Global Review of Upper Pleistocene (Substage 5e) Rocky Shores: Tectonic Segregation, Substrate Variation, and Biological Diversity

Markes E. Johnson and Laura K. Libbey

Department of Geology
Williams College
Williamstown, MA 01267, U.S.A.

ABSTRACT

JOHNSON, M.E. and 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. Fort Lauderdale (Florida), ISSN 0749-0208.

A bibliographic search using the computerized system, Georef, allowed effective screening of the geological and paleontological literature for research articles on abandoned rocky shores correlated with oxygen isotope substage 5e (mid-point of the last interglacial epoch approximately 125,000 years before present). Sixty articles covering 54 localities with a global distribution were selected for synopses, including information on substrate lithology, present elevation, and faunal character. The sites are sorted by tectonic regime: 37% occur on active continental margins (modest uplift); 13% on passive continental margins (little or no uplift); 35% on island arcs (significant uplift); 15% on island chains or continental margins affected by hot spots (minor uplift to modest subsidence). In terms of their geographical latitude, the sites represent a range from temperate shores with dominantly molluscan faunas to subtropical shores with mixed molluscan and colonial coral faunas, to tropical shores with dominantly colonial coral faunas. During the peak of the last interglacial epoch, the subtropical limits were extended between 300km and 600km farther north and south than at present. Differences in biological diversity are difficult to gauge based on the highly selective species lists available in this data set. Nevertheless, enough information is at hand to clearly demonstrate that encrusting, intertidal to very shallow subtidal biotas are being retained in the geological record.

ADDITIONAL INDEX WORDS: *Last interglacial epoch, marine terraces, wave-cut platforms, unconformities.*

INTRODUCTION

The subject of rocky shores readily conjures up a mental image of a Winslow Homer painting: a rugged Maine coast with waves dashed to spray in the red glow of sunset. In the face of such pounding energy, it is not surprising that paleontologists and geologists are reluctant to hold out much hope for the safe burial and preservation of rocky-shore biotas in the rock record. Through careful library reading, an earlier bibliography on ancient rocky shores brought together only 155 references (JOHNSON, 1992). Ignoring that several citations may deal with the same field locality or that some time intervals have a more dismal record than others, or that a few are actually Precambrian in age, the prorated incidence of these rocky shores entering the Phanerozoic rock record over the last 500 million years would be something on the order of one site every 3.3 million years. Thus, there is little to get enthusiastic over, unless the record is much better than generally given credit for in the existing literature.

Another approach to the problem is to organize a more focused search for rocky-shore biotas in the recent geological record. A reasonable assumption is that rocky shores are just as unlikely to be well represented in the geological record of the remote past if they are not found widespread in the recent past. Where, geographically, and within what geological time

frame should such an overview be directed? The distribution of modern rocky shores is heavily influenced by plate tectonics. Active continental margins, island arcs, and island chains associated with hot spots all exhibit significantly more rocky shores than passive continental margins (JOHNSON, 1988). This quantification excludes glaciated coasts and high-latitude coasts, where intertidal colonization is hampered by ice scour.

During the last interglacial epoch about 120,000 to 135,000 years ago, sea level stood higher than at any time afterwards or back through the last 350,000 years (CHAPPELL and SHACKLETON, 1986). This accounting of secular sea-level changes is based on fluctuations in oxygen isotopes from Upper Pleistocene deep-sea cores, in which the ratio of heavy oxygen to normal oxygen retained in calcitic shells of foraminifera act as a proxy for shifting volumes of glacial ice. The warmest part of the last interglacial epoch when sea level was presumably highest is called oxygen isotope substage 5e, based on terminology introduced by SHACKLETON and OPDYKE (1973). Many tectonically active coasts but fewer passive coasts should retain a geographically diverse record of rocky coastlines from this former highstand. Especially over the last two decades, geologists interested in climatic, eustatic, and tectonic rates of change have extended correlation of substage 5e from the record of deep-sea cores to the more spotty record of coastal deposits.

METHODS

The computer-based, bibliographic search system, Georef, was used to access research articles on abandoned rocky shorelines that formed between 120ka and 135ka before present. A variety of different key words were entered in different combinations to conduct searches: Pleistocene, substage 5e, last interglacial, marine terraces, wave-cut platforms, rocky shores, and unconformities. Just the combination of Pleistocene and marine terraces, for example, yields a listing of 118 references for the period between 1988 and 1994. Many authors under this combination do not specifically classify their study sites as rocky shores. Thus, the same criteria were applied as followed by JOHNSON (1992) in compiling an earlier all-inclusive bibliography on ancient rocky shores. Emphasis is on physical features, such as tidal notches, wave-cut platforms, sea stacks, sea cliffs, unconformities and basal conglomerates, as well as paleontological evidence of biotas associated with hard substrates in intertidal to very shallow subtidal environments. Finally, successful citations had to fall within the temporal limits of substage 5e, as generally established through analysis of U-series decay, amino acid racemization, electron spin resonance (ESR), or some other logical inference.

RESULTS

The following annotations cover 60 references culled from the literature on substage-5e rocky shores. Some citations refer to more than one locality and others are updated descriptions of localities previously recorded; a total of 54 different sites are represented. Brief summaries are arranged according to the tectonic classification of modern rocky shorelines (JOHNSON, 1988). They are also organized by chronological order, except where a subsequent researcher published on the same locality or area. Only 6 citations from the Quaternary listings in JOHNSON (1992) overlap with this more time-specific bibliography.

Active continental margins

Continental margins that are tectonically active usually sit on narrow shelves fronted by deep ocean trenches. Closure of ocean basins associated with the subduction of oceanic crust beneath an adjacent continent is typified by the Pacific west coasts of North and South America. In the Gulf of California and the Red Sea, however, ocean rifting in its early phases also involves significant tectonic uplift. In both settings, wave cut platforms, marine terraces, and other rocky shorelines are subject to vertical uplift. The single most extensive study of substage-5e rocky terraces on active margins is that by MUHS et al. (1994), including several locations in California and neighboring Baja California. Most studies focus on a single locality.

DURHAM (1947) noted islands in the Gulf of California off peninsula Baja California, Mexico, where there occur deposits with coral heads and even entire reefs composed of *Porites californica* associated with Upper Pleistocene terraces eroded on Miocene andesite. Two *in situ* reefs are briefly described from Carmen Island at Marquer Bay (3m thick) and Puerto

Balandra (6m thick). Coral heads 38cm in height form part of the deposit on the prominent 6m terrace of San Marcos Island. Heads of similar size belonging to the same species and at about the same elevation were observed by us in 1995 on the largest of the nearby Santa Inez islands. A previously undescribed 1m-thick reef also was found by us at an elevation 7.5m above sea level on the south side of the nearby Punta Chivato promontory. The profile of this reef is exposed in an arroyo for a distance of 71m, and consists of *in situ* colonies of *Porites californica,* each about 20cm in height. Burying the reef is a thin shell bed that converges with much thicker deposits in adjacent Bahia Santa Inez. U-series analyses of sample shell and coral materials from the expansive bay deposit led ORTLIEB (1984, p. 125) to interpret a correlation with substage 5e. *Dosinia ponderosa* yielded an age of 153±16ka and an unspecified coral provided an age of 117±8ka. The Punta Chivato, Islas Santa Inez, San Macros, and Carmen coral-bearing terraces all occur close to the same elevation and are probably the same age.

Coral-bearing conglomerates resting unconformibly on a wave-cut platform eroded from Cretaceous granite at Cabo Pulmo near the tip of the peninsula Baja California are described by SQUIRES (1959). The platform is situated 6m above present sea level. MUHS et al. (1994) collected two samples each of the corals *Porites* and *Pocillopora* from this conglomerate and dated them by U-series analysis. The former yielded ages of 120±3ka and 121±3ka, but the latter gave results of 132±4ka and 140±4ka, thus suggesting a correlation with substage 5e.

VEEH and VALENTINE (1967) investigated the Late Pleistocene Piedras Blancas terrace near Cayucos Point, California and reported a U-series age of 130±30ka based on the orange cup coral, *Balanophyllia elegans.* The same site, which sits at an elevation of 6m to 8m, was rechecked by MUHS et al. (1994), who found this species yielded ages between 117±3ka and 121±3ka. Additional coral samples collected nearby yielded older ages, but still within the normal range for substage 5e. The megafauna associated with the terrace includes 130 species "composed chiefly of rocky shore types mixed with a few inner sublittoral forms" (VALENTINE, 1958). Most abundant are intertidal rock-dwelling gastropods, including species belonging to the genera *Acmaea, Crepidula, Fissurella, Hipponix, Littorina, Olivella,* and *Tegula.* In addition to the orange cup coral, however, the only other encrusting fauna include *Mytilus californianus* and the barnacles *Balanus* and *Tetraclita.*

KU and KERN (1974) studied the Nestor terrace at several places in the San Diego area and determined an age of 120±10ka. Point Loma was restudied by MUHS et al. (1994), who derived a refined age estimate of 126±3ka based on samples of *Balanophyllia* collected 24m above present sea level. The rocky substrate on the Point Loma peninsula consists of Upper Cretaceous siltstones and mudstones.

An Upper Pleistocene marine-terrace veneer near Punta Camalú in Baja California, Mexico, was studied for its megafauna by VALENTINE (1980), who estimated an age of 120–125ka based on analysis of amino acid racemization. The fauna includes over 100 species, most of which represent intertidal species from an open-coast setting. Like the Cayucos

Point fauna, the Punta Camalú fauna is heavily dominated by gastropods, but also includes several species of chitons. Barnacles and *Mytilus californianus* are the only encrusters but the rock-boring bivalves *Penitella penita* and *P. gabbii* as well as the nestling bivalve *Petricolla carditoides* are also represented. The rocky substrate at Punta Camalú consists of Upper Cretaceous conglomerates and siltstones.

PASKOFF (1991) studied five terraces eroded in soft sandstone of the Miocene Coquimbo Formation near Coquimbo, Chile. Shells from these terraces were previously dated using amino acid epimerization, U-series, and ESR techniques. The first terrace is of Holocene age, the second (at an elevation of 20m) is said to belong to substage 5e, and the third to substage 9. The main focus of this paper is the large boulders deposited on the third terrace, which are hypothesized to have been emplaced by a tsunami.

MUHS and SZABO (1982) studied several emergent terraces on San Clemente Island, California. Situated at an elevation of 32m, the second terrace is called the Eel Point terrace. It is assigned to substage 5e on the basis of U-series analysis of the hydrocoral, *Allopora californica*, yielding an age of 127±7ka. This estimate is upheld by MUHS et al. (1994), although they treated a sample of *Balanophyllia* from the same terrace which yielded a younger age. Overall, megafaunas are sparse but Eel Point is said to be unusually fossiliferous including the bivalve *Epilucina*, gastropods *Tegula* and *Haliotis*, as well as limpets and barnacles indicative of a "rocky, intertidal environment" (MUHS and SZABO, 1982, p. 24). The hydrocoral is less abundant, however, and must have been transported because it thrives today only subtidally (MORRIS et al., 1980). The island is composed of Miocene andesite and the terrace deposits include rounded andesite cobbles and pebbles.

ASHBY et al. (1987) report on the distinctive harbor landmark known as El Sombrerito and adjacent terraces at Mulegé on the Gulf of California in Baja California Sur, Mexico. The landmark is a gabbro plug with a wave-cut platform incised around its circumference at a 12m elevation. U-series analyses of the coral, *Porites californica*, yielded an age estimate of 144±7ka for the wave-cut platform, but another coral sample from a nearby terrace at the same elevation yielded an estimate of 124±5ka. The main focus of their study is the calculation of local uplift, but a companion study by ASHBY and MINCH (1987) summarizes the Upper Pleistocene megafauna belonging to the Mulegé Formation. Fossils collected from the 12m terrace constitute one of the most diverse substage-5e faunas yet recorded, including 86 species of gastropods, 62 pelecypods, 1 scaphopod, 3 echinoids, 1 anthozoan, and 1 arthropod. The only encrusting forms are the bivalves *Arca pacifica, Ostrea angelica, O. megadon,* and *O. palmula* and the barnacle *Balanus*. Many of the gastropods, such as *Crucibulum spinosum, C. scutellatum, Cerithiem maculosum, Thais biserialis,* and *Turbo fluctuosus* are known by their extant descendants as strictly intertidal, rocky-shore dwellers.

ROCKWELL et al. (1989) document a succession of 12 marine terraces at Punta Banda on the Pacific coast of northern Baja California, Mexico. Terrace elevations vary laterally due to extensive faulting on the Punta Banda peninsula. The third, or Cave terrace, extends for over 15km at elevations between 34m and 40m above sea level. Although macrofossils were collected, only a few names useful for paleoclimatic inference are published; the authors assigned an age of 120ka to the terrace (ROCKWELL et al., 1989). Subsequently, MUHS et al. (1994) collected two samples of *Balanophyllia* from the Cave terrace for U-series analysis, which yielded ages of 120±3ka and 124±4ka, respectively. The rocky substrate in this region consists mainly of Cretaceous andesite.

HSU (1990) dated fossil bivalves using high-pressure liquid chromotography to determine the ages of transgressive deposits on the Pampa del Palo marine terrace in Peru. This terrace is 25m above present sea level, more than 10km long, and over 1km wide. Coarse shell debris contribute to intertidal deposits covering the seaward sloping platform. The most intriguing aspect of this study is that analysis reveals high stands in sea level at 125ka, 200ka, 300ka, and 400ka, all preserved on the same terrace. It is postulated that a very low rate of uplift over this part of the coastline allowed amalgamation of widely aged deposits.

Assemblages of Late Pleistocene megafossils from the second marine terrace on San Nicolas Island, California, are tabulated by RUSSELL (1991) and correlated to substage 5e. Forty-five species of rocky-substrate dwellers were recorded at 4 collection sites indicative of an open-coast, high-energy environment. Dominated by gastropods and bivalves, the only rock encrusters within these assemblages include *Mytilus californianus*, barnacles, and *Balanophyllia elegans*. Three samples of the orange cup coral from the second terrace (elevation between 33m and 36m) were subjected to U-series analysis by MUHS et al. (1994), yielding ages of 120±4ka, 117±3ka, and 111±3ka, respectively. The rocky substrate on San Nicolas Island consists of sandstone.

GVIRTZMAN et al. (1992) utilized U-series analysis to date reef corals associated with four morphological terraces in the southern Sinai on the Red Sea. Crystalline basement rock is unconformably overlain by terrace deposits. Beach rock typically forms the landward edge, but a wave-cut notch attributed to a substage-5e highstand in sea level is preserved as eroded in an older reef. The Na'ama reef is regarded as belonging to substage 5e, although only a single coral sample yielded an age of 141ka. No coral species or associated megafauna are described from this reef, which forms an almost continuous belt following the shoreline for 15km at elevations between 13m and 18m above sea level.

HEARTY and DIA PRA (1992) developed a detailed system of amino zonation for the Pleistocene-Holocene stratigraphy exposed on the Gulf of Taranto in southeast Italy. Some sections, such as the "staircase" terraces at Torre Castelluccia, represent an open coast high-energy setting correlated with substage 5e and the *Strombus bubonius* fauna. Gastropods of this species are preserved in lenses filling "circular depressions of a decimetric scale" eroded in algal calcarenite (HEARTY and DIA PRA, 1992, p. 890). These features, elevated 26m above present sea level, appear to be abandoned tidal pools.

KELSEY and BOCKHEIM (1994) found that where rates of coastal uplift are moderately high (0.7–0.9m/ka) along the Cascadia margin of southern Oregon, seven flights of emergent wave-cut platforms are preserved on the interfluves of

coastal drainages. Based on relationships with other dated terraces, it is speculated that the third, or Gowman terrace, formed during substage 5e. No direct fossil evidence, however, exists for this correlation (MUHS *et al.*, 1994). At Cape Ferrelo, the Gowman terrace has been uplifted to elevations between 72m and 134m above present sea level.

Unique associations of Upper Pleistocene megafossils are described by ZWIEBEL and JOHNSON (1995) from Punta Chivato on the open Pacific coast of northern Baja California, Mexico. A thick deposit of shells belonging to *Mytilus californianus* is preserved at the back of a deep pocket inlet. The nestling bivalve, *Petricola carditoides*, still occupies borings made directly on a nearby platform of Cretaceous andesite. The authors imply a possible correlation to substage 5a, but subsequent analysis of amino acid racemization in shells belonging to the bivavle, *Saxidomus nuttalli* from a closely associated deposit at the same elevation, has yielded values more consistent with substage 5e.

LIBBEY and JOHNSON (this volume) document an unusually well-preserved sea cliff occupied by an encrusting biota of bivalves (dominantly *Arca pacifica, Ostrea fischeri,* and *Pseudochama janus*), bryozoans, barnacles, vermetid gastropods, the tube coral *Tubastraea tenuilamellosa,* and coralline red algae. Fifteen species of organisms encrusting on an andesite substrate are supplemented by 29 other species of intertidal to shallow-subtidal molluscs preserved in abutting carbonate sediments. The cliff site is situated between 4.25m and 6.25m above present sea level on Playa La Palmita off Bahia Santa Ines on the Gulf of California, Baja California Sur, Mexico. ORTLIEB (1984, p. 125) correlated the deposits from this bay with substage 5e.

Island arcs

Tectonically active coastlines also occur on island arcs bordered by trench subduction, where two oceanic plates converge. Japan, the Philippines, and New Zealand in the western Pacific all belong to major island arcs. The Indonesian islands of Sumatra and Java in the eastern Indian Ocean; the Seychelles in the western Indian Ocean; and islands skirting the Puerto Rico Trench on the boundary between the Caribbean and Atlantic Ocean also constitute typical island-arc systems.

Many published reports on Pleistocene terraces in island-arc systems are devoted to the calculation of tectonic uplift rates taking into account the effect of coeval changes in eustatic sea level. A landmark contribution which stimulated much of this approach is the work by MESOLELLA *et al.* (1969) on the island of Barbados in the West Indies. The third inland terrace is called First High Cliff, which can be traced laterally for almost 50km along the west and south sides of the island at elevations between 30m and 60m above sea level. U-series analysis of *Montastrea annularis* and *Acropora palmata* from this reef tract yielded dates ranging between 122±6ka and 127±6ka, easily referable to substage 5e. The reef tract is locally 7.5m to 9m thick and rests unconformably on older calcarenites.

KONISHI *et al.* (1970) studied four limestone units on Kikai Island off the Ryukiu Trench south of Japan with the goal of calculating rates of vertical displacement. The uppermost three units were dated utilizing the ^{230}Th isotope and it was found that all three post-date substage 5e. The lowest unit is the oldest member of the Riukiu Limestone, consisting of coral-rich breccia and reef-wall limestone. It is inferred to be 130ka in age. This unit unconformably overlies the Pliocene Samachi Formation, a well-bedded series of marine siltstones and tuffs.

Another influential paper on tectonic coastlines and their terrace suites is by BLOOM *et al.* (1974), regarding the Huon Peninsula of New Guinea on the New Britain Trench. A flight of 20 reef terraces may be traced along the coast for 85km. Grouped together as the Wandokai Limestone, the succession developed morphologically as fringing and barrier reefs. They unconformably overlie clastic and limestone units of Miocene to Pliocene age. Corals from reef VIIa and VIIb were subjected to U-series analysis yielding dates of 138ka and 118ka, respectively. The elevation of the older reef ranges between 250m and 350m above present sea level and vertical uplift was found to approach 3m/ka. AHARON and CHAPPELL (1986) restudied the first seven terraces with regard to changing oxygen isotopes recorded by the bivalve, *Tridacna gigas,* which is often preserved in growth position on the terraces. Their analysis confirms correlation of reef VIIa and VIIb with substage 5e. Sea surface temperatures during that interval are interpreted to have been locally comparable to today.

CHAPPELL and VEEH (1978) investigated marine terraces on the islands of Timor and Atauro off the Timor Trough, which forms an eastern extension of the Java Trench. Volcanic agglomerates underlie some terraces and form old sea cliffs. Reefs are not lagoonal in morphology (as in Barbados) but sit on shelf conglomerates generated by marine erosion of the volcanic substrate. U-series analysis facilitated correlation of Reef 2 on Atauro terrace 2 with a 120ka highstand in sea level. The corals *Favia pallida* and *Goniastrea pecinata* yielded ages of 124±7ka and 120±7ka, respectively, but other corals from the same reef gave results ranging between 111±6ka and 160±8ka. The most common coral in Reef 2 is *Diploastrea heliopora,* with colonies up to 2.2m in diameter often preserved in life position on a cobble pavement. The crest of Reef 2 on Atauro Island sits 65m above sea level and the authors calculated an uplift rate of 0.47m/ka. Subsequently, the reef terraces and rate of uplift in the Kupang area of West Timor on the same trench system were studied by JOUANNIC *et al.* (1988). Two areas were considered: Cape Namosain with 7 terraces, and Cape Oeloimi on Semau Island with 4 terraces. Only the youngest terrace on Semau Island (7m above sea level) is correlated to substage 5e based on U-series analysis of an unspecified coral yielding an age of 124±8ka.

EMERY (1981) describes 6 terraces on Grand Cayman Island off the Cayman Trench in the Caribbean. The lowest terrace is considered Sangamonian in age. The Upper Pleistocene Ironshore Formation sitting on this terrace contains locally abundant corals and conch shells in a reef and/or back-reef setting. Corals are frequently preserved in growth position. The bedrock substrate forming the terrace surface consists of the Miocene-age Bluff Limestone.

Three elevated reef terraces on the Northwest Peninsula of

Haiti were studied by DODGE *et al.* (1983). All consist of massive reef-crest facies composed mainly of the coral *Acropora palmata.* The highest of these is the Nicolas terrace, a 500m wide surface with a lip 52m above sea level. It is correlated with the First High Cliff terrace on Barbados Island, on the basis of U-series analysis of *Acropora* samples yielding ages between 126±6ka and 132±5ka.

PILLANS (1983) examined twelve marine terraces in the South Taranaki area of New Zealand's North Island. Each consists of a subhorizontal wave-cut surface attached to an old sea cliff on the landward margin. Thick marine sands, usually on a basal conglomerate, uncomformably override erosion surfaces cut from Pliocene-Pleistocene marine sediments. Dates based on amino acid racemization were used to assign a 120ka age to the Rapanui Terrace. This third inland terrace stretches for approximately 60km at elevations between 35m and 60m above sea level. No specific macrofaunal data are provided.

OTA *et al.* (1984) described four marine terraces on the Conway coast of New Zealand's South Island. The Amuri Bluff terrace is inferred to correlate to the last interglacial epoch. It is backed by distinct sea cliffs and floored by an abrasion surface on Cenozoic limestone. Marine gravel unconformably overlies this flat substrate. Elevation of this marine deposit ranges between 35m and 45m above present sea level. No details of a fossil macrofauna are provided.

TAYLOR *et al.* (1985) studied uplift of the Torres Islands in northern Vanuatu off the New Hebrides Trench. Two unspecified corals were sampled for U-series analysis from a terrace 90m to 120m above sea level. These samples yielded age estimates of 122±7ka and 135±11ka for development of a limestone on limestone unconformity. Subsequently, STRECKER *et al.* (1986) described 6 marine terraces on nearby Santo Island. Unspecified corals collected for U-series analysis provided ages for 5 of the terraces at 42ka, 60ka, 85ka, 105ka, and 149ka. Not one correlated to substage 5e, but the fifth inland terrace is a broad, undated surface surmised to be 125ka in origin. All terraces are formed by reef limestone built unconformably on volcanic basement rocks.

LECOLLE *et al.* (1990) studied 4 localities on Efate Island in southern Vanuatu on the same trench system. Three terraces occur at each locality, one of which consistently dates to 125ka on the basis of unspecified corals collected from growth position and subjected to U-series analysis. Reef facies unconformably overlie an eroded substrate of basalts and volcanic tuffs.

WOODROFFE (1988) compared rates of tectonic uplift in Tonga (Pacific Ocean), the Cayman Islands (Caribbean Sea), and Christmas Island (Indian Ocean). Affected by subduction in the adjacent Tonga Trench, parts of Tonga show a 7m-high marine terrace is eroded in reef limestone. U-series analysis provides a date of 124ka. Adjacent to the Java Trench, a marine terrace composed of bedded calcarenites, phosphatic pebble conglomerates, and reef-talus deposits extends completely around Christmas Island. U-series analysis of corals collected from growth position also provides a date of 124ka.

MIYAUCHI (1988) utilized volcanic ash to determine the age of terrace deposits for six regions in northeast Japan, based on fission track dating and tephrostratigraphic relationships

with terrace deposits. Regionally, the Takadate surface on the Kamikita coastal plain is the lowest and widest terrace buried by volcanic ash. It is situated between 20m and 50m above sea level and includes an old sea cliff 10m in height. The terrace deposit consists of between 5m and 20m of transgressive sand, mud, and gravel bearing an unspecified macrofauna. An age of 120ka to 130ka is derived for the Takadate surface and its coeval terraces on Nishi-tsugaru and Noshiro coasts, as well as the Shimokita, Matsumae, and Oga peninsulas.

Limestone fabrics banked against old sea cliffs were inspected by MONTAGGIONI and HOANG (1988) on the Indian Ocean's Seychelles archipelago. Unconformities between granitic basement rocks and Upper Pleistocene limestones occur as high as 9m above sea level. Coralgal buildups are dominated by an *Acropora* framework adhering to low coastal cliffs and overhangs. Rubbly conglomerates, which fill cavities and joint patterns in the granite, include domal and encrusting corals such as *Leptastrea, Leptoria,* and *Goniastrea* together with molluscs such as *Turbo* and *Tridacna.* Capstones are composed of limestone with coralline red algae, such as *Porolithon* and *Lithophyllum* together with colonial vermetid gastropods such as *Serpulorbis.* At present, the latter community thrives in the uppermost limits of the subtidal zone. Among 5 samples collected for U-series analysis from material preserved in growth position, a single *Acropora* sample provided an age of 123±8ka and 2 Lesptastrea samples yielded ages of 135±10ka and 133±10ka, respectively.

WARD (1991) examined 13 marine terraces in the Waitutu district of the Fjordland region on New Zealand's South Island. Cretaceous plutonic and metamorphic rocks together with Tertiary mudstones with local conglomerates comprise the bedrock in this region. The terraces were dated using physiographic relations between marine terraces and glacial alluvial terraces. The fourth terrace, which includes an abrupt scarp representing an old sea cliff, is said to correlate to substage 5e. The bedrock surface of this terrace is covered by several meters of marine sand and gravel.

PIRRAZOLI *et al.* (1993) inspected 11 marine terraces at Cape Laundi on Indonesia's Sumba Island off the Java Trench. U-series and ESR analyses were employed to date corals from reef complex I_2, including *Favites flexuosa, Diplostrea heliopora, Porites* sp., and *Pseudosiderastrea tayami.* ESR results indicated ages between 93±14ka and 142±21ka and the [230]Th isotope suggested ages between 114±7ka and 136±8ka for this terrace situated about 19m above sea level. The authors make a correlation to substage 5e.

Work by DONOVAN and MILLER (1995) describes a 130ka-old rocky shoreline eroded from the dolomitized Pliocene Hopegate Formation on the Caribbean island of Jamaica off the Cayman Trench. At East Rio Bueno Harbour, the reefal Falmouth Formation sits unconformably on the Hopegate Formation. The shoreline includes an old sea cliff with an intertidal notch and a sloping shore platform. Platy corals, particularly *Siderastrea* sp. encrust directly on the platform surface. Borings are also evident on this surface, representing bivalves and clionid sponges. Age determination is on the basis of unpublished isotopic analyses.

Hot Spots

The tectonic swell which accompanies hot spots, or crustal invasion by mantle plumes, draws a high correlation with the development of volcanic islands. As mapped by CROUGH (1983), the global array of presently active hot spots includes 14 locations in the Pacific Ocean, 15 in the Atlantic Ocean, 4 in the Indian Ocean, and 8 on continents. Hot-spot traces occur where oceanic plates pass over stationary mantle plumes, resulting in the production of mid-plate island chains. The Hawaiian Islands and their link to the Emperor Seamounts is one example. The Afar region in East Africa is an example of a continental hot spot affecting a coastal area.

LINDBERG et al. (1980) tabulated the Upper Pleistocene megafossils from the conglomeratic Discovery Point Formation on Isla Guadalupe, located 330km off the Pacific coast of peninsular Baja California, Mexico. The island consists of two partly overlapping shield volcanos of Miocene age constructed on the axis of an extinct spreading center. They recognized a Sangamonian interglacial age for a mixed intertidal and shallow subtidal rocky-shore fauna of 86 species. The molluscs are the most diverse group represented, with 3 chitons, 59 gastropods, and 8 bivalves. The only encrusting forms are barnacles (Tetraclita squamosa) and an unidentified species of oyster. Samples of the coral, Pocillopora quadalupensis, were collected by MUHS et al. (1994) from three localities on the island and employed in U-series analyses yielding a range of dates between 117±3ka and 127±4ka. The +6m marine conglomerates of Isla Guadalupe sit on a basaltic substrate, which also is the source of eroded clasts.

FAURE et al. (1980) dated corals by U-series analysis from 4 areas in the Afar region. Among these, 3 coral samples from the Gulf of Tadjoura at elevations between 9m and 32m above sea level yielded a median age of 128±11ka. Six coral samples from the Obock area at elevations between 3m and 36m above sea level yielded a median age of 130±5ka. Corals such as Stylophora pistillata, Favites cf.virens, and F. cf. pallida as well as the bivalve Tridacna are very common.

SZABO et al. (1985) studied the subsurface stratigraphy of Enewetak Atoll, in the Marshall Islands chain. Six reef beds separated by erosional unconformities formed when the atoll was repeatedly submerged and reexposed. The second interval, dated by means of U-series analysis, has an age of 131±3ka.

WOODROFFE et al. (1991a) discuss the stratigraphy and chronology of fossil reefs in the southern Cook Islands, forming part of the Austral Islands chain in the South Pacific. Most of the islands studied have two reef units (upper and lower) separated by a pronounced unconformity. Upper Pleistocene reefs, with U-series dates correlating to substage 5e, sit on Lower Pleistocene reefs related to substage 7. Subsequently, GRAY et al. (1992) studied the chronology of fossil reefs in the northern Cook Islands. Their coring program on the Pukapuka and Rakahanga atolls reached to depths of 50m and established a history of 5 intervals of reef growth. One episode is said to have occurred between 125ka and 180ka. Age determination was on the basis of ESR and U-series analyses, but few recovered samples fall within the limits of substage 5e. One Porites colony recovered from a

depth of 2.5m gave an ESR result of 116ka-156ka and a U-series result of 130±8ka. Scarcity of this material is attributed to extensive erosion.

The Cocos Islands in the eastern Indian Ocean are suggested by CROUGH (1983) to have formed in response to a now inactive hot spot. A well-lithified limestone between 8m and 11m below the island surface was the source of a coral colony sampled by WOODROFFE et al. (1991b) for U-series analysis providing a date of 123±7ka. This is one of the few substage 5e sites known to have undergone notable subsidence.

The Waimanalo Limestone on the island of Oahu, Hawaii, is the focus of many papers on transgressive-regressive facies correlated with oxygen isotope cycles. Recent studies conflict over the question of whether one or two highstands in sea level may be correlated to substage 5e. SHERMAN et al. (1993), who argue for two highstands, cite an interesting example of the colonization of globular and branching corals together with coralline algae directly on the upper surface of beachrock slabs at Barbers Point. In situ samples of Cyphastrea ocellina and Porites lobata from this horizon (about 10m above present sea level) were used for ESR analysis yielding ages of 122±8ka and 152±25ka, as well as U-series analysis of P. lobata, yielding an age of 115±10ka. Based partly on facies discrimination, this surface is said to represent the second rise in sea level during substage 5e. MUHS and SZABO (1994) sampled coral material from different horizons in the Waimanalo Limestone at Kaena, Kahe, and Mokapu points and found no evidence for bimodal distribution of ages constrained to substage 5e.

Passive Continental Margins

Continental margins which do not coincide with the juncture of tectonic plates are generally considered passive. Data collated by BRYANT (1992) for trends in sea level around Australia through the last interglacial epoch and Holocene indicate that most of the coastlines of New South Wales and Western Australia are tectonically stable, for example, whereas the southern edge of the continent has risen 5m. Similarly, much of the coastline of Africa is stable, except for the Afar region and the Red Sea. For the purposes of this review, Bermuda and the Bahamas are included under this section.

VAN DE GRAAF et al. (1976) examined 4 marine terraces on the west side of Cape Range, Western Australia. The terrace deposits are Pleistocene in age and sit on eroded surfaces of Miocene limestone and sandstone. The second or Jurabi Terrace is correlated with a highsand in sea level during the early Riss-Wurm epoch and thus may be equated to substage 5e. In situ corals on this terrace occur at elevations ranging between 9m and 18m above present sea level along a 25km tract. Coralgal and algal boundstone predominate, but a pebble to cobble conglomerate also occurs in places. No species list is provided.

HARMON et al. (1983) compiled extensive data on the Pleistocene record of Bermuda. Although it is implied by CROUGH (1983) that Bermuda sits on a hot-spot trace, this interpretation is controversial. The main argument by HARMON et al. (1983) is that the island demonstrates long-term tectonic stability, during which the substage-5e highstand in sea level

was only one of two eposides when sea level was higher than at present. The Devonshire Formation is an intertidal marine conglomerate with abundant megafossils of the gastropod, *Citterium,* and bivalve, *Lucina.* The unit crops out at elevations between 2m and 6m above sea level and it sits unconformably on eolienites belonging to the Black Watch Pass Formation, but also incorporates clasts of beach calcarenite eroded from the older Belmont Formation. Corals collected from marine conglomerate for U-series analysis from the Devonshire Formation include species belonging to *Favia, Diploria, Millepora, Montastrea, Oculina, Porites,* and *Siderastrea,* yielding ages ranging between 118±6ka and 134±8ka. The mean value for 11 samples is 125±4ka.

GIRESSE *et al.* (1984) utilized U-series analysis to study marine terraces and uplift rates on the southern coast of Angola. The terrace deposits, containing a "littoral-rock fauna," are unconformably underlain by Cretaceous limestone. Out of 10 shell.samples analyzed, only one specimen of the bivalve *Arca senilis* from an Ouljian deposit at Baia Farta yielded an age referable to substage 5e (131±28–17ka). This result is on the high end of a wide array of ages extending to a low of 91ka and the association is attributed to mixing of faunas from the same intertidal facies but different ages. The locality is situated between 10m and 12m above present sea level.

A detailed chronology of eustatic changes on San Salvador Island and Great Inagua Island in the Bahamas is well documented by CHEN *et al.* (1991). At Cockburn Town on San Salvador, colonization of *Acropora palmata* took place on hardgrounds. The authors emphasize the significance of *Acropora* as an indicator of sea level, since it typically grows upward from a depth of 3m to 4m below mean high-tide level to reach the mean low-tide level. At Devil's Point on Great Inagua Island, a fossil patch reef is beveled by an old wavecut platform. In both examples, the fossil reef crest zone consists of *in situ* or nearly *in situ* colonies of *Acropora palmata* and *A. cervicornis.* Other common corals include *Montastrea annularis, Diploria strigosa,* and *Porites porites. Diploria clivosa* is a common encruster in associated fossil patch reefs. Reefs expanded to a level about 6m above present sea level beginning at 132ka, and declined when a drop in sea level occurred between 123ka and 120ka. U-series analysis of 37 coral samples tested in replicate was the basis for correlation to substage 5e.

The Houtman Abrolhos Islands 75km off the coast of West Australia are constructed on reefal limestone. Through an extensive coring program, COLLINS *et al.* (1993) discovered unconformities on two island groups, Wallabi and Easter, showing reef growth on hard substrates formed by eolienites and calcrete. These surfaces occur between 4m and 9m below sea level. From the Wallabi island group, fossil *Acropora* and Faviidae corals collected for U-series analysis yielded age estimates of 132.9±1ka and 132.8±0.9ka. From the Easter island group, fossil Faviidae corals yielded ages of 124±2ka and 134.3±1.3ka.

SCOTT and JOHNSON (1993) studied the geomorphology of an old rocky shoreline at Kalbarri in Western Australia. The area exhibits much variation over a distance of 8km, with a river-mouth bar, cobble pocket beach, intertidal abrasion platform with tidal pools, drowned paleovalley, and neptu-

nian dikes in massive sea cliffs. Fossil tidal pools include the gastropod, *Turbo intercostalis,* and the neptunian dikes include the limpet *Petella peroni.* All paleoenvironments occur at present sea level as preserved in the Chinaman's Rock Member, Upper Pleistocene Tamala Limestone. This unit sits unconformably on Silurian sandstone. Age is implied by geological inference.

At Cape Burney in Western Australia, the Tamala Limestone embraces a reef limestone called the Bootenall Member sitting unconformably on sandstone strata referred to the Cape Burney Member (JOHNSON *et al.,* 1995). The unconformity surface was colonized by an encrusting biota including the cup coral, *Rhizotrochus tuberculatus,* oysters, serpulid worms, coralline red algae, and the boring barnacle, *Lithotrya.* Shell beds dominated by the gastropods, *Turbo intercostalis* and *T. torquatus,* together with 28 other intertidal to shallow-water mollusks commonly drape the unconformity surface. With a maximum thickness in excess of 2m, the overlying reef limestone is dominated by a palmate species of *Acropora.* Analysis using ESR provides an age estimate for a specimen of this coral between 120ka and 132ka. Extending for a distance of 750m along the coastline, the unconformity between the two units occurs variably between present sea level and an elevation no more than 2.5m above sea level. Taking into consideration the maximum thickness of the limestone, the substage-5e highstand in sea level reached no more than 5m above present sea level.

DISCUSSION

Considering that six localities are combined under the synopses of coral-reef sites in the Gulf of California (DURHAM, 1947) and the newly documented rocky shore at Playa La Palmita in Baja California Sur (LIBBEY and JOHNSON, this volume), then the total number of substage-5e shorelines covered in this review is 54. The largest number occur on active continental margins (37%) and island arcs (35%). Fewer are well known from hot-spot associations (15%) or passive continental margins (13%). Tectonic segregation of these 120,000 to 135,000-year-old rocky shores is upheld by the nature of their bedrock substrate and the degree of subsequent change in elevation sustained since their formation (Table 1).

All sites on passive margins involve sedimentary bedrock with present elevations due essentially to an eustatic highstand in sea level about 6m above present sea level. The exceptions in this category are the Houtman Abrolhos Islands of Western Australia, with substage-5e reef platforms preserved up to 9m below present sea level. Most of the sites on active continental margins exhibit igneous bedrock, usually andesite, with a moderate contribution to tectonic uplift in the range of 20m to 30m above present sea level. The exception in this category is the southern coast of Oregon, with terrace elevations up to 134m above present sea level (KELSEY and BOCKHEIM, 1994). Abandoned rocky shores on island arcs retain a mix of sedimentary, igneous, and metamorphic bedrock, but show the largest component of tectonic uplift. The most extreme case is the Huon Peninsula of New Guinea (BLOOM *et al.,* 1974; CHAPPELL and VEEH, 1978), where substage-5e reef terraces reach an elevation 350m above present

Table 1. *Tectonic, bedrock, and biological differentiation of substage-5e rocky shorelines.*

Tectonic setting / Citation	Place	Substrate lithology	Elevation (m)	Dating method	Biota
Active continental margins					
Durham (1947)	Punta Chivato, Gulf of Calif. Sur	andesite	+7.5		subtrop. corals
Ortlieb (1984)	Gulf of Calif. Sur	andesite		U-series	
Valentine (1958)	Cayucos, Calif.	—	+6 to 8	U-series	temp. molluscs/corals
Veeh & Valentine (1967)	Cayucos, Calif.	—	+6 to 8	U-series	temp. molluscs/corals
Muhs et al. (1994)	Cayucos, Calif.		+6 to 8	U-series	
Squires (1959)	Cabo Pulmo, Baja Calif. Sur	granite	+6	U-series	trop. corals
Muhs et al. (1994)	Baja Calif. Sur	granite		U-series	trop. corals
Ku and Kern (1974)	San Diego, Calif.	siltstone	+24	U-series	temp. corals
Muhs et al. (1994)	San Diego, Calif.	siltstone	+24	U-series	
Valentine (1980)	Camalu, Baja Calif.	conglomerate		amino acid	temp. molluscs
Paskoff (1981)	Coquimbo, Chile	sandstone	+20	amino acid	temp. molluscs
Muhs & Szabo (1982)	San Clemente, Calif.	andesite	+32	U-series	temp. corals
Muhs et al. (1994)	San Clemente, Calif.	andesite	+32	U-series	
Ashby et al. (1987)	Mulegé, Baja Calif. Sur	gabbro	+12	U-series	subtrop. molluscs/corals
Ashby & Minch (1987)	Mulegé, Baja Calif. Sur	gabbro	+12	U-series	subtrop. molluscs/corals
Rockwell et al. (1989)	Punta Banda, Baja Calif.	andesite	+34 to 40	U-series	temp. corals
Muhs et al. (1994)	Punta Banda, Baja Calif.	andesite	+34 to 40	U-series	
Hsu (1990)	Pampa del Palo, Peru		+25		
Russell (1991)	San Nicolas Is., Calif.	sandstone	+33 to 36	U-series	temperate molluscs/corals
Muhs et al. (1994)	San Nicolas Is., Calif.	sandstone	+33 to 36	U-series	
Gvirtzman et al. (1992)	Sinai Peninsula	igneous	+13 to 18	U-series	trop. corals
Hearty & Dai Pra (1992)	Southeast Italy	limestone	+26	amino acid	subtrop. molluscs
Kelsey & Bockheim (1994)	southern Oregon	sedimentary	+72 to 134	position	
Zwiebel & Johnson (1995)	Punta Cabras, Baja Calif.	andesite	+1	amino acid	temp. molluscs
Libbey & Johnson (1996)	Playa Palmita, Baja Calif.	andesite	+4.25 to 6.25	U-series	subtrop. molluscs
Island arcs					
Mesolella et al. (1969)	Barbados	limestone	+30 to 60	U-series	trop. corals
Konishi (1970)	Kikai Is., Japan	siltstone		U-series	subtrop. corals
Bloom et al. (1974)	New Guinea	limestone	+250 to 350	U-series	trop. corals
Aharon & Chappell (1986)	New Guinea	limestone	+250 to 350	$\delta\,^{18}O$	trop. corals
Chappell & Veeh (1978)	Timor	igneous	+65	U-series	trop. corals
Jouannic et al. (1988)	West Timor	limestone	+7	U-series	trop. corals
Emery (1981)	Grand Cayman Is.	limestone			trop. corals
Dodge (1983)	Haiti	limestone	+52	U-series	trop. corals
Pillans (1983)	North Is., New Zealand	sedimentary	+35 to 60	amino acid	trop. corals
Ota et al. (1984)	South Is., New Zealand	limestone	+35 to 45		
Taylor et al. (1985)	Northern Vanuatu	limestone	+90 to 120	U-series position	trop. corals
Strecker et al. (1986)	Northern Vanuatu	igneous			
Lecolle et al. (1990)	Southern Vanuatu	basalt		U-series	trop. corals
Woodroffe (1988)	Tonga Is.; Christmas Is.	limestone	+7	U-series	trop. corals
Miyauchi (1988)	northern Japan		+20 to 50	vol. ash	temp. molluscs
Montaggioni & Hoang (1988)	Seychell Is.	granite	+9 m	amino acid	trop. corals
Ward (1991)	South Is., New Zealand	igneous/metamorphic		position	
Pirrazoli et al. (1993)	Sumba Is., Indonesia			U-series	trop. corals
Donovan & Miller (1995)	Jamaica	limestone	+19	U-series	trop. corals

Table 1. Continued.

Tectonic setting Citation	Place	Substrate lithology	Elevation (m)	Dating method	Biota
Hot spots					
Lindberg (1980)	Isla Guadalupe	igneous	+6		subtrop. molluscs/corals
Muhs et al. (1994)	Isla Guadalupe	igneous		U-series	
Faure (1980)	Afar, Somalia			U-series	trop. corals
Szabo (1985)	Enewetak Atoll, Marshall Islands	limestone	+9 to 32	U-series	trop. corals
Woodroffe et al. (1991a)	Southern Cook Is.	limestone		U-series	trop. corals
Gray et al. (1992)	Northern Cook Is.	limestone	-2.5	U-series	trop. corals
Woodroffe et al. (1991b)	Cocos Is.	limestone	-7	U-series	trop. corals
Sherman et al. (1993)	Oahu, Hawaii		+10	ESR/U-series	trop. corals
Muhs & Szabo (1994)	Oahu, Hawaii	beach rock		U-series	trop. corals
Passive continental margins					
Van de Graaf (1976)	W. Australia	limestone	+9 to 18	position	trop. corals
Harmon et al. (1983)	Bermuda	eolienites	+2 to 6	U-series	trop. molluscs
Giresse et al. (1984)	Angola	limestone	+10 to 12	U-series	trop. molluscs
Chen et al. (1991)	Bahamas	limestone	+6	U-series	trop. corals
Collins et al. (1993)	Houtman Abrolhos Islands, W. Australia	eolionite/calavete	-4 to -9 m	U-series	subtrop. corals
Scott & Johnson (1993)	W. Australia	sandstone	sea level	position	subtrop. molluscs
Johnson et al. (1995)	W. Australia	sandstone	0 to +2.5	ESR	subtrop. molluscs & corals

sea level. Most of the island-arc shorelines, however, fall within the range of 30m to 60m above present sea level, as exemplified by the substage-5e terrace on the First High Cliff at Barbados (MESOLELLA et al., 1969). Terraces associated with hot-spot traces tend to involve limestone platforms built up by reefs in an attempt to counter the relative rise in sea level tied to subsidence effected by island drift from a volcanic source. Larger islands, such as Oahu in the Hawaiian chain, are still relatively close enough to their volcanic source that a small component of tectonic uplift is still evident. Smaller atolls show a tendency for substage-5e platforms to drown to a depth as much as 7m below sea level. Locations in the Cocos Islands (WOODROFFE et al., 1991b) and Cook Islands (GRAY et al., 1992) are probably typical in this regard.

Biologically, the macrofossils preserved at the various rocky-shore localities range across latitude from temperate, mollusc-dominated faunas with cup corals, to subtropical mixed mollusc and colonial coral faunas to tropical colonial coral-reef faunas (Table 1). While the oxygen-isotope studies by AHARON and CHAPPELL (1986) indicate that surface-water temperature on the shores of New Guinea 125,000 years ago was locally comparable to today, the invasion of reef faunas to higher latitudes in both the northern and southern hemispheres suggests that subtropical environments were more expansive than now. The Ningaloo reef tract presently runs 300 km along the coast of Cape Range in Western Australia from a latitude of 22°S to a point slightly south of the Tropic of Capricorn at 24°S. The equivalent fossil *Acropora* reef at Geraldton (JOHNSON et al., 1995) lies 550 km farther south. Upper Pleistocene reefs also grew on the Houtman Abrolhos Islands 75km west of Geraldton, due to the Leeuwin Current which brought warm waters south to a region normally dominated by temperate marine biotas (COLLINS et al., 1993). Reefs no longer exist on the western flanks of these islands, although corals still do well in eastern lagoons. In the Gulf of California, modern reefs exist no farther north than La Paz, 80km north of the Tropic of Cancer. Fossil *Porites* reefs at Isla San Marcos, (DURHAM, 1947) and Punta Chivato lie between 315km and 330km north of the Tropic of Cancer.

Variations in macrofaunal diversity from place to place are more difficult to assess. Interest in correlation of abandoned shorelines with the oxygen isotope substages pioneered by SHACKELTON and OPDYKE (1973) has led to selection of particular species suitable for U-series or ESR analyses. The temperate cup coral, *Balanophyllia,* and many of the tropical reef corals, for example, are hard-substrate encrusters and much emphasis is placed on their *in situ* condition. This is an important guarantee, not only for the time specificity so crucial to wary geochronologists, but also for the authentication of membership in a given rocky-intertidal to shallow-subtidal association that is of interest ecologically.

Few of the more recent reports cited in this overview include census data of the quality offered by VALENTINE (1958, 1980) or ASHBY and MINCH (1987). Most mention only a few species, at most. It is possible that many of the sites covered herein truly preserve a low-diversity biota. For example, we have observed at Punta Chivato and neighboring Playa Palmita on the Gulf of California that a nearly monospecific *Porites* reef attached to a flat substrate occurs only a few kilo-

meters away from a high-diversity, vertically oriented rocky-shore biota. Another difficulty concerns differences in life style between encrusting and mobile organisms. A majority of the diverse molluscan faunas documented by VALENTINE (1958, 1980) and ASHBY and MINCH (1987) fall into the latter category. Their credibility as genuine rocky-shore dwellers is readily checked by comparison with extant relatives, but this test is increasingly difficult to sustain the farther back in geologic time rocky-shore biotas are traced. With as many as 15 encrusting species preserved at Playa La Palmita in Baja California Sur (LIBBEY and JOHNSON, this volume), it is the most diverse *in situ* rocky-shore biota of its kind yet known from any time interval. In any case, all substage-5e localities summarized herein remain available for future assembly of more complete census data.

CONCLUSIONS

Only 155 citations are listed in an earlier bibliography of research articles on rocky shores through geologic time (JOHNSON, 1992). This up-dated compilation of 60 references to 54 substage-5e rocky shores provides a globally diverse sample from the geological record 120,000–135,000 years ago. This includes a morphologically varied set of shore types, ranging from erosional platforms and vertical walls of barnacle-covered granite to constructional reef terraces. The data bank contained herein is certainly not comprehensive, but still fulfills three functions. It reconfirms the contention by JOHNSON (1988) that tectonic segregation of rocky shorelines is an important consequence of high continentality. It easily verifies the utility of abandoned rocky shores as superb coastal markers in the study of relative sea-level change through geological time, particularly with regard to the separation of eustatic and tectonic components. Finally, it represents the potential basis for a richly detailed portrait of rocky-shore ecosystems on an expansive geographical scale, but one also well constrained in actual geologic time. Such a portrait, although not unlike the ecosystems we find in place today, makes a reliable reference point comparably filtered by geological processes for comparison with far more ancient rocky-shore biotas.

ACKNOWLEDGEMENTS

LITERATURE CITED

AHARON, P. and CHAPPEL, J., 1986. Oxygen isotopes, sea level changes, and the temperature history of a coral reef environment in New Guinea over the last 10^5 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 56, 337–379.

ASHBY, J.R.; KU, T.L., and MINCH, J.A., 1987. Uranium series ages of corals from the upper Pleistocene Mulegé terrace, Baja California Sur, Mexico. *Geology*, 15, 139–141.

ASHBY, J.R. and MINCH, J.A., 1987. Stratigraphy and paleoecology of the Mulegé Embayment, Baja California Sur, Mexico. *Ciencias Marinas*, 13, 89–112.

BLOOM, A.L.; BROECKER, W.S.; CHAPPELL, J.M.A.; MATTHEWS, R.K., and MESOLELLA, K.J., 1974. Quaternary sea level fluctuations on a tectonic coast: New ^{230}Th/^{234}U dates from the Huon Peninsula, New Guinea. *Quaternary Research*, 4, 185–205.

BRYANT, E., 1992. Late interglacial and Holocene trends in sea-level maxima around Australia: Implications for modern rates. *Marine Geology*, 108, 209–217.

CHAPPELL, J. and SHACKLETON, N.J., 1986. Oxygen isotopes and sea level. *Nature*, 324, 137–140.

CHAPPELL, J. and VEEH, H.H., 1978. Late Quaternary tectonic movements and sea-level changes at Timor and Atauro Island. *Geological Society of America Bulletin*, 89, 356–368.

CHEN, J.H.; CURRAN, H.A.; WHITE, B., and WASSERBURG, G.J., 1991. Precise chronology of the last interglacial period: ^{234}U-^{230}Th data from fossil coral reefs in the Bahamas. *Geological Society of America Bulletin*, 103, 82–97.

COLLINS, L.B.; ZHU, Z.R..; WYRWOLL, K.-H.; HATCHER, B.G.; PLAYFORD, P.E.; CHEN, J.H.; EISENHAUER, A., and WASSERBURG, G.J., 1993. Late Quaternary evolution of coral reefs on a cool-water carbonate margin: The Abrolhos carbonate platforms, southwest Australia, *Marine Geology*, 110, 203–212.

CROUGH, S.T., 1983. Hotspot swells. *Annual Review of Earth and Planetary Sciences*, 11, 165–193.

DODGE, R.E.; FAIRBANKS, R.G.; BENNINGER, L.K., and MAURRASSE, F., 1983. Pleistocene sea levels from raised coral reefs of Haiti. *Science*, 219, 1423–1425.

DONOVAN, S.K. and MILLER, D.J., 1995. Aspects of ancient rocky shorelines: The Hopegate and Falmouth Formations, Jamaica. *Caribbean Journal of Science*, 31, 174–184.

DURHAM, J.W., 1947. Corals from the Gulf of California and the North Pacific Coast of America. *Geological Society of America Memoir 20*, 68p.

EMERY, K.O., 1981. Low marine terraces of Grand Cayman Island. *Estuarine, Coastal and Shelf Science*, 12, 569–578.

FAURE, H.; HOANG, C.-T., and LALOU, C., 1980. Datations ^{230}Th/^{234}U des calcaires coralliens et mouvements verticaux à Djibouti. *Bulletin de la Societe Géologique de France*, (7), t. XXII, n° 6, 959–962.

GIRESSE, P.; HOANG, C.-T., and 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, 177–187.

GRAY, S.C.; HEIN, J.R.; HAUSMANN, R., and RADTKE, U., 1992. Geochronology and subsurface stratigraphy of Pukapuka and Rakahanga atoll, Cook Islands -Late Quaternary reef growth and sea-level history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 91, 377–394.

GVIRTZMAN, G.; KRONFELD, J., and BUCHBINDER, B., 1992. Dated coral reefs of southern Sinai (Red Sea) and their implication to Late Quaternary sea levels. *Marine Geology*, 108, 29–37.

HARMON, R.S.; MITTERER, R.M.; KRIAUSAKUL, N.; LAND, L.S.; SCHWARCZ, H.P.; GARRETT, P.; LARSON, G.J.; VACHER, H.L., and ROWE, M., 1983. U-series and amino acid raceminzation geochronology of Bermuda -implications for eustatic sea level fluctuation over the past 250,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 44, 41–70.

HEARTY, P.J. and DAI PRA, G., 1992. The age and stratigraphy of Middle Pleistocene and younger deposits along the Gulf of Taranto (southeast Italy). *Journal of Coastal Research*, 8, 882–925.

HOANG, C.-T.; LALOU, C., and FAURE, H., 1973. Les Récifs soulevés à l'ouest du golfe d'Aden (T.F.A.I.) et les hauts niveaux de coraux de la dépression de l'Afar (éthiopie), géochronologie et paléoclimats interglaciaires. *Colloques Internationaux du C.N.R.S.*, 219, 103–114.

HSU, J.T., 1990. The Pampa del Palo marine terrace, 17.73°S. latitude, Peru: aminostratigraphic evidence of multiple sea level events in the deposits of one terrace. *Geological Society of America, Abstracts with Programs*, 22(7), 146.

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

JOHNSON, M.E., 1992. Ancient rocky shores: A brief history and annotated bibliography. *Journal of Coastal Research*, 8, 797–812.

JOHNSON, M.E.; BAARLI, B.G., and SCOTT, J.H., JR., 1995. Colonization and reef growth on a Late Pleistocene rocky shore and abrasion platform in Western Australia. *Lethaia*, 28, 85–98.

JOUANNIC, C.; HOANG, C.-T.; HANTORO, W.S., and DELINOM, R.M., 1988. Uplift rate of coral reef terraces in the area of Kupang, West Timor: Preliminary results. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 68, 259–272.

KELSEY, H.M. and 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, 840–854.

KONISHI, K; SCHLAGER, S.O., and OMURA, H., 1970. Neo-tectonic rates in the Central Ryukyu Islands derived from Th-230 coral ages. *Marine Geology*, 9, 225–240.

KU, T.L. and KERN, J.P., 1974. Uranium-series ages of the Upper Pleistocene Nestor Terrace, San Diego, California. *Geological Society of America Bulletin*, 85, 1713–1716.

LECOLLE, J.F.; BOKILO, J.E., and BERNAT, M., 1990. Soulevement et tectonique de Iile d'Efate (Vanuatu) arc insulaire des Nouvelles-Hebrides, au cours du Quaternaire récent: Datations de terrasses soulevees par la methode U/Th. *Marine Geology*, 94, 251–270.

LIBBEY, L.K. and JOHNSON, M.E., 1996. Upper Pleistocene rocky shores and intertidal biotas on the Gulf of California at Playa La Palmita (Baja California Sur, Mexico). *Journal of Coastal Research*, 12, in review.

LINDBERG, D.R.; ROTH, B.; KELLOGG, M.G., and HUBBS, C.L., 1980. Invertebrate megafossils of Pleistocene (Sangamon interglacial) age from Isla de Guadalupe, Baja California, Mexico. *In*: POWER, D.M. (ed.), *The California Islands: Proceedings of a multidisciplinary symposium, Santa Barbara Museum of Natural History*, Santa Barbara, California, pp. 41–62.

MESOLELLA, K.J.; MATTHEWS, R.K.; BROECKER, W.S., and THURBER, D.L., 1969. The astronomical theory of climatic change: Barbados data. *Journal of Geology*, 77, 250–274.

MIYAUCHI, T., 1988. Late Pleistocene marine terrace correlation and chronology in the northern Northeast Japan. *Geographical Reports of the Tokyo Metropolitan University*, 23, 29–47.

MONTAGGIONI, L.F. and HOANG, C.-T., 1988. The last interglacial high sea level in the granitic Seychelles, Indian Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 64, 79–91.

MORRIS, R.H.; ABBOTT, D.P., and HADERLIE, E.C., 1980. *Intertidal Invertebrates of California*, Stanford, California: Stanford University Press, 690p.

MUHS, D.R.; KENNEDY, G.L., and ROCKWELL, T.K., 1994. Uranium-series ages of marine terrace corals from the Pacific coast of North America and implications for last-interglacial sea level history. *Quaternary Research*, 42, 72–87.

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

MUHS, D.R. and SZABO, B.J., 1994. New uranium-series ages of the Waimanalo Limestone, Oahu, Hawaii: Implications for sea level during the last interglacial period. *Marine Geology*, 118, 315–326.

ORTLIEB, L., 1984. Field-trip Guidebook: Neotectonics and Sea Level Variations in the Gulf of California Area. Mexico City: Instituto de Geologia Universidad Nacional Autonoma de Mexico, 152 p.

OTA, Y.; TORAO, Y.; NOZOMI, I; ATSUMASA, O., and NOBOYUKI, Y., 1984. Marine terraces of the Conway Coast, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 27, 313–325.

PASKOFF, R., 1991. Likely occurrence of a mega-tsunami in the middle Pleistocene, near Coquimbo, Chile. *Revista Geologica de Chile*, 18, 87–91.

PILLANS, B., 1983. Upper Quaternary marine terrace chronology and deformation, South Taranaki, New Zealand. *Geology*, 11, 292–297.

PIRAZZOLI, P.A.; RADTKE, U.; JOUANNIC, C.; HOANG, C.-T.; CAUSSE, C., and BOREL BEST, M., 1993. A one million-year-long sequence of marine terraces on Sumba Island, Indonesia. *Marine Geology*, 109, 221–236.

ROCKWELL, T.K.; MUHS, D.R.; KENNEDY, G.L.; HATCH, M.E.; WILSON, S.H., and KLINGER, R.E., 1989. Uranium-series ages, faunal correlations and tectonic deformation of marine terraces within the Agua Blanca fault zone at Punta Banda, northern Baja California, Mexico. *In*: ABBOTT, P.L. (ed.), Geologic studies in Baja California, *Pacific Section, Society of Economic Paleontologists and Mineralogists*, Los Angeles, Book 63, 1–16.

RUSSELL, M.P., 1991. Modern death assemblages and Pleistocene fossil assemblages in open coast high energy environments, San Nicolas Island, California. *Palaios*, 6, 179–191.

SCOTT, J.H., JR. and 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.

SHACKLETON, N.J. and OPDYKE, N.D., 1973. Oxygen isoltope and paleomagnetic stratigraphy of equatorial Pacific core V23–238: Oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year time scale. *Quaternary Research*, 3, 39–55.

SHERMAN, C.E.; GLENN, C.R.; JONES, A.T.; BURNETT, W.C., and SCHWARCZ, H.P., 1993. New evidence for two high stands of the sea during the last interglacial, oxygen isotope substate 5e. *Geology*, 21, 1079–1081.

SMART, P.L. and RICHARDS, D.A., 1992. Age estimates for the Late Quaternary high sea stands. *Quaternary Science Reviews*, 11, 687–696.

SQUIRES, D.F., 1959. Results of the Puritan-American Museum of Natural History expedition to western Mexico. *Bulletin of the American Museum of Natural History*, 118, 367–432.

STRECKER, M.R.; BLOOM, A.L.; GILPIN, L.M., and TAYLOR, F.W., 1986. Karst morphology of uplifted Quaternary coral limestone terraces - Santo Island, Vanuatu. *Zeitschrift fur Geomorphologie*, 30, 387–405.

SZABO, B.J.; TRACEY, J.I., JR., and GOTER, E.R., 1985. Ages of subsurface stratigraphic intervals in the Quaternary of Enewetak Atoll, Marshall Islands. *Quaternary Research*, 23, 54–61.

TAYLOR, F.W.; JOUANNIC, C., and BLOOM, A.L., 1985. Quaternary uplift of the Torres Islands, northern New Herbrides frontal arc -comparison with Santo and Malekula Islands, central New Hebrides frontal arc. *Journal of Geology*, 93, 419–438.

VALENTINE, J.W., 1958. Late Pleistocene megafauna of Cayucos, California, and its zoogeographic significance. *Journal of Paleontology*, 32, 687–696.

VALENTINE, J.W., 1980. Camalú: a Pleistocene terrace fauna from Baja California. *Journal of Paleontology*, 54, 1310–1318.

VAN DE GRAAF, W.J.E.; DENMAN, P.D., and HOCKING, R.M., 1976. Emerged Pleistocene marine terraces on Cape Range, Western Australia. *Western Australia Geological Survey Annual Report*, 1975, 62–70.

VEEH, H.H. and VALENTINE, J.W., 1967. Radiometric ages of Pleistocene fossils from Cayucos, California. *Geological Society of America Bulletin*, 78, 547–550.

WARD, C.M., 1991. Marine terraces of the Waitutu district and their relation to the late Cenozoic tectonics of the southern Fjordland region, New Zealand. *Journal of the Royal Society of New Zealand*, 18, 1–28.

WOODROFFE, C.D., 1988. Vertical movement of isolated oceanic islands at plate margins: Evidence from emergent reefs in Tonga (Pacific Ocean), Cayman Islands (Caribbean Sea) and Christmas Island (Indian Ocean). *Zeitschrift fur Geomorphologies N.E.*, Suppl.-Bd. 69, 17–37.

WOODROFFE, C.D.; SHORT, S.A.; STODDART, D.R.; SPENCER, T., and HARMON, R.S., 1991a. Stratigraphy and chronology of late Pleistocene reefs in the southern Cook Islands, South Pacific. *Quaternary Research*, 35, 246–263.

WOODROFFE, C.D.; VEEH, H.H.; FALKLAND, A.C.; MCLEAN, R.F., and WALLENSKY, E., 1991b. Last interglacial reef and subsidence of the Cocos (Keeling) Islands, Indian Ocean. *Marine Geology*, 96, 137–143.

ZWIEBEL, J.A. and JOHNSON, M.E., 1995. Late Pleistocene mytilid and petricolid bivalves from the open rocky shores of Pacific Baja California (Mexico): Unusual preservation of macrofossils. *Journal of Coastal Research*, 11, 704–716.