Chapter 10

Traces of Coral Bearing Deposits on Lanai, Hawaii, and Implications for Their Origin (Island Uplift vs. Giant Tsunami)

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Additional information is available at the end of the chapter

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1. Introduction

Harold Stearns carried out geologic studies on the island of Lanai during 1936. The strand line deposits he described were interpreted as a series of high stands of sea level (Stearns 1938). But, he realized that this was not consistent with Sea Level Variation (SLV) records elsewhere in the world. Stearns (1985) interpreted the strandlines as being due to a combination of **SL**V and **I**sland u**P**lift (here referred to as SLIP). Moore and Moore (1984, 1988) proposed that these same deposits were debris thrown up on the island by giant waves generated by slope failure on the SW flank of the island of Hawaii (hereafter referred to as the Giant Wave Hypothesis, GWH). 1.1 Validity of Giant Wave Hypothesis vs. SLIP

Keating and Helsley (2002) revisited the three ancient Lanai shorelines reported by Stearns (1978) in Kaluakapo Crater (SE Lanai) with the objective of testing the validity of the GWH and SLIP (Sea Level oscillations and Island Uplift) scenarios. In this paper we report the results of field studies west of the previously studied Manele Bay and Kaluakapo Crater areas. These studies as well as geologic excursions around Lanai allowed the authors to: 1) observe the outcrops reported in Harold Stearns field notes and publications, 2) study the features assigned a GWH origin, 3) extend Stearns original observations, and 4) compare the coral bearing deposits. Evidence for SLIP is reported and geologic inconsistencies with the GWH are discussed.

1.1. Setting

Corals in boulder beach deposits as well as SLV notches were found preserved on the arid southern flank of Lanai where maximum precipitation (in the mountains) is less than 25 cm/yr. The field areas are located on the leeward side of the island of Lanai, which in itself is situated in the lee of the island of Maui (Fig. 1). Thus the modern environment is desert, with vegetation dominated by mesquite (locally called kiawe, *Prosopis pallida*, introduced in 1828) and other drought tolerant vegetation. Furthermore, due to long-term drought conditions and fires, vegetation was minimal providing excellent opportunities to view outcrops. Similar deposits are not present on the wet, windward sides of the islands, where erosion rapidly removes these deposits.

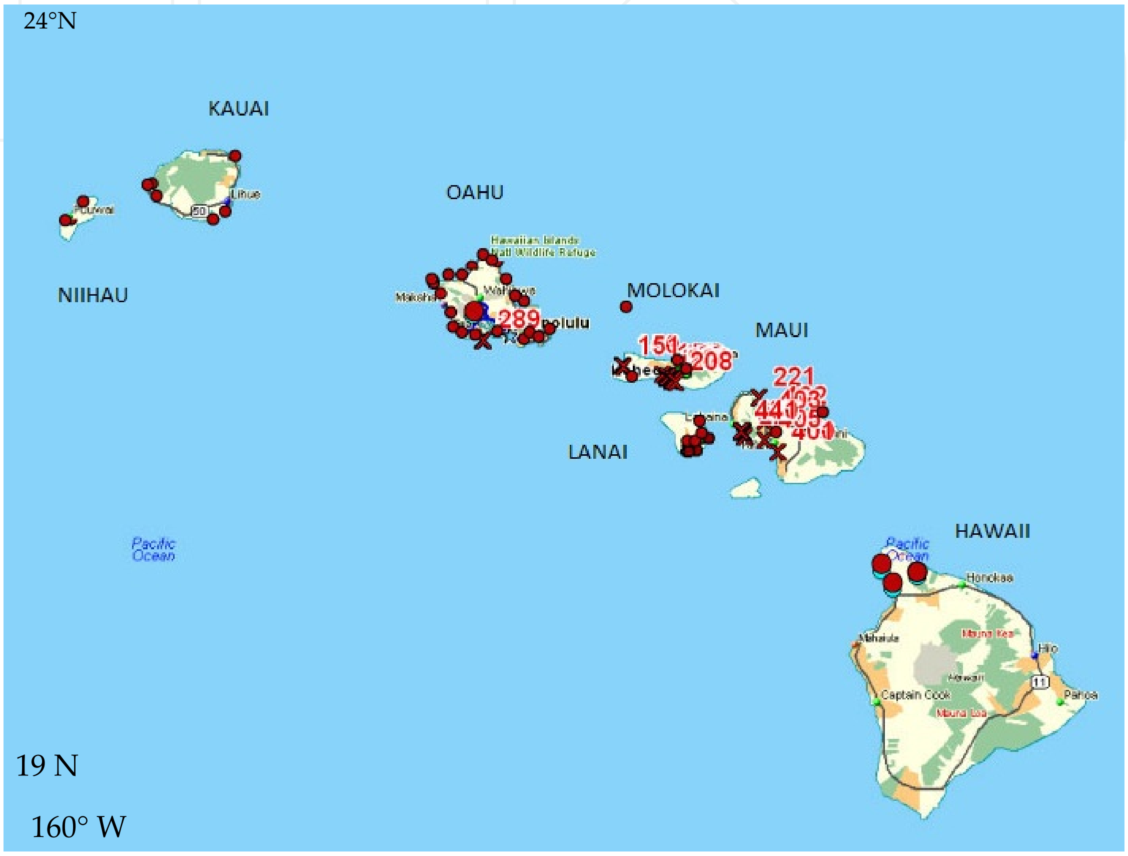


Figure 1. Map of the Hawaiian Islands showing sites of sedimentary carbonate rock outcrops (red dots) and drill core sites with sedimentary units (x-symbols). These units include: dunes, reefs, and marine conglomerates. The marine conglomerates have also been called gravels associated with the GWH.

1.2. Methodology

The geologic field area is situated west of the Manele Bay Resort golf course. Traverses on foot were made, beginning at the top of the slope at an elevation of nearly 800 ft, down the dry gullies, to elevations of 30 masl (meters above sea level). The coral and basalt deposits were found at various elevations within the dry gullies, and recorded as GPS landmarks, and were concentrated on the leeward eastern side of the gullies (side least exposed to waves at the time of formation. The exploratory traverses followed the gullies down slope (Fig. 2), and then were extended across the interfluves between gullies, GPS mapping of the coral and basalt bearing deposits show that the pattern of deposits extends across the island flank, in bath-tub ring fashion (Fig. 3) without any deposits on interfluves and rarely on the slopes between the 'bath-tub rings'.

Figure 2. Map showing the sampling sites (mapped by dots), situated on the southern flank of the island of Lanai associated with this study, and Poopoo and Anapuka gullies in particular. The cluster of sites on the extreme right (East) are situated at Kaluakapo Crater and extreme left (West) at Kaunolu Point. The elevations of fossil sampling sites were corrected with barometric measurements. Up to 25 fossils were collected at each site. At most sites, the marine fossils were abundant enough that the number collected needed to be restricted, due to the difficulty in transportation to the nearest access point.

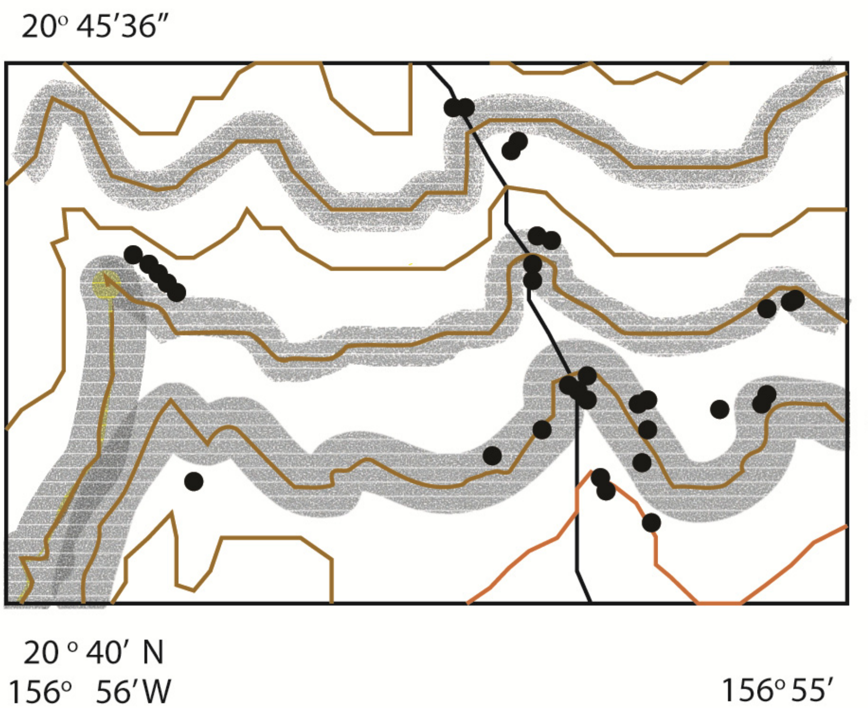


Figure 3. Detail of the center portion of Fig. 2, showing the location of sample sites, marked with black dots. Contour lines have been highlighted in gray to show the parallel “bathtub-ring” distribution of the deposits. Note that fossils were not found on the interfluves (surface between gullies) or on the slopes between the 'bath-tub rings'.

1.3. Prior related studies

During the 1980’s Harold Stearns (then retired) contacted several scientists, encouraging them to evaluate the GWH. Several publications have resulted from those discussions, including: Jones (1993, 1995) Grigg and Jones (1997), and later Felton, *et al.* (2000), Keating and Helsley (2002), Felton, *et al.* (2006), and Crook and Felton (2008). Felton *et al.* (2006) published a detailed facies analysis, describing a series of 14 beds separated by eight discontinuities. Three of these discontinuities were characterized by truncated paleosols; indicative the deposits accumulated over long periods of time, and thus were from several geological events separated in time. Keating and Helsley (2002) showed that the ancient shorelines described by Stearns at 190 and 170 m in Kaluakapo crater showed undisturbed marine deposits at 190 m, abundant marine carbonate deposits at 170 m elevation, and a total absence of fossil bearing deposits between 200 and 365 m.

Age dating studies by Grigg and Jones (Grigg 1997) and Rubin *et al.* (2000) provided evidence for more than one geologic event on Lanai. Sedimentary studies of SLV which bear on this study were carried out on Oahu (Fletcher and Sherman, 1995; Fletcher and Jones, 1996; Hearty, 2002; Hearty, 2011; and McMurtry *et al.*, 2011).

Numerical modeling of the GWH tsunami were carried out by Johnson and Mader, (1994), Jones and Mader (1995), and these models suggest a wave height of less than 100 m. Keating *et al.* (2011) published a compilation of a Tsunami Deposit Database that summarized the range of tsunami run-up values reported elsewhere in the literature. The maximum run up level reported was 70 m, and the compilation indicated that a 70 m run up is a rare and extreme event.

1.4. Field observations on Lanai

During this study, traverses were concentrated in the SW portion of Lanai across a series of dry gullies west of the Manele Bay Resort Golf Course. The Poopoo and Anapuka areas display an outcrop pattern of fossil-bearing deposits preserved in dry gullies, and in small notches eroded into basaltic rock and filled with lithified coral and basaltic detritus with rare boulders of beach rock, that display lateral continuity. These parallel notches, benches, and deposits display lateral continuity that is apparent in the map view of sampling sites shown in Fig. 3. Examples of the outcrops are shown in Figs. 4 through 6.

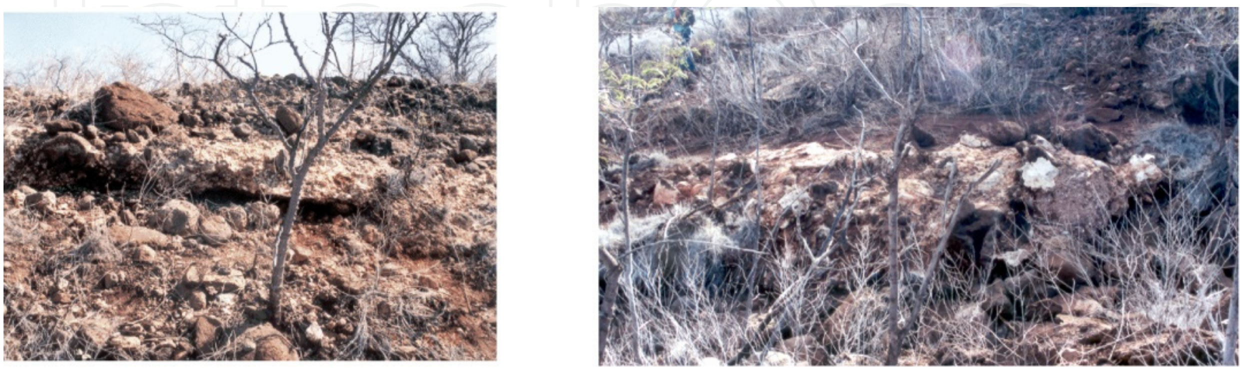


Figure 4. (Right) Photograph of a notch within lava rock containing shallow marine sediments and corals. This site is designated as GPS Landmark 241 at 140m above sea level in Poopoo Gullies. (Left) Photographs of a notch in the hillside filled with coral-bearing deposits. This site is designated GPS Landmark 172 at an elevation of 165m on the Poopoo Gullies.

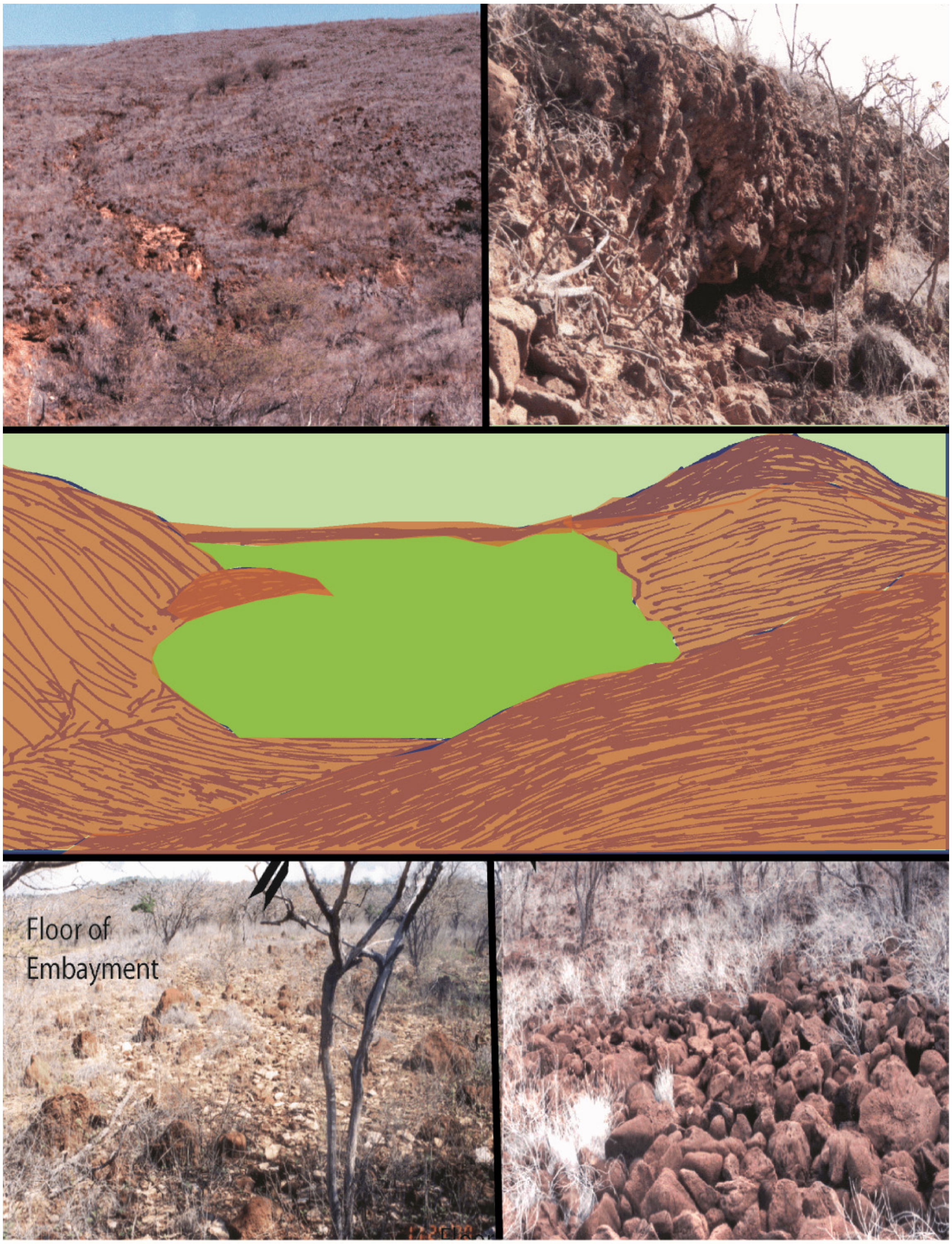


Figure 5. (Top left) Image of the dry gully that corresponds with the hill side drawn in the lower left corner in the landscape sketch. Fig. 5b. Center, cartoon drawing showing the distribution of geologic features. Fig. 5c. The floor of the embayment is shown in the photograph at the lower left. Fig. 5d. The image at the lower right shows an ancient boulder beach, situated on the left side of the embayment at the center of the drawing (Fig. 5c, center). Had there been a giant tsunami at this site, the boulder beach would have been disrupted. Its presence is a very strong indication that the Poopoo and Anapuka area was not affected by giant waves. Fig. 5d. Upper right, image of a small wave cut cliff at the toe of the slope on the right side of the embayment.

In the main Anapuka drainage, there are a series of parallel notches with coral fillings, between elevations of 35 and 240 m (Fig.4a & b). These deposits are similar in rock types and lithologies found at the present time along modern Hawaiian rocky shorelines including beach rock (cemented coral sand), rounded boulders, and coral and basalt conglomerates with coral fragments.

In the Anapuka area a semi-flat area was found, showing evidence of small wave-cut cliffs, Fig. 5b, boulder-clad shorelines (Fig. 5c), and outcrops of corals with one coral having grown upon another (Fig. 5d). Large pieces of lithified beach rock (up to 1 m across) are present in places along the margin of the platform. This area formed in a small sheltered embayment (see configuration Fig. 5c) that obviously favored the growth of abundant shallow marine organisms.

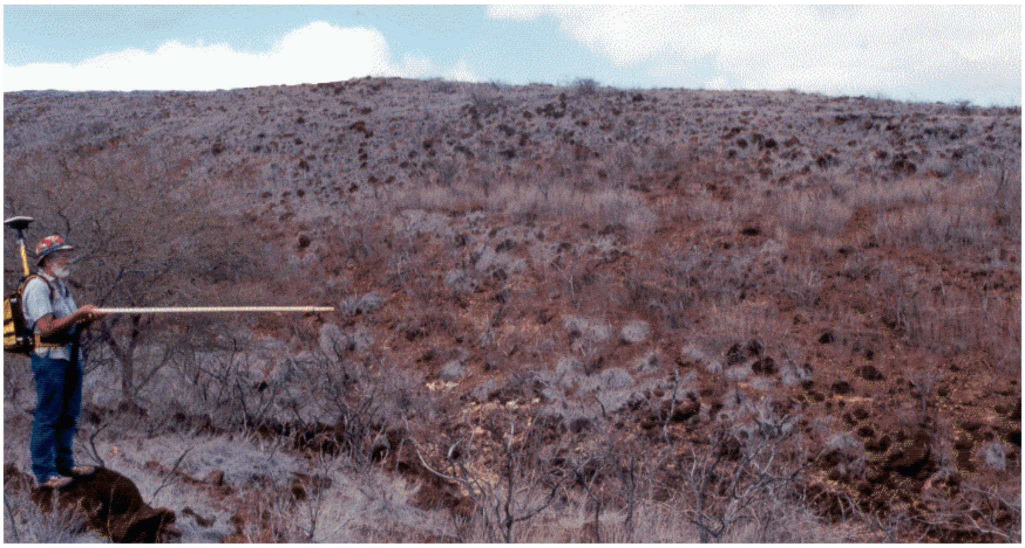


Figure 6. Photograph showing the position of fossil-bearing deposits on the margin of a dry gully. The fossil-bearing outcrop extends from the horizon marked by the horizontal bar and the feet of the observer, standing at the left edge of the picture. Notice the step in topography in the background.

Caliches (gravel, rocks, soil and alluvium cemented with soluble salts) are common throughout the arid south and leeward side of Lanai. They occur as: 1) fracture fillings within and between lava flows, 2) irregular masses and sheets between lava flows, 3) cementation within the marine conglomerates, and 4) casts of plant roots. The caliches are very common in lava flows roughly 10 m above the 190-m level platform at Poopoo and Ananpuka and elsewhere on the southern coast of Lanai. Caliches also occur at natural seeps, and at watering stations where there is, or has been, long-term water seepage. Ancient sea stacks were observed at several locations on the slopes of Lanai, e.g. near Kaluakapo Crater (illustrated in Keating and Helsley, 2002) and near the Naha Road/trail (east of Kaluakapo Crater). On the old Naha trail, a broad terrace at roughly 180 m on the southeastern flank of Lanai contains laminated ash deposits. Elsewhere on the central and west flank of Lanai outcrops of lava contain vein-filling caliche are common (non-fossiliferous carbonates) at roughly the 180 m elevation. In the Poopoo and Anapuka area, there is a transition at roughly 180 m, from deeply weathered red basaltic boulders (above) to smaller, more-rounded black volcanic boulders (lacking weathered rims) lower on the slopes.

1.5. Fossils

Symbols mark the location of sampling sites containing coral in Fig. 2. In general, the coral-bearing rocks are well cemented conglomerates and were collected using a sledgehammer and chisel. Samples collected from individual sites contained fossil specimens (mostly coral and mollusk). In some small sites, essentially all the mega-fossils exposed on the outcrop were collected. On the Anapuka plain, corals were far too numerous to be collected in bulk and transported in large numbers. Instead, a comprehensive collection was made of representative samples for laboratory study. Drs. Allison Kay, Julie Brock and Richard Grigg made fossil identifications. Dr. Richard Grigg made the selection of fossils that display the least alteration for radiometric age dating. The coral *Porites lobata* was the most abundant species found, followed by *Porites compressa*. The bioturbation was identified as moderate and typical of shallow Hawaiian coastal waters (A. Kay, P. Comm.). Some outcrops contain numerous shells and corals, that are whole, unbroken and abrasion-free, cemented in a matrix of sand; others are dominated by broken clasts. Clasts of volcanic material are found in most outcrops. At one locality there is a clear vertical progression from course fossil bearing rubble at the base to fine-grained fossiliferous gravel upward in the unit. At the 190 m elevation in the Anapuka drainage, an aeolian sand unit, similar to other back beach sand deposits in Hawaii, overlies the coral and basalt bearing units, and further up slope, there are weathered red basalts with abundant caliche filled fractures.

The major occurrences of fossils in the Poopoo and Anapuka dry gullies are at elevations of 180, 168-171, 156, 150 m (600, 560-570, 520, and 500 ft) above sea level. Stearns (1978) suggested wave-cut gently sloping platforms lie at altitudes of 45 and 168 m (150 and 560 ft) and between 97.5 and 112.5 m (325 and 375 ft). These platforms appear to be associated with in-situ deposits we identified at 45 m, 168-171 m, and the bench deposits at 120-135 m.

1.6. Ages

Abundant fossils are present in the strandline deposits we have studied and they display a general increase in weathering, and surface darkening with elevation. The coral *Favia* is no longer present in Hawaiian waters, but it was found in 7 sites between 147.3 and 181.5 m elevation (identified by Grigg). The abundance of the fossils no longer living in Hawaiian waters increases with elevation. This interval roughly corresponds with radiometric dating sample LanS (Rubin *et al.*, 2000), collected from an elevation of 155m, which yielded an age of 134 kya This observation is consistent with an overall pattern of increasing fossil age with elevation. Moore and Moore report U-series ages from the island of Hawaii, dated at 110 ka +/- 10). Moore and Moore (1988) reported 3 U-series ages from Lanai that yielded ages of 108 ka +/-5, 101 ka +/- 4 from Kawaiu Gulch and 134 ka +/-7 from Kaluakapo Crater. (These are equivalent to the Waimanalu sea level stand on Oahu).

Additional radiometric ages for Lanai were published by Rubin *et al.* (2000; U-series) and Grigg and Jones (1997; ESR, Electron Spin Resonance). ESR, U-series, TL (thermoluminence) and OSL (optical dating), age determinations have produced comparable results to those of Yoshida and Brumby (1999), Carew and Mylroie (1995), Tanaka *et al.* (1997) where ages are generally correlated to specific faunal assemblages. The original studies of the type Manele Bay deposits were concentrated on the lower 50 m (Felton *et al.*, 2000, 2006) of the Manele Bay outcrops. Most of the studies are from corals in the Manele Bay Resort complex at elevations less than 50 m. The studies of Poopoo and Anapuka gullies concentrate on the exposed deposits at higher elevations from 45 m to 200 m.

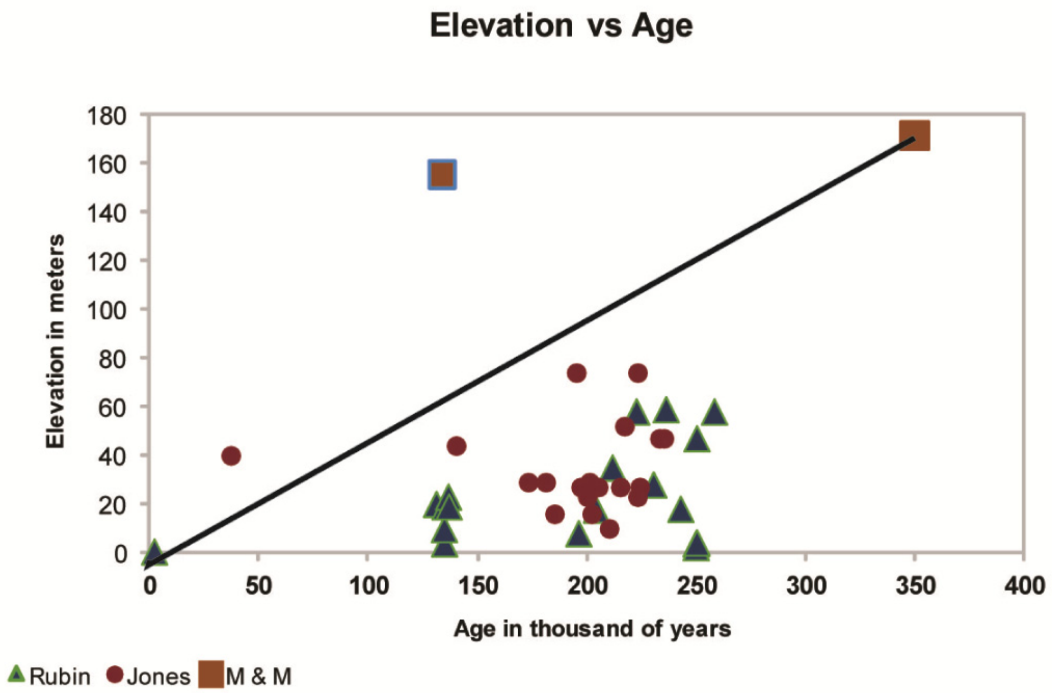
Plots of sample age and sample site occurrences versus elevation are shown in Fig. 7. The outcrops between 50-200 m elevations represent rocks equivalent to older Marine Isotope Stages (MIS stages 7 and 9 and perhaps 11). Numerous fossils with minimum alteration were collected for dating (by Ken Rubin). And, according to Rubin, the new collection should provide much more suitable candidates for dating, than those previously utilized.

Young ages of 2-3 thousand years ago (kya) occur near sea level (0.5 m). Ages of roughly 130 kya are observed up to roughly 50 m with one at 155 m (Szabo, 1984 reported in Moore and Moore, 1988). A cluster of ages between 200-250 kya occurs at elevations up to 80 m. One age of 350 kya has been reported at 190 m within Kaluakapo Crater.

Using the Marine Isotope Record as a proxy for a relative sea level curve for Lanai (Fig. 8) and using the oldest ages reported by Rubin *et al.* (2000), Moore and Moore (1984), and Grigg and Jones (1997) for controls; ages around 120 kya (MIS 5.5) occur up to 23 m elevation; 211-230 kya (MIS 7.1, 7.3) occur between 28-35 m; one age of 250 kya is reported at 58 m (MIS 7.5); a single age of 350 kya is reported from 171 m (MIS 9.3). A theorized uplift scenario for Lanai is illustrated using the proxy marine oxygen isotope records from Shackleton (2000) and others (Fig. 9). A comparison of radiometric ages versus elevation, and the uplift SLV curve are shown in Fig 9. These comparisons are similar to those Toscano and Lundberg (1999) and Tanaka et al, (1999) for Florida, Barbados and Haiti. A list of observed notches filled with corals, depositional benches, and platforms with ages are given in Table 1.

In conclusion, the complicated internal stratigraphy documented by Felton *et al.* (2000) and Felton et al. (2006) is much easier to explain if the interbedded soils are interpreted as erosional surfaces within marine carbonates and clastic deposits accumulated during low sea level stands during glacial periods.

Samples collected in submersible dives by Grigg (2002), yielded an age of 8 ka for submerged coral at -61m (-200 ft). Fig. 7a shows a pattern of increasing age of fossiliferous deposits with increasing elevation. Grigg and Jones (1997) report that a trend of increasing age of coral beach deposits with elevation (on Oahu and Molokai) have been interpreted as support for island uplift.



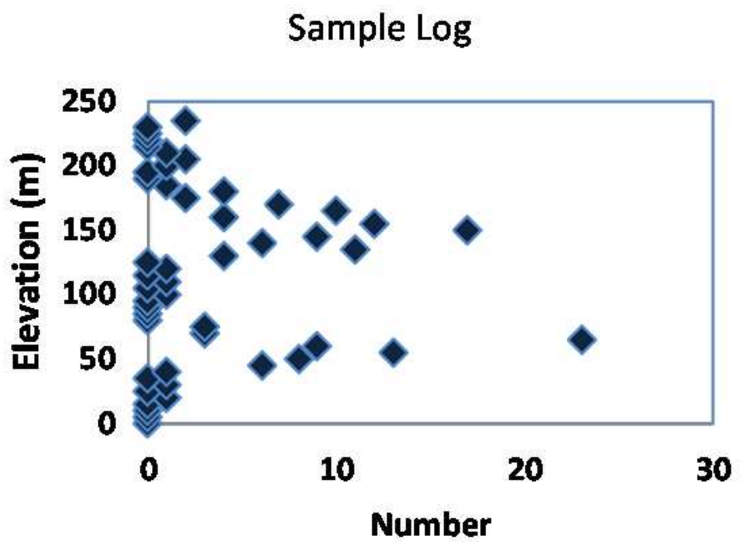


Figure 7. Fig. 7a (top) Plot of age versus elevation for coral samples from the southern slope of Lanai. The symbols represent the published radiometric ages: U-Series ages from Rubin et al (2000), ESR ages from Grigg & Jones (1997), and two other ages reported by Moore and Moore (1988). The line showing the uplift rate from today to the oldest ages date is a solid line.
Fig. 7b. A plot of sample occurrences versus elevations is shown above. The plot shows that a great number of the samples collected for this study came from elevations higher than those previously published. The number refers to the number of sampling bags that were collected: each bag contained from one to 25 rocks. Zero values indicate that no samples were found between the elevations occurring in a 'bath-tub' ring distribution.

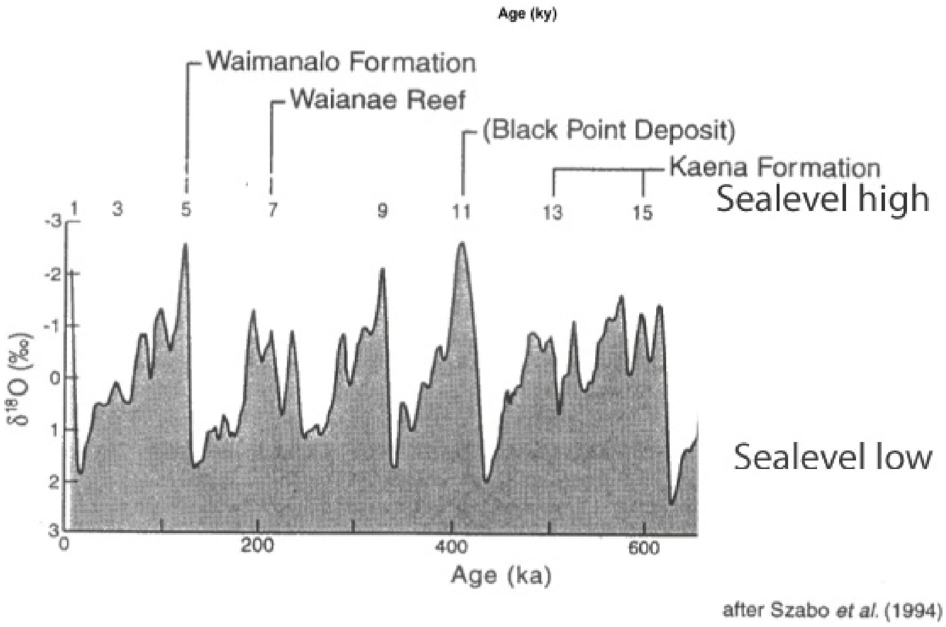


Figure 8. Sea Level Variations for Hawaii after the record by Szabo *et al.* (1994). The labels at the top list the equivalent rock units on the island of Oahu.

Elevation	Age (thousand yrs)	Isotopic Stage
225 m		(*Likely road construction material)
186-192 m		MIS11
180 m		
168-171 m	350 ka	MIS9.3
156 m		MIS 9.1
150 m		MIS 9.1
120-135		MIS 8.5
97.5-112.5m		MIS 8.3
78 m		MIS 8.3
45 m		MIS
35 m		Low stand 7/8
30 m	211-230 Ka	MIS 7.1, 7.3
23 m	120 ka	MIS 5.5
14 m		MIS 6.5
5 m		MIS 3

Table 1. Elevation (m), Age (ka), Correlated MIS

2. Mechanism for island uplift

The sinking of the active islands due to the unbalanced load applied to the crust by growing volcanoes has been well documented and sinking rates of one to three mm/y have been documented by many authors studying coral reef deposits and erosional surfaces near the big island of Hawaii. The consequences of this loading have been examined by Watts and ten Brink (1989), Wessel and Keating (1994) Smith and Wessel (2000), and others.

The volcanic edifice adds a load to the crust that causes the formation of a moat around the volcanic load and at greater distances the seafloor is uplifted in a broad low arch. This phenomenon can be seen in the bathymetry around the 'Big Island' as well as all along the Hawaiian Island chain where a portion of the sea floor has been raised a few hundred meters as two parallel ridges on either side of the chain. What is not generally considered is the uplift also affects the pre-existing islands immediately downstream of the hot spot. Here, a balance is struck between the continued slow sinking of the volcanic edifice due to the massive load on the crust with the flow of sub crustal material away from the latest volcanic load that forms the arch around that load. In the case of Lanai, it is at the appropriate distance for the inflow of the displaced sub crustal asthenosphere to form uplift in excess of the residual sinking of the island edifice due to its residual crustal loading. The SLIP hypothesis suggests that this balance of forces became positive, i.e. in favor of uplift, about 450 kya at the time that the volcanic edifice beneath the Kohala volcano ceased to be active. The peak uplift rate is probably past, since the center of volcanic edifice building has shifted to the SE in the past few hundred thousand years and Lanai is now at a distance equivalent to the outer edges of the arch to either side of the Big Island. It is our contention that the elevated strand lines we have observed are the result of coastal erosion and concurrent offshore and strand line deposition at times in the past when the island uplift rate and the rate of eustatic sea level rise due to changes in ice volume were approximately equal (Fig. 9). Comparably, low stand deposits did form at times when the uplift rate and the beginnings of sea level rise are again comparable. But in the low stand case, corals can continue to grow and sediments can continue to be accumulated beneath the sea through the sea level rise period and even into the sea level fall portion of the cycle. The deposits in the Manele Bay area (those between current sea level and 70 masl are part of the deposits that formed during previous low stands for they contain interbedded marine and non-marine clastic layers including soils and irregular erosion surfaces characteristic of karst surfaces as well as offshore reef material.

For simplicity, we have assumed an island uplift that begins about 450 kya and that remained constant until today. A more realistic model would be to assume the uplift rate rose from zero uplift to a maximum one as the island passed over the arch and then to a lower uplift rate after the peak had passed. But we have too few age constraints for the older and more elevated strand lines at present so a simple constant uplift rate has been used. The model, regardless of exact uplift history, is constrained by the strand line deposits we have observed at high elevation (190 m) on the slopes of Lanai (Fig. 9). Modelling results imply uplift rates for the past 350 kya plus years must average about 0.5 mm per year. We have added this cumulative time dependent uplift to the proxy sea level data (Waelbroeck 2002) to provide a model uplift to estimate where sea level might have been relative to the observed strandline and other carbonate deposits on Lanai. The high elevation strand lines are probably associated with the 400 kya maximum based on a single age of 350 kya for a sample collected at 170 meters. We also need to point out once again that the carbonate deposits near the present coast line with ages between 100 and 220 kya are most likely low stand accumulation deposits.

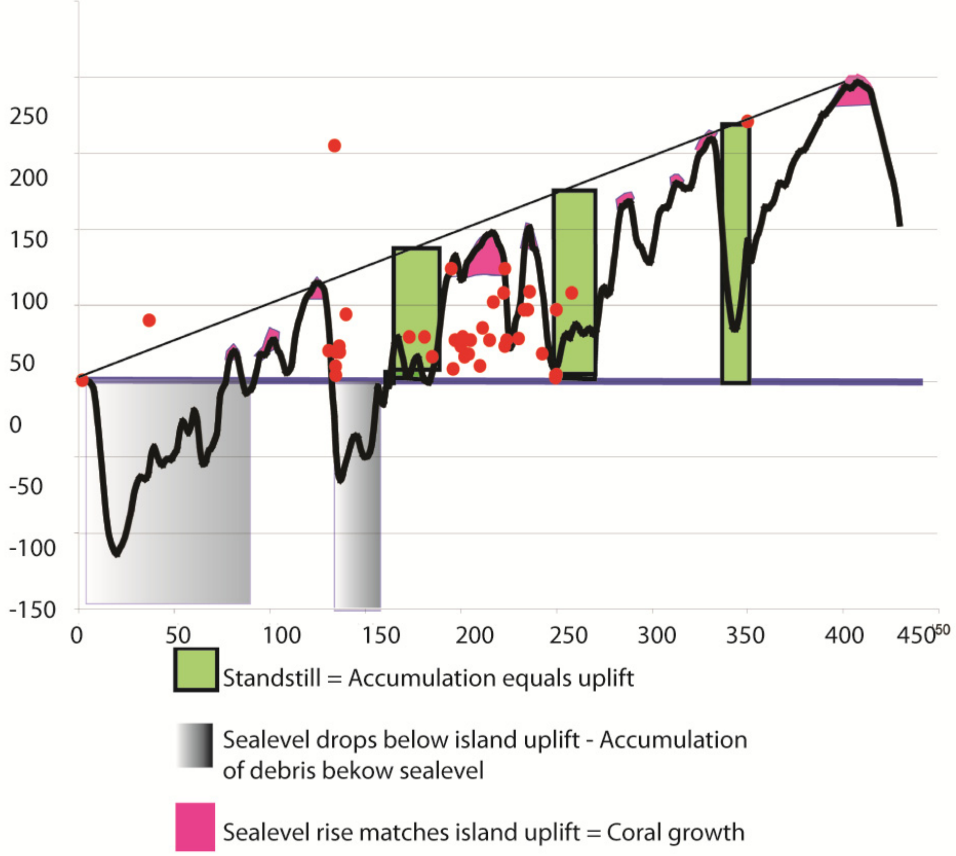


Figure 9. Plot of the MIS Proxy of sea level (Waelbroeck *et al.*, 2002) vs. elevation (on vertical axis) with the origin of the plot at modern sea level (0 on horizontal axis). The published ages are shown in red dots. The ages from Manele are from publications by Grigg and Jones (1997) and Rubin *et al.* (2000). The plot is constrained from modern sea level 0 to the maximum age of 350 kya at 200 m elevation. The slope of the line above the curve is interpreted as the rate of island uplift. The green shaded vertical bars mark periods of standstill when the accumulation of sediments matches the rate of uplift, at these times corals accumulate. The two gray shaded areas represent times when low stands of sea level allow accumulations of debris eroded from the island to accumulate below sea level. The violet colour represents times of maximum sea level when rate of coral growth equals the rate of uplift. High resolution sea floor mapping in the shallow water between the islands of Lanai and Molokai reveals submerged lagoons and terraces on the submerged flanks Lanai and Molokai and shows many submerged lagoons and terraces are present on the submerged flanks of Lanai (see the University of Hawaii SOEST Website www.soest.hawaii.edu/HMRG/Multibeam/3d.php) and Grigg *et al.*, 2002).

Many others have recognized the need for sea level variation (SLV) to be combined with island uplift to explain the uplifted reef deposits in the Hawaiian Islands -Stearns (1978) Stearns (1970) 0.3 mm/y, Bruckner and Radtke (1989); Jones (1993b); Muhs and Szabo (1994) 0.036-0.050 m/kya; Szabo *et al.* (1994); Grigg and Jones (1997) 0.33 +/- 0.03 mm/y; Grossman *et al.* (1998) 0.05 mm/y; Hearty et al. (2002) 0.03mm/y; (Hearty et al. 2011). There is a wealth of evidence that indicates the fossiliferous deposits above sea level in the Hawaiian Islands likely formed by a combination of normal geologic processes, rather than extreme events.

Elevation (1978)	**Locations (1978)** Other Islands	**Locations (1978)** Lanai
360 m (1200 ft)	Maybe Oahu, W. Maui, Molokai	Mahana Shoreline, Lanai
190 m (625 ft)		Kaluakapo Shoreline, Lanai
168 m (560 ft)	Oahu, Molokai	Manele Shoreline, Lanai
75m (250 ft)	Olowalu, Maui and Oahu	
29 m (95 ft)	Kaena, Oahu	
21 m (70 ft)	Laie, Oahu	
16.5 m (55 ft)	Kahuku, Oahu	
12 m (40 ft)	Waialae Shoreline, Oahu, Kohala, HI	
7.6 m (22 and 27 ft)	Waimanolo, Oahu PCA Lualualei Valley, Oahu	
3.6 m (12 ft.)	Kailua Shoreline, Oahu	
0.6 (2 ft.)	Leahi, Oahu	

Table 2. List of terraces recognized by Harold Stearns (1978).

3. Is the mega-tsunami concept valid?

Succinctly stated, the giant wave hypothesis (GWH) suggests a submarine landslide southeast of Lanai triggered three “giant waves” that rushed toward Lanai with initial velocities of 149 m/s, at intervals of only one and a half minutes. The first wave reached 190 m elevation on Lanai and eroded the soils and churned up boulders. The second wave reached the 375 m elevation, and picked up the gravels in suspension and stripped the terrain. The third wave reached 190 m high on the island slope taking boulders in suspension, then accelerated down slope, stripping soil and molding the boulders into mound-shaped bed forms. The GWH presents an exciting but problematic scenario of events.

As part of an effort to date drowned reefs around Hawaii (Moore 1987; Moore and Campbell, 1987; Ludwig, Szabo, Moore and Simmons, 1991; Campbell, 1986; Moore and

Moore, 1984; Moore, 1987) used both tide gauge records and radiometrically dated drowned reef corals to argue that the Hawaiian islands have sunk too quickly for there to be marine deposits remaining above sea level. This belief that all marine platforms in Hawaii are quickly drowned, led them to suggest the coral-bearing gravels on Lanai had been thrown above sea level by tsunami waves. But these surmises fly in the face of nearly a hundred years of published data that has documented in-situ marine carbonate deposits high above modern sea level. More recent studies report evidence inconsistent with the GWH (Jones, 1993b; Grigg and Jones, 1997; Rubin, *et al.* 2000; Felton, Crook and Keating, 2000; Keating and Helsley, 2002 and Felton *et al.* 2006, and this paper).

Basic Tenets of the Giant Wave Hypothesis:

1. Tide gauge records and dated drowned reefs indicate island subsidence.
2. Shell fragments have been reported at 326 m and 183 m above sea level.
3. Soils were stripped from the island slopes.
4. Deposits consist of "locally continuous gravel beds."
5. Gravel beds consist of 95% basalt, 5% coral and beach rocks.
6. Boulders form a continuous formation that thins landward to vestiges at 326 m.
7. Corals are not in growth position.
8. A cemented layer at the base thought to be "encrusted".
9. The gravels are clast-supported deposits with thickness and size of clasts decreasing inland.
10. The gravels originally blanketed the region as a single wedge-shaped deposit.
11. The deposits correspond to ages around 110 kya.
12. The deposits were ripped up from a coral reef.
13. The lower layers of gravel contain coral clasts that represent upsurge. The upper layers contain angular clasts representing tsunami wave retreat.
14. Deposits are the result of giant waves triggered by a giant landslide.

Table 3.

Our field observations and other evidence from the literature suggest that these tenets are not supported by field evidence. The reasoning behind this statement is provided in the point by point discussion that follows.

4. Problems with the GWH

4.1. Subsidence

A basic tenet of the GWH is the contention that the island of Lanai was sinking too quickly for marine deposits to be preserved near sea level. Yet, elevated strand line related, sedimentary deposits are found on each of the main Hawaiian Islands, and described in the classic geologic texts describing the Hawaiian Islands (Macdonald and Abbot, 1970; MacDonald, Abbot and Peterson, 1983; Stearns, 1966, Stearns, 1985) as well as our own publications. The presence of numerous marine deposits throughout the Hawaiian island chain refutes this basic tenet.

4.2. Marine fossils at 326 m

The GWH attributes observations of coral and shell fragments at high elevations on Lanai to Harold Stearns but ignores Stearns's evidence for ancient shorelines preserved in the GWH inundation zone. Instead the GWH theorizes that tsunami wave run up was responsible for fossils at 326 masl. Jim Moore (P. Comm., 1997) reports that he was unable to locate the Stearns' fossil outcrop. Subsequently numerous scientists (including: Grigg, Jones, Walter, Gavenda, Felton and Crook) concentrated a great effort looking for the reported 326 m limestone outcrop without success. Keating and Helsley (2002) used Stearns's field maps and notebooks to identify the Stearns' outcrops. But, these geologists failed to find marine limestones at the 326 m elevation. Instead, the authors observed sub-aerially deposited caliche vein-fillings (Fig. 10b). Caliches are cements that fill cracks in existing rocks associated with the wetting and drying of rocks within an arid environments (Fig. 10a &b). The caliche results from meteoric waters leaching minerals from the rocks and the precipitation of these minerals at rock surfaces as the waters evaporate. This deposition is subaerial not submarine (Thomas, 1994). With rainfall on Lanai less than 25 cm/yr (Ziegler, 1986) caliche cements form extensively along the southern arid coasts. Samples were collected of vein-fillings between 326 and 200 m at Kaluakapo Crater and the samples were examined for fossils by micropaleontologist J. Resig who found no evidence of biological structures in any of the samples. Thus, despite extended research (involving on the order of ten man-days) no evidence exists to verify the presence of any tsunami-related marine deposits at 326 m on Lanai.

There are root casts in these caliche deposits at Stearns Swale that may have been thought to be fossils, but it is more likely that a bag of Stearns' samples became mislabeled and thus a misidentification of material has occurred. On the same day Stearns visited a locality at approximately 150 m elevation to the east of the 326 m site that is known to be quite fossiliferous. His notes indicate that he made extensive fossil collections that included corals, pelecypods, and gastropods. In our view, it is likely that some of these samples became mixed or mislabeled with the caliche samples collected at 326 m. A subsequent study that bears on this topic will be raised in the discussion (Crook and Felton, 2008).

4.3. Soil stripping and scouring

A basic tenet of the GW Hypothesis is that soils were stripped from the island, "at an altitude of 365 m, is an irregular boundary below which the thick red soil typical of the uplands has been removed, presumably by wave erosion associated with deposition of the Hulopoe Gravel."

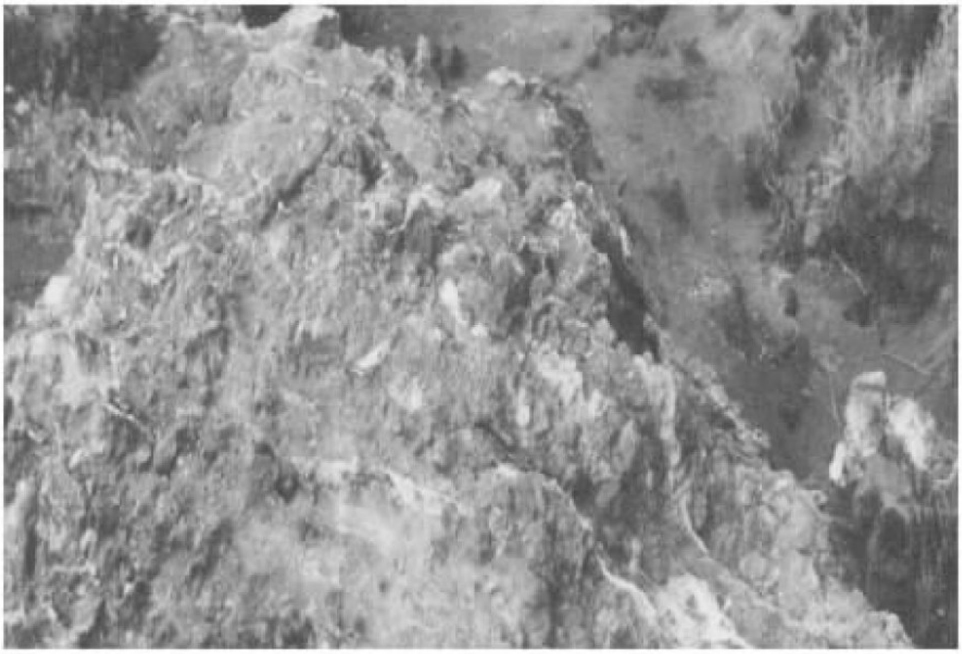


Figure 10. (Top) Caliches are common throughout southern Lanai. Caliche deposits from the Stearn's Swale site at 326 masl, were proposed as the upper limit of tsunami deposits in the GWH. Fig. 10b. The photograph at bottom was taken on the margin of a dry gully near the shore in the Poopoo-Anapuka area.

Soil scientists (Foote, Hill, Nakamura, and Stephens, 1972) in fact described the southern slopes of Lanai as very stony ground. During repeated visits to Lanai, both red and black soils were found within the hypothesized giant tsunami inundation zone (Keating, 1997). With the assistance of Robert Gavenda (U. S. Department of Agriculture) test pits were dug on interfluves along the south coast of Lanai. Soils of up to 1.2 m thickness were observed (Fig. 11a-e). A road cut on the interfluv (the area between dry gullies) adjacent to the type section shows 50 cm of soil. Natural outcrops reveal roughly 50 cm of black soil exposed at the Kaunolu Archeological site on southwest Lanai. In tens of archaeological test pits dug throughout the Manele/Hulopoe Bay area, 70 cm of soil were found lying directly on basaltic bedrock (Kaschko, 1991). These same black, montmorillonite-rich soils were also found in excavations for foundations at the Manele Bay Resort (Cacalda, 2000). Other significant deposits of the highly expansive soils are present throughout the proposed tsunami inundation area. Soil scientists report that black soils are commonly found in coastal zone deposits around the Hawaiian Islands a result of coastal emergence from the sea. These soils expand when wet and then shrink when dried, leading to serious toppled walls and damaged concrete foundations. The expansion and shrinking of the soils works rocks upward from the underlying substrate until the rocks are exposed at the surface. Subsurface coring shows no loose rocks remain in the soils but instead, the loose rocks occur at the surface as an one-clast thick layer, thus classified as very stony ground. The unusual rock studded surface was misinterpreted as tsunami deposits.

There is an abundance of fine-grained material within the study area. Fig. 12 shows an example of the suspension of fine grain soil washed off the island after a winter storm. Also, ash deposits have been found in the proposed inundation zone along the Naha road (Fig. 13a). It is surprising that the ash would not be eroded away by “Giant waves.”

Scour

A compilation of the characteristics of tsunami deposits was published as a data base (TDDB) by Keating *et al*. (2008). The compilation shows that during the drain back phase of tsunami waves, tsunami waves do strip coastal sediments (particularly sands) and they scour the pre-existing drainages. This observation is inconsistent with the GWH. On Lanai the Hulopoe and Kapihua gullies were filled rather than scoured.

4.4. Locally continuous gravel beds

The GWH describes locally continuous gravel beds. We observed numerous locally continuous gravel beds that are commonly associated with strandline carbonate deposits. We did not observe a continuous gravel sheet.

4.5. Lithostratigraphy

The original GWH publication (1984) described a lithologic section along the major gulch which drains into the northernmost extent of Kapihua Bay, directly west of Hulopoe Bay, about 200 m from the shore. The series of beds were originally described as follows: a bed 5

Figure 11. Soils are common throughout the GWH type field. Fig. 11A (Top left). Photograph of an example of a fossil soil in Kapihua Gully showing soil overlain by carbonate fragment gravel. These soils at the base of the gravels are approximately 0.3 m thick. Fig. 11b (Top right) Geologists investigate bed forms situated off the west side of the Manele Bay Road and above the Manele Bay Resort. There, lava boulders were stacked together to form small basins that were filled with the black-brown soil. This is the traditional method of growing sweet potatoes by native Hawaiians and is most likely a cultural artefact rather than a 'bedform'. Fig. 11c (Lower and middle left). Digging through the rock-strewn surface of the GWH type area reveals a thick soil layer beneath it. The lower left photograph shows a hole in the expansive soils (roughly 0.3 m deep) extending down to basaltic rocks. The rocks have been worked upward by the shrinking and swelling of the soils under dry and wet weather conditions. The surface of the expansive soils is now covered by the loose boulders derived from the lava flows below, and the soils are free of loose expelled rocks. Fig. 11d (Lower right) A geologist points out the thickness of the soils in the GWH type area, approximately 0.5 m thick.

Figure 12. Rain showers from the day prior, washed abundant soils off shore at Hulopoe gully, adjacent to the Manele Bay Resort Hotel. Clearly, the soils forming the light colour plume in the ocean off the Manele Bay area were not stripped by extreme tsunami waves. They are instead present and are being eroded by normal geological processes.

m thick overlying nonweathered basalt consisting of 2 layers: a lower layer of subrounded to rounded clasts of basalt (about 95%) and limestone (about 5%) representing the upsurge of the wave and an upper layer of sub-angular to angular clasts of basalt ranging from 20 cm to 1.5 m assigned as debris from the drain back of the same wave." Four years later, these original descriptions were revised with the description of the Hulopoe Gravel section calling for three beds (a lower bed of 2m, an intermediate bed of 4 m, and an upper bed of 2 m), with the limestone clasts mainly confined to the lower third of the three beds. The publication states, "in the limestone-free upper part of the bed, which is distinctly bimodal in size distribution, basalt boulders are enclosed in a silty pebbly matrix that in places contains abundant marine debris..."

Felton *et al.* (2000) published detailed lithological descriptions of the section. Thirteen beds were documented at this location showing the limestone-to-basalt clast ratio varying significantly from bed to bed (from roughly 5-40% limestone). The initial lithological description of the Lanai section is poorly representative of the southern Lanai rock unit. These rock units are considered to represent a sequence of marine gravels and non-marine soils by Felton et al. (2006) and that paper contains detailed descriptions of the rocks and environments of deposition. Most likely, these deposits represent subaerial low stand deposits.

4.6. Boulders form a continuous formation that thins landward to vestiges at 326 m elevation

Our observations do not support a continuous and thinning boulder bed. Patches of well-rounded beach boulders are present to an elevation of 190 m (see Fig. 5c). Locally derived quasi-rounded boulders are present throughout the slopes on lanai, irrespective of elevation. Other than the boulder beds associated with strand line carbonates, the boulders rarely occur in concentrations. We conclude that the isolated boulders are ubiquitous and are boulders formed by chemical weathering of the basaltic substrate (see Fig 6).

4.7. No corals in growth position

The GWH publications indicate that the Hulopoe Gravels unit contains no corals in growth position. Indeed, most corals do not occur in growth position, but A. Kay (P. Comm., 1998) has found assemblages of mollusks that display in-situ preservation and indicate a water depth of 80 m. If the Hulopoe gravels were deposited along a highly energetic rock-bound coast like the modern one, even large boulders would be moved by storm waves, so corals growing on these boulders would not be found in growth positions. But biological assemblages, particularly micro-mollusks living within sheltered patches between boulders, are preserved in growth position, and an isolated site reported here showed single corals growing one on the top of another, suggesting that remnants of a short-lived embayment remain.

4.8. Encrusted base

The GWH states that a cemented layer at the base of the Hulopoe gravel is an "encrusted" surface (Fig. 13b). We have observed this layer and identify it as caliche, a subaerial deposit (formed after the gravels were deposited).

Figure 13. (Left) Fine grain ash deposits are present within the inundation area, on the Naha Road, west of Kaluakapu Crater. Fig. 13b. The base of the gravel unit in Kapihua gully is marked by caliche.

4.9. Clast-supported deposits

The GWH publications describe clast-supported gravels in the Hulopoe gully. The argument was made that clast-supported boulders were water-laid, not transported in a submarine debris flow (which would produce matrix-supported debris), the implication being that the powerful tsunami waves had removed the finer grain material leaving only large boulders, free of fine-grained material. But the deposits exposed in gullies only 100 m and 400 m west of the type section do have sand and clay size components clearly present. Modern boulder deposits in coves along the modern shore lack often lack sand filing yet are clearly storm derived deposits. This is not a diagnostic feature.

Sorting and grain size

The GWH contends that the original thickness of the gravels and size of clasts decrease systematically with distance and elevation above sea level. But extended field observations upslope (approximately 60 m upslope of the Hulopoe section and up to 200 m elsewhere), show that boulders up to 1m can be found in many places. There is no size trend with either elevation or distance from shore. All of our observations suggest that the modern shore line assemblage is characteristic of these upland boulder deposits. Observations in the Poopoo and Anapuka drainage gullies also confirm that large boulders are found upslope (particularly around 100 m) that do not conform to the size/elevation distribution described by the GWH. Boulder pavements are associated with each of our 'strandlines' and are present at the modern shore. Also, we have frequently observed boulders of up to 1 m diameter, but no mega-boulders (over 3 m) were found. Had a giant tsunami taken place, it would be expected that mega-boulders would occur somewhere along the southern coast of Lanai.

4.10. Wedge-shaped unit

The GWH indicates that the coral-bearing gravels originally blanketed the region as a continuous wedge-shaped deposit. Instead, horizontal fossil-bearing notches are exposed in gullies in SW Lanai (this publication) that occur in a “bathtub ring” fashion. These notches and coral-rich deposits extend for kilometers along slope with the interfluves between the gullies barren of fossils. The deposits have the appearance of “high stand deposits” described elsewhere in the geologic literature and thus are contradictory to a proposed wedge-shaped gravel unit.

Inside Kaluakapo Crater (east of Manele Bay), Keating and Helsley (2002) found: no in situ fossils between 190-326 m, the absence of weathered rounded boulders (i.e., lacking weathering rinds) between 190-365 m, the preservation of an essentially undisturbed boulder and coral platform deposit at 190 m, the presence of marine deposits confined to limited stratigraphic intervals with a systematic internal stratigraphy at 170 m, the presence of both fine-grained and coarse material in distinct stratigraphic relationship in Kaluakapo Crater, and the presence of fragile fossils in deposits at 170m, and sea stacks preserved All of these geologic observations conflict with the notion of a wedge-shaped tsunami debris unit.

4.11. Ages

Uranium-series dating methods were used for dating rocks ages on Lanai reported by Moore and Moore (1984), Rubin *et al.* (1995), and Bryan, et al. (1997). Reported age clusters around 100 kya and 200 kya. (The rocks from Molokai had older ages, clustering around 200 kya and 350 kya, according to Jones and Grigg, 1997).

In 1988, the GWH theorized that the coral and basalt units were formed by a tsunami generated by the submarine collapse of the margin of Hawaii. Later, with an established age of roughly 105 kya from the coral clasts, the source of the tsunami was suggested to be the Alika landslide on the west coast of Hawaii, believed to have a corresponding age. During a 1997 Geological Society of America field trip to the outcrops, Jim Moore (1997, P. Comm.) concluded the radiometric ages indicated there had been more than one tsunami event on Lanai.

Numerous investigators have published radiometric-dating results for Hawaiian coastal deposits. The radiometric dating includes: 13 different techniques described in roughly 40 publications. The published ages for Lanai are incorporated in the plot in Fig. 7a.

Published radiometric analyses for other Hawaiian Islands have largely been concentrated on corals in-situ (i.e., growth position), with fewer analyses of marine conglomerates or sand units. But where the comparison of dates from the same site derived from in-situ coral versus dates of coral clasts extracted from coral and basalt conglomerates, reveals that no significant age difference exists between the two rock types (Muhs and Szabo, 1994). The deposits (Fig. 14) are lithologically and stratigraphically very similar to modern shoreline deposits (e.g. Queen's Beach on Oahu) and they are generally considered to be uplifted reef and coastal material derived from normal coastal processes (Keating, Whelan et al. 2004). On Oahu, marine conglomerates occur along the shore of Queens Beach, Makai Pier, and Waianae where sand and shell fragments fill the crevices between cracks in volcanic rocks.

Figure 14. The GWH refers to the rocks as "gravels", but they are also referred to as marine conglomerates. The outcrop at left is from the island of Lanai, while the marine conglomerates at right are from the modern shoreline at Queen's Beach, Makapu'u, Oahu.

Like Lanai, age dating of sedimentary deposits at Waimanalo, S.E. Oahu, demonstrates that erosional notches were cut by wave activity at 7- 9 m (22 and 27 ft) above modern sea level at 120 kya. Sherman *et al.* (1993) report two distinct high stands on the Ewa Plain (SW Oahu) associated with the Waimanalo Formation, with ages correlated to Marine Isotope sub stage 5e. Studies reported by Stearns (1985); Muhs and Szabo (1994); Ku et al. (1974) and Szabo et al. (1994) prove that numerous outcrops of Waimanalo Limestone around Oahu have a similar age range. Radiometric dates of sediments from Kapapu Island, E. Oahu were reported by Grossman *et al.* (1989) and dates from an intertidal notch from Mohulua Island (Grossman and Fletcher, 1998) were in agreement with the Stearns (1935; 1978) high stand prior to 3889-3665 cal ya. These ages help constrain Oahu's long-term average uplift rate (0.03-0.07 mm/yr) based on Pleistocene age shorelines (Hearty, 2002). The coral bearing deposits at about 2 m elevation on Hawaii are reported to be a similar age to the Waimanalo Formation on Oahu (McMurtry, Fryer et al. 2004b) (While these latter authors suggest these deposits are associated with a submarine landslide generated tsunami (GWH), these rock ages are equivalents of the Waimanalo Formation exposed on other islands, consistent with the SLIP.)

Problems with radiometric dating

Hearty (2011) commented on the age of rocks in a publication (McMurtry, Campbell et al. 2011) and Reply (McMurtry, Campbell et al. 2011) and concludes, "their age data are flawed and lack supportive field and proxy evidence." Furthermore he writes, "such allochtonous cobbles have been emplaced by younger transgressions or tsunami any time after coral growth, but screening protocals (e.g. Mortlock *et al.*, 2005) should exclude Ko Olina and Lualualei. . ." See the publication of Sherman *et al.* (1999) that described marine and meteoric diagenesis from Oahu emergent sediment and the work of Oliver Chadwick and colleagues for pertinent studies on the island of Hawaii

Hearty concludes, "unsupportable interpretations such as theirs should not become embedded in the literature." Hearty writes, "ages as incontrovertibly unreliable due to excessive recrystallization and detrital Th greater than 1-2 ppb…. Lacking reliable ages and ESL's [Eustatic Sea Level], it is not possible to determine accurate uplift rates…."

Basing geologic models on single sample radiometric dates or age correlated with distant sites need also to be reconsidered. The original (1984) estimate of the age of the deposits within the GWH and the revised ages Moore and Moore (1988) are problematic. One age is from the island of Hawaii, with no supportive field evidence between the two islands. Other dates use less than ideal numbers of samples.

4.12. Source material

The GWH states that tsunami waves ripped up corals from an offshore reef as tsunami waves reached shallow depths.

Outcrops in gullies draining into Manele Bay and Hulopoe Bay contain individual specimens of corals, not aggregations of corals common on modern and ancient reefs, e.g., corals exposed in emergent outcrops on the Ewa plain of Oahu Island, Hawaii. Additionally, the maximum size of the coral clasts is small (a few to 20 cm across) compared to the basalt boulders. If a reef were present offshore, a tsunami could have moved coral clasts comparable to the size of the basalt boulders. Since it did not, it is concluded that the carbonate source material was composed of isolated corals of restricted size growing on boulders, like those observed in the modern shore and shallow offshore environment, as opposed to a developed reef complex.

4.13. Wave couplets

The GWH suggested that bedding couplets rich with coral clasts occur in their lower layers (representing upsurge of the wave) while the upper layers contain angular clasts (representing wave retreat). Detailed lithological descriptions are now available Felton, *et al.* (2000) and Felton *et al.* (2006) that show that rather than couplets, 14 beds were found along with 8 unconformities between beds.

Paleosols are identified at several boundaries within the gully-filling deposits proving a subaerial history for parts of the deposits. Root clasts are found as well as insect remains according to Resig (1999). At least one bed of the GWH locality is alluvial, i.e., a stream deposited unit of subaerial origin (Felton et al., 2006). These observations are inconsistent with the GWH. Had a giant tsunami taken place, it is extremely doubtful that insect remains would be preserved, since they are light enough to be blown away in the wind or washed away by rain.

4.14. Bed forms

The GWH describes branching dune-like gravel ridges (called bed forms) generally 1 m high. The deposits are situated in a location that was long occupied by native Hawaiians. In their preliminary survey of the area, archaeologist Steve Athens identified 182 archaeological structures. Ancient Hawaiians made extensive use of basalt boulders for construction in the Manele/Hulopoe Bay area including: platforms, grinding stones, game stones, hammer stones, hearths, rock walls, canoe sheds, cairns marking upland trails, cairns such as fishing shrines, holding pens, housing (oval terraces, rectangular shelters, curved wall enclosures), rock shelters, temporary fishing shelters, burial structures, boundary walls (Athens, 1991). The structures described as GW-derived bed forms (Fig. 15a-e) appear to be the remains of ancient anthropogenic structures. The photograph in GWH publication (1984, p. 1313, Fig. 4) even looks like an archaeological site illustrated by Emory (1924, Fig. 4).

Athens (1991) remarks on a description of the south and west coast of Lanai made by Captain King in 1785, a member of Captain Cook's expedition, who wrote, "the country to the south is high and craggy; but the other parts of the island had a better aspect and appeared to [be] well inhabited. We were told it produced very few plantains, and breadfruit trees; but that it abounds in roots such as yams, sweet potatoes and tarrow [taro]." Furthermore, Stearns (1940) wrote, "around the old native village sites especially at

Kaunolu and Manele are traces of rock terracing representing considerable industry. These terraces are reported to have been sweet potato gardens." Since the structures were built on expansive soils, they have toppled.

Figure 15. (Upper Left) the GWH describes bed forms in the Manele Bay Resort property. However, there are archaeological sites spread throughout the area that can be easily misinterpreted as bed forms. Athens (1991) described 182 structures built by native Hawaiians. Fig. 15b. (Upper right) The image shows a Hawaiian structure, while the rock walls have toppled, the rectangular shape of the foundation is still apparent. Fig. 15c. (Middle left) A drawing made by Emory (1924) of some of the numerous archaeological sites that dot the southern slope of Lanai (compare this drawing to Fig. 12b). Fig. 15d. (Lower left) The hillside above the Manele Bay Resort is marked by rock wall structures. They consist of rock walls laid in c-shaped configuration with the expansive black soils filling the structures to provide raised beds for growing sweet potatoes. Similar structures are in use in Hawaii currently. When the Captain Cook Expedition reached the Hawaiian island chain, the Lanai sweet potatoes were obtained for the expedition. Fig. 15e. (Lower right) Geologists examine the rock walls and soils still present in the growing beds.

4.15. Additional considerations

The GWH compares the postulated catastrophic tsunami flooding on Lanai to the catastrophic draining that took place when dammed glacial melt water of Lake Missoula (W. USA) broke through a topographic barrier and eroded basaltic terrain to produce the "scablands" terrain of western Oregon and Washington (Baker, 1973). (These scabland deposits were examined by the authors on several occasions.) The "scablands" surfaces, display extensive scarring and breakage of the boulders and cobbles and bedrock. In marked contrast, the Lanai deposits lack the scarring obvious in the scablands. The coral clasts instead display abrasion and breakage comparable to that of the modern boulder beach and are generally associated within the gravel or boulder deposit, that is, they are beach deposit, not giant wave deposits.

Furthermore, basalt boulders found below 200m m generally have a well rounded nature typical of beach boulder deposits. Basalt exposed on small cliffs generally have well-preserved irregular a'a surface textures as well as delicate surface structures (Fig. 16). If the boulders had been transported by tsunami waves, these delicate surface textures would likely have been destroyed or at least heavily scraped and scarred. A cone of red cinder sits at roughly 120 m elevation at the west side of the Manele Bay section. Felton et al. (2000) report that red cinders were found in a bed in the nearby gully. Given the extreme height, turbulent, and erosive nature of the proposed "giant waves", the red cinders would be expected to be distributed throughout the presumably tsunami-derived gravels of southern Lanai, yet they are not. The observation that this rock type is restricted indicates that its deposition is due to local erosional processes that segregate rocks rather than a giant catastrophic event that would widely distribute distinctive cinders.

Figure 16. A photograph of a highly vesicular basalt boulder shows delicate surface of lava preserved. The boulders in the GWH type area are not marked by heavy scratching causes by abrasion in a mass flow. They have not been heavily abraded similar to debris left by the flooding of glacial Lake Missoula.

Alignment of boulders has also been cited as evidence for tsunami. Nanayama *et al.* (1998) examined the deposits of the 1993 tsunami (with maximum wave run up of 8.6 m) on the Hirahama coast at Taisei town, southwest Hokkaido, Japan. They found that the imbrication of gravel was restricted to a small area of only a few meters indicating an outward (seaward flow) and beach drainage (the long axis of gravels inclined seaward). Dominey-Howes (1999) reported similar observations from the Mediterranean. There is no obvious imbrication observed in Lanai deposits (see .Fig. 17).

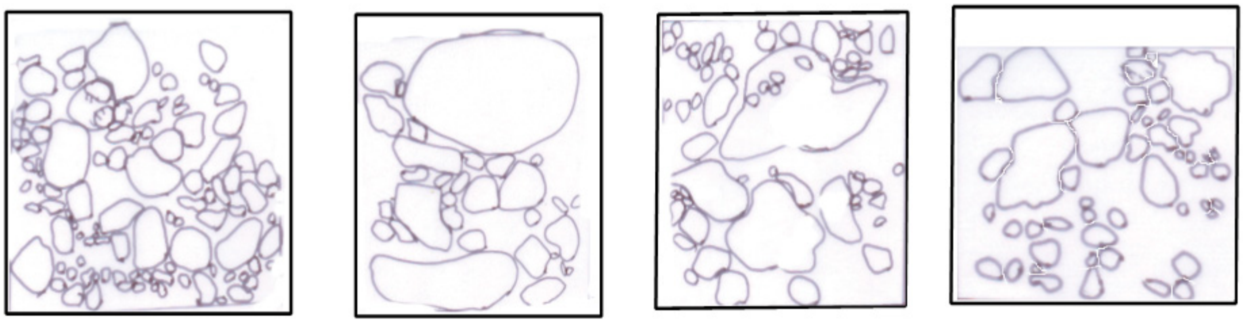


Figure 17. The figure above consists of a set of tracings of outcrop photographs, made to examine the alignment of clasts. The photographs were taken perpendicular to the outcrop so that the upslope direction is to the left and down slope direction is to the right, in the gully adjacent to Hulopoe Gully. In general there is little evidence of alignment. The images are roughly 1.5 m, in dimension. The grain size varies from boulders to pebbles in a caliche-encrusted matrix. The clasts range from well-rounded to angular shapes, and the largest clasts are roughly 0.3 m in diameter.

4.16. Erosion versus deposition

Shepard *et al.* (1950) documented the destructive effects of the 1946 tsunami in Hawaii. The photographs in that report show areas of maximum flooding marked by floating debris (including wooden buildings), large areas swept clean of debris other than sand deposited as a sheet, and eroded and fragmented corals and shells found along drainages and in poorly drained, low-elevation coastal areas. Sheppard *et al.* (1950) remark that some areas were so thoroughly swept clean of debris by the tsunami waves that they could be used to land an airplane.

The pattern seen in the historic Hawaiian tsunami is one of erosion with sporadic deposition of limited nature and breakage of corals and shells. This pattern of tsunami erosion along drainages is often reported in the literature (see, Keating et al, 2008; Keating *et al.*, 2011). This pattern is entirely different from the pattern suggested by the GWH. On Lanai, rather than seeing evidence of erosion sweeping the drainages clean, rocks are deposited in the drainages. If the southern slope of Lanai was the site of giant tsunami waves, it seems logical that the waves on the moderately steep slope would have preferentially scoured out existing drainages, rather than using them as “sediment traps” for the rock mobilized by wave action, as proposed by the GW hypothesis.

The southern coast of Lanai seldom receives rain, but when it does, it is often in the form of a winter storms with several inches or feet of rain fall within several hours to several days. The surface run-off from these storms can move large rocks significant distances downhill and erode soils. This normal process of reworking of rocks from higher to lower elevations has taken place throughout the history of the island and should be expected to produce a scattered pattern of ages but retain a pattern of increasing age with elevation. Also, the SLV during the last 400 kya has provided repeated opportunities for rock deposition (and erosion) at any given elevation within the Poopoo and Anapuka gullies.

High elevation fossils are also a problem. Crook and Felton (2008) report on the microscopic study of samples from Stearns Swale, a site situated at 326 m on the outside of Kaluakapo crater. They report "we found only veins of carbonate concentrated in cracks in lava outcrops….'" Despite numerous visits to the site by numerous scientists, no fossils have been found. And, all samples collected by Keating and Helsley from the site were studied by micro-paleontologist J. Resig (specialist in foraminifera) who found no biological structures in any of the roughly 30 samples collected.

Crook and Felton examined a sample collected by Harold Stearns during 1936 that was stored in the U.S. National Museum, in Washington, D.C. Stearns in 1936 (Stearns 1936) recorded in his notes, "Rode down into fault country between Manele and Kawaio [Naha side of Kaluakapu Crater] (by horseback). While riding thru here I notice [sic] some fossil limestone fragments but that they had been packed up here after riding past them I realized how weathered they were and that no one would pack [carry] them up so I went back and found plenty of loose fragments and two places where fossiliferous limestone fills cracks in the bedrock.…"

In 1936, Stearns visited two sites on the same day. Since no fossils have been found at the swale by subsequent investigators, we question whether the sample examined by Crook and Felton (2008) was mislabeled when collected. This question arises because Helsley observed rocks of a similar nature to those in the Stearns collection at the locality that Stearns visited later that day. Further field work on the Naha side of the crater will be required to resolve this question.

Stearns wrote, "Henry says the old Hawaiians used this white (montmorillonite?) in the gulch east of the high coral locality for chalk." The only white material in this area of the swale is crack filling caliche, some having thicknesses of more than 3 cm. These caliches have root casts and other 'organic' looking structures but under the microscope, all such structures are inorganic in origin (as reported by Resig). This raises another concern; there is no gulch east of the Stearns Swale. The swale is located on the outside of Kaluakapo Crater, on the west flank of the crater. There is a small gully inside the crater but no white montmorillonite deposit. There is a significant deposit of white material in the gully to the east near the outcrops that Helsley thinks are the source of the fossils in the Stearns Collection at the Smithsonian Museum.

Crook and Felton (2008) also refer to disturbance of the Stearns site due to a military installation. Our understanding is that the high point served as an observation point, rather than any full-blown military installation. The disturbance seems to be limited to the construction of a jeep road into the swale area that terminates short of the observation post. This construction does not seem to impact areas beyond the jeep road but it is possible that the road destroyed the small outcrop that Stearns described. Also, the publication cites that Stearns mentioned that limestone would not have been carried up to the site. Keating raised the question to Manele Bay Resort game manager Gary Onuno. He reported that limestone was used in ceremonials when young Hawaiian boys came of age and that it was carried from the coastal area to the uplands, and it would not have been a miniscule amount. One such route from Manele bay to the interior passes by the swale that Stearns defines as the source of his samples.

Giant Wave Hypothesis Basic Tenets	**Our Observations**
Island Subsidence	Island Uplift and Sea Level Variation
Shells at 365 m and Shells at 183 masl	Multiple strandlines below 190 m. No fossils at 326 m. Marine Terrace at 190 masl
Soils Stripped	Highly expansive vertisols present having a thickness of 50 cm to 1 m.
Locally continuous gravel beds	Coral bearing strandlines and notches And gully filling gravels near sea level
95% basalt, 5% corals	Complex stratigraphy with four discontinuity bounded transgressive-regressive cycles with soils and insects marking subaerial intervals
Continuous deposits to 326 m	No carbonates above 190 m. Carbonates not continuous – tends to be elevation limited strandlines
Corals not in growth position, repositioned by tsunami inundation and retreat	Growth position corals are not expected in rocky shoreline littoral deposits – some evidence for in-growth position in biofacies and growth on substrate.
Encrusted layer	Caliche (post depositional)
Clast-supported with thickness and clast size decreasing inland.	Rocky shoreline deposits with wave cut notches in bathtub-ring configuration.
Single wedge-shaped deposit	Multiple strandlines representing both high and low stands
Ages around 110,000 ybp, then revised to include another event around 220,000 ybp	Multiple age strandlines with older material at higher elevations, also fossils of corals no longer living in Hawaiian waters occur at high elevations.
Source: coral reef	Shallow water transgressive strandlines and regression hiatuses and low stand deposits
Bimodal lithofacies representing tsunami upsurge and tsunami wave retreat	Complex stratigraphy representing multiple depositional events of high stand and low stand origin.
Disturbance resulting from giant waves	Multiple lines of evidence represent strandline origins

Table 4. Comparison of the basic tenets of the Giant Wave Hypothesis with the geologic features described in this publication.

5. Conclusion

Our observations on coral-bearing deposits on the south flank of Lanai are totally supportive of the hypothesis that these deposits represent uplifted strandlines formed during island uplift and glacial eustatic sea level variations documented elsewhere in the world. The formation of these uplifted coral-bearing deposits does not require a giant wave origin. Moreover, had a Giant Wave(s), of the sort proposed by others, occurred, the loose fragmented coral, sand, and boulder deposits characteristic of some of these strandlines would have been disturbed or destroyed and some of the transported material would have been deposited at higher elevations. Yet, no evidence of coral bearing deposits was found above 190 masl.

Erosion and boulder stripping is a normal process and all the geomorphic features described by the Giant Wave Hypothesis can be attributed to normal geologic processes and occasional but significant rainfall events, such as winter storms or hurricanes. The large number of geologic publications describing exposed carbonate units in the Hawaiian islands, the abundance of published radiometric dates, the consensus of scientists that these rocks represent deposition by normal coastal processes and the display of a pattern of increasing rock ages with elevation contradict a mega-tsunami origin for deposits on Lanai. An extreme catastrophic event is not necessary to explain these marine deposits. While the GW hypothesis is an exciting notion, the concept is not supported by field evidence on Lanai.

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