Fossiliferous Lana'i deposits formed by multiple events rather than a single giant tsunami

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Giant tsunamis, generated by submarine landslides in the Hawaiian Islands, have been thought to be responsible for the deposition of chaotic gravels high on the southern coastal slopes of the islands of Lana'i and Moloka'i, Hawaii. Here we investigate this hypothesis, using uranium–thorium dating of the Hulopoe gravel (on Lana'i) and a study of stratigraphic relationships, such as facies changes and hiatuses, within the deposit. The Hulopoe gravel contains corals of two age groups, representing marine isotope stages 5e and 7 (~135,000 and 240,000 years ago, respectively), with significant geographical and stratigraphic ordering. We show that the Hulopoe gravel was formed by multiple depositional events, separated by considerable periods of time, thus invalidating the main premise of the 'giant wave' hypothesis. Instead, the gravels were probably deposited during interglacial periods (when sea level was relatively high) by typical Hawaiian shoreline processes such as seasonal wave patterns, storm events and possibly 'normal' tsunamis, and reached their present height by uplift of Lana'i.

Lana'i is an eroded, extinct shield volcano about 1 Myr old, overlain at lower elevations by discontinuous sedimentary rock outcrops. Early detailed studies reported bioclastic gravels on the island's southern slopes to 60–70 m elevation (primarily preserved in gullies and canyons of the arid coastal region; Fig. 1) and much less extensive, isolated outcrops up to ~170 m elevation[1]. The largest concentration of coral-bearing conglomerates is a 0.6 km^2 area upslope of Hulopoe and Kapihaa Bays[1] (Fig. 1); the thickest deposits (~10 m) are near the present shoreline. A site within Kapihaa gully was later named the "Hulopoe gravel" type locality[2]. These deposits were originally attributed to a succession of relative glacioeustatic marine high stands[3]. Given the elevation range of the deposits, uplift of Lana'i would be required. Besides the main deposits, two small higher-elevation, presumed older, fossiliferous limestone localities occur. These are isolated conglomerates at 190 m in Kaluakapo crater and vein-filling calcite <1 cm wide by <1 m long at 326 m; both localities rest astride upthrown (relative) blocks of the normal-fault-bounded fossil south rift zone of the Lana'i shield[1]. This, and a change in soil type and thickness and rounded boulders at 326–375 m were also interpreted as a relative marine high stand, with unspecified uplift mechanism[1,3].

An alternative, dominantly accepted hypothesis[2,4] suggests that a "giant wave" tsunami[2] (or tsunami wave train[4]) formed the Hulopoe gravel. Wave run-up to ~375 m (refs 2 and 4) was to have stripped soil and arranged basalt boulders on drainage interfluves. This single, catastrophic, 'above sea level' event was proposed because tidal gauge data and ages of drowned fossil reefs indicated subsidence on the southernmost islands of Hawaii (2.4 mm yr^{-1}) and southern Maui (0.3 mm yr^{-1})[5,6], thus suggesting that now-emergent palaeo-shoreline deposits were not possible on Lana'i[2,4]. However, other than the circumstances of the proposed tsunami there is no published evidence (such as stratigraphic or geochronological evidence) that links the deposits comprising the Hulopoe gravel together or to other geological features on Lana'i. The event was 'dated' at 105 kyr ago using coral clast U-series ages determined by traditional α-counting methods (one at 134 kyr ago from 155 m in Kaluakapo crater and one each at 108 and 101 kyr ago from 115–120 m in Kawaiu gulch). None of the dated clasts were from the type locality, nor were stratigraphic correlations to the type locality presented[2,4]. A giant wave is a plausible mechanism for forming chaotic deposits like the Hulopoe gravel[7,8] and has been invoked for other features globally (for example, the 105 kyr ago 'Lana'i' wave was proposed to have caused widespread coastal erosion in western Australia)[9]. A bioclastic deposit exposed to 65 m elevation on Moloka'i has also been attributed to a giant tsunami (at 200–240 kyr ago)[10].

This project is a test of Hulopoe gravel depositional scenarios using mapping and radiometric ages of clasts. The giant wave scenario should not result in a meaningful relationship between clast ages and distribution through the Hulopoe gravel, as source material would be randomly mobilized and deposited. The successive marine high stands scenario should result in an upslope age progression as long as uplift outpaced sea level change[11]. Downslope reworking of clasts from older deposits and depositional succession would also cause down-section age increases at lower elevations.

Hulopoe gravel outcrops and stratigraphy

To better define the origin(s) of the Hulopoe gravel we began in 1995 to map, sample and date clasts from Kapihaa gully, an unnamed gully immediately to the west (referred to here as Archeology gully) and the coastal headlands extending to Kaluakoi point (Fig. 1). Our earliest stratigraphy and five high-resolution thermal ionization mass spectrometry (TIMS) ^{230}Th–^{234}U–^{238}U analyses confirmed a Pleistocene age for the coral clasts (marine isotope stages 5e and 7), indicated more than three mappable units with distinct sedimentary facies, and suggested several depositional events[12]. We have since completed additional mapping, sampling and dating; in addition, a sedimentological study of the type locality section was carried out[13]. Conglomerates in and around the type locality include lenticular beds of a range of cementation characteristics (dense micrite to mud), and a wide variety of clast types, sizes and shapes. None of the mapped deposits appear to be *in situ* reef. Instead, clast size and matrix variations indicate original and reworked littoral and alluvial deposits from a spectrum of medium to high-energy environments.

Our mapping was accomplished using EDM (electronic distance meter) surveys, with results similar to those of Stearns[1]. Our results differ significantly from later reports that show a continuous apron extending from sea level to ~100 m elevation[2]. Our observations differ in two other specific ways that bear on their origin: (1) we do find extensive deposition on coastal headlands near Kapihaa gully;

and (2) in three gullies examined we do not find deposits concentrated on the west sides[4] (for example, most Archeology gully gravels are on the eastern wall). Supposed deposit thickening on western sides of gullies and lack of deposition on headlands was argued to indicate an oblique giant wave deposition angle and backwash stripping of headlands, respectively[4]. Our multiple unit stratigraphy[12] also differs from the tsunami model[2,4] (which has one stratigraphic unit composed of six beds of alternating coarseness and coral abundance, proposed to result from run-up and backwash of a three-wave giant tsunami). Eight stratigraphic units have since been identified at the type locality, including three subaerial time break disconformities (with truncated palaeosols and root casts)[13]. Our geochronological system of sampling is consistent with the newest stratigraphy, and includes a thick sequence of poorly-sorted conglomerates organized in the lower elevations of Archeology and Kapihaa gullies into two reversely graded sequences dominated by subrounded to subangular clasts of basalt (⩾80%) and coral (0–20 vol.%). Coral clasts are conspicuously absent from these beds in two 75–100 m stretches along Kapihaa gully, although other apparently non-marine calcareous clasts (for example, pieces of caliche) occur, indicating discontinuity of bioclast deposition. These beds overlie a well-cemented bioclastic basal unit in Kapihaa gully that at 18–25 m elevation forms prominent gully floor outcrops. In other places, bedrock basalt floors the gully. An important feature of the type locality stratigraphy is a red-brown mud/sand matrix-supported basalt gravel layer just above our basal unit (units A and B in

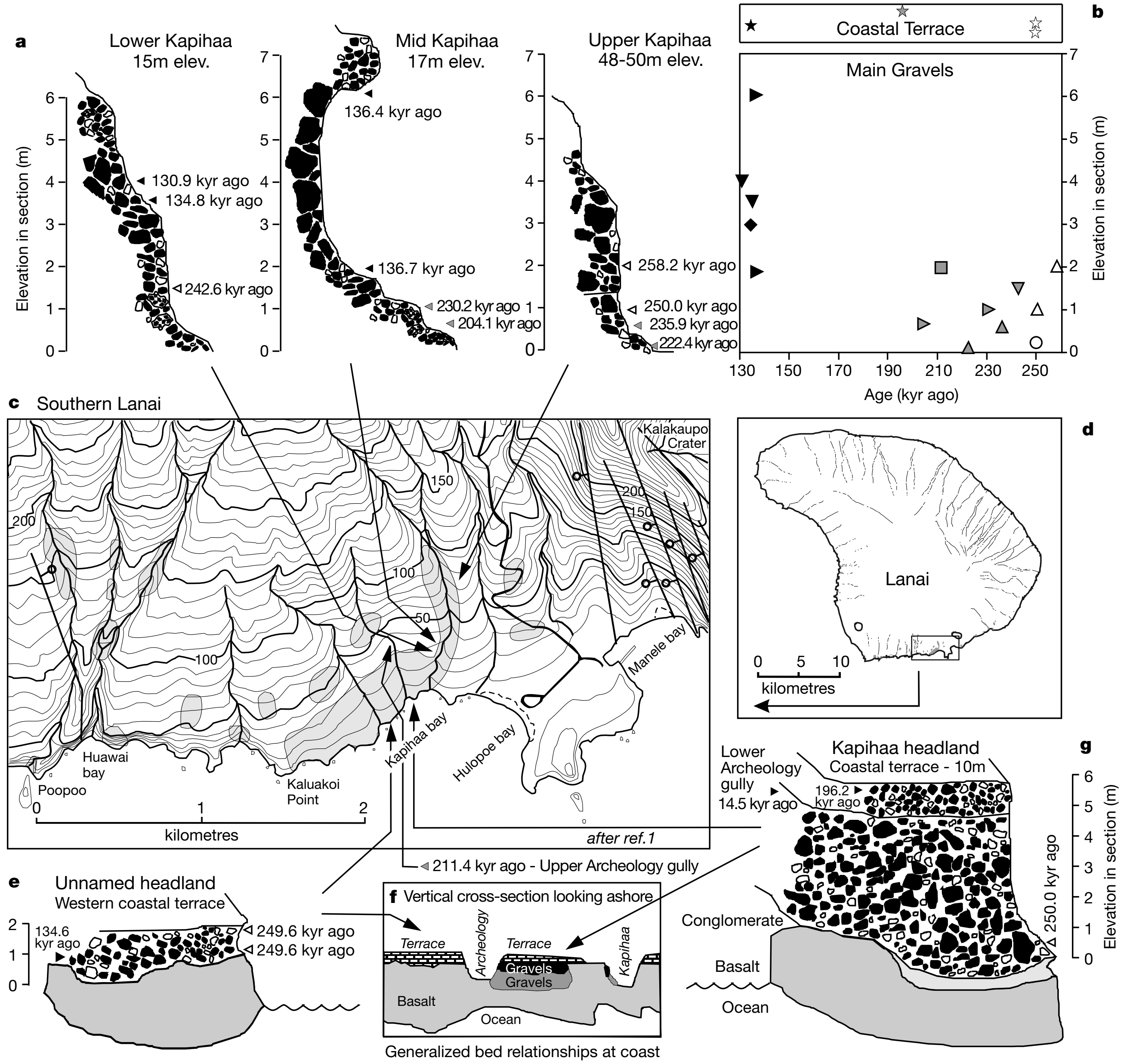

Figure 1 Summary of the study area on the southern coast of Lana'i, Hawaii. **a**, **e**, **g**, Graphical representations of each outcrop studied (basalt clasts are black, corals are white, and basalt bedrock on the headlands is grey). Sampling elevations within the sections are depicted by arrowheads with Th–U ages as labels. **c**, Map with sampling sites for coral clast dating (10-m contour interval). Outcrops of Hulopoe gravel are shown in light grey, normal faults are depicted by lines with a circle on the down-dropped side[1]. **d**, Map of Lana'i. The area depicted in **c** is enclosed within the rectangle. **f**, Representation of the general relationships between gravel beds (black, dark grey), basalt basement (light grey), and the coastal terrace (white bricks). **b**, Composite plot of age versus elevation in section. Symbols in this panel are keyed to outcrop location: lower (inverse triangles), mid (right triangles), and upper (triangles) Kapihaa gully; lower (diamonds) and upper (squares) Archeology gully; Kapihaa headland (circles); coastal terrace (stars)). **a**–**g**, Black and grey filled symbols represent most reliable stage 5e and stage 7 ages (respectively) and open symbols represent least reliable ages (see Methods for tests of age reliability).

ref. 13), interpreted as an alluvial deposit and bounded by two of three "time-gap" disconformities of the sequence[13].

This entire sequence is overlain in the near-coastal region by what we term a 'Coastal Terrace' deposit, which is a weakly lithified unit with calcareous cement containing a somewhat higher percentage of coral clasts (30–40%), as well as mollusc and gastropod shells, foraminifera, and lithified beach rock (Fig. 1e–g). Importantly, this lithologically distinct unit clearly overlies all other gravel units near the mouths of gullies, mantles bedrock basalt unconformably at nearby coastal headlands and sea cliffs[12], and contains clasts that were probably reworked from stratigraphically lower beds[13]. The terrace mantles the other deposits and basalts uniformly and was thus clearly deposited in a separate event with significantly different preservation characteristics and a different immediate origin from that of the other gravel beds. Where the terrace overlies gravels at the coast it is uniformly 1 m thick but locally reaches 2 m thick over bedrock, infilling pre-existing topography. It has a uniform 6–8° seaward dip, forming a relatively constant elevation terrace at equal distance back from the sea, and on headlands is commonly undercut by erosion at its base, forming a visor. It is restricted to near the coast and in Archeology gully can be traced as a continuous layer inland to ~100 m from Kapihaa headland (Fig. 1).

Thus, the previously named Hulopoe gravel is a collection of several units that we group into 'Basal', 'Middle' and 'Coastal Terrace' for ease of discussion. Together the basal and middle packages form the 'Main body' of the Hulopoe gravel (MB). We sampled five locales within the MB, a series of coastal terrace sites where it overlies basalt to the west of Archeology gully, and a modern lithified shoreline gravel (LSG) of subrounded basalt clasts, coral clasts, and coralline algae. No suitable samples for dating were found at the Hulopoe gravel type locality outcrop, although our lower and mid Kapihaa sites bracket it by ~75 m on either side. Dated clasts were massive coral forms (primarily *Porites lobata*) excavated from well-lithified strata.

Geochronology

The ages of 18 Hulopoe gravel coral clasts were determined by high-resolution TIMS ^{230}Th–^{234}U–^{238}U analyses (Table 1). Calculated ages fall into two groupings: 130.9–136.7 kyr ago, and 196.2–258.2 kyr ago (Fig. 2). These correspond to the last two interglacial marine high stands and were times of enhanced coral growth/reef preservation in Hawaiian waters[14–16]. Three clasts from the LSG were also dated late Holocene (2.0–3.2 kyr ago), correlating with the age of the Kapapa marine high stand[17].

Eight of the 18 Hulopoe gravel samples were analysed in replicate, agreeing to 0.06 to 0.8%. The stage 7 group age range is larger than expected from analytical reproducibility (the best and worst replicates were in this group and replicate to 0.2 to 3% of the overall age range). Analytical errors do not appear to have contributed significantly to the data spread, but geological errors may very well have done so, owing to the complex depositional history and the present conditions of subaerial exposure. Broadly speaking, all of the dated specimens show evidence for meteoric diagenesis (exterior surface discolouration, recrystallization to calcite, Fe-rich mineralization on interior domains, minor dissolution textures) as well as a second phase of either meteoric or marine diagenesis (micritic cementation). Although we took great care to obtain the most-pristine appearing part of each sample, almost certainly some altered material was analysed, and some ages may thus be less reliable than others. Commonly employed geochemical tests of closed-system isotopic evolution since coral death are described in the Methods.

Samples with reliable stage 5e ages (based primarily on calculated initial ^{234}U/^{238}U) span 130.9 to 136.7 kyr. Many of these ages overlap with a recently suggested age for the penultimate 5e deglaciation (135 ± 2.5 kyr ago)[18] and with coral ages within the *in situ* 5e reef formation on O'ahu[14,15]. Some but not all of the stage 7 age range is likely to be real: the most reliable stage 7 samples are in two clusters (196.2 to 211.4 kyr ago, three sample mean is 204 kyr ago and one sample was 230.2 kyr ago). Two other less reliable ages (222.4 and 235.9 kyr ago) are sufficiently close to the latter to suggest that they are also valid (mean of second three-sample cluster is 230 kyr ago). The younger cluster correlates with late in the stage 7 interglacial (events 7.1–7.3) and the older cluster correlates with event 7.5[19].

Table 1 Sample particulars, U-series data, ages and 2σ uncertainties

Location and samples	Site	Elevation (m)	Calcite %	U (ng g^{-1})	Th (pg g^{-1})	^{232}Th/^{238}U atom ratio × 10^5	(^{230}Th/^{238}U) activity ratio	δ^{234}U measured	Age (kyr ago)	δ^{234}U$_i$ initial
Hylopoe bay										
Lan2-1-2	Tidal	0.50	0	2,612 ± 7	101 ± 0.4	4.01 ± 0.02	0.0210 ± 0.0007	146.1 ± 2.3	2.01 ± 0.07	147 ± 2
Lan2-1-1	Tidal	0.50	0	3,248 ± 8	379 ± 0.9	12.1 ± 0.04	0.0213 ± 0.0006	147.1 ± 1.5	2.04 ± 0.06	148 ± 1
Lan2-1-4	Tidal	0.50	0	2,692 ± 7	198 ± 0.4	7.60 ± 0.02	0.0334 ± 0.0007	145.0 ± 3.2	3.22 ± 0.07	146 ± 3
Coastal										
Lan3-3-1	Western	3.8	<2.3	2,861 ± 7	287 ± 0.5	10.4 ± 0.03	0.795 ± 0.004	102.8 ± 2.2	134.6 ± 0.9	151 ± 3
Lan3-2-2	Western	3.8	<2.3	2,705 ± 7	170 ± 0.3	6.51 ± 0.02	1.004 ± 0.005	91.0 ± 1.9	249.6 ± 1.6	185 ± 4
Lan3-4-1	Western	2.3	<2.3	3,001 ± 8	110 ± 0.2	3.78 ± 0.01	0.996 ± 0.005	83.8 ± 1.9	249.6 ± 1.6	170 ± 9
Lan1-0-1	Kapihua headland	8	0	3,153 ± 9	25 ± 0.3	0.82 ± 0.01	0.923 ± 0.005	85.0 ± 5.1	196.2 ± 1.3	148 ± 9
Lan2-2-3	Kapihua headland	4.2	<2.3	2,754 ± 7	209 ± 0.7	7.86 ± 0.03	0.997 ± 0.006	84.7 ± 2.0	250.0 ± 1.7	172 ± 4
Archeology gully										
Lan2-7-1	Low	9.7	0	2,838 ± 7	145 ± 2.5	5.28 ± 0.09	0.803 ± 0.004	111.7 ± 2.3	134.5 ± 0.9	164 ± 3
Lan2-8-1	Upper	35	3.3	3,068 ± 8	607 ± 2.1	20.4 ± 0.09	0.945 ± 0.006	82.4 ± 1.8	211.4 ± 1.5	150 ± 3
Kapihua gully										
Lan1-2h-1	Low	20	2.3	3,043 ± 8	637 ± 2.7	21.6 ± 0.11	0.783 ± 0.009	102.0 ± 3.2	130.9 ± 1.5	148 ± 5
Lan3-6-2	Low	19	0	2,741 ± 7	244 ± 0.5	9.20 ± 0.03	0.801 ± 0.004	108.2 ± 2.0	134.8 ± 0.9	159 ± 3
Lan2-3-1	Low	18	0	3,048 ± 8	98 ± 0.2	3.31 ± 0.01	0.985 ± 0.005	81.2 ± 1.9	242.6 ± 1.6	161 ± 4
Lan3-5-3	Mid	23.0	0	3,468 ± 9	1,256 ± 2.3	37.4 ± 0.12	0.798 ± 0.004	99.5 ± 1.4	136.4 ± 0.9	146 ± 2
Lan2-4-3	Mid	19	<2.3	3,071 ± 8	739 ± 1.1	24.9 ± 0.07	0.800 ± 0.005	101.4 ± 1.2	136.7 ± 1.0	149 ± 2
Lan1-4-1	Mid	28	2.3	3,133 ± 8	582 ± 3.7	19.2 ± 0.13	0.967 ± 0.016	78.4 ± 3.6	230.2 ± 3.9	151 ± 7
Lan3-5-1	Mid	17.7	2.3	3,094 ± 8	1,241 ± 2.1	41.4 ± 0.13	0.932 ± 0.005	81.3 ± 2.0	204.1 ± 1.4	145 ± 4
Lan1-6-1	Upper	58	0	2,896 ± 8	151 ± 0.5	5.39 ± 0.02	0.965 ± 0.005	86.3 ± 4.1	222.4 ± 1.5	162 ± 8
Lan2-6-2	Upper	58.9	0	3,008 ± 8	18 ± 0.3	0.62 ± 0.010	0.980 ± 0.005	83.7 ± 2.1	235.9 ± 1.5	163 ± 4
Lan2-5-2	Upper	47	<2.3	2,849 ± 7	12 ± 0.4	0.44 ± 0.02	1.005 ± 0.021	91.3 ± 2.3	250.0 ± 5.2	185 ± 5
Lan3-7-1	Upper	58	0	2,745 ± 8	1,029 ± 1.0	38.7 ± 0.05	1.006 ± 0.005	85.2 ± 1.9	258.2 ± 1.0	177 ± 3

Activity ratios were calculated using $\lambda^{238}U = 1.551 \times 10^{-10}\,yr^{-1}$, $\lambda^{234}U = 2.835 \times 10^{-6}\,yr^{-1}$ and $\lambda^{230}Th = 9.195 \times 10^{-6}\,yr^{-1}$. U isotopic compositions are reported using the δ^{234}U notation, where $\delta^{234}U = [(^{234}U/^{238}U)_{measured} - 1] \times 1{,}000$; errors in Th and U concentrations are based on replicates and standards analysis[32]. Errors on δ^{234} ratios are based on ^{234}U/^{238}U analysis errors. (^{230}Th/^{238}U) errors are based on ^{230}Th/^{232}Th analysis errors, and errors on Th and U concentration. Fractional errors in all of these parameters were propagated through the appropriate equations to estimate errors in ages and δ^{234}U$_i$. Reported uncertainties in activity ratios and ages also include errors in λ values.

Analyses were conducted at the University of Hawaii by peak-jumping of masses 229-230-232 (Th) and 233-234-235 (U) in single-collector ion-counting mode using a Vacuum Generators Sector54 mass spectrometer outfitted with a Daly detector and a WARP (wide area reducing potential) secondary energy filter for improved abundance sensitivity. Data were corrected for Daly Bias of 0.58‰/a.m.u. relative; other instrument-related metadata are given elsewhere[32]. U isotopic fractionation was calibrated with external standards: Nine analyses of NIST certified reference material U010 yielded $^{234}U/^{238}U = 5.4637 \times 10^{-5} \pm 0.3\%$ (2σ relative), which is 0.03% lower than the certified value ($5.4655 \times 10^{-5} \pm 0.9\%$).

The remaining less reliable ages (243 to 258 kyr ago) are probably too old by ~15–30 kyr).

Ages of clasts are used here as indicators of general relationships and as tracers of source material to test depositional scenarios. Although the youngest clast limits the maximum age of a host stratum, clast ages are not deposit ages, as they may have had a finite age before their incorporation into a deposit, particularly if they have been reworked and redeposited from older strata. Ages in the LSG deposit in Hulopoe bay indicate that the time interval between coral death and subsequent incorporation into a potentially analogous deposit can be relatively short (2–3 kyr ago), but this may not always be the case.

Clast age distribution patterns

On the basis of our dating results, a single depositional event (such as the proposed giant tsunami) would require mobilization of a mixed-age assemblage of corals from one source (almost certainly the bay floor fronting the deposits). Age relationships within the MB (that is, material unconformably mantled by the coastal terrace) can be used to discriminate single-deposit versus multiple-deposit scenarios. Rationally, a single-depositional event (a giant tsunami) should not produce statistically significant clast age sorting and should be distinguished from non-catastrophic, sequential deposition of strata by lack or presence of such sorting.

We used standard probability and statistical hypothesis-testing methods to investigate whether the observed clast-age distribution could have been derived from a single clast assemblage. Clast distribution was examined using spatial domains defined by geography and stratigraphy within the MB. Calculated probabilities are not likely to have been biased by sampling deficiencies because the proportion of dated clasts relative to those collected from each of the spatial domains (33–56%) was not significantly different from the overall analysis rate of 42%. Overall, two-thirds of the Hulopoe gravel coral clasts are stage 7 (broadly) and one-third are stage 5e (regardless of whether the coastal terrace samples are included). We can use this as a source clast population or assume equal numbers of both ages and the result is the same, so long as the source clast pool is large.

Strong age sorting trends by height in the section and relative elevation of deposition are observed. There is a natural break in ages (Fig. 1a and b) distributed throughout the gravels at about 2 m height from the gully floors (<2 m, 90% of the clasts are stage 7, 10% are stage 5e; >2 m elevation, 100% are stage 5e). The probability of this sorting arrangement from a large pool of stages 7 and 5e clasts is 1 in 10,000 (0.01%). Within the present sample set, no stage 5e samples were collected over 30 m in elevation. There is again less than 0.01% probability that a single event could have divided clasts into the observed populations of >30 m (100% stage 7) and <30 m (56% stage 5e, 44% stage 7). If the clast ages are separated into four populations (on the basis of height from gully floor, above/below 2 m, and elevation, above/below 30 m), the probability that the observed sorting was derived from a single event diminishes to 3 in 100,000.

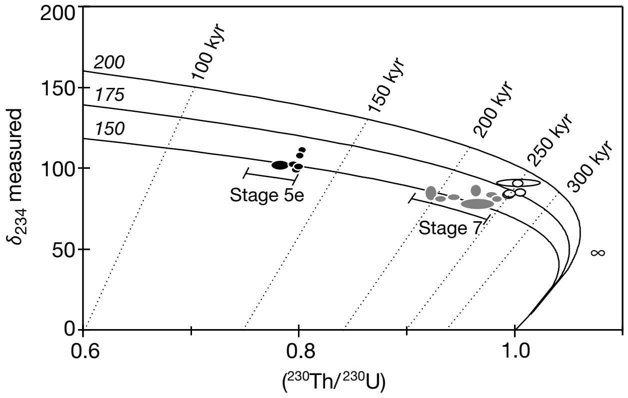

Figure 2 ^{230}Th–^{234}U–^{238}U data for Hulopoe gravel coral clasts. Closed-system evolution curves with different initial ^{234}U/^{238}U (given as δ values of 150, 175 and 200) and isochrons through the data field (dashed lines) are also shown. Data are plotted as ellipses centred on the data points and extending in the *x*- and *y*-directions to encompass 2σ analytical errors in (^{230}Th/^{238}U) and δ^{234}U. Symbol fill patterns as in Fig. 1.

The number of dated samples is relatively small, but we tested the statistical significance of these sample populations using the null overlap hypothesis for mean ages and variances with the Student's *t*-distribution for small sets (95% confidence limit). Our results demonstrate that these probabilities are derived from valid distinct populations. Mean ages in the sample groups <2 m and >2 m from gully floor, and in the sample groups <30 m elevation, >2 m from base and >30 m elevation, <2 m from base could not have been drawn from the same original sample population because their upper and lower *t*-distribution limits do not overlap. Thus both height in section and combined height in section plus depositional elevation are robust groupings for deposit discrimination using clast ages. By contrast, mean ages of samples in the >30 m and <30 m groups do overlap at the 95% confidence limit, indicating that depositional elevation alone is not a robust discriminant.

We conclude that the degree of stratigraphically controlled clast age sorting is incompatible with deposition of the entire package of gravels in a single event (tsunami or otherwise), invalidating the main premise of the giant wave hypothesis. On the basis of the 95% confidence level statistics, additional clast ages are unlikely to change the observed sorting, and thus the multi-event result (although they might extend the geographical coverage of the stage 5e strata). The geological significance of this clast age distribution is that the 2 m horizon within the MB correlates with the top of the basal units in the lower-elevation portions of the gullies studied. No datable samples were recovered from the intervening alluvial stratum, yet all samples at higher MB stratigraphic levels are stage 5e aged. Thus clasts in strata above and below 2 m were derived from fundamentally different source material (specifically, stage 5e versus stage 7 reef). The change in source materials aged ~70 kyr apart suggests a considerable time break between deposition of the basal layers (followed by erosion, soil formation, alluvial deposition and additional soil formation[13]) and the stage 5e layers. Only stage 7 samples were found in the upper elevation outcrops. Their stratigraphic relationship to the lower elevation basal units is unclear but they may be the source beds of stage 7 clasts (via down slope reworking after their original deposition).

Formation of the Hulopoe gravel

Besides that of the giant wave hypothesis, other studies have used geochronology to explain subaerial exposures of bioclastic sediments found throughout Hawaii[14,15,20,21]. Late Quaternary uplift in the high central Hawaiian Islands was used to rationalize now-emergent *in situ* reef deposits on O'ahu[14,15]. Also, uplift was proposed[21] from a broad range of electron-spin resonance (ESR) ages of coral clasts at 5–30 m elevation on O'ahu (9 at 122 to 562 kyr ago) and 10–70 m elevation on Moloka'i and Lana'i (27 at 170 to 303 kyr ago, 2 at 140 to 146 kyr ago, and 1 at 37 kyr ago). Clast ages in both previous Lana'i studies[4,21] were determined by relatively imprecise methods and were not meaningfully tied to the geologic origins of the beds where they were sampled. Although ages differ, neither previous study documented an age progression through the Hulopoe gravel[21].

Other authors have also discussed whether the giant wave could have formed all or part of the Hulopoe gravel[2,4,10,13,21–23]. Even before the present data were obtained there were difficulties with the giant wave model: analogous modern deposits have not been observed (most tsunami deposits are significantly thinner, containing primarily sand-sized grains and few boulders[24]); the Hulopoe gravel contains numerous different deposition facies; tsunami models do not predict such large run-up heights from likely Hawaiian landslides; and the volume of living and dead coral just offshore of Lana'i is a small fraction of that required to instantaneously form a similar deposit today. There are also two ways to explain clast size observations[23] in the Moloka'i gravels (up-gully diminishing-mean coral clast sizes and abundances at constant basalt clast sizes and at increasing abundances). One explanation is that clast size variations reflect coral mobilization from a point source (an offshore reef) and "distal" fining as a tsunami wave decelerated across the landscape, leaving basalt clasts unsorted because they were not point-source-derived[23]. But this sorting can also be rationalized in a second way, by a variable-energy depositional environment (for example, approaching a beach from offshore), wherein the less robust coral clasts are preferentially fragmented, resulting in diminished sizes and abundance up the energy gradient, without affecting basalt clasts. In fact, it is difficult to envisage how the tsunami mechanism would size-sort corals and yet not sort denser basalt clasts of the same size modes.

We recognize the significance of large mass-wasting events in shaping the Hawaiian landscape (see citations in refs 8, 10, 21) and the probability that such events sometimes result in tsunamis. However, the difficulties noted above and our data, which require several depositional events, oblige us to take a uniformitarian approach and reconsider the geologically plausible explanation that the Hulopoe gravel resulted primarily from more benign littoral deposition and relative sea-level change, as originally proposed[1,3]. Such a scenario allows for large storms or normal tsunamis to have deposited local pockets of high-energy strata in the gravels.

Potential histories of the Hulopoe gravel should allow for two depositional events separated by ≤70 kyr (that is, the clast age differences between the basal unit and stratigraphically higher gravels in lower Kapihaa and Archeology gullies), as well as a second time gap of undetermined length preceding coastal terrace deposition. These histories should also consider the modern shoreline depositional environment, which has unconsolidated gravels with clasts of similar size, shape and type populations at the mouths of most gullies, extending to ~4 m above and to several metres below mean sea level. The proximal LSG deposit at about the modern mean sea level (composed of Holocene corals, dated here

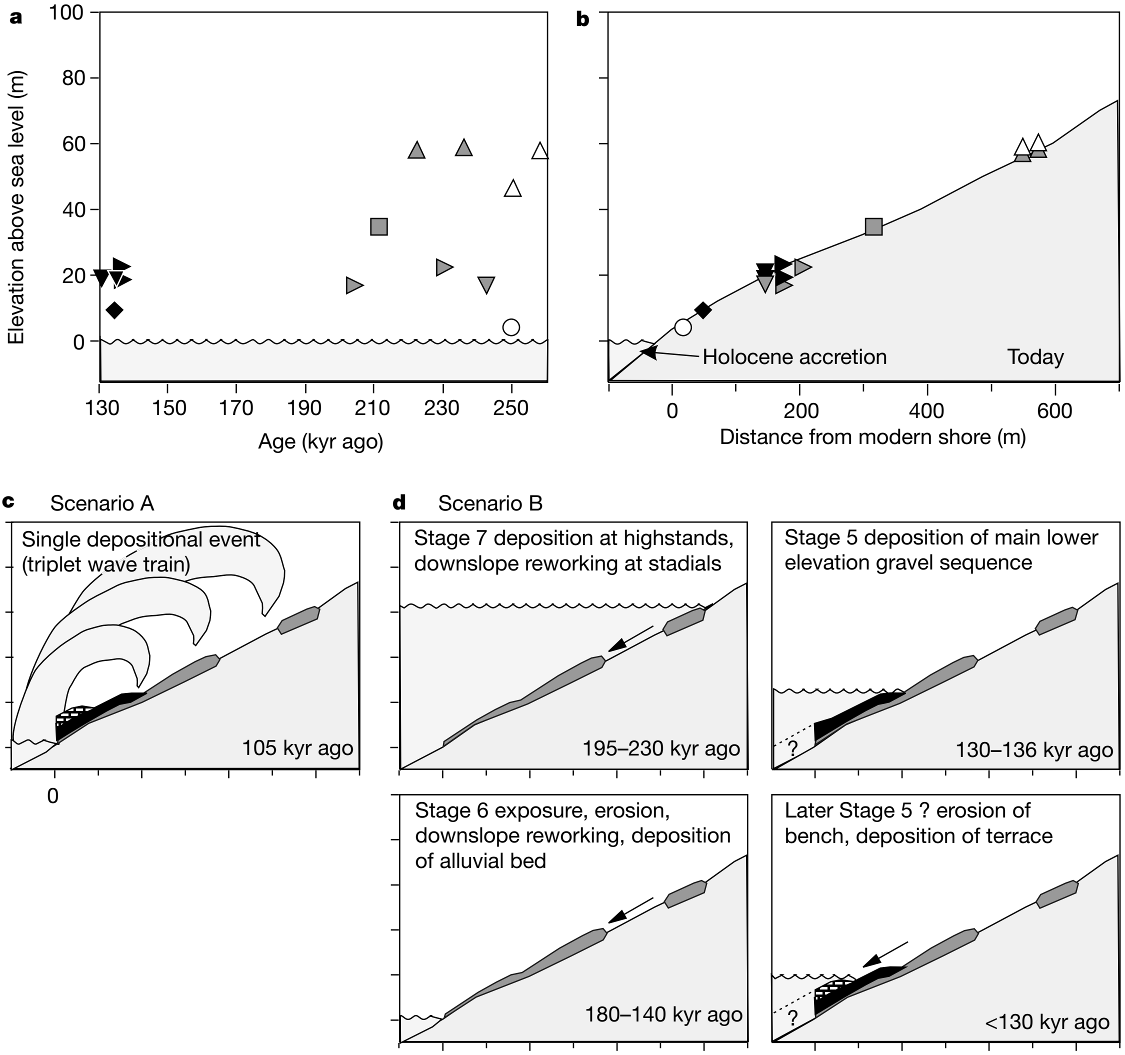

Figure 3 Age-elevation relationships for Hulopoe gravel coral clasts. **a**, Plot of age and present elevation above sea level. **b**, Composite section of Kapihaa and Archeology gully samples superimposed on the cross-sectional topography (vertical exaggeration is 5 times). Symbol types and fill patterns as in Fig. 1. The coastal terrace is shown as white bricks. Two scenarios (A and B) for forming the deposits are also shown in **c** and **d** (outcrop thicknesses have been exaggerated vertically by 100% to make them easier to see; axes are as in **b**). Scenario A is the giant tsunami hypothesis. Scenario B involves sea-level variations and recent uplift of Lana'i. Arrows depict downslope reworking of the deposits. Only relative sea levels are given, as this scenario takes place in the context of both rising/falling sea levels and uplift of the island (the later of which has an unknown time–elevation pathway). Fill patterns for deposits in **b**–**d** are the same as in Fig. 1f.

at 2.5 ± 0.5 kyr ago, and older basalts) probably formed in an analogous environment to some Hulopoe gravel beds.

One scenario (Fig. 3) is that coral-bearing conglomerates were deposited, possibly over a range of upper and lower shoreface elevations, as sea level reached a maximum during the stage 7 deglaciation, and subsequently lithified. Like today, the stage 7 shoreline deposition was probably localized within relief at pre-existing gully mouths and laid down as a thinner veneer on interfluves. Our maximum mapped extent of coral-bearing conglomerate was 63 m (in Kapihaa gully), although it is possible that it extended further upslope in the past. As sea level retreated, some stage 7 material was re-worked down slope, accompanied by new deposition, to form the lower elevation basal layers. On the basis of the maximum elevation difference today between *in situ* stage 7 reef (−15 m)[16] and clastic deposits (15 m) containing stage 7 corals at Kahe point, O'ahu[20], we would expect to find remnants of *in situ* reef at lower elevations in Kapihaa gully today if it had existed in the past. Either it has been completely eroded or a large fringing reef never existed.

Following sea-level retreat, the basal deposit was partially eroded, an alluvial deposit was emplaced, sea levels subsequently rose to the stage 5e interglacial maximum, and the next sequence of gravels were deposited, again primarily filling preexisting topography. These attain a maximum elevation of 25 m in our sample set, which is some 18 m higher than the *in situ* stage 5e reef on O'ahu today[14,15]. After the maximum stage 5e interglacial, the terrace sequence was deposited over both gravel-filled gullies and bare basalt headlands. Clast type[13] and age populations indicate that it probably contains upslope alluvium. The time gap is difficult to determine, but the terrace is probably also a stage 5 deposit, possibly a prograding bed from the 5e regression, as no younger clasts were found. The large proportion of sand-size marine fossils, abundant corals and macrofaunal shells, strong cementation and beach rock clasts are consistent with deposition in a marine littoral environment.

Although the Hulopoe gravel is consistent with transgressive–regressive sea-level cycles, its vertical extent is significantly greater than sea-level change over the period and clearly implies that the island has been uplifted. Taking into account the range of estimated global stage 7 and 5e sea levels (−6 m to +9 m and +2 to +8 m, respectively)[15,25–27], maximum elevations of stage 7 and 5e outcrops in Kapihaa gully today suggest mean uplift of 0.23–0.29 and 0.15–0.22 mm yr^{-1}, respectively. The ranges depend on uncertainty in maximum elevations, palaeo sea levels, and depositional depths. These rates are means derived from one time-elevation point but the data do not require that uplift be a smooth function in time. These rates are lower than previous estimates (0.33 mm yr^{-1})[21], are ~3–5 times that of O'ahu[14,15,21], and are at the low end of the Sumba Island, Indonesia, range (0.2–0.5 mm yr^{-1}; ref. 11).

There are a number of potential causes for Late Quaternary uplift of tectonically active Lana'i (which experienced one of the largest historical Hawaiian earthquakes, the $M = 7.0$ earthquake of 1871 (ref. 28)). We do not discuss them in detail here, but two viable mechanisms are lithospheric flexure of the Pacific plate in response to volcanic loading on the Big Island[29,30] and isostatic rebound following mass redistribution in large landslides[31]. Isostatic rebound can cause uplift of 1–100 m using a range of plausible landslide volumes[31]. Likewise, uplift can be plausibly modelled at Lana'i and Moloka'i by lithospheric flexure within reasonable bounds on elastic plate thickness and on the local rheology of the lithosphere/asthenosphere, the time-dependence of volcanic loading on the Big Island, and the potential effect of the Molokai fracture zone (P. Wessel, personal communication). Notably, flexure models predict a steep increase in subsidence approaching the Big Island, such that it and parts of southern Maui can be subsiding while Lana'i, Moloka'i and O'ahu are uplifting. Thus, tidal gauge evidence originally used to dismiss emergent sea level deposits on Lana'i[2,4] is not necessarily applicable.

Although great landslides are a common part of the evolution of Hawaiian volcanoes and probably result in tsunamis of some sort, we here present evidence that the Hulopoe gravel was not deposited in a single event. This invalidates the basic premise of the original giant wave hypothesis[2,4]. Rather than being the type deposit of a mega-tsunami with a 375-m run-up, we propose that coral clast ages, gravel stratigraphy, and facies variations within these gravels record a multi-event/multi-environment sequence of normal littoral and alluvial deposition. Additional work is required to fully parametrize the uplift and subsidence history of the Pacific plate around Hawaii, although the magnitude of uplift proposed here is not unreasonable. Despite the present analysis, controversy about other subaerial fossiliferous sediments in Hawaii might continue, as the sedimentary records are difficult to interpret in the field. Future study could focus on the less fully understood aspects of the proposed alternative model for deposition during eustatic sea-level variations and vertical movement of Lana'i, or on other plausible depositional scenarios consistent with the geological and geochronological observations. ☐

Methods

Sample chips (~2 g) were taken from coral clasts that appeared to be largely pristine in all or part of their interiors (discernible skeletal structure, visual lack of secondary precipitates and/or extensive discoloration). In all, 50 corals were sampled at 8 sites; 36 of these were fresh enough to screen for mineralogical purity. Chips were physically cleaned under a binocular microscope, ultrasonically washed/leached with ultra pure water and 0.05 M HNO_3 in a clean room, dried under filtered air, and powdered in a synthetic corundum mortar. Powdered splits were analysed for aragonite and calcite abundance by X-ray diffractometry. Calcite was fully resolved from baseline at 2.3% and only samples with ≤2.3% calcite were analysed for U-series isotopes. One 'acceptability threshold' exception was made (Lan2-8-1, with 3.3% calcite) because landscape grading subsequently destroyed the sampling locale.

Th and U were separated and purified from the bulk sample by anion exchange methods[32]. Samples were weighed, dissolved in 0.5 M HNO_3, centrifuged to remove any insoluble (non-carbonate) material, spiked with calibrated ^{229}Th and ^{233}U tracers, evaporated to dryness, fumed in ultra pure aqua regia, evaporated to dryness, and equilibrated and dissolved into 500 μl of 7.5 M HNO_3 for Th and U separation. Th and U concentration and isotopic composition analysis was by high precision thermal ionization mass spectrometry of samples loaded on Aquadag carbon on outgassed single Re filaments. Total procedural blanks were 1–5 pg U, 5–10 pg Th. U-series results are reported in Table 1 using parentheses to denote activity ratios. Data uncertainties are discussed in Table 1.

Ages were calculated using[33]: $1 - (^{230}\mathrm{Th}/^{238}\mathrm{U}) = e^{-\lambda 230 T} - (\delta_{234}/1{,}000)(\lambda_{230}/(\lambda_{230} - \lambda_{234}))(1 - e^{(\lambda 234 - \lambda 230)T})$. A detrital Th correction[15] was not applied because corrections assuming Th/U of a Hawaiian tholeiite as detritus are smaller than analytical errors. Age reliabilities were investigated with geochemical tests for closed-system isotopic evolution since coral death, including evidence of diagenesis (recrystallization to and/or secondary deposition of calcite), U content, Th/U ratio, ^{234}U/^{238}U, and initial ^{234}U/^{238}U (calculated assuming closed-system evolution with: $\delta^{234}\mathrm{U} = \delta^{234}\mathrm{U}_i e^{-\lambda 234 T}$)[33]. Calcite content ranges from 0 to 3.3% but calculated ages and other U-series parameters are not correlated with it. U content ranges from 2.61 to 3.47 p.p.m.—comparable to other Hawaiian corals (for example, 2.3 to 3.4 p.p.m. for >30 last interglacial corals[15]). Th/U ratios are variable (4.4×10^{-6} to 4.1×10^{-4}) and may indicate some detrital Th addition or U loss (for example, Th/U in Atlantic Ocean sea water[34] is 3.7×10^{-5}), but even our highest Th/U value is well within the range of Th/U in pristine corals from localities worldwide[26,27,33,35], and calculated age does not correlate with Th content or Th/U.

Age-corrected ^{234}U/^{238}U in a coral should compare to that of modern sea water if the coral has remained chemically closed since death and if ^{234}U/^{238}U in sea water has remained constant since formation. δ^{234}U in modern corals and $\delta^{234}\mathrm{U}_i$ in Holocene corals are typically indistinguishable from the modern seawater value (see refs 32 and 33; K.H.R., unpublished work). Elevated $\delta^{234}\mathrm{U}_i$ observed in some older corals probably indicates open-system behaviour[11,16,26,36] (although it has been suggested that ^{234}U/^{238}U in sea water may have differed in the past[36]). Most workers apply a working definition of ^{230}Th-^{234}U-^{238}U age quality based on $\delta^{234}\mathrm{U}_i$ relative to modern: 145–150 is considered highly reliable, 150–160 or 165 is moderately reliable, and $\delta^{234}\mathrm{U}_i > 165$ is less reliable[11,15,35]. These ranges are somewhat arbitrary because acceptable $\delta^{234}\mathrm{U}_i$ varies with how and when open-system behaviour occurred and the absolute age of the sample, and because not all open-system events that modify $\delta^{234}\mathrm{U}_i$ also affect sample age[27,36]. All of the Holocene Lana'i samples, 4 of 6 stage 5e samples, and 3 of 12 stage 7 samples have modern $\delta^{234}\mathrm{U}_i$ values; this supports an essentially constant ^{234}U/^{238}U in sea water over the past 250 kyr[37] and suggests that samples with elevated $\delta^{234}\mathrm{U}_i$ have been variably compromized. There is a clear inverse correlation of age and U content in the Lana'i stage 7 samples, suggesting U loss from the oldest samples (most probably leached by meteoric water without associated calcite recrystallization, consistent with the arid environment and lack of significant ground water in the deposits today). Contemporaneous *in situ* redeposition of ^{230}Th may also have occurred[27]. There is also an inverse correlation of δ^{234}U and $\delta^{234}\mathrm{U}_i$

with U in the stage 7 samples, as well as a lesser but still discernible correlation in the stage 5 samples (although ages do not covary with U content in these). It is likely that ^{234}U was recently added in a second alteration event in proportionally greater amounts to samples with lower U concentrations, although this was not by wholesale modern marine U addition from abiogenic calcitic or aragonitic cements as this would result in a negative correlation of δ^{234}U and age, opposite to that observed.

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