Reports

Deposit from a Giant Wave on the Island of Lanai, Hawaii

Abstract. *Limestone-bearing gravel, the newly named Hulopoe Gravel, blankets the coastal slopes on Lanai. The deposit, which reaches a maximum altitude of 326 meters, formerly was believed to have been deposited along several different ancient marine strandlines, but dated submerged coral reefs and tide-gauge measurements indicate that the southeastern Hawaiian Islands sink so fast that former worldwide high stands of the sea now lie beneath local sea level. Evidence indicates that the Hulopoe Gravel and similar deposits on nearby islands were deposited during the Pleistocene by a giant wave generated by a submarine landslide on a sea scarp south of Lanai.*

Early investigators reported boulders of limestone at high levels on the south slopes of the islands of Molokai and Lanai (*1, 2*), and later workers suggested that this limestone was deposited along ancient shorelines formed at times during the Pleistocene when sea level at the Hawaiian Islands is inferred to have stood above its present level (*3*). More recent evidence indicates that the young southeastern islands subside too fast for former worldwide high stands of sea level to have created shorelines that would now be above local sea level (*4*). We have reexamined these marine limestone boulders in an effort to learn how they reached their present positions (Fig. 1).

Several facts regarding the deposits are clear. (i) The conspicuous white limestone boulders occur in a gravel bed in which most clasts, typically 95 percent, are basalt. (ii) The skeletons of corals and other reef organisms invariably occur as clasts and not in growth position. (iii) Within the boulder bed a cemented layer that previously was considered to have been formed by encrusting reef organisms commonly extends down into the underlying basaltic bedrock, and the lithology of the cemented layer suggests that it is a calcite-cemented soil horizon.

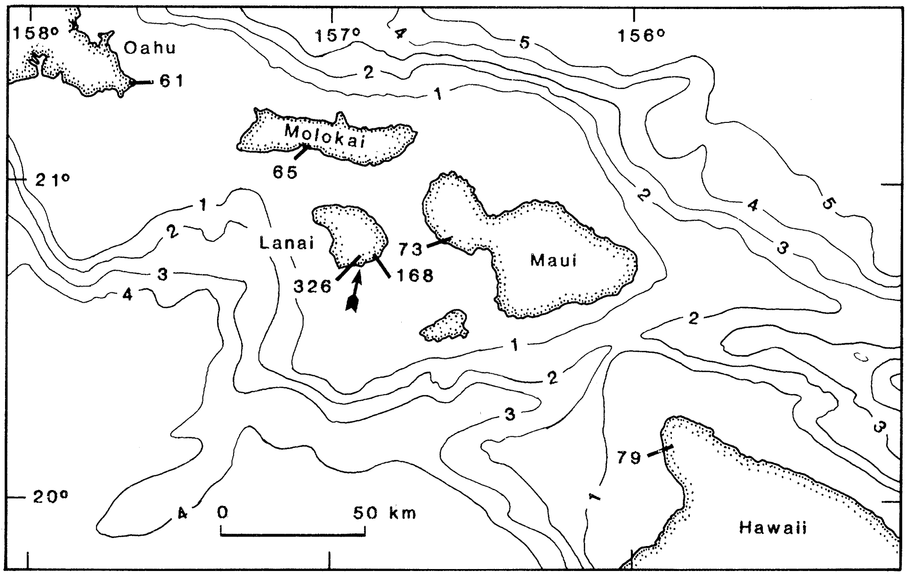

Fig. 1. Index map of the southeastern Hawaiian Islands showing the location of Fig. 2 (arrow) and the local maximum height, in meters, of limestone clasts in the Hulopoe Gravel on Lanai and of other tentatively correlated high-level limestone-bearing deposits. Bathymetric contours are in kilometers.

We mapped an area around Hulopoe Bay on the south coast of Lanai, where the gravel bed is known to be especially thick and widespread, to determine the distribution and attributes of the deposit (Fig. 2). We here name the limestone-bearing gravel bed on Lanai the Hulopoe Gravel, for Hulopoe Bay, and designate as the type locality the exposures along the major gulch which drains into the northernmost extent of Kapihua Bay, the bay directly west of Hulopoe Bay (Fig. 2). The bed is 5 m thick and directly overlies nonweathered basalt at the type locality, about 200 m from the shore (Fig. 3). The bed consists of two layers: a lower layer of subrounded to rounded clasts of basalt (about 95 percent) and limestone (about 5 percent), ranging in size from 3 cm to 1 m, and an upper layer of subangular to angular clasts of basalt ranging from 20 cm to 1.5 m. The boulders of both layers are clast-supported rather than matrix-supported; this evidence suggests that they were water-laid rather than transported in a submarine debris flow. Both the basalt and limestone boulders are varied as to type. Basalt boulders are reddish to dark gray and vesicular to dense; limestone boulders are fragments of honeycomb coral, botryoidal coralline algae, and very coarse grained to fine grained fossiliferous calcareous sandstone derived from beach rock.

Locally in valleys, the upper layer seems to truncate the limestone-bearing lower layer, whereas on ridges the upper layer is commonly thin or missing so that scattered limestone cobbles and boulders from the lower layer are exposed as float. At the surface, limestone clasts are weathered and etched and small ones generally are scarce.

The original thickness of the Hulopoe Gravel and the size of its clasts decrease systematically with distance from the shore and with elevation above sea level. At an altitude of 50 m, where the gravel locally is 4 m thick, the largest clasts are commonly 0.5 m but a few are 1 m in diameter. At an altitude of 100 m, where the deposit is as much as 2 m thick, the largest clasts are commonly 25 cm and rarely 50 cm. A notable exception to the systematic decrease in grain size occurs within Kaluakapo Crater at 150 m (Fig. 2), where clasts attain 75 cm in greatest dimension. Despite the fact that the crater is drained by a narrow gorge, some aspect of its bowl-like geometry favored deposition of a particularly thick and coarse facies of the gravel.

Above an altitude of 200 m, the chief remnant of the deposit is calcareous sand and silt that has sifted down between basalt fragments and into cracks and joints in the basaltic bedrock. In places, small fossils and fossil fragments were lodged in the cracks and cemented, producing veinlike fillings of fossiliferous limestone. Careful tracing of the highest occurrence of these fossiliferous crevice fillings to an altitude of 326 m by Stearns (*5*) led him to designate this as the type locality of the Mahana stand of the sea (Fig. 2). Above the level of calcareous crevice fillings, at an altitude of about 365 m, is an irregular boundary below which the thick red soil typical of upland Lanai has been largely removed, presumably by wave erosion associated with deposition of the Hulopoe Gravel.

The Hulopoe Gravel lies on basaltic bedrock and in a few places on a reddish-brown fossil soil developed on bedrock. The upper surface commonly consists of loose 0.5-m basalt boulders locally deposited as banks and ridges a few meters high along the flanks of ridges and around the heads of gulches (Fig. 4). Beyond the mapped limit of the gravel, rounded basalt boulders extend as a layer no more than one boulder thick, and farther upslope the spacing of these boulders becomes increasingly wide. In Kaluakapo Crater, the gravel is overlain by a thin bed of water-laid reddish-brown silt, and on the flat surface between Manele and Hulopoe bays by pebbly reddish-brown silt.

In a summary of many years' work, Stearns (*3*) interpreted the wide range of altitude for the limestone-bearing material as a series of individual terrace deposits formed at different times by different stands of the sea. The area of Fig. 2 contains the type localities of three presumed ancient stands of the sea: Mahana at 365 m (*3*); Kaluakapo at 183 m (*6*); and Manele at 170 m (*3*). Our observations, however, lead us to conclude that the gravel bed originally blanketed the region as a single deposit.

One of the highest known marine deposits yet found on a Hawaiian Island other than Lanai is located as much as 73 m above sea level in a gulch on the southwestern side of Maui. This fossiliferous marine conglomerate lies 30 km east-northeast from the exposures of the Hulopoe Gravel on Lanai (Fig. 1). The deposit on Maui, which is 1 km north-northwest of Oluwalu, has been designated by Stearns as the type locality of the Oluwalu shoreline (*7*). Similar fossiliferous marine conglomerate beds have been found on the Island of Molokai at 65 m above sea level near the town of Kaunakakai, as large blocks of limestone in talus at 61 m above sea level on easternmost Oahu, and on the Island of Hawaii at 79 m above sea level on Kohala Volcano (*3*). Our observations indicate that the Maui and Hawaii deposits closely resemble the part of the Hulopoe Gravel on Lanai that is about 1 m thick.

Basalt on Lanai dated by the potassium-argon method is 1.25 million years old (*8*), which places an upper limit on the age of the Hulopoe Gravel. Deep soil formed from weathered basalt covers the island at higher elevations than the gravel, and the gravel is younger than the soil; this finding suggests that the gravel is considerably younger than the basalt. A brown weathering rind about 1 cm thick on the surficial basaltic boulders of the gravel deposit indicates substantial age, however, as does the calcite-cemented soil within the gravel, which forms a 1-m-thick hard layer about 3 m below the ground surface. A collection of fossil mollusks (U.S. Geological Survey sample M8475) from 350 m northwest of Kaluakoi Point (Fig. 2), identified and interpreted by Moore (*9*), indicates a habitat of intertidal to 20-m depth and includes *Strombus (Gibberulus) gib-*

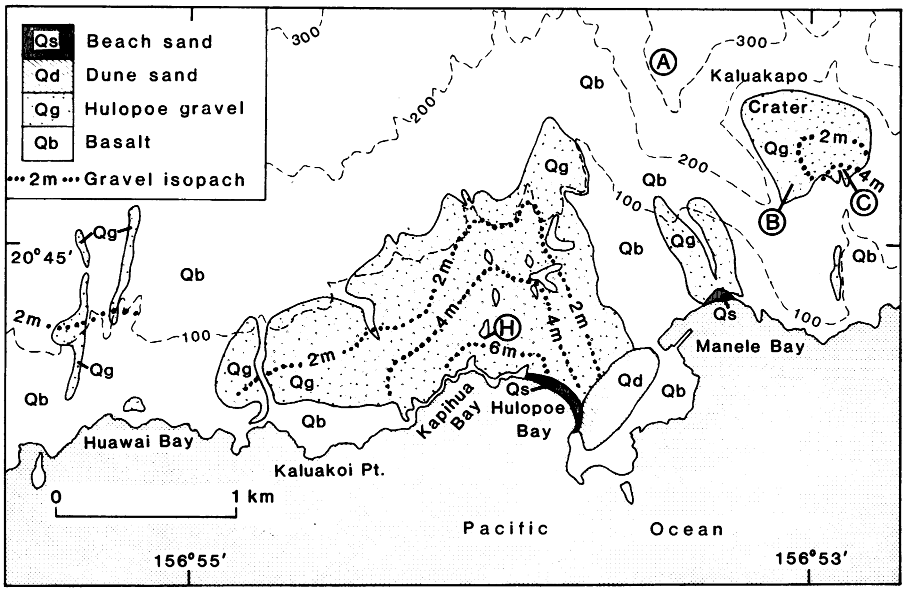

Fig. 2. Geologic units of Quaternary age on part of the south coast of the Island of Lanai, showing the type localities of the Hulopoe Gravel (H) and of previously named presumed ancient shorelines: Mahana (A), Kaluakapo (B), and Manele (C); contour interval, 100 m.

Fig. 3. Outcrop of the Hulopoe Gravel near its type locality, showing limestone and basalt clasts.

Fig. 4. A long ridge of basalt boulders, about 5 m wide, at the upper surface of the Hulopoe Gravel near its type locality.

berulus gibbosus (Röding). This marine snail now lives at the more equatorial Marshall Islands and Line Islands but is locally extinct in Hawaii; this result suggests a Pleistocene age and a warmer oceanic temperature for the Hulopoe Gravel.

Fossiliferous conglomerate on Kohala Volcano on the Island of Hawaii, similar to that of the Hulopoe Gravel, lies on basalt that has been dated by the potassium-argon method at about 0.4 million years (*10*). If this conglomerate was deposited at the same time as the Hulopoe Gravel on Lanai, then the maximum age of the gravel is further constrained.

Two uranium-series dates have been published for limestone clasts on the southeastern Hawaiian Islands: a specimen from Lanai at an altitude of 171 m was dated by J. K. Osmond as more than 350,000 years old (*11*); and a coral fragment from Hawaii at 6 m was dated by H. H. Veeh at 110,000 ± 10,000 years old (*12*). The Island of Hawaii subsides at a rate of 2 mm/year; this estimate is based on tide-gauge measurements and dated submerged coral reefs (*4*). Considering this rate of subsidence for Hawaii and the age of the bedrock there, if the limestone boulders on all the southeastern islands are the same age as the Hulopoe Gravel, the 110,000-year age seems the more reasonable for them. At the subsidence rate for the Island of Hawaii, the original position of the 110,000-year-old specimen would have been at an altitude of about 230 m, and the nearby fossiliferous conglomerate at a present altitude of 79 m on Hawaii, if 110,000 years old, would have been laid down at an altitude of about 300 m. The highest known occurrence of fossils associated with the Hulopoe Gravel on Lanai, at 326 m (*5*), if corrected for an estimated subsidence rate of Lanai of 0.5 mm/year, would have been deposited at an altitude of about 380 m. Traces of soil stripping are about 40 m higher than the fossils.

The proposition that ancient high-level emerged shorelines exist on the Hawaiian Islands has prompted controversy for half a century, especially in view of the well-defined submerged shoreline terrace and reefs. Stearns (*3*) realized that the altitude and depth range of these features is so great that they could not have resulted wholly from worldwide fluctuations of sea level caused by the withdrawal and return of water to the oceans by the growth and melting of glacial ice sheets. He also recognized that the sea had remained only briefly at the various high shorelines that he proposed. Early suggestions that the high-level fossiliferous material was carried uphill by native Hawaiians (*2*), or blown uphill by the wind (*13*), have been successfully refuted by Stearns (*3*). His preferred model includes an early Pleistocene subsidence caused by volcanic loading to explain the evidence for submergence, followed by a dramatic emergence, caused either by the local intrusion of a tremendous body of magma or by a worldwide change in sea level caused by a sinking of the ocean floors.

Our investigation indicates that all the proposed ancient high-level shorelines, including three with type localities on Lanai and one on Maui, can be correlated with a single event, the deposition of the Hulopoe Gravel. Furthermore, many features of the Hulopoe Gravel indicate that it was deposited by the surge of a giant ocean wave that swept several hundred meters up the flanks of Lanai and nearby islands about 100,000 years ago. The marine material in the deposit was ripped up from the littoral and sublittoral zone and was mixed with basaltic debris as the wave swept inland. The resulting deposit mantles the surface and both thins and becomes finer grained with increasing distance from the shoreline. The deposit is particularly well preserved where topographic traps blocked backflow from such a wave, for example, within Kaluakapo Crater (Fig. 2). The lower layer containing rounded clasts and limestone may represent the upsurge of the wave, and the upper layer containing angular basaltic clasts may represent the backflow from the same wave.

Because of the great run-up of the wave, it was probably not a seismic sea wave caused by a subsea earthquake. Run-up of the highest recorded Hawaiian tsunami reached only 17 m above sea level in Pololu Valley on the Island of Hawaii in 1946 (*14*). Either the impact of a meteorite on the sea surface or a shallow submarine volcanic explosion could have generated the Hulopoe wave. We believe, however, that a more likely explanation is a rapid downslope movement of a subsea landslide on the Hawaiian Ridge, which is among the steepest and highest landforms on earth. The occurrence of several major subsea landslides of various ages, possibly triggered by local earthquakes, indicates that the Hawaiian Ridge is a site of repeated slope failure (*15*). A landslide in a confined fjord in Alaska in 1958 produced a run-up of 524 m, the highest on record (*16*). We infer that rapid movement of a submarine slide near Lanai displaced seawater forming a wave that rushed up onto the islands, carrying with it rock and reef debris from the nearshore shelf and beach.

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Specific Sequence Homology and Three-Dimensional Structure of an Aminoacyl Transfer RNA Synthetase

Abstract. *Few and limited amino acid sequence homologies have been found among eight bacterial aminoacyl transfer RNA (tRNA) synthetases whose primary structures are known. The entire 939–amino acid primary structure of* Escherichia coli *isoleucyl-tRNA synthetase is now reported. In a sequence of 11 consecutive amino acids matching a sequence in* E. coli *methionyl-tRNA synthetase, there are ten identical residues and one conservative change. This is the strongest homology recorded between any two aminoacyl tRNA synthetases. This part of the methionine enzyme's three-dimensional structure has been determined, and it occurs in a mononucleotide binding fold; a close three-dimensional structural homology of this part of the enzyme with* Bacillus stearothermophilus *tyrosyl-tRNA synthetase has also been reported. The three synthetases probably fold identically in this region.*

Aminoacyl transfer RNA (tRNA) synthetases presumably arose early in evolution and established the rules of the genetic code by means of the aminoacylation reaction, in which amino acids are matched with trinucleotide sequences within tRNA molecules. It has appeared that the evolutionary relations between these canonical enzymes are weak because (i) the enzymes vary in size, (ii) there are diverse quaternary structures (*1*), and (iii) sequence homologies between the bacterial enzymes sequenced so far are sparse or nonexistent (*2–5*). We now report the first strong homology between any two synthetases and further evidence that, in spite of the various sizes of these enzymes, the catalytic portions are toward the amino terminus.

A restriction map of an 8-kilobase (kb) segment of *Escherichia coli* K12 DNA cloned into plasmid pGM21 (*6*) (Fig. 1) shows three coding regions that have been defined: ribosomal protein S20 (*7*), Ile-tRNA synthetase, and an overlapping unidentified open reading frame that would encode a polypeptide approximately 17 kilodaltons (kD) in size. The organization of restriction sites in this region suggests that the open reading frame encodes the prolipoprotein signal peptidase (*8*); this suggestion has been confirmed (*9*). We sequenced the coding region for Ile-tRNA synthetase and extended the sequencing through the region encoding the 17-kD polypeptide.

The long open reading frame encoding Ile-tRNA synthetase is located 1.4 kb from the gene encoding S20 and is transcribed in the opposite direction from it. Extensive polypeptide sequence information was independently obtained from the enzyme isolated from *E. coli* MRE600. The amino and carboxyl terminal sequences determined for the polypeptide (*10*) match exactly those encoded by the long open reading frame of the DNA sequence, rigorously defining the location and span of the *ileS* coding region.

The translated amino acid sequence of *E. coli* K12 Ile-tRNA synthetase (Fig. 2) shows stretches of the translated polypeptide sequence that were established by amino acid sequencing of purified peptides isolated from digests of the *E. coli* MRE600 protein. Altogether about 70 percent of the sequence was independently confirmed in this way. There is a strong amino acid sequence homology between residues 57 to 67 of Ile-tRNA synthetase and residues 14 to 24 of *E. coli* Met-tRNA synthetase (*4*) (Fig. 3, a and b). The homology starts with a proline which, in the methionine enzyme's structure (*11*), is near the end of the first β segment of the alternating βαβ . . . structure that is characteristic of mononucleotide binding folds. The subsequent residues (15 to 24) complete the β piece and form a characteristic loop which joins that piece to the first α-helix segment.

The significance of this region is reinforced by its strong three-dimensional structural homology, if not perfect sequence homology, with an identical structural arrangement near the amino terminus of *Bacillus stearothermophilus* Tyr-tRNA synthetase (Fig. 3c) (*12, 13*). In that enzyme the corresponding proline occurs at position 39, and the local conformation of the chain is almost superimposable with that of the methionine enzyme. The α carbons of residues 14 to 28 of the methionine enzyme, for example, have a root-mean-square deviation of 1.8 Å when they are superimposed on residues 38 to 52 of the tyrosine enzyme (*12*).

It is with this part of the methionine enzyme that the strong amino acid sequence homology occurs with Ile-tRNA synthetase (Fig. 3b). This sequence homology and the close structural homology (in this region) between the Tyr- and Met-synthetases implies that Ile-tRNA synthetase is folded in the same way. The *E. coli* Gln-tRNA synthetase is also homologous in exactly the same region (Fig. 3d). We surmise that this is because of powerful selective pressures exerted on the structure in this region.

One constraint is possibly the contact points between adenosine triphosphate (ATP) (or the adenyl part of the adenylate intermediate) and the protein. In the tyrosine enzyme, His^{48} is probably hydrogen-bonded to a ribose oxygen and His^{45} is in close proximity (*12*). Although ATP binds in the analogous place in the methionine enzyme, structural details are still unresolved (*12*). The two analogous histidines are at positions 22 and 25 in the methionine enzyme and align with histidines 64 and 67 of Ile-tRNA synthetase.

The αβ mononucleotide fold in Tyr- and Met-tRNA synthetases extends over

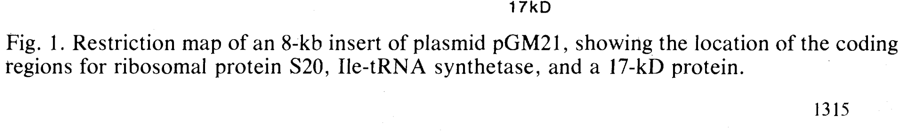

Fig. 1. Restriction map of an 8-kb insert of plasmid pGM21, showing the location of the coding regions for ribosomal protein S20, Ile-tRNA synthetase, and a 17-kD protein.