the whole data set allows for the identification of four "statistically-defined" sedimentary facies. These four "statistically-defined" facies have textures of; (1) packstone, (2) grainstone, (3) grainstone to grain-rudstone and (4) grain-rudstone to grain-rud-packstone (Fig. 10). The dendrogram demonstrates a large degree of sediment homogenisation in that at ~40% dissimilarity the sediments are still largely grouped as the same cluster. The cophenetic correlation coefficient value for the dendrogram at 0.9017 is very high, and indicates that the dendrogram accurately reflects the original sediment characteristics (Fig. 10).

5. Interpretation and Discussion

5.1 Environmental facies distributions, sediment characteristics and controlling influences

As is the case for other modern humid equatorial carbonate systems, or indeed those from elsewhere, the distribution of environmental facies and their associated sediments from shallow platforms can be complex (cf. Scrutton, 1978; Park et al., 1992, 2010; Jordan, 1998, O'Shea, 2005). An important consideration for understanding spatial facies patterns well enough to be predictive about their inherent characteristics is whether or not a relationship can be established between observable sedimentary characteristics and the identifiable environmental associations (cf. Harris and Vlaswinkel, 2008). The classification of the Kaledupa- Hoga reef systems demonstrates a heterogeneous distribution of environmental facies. Field observations have identified 10 observable environmental facies. However,although the combined petrographic and sedimentological study allowed subtle deposit variations to be identified for the different environmental facies there is similarity between many of the facies, as corroborated by the cluster analysis of the deposits (Figs. 10, 11). Sediment characteristics, whilst distinctive would appear to identify broader environmental facies groupings than the facies breakdown presented in the Landsat derived facies map (Figs. 9-11).

Foreshore deposits are a minor component of the Kaledupa-Hoga system, distributed adjacent to the emergent landmasses. The highly abraded allochems, general absence of fine material and fragmented reworked reef debris are due to the accumulation of skeletal sands and coarse coral debris concentrated by wave and storm activity. These same features of foreshore and/or beach deposits are seen regionally, notably in the isolated carbonate systems of Kepulauan Seribu, offshore Jakarta (Jordan, 1998; O'Shea, 2005). The adjacent facies of intertidal reef flat without seagrass form a relatively wide perimeter to the foreshore deposits and are highly distinctive. The accumulation of poorly to well sorted very fine to very coarse sands reflects variable energy settings. The Sumbano deposits, in the lee of Kaledupa Island, having a trimodal grain-size distribution (fine to very coarse sand and low to moderate silts-clays and gravels) reflect the lowest energy depositional conditions. The highest percentage of silts and clays, albeit at only 4-7% (Fig. 6), likely reflects the leeside setting and are also a consequence of the broad reef flat, providing some protection from wave activity. Although

Hoga Buoy 2 is situated in the lee of the smaller island of Hoga the limited width of the reef flat likely contributed to the apparently higher energy, well sorted coarse to very coarse intertidal deposits with minimal silts and clays (<2%; Fig. 4). Although the intertidal deposits of Hoga Gilge Gilge are sited in the lee of small offshore "mushroom" islands and inboard of a broad reef flat the paucity of clays and silts (<2%) reflects the windward setting with respect to the strong westerly monsoon (Fig. 5). The coral- and shell-rich content of both the foreshore/backshore and intertidal deposits reflects reworking and deposition from the reef flat environments. Micritisation of the intertidal deposits is pervasive and consistent with endolithic micro-borers being most active in moderate to lower energy shallow-photic environments (cf. Swinchatt, 1965; Budd and Perkins, 1980; Perry and Bertling, 2000; Perry and Hepburn, 2008). These foreshore and intertidal deposits are almost exclusively grainstones, a product of strong shoreward reworking of reefal material and localised turbulence and/or winnowing associated with waves breaking at the shore. However, cluster analysis of these samples does not fully resolve these grainstones into their own distinctive facies. Instead, cluster analysis results in a grouping of the heavily micritised foreshore and intertidal deposits of Hoga Gilge Gilge (Fig. 10). The remainder of the foreshore and intertidal environmental facies is clustered together with the sedimentary facies of grainstones to grain-rudstones that are pervasive across many environments of the Kaledupa-Hoga fringing reefs; indicating strong homogenisation of the sediments (Fig. 10).

Despite the presence of distinct reef flat environmental facies, detectable from field observations and Landsat interpretation, the sedimentological characteristics are less varied. There is a broad similarity of sedimentological features of the back reef in terms of allochem composition, grain size and early alteration characteristics (Figs. 2-8, 10, 11). Furthermore the controls of leeward versus windward settings and the effects of sheltering by a broad reef flat that are evident in the foreshore and intertidal deposits are not as apparent in the back reef facies. Reef flat deposits on the basis of their sedimentological characteristics may be grouped into two broad categories: (1) seagrass facies and (2) coral facies.

Seagrass facies are heterogeneous in their distribution and continuity across and between transects, a feature highlighted by their patchy distribution on the Landsat-derived facies map (Fig. 9). In general seagrass facies deposits are poorly sorted very fine to very coarse sands, with comparable abundances of clay-silt and gravel sized fractions (typically 3-<10%). This apparent homogeneous grain size distribution across both leeward and windward transects and inbound from both broad and narrow reef flats is indicative that the prevailing energy conditions are not the primary controlling factor for the development of high versus low energy deposits, as is the case for foreshore/backshore and intertidal settings. The bioclastic content of the seagrass facies deposits is composed dominantly of moderately abraded and fragmented coral and shell material, lesser imperforate foraminifera and *Halimeda,* and minor miliolid and calcarinid foraminifera, echinoderm material and alcyonarian sclerites. Micritic walled imperforate foraminifera, including miliolids, and calcarinids are associated with the development of seagrass beds where seagrass blades provide renewable substrate upon which such benthic organisms can attach and grow (Ginsburg and Lowenstam, 1958; Renema and Hohenegger, 2005), and where locally protected settings are developed by the baffling effect of the seagrass (e.g. Ginsburg, 1957; Scoffin, 1970; Brasier, 1975; Almasi et al., 1987). These same locally protected settings also act as sediment baffles trapping the highest abundances of silt and clays from the reef flat, resulting in the grain-rud-packstones textures in addition to grain-rudstones. Despite the presence of seagrass facies indicators (poorly sorted sediments, moderate to high silt-clay and imperforate foraminifera) there is an overriding bioclastic signature i.e., a high abundance of reworked corals with accessory echinoids and alcyonarian sclerites. This bioclastic signature is more typical of the coral associated facies occurring seaward of the seagrass facies deposits, although some corals are locally present in the seagrass areas. Reworking of coral reef material into the seagrass facies is attributed to the “wash-over effect” of wave activity and strong diurnal tidal currents promoting the shoreward movement of reef material. The lack of a well-defined or emergent reef crest that would act to protect the back reef areas likely contributed to the shoreward movement of reefal material. Similar to the foreshore/backshore and particularly the intertidal deposits, seagrass facies deposits show high degrees of micritisation consistent with low energy shallow-photic environments, as inferred above.

Coral facies are widespread throughout the study area, comprising 40% of the Landsat classification. The sedimentology of these deposits is reflected in the overall moderately sorted medium to very coarse sands and gravels with a typically low (<5%) silt-clay content and grainstone to grain-rudstone classifications. Coral facies deposits show little variability, with coral contents typically constituting up to 90% of a sample. Less abundant clasts commonly include perforate (including calcarinids) and imperforate foraminifera, *Halimeda*, echinoderm material and alcyonarian sclerites. High abundances of highly fragmented coral with robust forms of perforate foraminifera are distinctive of high energy environments (Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004). However, the presence of non-robust imperforate foraminifera, rare miliolids, calcarinids, and rare highly abraded clasts with pervasive micritisation are indicators of reworking of seagrass facies material into the coral facies deposits. Seaward reworking of sediments is best attributed to the strong semi-diurnal tidal currents in combination with bi-directional monsoonal winds, perhaps in combination with storm-waves, affecting shallow platform environments. Whilst reef crest and slope deposits were not identifiable on the Landsat derived facies map they are perhaps the most distinctive deposits sampled. These deposits are dominantly coarse to very coarse sands with consistently very high (<45%) gravel and low (typically <2%) silt-clay sized fractions, indicative of a high energy platform margin. Despite the inferred high energy setting of the reef crest/slope environments reef slope samples from Hoga Buoy 2 and Sumbano have moderate silt-clay contents of 3 to <6% respectively. This accumulation of some fine sediment is likely the result of their protected leeward setting that is also reflected in the foreshore/intertidal deposits for the same transects.

Despite the presence of identifiable seagrass and coral based environmental facies there is a strong homogenisation of sedimentary characteristics, a result of wash over, bi-directional monsoonal winds and strong semi-diurnal tidal currents. This homogenisation of sedimentary characteristics is clearly highlighted through cluster analysis of the sediments (Fig. 10). The dominance of coral and shell material as coarse bioclasts imparts a grainstone to grain-rudstone texture to the majority of the reef flat sediments (Fig. 10). However, where seagrass deposits have developed in the lee of Kaledupa (Sumbano transect) and in the more protected settings of Sampela transect; the concentration of fines allows for the identification of grain-rudstone to grain-rud-packstone sediments which are distinctly representative of locally protected seagrass environmental facies. There is an apparent disconnect between the ability to map environmental facies from satellite imagery and what is preserved in the geologic record i.e., the lack of identifiable reef crest and reef margin facies. The reef crest and margin facies sediments whilst initially appearing as distinctive are still clustered with the largely homogenised sediments of the reef flat, i.e., grainstones-grain-rudstones (Fig. 10). These reef crest and margin deposits are likely, however, to be traceable in the rock record through combined component and/or textural class variations, with prior studies detailing the potential of diagenetic overprinting by early marine cements of reef margin sediments

(Grötsch and Mercadier, 1999; Wilson and Evans, 2002; Madden and Wilson, 2013). The very small spatial extent of these reef margin and crest deposits and associated inability to detect sub-pixel scale features from this form of satellite imagery is not considered a major failing of this study since the broader sedimentary facies are still discerned (Figs. 9, 10).

5.2. Kaledupa-Hoga summary and comparisons with other fringing reefs

Sediment samples across all fringing reef environments from the Kaledupa-Hoga transects have almost exclusively grain-rudstone textures, with <2-5% silt and clay size fractions (85% of all samples). Grain-packstone textures (albeit with only up to 7-9% silts and clays) are seen in the seagrass beds and intertidal deposits just from the broader reef flats and predominantly on leeside transects with respect to the predominant monsoonal wind direction. It appears that seagrasses are a key baffler of fine grained sediment on these small–scale isolated systems, and are also areas of enhanced biologically-mediated breakdown and alteration of grains (cf. Ginsburg and Lowenstam, 1958). Tomascik et al. (1997) reported that seagrasses are a ubiquitous feature of many Indonesian fringing reefs and that there are important biological, and it now appears sedimentological, dynamics between the reef-seagrass systems (cf. Salinas de León et al., 2010; Unsworth, 2010). Fines in packstones from the Central Kaledupa transect are linked to the physical breakdown of island-derived lithics (marls) and their accumulation in the inter-platform "channel" and deep water "lagoon" area. There may also be anthropogenic influences on environments and grain sizes, particularly in the Sampela transect (Crabbe and Smith, 2002). The paucity of fines across the Kaledupa-Hoga system as a whole is attributed to: (1) high wave/current energies, (2) the small size of the islands rendering limited protection, (3) bidirectional monsoon winds and (4) the lack of reef rimmed margins built to sea level. Additionally the equatorial tropics unlike the sub-tropics is not a region of significant marine carbonate precipitation, whether in the form of micrite "whitings", ooid formation or cements (Lees and Buller, 1972; Wilson, 2002; 2012), as attested to by the paucity of early cementation throughout the fringing reef deposits. The degree of homogenisation of sediment characteristics across the different field- and satellite-identifiable environmental facies with evidence for both seaward and landward transportation of grains is again attributed to these same four factors listed directly above (cf. Cordier et al., 2012).

Similar features to those described here and a predominance of grain-rudstone sediments across reef flat, crest and slope deposits are also seen regionally in the high-energy, monsoon-influenced carbonate systems of Kepulauan Seribu, offshore Jakarta. In general the reef flat environments with widths of up to 2 km (including seagrass beds, lithified coral flats and patchy coral cover) are characterised by medium to coarse bioclastic sands where coral rubble constitutes 40-70% of the bioclastic material, molluscs 50-70% and minor foraminifera and echinoid material are widespread, and silt-clay size fractions are low (Scrutton, 1976, 1978; Jordan, 1998; O'Shea, 2005; Park et al., 2010). The reef crest and slope environments of Pulau Seribu are dominated by 40-95% coral rubble with a typically poor degree of sorting and <2% silt-clay sediment fraction (Scrutton, 1976, 1978; Jordan, 1998; O'Shea, 2005; Park et al., 2010). The Pulau Seribu system differs from those described here from Kaledupa-Hoga in being shelf patch reefs, with or without coral rubble/sand cays and/or interior lagoons, and in having prominent rampart rims, often with a landward developed moat and lesser seagrass development (Park et al., 1992; 2010; Tomascik et al., 1997; Jordan, 1998). The fringing reef deposits from around the 1.5 km across Danjugan Island in the Philippines, as with those described here, are dominated by sand- to gravel-grade bioclastic grains with homogenisation of grain types across different environments (Hewins and Perry, 2006). Where the Danjugan reefs differ is in showing strong differentiation between “windward, leeward and lagoonal” transects in addition to bathymetric trends, with the systems as a whole influenced by predominant prevailing winds from the southwest (Hewins and Perry, 2006). Tomascik et al. (1997) noted that some of the variability in SE Asian fringing reef development relates to: (1) geographic location (e.g. continental shelf vs. oceanic), (2) topography and nature (e.g. volcanic or limestone) of the antecedent foundations, and (3) their geomorphological attributes. In the latter case this may include the presence of spurs and grooves, lagoons, boat channels, reef crest, reef flats and the angle of the reef slope.

Other fringing reefs from isolated equatorial tropical carbonate systems, such as Mahé in the Seychelles, show similarities to those from the Tukang Besi Archipelago in being dominated by bioclasts, showing similar distinct environmental facies zonations, but in having sediment characteristics in terms of grain-sizes and/or components that may be difficult to relate to their primary environments (Lewis, 1969). As with the Wakatobi region, seagrass beds are zones of accumulation of the finer grained sediments, although rarely more than a few percent silt- or clay-grade material, and mostly in leeside settings (Lewis, 1969). The fringing reefs of Mahé differ from those of Kaledupa-Hoga in showing more distinctive zonation on windward versus leeside reefs, just having predominantly landward transport directions of marine sediments and in showing significant development of outer reef-flat to reef-crest algal ridges. These differences may reflect the slightly larger size of Mahé at 25 km compared with Kaledupa-Hoga (20 km), the lack of island-transecting tidally-influenced channels, less oceanic-current influence and sea swells mainly during a predominant monsoon season (Lewis, 1969). Kuenen (1933) and Umbgrove (1947) noted that the thick algal sheets and ridges that characterise large areas of the Great Barrier Reef and many

Pacific atolls are rare within the Indonesian archipelago, and these features are also not present in Pulau Seribu, Danjugan or Kaledupa-Hoga (cf. Hewins and Perry, 2006; Park et al., 2010).

Fringing reefs in the sub-tropics, such as those from Grand Cayman, New Caledonia or Réunion (Gabrié and Montaggioni, 1982; Cabioch et al, 1995; Blanchon et al., 1997; Blanchon and Jones, 1997), tend to differ significantly from those in the equatorial tropics. At 25 km across Grand Cayman is similar in size to Kaledupa and Mahé but the fringing reefs differ in their zonation, their reef morphology, not developing on leesides, having little seagrass development, being dominated by zones of coral-cobble rubble underlying the reef crest and in having spur and groove development downslope of the reef crest (Blanchon et al., 1997). An overriding control on fringing reef development in Grand Cayman is inferred to be hurricanes (Blanchon and Jones, 1997; Blanchon et al., 1997): i.e. a process not affecting the equatorial tropics. Braithwaite et al. (2000) and Montaggioni (2005) noted that fringing reefs have a spectrum of development and internal structure related to lower or higher fair-weather energy conditions versus storm severity. Accommodation space and relative sea level change in addition to hurricanes are other important controls on the growth and morphology of fringing reefs (Kennedy and Woodruffe, 2002). The fringing reefs of Kaledupa-Hoga developed under high fair-weather energy, but low storm severity and their development is consistent with the trends described by Braithwaite et al. (2000) and Montaggioni (2005). Fringing reefs with near horizontal reef flats that are partially exposed landward of the reef flat at low tide, as is the case for those of Kaledupa-Hoga, are commonly reported throughout the Indo-Pacific (Kennedy and Woodruffe, 2002). Many of these Indo-Pacific reef flats that dry at low tide appear to have experienced relative sea level fall (Kennedy and Woodruffe, 2002). The fringing reef systems of Kaledupa-Hoga are no exception, surrounding islands with “stepped” coral reef terraces that have been uplifted to maximum heights of 300 m within the last 5 million years (Wilson, 2008b).

5.3 Limitations of, and Comparisons with, Landsat-Derived Environmental Facies Maps.

Given the heterogeneous and complex biological and morphological structure of coral reef environments it is perhaps unsurprising that many satellite based facies maps, whether environmentally or sedimentologically focused, typically fall short of 100% accuracy (e.g., Green et al., 2000; Kaczmarek et al., 2010). Discrepancies between the field determined environmental facies and the Landsat derived facies map presented here (i.e. 71.43% agreement) are attributable to several factors. The main source of error in the facies map generated for Kaledupa and Hoga is the misclassification of the reef crest and reef slope environments (Table 1, Fig. 9). This misclassification of forereef environments is an error inherent to the study area where reef crests and slopes with narrow <30 m wide profiles are juxtaposed against steep drop-offs and deep water. The occurrence of sub-pixel scale (<30 m) reef features, and the absence of a well defined highly reflective reef crest result in misclassification and placement of these pixels into adjacent thematic classes. It has been suggested that the optimal spatial resolution for most coral reef mapping exercises is 1-10 m (Joyce and Phinn, 2001; Andréfouët et al., 2003). Whilst it is possible to utilise hand digitising, filtering algorithms and/or sub-pixel classification techniques to correct these misclassified pixels the techniques are labour and time intensive. Given the low spatial extent of the observable reef crest and reef margin environments and their sedimentary facies grouping within a broader coral environmental facies (Fig. 10) their misclassification does not significantly affect the overall success of the presented facies map (i.e. 86% agreement without the reef crest and slope). Lesser sources of error are likely attributable to the similarity in reflectance of chlorophyll-producing organisms present in the different environmental facies (Kaczmarek et al., 2010), most notably the seagrass environmental facies (Table 1, Fig. 9). Further sources of error are well established including sampling frequency where the resolution of the transect data is greater than the resolution of the Landsat sensor and local conditions of cloud cover and wave activity which alter the colour and brightness of the satellite image (Harris and Kowalik, 1994; Kaczmarek et al., 2010).

Primary depositional facies are a main controlling factor in the heterogeneity of deposits across a carbonate system. Accurately mapping and constraining primary facies variability are key to understanding resultant sedimentological variability for a system. There are few studies that attempt to characterise the facies and deposit characteristics of modern shallow water carbonate systems, utilising remote sensing data. In one key study, environmental facies are defined and accurately mapped for 19 modern isolated carbonate platforms (Harris and Vlaswinkel, 2008). In this study the colour, texture, shape and relative context of reef features were used to identify, map and hand-digitise nine distinct facies groupings from Landsat images. The resultant facies maps accurately outline the extent of reef environments from a fully aggraded reef crest through to the platform interior. Whilst this subjective method of hand-digitising features provides valuable data on facies metrics and distributions, no links are made between primary environmental facies and primary sedimentological characteristics. Furthermore the use of subjective, hand-digitised facies groupings may contribute to a limited understanding of facies variability and heterogeneity across smaller scales. Conversely several studies have demonstrated the use of quantitative approaches in producing satellite-based maps of benthic sediments and reef biota (Purkis and Pasterkamp, 2004; Ouillon et al., 2004; Riegl et al., 2007; Kaczmarek et al., 2010). Whilst the approaches of such studies are effective in determining the distribution of benthic biota types or broad sediment observations (i.e. grainstone to mudstone identification) with high accuracies (e.g. >85%; Kaczmarek et al., 2010), such studies do not demonstrate the variability of sediment characteristics in relation to the primary environment of deposition. The Kaledupa-Hoga model presented here demonstrates that primary environmental facies are, for the most part, detectable at the moderate resolution (28.5 m) of the Landsat sensor, and that these environments have some consistent primary sedimentological, and early alteration characteristics (Figs., 10, 11).

Sub-tropical to tropical isolated carbonate systems are well known from areas such as Central America, the Indian Ocean and south Pacific, with their sedimentology and satellite characterisation well documented (Gischler and Lomando, 1999; Rankey, 2002; Gischler et al., 2003; Gischler, 2006, 2011; Rankey and Harris, 2008; Harris, 2010; Harris et al., 2010; Rankey and Reeder, 2010, Harris et al., 2011). Detailed combined Landsat imagery and sediment studies are lacking from other fringing reef systems globally. The sedimentology of four modern equatorial isolated carbonate platforms from Belize-Yucatan, (Central America) studied utilising Landsat imagery, provides some analogues for comparison with the isolated carbonate system of Kaledupa-Hoga. The composition and texture of surface sediment samples from the modern sedimentary facies of the four isolated carbonate platforms from Belize-Yucatan, define four major sediment types across nine depositional environments (Gischler and Lomando, 1999). A comparison of Landsat images with sediment distribution maps shows that correlations between satellite image characteristics (depositional environments) and sediment composition and/or texture is mostly very good for isolated carbonate systems in Belize-Yucatan (Gischler and Lomando, 1999). That is, as with Kaledupa-Hoga there is some degree of sediment homogenisation across different field- and satellite-identifiable environmental facies. However, many of the depositional environments that are identified in the Belize-Yucatan systems are not present in the Kaledupa-Hoga system, nor are the broad sediment types; packstone, grain-rich wackestone and mud-rich wackestone of Gischler and Lomando (1999). Instead the sediment types of Kaledupa-Hoga are dominantly homogeneous, represented mainly by grainstones to grain-rudstones. Another thing observed in the Belize-Yucatan platforms, not seen in Kaledupa-Hoga is the presence of high energy windward versus low energy leeward settings, clearly identifiable through both satellite and sediment characterisation. Near continuous surface breaking reef rims on the windward side, characterised by an encrusted and cemented coral rubble build up with a low (<5%) fine sediment (<125 μm) content. The high energy reef rims are absent on the leeward sides of these reef systems where unconsolidated, discontinuous and surface-breaking loose coral-rubble rims are present (Gischler and Lomando, 1999). Back reef lagoonal settings protected by the emergent reef rim in Belize contain high concentrations of shell material, *Halimeda*, and imperforate miliolid foraminifera with fine sediment (<125 μm) fractions as high as >23% (Gischler and Lomando, 1999). However, despite evidence of protected back reef settings redistribution of grains derived from windward margins towards back reef areas produces wide sand aprons that fill in the interior lagoons, and there is corresponding transport towards and across the leeside of the platforms (Gischler and Lomando, 1999). On the easterly side of Kaledupa is a broad coral reef flat partially draped by sediment (Class 7; Fig. 9). It is likely that this “apron” has developed due to sediment accumulation and reef progradation in response to the predominant prevailing monsoonal wind direction (cf. Harris and Vlaswinkel, 2008)..

6. Conclusions

The environments, sediments and satellite image characteristics of fringing reefs surrounding oceanic islands in the Tukang Besi Archipelago of Central Indonesia are detailed for the first time. Ten ground-truthed modern environmental facies were recognised across the fringing reef system, and although these have some distinctive primary depositional characteristics there is a degree of sediment homogenisation across facies. Foreshore/backshore deposits are characterised by moderately sorted, coarse to very coarse sands with a low silt and gravel content and high degrees of abrasion and fragmentation (grainstones). Seagrass-associated facies are typically poorly sorted, fine to very coarse sands with up to 9% silt and some gravel content together with moderate degrees of fragmentation and abrasion (grain-packstones). Reef flat coral facies are moderately sorted medium to very coarse sands with low silt and typically high gravel contents (grainstones to grain-rudstones). Bioclasts within the coral facies are generally highly fragmented and show some abrasion. Distinctive moderately to poorly sorted coarse sands and abundant gravels with low silt contents are present in fore reef settings (grain-rudstones). The identification of different environmental facies has allowed a Landsat derived facies map to be generated with overall good accuracy. The paucity of fines across the fringing reef systems as a whole and the degree of homogenisation of sediment characteristics across the different field- and satellite-identifiable environmental facies are attributed to: (1) high wave/current energies, (2) the small size of the islands rendering limited protection, (3) bidirectional monsoon winds and (4) the lack of reef rimmed margins built to sea level. This study probably only hints at some of the variability within SE Asia's vast, and virtually unstudied fringing reef systems (>7500 km^2 of Indonesia's coast is fringed by reefs: Tomascik et al., 1997). However, it highlights apparent significant differences between some equatorial fringing reefs and those from the subtropics. The systems studied here reveal the importance of seagrass bed development, the influence of the monsoons and a degree of sediment homogenisation, lack of windward-leeward effects, and a lack of hurricane influence on these equatorial SE Asian fringing reefs. In addition to fostering a time and cost effective method to map system-scale facies distributions, the facies map presented here may have further applications for understanding modern carbonate system heterogeneity and controlling influences. Additional applications are likely for monitoring and assessment of modern coral reef related habitats and ecosystems, and for potential hydrocarbon reservoir analogue modelling.

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Figures

Figure 1. Location of the Tukang Besi Archipelago (Wakatobi Marine National Park) offshore SE Sulawesi, Indonesia (a). Landsat 7 image of the Tukang Besi Archipelago captured on 6th February 2009 (b). Subset image of Pulau Kaledupa and Hoga, with pixels outside the area of interest removed (c). Magnified view of sample sites and transect locations utilised in this study, shown in both quasi-natural colour (RGB:123) and false colour (RGB:421) display format (d, e).

Figure 2. Binocular microscope photographs and Plane Polarised Light (PPL) photomicrographs of unsorted modern sediments from the various environmental facies of Kaledupa-Hoga. (a) Binocular microscope photo of foreshore sample Kal21; well sorted sediment composed dominantly of highly abraded and fragmented shell and coral allochems. (b) Thin-section photomicrograph of foreshore sample HGG10; moderately sorted sediment composed of highly abraded and fragmented shell material. Allochems are highly micritised and in places their fabrics have been completely destroyed through micritisation by microborers. (c) Binocular microscope photo of sample Kal18, from the intertidal with no seagrass facies. Sample is very poorly sorted sediment with sands and gravels the dominant size fraction. Coral and shell allochems are dominant and highly abraded and fragmented, but also present are whole imperforate foraminifera. (d) Thin-section photomicrograph of sample Kal19 from the intertidal with no seagrass facies, showing high degree of micritisation and the presence of abraded perforate calcarinids. (e) Binocular microscope photo of sample HSB2S-5 from the short seagrass facies. Sample is very poorly sorted, with grain-sizes varying from silt to gravel sized fractions. Coral and shell material is dominant, showing a minor degree of abrasion and moderate fragmentation. Minor imperforate

foraminifera and miliolids are also present. (f) Thin-section photomicrograph of short seagrass facies sample HGG7. Sample is moderately to poorly sorted and highly fragmented. Coral and shell allochems are heavily micritised with lesser bioerosion on foraminifera. (g) Thin-section photomicrograph of long seagrass facies sample HGG4. Sample is moderately to highly fragmented with coral and foraminifera showing moderate abrasion. Coral clasts are pervasively micritised. (h) Binocular microscope photo of mixed long and short seagrass facies sample Kal17. Sample is very poorly sorted silts to gravel. Characteristic *Halimeda*, imperforate foraminifera and miliolids are dominant with lesser coral and shell allochems. (i) Binocular microscope photograph of mixed coral and seagrass facies sample HGG3. Sample is moderately sorted and dominated by moderately to highly abraded and fragmented shell allochems. Imperforate, perforate and calcarinid foraminifera are present. Calcarinid spines are generally abraded. (j) Thin-section photomicrograph of mixed coral and seagrass facies sample HGG2. Sample shows abraded and micritised coral fragments with well preserved perforate foraminifera. (k) Thin-section photomicrograph of mixed coral and seagrass facies sample Kal3. Sample shows highly abraded and fragmented coral clasts with minor to moderate micritisation. (l) Binocular microscope photo of coral with/without sediment cover facies sample HSB2S-2. Sample is moderately sorted medium sands to gravel. Coral and shell allochems are dominant and show moderate abrasion and fragmentation. Minor alcyonarian sclerites and echinoid spines are present, as is a serpulid worm tube. (m) Binocular microscope photo of reef slope sample PK10. Sample is well sorted and has an overall low degree of micritisation. Sample has high abundances of alcyonarian sclerites, with the abundant coral and shell allochems highly fragmented. (n) Binocular microscope photo of deep water facies sample Kal34. Sample is almost 100% lithic marl with a single fragment of shell material. (o) Binocular microscope photo of deep water facies sample Kal40. Sample is very poorly sorted with high abundances of perforate, imperforate and mililoid foraminifera and shells. Lithic marl clasts comprise the fine grain sizes of this sample.

Figure 3. Combined environmental transect, field, component and grain size data for the Pak Kasim's transect undertaken on Hoga. The transect location is identified on both the quasi-natural (RGB:123) and false colour (RGB:421) images, with sample locations identified on the highly magnified displays. The environmental transect correlates with the individual pixels identified in the Landsat image, with field observations, detailed component, early alteration and grain size data beneath. Deposit texture characteristics are given at the base of the composite image with dominant textures listed first and those identifiable from field characteristics only parenthesised.

Figure 4. Combined environmental transect, field, component and grain size data for the Hoga Buoy 2 transect. The transect location is identified on both the quasi-natural (RGB:123) and false colour (RGB:421) images, with sample locations identified on the highly magnified displays. The environmental transect correlates with the individual pixels identified in the Landsat image, with field observations, detailed component, early alteration and grain size data beneath. Deposit texture characteristics are given at the base of the composite image with dominant textures listed first and those identifiable from field characteristics only parenthesised.

Figure 5. Combined environmental transect, field, component and grain size data for the Hoga Gilge Gilge transect. The transect location is identified on both the quasi-natural (RGB:123) and false colour (RGB:421) images, with sample locations identified on the highly magnified displays. The environmental transect correlates with the individual pixels

identified in the Landsat image, with field observations, detailed component, early alteration and grain size data beneath. Deposit texture characteristics are given at the base of the composite image with dominant textures listed first and those identifiable from field characteristics only parenthesised.

Figure 6. Combined environmental transect, field, component and grain size data for the Kaledupa Sumbano transect. The transect location is identified on both the quasi-natural (RGB:123) and false colour (RGB:421) images, with sample locations identified on the highly magnified displays. The environmental transect correlates with the individual pixels identified in the Landsat image, with field observations, detailed component, early alteration and grain size data beneath. Deposit texture characteristics are given at the base of the composite image with dominant textures listed first and those identifiable from field characteristics only parenthesised. Detailed sediment characteristics are not shown for samples Kal14, 12, 10, 8 and 6 due to space constraints, but for individual samples are very similar to those directly on their right (i.e. to their ENE).

Figure 7. Combined environmental transect, field, component and grain size data for the Sampela transect, undertaken on Pulau Kaledupa. The transect location is identified on both the quasi-natural (RGB:123) and false colour (RGB:421) images, with sample locations identified on the highly magnified displays. The environmental transect correlates with the individual pixels identified in the Landsat image, with field observations, detailed component, early alteration and grain size data beneath. Deposit texture characteristics are given at the base of the composite image with dominant textures listed first and those identifiable from field characteristics only parenthesised.

Figure 8. Combined environmental transect, field, component and grain size data for the Kaledupa Centre transect, undertaken on the deep water back reef areas of Pulau Kaledupa and the deep water lagoon separating Pulau Kaledupa and Hoga. Sample locations are identified on the false colour image (RGB:421). No environmental transect is shown here due to no underwater surveys being undertaken since samples in this transect were collected using a sediment grab. The environmental descriptions correlate with the individual pixels identified in the Landsat image, with field observations, detailed component, early alteration and grain size data beneath. Deposit texture characteristics are given at the base of the composite image with dominant textures listed first and those identifiable from field characteristics only parenthesised.

Figure 9. Landsat derived environmental facies map, generated through the unsupervised classification utility of ER Mapper software. Land areas at the centre of Kaledupa and Hoga have been masked, along with several small scale areas of cloud cover. Foreshore/backshore facies are relatively sparse and narrow and in few areas have been removed due to the effects of the land masking algorithm applied during image processing.

Figure 10. Dendrogram of cluster analysis of sediment data from the Kaledupa-Hoga study area. Represented variables are the abundances of components measured in the <2 mm size fraction and the silt to clay sized sediment fraction of each sample (cf. Figs. 3-8). The unweighted pair-group average and Euclidean distance algorithms were selected as they generated the most meaningful dendrogram. The dendrogram was generated with PAST (Paleontological Statistics; Hammer et al., 2001). Deposit texture characteristics are given after each sample identifier with dominant textures listed first and those identifiable from

field characteristics only parenthesised. The Number in parentheses after each sample is the environmental facies group each sediment has been sampled from (Fig. 9)

Figure 11. Schematic summary transect of modern environments and their associated sedimentary characteristics, determined from high resolution sediment sampling and field observations from the shallow fringing reefs of Pulau Kaledupa and Hoga. There is similarity between many features and components from the different environments, although subtle variations in biotic assemblages and early alteration features correspond to groupings of environmental facies. a) Modern environment photograph (Hoga beach) showing both foreshore (1) and intertidal with no seagrass (2) environments. (a*) Unsorted modern sediment sample (Kal21), representative of foreshore sediments. (b) Modern environment photograph of short (nibbled) seagrass facies with accumulation of fine sandy material (Hoga Buoy 2). (c) Modern environment photograph (Sampela) of long seagrass facies, with accumulations of both coarse and fine material. (b-c*) Unsorted modern sediment sample (HBS2-7), representative of seagrass facies environments. (d) Modern environment photograph (Pak Kasim's) of mixed coral and seagrass facies. (d*) Unsorted modern sediment sample (Kal5), representative of mixed coral and seagrass facies. (e) Modern environment photograph (Pak Kasim's) showing relatively clear non-turbid waters and minor patchy accumulations of sandy deposits between and around branching coral forms. (e*) Unsorted modern sediment sample (HGG1), representative of coral with or without sediment cover facies deposits, with occurrence of echinoderm spine (1). (f) Modern environment photograph (Hoga Buoy 2) showing typical high energy reef margin, with abundant hard and soft corals. (f*) Unsorted modern sediment sample (HSB41), representative of reef crest and reef slope deposits. Abbreviated component names are; Echino.-Echinodermata and A.ScleritesAlcyonarian sclerites.

Table 1. Percentage agreement (overall accuracy) metrics as determined through a count of correctly identified Landsat pixels/locations divided by the total number of samples/known pixels available. The overall accuracy has been broken down into individual accuracies for each identified environmental facies. Key sources of error and misclassification of pixels are from the reef slope and reef crest facies.

Appendix 1. Detailed component analysis of the >2 mm and <2 mm grain size fractions and early grain alteration features from a range of modern carbonate sediments sampled from Pulau Kaledupa and Hoga.

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[i] Insalaco's (1998) scheme is a descriptive expansion, and modification, of the Embry and Klovan (1971) extension to Dunham's classification, and is suited to describing *in situ* reef-related growth fabrics with subdivisions based on dominant growth forms. The subdivisions are domestone (domal and massive colonies), pillarstone (vertical branches), platestone and sheetstone (flattened horizontal forms with a width-to-height ratio of between 30:1–5:1 and > 30:1, respectively) and mixstone (no one growth form dominates). Use of the Insalaco (1998) scheme rather than the Embry and Klovan terms of frame-, baffle-, and bindstone removes potential ambiguity over interpretive nomenclature. For example in the Wakatobi area, seagrass beds act as sediment "baffles", but do not result in bafflestone deposit textures (*sensu* Embry and Klovan), whereas branching coral-rich areas do not appear to act as baffles to sedimentation but would have bafflestone deposit textures as defined by Embry and Klovan (1971).