The morphology and distribution of submerged reefs in the Maui-Nui Complex, Hawaii: New insights into their evolution since the Early Pleistocene

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ABSTRACT

Reef drowning and backstepping have long been recognised as reef responses to sea-level rise on subsiding margins. During the Late Pleistocene (~500–14 ka) Hawaiian reefs grew in response to rapid subsidence and 120 m 100 kyr sea-level cycles, with recent work on the submerged drowned reefs around the big island of Hawaii, and in other locations from the last deglacial, providing insight into reef development under these conditions. In contrast, reefs of the Early Pleistocene (~1.8–0.8 Ma) remain largely unexplored despite developing in response to significantly different 60–70 m 41 kyr sea-level cycles. The Maui-Nui Complex (MNC — forming the islands of Maui, Molokai, Lanai and Kahoolawe), provides a natural laboratory to study reef evolution throughout this time period as recent data indicate the reefs grew from 1.1 to 0.5 Ma. We use new high resolution bathymetric and backscatter data as well as sub-bottom profiling seismic data and field observations from ROV and submersible dives to make a detailed analysis of reef morphology and structure around the MNC. We focus specifically on the south-central region of the complex that provides the best reef exposure and find that the morphology of the reefs varies both regionally and temporally within this region. Barrier and pinnacle features dominate the steeper margins in the north of the study area whilst broad backstepping of the reefs is observed in the south. Within the Au’au channel in the central region between the islands, closely spaced reef and karst morphology indicates repeated subaerial exposure. We propose that this variation in the morphology and structure of the reefs within the MNC has been controlled by three main factors: the subsidence rate of the complex, the amplitude and period of eustatic sea-level cycles, and the slope and continuity of the basement substrate. We provide a model of reef development within the MNC over the last 1.2 Ma highlighting the effect that the interaction of these factors had on reef morphology.

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1. Introduction

In recent years, significant work has been carried out on Late Pleistocene drowned reefs on rapidly subsiding margins such as the Huon Gulf, Papua New Guinea (PNG) and Hawaii (e.g., Galewsky et al., 1996; Webster et al., 2004b). In Hawaii, drowned reefs have been used to determine subsidence rates (Ludwig et al., 1991; Moore and Fornari, 1984) and investigate the timing of Meltwater Pulse 1A — a catastrophic sea-level rise responsible for reef drowning during the last deglaciation (Webster et al., 2004a). Numerical modelling of Late Pleistocene reef growth on Hawaii (Webster et al., 2007b) also suggests that the internal stratigraphy of these drowned reef terraces is complex, controlled by frequency and amplitude of eustatic sea-level variations. Webster et al’s (2007b) numerical modelling also indicate that the terraces’ gross morphology was influenced by the subsidence and carbonate platform growth rates. These studies advanced our knowledge of reef development in response to rapid subsidence during the Late Pleistocene, but little is known about reef development during the Early Pleistocene in these settings.

During the Late Pliocene and Pleistocene, global climate, ice volume and eustatic sea level oscillated at a different period and amplitude compared with the last 0.8 Ma. From about 2.5 to 0.8 Ma (Hays et al., 1976) this oscillation was dominated by a period of 41 kyr and eustatic sea-level fluctuations with amplitude of 60–70 m (Dwyer et al., 1995). This period was followed by climate oscillations with a period of 100 kyr with eustatic sea-level fluctuations of up to 120 m...
sea level. The interval characterising the change from one dominant climatic forcing to the next (i.e., 40 kyr to 100 kyr worlds) is known as the Mid-Pleistocene Transition. The Maui-Nui Complex (MNC) (Fig. 1) has developed over the last 2 million years with shield building volcanic rocks from the islands of the Complex (Molokai, Lanai, Maui and Kahoolawe — in age order) having been dated from 1.90 to 0.75 Ma (Clague and Dalrymple, 1989). These ages indicate that the entire MNC evolved from the Late Pliocene to Present Day. Further studies show the MNC’s initial subsidence to be rapid, with a slowing as it moved away from the hotspot (Moore, 1987). Recent lithological and Sr isotope investigations of submarine terraces in the MNC (Webster et al., In review) confirm that: (1) most of these features are coral reefs; (2) the terraces get older as they get deeper, but that; (3) the MNC terraces are significantly older than their Hawaiian counterparts at similar depths, initiating growth soon after the end of major shield building (~1.2 Ma), Webster et al. (In review) confirm that the 12 reefs (L1 to L12, Table 2) forming the submerged MNC terraces grew from the Early Pleistocene to Present Day, i.e. before (≥19), during (L8–L5) and after (L4≤) the Mid-Pleistocene Transition. As such, the submerged reefs around the MNC represent a unique opportunity to explore the response of reefs to varying subsidence rates as well as varying rates and amplitudes of sea-level changes since the Early Pleistocene.

This study focuses on characterising the morphology of the submerged reefs around the MNC and investigating any changes that would indicate variation in reef development. New high resolution bathymetric data around the MNC have allowed a detailed analysis of the morphology of these reefs. Field observations from submersible and ROV dives allow “ground-truthing” of the reef growth structures associated with their development. We document changes in reef morphology between terraces by: 1) using the new high resolution bathymetric and backscatter to illustrate the structure and morphology of the terraces both regionally and individually, and 2) using observations from ROV and submersible dives to describe outcrop style and reef morphology. We then compare the deeper MNC reefs (>800 m) that grew in response to rapid subsidence and 41 kyr global sea-level changes with the Hawaiian reefs that grew in response to rapid subsidence in a 100 kyr sea-level cycle. Finally, we use these data to develop a model to illustrate reef development around the MNC since the Early Pleistocene.

2. Location and methods

2.1. Location and geological setting

The MNC is located toward the south-eastern end of the Hawaiian-Emperor Seamount Chain and has developed progressively as a series of linked volcanoes that grew and subsided due to the passage of the Pacific plate over the Hawaiian hotspot (Fig. 1). This study concentrates on the southern section of the MNC where a series of submerged

Fig. 1. Introduction map of MNC showing dive locations and bathymetry. Location and bathymetric map of the MNC within the Hawaiian Islands. The locations of the ROV and submersible dives discussed in the text are shown in red stars, the dredges are shown in blue stars and samples are shown as yellow stars. The locations of Figs. 2, 3 and 4 are also marked. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
terraces (from 150 m down to 1200 m) has been long recognised (Campbell, 1986). Moore and Campbell (1987) briefly addressed their morphology, identified eight terraces, correlated them by depth with terraces offshore Hawaii, and proposed them to be of similar age. Webster et al. (2009-in review) confirm that these terraces are much older than the Hawaiian terraces, placing their earliest development from the Early Pleistocene. Investigations of the shallower reef terraces in the Au’au channel have revealed karst-like morphologies (Grigg et al., 2002), and coralline algal build-up and drowning (Webster et al., 2006). These studies indicate reef growth in response to slow subsidence, subaerial exposure of the terraces shallower than 120 m and deep-water algal re-occupation of terraces 1 and 2 during the low-stands. With the exception of a few dredged samples from the Haleakala Ridge (Moore et al., 1990), Campbell’s (1986) subsidence study and bathymetric atlas (Campbell, 1987) and the recent Sr isotope study by Webster et al. (in review), the deeper terraces of the MNC have not been investigated.

2.2. Multibeam bathymetry and backscatter analysis

All available high resolution and regional bathymetry and backscatter data for the MNC have been compiled from multiple sources including the Monterey Bay Aquarium Research Institute (MBARI), the University of Hawaii (UH), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS), Scripps Institution of Oceanography (SIO) and Woods Hole Oceanographic Institute (WHOI). The data are predominantly from a SIMRAD EM300 (30 kHz) system in the shallow regions (Dartnell and Gardner, 1998) and co-registered SIMRAD EM1002 (100 kHz) and EM120 (12 kHz) systems in the deeper regions (UH, http://www.soest.hawaii.edu/HMRG/Multibeam/). The latter were mainly collected using the UH vessel R/V Kilo Moana in 2005. Additionally, coastal LiDAR data, collected by the US Army Corp of Engineers (USACE), was incorporated for the very shallow and coastal areas. Most of the multibeam data were processed in MBSystem (5.1.1beta7) (Caress and Gardner, 2000) and correlated using the slope-map images within the ArcScene terminology analogue (WHOI). The region between Lanai and Kahoolawe, (south-central MNC), was mapped and correlated using the slope-map images within the ArcScene function of ArcGIS and sun-shaded bathymetry models in Fledermanas. Geo-referenced Chirp seismic profiles collected by the SEF Education Association (SEA) and multibeam backscatter images were also imported into ArcGIS to assist in the seafloor and sub-bottom characterisation of the terraces and structures. Seismic data from the Benthos 2-7 kHz Chirp-II sub-bottom profiling system onboard the SS Robert C. Seamans were imported into SeisSee 2.3-Beta-1. These data were used to measure sediment thickness in milliseconds of two way travel time which was then converted to thickness in metres (m) assuming a sonic velocity the same as water (1500 m/s). The spatial coverage of sediment was interpreted from the backscatter images in ArcGIS with low backscatter (dark) interpreted as soft-sediment cover and high backscatter (light) areas as exposed outcrop or steep terrain. To provide quantifiable data on terrace morphology, observations of each terrace were made including length, relief, sinuosity and the calculation of a Rim-Index — defined as the normalised length of raised rim divided by the length of the terrace itself (i.e. Rim-Index = (R1 + R2 + R3 + Rx) / L) where R1, R2, R3 to Rx are the lengths of sections of the terrace exhibiting raised rims, and L is the total length of the terrace (Schlager, 2005).

2.3. Dive and dredge operations

Dive and dredge operations have been carried out across the MNC for the past thirty years, but sampling has been concentrated in the south-central section of the Complex (Fig. 1). In 2001, MBARI conducted a series of dives using the ROV Tiburon launched from the RV Western Flyer. Dives used in this study include T309, T294 and T295 southwest of Lanai at 580 m, 550 m and 475 m, respectively, T310 directly south of Lanai at 150 m, and T311 and T312 northwest of Kahoolawe at 230 m and 275 m. Data from these six dives include 139 carbonate samples obtained from the slopes and the tops of the submarine terraces, and approximately 15 h of video footage. Additionally, the Hawaiian Undersea Research Laboratory (HURL) at UH has conducted Pisces submersible dives from the R/V Kaimikai-o-Kanaloa across the Complex. Samples and video from Pisces dives (P4-026, P4-027, P5-191, P5-217, P5-218, P5-254) and video from ROV dives (RCV-108, RCV-109, RCV-110, RCV-111, RCV-115, RCV-116, RCV-117, and RCV-118) have been studied for patterns in outcrop morphology, and to correlate morphology between sample sites. Rock dredging operations (91-WA; 87RTE-D3, D4, and D7; F2-88-HW-D32; and TUM01MV-D9) by the USGS and SIO yielded a further suite of samples that were also analysed in hand sample. The P2-88-HW dredges were conducted over tentatively interpreted coral reefs on the basis of GLORIA images and 3.5 kHz Chirp profiles. There are a total of 234 limestone samples collected from all dives and dredge operations that have been used in this study to confirm their reefal composition and origin. The detailed lithological investigation of the samples, sedimentary facies analysis and palaeoenvironmental implications will be presented separately.

3. Results

The region between Lanai and Kahoolawe, (south-central MNC), Fig. 1, shows the best development of the submerged reef terraces of

<table>
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<th>Table 1</th>
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<tr>
<td><strong>Table of terrace morphology features and definitions.</strong></td>
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<td><strong>Fager terminology</strong></td>
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<tr>
<td>Slope</td>
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<tr>
<td>Crest</td>
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<td>Flat</td>
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<td>Lagoon</td>
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<tr>
<td>Patch</td>
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<tr>
<td>Pinacle</td>
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<tr>
<td>Barrier</td>
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<td>Fringe</td>
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the MNC. We have mapped the reefs throughout the entire MNC, but this paper concentrates on the most well developed terraces in this south-central section. Twelve separate fringing-reef terraces (L1–L12) have been identified and mapped in this region (Fig. 1) and Table 1 defines the morphologic terminology used to describe the features and their likely modern reef analogs.

3.1. Structure and morphology of the MNC

On a regional scale, the terraces of the MNC generally follow the flanks of the volcanoes of the Complex; however, they are also present where volcanic rifts extend from the summits — i.e. Penguin Bank, west of Kahoolawe, and north and east of Maui (Fig. 1). The seaward face of the MNC is marked in most places by a steep scarp (Fig. 1), that Price and Elliot-Fisk (2004) associated with the end of subaerial post-avalanche volcanic flows.

Immediately offshore the coastlines on the north of Molokai, the northeast and southwest of Oahu and south of Kahoolawe, submarine canyons incise deeply (200 m–600 m at the foot of the slope) into the flanks of the volcanic islands (Fig. 1). These canyon incisions obscure terrace identification and correlation in these areas of the MNC, with widely spaced cuts in the breaks in the slope of the terraces. These incisions widen further at greater distance from the coast so the deeper reef terraces are more affected. Additionally, common erosive slump features on the steep margins of the canyons also make identification of terrace breaks in the slope more difficult to differentiate from erosive scarps. The deeper reef terraces, where identifiable, generally have much higher vertical relief than the shallower terraces (Table 2). The shallower slopes of these canyon regions are clear of the slump features however the crests of the terraces are much smoother and less distinct (south of Kahoolawe in Fig. 1).

The south-central MNC can be divided into three regions based on the presence of reef terraces and their differing morphology: immediately south of Molokai and Penguin Bank — the northern region (Fig. 2), the south of Lanai — the southern region (Fig. 3) and between the islands of Lanai, Maui and Kahoolawe — the central region (Fig. 4). The pinnacle and barrier structures, clearly observed in the bathymetry data of the northern section, do not appear on the broader flats of the southern section or elsewhere within the MNC. Additionally, the deeper reef terraces, L10 to L12, do not appear in the southern region except for L10

<table>
<thead>
<tr>
<th>Terrace</th>
<th>Depth to top of terrace(m)</th>
<th>Mapped length (km)</th>
<th>Relief (m)</th>
<th>Rim Index</th>
<th>Rim height and width (m)</th>
<th>Shape (sinuosity)</th>
<th>Sediment cover(m)</th>
<th>Backscatter</th>
<th>Structure</th>
<th>Age(Ma)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>100–150</td>
<td>281</td>
<td>40</td>
<td>0.00</td>
<td>n/a</td>
<td>Low as fringing, high between the islands</td>
<td>2</td>
<td>Moderate across most of the terrace</td>
<td>Low angle of the slope, patches and lagoons. Karst formations including small scale depressed sinkholes and raised patches.</td>
<td>0.303</td>
</tr>
<tr>
<td>L2</td>
<td>230–270</td>
<td>35</td>
<td>60–75</td>
<td>0.00</td>
<td>n/a</td>
<td>Low as fringing, moderate between the islands</td>
<td>Up to 9</td>
<td>Very high across terrace crest and flat</td>
<td>Low promontory terrace. Variable slope of terrace from gently to moderately sloping. Fringing, fairly narrow terrace.</td>
<td>0.708</td>
</tr>
<tr>
<td>L3</td>
<td>285–330</td>
<td>110</td>
<td>40–60</td>
<td>0.00</td>
<td>n/a</td>
<td>Nil on open terrace. 6–8, with 11 max in lagoon</td>
<td>Nil</td>
<td>High along the terrace crest</td>
<td>Nil</td>
<td>0.653–0.715</td>
</tr>
<tr>
<td>L4</td>
<td>355–380</td>
<td>28</td>
<td>50</td>
<td>0.00</td>
<td>n/a</td>
<td>Low to moderate</td>
<td>Nil</td>
<td>High across entire slope, and on crest High across entire barrier (North). High across slope of fringing (South). High along terrace crest in the north, no data in the south</td>
<td>Winnowed dip at the foot of the slope, fringing, very wide terrace.</td>
<td>0.643–0.788</td>
</tr>
<tr>
<td>L5</td>
<td>365–555</td>
<td>105</td>
<td>80</td>
<td>0.45</td>
<td>2–11, also exhibits buried patch reefs</td>
<td>Very low in the south and moderate to high in the north</td>
<td>Nil</td>
<td>Fringing with patches evident</td>
<td>Winnowed dip at the foot of the slope, hummocky structures on reef flats. Cut by drainage ravines to the south of Kahoolawe, Northern section shows barrier and pinnacle features, fringing terrace in southern section.</td>
<td>0.509–1.178</td>
</tr>
<tr>
<td>L6</td>
<td>334–780</td>
<td>129</td>
<td>55</td>
<td>0.13</td>
<td>2–13, from crest of L7 to foot of L6, numerous reflectors</td>
<td>Low to moderate</td>
<td>1–6 on reef flat, max 13</td>
<td>Variable across fringing terrace in the north. No data in the south No data</td>
<td>Northern section shows barrier and pinnacle features, fringing terrace in southern section.</td>
<td>1.094</td>
</tr>
<tr>
<td>L7</td>
<td>520–790</td>
<td>110</td>
<td>60</td>
<td>0.41</td>
<td>2–13, from crest of L7 to foot of L6, numerous reflectors</td>
<td>Low in the south and moderate to high in the north</td>
<td>No data</td>
<td>Northern section shows barrier and pinnacle features, fringing terrace in southern section.</td>
<td>0.509–1.178</td>
<td></td>
</tr>
<tr>
<td>L8</td>
<td>605–1050</td>
<td>210</td>
<td>35–90</td>
<td>0.29</td>
<td>2–4 on reef flat</td>
<td>Low in the south and moderate to high in the north</td>
<td>No data</td>
<td>Nil</td>
<td>No data</td>
<td></td>
</tr>
<tr>
<td>L9</td>
<td>605–1140</td>
<td>152</td>
<td>100–600</td>
<td>0.78</td>
<td>1–6 on reef flat, max 13</td>
<td>Low in the south and moderate to high in the north</td>
<td>No data</td>
<td>Raised rim along terrace crest. Very steep high-high-relief scarps. Depressed sinkholes on flat. Barrier and pinnacle features in northern section.</td>
<td>0.509–1.178</td>
<td></td>
</tr>
<tr>
<td>L10</td>
<td>700–835</td>
<td>120</td>
<td>100–400</td>
<td>0.78</td>
<td>Low to moderate</td>
<td>Low in the south and moderate to high in the north</td>
<td>No data</td>
<td>Nil</td>
<td>No data</td>
<td></td>
</tr>
<tr>
<td>L11</td>
<td>910–1040</td>
<td>21</td>
<td>40–60</td>
<td>1.0</td>
<td>Low</td>
<td>Low in the south and moderate to high in the north</td>
<td>No data</td>
<td>Fringing terrace along northern section</td>
<td>Fringing terrace in northern section. Dramatic vertical relief scarps.</td>
<td>1.094</td>
</tr>
<tr>
<td>L12</td>
<td>1170–1270</td>
<td>47</td>
<td>300–450</td>
<td>1.0</td>
<td>Low</td>
<td>Low in the south and moderate to high in the north</td>
<td>No data</td>
<td>No data</td>
<td>No data</td>
<td></td>
</tr>
</tbody>
</table>

* Ages are averaged according to depth, after Webster et al., 2009 (In review).
3.2. Structure and morphology of the reefs

To quantify the morphological variation between the reef terraces, different measures of morphology such as Rim-Index, sinuosity, vertical relief, sediment cover and shape are summarised below (see also Table 2). These regional observations are enhanced wherever possible by a detailed analysis of individual reefs using dive observations from video footage of the RCV and Tiburon ROVs and Pisces submersible dives across the MNC. Basic lithological summaries of samples taken from these terraces are also included to support the observations made.

3.2.1. Terrace L1

The shallowest terrace identified within the complex, L1, is of low relief, with an average vertical rise of 40 m (Fig. 5a) at an average incline of 12°. It ranges in depth from 100 to 150 m depending on location within the MNC and exhibits no Rim-Index value. This is the best defined terrace within the MNC with a total mapped length of 281 km. L1, displaying a moderate degree of sinuosity (Fig. 4), follows the coasts of the islands relatively closely except for Penguin Bank and the shallow areas between the south-eastern four islands. In these shallowest regions between the islands, L1 shows lagoon and patch morphologies. These depressions are up to 2.5 km long and 1 km wide, and contain thin (2 m) sediment packages along the top of the terrace. The central region between the islands displays an upper terrace development, that we designate L0, which shows common karst features such as solution basins and solution ridges, as described by Grigg et al. (2002).

3.2.1.1. T310 and T311 dive observations. Dive T310 exhibits a stepped profile in L1 with a prominent ledge halfway up the slope at 155 m that is well lithified and at least 4-5 m thick and is directly overlying a sandy bottom. The crest reveals a small rubble field that continues landward across the flat before giving way to a sand sheet with low-relief outcrops running perpendicular to the terrace crest protruding through the sediment. The dive T311 site of L1 shows a slightly different outcrop style, with nodule fields being the only outcrop style right up to the crest of the terrace (163 m) where the nodules are cemented into a pavement-style outcrop that stretches landward across the flat. Coralline algal limestones dominate the samples from these dives confirming coralgal deposits on L1.

3.2.2. Terrace L2

L2 is a 35 km long terrace and was observed during two ROV dives. It has vertical relief of 75 m at T311’s location and 60 m at T312 (Fig. 5b and c) at a depth of 220 m and 280 m respectively. L2 is characterised by low sinuosity, has no Rim-Index and forms a lagoon between Lanai and Kahoolawe as it creates a bridge between the islands (Fig. 4). The Chirp data across this region reveal no sediment on L2 and backscatter data show mottled high values across this promontory with high values being characteristic of all of L2. Between the series of patch reefs of L1, landward of the main lagoon, Chirp data indicate sediment up to 9 m thick (Fig. 6a) however the limited mappable extent of L2 makes it unclear whether this sediment is on L2 or L3.
3.2.2.1. T311 and T312 dive observations. Outcrop begins on dive 311 at the foot of the slope as nodules cemented into a pavement-style outcrop that, along with minor hummocky outcrop, composes the face of the slope (Fig. 5b). The pavement outcrop gives way to a rhodolith field at the crest at a depth of 163 m that stretches across the flat to the foot of the slope of L1. This rhodolith field has previously been correlated with the mottled backscatter of the L2 flat (Webster et al., 2006). T312 video reveals a very similar pattern with nodules at the foot of the slope that are cemented into a pavement outcrop. At this location though, the pavement provides the only outcrop style for the entire terrace face. At the top of L2 this pavement gives way to the same style of rhodolith fields that are seen at the T311 site (Fig. 5c), which continue across the flat. Samples from these dives confirm coralline algal nodules to be the main limestone across these reef terraces with a minor occurrence of a *Halimeda* facies.

3.2.3. Terrace L3

L3 is characterised by high backscatter values along the crest of the terrace and is best developed around and between the islands of Lanai and Kahoolawe. It lies at a depth of between 285 m and 330 m depending on location. It shows no elevated rim, moderate relief of 60 m, and a low degree of sinuosity for most of its 110 km length. In contrast to the rest of L3, the section between Lanai and Kahoolawe shows moderate sinuosity and lower vertical rise of 40 m. Chirp data indicate little or no sediment was deposited seaward of the L2 promontory in contrast with the lagoon behind L2, where the data indicate both thick sediment deposits (averaging 6–8 m with maximum of 11 m) and buried patch structures (Figs. 4 and 6a). Sediment is visible in dive video (RCV-108) with low backscatter values in the same region that cover most of the floor of the lagoon. There are no ROV or submersible dives over the slope or crest of L3 seaward of the L2 promontory, so no other observations have been made for this part of the terrace.

3.2.4. Terrace L4

L4 is the least developed terrace with a total length of 28 km and ranges from 360 m to 380 m depending on location. It exhibits low sinuosity crossing the Kealaikahiki Channel between Lanai and Kahoolawe, before wrapping around the western rift zone of Kahoolawe. A large patch located centrally on the flat of L5 is correlated with L4. Its 50 m vertical rise is larger than the fringing sections of the terrace that show a more modest vertical relief of 35 m. Chirp data across this terrace show no sediment deposits associated with L4. Backscatter data exhibit low values over the central patch reef indicating sediment coverage but there is no corroborating Chirp data. High backscatter values are shown along the slope of L4 and across the flat at the crest of the terrace which is confirmed by a lack of sediment in the Chirp data in these areas. This terrace displays no raised rim, and thus no Rim-Index can be calculated, and due to its limited extent there are no ROV or submersible dives across L4 and so no direct observations were made.

3.2.5. Terrace L5

L5 exhibits very low sinuosity along 56 km south of Lanai and it is the shallowest terrace not to trend shoreward toward the Kealaikahiki...
Channel between Lanai and Kahoolawe. The 80 m vertical rise of L5 is marked by a winnowed depression at the foot of its slope. The depth of this terrace ranges from 360 m to 550 m depending on location. Chirp data show no sediment either on the terrace flat or within the dip at the foot of the slope. This is confirmed by video footage of P5-217 at the bottom of the terrace but the dive did not reach the crest so there is no ground-truthing at the top of the terrace. High backscatter values are observed along the slope of the terrace in the southern region, and across the entire barrier structure in the northern region; however both these areas are steep terrain, and thus this is not interpreted as a hard substrate. The northernmost 49 km of L5 shows a moderate to high sinuosity where the terrace consists of pinnacles and barriers separated from the island's coastline. These barrier and pinnacle features account for the moderately high Rim-Index of 0.45.

3.2.5.1. P5-217 dive observations. Outcrop begins on L5 with a low-relief (~1 m) rocky scarp rising from a sediment covered plain (Fig. 7a), with numerous corals visible within the face of the outcrop and small loose limestone blocks sitting at its base. This scarp is the first in a series of stepped ledges at the foot of the main slope that are also visible in the high resolution bathymetry (Fig. 3). These scarps commonly show 1-2 m of vertical relief, with large blocks (~4-5 m) immediately down slope of the face. The flat of the lowest of these scarps contains individual coral colonies in growth position, steadily increasing in number toward the second ledge until there are continuous coral-rich outcrops at the base of scarp face. From this point (430 m) up, the outcrop on the flatter sections of the ledges appears smoother and more weathered often in layers lying in-dip with the slope, with common large blocks and rubble fields at the base of the scarps. Outcrop in the faces of the scarps has common vertical elements of corals in growth position with layering that lies across the direction of the slope. The main slope of L5 consists of similar form with vertical elements that look like in-situ coral in horizontal bedding. This reef face is of an order of magnitude bigger (approximately 25 m) than the stepped scarps below, but also has a relatively large rubble field and larger blocks at its base. The other major feature of the L5 is the crest at ~390 m that is composed of a massive unit lying stratigraphically above the lattice-work of the main slope. Samples from P5-217 consist of shallow reef building corals, which when taken with the dive observations, confirm coral reef development on L5.

3.2.6. Terrace L6

Terrace L6 is a steep terrace, averaging 18° along a total length of 129 km from west of Lanai around the canyons south of Kahoolawe and ranges in depth from 330 m to 780 m. For much of this length L6 has a depression at the foot of the slope (Fig. 3), similar to L5. However L6 displays none of the barriers or pinnacles prevalent in northern L5, and subsequently has a much lower Rim-Index (0.13). Whilst Chirp data indicate sediment on the flat of L6, that thickens from 2 m near the hummocky structures in the centre of the flat to 11 m approaching the base of L5 (Fig. 2b), this sediment is not observed in the dive video over most of the terrace slope. Backscatter data define the crest of L6 in the northern region with high values along its length. This pattern is not visible in the limited coverage of data in the southern region with low values displayed across the whole terrace.
3.2.6.1. T295 dive observations. Outcrop starts at the foot of the slope with large (2 m across) blocks protruding through the sediment (Fig. 7b). The first of these outcrops are loose, likely derived from upslope. Further along the dive track, sitting in the dip at the foot of the slope, the blocks give way to similar outcrops that appear as a broken unit, with piles of coral appearing between blocks. At the foot of the slope proper, the sedimentary blocks are overlain by pavement-style outcrop. This pavement continues into the slope and is overlain firstly by unconsolidated sediment, and then the same blocky outcrop appears down slope. These hummocky blocks are broken into smaller pieces in parts. Further upslope these are overlain by a smooth pavement drape in a small scarp, and this pavement continues upslope to the crest of the terrace at ~490 m. The top of the terrace is marked by a small rubble sheet with a low linear outcrop of pavement running parallel with the crest, set back about 30 m. Thin sediment covers the flat landward of the crest. Samples from T295 confirm coral reef growth on L6.

3.2.7. Terrace L7

This terrace rises vertically over 60 m with an average incline of 11° in dive 294 (Fig. 7c) where the crest lies at 550 m. At the northern end, dive T308 is characterised by a steep slope of 31° (Fig. 8a) at 520 m depth however this dive was on a pinnacle rather than a terrace, which could account for the difference in the slope. L7 shows a marked difference in morphology over part of its mapped 110 km length. In the northern region, west of Lanai, L7 shows a fringing morphology proximal to the landmass, and a series of barrier and pinnacle structures seaward of this. In the southern region, south of Lanai, the fringing terrace continues but there are no pinnacle or barrier structures associated with it. L7’s moderately high Rim-Index is associated with the occurrence of the barrier and pinnacle features in the northern region. The fringing terrace illustrates a very low sinuosity along its entire length and contrasts with the high sinuosity of the pinnacle and barrier features of L7. Backscatter data for L7 only cover the fringing terrace section in the northern region and show low values for this section. Chirp data cross the southern end of L7’s mapped extent revealing several prominent sub-bottom reflectors across the flat. These reflectors represent multiple sediment packages that thicken from 2 m close to L7’s crest, to 13 m close to the dip at the foot of the slope of L6 (Fig. 6b).

3.2.7.1. T294 and T308 dive observations. At the T294 location (Fig. 7c), outcrop begins at the foot of the slope as solitary blocks protruding through unconsolidated sediment. Further up the slope at ~590 m, these
samples from dive T294 indicate coral reef growth for at least part of L7's style outcrop is divided by small rubble fields in hollows with small low-relief (<1 m) cliffs of exposed outcrop at the edges of these hollows. The pavement-style outcrop is unbroken at the crest of L7 at -550 m however here L7 exhibits a hummocky outcrop style. The only outcrop style visible in the T308 dive location (Fig. 8a), is a similar near-continuous outcrop that forms a smooth pavement. This pavement is also at the same angle as the slope, and there are no rubble fields evident at the T308 location. Samples from both these dives confirm limestones across the terrace and the detailed composition and chronology of these samples are presented in Webster et al. (in review).
Fig. 7. Outcrop style and terrace schematics. The different outcrop styles represented are taken from ROV dive observations. Part (a) is not to scale as there was no navigational data to construct transects from — this figure is purely observational. (a) Terrace L5 from dive video of P5-217. (b) Terrace L6 from dive video of T295. (c) Terrace L7 from dive video of T294. Ages are averaged ages relative to depth, taken from Webster et al. (In review).

situ coral framework sloping at the same angle as the terrace slope. This pavement is thinly covered by sediment, with the corals evident as blocks protrude through the mud. Samples of shallow water corals and associated coralline algae confirm this terrace to be coral reefal in origin.

3.2.11. Terrace L11
L11 is the second least developed terrace identified in the MNC with its 21 km mapped extent all occurring as fringing reef on the substrate of the Clarke debris avalanche to the west of Lanai. Its crest lies at between 930 m and 1040 m depth and exhibits relatively low relief of 40-60 m. L11 has a raised crest (1.0 Rim-Index) of low sinuosity, and no distinctive features, with no backscatter, Chirp, or submersible/ROV data to confirm the details of this terrace.

3.2.12. Terrace L12
L12 is also a fairly poorly developed terrace with only 47 km mapped. Due to its distal location on the edge of the MNC, L12's vertical relief is one of the largest, ranging between 300 and 450 m. The crest lies at 1170 m to 1270 m depth and shows low sinuosity except for one small section directly west of the northern tip of Lanai and has a Rim-Index of 1.00. There is no evidence on the nature and composition of this terrace as no dives or dredges have been conducted over it. Additionally, the quality of Chirp data recovered over L12 was poor due to the terrace's depth and its location on a steep incline.

4. Discussion
4.1. Regional and temporal differences in reef development

The large-scale morphology of the submerged reefs of the MNC shows major regional variation with the presence of pinnacles and barrier structures west and south of Lanai and the absence of these features elsewhere. Additionally, the southern region of the southeastern MNC (Fig. 3) shows greater terrace width than the northern region (Fig. 2), and the central region (Fig. 4) displays lagoon and patch morphologies that are absent elsewhere within the MNC. These variations in the distribution and morphology of the reefs indicate regional change in factors such as accommodation space and substrate across the MNC. More importantly the reefs were dominated by a
temporal change in sea-level cyclicity — the Mid-Pleistocene Transition (MPT). In the following sections by looking at the pre-MPT, the MPT, and the post-MPT reefs independently, we show how this temporal change is the primary factor influencing the observed variations in the reef morphology.

4.2. Pre-MPT Maui-Nui Complex vs post-MPT Hawaiian

Reef growth prior to the MPT was restricted to the outer margin of the Complex to the south and west of Kahoolawe and the southwest and west of Lanai (Fig. 9). Additionally, the complex was subjected to eustatic sea-level cycles of 60–70 m amplitude over a 41 kyr period during this time. Using the Sr age data Webster et al. (2009 (in review)) calculated an average subsidence rate of 0.85 m/kyr for the deepest dated terrace, L10. Given the last 250 kyr has likely been nearly stable (Webster et al., 2007a), it is probable that this 0.81 m/kyr linear rate is a poor approximation, with the MNC undergoing initially rapid subsidence that slowed as the Pacific plate moved the complex beyond the hot spot. Thus with the growth of Lanai, West Maui and Kahoolawe all occurring during the time of L12-L9 (−1.3–0.9 Ma), the MNC would have been experiencing rapid subsidence, approaching the modern subsidence rate of 2.2 m/kyr of the big island of Hawaii (Moore et al., 1996).

Given the subsidence rates for the pre-MPT MNC and Hawaii, it is reasonable to look to the submerged reefs offshore of the Big Island of Hawaii for comparison with pre-MPT MNC in respect to morphology and development patterns. Campbell (1986) was the first to identify the Lanai terraces and correlate them with the terraces offshore Hawaii based on depth and gross morphology. Campbell (1986) also identified barrier reef, lagoon and patch reef features on the Hawaiian 425 m terrace and presented two bathymetric profiles comparing the MNC terraces in the northern region with the series of terraces offshore Hawaii. Campbell's figure shows that the Hawaiian reefs are more broadly backstepping than the terraces on the MNC, and display none of the offshore barrier and pinnacle features present within the MNC. Campbell’s (1986) barrier and lagoon system on the 425 m terrace was also highlighted by Jupiter et al. (2002) who conducted a detailed morphologic study of this terrace. These features are similar to those found on the upper terraces of the MNC (Fig. 3) that also grew in response to 100 kyr sea-level cycles.
Given the likely similar subsidence rates of the pre-MPT MNC and the current rates observed on Hawaii, we propose that it is the difference in eustatic sea-level cyclicity either side of the MPT that is the major driving factor in the variation in terrace morphology observed between the MNC and offshore Hawaii. We propose that the conditions of rapid subsidence and short, low-amplitude sea-level oscillations dominant for the MNC prior to the MPT produced a different mode of reef morphology. During regression, flank subsidence allowed reef growth on these platforms; however instead of drowning and backstepping during sea-level rise, the smaller amplitude of the sea-level oscillations and shorter time-scale for subsidence to take place allowed the reefs to re-occupy and resume growth upon the next regression. This process allowed numerous cycles of reef growth in the same location before island subsidence submerged a terrace out of the growth zone. Importantly, in the northern region, extensive backstepping did not occur due to the steep substrate and rapid sea-level cycles, with the re-occupation and re-growth producing offshore barriers and pinnacles. Additionally, in the absence of raised and isolated substrate in the southern region, (i.e. no complex topography associated with the Clarke debris avalanche) re-occupation episodes were expressed as a thicker fringing-reef face. This formation of pinnacles and barrier structures in the northern region and thick reef face to the south results in higher Rim-Index values for these terraces. The proposed model is supported by both the pinnacle and barrier features themselves, and thick in-situ reef face observed during dive T309 (Fig. 8b).

In Hawaii, where submerged reef terraces have also developed in response to rapid subsidence, terrace backstepping is the dominant terrace morphology. In the Hawaii case however, eustatic sea-level cycles were of much larger amplitude and longer period, hence terrace re-occupation could not take place to the same extent as in the MNC.

4.3. MPT terraces

The time frame between 900 and 800 ka represents the Mid-Pleistocene Transition, and as such, the period of transition from 41 kyr cycles to 100 kyr sea-level cycles. It also represents a time when the centre of subsidence was moving from fairly central MNC (west Maui) to a more marginal location on the complex (south-eastern
Haleakala) as Haleakala became the dominantly growing volcano and Kohala started forming (Fig. 10). This movement of the centre of subsidence is reflected in a slowing subsidence rate across the complex. Thus the L8 to L5 terraces developed in a response to a situation of slowing subsidence and changing eustatic sea-level cyclicity. Reef growth in this period was located west and south of Lanai and to the west and south of Kahoolawe (Fig. 10). The terraces of the MPT, L8 to L5, exhibit variable but relatively uniform morphological characteristics (Table 2). There is not any identifiable pattern or general trend within this group.

When compared to terraces both before and after the MPT, however, trends are apparent in both vertical relief and Rim-Index. The pre-MPT terraces of the MNC (L12–L9) have more continuous raised platform margins, i.e. Rim-Index values significantly higher (averaging 0.89) than that of terraces developed within the MPT (L8–L5) which average 0.256. The MPT terraces in turn have a higher Rim-Index than post-MPT terraces (L4–L1) for which it is zero in each case. The vertical relief of the terraces also diminishes from pre-MPT, to MPT, to post-MPT time periods.

Schlager (2005) defined a Rim-Index as a measure of the continuity of a platform rim and used this measure to comment on wave energy entering the lagoon. Alternatively, we suggest that the Rim-Index could be interpreted as a proxy for the terrace edge as being the preferred location of frame-building corals. Kennedy and Woodroffe (2002) highlight six models of fringing-reef development on various substrate types and tectonic settings, and show that with ample accommodation space vertical growth is faster on the reef crests. As such, we apply this index to comment on the accommodation space of a terrace as it develops; i.e. a high Rim-Index indicates that the terrace was created by an active coral reef crest with ample accommodation space. We propose that this temporal variation in Rim-Index is a direct reflection of a change in accommodation space caused by variation in subsidence rate, eustatic sea-level cycles and the slope of the substrate. The more rapid subsidence experienced by the MNC pre-MPT coupled with the smaller and more rapid sea-level oscillations resulted in continuous formation of accommodation space that allowed rapid reef growth. With either a slowing in subsidence, or a shift in sea-level cyclicity, (both are seen with the onset of the MPT), this creation of accommodation space is reduced and rapid reef growth at the terrace rim will slow down, lowering the Rim-Index. It is important to note that solutional erosion of reefs when subaerially exposed can amplify the elevated rims of fossil reefs, however the data we present on the morphology of the reefs indicate the terraces more...
likely to be exposed and subject to extensive subaerial/solution erosion (L0, L1, L2 and L3) show little to no Rim-Index, and we argue that our interpretation of the Rim-Index is the reason why this is the case.

The changing conditions within the MPT gave rise to variation within these terraces (Table 2), however no overall temporal pattern for this period can be identified. Even within the time frame of the MPT, the L8 to L5 reefs show significant variation in the nature of backstepping evident between the terraces (Figs. 2 and 3). Generally speaking, the slope of the underlying substrate is critical to regional terrace morphology with respect to the amplitude of any terrace backstepping. Within the southern region of the MNC, the transition from the steeper distal flanks of the volcanos (broadly evident in the pre-MPT terrace L9), to the more gently sloping upper substrate (Fig. 3) allowed larger backstepping to occur. This change in substrate slope coincided with the start of the increase in amplitude of eustatic sea-level cycles (Marine Isotope Stage 19, 21). In contrast, the steeper substrate of the northern region (Fig. 2) produced closer spacing of terraces under the same conditions, similar to the spatial distribution of the deeper terraces. We propose that two factors contribute to the pinnacles and barriers continuing to form on MPT terraces (L8, L7 and L5). These two factors are 1) the reduced nature of the backstepping in the northern region due to steeper substrate, and 2) the persistence, albeit reduced in strength, of the 41 kyr periods of interglacial/glacial cyclicity throughout the MPT.

4.4. Post-MPT terraces

These reefs (L4–L1) grew in response to the conditions since the Mid-Pleistocene Transition. For this period, the interglacial/glacial cycles are dominated by a 100 kyr period, and the centre of subsidence was further from the MNC, near Kohala (Fig. 11). Reef growth in this period was located primarily between the islands of Molokai and Lanai, and Lanai and Kahoolawe (Fig. 11). Terraces developing at this time exhibit no raised rim and are of lower vertical relief than the earlier terraces.

Webster et al. (2007a) propose that the MNC is currently nearly stable with calculations indicating between 0.1 m/kyr uplift and 0.4 m/kyr subsidence over the last 30 kyr and perhaps the last 250 kyr. Similarly, Webster et al.’s (in review) Sr dating indicates that since 13’s formation at 0.533 Ma, there has been an average of 0.58 m/kyr subsidence. These data indicate a slowing in subsidence within the MNC, that correlates with the movement of the MNC away from the Hawaiian hotspot as the Pacific plate migrated to the northwest. This
time frame also coincides with the onset of the domination of the 100 kyr oscillation in eustatic sea-level cyclicity. Both the amplitude and style of sea-level oscillation during the 100 kyr cycles changed from pre-MPT sinusoidal 60–70 m cycles to a more saw-tooth pattern and a greater amplitude of up to 120 m.

Large amplitude of sea-level variation, slow subsidence (or stability) of the complex, and limiting reef growth to the central region of the complex have created reef growth conditions where reef terraces stack on each other, with little or no lateral movement or backstepping possible. The promontory relationship of L2 and L1 and the lagoonal feature of L3 (Fig. 3) suggest stacking of the terraces with little or no backstepping with reef stacking evident in the antecedent topography Grigg et al. (2002) highlighted in the Au’au channel. These reefs forming the post-MPT terraces developed during sea-level high-stands, similar to the modern environment, with the successive terraces developing on the successive sea-level high-stands. Age control (Webster et al., in review) indicates that L3 developed during Marine Isotope Stage (MIS) 11 with L2 then developing during the next cycle (MIS 9), L1 during MIS 7 and L0 during MIS 5. This would suggest that these terraces have also undergone some subsidence to be at their current depths, implying that Webster et al’s (2007a) potential subsidence rate of 0.4 m/kyr is more likely than their potential 0.1 m/kyr uplift rate. Additionally, during the sea-level low-stands, at least L1, L2 and L3, and possibly L4 were likely reoccupied by intermediate to deep-water coralline algal nodule and coralline crust development (Webster et al., 2006; Webster et al., 2009). Lithologic, chronologic and morphologic data (Webster et al., 2006) confirm that this low-stand re-occupation scenario has taken place on L1 and L2 during the LGM (MIS 2).

With such large amplitudes and long periods of sea-level oscillations, the upper part of L1 (i.e. L0) would have been subjected to significant subaerial exposure during successive low-stands. This conclusion is supported by terrace morphology, (Fig. 4) and the presence of karst-like features identified by Grigg et al. (2002). Grigg et al. (2002) suggest that around 14 ka sea level was - 82 m in the Au‘au channel – the upper parts of L0 would have been exposed. Assuming recent stability and using a 6°18 sea-level proxy from ODP site 677 and current depth, over the past 500 kyr, L0 would have been repeatedly subaerially exposed for a total of at least 145 kyr. This sort of time frame would have been ample to produce the well developed and defined karst morphologies evident in the multibeam bathymetry. Repeated subaerial exposure of this magnitude and over this time frame would lead to higher erosion rates than experienced by deeper terraces that remained submerged. The total exposure of 145 kyr would have occurred over 5 distinct periods, each greater than 10 kyr, with the longest period being just over 50 kyr. These sorts of periods and lengths of subaerial exposure would produce significant amounts of mud and silt by mechanical erosion in addition to solution weathering of the karst landscapes.

5. Conclusions

1. We have identified 12 reefs offshore Lanai in the Maui-Nui Complex that line the volcanic flanks of the islands, and range in depth from 150 m to 1200 m. Modern reef features such as slopes, crests, lagoons
and patch reefs have been identified on the submerged terraces, and video observations and samples confirm the terraces to be reefs.

2. The morphology and structure of the reef terraces vary spatially within the study area displaying three distinct morphologies in three different regions. The northern region is dominated by offshore pinnacle and barrier structures; the southern region is characterised by large-scale terrace backstepping and the central, most recent, region shows lagoonal, patch and karst development.

3. The morphology of the reefs displays distinct temporal variation correlating with ages before, during and after the Mid-Pleistocene Transition. Thick reef faces and offshore pinnacle and barrier structures characterise the Pre-MPT reefs. There is a shift to broad backstepping in the south and a reduction in the offshore pinnacle and barrier structures in the northern region with the onset of the MPT. The Post-MPT reefs show evidence of reef stacking with karst development features evident on the shallowest reef terrace.

4. Over the past 1.2 Ma, the northwest migration of the Pacific Plate has carried the Maui-Nui Complex away from the Hawaiian hotspot. Coupled with the development of the big island of Hawaii, this migration has resulted in the movement of the centre of subsidence away from MNC towards Hawaii and a slowing in the subsidence rate experienced within the complex.

5. We argue the observed variation in morphology in MNC reef development was controlled by three main factors (Fig. 12);

(a) the subsidence rate of the MNC. Subsidence varied from rapid, to slow, to finally nearly stable with the migration of the Pacific plate across the Hawaiian hotspot and affected the style of reef backstepping in addition to inducing subaerial exposure, erosion and karst dissolution of the shallowest reef terraces.

(b) the amplitude and period of eustatic sea-level cycles. This forcing changed in both amplitude and frequency during Mid-Pleistocene Transition and affected reef growth morphologies with multiple re-occupations of reef terraces under 41 ky cycles producing large vertical relief structures (e.g. pinnacles, barriers and thick fringe reef faces) not replicated under 100 ky cycles.

(c) the slope and continuity of the substrate. This aspect varies at the location of the Clarke debris avalanche which steepened the slope such that pinnacle and barrier structures could be formed and closely spaced reef terraces could dominate.

6. We present a model of terrace and reef development within the MNC (Figs. 9, 10 and 11) that is consistent with the available data and could be tested with scientific drilling of the pinnacles or further test our model. Alternatively, deep seismic profiling and could be tested with scientific drilling of the pinnacles or offshore pinnacle and barrier structures, the southern region is characterised by large-scale terrace backstepping, and the central, most recent, region shows lagoonal, patch and karst development.

References


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