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Sedimentology of rocky shorelines: 1. A review of the problem, with analytical methods, and insights gained from the Hulopoe Gravel and the modern rocky shoreline of Lanai, Hawaii

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Abstract

Hypotheses advanced concerning the origin of the Pleistocene Hulopoe Gravel on Lanai include mega-tsunami, abandoned beach, ‘multiple event,’ rocky shoreline, and for parts of the deposit, Native Hawaiian constructions and degraded lava flow fronts. Uplift of Lanai shorelines has been suggested for deposits occurring up to at least 190 m. These conflicting hypotheses highlight problems with the interpretation of coarse gravel deposits containing marine biotic remains. The geological records of the processes implied by these hypotheses should look very different. Discrimination among these or any other hypotheses for the origins of the Hulopoe Gravel will require careful study of vertical and lateral variations in litho- and biofacies, facies architecture, contact relationships and stratal geometries of this deposit. Observations of modern rocky shorelines, particularly on Lanai adjacent to Hulopoe Gravel outcrops, have shown that distinctive coarse gravel facies are present, several of which occur in specific geomorphic settings. Tectonic, isostatic and eustatic changes which cause rapid shoreline translations on steep slopes favour preservation of former rocky shorelines and associated sedimentary deposits both above and below sea level. The sedimentary record of those shorelines is likely to be complex. The modern rocky shoreline sedimentary environment is a hostile one, largely neglected by sedimentologists. A range of high-energy processes characterize these shorelines. Long-period swell, tsunami and storm waves can erode hard bedrock and generate coarse gravel. They also erode older deposits, depositing fresh ones containing mixtures of materials of different ages. Additional gravelly material may be contributed by rivers draining steep hinterlands. To fully evaluate rocky shoreline deposition in the broadest sense, for both the Hulopoe Gravel and other deposits, sedimentary facies models are needed for rocky shorelines occurring in a range of settings. Recognition and description of rocky shoreline deposits are crucial for correctly interpreting the geological history of oceanic and volcanic arc islands, for distinguishing between ancient tsunami and storm deposits, and for interpreting coarse-grained deposits preserved on high energy coasts of continents. Problems include not only the absence of appropriate sedimentary facies models linking rocky shoreline deposits and environments but also, until recently, lack of a systematic descriptive scheme applicable to coarse gravel deposits generally. Two complementary methods serve to integrate the wide range of bed and clast attributes and parameters which characterize complex coarse gravel deposits. The composition and fabric (CAF) method has a **materials** focus, providing detailed description of attributes of the constituent clasts, petrology, the proportions of gravel, sand and mud, and the ways in which these materials are organized. The sedimentary facies model building (FMB) method emphasizes the organization of a

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deposit on a bed-by-bed basis to identify facies and infer **depositional processes**. The systematic use of a comprehensive gravel fabric and petrography log (GFPL), in conjunction with detailed vertical profiles, provides visual representations of a range of deposit characteristics. Criteria useful for distinguishing sedimentary facies in the Hulopoe Gravel are: grain-size modes, amount of matrix, bed geometry, sedimentary structures, bed fabric and clast roundness.

Keywords: Gravel deposits; Coastal sedimentation; Shallow-water environment; Shoreline features; Morphology; Field methods

1. Introduction

This paper has its origin in problems arising from a detailed study of the Pleistocene Hulopoe Gravel on Lanai, Hawaii. This enigmatic coral-bearing, coarse gravel-dominated unit outcrops on the slopes of south Lanai to at least 190 m elevation, and possibly as high as 326 m (Stearns, 1938; Stearns, 1940; Fig. 1). A number of hypotheses have been published concerning its origin: one or more "giant waves" or mega-tsunami (Seymour, 1981; Moore and Moore, 1984, 1988; Bryan and Moore, 1994), one or several beach deposits (Stearns, 1938, 1978; Grigg and Jones, 1997; Keating and Helsley, 2002), punctuated deposition associated with a rocky shoreline (Felton et al., 2000) and deposition by multiple events typical of Hawaiian shoreline processes, followed by uplift (Rubin et al., 2000). It has also been suggested that parts of the deposits might consist of degraded lava flow fronts or remains of Native Hawaiian constructions (Grigg and Jones, 1997). Various inferences have been made concerning the causes of both the alleged mega-tsunami and the sea-level changes which produced the "beach deposits". Numerous observations and data, including sedimentary data, are presented by different proponents to support conflicting hypotheses. Not only is there disagreement about observations (Grigg and Jones, 1997), but the same data have been used to draw different conclusions (Stearns, 1938; Moore and Moore, 1984). Sedimentary data presented in all these studies do not comprehensively describe and characterize the deposit, and thus are inadequate to constrain inferences about depositional processes. Much more critically, differing views of the Hulopoe Gravel imply very different shoreline histories and hence interpretations of the relative effects of tectonism, isostasy and eustatic sea level changes on the island, quite apart from the nature of any storm or tsunami depositional record. Furthermore, these differing views reflect a clash of paradigms: a "eustasy" paradigm exemplified by the work of Stearns (1938, 1940) and Rubin et al. (2000); an "event" paradigm (Seymour, 1981; Moore and Moore, 1984, 1988; Bryan and Moore, 1994; Rubin et al., 2000) for which no formal analytical framework has been developed; an "uplifted Lanai" paradigm (Stearns, 1978; Grigg and Jones, 1997; Keating and Helsley, 2002; Rubin et al., 2000) resulting from recent recognition that both flexure of the lithosphere surrounding the Hawaiian Islands, and isostatic adjustment consequent on giant submarine landslides on their flanks, can result in island uplift; and a "facies model" paradigm (Felton et al., 2000) based on well-established principles of sedimentary facies analysis. These paradigms reflect not only advances in geological understanding, but also the tendency to apply the latest paradigm to old problems, whether or not such application is appropriate (Miall and Miall, 2001).

A preliminary study of the type section of the Hulopoe Gravel (Felton et al., 2000) showed features inconsistent with deposition by a single event, as proposed by Moore and Moore (1984, 1988). The variety of coarse gravel sedimentary facies present, and several depositional hiatuses in the 9.2 m section, imply punctuated deposition by several different processes. Many features are inconsistent with wholly tsunami deposition, including the presence of an alluvial unit and palaeosols within the type section. That study also showed that existing methodology for describing and characterizing coarse gravel sedimentary facies was inadequate. Subsequent work by Blair and McPherson (1999) has provided a framework, but this required further elaboration to characterize the range of sedimentary facies present in the Hulopoe Gravel.

The sedimentary facies represented in the Hulopoe Gravel (except for the alluvial unit) do not correspond with those of any of the well-described coarse gravel-dominated depositional environments. During the search for examples of well-described similar facies, it became clear that parts of the Hulopoe Gravel resembled strata attributed to ancient rocky shoreline deposition. However, like the Hulopoe Gravel itself, the sedimentary facies characteristics of those ancient deposits are not represented in any of the existing facies models for coarse gravelly sediments. Lacking such models, recognition of ancient rocky shorelines relies substantially on non-sedimentary evidence, such as geomorphic features and characteristic biotic assemblages, (e.g., Johnson et al., 1995; Johnson and Libbey, 1997; Johnson and Ledesma-Vázquez, 1999). The erosional processes that produce characteristic rocky shoreline landforms such as cliffs, stacks and shore platforms have been comprehensively described and modelled (Trenhaile, 1987; Sunamura, 1992). Erosional products, however, are rarely mentioned. Modern rocky-shore ecology is another area of specialty research, and the topic of both general and specialized texts, e.g., Stephenson and Stephenson (1972) and Wilson and Palmer (1992). From ecological and geomorphic perspectives, sediments are substrates for biological colonization, or tools to attack and armour to defend the shoreline. The rocky shoreline as a **sedimentary** environment is acknowledged only briefly in the latest editions of sedimentary geology textbooks (Reading and Collinson, 1996; Nichols, 1998). Nichols (1998) also emphasizes rocky- shore biotas.

The contribution that rocky shoreline deposits can make to studies of coastal change, through understanding shoreline processes and histories, has yet to be realized. Coarse gravel deposits are potentially the only depositional record of a range of high-energy processes occurring on rocky shorelines. For example, megaclasts (coarse boulders and blocks) found on modern rock platforms are evidence of rapid coastline changes, caused by high-energy, low-frequency events, such as tsunami, hurricane (cyclone) or storm waves (Süssmilch, 1912; Bourrouilh-Le Jan and Talandier, 1985; Nott, 1997; Noormets et al., in press). Modelling the wave power required to move the largest megaclasts can give reliable estimates of wave energies where wave records do not exist, and can be linked to specific tsunami and storms, e.g., Noormets et al. (2002b). In addition, these and other shoreline gravel bodies that rest on erosion surfaces cut in bedrock are potential basal conglomerates (Twenhofel, 1926; Bates and Jackson, 1980), important stratigraphic markers in the rock record. Johnson (1992) stated that "all ancient rocky shores are represented in the geologic record by unconformities", but noted that not all unconformities represent former rocky shorelines. The omission of rocky-shore unconformities and their associated sediments from the classic work "Facies Models. Response to Sea Level Change" (Walker and James, 1992), especially in view of the allostratigraphic approach advocated for sequence stratigraphic studies by Walker (1992a), suggests that the contribution of rocky shoreline studies to this topic is particularly under-appreciated by sedimentologists.

Reasons for sedimentologists' neglect of the rocky shoreline environment are not hard to find. Many modern rocky shorelines are subject to high energy waves for much of the time, and so are hostile to direct investigations on land or by sea. Innovative techniques may be required to gather essential data (e.g., Beach et al., 1995), together with new methodologies to describe and illustrate deposits, particularly very coarse grained sediments (Blair and McPherson, 1999). Thicker deposits may be largely concealed on shorefaces with even moderate relief. Coarse grained deposits may be buried by finer sediment, particularly during periods of calmer sea states when the coastline might be approached more safely. Rocky shorelines have been perceived as too energetic for sediment deposition to occur; and as seldom preserved in the geological record (Johnson, 1988). Johnson (1992) initially found a sparse literature on Phanerozoic rocky shorelines. Later, a more focused literature search for rocky shorelines that formed between 120 and 135 ka yielded more references, and showed that many authors do not describe their study sites as rocky shorelines (Johnson and Libbey, 1997). However, recognition and description of rocky shoreline deposits are crucial for correctly interpreting the geological history of oceanic hotspot and volcanic arc islands, for distinguishing between ancient tsunami and storm deposits, and for interpreting the range of coarse-grained deposits preserved on high energy continental coasts.

2. Ancient rocky shoreline gravel facies

A search for detailed descriptions of rocky shoreline sediments yielded little usable information. Studies cited in the rocky shoreline bibliographies published by Johnson (1992) and Johnson and Libbey (1997) include a number of papers which mention associated sediment, usually pebble and cobble gravel and sand containing marine fauna, or occasionally, boulders and blocks. Many studies have a focus on topics other than sedimentary environments, and provide only limited descriptions of sediment. While written descriptions tend to be sketchy, photographs of deposits often provide more detail. Sedimentary data for coarse gravel deposits are particularly sparse, and key parameters, such as clast size and shape, needed to build a robust facies model for the rocky shoreline environment, are often missing from deposit descriptions. Coarse conglomerate containing bedrock clasts and resting on an erosion surface tends to be described simply as "basal conglomerate", even if no supporting details such as grading, and relationships with overlying sediment are provided.

The few interpretations made (e.g., boulder beach conglomerates; Sloan, 1964) also lack supporting data. Weathered blocks occurring above sea level on tsunami-prone modern coastlines are usually ascribed to tsunami (e.g., Paskoff, 1991); tsunami deposition is also argued for blocks found tens of metres above modern sea level on tectonically stable coasts not known to have been impacted by tsunami in historic time, such as along the storm-prone southeastern Australian rocky shorelines (Young et al., 1996; Bryant, 2001). Cobble and pebble gravel deposits are described as "beach" or "terrace" deposits (Muhs and Szabo, 1982; Giresse et al., 1984; Gvirtzman et al., 1992), although details of the geomorphic context may be described only briefly or not at all. This leaves an impression that many deposits are too thin or poorly preserved to warrant detailed study. It also indicates a lack of knowledge about or interest in sediment deposition on rocky shorelines. However, at least some deposits retain sufficient thickness, extent or geomorphic context to support palaeo-environmental interpretations (Dupré, 1984; Semeniuk and Johnson, 1985; Scott and Johnson, 1993; Gupta and Allen, 1999).

As has been the case for other sedimentary depositional environments, a series of papers dealing with this poorly understood class of sediments will be required to establish a systematic basis for their study. This initial paper reviews the field of study, identifies problems, and proposes analytical methods to overcome them, using the Hulopoe Gravel as an example.

3. The rocky shoreline sedimentary environment

3.1. Settings

Three quarters of the world's coastlines are cliffed and rocky (Bird, 2000). Rocky shorelines are defined by their cliff and shore platform morphologies cut by waves in consolidated material (Grabau, 1913; Semeniuk and Johnson, 1985; Sunamura, 1992). Boulder shores in high latitudes are a particular class of gravel-dominated shoreline, where large clasts eroded from glacial moraines are worked by the actions of waves and sea ice into shoreline pavements (Grabau, 1913; Eyles, 1994). These ice-influenced boulder shorelines are not considered here.

Rocky shorelines form when wave erosion exposes hard bedrock, and begins to carve cliffs and shore platforms. Most cliffs have developed in Pleistocene and Holocene times, mainly during the past 6000 years, when the sea has stood close to its present level (Bird, 2000). Once formed, rocky shorelines persist as long as the sea can continue to erode the cliff base. When marine erosion ceases, cliffs degrade by subaerial processes.

In a review of literature, Johnson and Libbey (1997) found that Upper Pleistocene (Substage 5e) rocky shorelines occur preferentially in tectonically active settings: active continental margins (37% of citations), island arcs (35%) and island chains or continental margins affected by hot spots (15%). Modern rocky shorelines are interfaces between the mountainous hinterlands and steep submarine slopes that characterize these settings. Tectonic, isostatic and eustatic changes cause rapid shoreline translations on steep slopes, favouring preservation of former rocky shorelines both above and below sea level by removing them from further wave attack. Within the modern coastal zone bounded by 100 m topographic and bathymetric contours in many tectonically active settings, geomorphic features are typically terraces and cliffs transected by canyons (Coulbourn et al., 1974; Trenhaile, 1989; Ludwig et al., 1992; Jones, 1993; Keating, 1994; Ortlieb et al., 1996; Storlazzi and Field, 2000; Spinelli and Field, 2001). These features of abandoned shorelines reflect relative sea level changes, mainly during the Pleistocene. Tectonically active coasts of oceanic and volcanic arc islands typically lack well-defined shelves, but narrow shelves may be present on active continental margins. However, the cliff/terrace/canyon morphologies on oceanic island slopes are analogous to those in certain continental settings, such as California and Oregon on the Pacific coast of the continental United States (Kelsey and Bockheim, 1994; Anderson et al., 1999; Storlazzi and Field, 2000).

Only 13% of papers cited by Johnson and Libbey (1997) described abandoned rocky shorelines on passive continental margins. Passive margin rocky shorelines include large parts of the coasts of southeastern, southern and southwestern Australia. On Australia's west coast, some modern and Pleistocene rocky shorelines are cut in limestones, and Semeniuk and Johnson (1985) suggested that early lithification of carbonate sediments makes limestone rocky shorelines particularly amenable to preservation.

Modern rocky shorelines are dynamic, high-energy environments, where the energy of incoming waves is focused and dissipated in the surf zone at the land–sea interface, and erosive power is at a maximum. These shorelines often face open oceans or seas with long fetches that promote formation of short- and long-period swell waves (e.g., Semeniuk and Johnson, 1985; Postma and Nemec, 1990; Shaw, 1996). Many rocky shorelines are also subject to periodic attack by very large waves associated with tsunami, great storms and hurricanes. Narrow shelves and steep submarine slopes enable waves to approach the shoreline with little energy loss. Large waves not only erode and sculpture hard bedrock exposed at the shoreline to form the cliffs and shore platforms that define rocky shorelines, but also maintain the shoreline by removing sediment from the littoral zone and exposing more bedrock to direct wave attack (e.g., Bird, 2000).

3.2. Sediment supply and deposition

The same wave-cutting processes that sculpture rocky shorelines generate a supply of gravel-rich sediment by shoreline erosion. Undercutting of cliffs results in falls and topples on to shore platforms or directly into the sea. Large clasts may be detached from platform edges, or quarried from platform surfaces (Süssmilch, 1912; Noormets et al., in press). Marine biota contribute their skeletal detritus and the products of bioerosion, and large amounts of biotic detritus are supplied from the physical breakage of fringing reefs during high wave events (Highsmith et al., 1980; Talandier and Bourrouilh-Le-Jan, 1988; Dollar and Tribble, 1993). Where the hinterland has low relief and lacks well-developed surface drainage, such as the limestone hinterland backing Western Australian limestone shorelines (Semeniuk and Johnson, 1985; Johnson et al., 1995), shoreline sediment is derived entirely from bedrock erosion and from biological activity in the littoral zone.

On most rocky shorelines, streams and debris fans deliver sediment to the shoreline where it mixes with the material being generated at the shoreline itself. Given the steep coastal slopes in the most common rocky shoreline settings, eroded material is often gravel-rich, particularly in temperate or arid climates where physical weathering processes predominate over chemical weathering. The mixed gravelly sediment is wave-worked on the beach and shoreface. The greater the sediment volume, and the coarser the material accumulating at the shoreline, the greater is the energy, in the form of large or frequent swell and storm waves and strong rip and longshore currents, required to remove it and thus maintain the rocky shoreline. Waves and currents mobilise and transport sediment seawards away from the shoreline where it may move along-shore (Storlazzi and Field, 2000) or downslope out of the coastal depositional system. Tsunami also remove sediment from the littoral zone by advection landward (Dawson et al., 1991, 1996; Clague and Bobrowsky, 1994; Shi et al., 1995) or seaward (Coleman, 1978).

When the rate of delivery of a gravel-rich sediment supply exceeds the capacity of the sea to carry it away, gravel accumulates at the shoreline. Such shorelines form one end-member of a spectrum of gravel-dominated rocky shorelines. The other end-member is a sediment-starved shoreline, such as the western Australian example described above, where gravel is supplied only by shoreline erosion. However, not all gravelly shorelines are part of a rocky shoreline depositional system (see chapter on Clastic Coasts in Reading and Collinson, 1996). Clearly, patterns of shoreline and shoreface sediment distribution, and the sedimentary facies present in the littoral zone and beyond, will depend critically on the range of grain sizes in available sediment, sediment supply rates, and on the oceanographic regime.

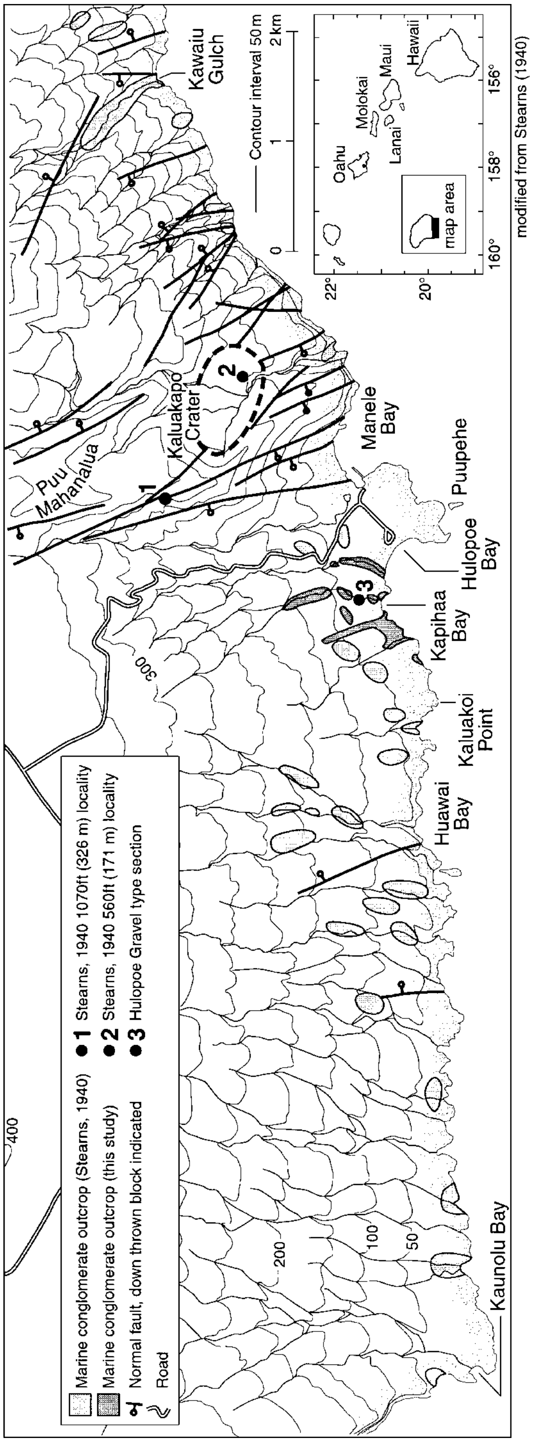

Fig. 1. Location map, south Lanai.

4. Modern rocky shoreline of south Lanai

The shoreline and inner shoreface of the sand-poor rocky shoreline of south Lanai between Hulopoe Bay and Huawai Bay (Fig. 1) was inspected both at sea level and from cliff tops using polarized sunglasses to reduce sea surface reflections. Additional shoreface details to approximately 20 m depth are revealed by low-level colour aerial photographs of the Lanai coastline flown for the National Ocean Service's Biogeography Program, available at its web site (National Ocean Service, 2000).

4.1. Morphology

In plan view, the coastline between Hulopoe Bay and Kaluakoi Point is scalloped or indented, with small embayments and headlands (Figs. 1–3). Cliff heights vary from 3 to 30 m with an overall increase from east to west. Remnants of a submarine terrace at about 5 m depth flank the shoreline, best developed along the western side of Hulopoe Bay. The seafloor appears to slope gently from the step at the seaward edge of the terrace, and is cut by small canyons normal to the shoreline, most of which terminate at the terrace edge. Of the few canyons which cut across the terrace, not all are offshore extensions of modern stream gullies. On and beyond the terrace, sea stacks and their submarine remnants offshore of headlands are the only positive-relief geomorphic features.

Further west, between Kaluakoi Point and Huawai Bay, cliffs are higher, up to 50 m, and headlands and embayments are wider (Figs. 1 and 2). Geomorphic features of the shoreline and shoreface, and the distribution of coarse gravel facies in this area are shown schematically in plan and section views in Fig. 4. Shore platforms front the headlands, narrowing towards the shoreline along the sides of the headlands. The submarine terrace is absent. In an embayment in the bay west of Kaluakoi Point, the inner shoreface is partly concealed by cobble gravel (Fig. 5), but to seaward in the centre of the embayment, bedrock is exposed and the shoreface is gently sloping and ramp-like.

4.2. Sediment distribution

Between Hulopoe Bay and Kaluakoi Point, pocket beaches of basalt cobbles and coral pebbles occur at the heads of embayments where ephemeral streams debouch into the ocean (Fig. 2). The submarine terrace is almost bare of sediment, apart from isolated boulders. On the colour air photos, some of the small canyons appear light blue, others deep blue (light and dark shades of grey in Fig. 2). The "light" canyons are interpreted to contain sediment, the "dark" being

Fig. 2. Enlargement of National Ocean Service Biogeography Program aerial photograph showing Hulopoe Bay at the left. Scale 4 cm = 1 km. More detail can be seen on image Lanai 1357 posted at the program's web site <http://biogeo.nos.noaa.gov/products/data/photos/hawaii.shtml>.

Fig. 3. Indented shoreline with shore platforms fronting small headlands, looking west near head of Kapihaa Bay (see Fig. 1 for location). Shore platforms are cut in basalt flows. A coral-bearing cobble gravel unit of the Hulopoe Gravel is exposed at the tops of 4-m-high cliffs in the foreground and middle ground. This shore-parallel cliff exposure represents an XY section subparallel to depositional strike (see text for discussion of XYZ exposures). Rounded basalt cobbles floor the small embayment at left foreground. These represent XZ exposures, which characterize deposits on the seafloor.

sediment-free. Beyond the terrace, and between the canyons, the medium blue (grey) areas could be floored by bedrock or basalt gravel.

In the bay west of Kaluakoi Point, a narrow cobble beach occurs at the embayment head below high cliffs, and subtidal sheets or shallow wedges of boulders flank narrow shore platforms alongside headlands. These boulder sheets thin out in the X-direction towards the central ramp in the embayment (Figs. 4 and 5). Isolated and clustered coarse and very coarse boulders lie scattered on the ramp. Where cliffs collapse directly into the sea, rather than on to shore platforms, the flat seafloor beneath the cliffs is carpeted by well-rounded coarse boulders.

4.3. Limitations

Several features of the littoral zone of south Lanai are immediately apparent. First, the shoreface consists of large areas of bedrock erosion surfaces; second, parts of those surfaces possess considerable relief; third, there is a variety of coarse gravelly deposits; fourth, sediment distribution is controlled by bedrock morphologic features; and fifth, deposit geometry is controlled by bedrock morphologic features. It seems reasonable to assume that sedimentary facies are also controlled by bedrock morphology. This certainly appears to be true of some boulder facies on the south Lanai shoreface, whose geometries are distinctive, varying both parallel and normal to the shoreline (Fig. 5).

While it is possible to observe and map the sediment distribution in the littoral zone, direct comparison cannot readily be made between these deposits, or indeed any modern coarse-grained seafloor deposits, and ancient deposits such as the Hulopoe Gravel. The visible parts of modern shoreline and shoreface deposits, and beyond, are essentially planar exposures in an XZ orientation (e.g., Figs. 3–5). Typically, only deposit surfaces are available for study.

5. Insights from the Hulopoe Gravel study

5.1. Problems of deposit description

Rubin et al. (2000) have dated coral clasts from the Hulopoe Gravel to the last two sea-level high stands. Their palaeoenvironmental interpretations from in-

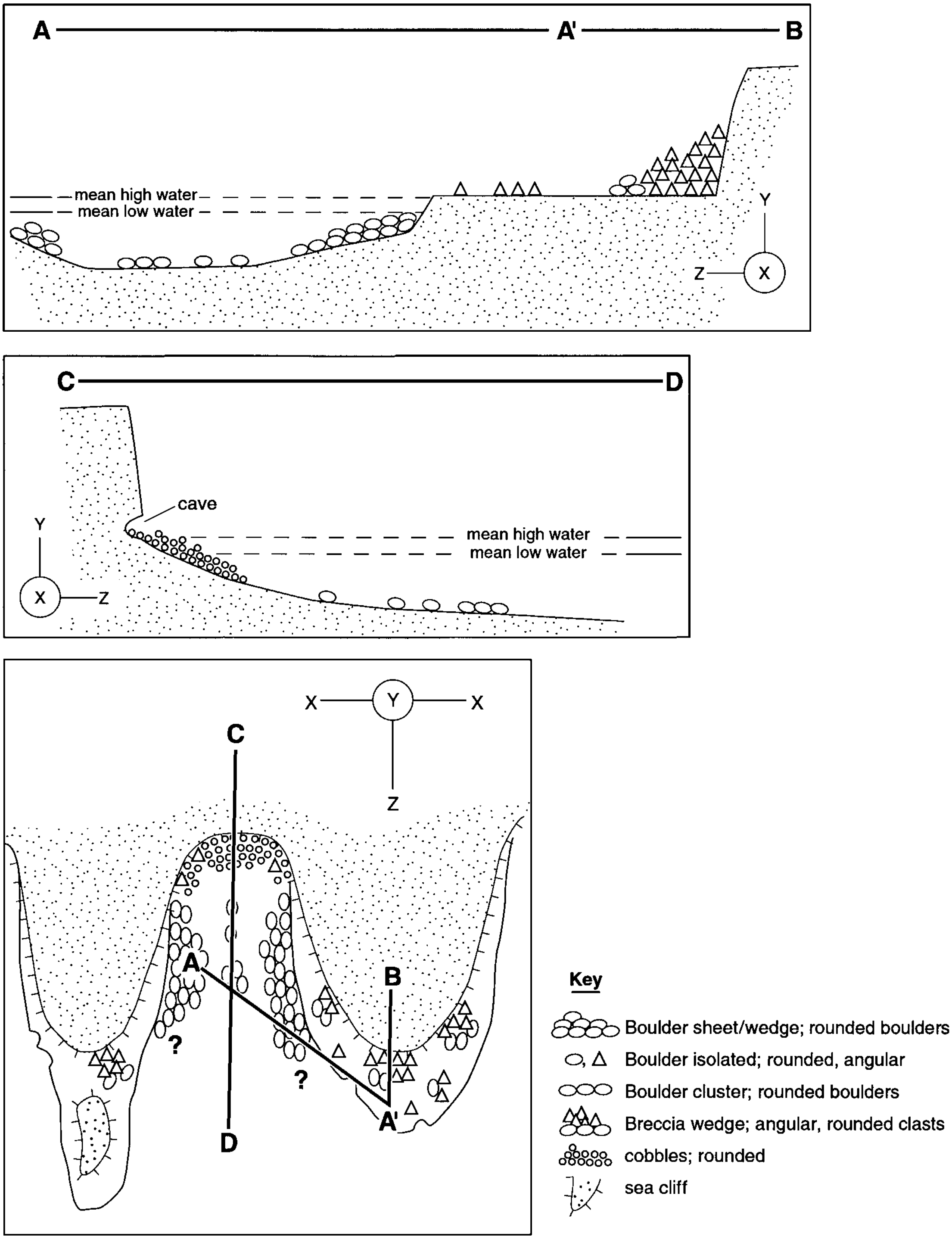

Fig. 4. Plan and section view of part of south Lanai shoreline and shoreface (schematic), illustrating the geomorphic settings of several gravel facies.

Fig. 5. Bayhead immediately west of Kaluakoi Point (see Fig. 1 for location). A basalt and coral cobble beach with berm occupies the bayhead below a 20-m cliff cut in basalt. Angular coarse boulders fallen from the cliff flank the beach at the sides of the embayment. The shoreface is gently sloping and ramp-like. Basalt boulder sheet/wedge facies B$\underline{sh}$ (well-rounded medium boulders) occupies the subtidal zone at each side of the embayment, thinning towards the bay centre, which is littered with isolated coarse boulders and blocks of basalt (boulder isolated clast facies, B$\underline{ic}$; arrowed). The boulder sheet/wedge facies is an XZ exposure typical of seafloor deposits.

cluded biota and observations of the modern shoreline imply marine littoral deposition, possibly with a coral reef sediment source. It seems reasonable that the Hulopoe Gravel may be an ancient analogue of contemporary Lanai rocky shoreline facies. But there are problems in establishing this. Hulopoe Gravel exposures are vertical sections through the deposit subparallel to either depositional dip or strike (XY and YZ orientations, respectively; e.g., Figs. 3 and 6). The only parts of the Hulopoe Gravel that can be compared directly to deposits in the modern littoral zone are the XZ exposures, which comprise undisturbed parts of the unit's uppermost boulder beds, that lie on the ground surface (Figs. 6 and 7). In these surface boulder beds, the internal structures of piled boulders (some of which may be bed forms) can seldom be seen.

Very different geological records should result from the processes implied by the diverse hypotheses concerning the origin of the Hulopoe Gravel—megatsunami, abandoned beach, rocky shoreline, 'multiple event' with uplift. Distinction among these or any other hypotheses necessitates careful study of vertical and lateral variations in litho- and biofacies, facies architecture, contact relationships and stratal geometries. However, a fundamental difficulty arose at the outset of the Hulopoe Gravel study: how best to describe and characterize each gravel bed. An objective descriptive framework for coarse gravelly sediment in a range of settings, not only rocky shorelines, was lacking. There was no consistent way of classifying deposits, and even basic descriptions of sediment particle sizes and fabrics were quite diverse. Subsequently, Blair and McPherson (1999) reviewed and discussed in detail the range of problems encountered in describing gravelly sediment. Walker (1975) had noted that most sedimentologists are uncertain about which aspects of gravel deposits should be measured and recorded.

5.2. Analytical methodology

5.2.1. Strategy

Two methods have been developed to deal with these problems: the "composition and fabric" (CAF) method, and the "sedimentary facies model building" (FMB) method. Both aim to describe and characterize gravelly sediments, but with different objectives. The CAF method has a **materials** focus, providing detailed

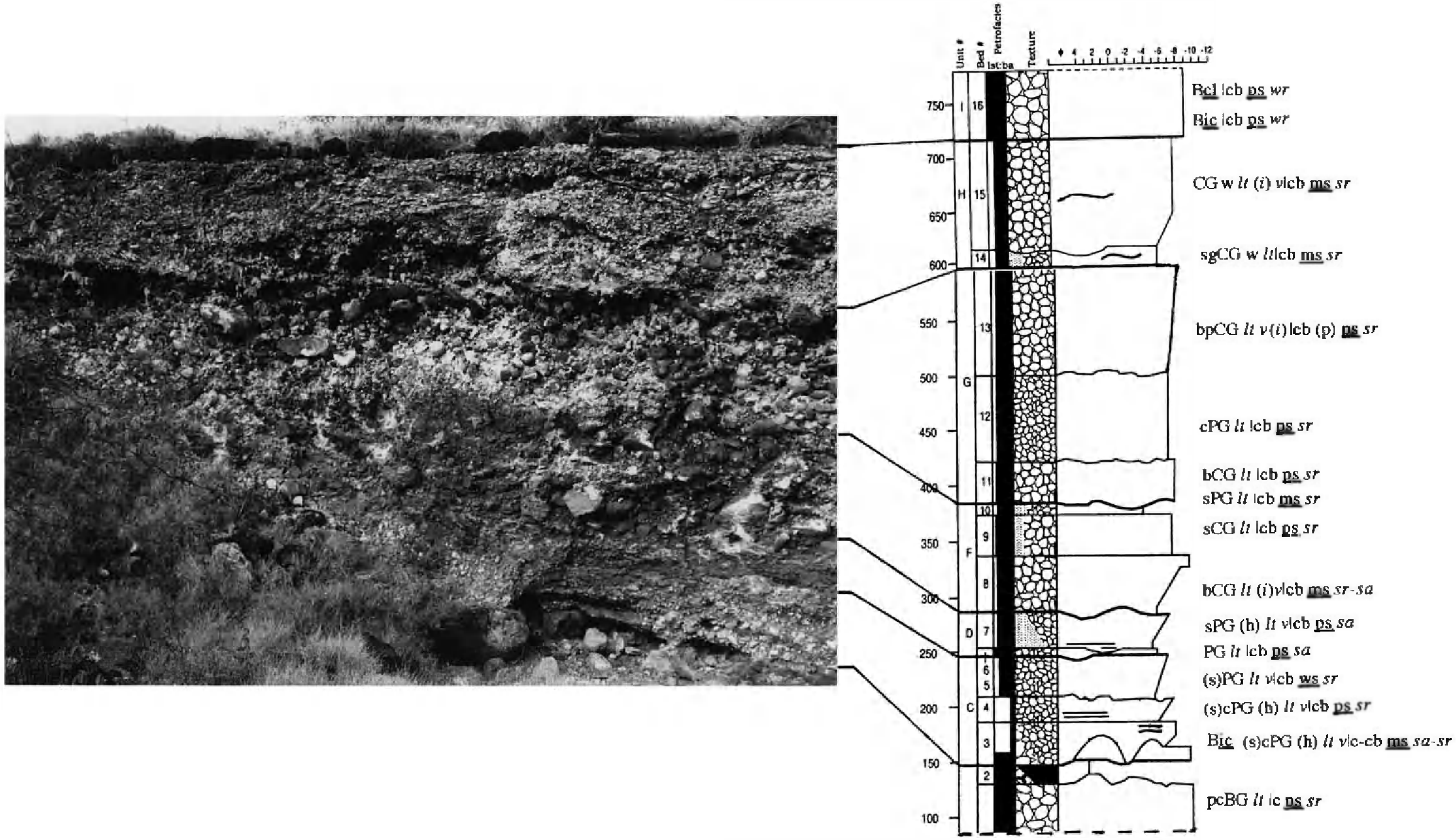

Fig. 6. Exposure of Hulopoe Gravel near mouth of gully immediately west of head of Kapihaa Bay (see Fig. 1). This gully section represents a two-dimensional YZ exposure subparallel to depositional dip. Stratigraphic section is approximately 8 m thick. Six of the gravel facies listed in Table 2 can be identified in this photo: slightly sandy cobbly pebble gravel, plane bedded: (s)cPGh (Beds 3 and 4, Unit C); slightly bouldery pebbly cobble gravel, inversely graded, (b)pCG*v* (Bed 13, Unit G); sandy granular pebbly cobble gravel, cemented, swaley bedded sgpCGcmw (Unit H); Unit I (at the ground surface) consists of two boulder facies: boulder cluster subfacies (a) rounded clasts Bcl|*wr* and boulder isolated clasts subfacies (a) rounded clasts Bic|*wr*.

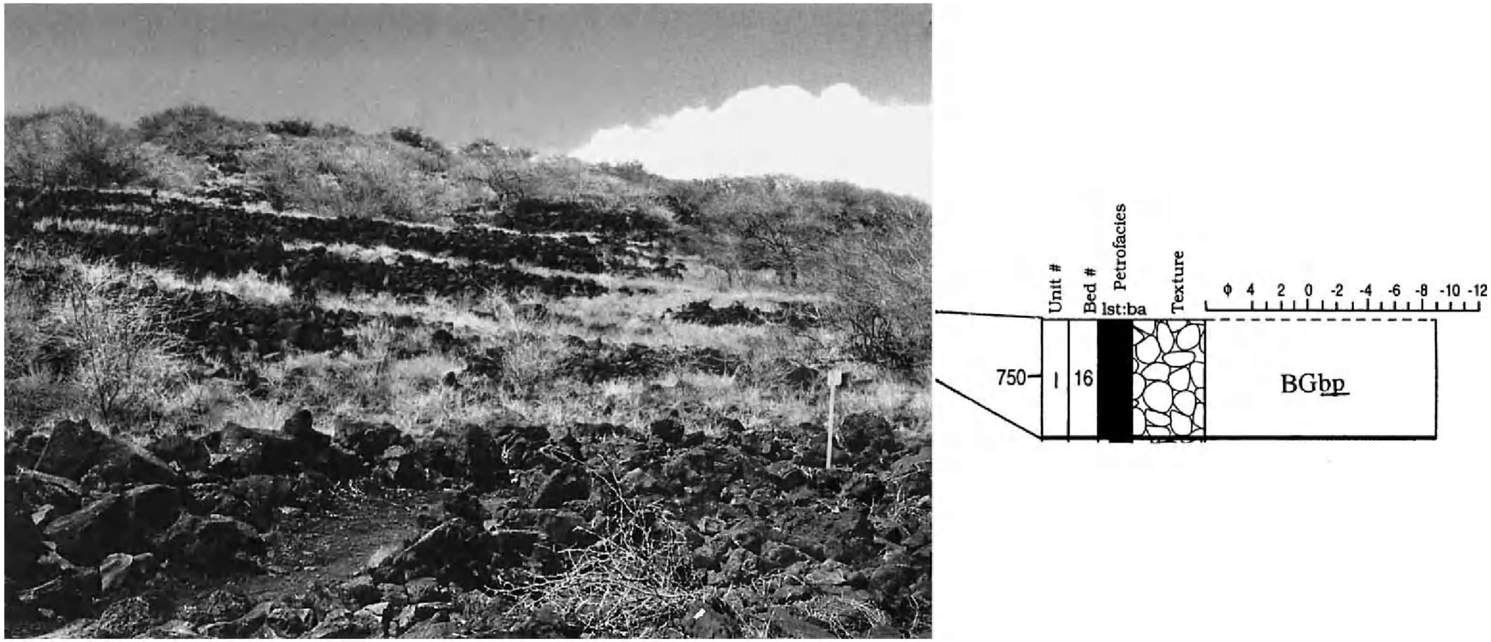

Fig. 7. Basalt boulder gravel parallel bands facies BGbp resting on basalt bedrock, inland of head of bay west of Kaluakoi Point (see Fig. 1 for location). Boulders in foreground have been partly disturbed during clifftop trail construction. Sign is 1.5 m high.

Table 1
Letter symbols used to describe gravelly sediment

Basic textural class (upper case)[a]	
GG	granule gravel
PG	pebble gravel
CG	cobble gravel
BG	boulder gravel
KG	block gravel
Adjectival qualifier (lower case)[b]	
m	muddy
s	sandy
g	granular
p	pebbly
c	cobbly
b	bouldery
k	blocky
Bed attributes[c]	
Colour	
Post-depositional modification	
Biological	
bt	bioturbation
bu	burrows
rt	roots
Cement	
cm	cemented
un	uncemented
Geometry	
wd	wedge
bp	parallel bands
bn	anastomosing bands
sh	sheet/tabular
cl	cluster
ic	isolated clast
Bed thickness	
tk	thick
tn	thin
Sedimentary structure	
h	plane bedded
w	wavy bedded
Organization	
o	organised
(o)	weakly organised
d	disorganised
Fabric (in *italics*)	
lt	clast support
m	matrix support
i	imbricate clasts
a	aligned clasts

Table 1 (*continued*)

Bed attributes[c]	
Fabric (in *italics*)	
v	inversely graded
n	normally graded
Packing	
l	loosely packed
c	closely packed
Clast attributes[d]	
Shape	
c	compact[e]
e	elongate
p	platy
b	bladed
Sorting	
ws	well sorted
ms	moderately sorted
ps	poorly sorted
us	unsorted
Roundness (in italics)	
wr	well rounded
sr	sub-rounded
sa	sub-angular
an	angular

[a] After Blair and McPherson (1999).
[b] When adjectival qualifier is bracketed, signifies that quality is present to only a small extent.
[c] Bed attributes follow the textural class in the order shown, with letter symbols for geometry underlined and letter symbols for fabric in italics; e.g., slightly sandy pebbly cobble gravel (s)pCG pebbly cobble gravel, thick sheet, weakly organised, inversely graded pCG sh tk (o)*v*.
[d] Clast attributes follow bed attributes, from which they are separated by a vertical bar; e.g., pebbly cobble gravel, thick sheet, weakly organised, inversely graded; clasts compact, poorly sorted, sub-angular pCG sh tk (o)*v*|c ps *sa*.
[e] Abbreviations for combinations of these three basic shapes can be used: e.g. ce: compact-elongate; vp: very platy etc. (see Sneed and Folk, 1958).

description of a wide range of attributes of the constituent clasts, their petrology, the proportions of gravel, sand and mud, and the ways in which these materials are organized. This amplifies the approach taken by Blair and McPherson (1999). The FMB method emphasizes the organization and geomorphic context of a deposit, on a bed-by-bed basis, to identify facies and infer **depositional processes**. It exemplifies the methods advocated by Walker (1975).

Logged by:
date:

Gravel Fabric & Petrography Log
(version 1.1)

(Format prepared by Anne Felton & Keith Crook)

Graphic Log #: **Unit #:** **Log basis:** outcrop/ photo/ video/...............................

Orientation of face: bedding normal / bedding \\ (viewed from above/below) / other..						
Face: transects clasts / does not transect clasts						
Framework: clast supported / matrix supported / matrix type:						
Grainsize: (b-axis)	**Max. (5 largest)** 1:	2:	3:	4:	5:	**Minimum:**
Size Modes:	**I:**	**II:**	**III:**			
Estimated %:	**gravel:**	**sand:**	**mud:**	**Folk descriptor:**		

Estimated %:	**Mode I pop^{n}:**	**Mode II pop^{n}:**	**Mode III pop^{n}:**	**Mode IV pop^{n}:**

Sorting: (comparator)	**Overall:**	**Mode I pop^{n}:**	**Mode II pop^{n}:**	**Mode III pop^{n}:**	**Mode IV pop^{n}:**

Clast types: **Name:** **Mode I %:** **surface text:** **special shape**	**Rock Type 1** %	**Rock Type 2** %	**Rock Type 3** %	**Rock Type 4** %	**Rock Type 5** %		**Determined by:** # count /pt. count /visual estimate /other. **Surface textures:** weathered/dull/ polished/striae/ percussion marks/ smooth/rough/not visible/other **Special shapes:** flat irons/semilunate/ dreikanter/other
Clast types: **Name:** **Mode II %:** **surface text:** **special shape**	**Rock Type 1** %	**Rock Type 2** %	**Rock Type 3** %	**Rock Type 4** %	**Rock Type 5** %		**Determined by:** # count /pt. count /visual estimate /other. **Surface textures:** weathered/dull/ polished/striae/ percussion marks/ smooth/rough/not visible/other **Special shapes:** flat irons/semilunate/ dreikanter/other
Clast types: **Name:** **Mode III %:** **surface text:** **special shape**	**Rock Type 1** %	**Rock Type 2** %	**Rock Type 3** %	**Rock Type 4** %	**Rock Type 5** %		**Determined by:** # count /pt. count /visual estimate /other. **Surface textures:** weathered/dull/ polished/striae/ percussion marks/ smooth/rough/not visible/other **Special shapes:** flat irons/semilunate/ dreikanter/other
Clast types: **Name:** **Mode IV %:** **surface text:** **special shape**	**Rock Type 1** %	**Rock Type 2** %	**Rock Type 3** %	**Rock Type 4** %	**Rock Type 5** %		**Determined by:** # count /pt. count /visual estimate /other. **Surface textures:** weathered/dull/ polished/striae/ percussion marks/ smooth/rough/not visible/other **Special shapes:** flat irons/semilunate/ dreikanter/other
Clast compositions	**Sand:**			**mud:**			

Fig. 8. Gravel fabric and petrography log.

Clast Roundness Mode I	**Rocktype 1:** ρ:	**Rocktype 2:** ρ:	**Rocktype 3:** ρ:	**Rocktype 4:** ρ:	**Rocktype 5:** ρ:		
Clast Roundness Mode II	**Rocktype 1:** ρ:	**Rocktype 2:** ρ:	**Rocktype 3:** ρ:	**Rocktype 4:** ρ:	**Rocktype 5:** ρ:		
Clast Roundness Mode III	**Rocktype 1:** ρ:	**Rocktype 2:** ρ:	**Rocktype 3:** ρ:	**Rocktype 4:** ρ:	**Rocktype 5:** ρ:		
Clast Roundness Mode	**Rocktype 1:** ρ:	**Rocktype 2:** ρ:	**Rocktype 3:** ρ:	**Rocktype 4:** ρ:	**Rocktype 5:** ρ:		
Clast roundness	**Sand:** ρ:						
Clast Shape (measured) Mode I:	**Rocktype 1:** **a:** **b:** **c:**	**Rocktype 2:** **a:** **b:** **c:**	**Rockype 3:** **a:** **b:** **c:**	**Rocktype 4:** **a:** **b:** **c:**	**Rockype 5:** **a:** **b:** **c:**		
Clast Shape (measured) Mode II:	**Rocktype 1:** **a:** **b:** **c:**	**Rocktype 2:** **a:** **b:** **c:**	**Rockype 3:** **a:** **b:** **c:**	**Rocktype 4:** **a:** **b:** **c:**	**Rockype 5:** **a:** **b:** **c:**		
Clast Shape (measured) Mode III:	**Rocktype 1:** **a:** **b:** **c:**	**Rocktype 2:** **a:** **b:** **c:**	**Rockype 3:** **a:** **b:** **c:**	**Rocktype 4:** **a:** **b:** **c:**	**Rockype 5:** **a:** **b:** **c:**		
Clast Shape (measured) Mode :	**Rocktype 1:** **a:** **b:** **c:**	**Rocktype 2:** **a:** **b:** **c:**	**Rockype 3:** **a:** **b:** **c:**	**Rocktype 4:** **a:** **b:** **c:**	**Rockype 5:** **a:** **b:** **c:**		
Clast Shape (comparator) Mode I:	**Rock Type 1:**	**Rock Type 2:**	**Rock Type 3:**	**Rock Type 4:**	**Rock Type 5:**		
Clast Shape (comparator) Mode II:	**Rock Type 1:**	**Rock Type 2:**	**Rock Type 3:**	**Rock Type 4:**	**Rock Type 5:**		
Clast Shape (comparator) Mode III:	**Rock Type 1:**	**Rock Type 2:**	**Rock Type 3:**	**Rock Type 4:**	**Rock Type 5:**		
Clast Shape (comparator) Mode :	**Rock Type 1:**	**Rock Type 2:**	**Rock Type 3:**	**Rock Type 4:**	**Rock Type 5:**		
Clast Shape (comparator) Sand:							
Apposition Fabric (bedding normal/parallel): imbricate (∠= °) / edgewise (∠= °) / random a-axes / a-axes \\ lamination / other:							
Vector Fabric 1: orientation: ; **based on:** **Vector Fabric 2: orientation:** ; **based on:**							

Fig. 8 (*continued*).

5.2.2. The composition and fabric (CAF) method

The Udden–Wentworth particle size grade system (Folk, 1954) does not adequately describe gravelly sediment, because it classifies all particles larger than 2 mm (-1ϕ) as gravel (Blair and McPherson, 1999). To rectify this, Blair and McPherson (1999), in their Fig. 3A and B, proposed a sediment textural classification of gravel/sand/mud, modified from Folk et al. (1970), that increases the number of textural classes of gravel-bearing sediment from 10 to 15, and introduces new terms for mixtures of gravel, sand and mud with gravel $<90\%$ and sand/mud ratios between 1:9 and 1:1. Blair and McPherson's (1999) summary of the origins, emplacement processes and terrestrial occurrence of coarse sedimentary particles convincingly demonstrates the utility of the new classification and textural description schemes. However, the gravelly sediments illustrated by Blair and McPherson (1999)

Table 2
Facies of the Hulopoe Gravel

Facies	Bed attributes		Clast attributes	Petrofacies; Biota
	Sedimentary structures	Geometry; sorting; packing; fabric	Shape; roundness; roundness sorting; surface markings	
I. Pebble and cobble gravel, matrix <20% (four facies)		**All four facies:** tabular; poorly sorted overall; clast-supported; openwork; close-packed	**All** compact to compact bladed; small proportion of platy shapes; sub-angular to subrounded; moderate to poor roundness sorting	**All** basalt and limestone framework; whole and broken molluscs (mainly gastropods)
(i) Slightly sandy cobbly pebble gravel, plane-bedded, (s)cPG h (*i*)	Lower half of bed plane bedded	Inversely graded; clasts aligned in lower half of bed, slightly imbricate in upper half	Small proportion of discoid (platy) shapes in cobble fraction	Benthic in-fauna in part?
(ii) Slightly sandy pebbly cobble gravel, inversely graded, (s)pCG *v* (*i*)		Inversely graded; seaward dipping imbrication in coarser tops of beds, some platy clasts within the bed have opposed landwards and seawards dips	Small proportion of discoid (platy) basalt cobbles; proportion of well-rounded cobbles	
(iii) Slightly bouldery pebbly cobble gravel, inversely graded, (b)pCG *v* (*i*)		Inversely graded; seaward imbrication of discoid shapes, and seaward dip of long axes of elongate shapes (both in part, near bed top)	Significant proportion of well-rounded discoid (platy) cobbles	Whole and broken molluscs
(iv) Sandy granular pebbly cobble gravel, wavy-bedded, sgpCG w	Wavy beds	Bimodal: pebbles moderately sorted, cobbles well-sorted; variably open- to closedwork	Compact bladed to compact platy shapes in cobble fraction	Benthic infauna?
II. Pebble and cobble gravel, matrix >10% (two facies)		**Both** facies: poorly and very poorly sorted; matrix-supported; closedwork	**Both:** compact to compact bladed; sub-angular to subrounded; moderate to poor roundness sorting	**Both:** basalt and limestone framework
(i) Sandy cobbly pebble gravel, clast- to matrix-supported, scPG*lt-m*		Tabular; clast-supported in part		Matrix of mixed bioclastic and basalt sand; granule- and small pebble-sized soil peds
(ii) Muddy cobbly pebble gravel, mcPG*m*		Tabular to wedge		Matrix of reddish mud and silt, and basalt sand

Table 2 (*continued*)

Facies	Bed attributes		Clast attributes	Petrofacies; Biota
	Sedimentary structures	Geometry; sorting; packing; fabric	Shape; roundness; roundness sorting; surface markings	
III. Boulder gravel, matrix < 10% (6 facies)		**All** openwork	**All** subrounded to well rounded (but see III [iv] below); well sorted, moderate to good roundness sorting	
(i) Coarse boulder gravel, wedge, BGwd*i*		Wedge to cluster; openwork; Imbricate with steep seawards dips of long axes of compact-elongate clasts	Compact-elongate clasts	Basalt, minor bioclastic sand in top; no biota
(ii) Boulder gravel, parallel bands, BGbp*i*		Linear; openwork, imbricate in part with seawards dips		Basalt; no biota
(iii) Boulder gravel, sheet/wedge, BGsh (*i*)		Tabular to wedge; openwork, may be imbricate in part		Basalt; no biota
(iv) Boulder gravel, clusters, BGcl				Basalt; no biota
Subfacies (a): Boulder gravel clusters, rounded clasts, BGcl|*wr*			Well-rounded boulders	
Subfacies (b): Boulder gravel clusters, angular clasts, BGcl|*an*			Angular boulders	
(v) Boulder gravel, isolated clasts, BGic		Seawards dips in part		
Subfacies (a): Boulder gravel, isolated clasts, rounded clasts, BGic|*wr*				
Subfacies (b): Boulder gravel, isolated clasts, angular clasts, BGic|*an*			Several sets of surface scratches and grooves on at least one face: different orientations	
IV. Boulder gravel, matrix >10% (1 facies)				
(i) Sandy boulder gravel, inversely graded, sBG*v*		Variably open- to closedwork, weakly inversely graded, moderately to well sorted		

are largely taken from subaerial settings, and rocky shorelines are not included.

To describe gravelly sediments such as the Hulopoe Gravel accurately and comprehensively, a much greater range of bed and clast attributes and parameters must be documented than for finer sediments (Table 1). A gravel fabric and petrography log (GFPL; Fig. 8) was developed to standardise the large range of sedimentological data needed to characterise complex gravel facies. This log also served as an **essential** checklist for recording data at the outcrop, with one log sheet being completed for **each bed** in each stratigraphic section. Key data are readily extracted from the GFPL to use in graphical plots of component characteristics, and to assist in naming a particular bed, using a modification of Blair and McPherson's (1999) naming protocol.

In the CAF method, as used for the Hulopoe Gravel study, the basic textural class of each bed, qualified as appropriate (see footnote b, Table 1), is placed first in the name, so as to establish the fundamental nature of the sediment. Other descriptors distinguished as **bed attributes** or **clast attributes** follow, with bed attributes preceding clast attributes in the description (see footnotes c and d, Table 1). This separates those attributes of the deposit that are related to its most recent transport and depositional processes, from those attributes that pertain to the nature of the material from which the deposit is derived. Some attributes of clasts in reworked materials will clearly be inherited from earlier episodes of transport and deposition. Some bed attributes, such as bioturbation, rooting and cementation, may be due to post-depositional modification. Colour, which should include the Munsell colour (Munsell®, 1992), is placed first in the descriptive string, followed by attributes due to post-depositional modification, then other bed attributes, then clast attributes. This information can be summarised using letter symbols (Table 1), e.g., bouldery pebbly cobble gravel, rooted, reddish (Munsell colour), (carbonate) cemented, sheet, plane bedded, clast-supported, inversely graded, closely packed; cobbles compact (some platy), moderately sorted, sub-angular to sub-rounded: bpCG rt 5YR/6 cm sh h *lt v* c|c(p) ms *sa-sr*. A vertical bar separates bed and clast attributes in the letter symbol.

Most beds in the Hulopoe Gravel consist of mixtures of boulders, cobbles and pebbles, in which sand and mud are absent or constitute < 20% of the bed. These beds fall into only two of Blair and McPherson's (1999) textural classes: gravel and slightly sandy gravel. To better characterize these sand-poor gravels, textural data from the GFPL were plotted on a boulder/cobble/pebble texture triangle (Fig. 9). The subdivision and nomenclature of this triangle is based on Fig. 3B of Blair and McPherson (1999).

Deposit characteristics are represented visually on vertical profiles (stratigraphic logs) modified to depict petrology and a wider range of gravel bed textures. Letter symbols describing features of each bed in the vertical profile highlight bed-by-bed changes (Fig. 6). Data in the vertical profile are complemented by a GFPL for each bed, and by detailed photography.

5.2.3. The sedimentary facies model building (FMB) method

Middleton (1978) noted that "facies definition is quite objective" and that "the key to interpretation of facies is to combine observations made on their spatial relations and internal characteristics...with comparative information from other well-studied stratigraphic units, and particularly from studies of modern sedimentary environments". In demonstrating the building of a sedimentary facies model for a gravel-dominated depositional setting, Walker (1975) used published descriptions of resedimented conglomerates of the deep water turbidite association, together with new field observations. From such generalized facies models depositional processes and environments can be deduced. The study of ancient gravel and conglomerate deposits has been guided by the development of facies models for various depositional settings: alluvial systems including fans, fan deltas, debris flows and rivers (Colella and Prior, 1990; Miall, 1992; Marzo and Puidefábregas, 1993; Blair and McPherson, 1994), and deep marine slopes (Pickering and Hiscott, 1989; Walker, 1992b). However, except for fan deltas, gravelly shoreline settings of all kinds are poorly represented.

Detailed descriptions of coarse gravelly deposits utilise a much larger range of attributes than those used for finer-grained sediments (see GFPL, Fig. 8), so that, potentially, a very large number of facies could be derived from the descriptions. The key task is to identify attributes that best distinguish and characterize constituent gravel facies. Most authors take an empirical approach: facies are distinguished by combinations of bed

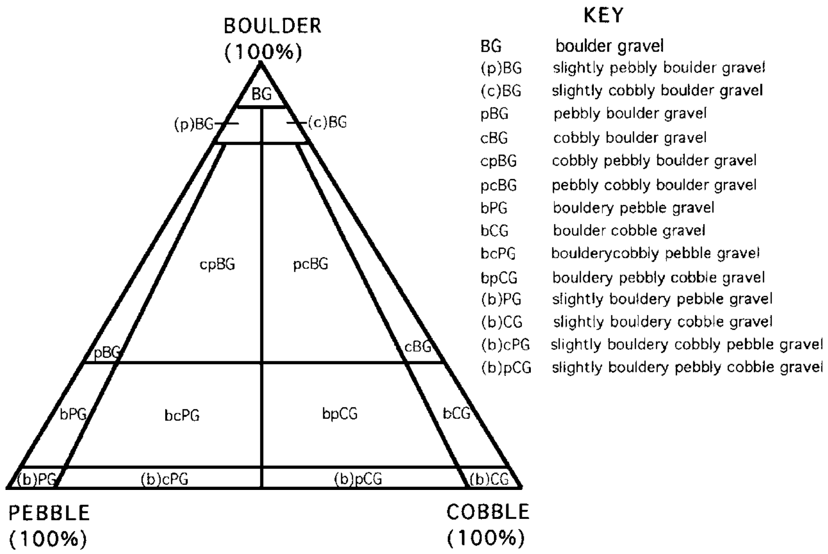

Fig. 9. Ternary diagram illustrating basic textural classes for boulder/cobble/pebble mixtures with <20% fine sediment.

attributes and/or clast attributes. For example, Walker and Mutti (1973) subdivided clast-supported conglomerates into two basic types based on the overall appearance of the bed: disorganized and organized with further subdivision of organized beds based on particular attributes such as clast fabric, graded bedding, and stratification. Grabau (1913) utilized both bed attributes (geometry) and clast attributes (size, roundness) in defining the three coarse gravel facies he identified as characteristic of the modern coastal zone; viz.: rocky cliff facies, bouldery facies, and gravel facies.

Because the depositional environment of the Hulopoe Gravel must be regarded as unknown, the principles outlined by Walker (1975) were used to build the elements of an "internal facies model", based on features of the deposit itself. These principles assisted in isolating the particular features—bed and clast attributes—that defined the essential nature or distinctiveness of each bed, and enabled recognition of discrete coarse gravel facies in the Hulopoe Gravel sequence.

5.3. Applying the analytical methodology to the Hulopoe Gravel: an outline

The Hulopoe Gravel consists entirely of gravel facies. Twelve coarse gravel facies were distinguished using a selection of bed and clast attributes. **Size modes** of framework clasts together with the **amount of matrix** present provided an initial broad subdivision. **Sedimentary structures** and **fabric** best distinguish pebble/cobble facies, whereas bed **geometry** is the most distinctive feature of various boulder facies (Table 2). Clast **roundness** distinguishes subfacies in two of the boulder facies.

The conjoint application of the CAF and FMB methods provides a reliable basis for systematic study and interpretation of these and other unusual gravel deposits. As an example, the facies comprising a well-exposed section of the Hulopoe Gravel are illustrated in Fig. 6. Detailed descriptions, facies analyses and interpretations of the Hulopoe Gravel will be covered in a later paper. To progress from description to interpretation, two preliminary assumptions were made about the Hulopoe Gravel sequence. First, because the sequence included some beds with significant amounts of limestone biolithite clasts, as well as alluvial beds and palaeosols, a coastal setting was assumed. Secondly, the coarse grain size and overall lack of sand and fine sediment suggested high-energy nearshore environments.

The Hulopoe Gravel sedimentary facies were compared with published descriptions of gravels from a range of coastal settings, so as to constrain interpretations of gravel sources, their transport and depositional processes, and the palaeoenvironments represented.

The lack of sand in the Hulopoe Gravel appears to be unusual for marine deposits. Most published descriptions of modern and ancient gravels from a variety of shallow and deep marine settings report sand to be present in large amounts, intermixed or interbedded with the gravel (Wright and Walker, 1981; Colella and Prior, 1990); see also papers in Koster and Steel (1984). Deposits of modern tsunami in backshore areas and beyond also contain much sand (Bourrouilh-Le Jan and Talandier, 1985; Saito, 1996; Shigeno et al., 1997; Nichol and Carter, 1998). However, modern coarse gravel tsunami deposits lacking sand have been reported. Dominey-Howes et al. (2000) recently described a single layer of shingled (imbricate) cobble gravel with only minor sand, attributed to deposition by a 1956 tsunami, and Noormets et al. (2002a) presented evidence that limestone blocks and very coarse boulders on a rock platform were emplaced there by modern tsunami and storm waves. However, facies similar to these do not occur in the Hulopoe Gravel.

6. Some implications of this review

To fully evaluate the possibility of rocky shoreline deposition for the Hulopoe Gravel, it will be necessary to develop facies models for a variety of rocky shorelines. Data must be distilled from many modern and ancient examples (Walker, 1984; Walker and James, 1992). Most of those data will necessarily be derived from well-exposed ancient examples, as has been the case for most facies models of marine sediments. However, recognizing rocky shorelines in the rock record is not always straightforward. Johnson (1992) noted that a "basal conglomerate" of coarse gravel deposits resting on an erosion surface may represent "scree–alluvial fan deposits, fluvial gorge deposits, glaciogenic boulder beds, fault-scarp breccias, intraformational conglomerates, and fan-channel conglomerates".

Within ± 100 m of modern shorelines, a zone in which many Pleistocene shorelines are preserved (Johnson and Libbey, 1997), the possibilities are even more complex, and unconformity-related sedimentary facies containing marine biotic remains may have originated in settings other than the immediate rocky shoreline littoral zone. Consider a deposit of bedrock-derived sub-angular boulders, resting against a small bedrock cliff and terrace 10 m above a modern rocky shoreline, and containing pinned or entrapped coral clasts. Subaerial, submarine or "mixed" deposition could be argued. "Mixed" deposits could consist of boulders broken from the modern shore platform edge by large waves and washed shoreward along with littoral sediment (e.g., Noormets et al., 2002a), talus from collapse of shore cliffs inundated by storm surge or tsunami (e.g., Nott, 1997), or fluvial gully deposits inundated by storm surge or tsunami. Subaerial deposits could include fluvial gully deposits containing ancient coral clasts eroded from older marine deposits upslope, or ruins of human constructions decorated with coral (e.g., Emory, 1933; Grigg and Jones, 1997). Submarine deposits might include not only fan-channel deposits and intraformational conglomerates as Johnson (1992) suggested, but also subtidal breccia wedges (Semeniuk and Johnson, 1985). Any of the above examples might incorporate mixtures of contemporary and older biotic remains, depending on the shoreline history. These examples illustrate not only the pitfalls of rocky shoreline recognition, but also the range and complexity of erosional and depositional processes taking place on storm- and tsunami-prone rocky shorelines on which sea-levels have repeatedly risen and fallen. This complexity will be reflected in rocky shoreline stratigraphic records, both above and below sea level (e.g., Gupta and Allen, 1999). Ideally, a combination of unequivocal sedimentologic, geomorphic and biologic criteria is required to identify, characterize and interpret the geological records of rocky shorelines.

Early studies of modern rocky shoreline sedimentation recognized that the coarsest material occurred at the shoreline, with shore-parallel zones of progressively finer sediment to seaward (Lavoisier, 1789; Grabau, 1913). Thus, a simple model of rocky shoreline sedimentation might predict that the coarsest available materials will be concentrated in the highest energy locations, that is, within the zone of breaking waves, and that finer material will be distributed along or across-shore and deposited in lower-energy conditions. A snapshot of idealized cross-shore and alongshore profiles of mean and maximum sediment particle sizes outwards from a single point of sediment input should show progressive decrease in mean and maximum sizes. This simple model also predicts that any record of extreme wave events, expressed as the size of the largest clasts, will also occur close to where waves break (Süssmilch, 1912; Zazo et al., 1998; Crook et al., 2000; Noormets et al., in press), and that the coarsest materials should rest on eroded bedrock.

The relatively well-studied pebble and cobble beach and shoreface environments (the "Clastic Coasts" of Reading and Collinson, 1996; see also Hart and Plint, 1995), whether or not they are floored on bedrock erosion surfaces, will potentially contribute to facies model development for the sediment-rich, gravel-dominated end of the rocky shoreline spectrum where the gravel consists of pebbles and cobbles. Beaches composed of boulders are much more poorly known; clast fabric and size distribution are distinctly different from those of cobble and pebble beaches, and reflect different processes (Oak, 1984; Waag and Ogren, 1984; Ogren and Waag, 1986). On all rocky shorelines, but especially those dominated by coarse gravel, the range of cross-shore sedimentary environments and processes remains to be studied in detail.

Along a rocky, embayed shoreline on the California coast, the distribution of mainly sandy beach and shoreface sediment as mapped by Storlazzi and Field (2000) revealed distinctive differences between adjacent stretches of coast, and demonstrated the influence of variations in shoreline and shoreface morphology, sediment provenance, and wave climate on the distribution and geometry of the sediment bodies present. Sediment distribution patterns on this shoreline enabled Storlazzi and Field (2000) to interpret sediment transport pathways and sinks. A similar sediment transport model could be developed for the south Lanai modern shoreline. Such models contribute to understanding the range of transport and depositional processes taking place.

The geometry of shorefaces developed on mobile sedimentary substrates has conventionally been attributed to two factors: sediment grain size and wave climate, and the role of exposed bedrock in controlling shoreface sediment distribution is not clearly understood (Cowell et al., 1999). It is possible that the south Lanai rocky shoreline, where sediment is sparse and shoreface morphology clearly plays a role in controlling the distribution of sediment bodies, may throw some light on this problem, as key controls such as sediment grain size and wave climate remain constant for a particular shoreline orientation, and relationships between sediment supply rate, sediment distribution and shoreface morphology can be evaluated on different parts of the shore.

Shorelines of tropical hotspot ocean islands are either coral reef shorelines or rocky shorelines, which subside to depth as islands move away from the hotspot (Moore, 1987). Consequently, submarine slopes of islands and seamounts are composed largely of rocky shorelines or coral shorelines which have been drowned. Mass wasting, submarine landslides (Moore et al., 1994), sedimentation and marine degradation will have destroyed or buried part of the geological record of drowned shorelines, but it is clear from available data (Keating, 1994; Jones, 1995) that large areas of Hawaiian island submarine slopes and nearby seamounts consist of relict shorelines. Around the Hawaiian islands, hard rock terraces and ledges, caves, and associated bodies of piled rocks and gravelly sediment—all features of rocky shorelines—may become important habitats for a variety of fishes, shrimp, and marine mammals (Ralston et al., 1986; Moffitt and Parrish, 1992; Chave and Mundy, 1994; Parrish et al., 1996, 2000). Elsewhere, many geomorphic and sedimentary features on deep marine slopes are habitats for benthic organisms (Greene et al., 1999; Yoklavich et al., 2000), and fine- and coarse-grained sedimentary deposits form macro- and micro-habitats that may be highly specific to particular organisms (Fig. 4A,B of Greene et al., 1999). Thus, a "drowned shorelines" model incorporating sedimentary facies associations with specific geomorphic features can be applied to characterizing and mapping geo-biologic meso-habitats of submarine slopes of oceanic islands, and some continental slopes.

7. Conclusions

The conflicting hypotheses concerning the origin of the Pleistocene Hulopoe Gravel on Lanai highlight problems of interpreting coarse gravel deposits containing marine biotic remains, particularly those near storm- and tsunami-prone modern shorelines. These include a lack of sedimentary facies models for rocky shoreline environments, with which to compare such deposits, and inadequate methodologies for describing and characterizing coarse gravel deposits generally. Such problems are amenable to resolution by developing new methodologies which focus on vertical and lateral variations in petro-, litho- and biofacies, facies architecture, contact relationships, geomorphic settings and stratal geometries of these deposits and by comparing deposits with a range of modern and well-described ancient rocky shoreline examples.

A new methodology for sedimentary data collection and representation met the requirement for detailed bed by bed description of sand-poor coarse gravelly sediments of the Hulopoe Gravel. The two complementary methods used—the composition and fabric (CAF) method and the sedimentary facies model building (FMB) method—focus on constituent **materials**, and deposit organization and **depositional processes**, respectively. **Both** are essential in dealing with enigmatic deposits like the Hulopoe Gravel. The newly devised gravel fabric and petrography log (GFPL) standardizes the wide range of bed and clast attributes required to describe component materials in mixtures of coarse gravels, and serves as an essential field checklist. Key data are readily extracted from the GFPL to use in graphical plots of component characteristics, and to assist in naming a complex deposit. Clarity of complex names is improved by stating the textural class of gravel first, and separating clast attributes from bed attributes in the adjectival string which follows. Deposit characteristics are represented visually on vertical profiles (stratigraphic logs) modified to depict petrology and a wider range of gravel bed textures. Letter symbols for each bed in the vertical profile can visually highlight bed-by-bed changes. Data in the vertical profile are complemented by a GFPL for each bed, and by detailed photography. Bed and clast attributes of the Hulopoe Gravel which best distinguish constituent sedimentary facies are clast size, amount of matrix, and bed geometry (for boulder lithofacies), and sedimentary structures and bed fabric (for pebble and cobble lithofacies).

The rocky shoreline sedimentary environment is a hostile one, and has largely been neglected by sedimentologists. A range of high-energy processes occur on rocky shorelines, which erode hard bedrock and generate coarse gravel. Sediment contributed to the shoreline by rivers and debris fans, and by bioerosion and physical destruction of reef biotas, mixes with the material being generated at the shoreline itself. Observations of the modern rocky shoreline and shoreface on Lanai and elsewhere have shown that a number of distinctive coarse gravel sedimentary facies are present, and that several facies occur in specific geomorphic settings. Some of these facies and settings are similar to parts of the Hulopoe Gravel.

Rocky shoreline deposition potentially extends landward and seaward well beyond the shoreline and shoreface, especially deposits of large waves. To fully evaluate the possibility of rocky shoreline deposition in this broad sense for the Hulopoe Gravel, it will be necessary to develop facies models for rocky shorelines which occur in a range of settings. Rocky shoreline sedimentary records on coasts affected by tectonic, isostatic and eustatic changes are likely to be complex. Given the lack of knowledge about rocky shoreline sedimentary deposits, it is conceivable that ALL the hypotheses proposed for the Hulopoe Gravel may be partly correct. Currently, the Hulopoe Gravel resembles the elephant described by a blindfolded committee, each member of which grasps a different body part. Sedimentologists are now looking to Mars and beyond (Blair and McPherson, 1999; Malin and Edgett, 2000). However, rocky shorelines may well be the last frontier of sedimentary environments for study on planet Earth.

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References

Anderson, R.S., Densmore, A.L., Ellis, M.A., 1999. The generation and degradation of marine terraces. Basin Research 11, 7–19.

Bates, R.L., Jackson, J.A. (Eds.), 1980. Glossary of Geology. American Geological Institute, Falls Church, VA, 749 pp.

Beach, R.A., Holman, R.A., Stanley, J., 1995. Measuring nearshore bathymetry on high energy beaches (abstract). EOS, Transactions American Geophysical Union, F286.

Bird, E.C.F., 2000. Coastal Geomorphology: An Introduction. Wiley, Chichester, 322 pp.

Blair, T.C., McPherson, J.G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. Journal of Sedimentary Research A64, 450–489.

Blair, T.C., McPherson, J.G., 1999. Grain-size and textural classification of coarse sedimentary particles. Journal of Sedimentary Research 69 (1), 6–19.

Bourrouilh-Le Jan, F., Talandier, J., 1985. Sédimentation et fracturation de haute énergie en milieu recifal: tsunamis, ouragans et cyclones et leurs effets sur la sédimentologie et la géomorphologie d'un atoll: motu et hoa, à Rangiroa, Tuamotu, Pacifique SE (Major high-energy events in a reef environment: Tsunamis, Hurricanes and tropical cyclones and their effects on the sedimentology and geomorphology of an atoll: Rangiroa, Tuamotu, SE Pacific). Marine Geology 67, 263–333.

Bryan, W.B., Moore, J.G., 1994. Geologic Effects of Giant Tsunami Waves, Lanai and Molokai, Hawaii (abstract). Geological Society of America, 1994 annual meeting, Seattle, WA., p. 378.

Bryant, E., 2001. Tsunami—The Underrated Hazard. Cambridge Univ. Press, New York, NY, 350 pp.

Chave, E.H., Mundy, B.C., 1994. Deep-sea benthic fish of the Hawaiian Archipelago, Cross Seamount and Johnston Atoll. Pacific Science 48 (4), 367–409.

Clague, J.J., Bobrowsky, P.T., 1994. Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia. Geological Society of America, Bulletin 106, 1293–1303.

Colella, A., Prior, D.B. (Eds.), 1990. Coarse-Grained Deltas. International Association of Sedimentologists, Special Publication, vol. 10, Blackwell, Oxford, 357 p.

Coleman, P.J., 1978. Tsunami sedimentation. In: Fairbridge, R.W., Bourgeois, J. (Eds.), The Encyclopedia of Sedimentology. Dowden, Hutchison and Ross, Stroudsburg, PA, pp. 828–831.

Coulbourn, W.T., Campbell, J.F., Moberly, R., 1974. Hawaiian submarine terraces, canyons, and Quaternary history evaluated by seismic reflection profiling. Marine Geology 17, 215–234.

Cowell, P.J., Hanslow, D.J., Meleo, J.F., 1999. The shoreface. In: Short, A.D. (Ed.), Handbook of Beach and Shoreface Morphodynamics. Wiley, Chichester, pp. 41–71.

Crook, K.A.W., Noormets, R., Felton, E.A., Minty, L., Franklin, D., 2000. Megaclast emplacement and movement on shore platforms: an index of extreme events at the land–sea interface (abstract). 15th Australian Geological Convention, Sydney, Australia.

Dawson, A.G., Foster, I.D., Shi, S., Smith, D.E., Long, D., 1991. The identification of tsunami deposits in coastal sediment sequences. Science of Tsunami Hazards 9 (1), 73–82.

Dawson, A.G., Shi, S., Dawson, S., Takahashi, T., Shuto, N., 1996. Coastal sedimentation associated with the June 2nd and 3rd, 1994 tsunami in Rajegwesi, Java. Quaternary Science Reviews 15, 901–912.

Dollar, S.J., Tribble, G.W., 1993. Recurrent storm disturbance and recovery: a long-term study of coral communities in Hawaii. Coral Reefs 12, 223–233.

Dominey-Howes, D., Cundy, A., Croudace, I., 2000. High energy marine flood deposits on Astypalea Island, Greece: possible evidence for the AD1956 southern Aegean tsunami. Marine Geology 163, 303–315.

Dupré, W.R., 1984. Reconstruction of paleo-wave conditions during the Late Pleistocene from marine terrace deposits, Monterey Bay, California. Marine Geology 60, 435–454.

Emory, K.P., 1933. Stone remains in the Society Islands. Bishop Museum Bulletin 116, 182.

Eyles, C.H., 1994. Intertidal boulder pavements in the northeastern Gulf of Alaska and their geological significance. Sedimentary Geology 88, 161–183.

Felton, E.A., Crook, K.A.W., Keating, B.H., 2000. The Hulopoe Gravel, Lanai, Hawaii: new sedimentological data and their bearing on the "giant wave" (mega-tsunami) emplacement hypothesis. Pure and Applied Geophysics 157, 1257–1284.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature. Journal of Geology 62, 345–351.

Folk, R.L., Andrews, P.B., Lewis, D.W., 1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. New Zealand Journal of Geology and Geophysics 13, 937–968.

Giresse, P., Hoang, C.-T., Kouyoumontzakis, G., 1984. Analysis of vertical movements deduced from a geochronological study of marine Pleistocene deposits, southern coast of Angola. Journal of African Earth Sciences 2 (2), 177–187.

Grabau, A.W., 1913. Principles of Stratigraphy. A.G. Seiler & Co., New York, 185 pp.

Greene, H.G., et al., 1999. A classification scheme for deep seafloor habitats. Oceanologica Acta 22 (6), 663–678.

Grigg, R., Jones, A.T., 1997. Uplift caused by lithospheric flexure in the Hawaiian Archipelago as revealed by elevated coral deposits. Marine Geology 141, 11–25.

Gupta, S., Allen, P.A., 1999. Fossil shore platforms and drowned gravel beaches: evidence for high-frequency sea-level fluctuations in the distal Alpine Foreland Basin. Journal of Sedimentary Research 69 (2), 394–413.

Gvirtzman, G., Kronfeld, J., Buchbinder, B., 1992. Dated coral reefs of southern Sinai (Red Sea) and their implication to late Quaternary sea levels. Marine Geology 108 (1), 29–37.

Hart, B.S., Plint, A.G., 1995. Gravelly shoreface and beachface deposits. In: Plint, A.G. (Ed.), Sedimentary Facies Analysis. International Association of Sedimentologists, Special Publication, vol. 22. Blackwell, Oxford, pp. 75–99.

Highsmith, R.C., Riggs, A.C., D'Antonio, C.M., 1980. Survival of hurricane-generated coral fragments and disturbance model for reef calcification/growth rates. Oecologia 46, 322–329.

Johnson, M.E., 1988. Why are ancient rocky shores so uncommon? Journal of Geology 96, 469–480.

Johnson, M.E., 1992. Studies on rocky shores: a brief history and annotated bibliography. Journal of Coastal Research 8, 797–812.

Johnson, M.E., Ledesma-Vázquez, J., 1999. Biological zonation on a rocky-shore boulder deposit, Upper Pleistocene Bahía San Antonio (Baja California Sur, Mexico). Palaios 14, 569–584.

Johnson, M.E., Libbey, L.K., 1997. Global review of Upper Pleistocene (Substage 5e) Rocky Shores: tectonic segregation, substrate variation and biological diversity. Journal of Coastal Research 13 (2), 297–307.

Johnson, M.E., Baarli, B.G., Scott Jr., J.H., 1995. Colonization and reef growth on a Late Pleistocene rocky shore and abrasion platform in Western Australia. Lethaia 28, 85–98.

Jones, A.T., 1993. Review of the chronology of marine terraces in the Hawaiian Archipelago. Quaternary Science Reviews 12, 811–823.

Jones, A.T., 1995. Geochronology of drowned Hawaiian coral reefs. Sedimentary Geology 99 (3,4), 233–242.

Keating, B.H., 1994. Analysis of Seismic Profiles, Drowned Reefs and Terraces around the Hawaiian Island Chain. Hawaii Institute of Geophysics and Planetology, Honolulu, HI. Sheet 8, Hawaii Seafloor Atlas.

Keating, B.H., Helsley, C.E., 2002. Island uplift and the ancient shorelines of Lanai, Hawaii. Sedimentary Geology (in press).

Kelsey, H.M., Bockheim, J.G., 1994. Coastal landscape evolution as a function of eustasy and surface uplift rate, Cascadia margin, southern Oregon. Geological Society of America, Bulletin 106 (7), 840–854.

Koster, E.M., Steel, R.J. (Eds.), 1984. Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Memoir, vol. 10. Calgary, 441 pp.

Lavoisier, A.L., 1789. Littoral and pelagic beds. Mémoires de l'Académie des Sciences, 351–371. Partly translated in Mather, K.F. and Mason, S.L. (1939). Source Book in Geology. McGraw-Hill Book Company, Inc., New York, pp. 126–128.

Ludwig, K.R., Muhs, D.R., Simmons, K.R., Moore, J.G., 1992. Sr-isotope record of Quaternary marine terraces on the California coast and off Hawaii. Quaternary Research 37 (3), 267–280.

Malin, M.C., Edgett, K.S., 2000. Sedimentary rocks of early mars. Science 290, 1927–1936.

Marzo, M., Puidefábregas, C. (Eds.), 1993. Alluvial Sedimentation. International Association of Sedimentologists, Special Publication, vol. 17. Blackwell, Oxford, 586 pp.

Miall, A.D., 1992. Alluvial deposits. In: Walker, R.G., James, N.P. (Eds.), Facies Models. Response to Sea Level Change. Geological Association of Canada, St. Johns, NF, pp. 119–142.

Miall, A.D., Miall, C.E., 2001. Sequence stratigraphy as a scientific enterprise: the evolution and persistence of conflicting paradigms. Earth-Science Reviews 54, 321–348.

Middleton, G.V., 1978. Facies. In: Fairbridge, R.W., Bourgeois, J. (Eds.), Encyclopedia of Sedimentology. Dowden, Hutchinson and Ross, Stroudsburg, PA, pp. 323–325.

Moffitt, R.B., Parrish, F.A., 1992. An assessment of the exploitable biomass of *Heterocarpus laevigatus* in the main Hawaiian Islands: Part 2. Observations from a submersible. Fishery Bulletin 90, 476–482.

Moore, J.G., 1987. Subsidence of the Hawaiian Ridge. In: Decker, R.W., Wright, T.L., Stauffer, P.H. (Eds.), Volcanism in Hawaii. United States Geological Survey Professional Paper, vol. 1350. Reston, VA, pp. 85–100.

Moore, J.G., Moore, G.W., 1984. Deposit from a Giant Wave on the island of Lanai, Hawaii. Science 226, 1312–1315.

Moore, G.W., Moore, J.G., 1988. Large scale bedforms in boulder gravel produced by giant waves in Hawaii. Geological Society of America Special Paper 229, 101–110.

Moore, J.G., Normark, W.R., Holcomb, R.T., 1994. Giant Hawaiian underwater landslides. Science 264, 46–47.

Muhs, D.R., Szabo, B.J., 1982. Uranium-series age of the Eel Point terrace, San Clemente Island, California. Geology 10, 23–26.

Munsell®, 1992. Munsell® Soil Color Charts. Macbeth® Division of Kollmorgen Instruments, New York, p. 10, 9 charts.

National Ocean Service, 2000. NOS Biogeography Program. <http://biogeo.nos.noaa.gov/data/hawaii/images_2000>.

Nichol, S.N., Carter, C.H., 1998. Tsunami or coastal storms; two coarse-grained deposits from northern New Zealand (abstract). Geological Society of America, 1998 Annual Meeting, Toronto, Ontario, Canada, p. 228.

Nichols, G.J., 1998. Sedimentology and Stratigraphy. Blackwell, Malden, MA, 368 pp.

Noormets, R., Felton, E.A., Crook, K.A.W., 2002a. Sedimentology of Rocky Shorelines: 2. Shoreline megaclasts on the north shore of Oahu, Hawaii: origins and history. Sedimentary Geology (in press).

Noormets, R., Crook, K.A.W., Felton, E.A., 2002b. Hydrodynamics of Megaclast Emplacement and Transport on a Shore Platform, Oahu, Hawaii (abstract; submitted). 2nd Tsunami Symposium. International Tsunami Society, Honolulu, Hawaii.

Nott, J., 1997. Extremely high-energy wave deposits inside the Great Barrier Reef, Australia: determining the cause—tsunami or tropical cyclone. Marine Geology 141, 193–207.

Oak, H.L., 1984. The boulder beach: a fundamentally distinct sedimentary assemblage. Annals of the Association of American Geographers 74, 71–82.

Ogren, D.E., Waag, C.J., 1986. Orientation of cobble and boulder beach clasts. Sedimentary Geology 47 (1–2), 69–76.

Ortlieb, L., Zazo, C., Goy, J.L., Dabrio, C., Machare, J., 1996. Pampa del Palo; an anomalous composite marine terrace on the uprising coast of southern Peru. Journal of South American Earth Sciences 9 (5–6), 367–379.

Parrish, F.A., DeMartini, E.E., Ellis, D.M., 1996. Nursery habitat in relation to production of juvenile pink snapper, *Pristipomoides filamentosus*, in the Hawaiian Archipelago. Fishery Bulletin 95, 137–148.

Parrish, F.A., Craig, M.P., Ragen, T.J., Marshall, G.J., Buhleier, B.M., 2000. Identifying diurnal foraging habitat of endangered Hawaiian monk seals using a seal-mounted video camera. Marine Mammal Science 16 (2), 392–412.

Paskoff, R., 1991. Likely occurrence of a mega-tsunami in the Middle Pleistocene, near Coquimbo, Chile. Revista Geológica de Chile 18 (1), 87–91.

Pickering, K.T., Hiscott, R.N., 1989. Deep Marine Environments; Clastic Sedimentation and Tectonics. Unwin Hyman, London, 416 pp.

Postma, G., Nemec, W., 1990. Regressive and transgressive sequences in a raised Holocene gravelly beach, southwestern Crete. Sedimentology 37, 907–920.

Ralston, S., Gooding, R.M., Ludwig, G.M., 1986. An ecological survey and comparison of bottom fish resource assessments (submersible versus handline fishing) at Johnston Atoll. Fishery Bulletin 84, 141–155.

Reading, H.G., Collinson, J.D., 1996. Clastic coasts. In: Reading, H.G. (Ed.), Sedimentary Environments: Facies, Processes and Stratigraphy. Blackwell, Oxford, UK, pp. 154–231.

Rubin, K.H., Fletcher III, C.H., Sherman, C., 2000. Fossiliferous Lanai deposits formed by multiple events rather than a single giant tsunami. Nature 408, 675–681.

Saito, Y., 1996. Tsunami deposits on the Okushiri Island shelf caused by the 1993 Hokkaido Nansei-Oki earthquake (abstract). EOS, Transactions of the American Geophysical Union 77 (46), F511.

Scott Jr., J.H., Johnson, M.E., 1993. Lateral variation in the geomorphology of a Pleistocene rocky coastline at Kalbarri, Western Australia. Journal of Coastal Research 9, 1013–1025.

Semeniuk, V., Johnson, D.P., 1985. Modern and Pleistocene rocky shore sequences along carbonate coastlines, southwestern Australia. Sedimentary Geology 44, 225–261.

Seymour, R.J., 1981. Evidence of oceanic impact of large meteorites (Lunar and Planetary Institute Contribution 449). Conference on Large Body Impacts and Terrestrial Evolution; Geological, Climatological, and Biological Implications, Snowbird, UT, p. 51.

Shaw, C.E., 1996. Coastal geomorphology of the Mexican Caribbean; a legacy from the Pleistocene (abstract). Geological Society of America, 28th Annual Meeting. Geological Society of America, Abstracts with Programs, Denver, CO, United States, p. 301.

Shi, S., Dawson, A.G., Smith, D., 1995. Coastal sedimentation associated with the December 12, 1992 tsunami in Flores, Indonesia. Pure and Applied Geophysics 144, 521–536.

Shigeno, K., Shimokawa, K., Satake, K., 1997. Deposits of modern tsunamis and storms in Hokkaido (abstract). EOS, Transactions AGU 78, F640.

Sloan, R.E., 1964. The Cretaceous System in Minnesota. Minnesota Geological Survey Report of Investigation 5, 64.

Sneed, E.D., Folk, R.L., 1958. Pebbles in the Lower Colorado River, Texas, a study in particle morphogenesis. Journal of Geology 66, 114–150.

Spinelli, G., Field, M., 2001. Evolution of continental slope gullies on the northern California margin. Journal of Sedimentary Research 71 (2), 237–245.

Stearns, H.T., 1938. Ancient shorelines on the island of Lanai, Hawaii. Geological Society of America, Bulletin 49, 615–628.

Stearns, H.T., 1940. Geology and groundwater resources of the islands of Lanai and Kahoolawe, Hawaii. Territory of Hawaii, Division of Hydrography, Bulletin 6.

Stearns, H.T., 1978. Quaternary Shorelines in the Hawaiian Islands. Bernice P. Bishop Museum Bulletin 237, 57.

Stephenson, T.A., Stephenson, A., 1972. Life Between Tidemarks on Rocky Shores. Freeman, San Francisco, CA, 425 pp.

Storlazzi, C.D., Field, M.E., 2000. Sediment distribution and transport along a rocky, embayed coast: Monterey Peninsula and Carmel Bay, California. Marine Geology 170 (3–4), 289–316.

Sunamura, T., 1992. Geomorphology of Rocky Coasts. Wiley, Chichester, 302 pp.

Süssmilch, C.A., 1912. Note on some recent marine erosion at Bondi. Royal Society of New South Wales, Journal and Proceedings 46, 155–158.

Talandier, J., Bourrouilh-Le-Jan, F., 1988. High energy sedimentation in French Polynesia: cyclone or tsunami? In: El-Sabh, M.I., Murty, T.S. (Eds.), Natural and Man-Made Hazards. Reidel, Dordrecht, Netherlands, pp. 193–199.

Trenhaile, A.S., 1987. The Geomorphology of Rock Coasts. Oxford Research Series in Geography. Clarendon Press, Oxford, 384 p.

Trenhaile, A.S., 1989. Sea-level oscillations and the development of rock coasts. In: Lakhan, V.C., Trenhaile, A.S. (Eds.), Applications in Coastal Modeling. Elsevier, Amsterdam, pp. 271–295.

Twenhofel, W.H., 1926. Principles of Sedimentation. Williams & Wilkins, Baltimore, 661 pp.

Waag, C.J., Ogren, D.E., 1984. Shape evolution and fabric in a boulder beach, Monument Cove, Maine. Journal of Sedimentary Petrology 54 (1), 98–102.

Walker, R.G., 1975. Generalized facies models for resedimented conglomerates of turbidite association. Geological Society of America, Bulletin 86, 737–748.

Walker, R.G. (Ed.), 1984. Facies Models. Geoscience Canada Reprint Series, vol. 1. Geological Association of Canada, St. Johns, NF.

Walker, R.G., 1992a. Facies, facies models and modern stratigraphic concepts. In: Walker, R.G., James, N.P. (Eds.), Facies Models. Response to Sea Level Change. Geological Association of Canada, St. Johns, NF, pp. 1–14.

Walker, R.G., 1992b. Turbidites and submarine fans. In: Walker, R.G., James, N.P. (Eds.), Facies Models. Response to Sea Level Change. Geological Association of Canada, St. Johns, NF, pp. 239–264.

Walker, R.G., James, N.P. (Eds.), 1992. Facies Models. Response to Sea Level Change. Geological Association of Canada, St. Johns, NF, 409 pp.

Walker, R.G., Mutti, E., 1973. Turbidite facies and facies associations. In: Middleton, G.V., Bouma, A.H. (Eds.), Turbidites and Deep Sea Sedimentation. SEPM, Los Angeles, pp. 119–157.

Wilson, M.A., Palmer, T.J., 1992. Hardgrounds and hardground faunas. Institute of Earth Studies Publications, vol. 9. University of Wales, Aberystwyth, Wales, 131 pp.

Wright, M.E., Walker, R.G., 1981. Cardium Formation (U. Cretaceous) at Seebe, Alberta: Storm-deposited sandstones and conglomerates in shallow marine depositional environments below fair-weather wave base. Canadian Journal of Earth Sciences 18, 795–809.

Yoklavich, M.M., et al., 2000. Habitat associations of deep-water rockfishes in a submarine canyon: an example of a natural refuge. Fishery Bulletin 98 (3), 625–641.

Young, R.W., Bryant, E.A., Price, D.M., 1996. Catastrophic wave (tsunami?) transport of boulders in southern New South Wales, Australia. Zeitschrift für Geomorphologie N.F. 40, 191–207.

Zazo, C., Bardaji, T., Dabrio, C.J., Goy, J.L., Hillaire-Marcel, C., 1998. IAS 98 Excursion A-7: Record of Late Pliocene and Quaternary sea-level changes in coastal settings, southeast Spain. International Association of Sedimentologists, Alicante, Spain, 151–169.