Int J Earth Sci (Geol Rundsch)
DOI 10.1007/s00531-006-0107-5

ORIGINAL PAPER

Support for the Giant Wave Hypothesis: evidence from submerged terraces off Lanai, Hawaii

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Received: 20 March 2006 / Accepted: 8 June 2006

Abstract The origin of subaerial coral conglomerate deposits on the Hawaiian islands of Lanai and Molokai is controversial, primarily because these deposits are difficult to interpret and the vertical motion of these islands is poorly constrained. Based on bathymetry, dive observations, sedimentary and radiocarbon data from coralline algal dominated deposits from two submerged terraces at –150 and –230 m off Lanai, Lanai has experienced relatively little vertical movement over the last 30 ka. Using internally consistent age versus depth relationships, paleowater depths, and published sea level data, we estimate that Lanai has experienced maximum rates of uplift of 0.1 m/kyr or subsidence of 0.4 m/kyr over this period. Our analysis of possible uplift mechanisms, published geophysical, numerical modelling, and recent tide data suggests that this is also the maximum uplift rate for the last several hundred thousand years. Taken together these data support the interpretation that coral conglomerates at elevations higher than +35 m on Lanai are tsunami deposits with a minimum wave run up > 170 m, rather than shoreline deposits formed during the last two interglacials, then uplifted to their present elevations.

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Keywords Hawaii · Lanai · Submerged reef terraces · Subaerial coral conglomerates · Tsunami

Introduction

The origin and interpretation of subaerial coral conglomerate deposits on Lanai and Molokai continues to be controversial (Moore and Moore 1984; Grigg and Jones 1997; Rubin et al. 2000; McMurtry et al. 2004a). These deposits were first interpreted as highstand deposits (Stearns 1966, 1978), then mega-tsunami deposits (Giant Wave Hypothesis) (Moore and Moore 1984, 1988; Moore 2000), then re-interpreted as highstand shoreline features deposited during the last two interglacials (Grigg and Jones 1997; Rubin et al. 2000; Keating and Helsley 2002; Felton et al. 2006). These different origins of the coral conglomerates (Giant Wave Hypothesis or uplifted shorelines) imply very different vertical histories for Lanai, a difference so large that even broad constraints on the vertical motion can distinguish between the two models.

The lack of agreement on the observations and interpretation of the subaerial deposits (outlined below) suggests that the resolution of the controversy lies in constraining the vertical motion of Lanai and Molokai (McMurtry et al. 2004a). Some studies indicate these islands are sinking (Campbell 1986; Moore 1987; Watts and ten Brink 1989; Wessel 1993), while others suggest they are now rising over the lithospheric bulge caused by loading from continued volcanism on Hawaii (Wessel and Keating 1994; Grigg and Jones 1997; Rubin et al. 2000) or isostatic rebound following large landslides (Smith and Wessel 2000). An approach used successfully in Hawaii (Moore and

Fornari 1984; Ludwig et al. 1991; Webster et al. 2004a) and Papua New Guinea (Galewsky et al. 1996; Webster et al. 2004b) to constrain the directions and rate of vertical movement is to investigate morphology, composition, and ages of submerged terraces offshore Lanai (Fig. 1) (Webster et al. 2006).

In this paper we outline and review published data from the subaerial coral conglomerate deposits as well as recent data on the submerged terraces around Lanai. Finally, on the basis of these data, combined with available sea level, geophysical, numerical modelling and recent tide gauge data, we present a new analysis and discuss its implications for the origin of the subaerial coral conglomerates and possible large tsunami run-ups on Lanai.

Subaerial coral conglomerate deposits

Stearns (1966, 1978) recognized several coral conglomerate deposits as high as +326 m above current sea level on Lanai and interpreted them as past shoreline deposits. U-series dating of a single coral from +171 m gave an age of 350 ka (Stearns 1966), indicating either previously high eustatic sea levels or uplift. It is now known that eustatic sea levels over the last 500 ka probably did not exceed +11 m (Lambeck et al. 2002; Lea et al. 2002) implying significant uplift of Lanai. However, Moore and Moore (1984, 1988) re-interpreted these deposits as having formed as a result of a mega-tsunami at 105 ka (based on three new U-Th ages), associated with submarine slumping off Lanai (Moore and Moore 1988), or Hawaii (Alika 2 slide: 112–127 ka) (Lipman et al. 1988; Moore et al. 1989; McMurtry et al. 1999). Moore and Moore (1984, 1988) supported their interpretation with: (1) sedimentologic data (ie. chaotic deposits; no corals in growth positions; soil stripping to +365 m (Stearns 1978); mixed shallow and deepwater molluscan assemblages; (2) the age (102–134 ka) and height of the deposits above sea level (+115–155 m) imply uplift of 1.1–1.6 m/kyr while tide-gauge data from nearby Maui shows subsidence (0.3 m/kyr) (Moore 1987), and (3) that huge landslides on the submarine flanks of nearby islands occur frequently and are big enough to produce large tsunamis (Figs. 1, 2). A similar deposit at +85 m on Molokai was dated using U-series at 200–240 ka (Moore et al. 1994), and correlated with the older submarine South Kona slide (Moore et al. 1995; McMurtry et al. 1999) (Fig. 2).

Subsequent workers (Grigg and Jones 1997; Rubin et al. 2000; Keating and Helsley 2002; Felton et al. 2006) presented sedimentologic and radiometric data

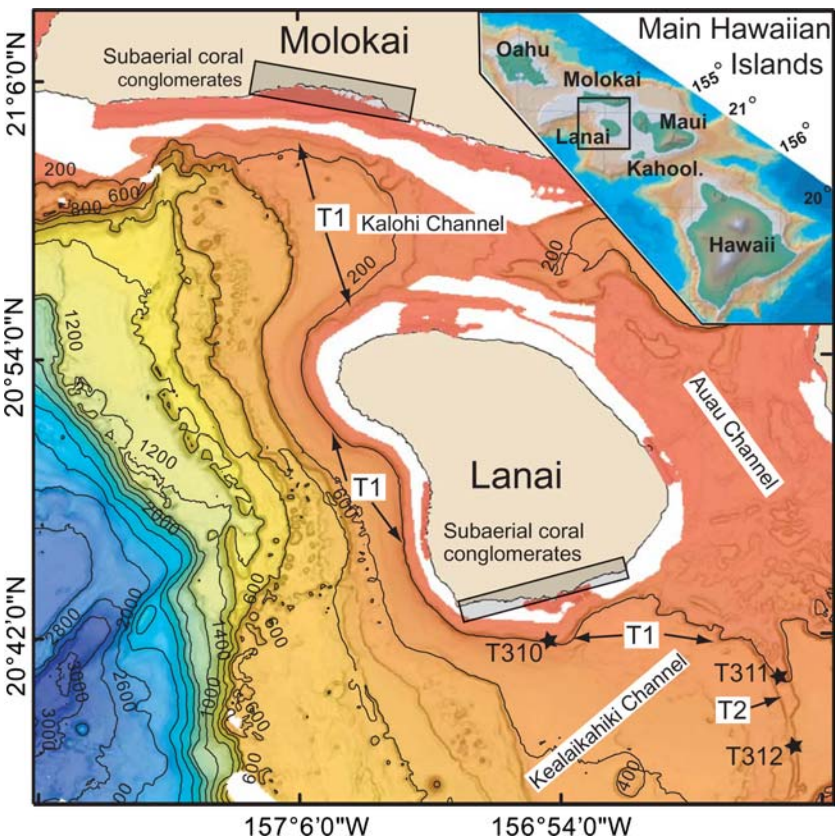

Fig. 1 Bathymetry data showing the submerged carbonate terraces around Lanai (after Webster et al. 2006). Recent ROV *Tiburon* sampling dives (*black stars*) and subaerial coral conglomerate deposits (*black rectangles*) on Molokai and Lanai are also shown

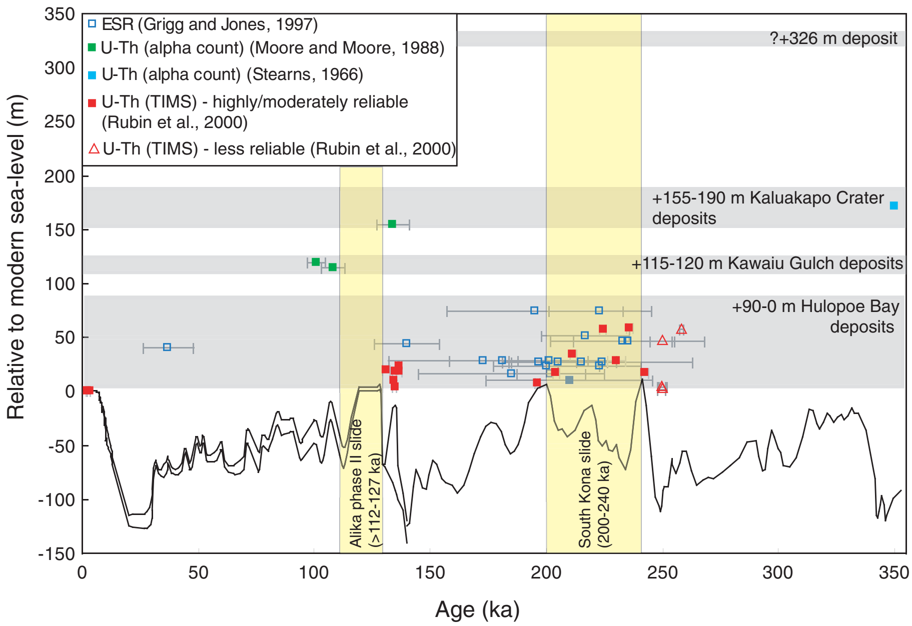

Fig. 2 Available age versus elevation of corals from the Lanai subaerial coral conglomerate deposits plotted against eustatic sea level change (after Lambeck and Chappell 2001; Lea et al. 2002). Landslide timing after McMurtry (2004a). The *errors bars* on the U/Th (TIMS) ages (Rubin et al. 2000) are less than the size of the *symbols*

and interpreted the deposits as shoreline features formed during previous highstands (MIS5e and MIS7), and at their present elevation due to uplift. Grigg and Jones (1997) located deposits up to +74 m and dated 19 coral clasts using electron spin resonance (ESR) (Fig. 2) and support their shoreline interpretation with: (1) sedimentologic data (i.e. in situ corals, horizontal bedding, and wave-cut notches) consistent with shoreline deposition, (2) increasing age of the deposits with height, and (3) the inability of submarine landslides to generate waves large enough to transport material > +180 m (Johnson and Mader 1994). Grigg and Jones (1997) calculated an average uplift rate of 0.33 ± 0.03 m/kyr over the last 223 ka from deposits at +74 m.

Rubin et al. (2000) presented 21 precise U-Th ages and found corals representing MIS5e (~135 ka) and MIS7 (~240 ka) with geographic and stratigraphic ordering (Fig. 2). Based on coral ages, gravel stratigraphy and facies variations they concluded that the deposits represent shoreline deposition during these highstands. Rubin et al. (2000) estimated uplift rates of 0.15–0.29 m/kyr, based on the maximum elevations (23 and 59 m, respectively) of the dated MIS5e and MIS7 deposits, paleo-sea levels, and depositional depths. Subsequently, Keating and Helsley (2002) relocated the deposits at +170 and +190 m in Kaluakapo crater, close to those dated by Moore and Moore (1988), and interpreted them as shoreline features, thereby requiring minimum uplift rates of 1.2–1.4 m/kyr using the Moore and Moore (1988) 134 ka age for the +155 m deposits.

An argument against the Giant Wave Hypothesis (but for the uplift of Lanai) has been the size of the tsunami runup required to entrain coral material to a height of +326 m. Based on model calculations (Johnson and Mader 1994), Grigg and Jones (1997) argued that a tsunami striking Lanai triggered by the Lanai slump or the Alika phase 2 slide would not have been large enough to produce deposits at elevations > +180 m. This is roughly the maximum elevation of any of the deposits described by Moore and Moore (1984, 1988), or Keating and Helsley (2002), since no one has relocated the deposits from +326 m (Stearns 1966, 1978). More recent tsunami modeling studies (McMurtry et al. 2004b) and observational data from Hawaii (McMurtry et al. 2004a) support tsunami runups > 400 m caused by huge submarine landslides. Proposed runups this large have only led to greater debate.

Given the limited extent and poor preservation of the coral conglomerates deposits and the differing interpretations of their sedimentologic features, we use a different approach that focuses on the submerged terrace deposits around Lanai.

Submerged terraces off Lanai: vertical movement during the last 30 ka

Six submerged terraces are imaged in the bathymetry and backscatter data (Campbell 1986; Webster et al. 2006) south and west of Lanai, forming sinuous, steep-sided high backscatter features, that generally follow the bathymetric contours (Fig. 1). A continuous well-developed terrace (called T1 by Webster et al. 2006) occurs between 110 and 160 m and can be traced 80 km from the Kalohi Channel, along the western margin of Lanai, within the Kealaikahiki Channel and off the north and west coasts of Kahoolawe. The bathymetric data show that the break-in-slope defining T1 deepens (slope of 0.8 m/km, $R^2 = 0.82$, $n = 54$ cross sections spaced 0.5–1 km) over this distance systematically SE towards Hawaii (Fig. 3). A second deeper, less extensive terrace (called T2) is observed within the Kealaikahiki Channel between –230 and –250 m and also deepens towards Hawaii.

Dive observations, acoustic backscatter and samples from 3 ROV *Tiburon* dives (T310–312) (Fig. 1) in 2001 (Webster et al. 2006) indicate that the tops of T1 and T2 are composed of relatively thin (< 5 m) in situ deposits of coralline algal nodule, coralgal nodule, and *Halimeda* facies, which they inferred are superimposed on top of pre-existing coral reef terraces. Based on their sedimentary characteristics, crust morphology, species composition, and comparison with modern analogs around Hawaii and elsewhere in the Pacific, Webster et al. (2006) concluded that both the coralline algal nodule and *Halimeda* facies were deposited in deeper fore-reef slope settings (60–120 m), whereas the coralgal nodules formed in shallower but still relatively deep fore-reef slope settings (30–60 m).

The calibrated radiocarbon (i.e. calendar ages), sedimentary and bathymetry data (Webster et al. 2006), confirm that the evolution of these deposits is consistent with eustatic sea level variations of the last 30 ka (Fig. 4). The age data indicate that both nodule facies on T2 and T1 initiated growth 30–29 ka following a fall in sea level of 40–50 m during the transition from MIS3 to MIS2 (Fairbanks 1989; Bard et al. 1990; Yokoyama et al. 2000; Lambeck and Chappell 2001; Cutler et al. 2003). They accreted slowly throughout the last glacial maximum (LGM) when sea level was apparently relatively stable, drowned about 17–14 ka during the early-mid deglaciation, and were followed by deposition of the *Halimeda* facies on top of the coralline algal deposit on T1. Because these data are internally consistent with respect to age vs. depth relationships, paleowater depths and published sea levels curves, Webster et al. (2006) estimated the maximum possible rate of uplift or subsidence of Lanai over the last 30 ka.

Figure 4a, b shows the age versus depth relationship for samples recovered either in situ or from on top of T1 and T2 plotted against available sea level data. The grey rectangles represent a reconstruction of the paleowater depth of each sedimentary facies (after Webster et al. 2006). Using the lower and upper paleowater depth ranges of each sample and published sea level data we estimate the maximum possible rates of uplift or subsidence over the last 30 ka. The uplift and subsidence rates should be no greater than the values above or below the grey rectangles, respectively, otherwise the facies would be too deep or too shallow and inconsistent with the paleowater depth ranges. On this basis we estimate, noting possible uncertainties (e.g. variance in sea level data, minor glacial-hydro isostatic effects, error in paleowater depth reconstructions), maximum rates of 0.1 and 0.4 m/kyr for uplift or subsidence, respectively. We cannot determine the direction of movement but these values represent a well-constrained 'envelope' over the last 30 kyr, and we will argue below, the last several hundred thousand years.

Vertical movement of Lanai over the last 200–250 ka

Our maximum rate of uplift of 0.1 m/kyr is lower than longer term rates proposed by Grigg and Jones (1997) (0.33 m/kyr) and Rubin et al. (2000) (0.15–0.29 m/kyr), and significantly lower than the minimum 1.1–1.4 m/kry

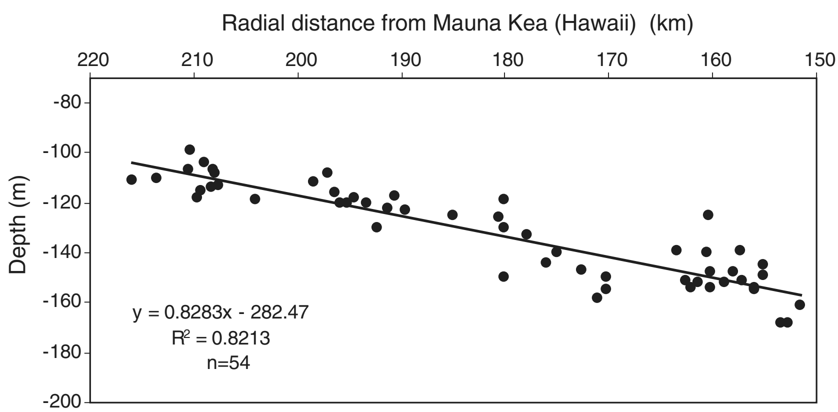

Fig. 3 Plot showing depth of the slope break of T1 (i.e. Fig. 1) relative to the radial distance from Mauna Kea on the Hawaii (bathymetry data from Webster et al. 2006)

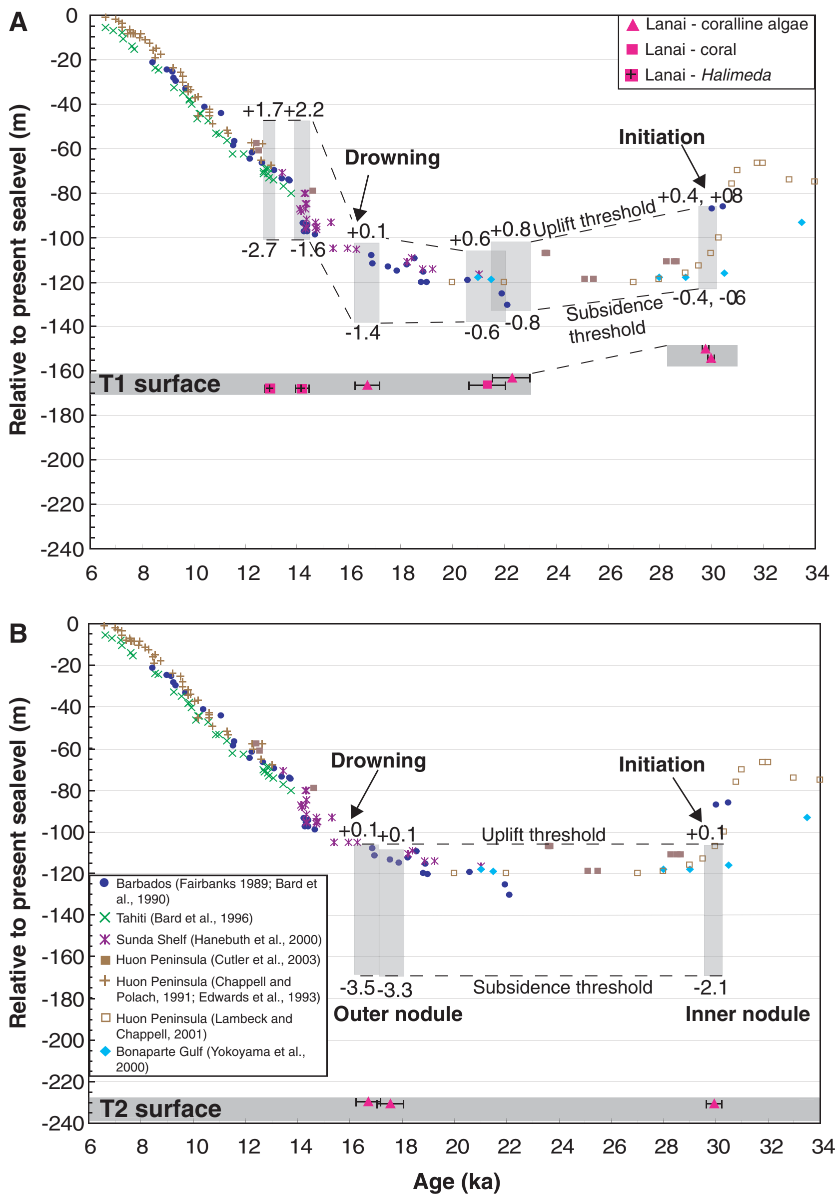

Fig. 4 Calibrated (calendar) radiocarbon age versus depth data for the submerged T1 (**a**) and T2 (**b**) deposits off Lanai (*purple symbols*) plotted against other relative sea level records. Paleowater depth ranges are shown by the *grey rectangles* above each sample. The numbers above and below the *grey rectangles* represent the maximum uplift (positive values) or subsidence (negative values) rates (m/kyr) allowed given the paleowater depth ranges, ages versus depth, and published sea level data. The coralline algal nodules from T2 (Fig. 4b) are multi-generational (see Webster et al. 2006 for details) with calibrated radiocarbon ages from the inner and outer parts nodules reporting significantly older and younger ages, respectively

implied by Moore and Moore (1988) and Keating and Helsley (2002), based on the interpretation of the coral conglomerate deposits on Lanai as MIS5e and MIS7 shoreline features. Furthermore, our maximum subsidence rate of 0.4 m/kyr is significantly lower than Campbell's (1986) estimated 1.9 m/kyr rate based on correlation with the submerged Hawaiian terraces.

We note that the vertical motion 'envelope' for Lanai is estimated from data only for the last 30 ka. However, previous observational data (Grigg and Jones 1997) and geophysical modeling (Watts and ten Brink 1989; Zhong and Watts 2002) arguing long term (0–250 ka) uplift of Lanai also suggest uplift rates that increase as Lanai rides up the flexural arch. Smith and Wessel (2000) showed that uplift of Lanai could also be caused by isostatic rebound following large landslides. However, their model accounts for < 8 m of the predicted uplift of Lanai (Zhong and Watts 2002), and combined with the observation that most landslide material is retained on the insular shelves of the islands argues against significant uplift via this process.

Geophysical, observational, numerical modelling and recent tide gauge measurements support our envelope of uplift or subsidence and their long-term implications. Observational data and modeling of lithospheric flexure associated with volcanic loading of Hawaii (Watts and ten Brink 1989) show that the null line between subsidence and uplift occurs ~275–300 km from the centre of Hawaii, placing it between east Molokai and Oahu. Newer models by

Zhong and Watts (2002) confirm the relative stability of Lanai, predicting either subsidence or slow uplift (< 0.05 m/kyr) depending on the elastic plate thickness and a maximum dynamic uplift rate of 0.15 m/kyr if plume temperatures > 400 K and a plume radius < 70 km is invoked. The presence of unambiguous raised coral reefs on Oahu (Szabo et al. 1994; Grigg and Jones 1997; Muhs 2002) and geophysical modelling (Watts and ten Brink 1989; Zhong and Watts 2002) confirm that uplift (0.02–0.07 m/kyr) of Oahu occurred over the last ~500 ka, due to its location on the fore-bulge or arch. Located ~50 km SE of the null line, Lanai should be experiencing little or no uplift but rather slow subsidence, with respect to the loading of Hawaii (Watts and ten Brink 1989; Wessel 1993) and mantle/plume dynamics (Zhong and Watts 2002). Tide gauge data also indicate that Maui (Kahului) is currently subsiding at 0.3 m/kyr (Moore 1987), similar to the maximum rate (0.4 m/kyr) we estimate for Lanai using the submerged terraces. The four deeper reefs (Fig. 1) clearly grew and drowned after Lanai formed 1.2 Ma (Webster et al. 2006), adding support to the idea that Lanai has a long-term history of subsidence. Finally, the systematic tilting we observe of T1 and T2 towards the SE (Figs. 1, 3), combined with similar tilting of the 750 ± 13 ka submerged reef on Haleakala Ridge, East Maui (Moore et al. 1990), indicate a persistent, long-term trend of subsidence towards Hawaii. These data all support our contention that our upper limit of the uplift rate of 0.1 m/kyr over the last 30 ka also represents the maximum rate over the last ~250 ka.

Mega-Tsunami or uplifted shoreline deposits?

The submerged terrace data constrain maximum rates of 0.1 and 0.4 m/kyr for uplift and subsidence, respectively, over the last 30 ka (Webster et al. 2006). Furthermore, our analysis of available geophysical, observational, numerical modelling, and tide gauge data from the region indicates this uplift rate probably represents the maximum rate over the last ~250 ka. This finding is inconsistent with the interpretation that the subaerial coral conglomerate deposits, particularly those above +35 m, reached their present elevations via uplift. Using published ranges of MIS5e (0 to +6 m) and MIS7 (+7 to +11 m) sea levels (Lambeck and Chappell 2001; Lea et al. 2002), the age of the deposits (Fig. 2) and assuming they were at or close to these paleo-sea levels during deposition, our calculated uplift rate of 0.1 m/kyr can account for only +14–20 m and +31–35 m of the current elevations of the MIS5e and MIS7 deposits, respectively. This uplift rate does not preclude the interpretation that the conglomerates below these elevations are MIS5e and MIS7 shoreline deposits (Grigg and Jones 1997; Rubin et al. 2000), but it is not fast enough to account for the deposits above these elevations, particularly those > +155–190 m within Kaluakapo crater (Moore and Moore 1984, 1988; Keating and Helsley 2002).

This analysis provides independent evidence that indirectly supports the Giant Wave Hypothesis, originally proposed by Moore and Moore (1984, 1988). Furthermore, the vertical motion 'envelope' for Lanai implies a minimum wave run up of > 170 m given the age and elevation of the Kaluakapo crater deposits at +155–190 m. If sea level at the time of this event was not at full interglacial levels, as the age scatter of the corals implies for both MIS5e and MIS7 aged deposits (Fig. 2), then the wave run ups could be 50–100 m higher when combined with our maximum subsidence estimate of 0.4 m/kyr.

The large wave run ups indicated by our Lanai data confirm the importance of determining the origin of subaerial coral conglomerate deposits on other tropical islands. Recent observational and modelling investigations of the flanks of Tahiti-Nui (Hildenbrand et al. 2006), La Palma (Canary Islands) (Ward and Day 2001), Reunion (Labazuy 1996) and Ritter Islands (Papua New Guinea) (Ward and Day 2003; Silver et al. 2005) indicate that massive landslides are common features of tropical, volcanic islands. Given the large run ups possible (> 170–400 m) in the Hawaiian Islands (this study and Moore and Moore 1988; Moore et al. 1994; McMurtry et al. 2004a), it is entirely plausible that subaerial coral conglomerate and boulder deposits observed on other tropical islands such as Papua New Guinea (Morgan et al. 2005) and Mauritius (Camoin et al. 2004) were emplaced by tsunami waves. Better constraints on the maximum height and timing of the emplacement of these deposits, has great potential for testing models of volcano collapse, and of tsunami generation and propagation (i.e. landslide velocities and peak wave heights).

Conclusions

Analysis of recent bathymetric, dive observations, sedimentologic, and radiocarbon data from two submerged terraces around Lanai indicate little vertical movement over the last 30 ka. We estimate Lanai has experienced maximum rates of uplift of 0.1 m/kyr or subsidence of 0.4 m/kyr during this period. Analysis of available geophysical, observational, numerical modelling, and tide gauge data indicate that this uplift rate represents the maximum for Lanai over the last ~250 ka, if uplift is associated with lithospheric flexure. This finding is inconsistent with the interpretation that the subaerial coral conglomerates now above +35 m are uplifted MIS5e and MIS7 shoreline deposits, but rather support the hypothesis that they are tsunami deposits with a minimum wave run-up > 170 m in the case of the MIS5e event. Massive landslides, large wave run-ups, and the resulting mega-tsunami deposits may be common features of tropical, volcanic islands.

Acknowledgments We acknowledge the support of the David and Lucile Packard Foundation through a grant to MBARI. We are grateful to Gilbert Camoin, Yasufumi Iryu, Simon Day and two anonymous reviewers for their very constructive comments which improved the manuscript.

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