

# GLOBAL SEA LEVEL STRATIGRAPHY: AN APPRAISAL

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Although Pleistocene sea level concepts were first developed in the Mediterranean Basin, research has been revolutionized during the past 15 years by massive dating programs applied in other world areas. Reappraisal of four key sequences nonetheless shows that the chronometric framework is imperfect. As a result, available paleosea level traces continue to depend on deep-sea stratigraphy for confirmation rather than the reverse; they do not provide independent support for the Milankovitch radiation cycles, nor do they invite deductive-hypothetical 'dating' by means of such astronomical reconstructions. Inferred 'initial' sea levels, based on uplift assumptions or  $\delta^{18}\text{O}$  determinations on coral and mollusca, show considerable divergence but broadly agree that sea levels assigned to isotope stages 5a and 5c were lower than today. Systematic studies should be expanded in environments that allow lithostratigraphic resolution of interdigitated marine and continental sediments, meticulously complemented by biostratigraphic work. Direct information on the complexity and significance of regressional hemicycles helps place sea level stages recorded by transgressive facies into a multidimensional context essential for comprehensive interpretation.

## HISTORICAL PERSPECTIVES

In the Mediterranean Basin it seems that an inordinate proportion of Quaternary research has been invested in the study of marine shorelines. These efforts have paralleled the attention given to demarcating and interpreting glacial moraines in higher latitudes and at higher elevations. Molluscan faunas have served to organize the shorelines into stages, much as paleosols and superposed tills or glaciofluvial outwash have permitted identification of a complex, if incomplete stratigraphy of glacial advances and protracted retreats.

By the mid-1960s, chronometric dating techniques were being applied to glacial features as well as shorelines, often requiring substantial revisions of over-simplified stratigraphic schemes. Deep-sea research, in the form of extremely detailed studies of long sediment cores, began to overshadow other Quaternary studies and eventually provided substantial arguments for a much more detailed and extended geochronology of Pleistocene glacials than had ever been anticipated from traditional glacial geology. This spurred a renewed interest in shorelines, as it became increasingly apparent that this record also was more complex, and liable to refined analysis — not only in the Mediterranean region, but on many other world coasts.

Approaches to shoreline study have of course shifted their emphasis with time. The earliest work (L. de Lamothe, C. Depéret) focused on altimetric correlation of shorelines in the western Mediterranean region. It received a renewed impetus from Zeuner (1946), who favored exact leveling and firmly believed that shorelines of similar age would be at similar elevations on all tectonically stable and undeformed coasts. The pitfalls of this approach were summarized by Hey (1978), who had supervised the systematic collation of altimetric data from the Mediterranean Basin: the preserved horizontal shorelines are essentially random in their vertical distribution, indicating differential uplift. The principal value of such data lies in their potential information for vertical displacement rates, provided an independent means of dating is available.

Altimetric work was soon complemented by molluscan study that allowed the recognition of distinct, faunal zones defining successive Pleistocene stages in Italy and Morocco (M. Gignoux, A. Issel, A.C. Blanc, G. Lecointre). The faunal approach served to limit the potential errors of simple, altimetric correlations, but the emphasis on a few indicator fossils allowed identification of only a limited number of marine stages that tended to subsume distinct shorelines in some areas. In the meanwhile, several authors began to apply altimetric and faunal stage designations interchangeably, e.g., Monastirian and Tyrrhenian.

During the 1950s Mediterranean shoreline studies shifted their emphasis again, this time to the interdigitation of marine and continental deposits. Following the precedent of A.C. Blanc's work in Italy, new research in the Provence, Corsica, Mallorca, Morocco, Algeria, Lebanon, and Israel explicitly described fossiliferous beaches as interdigitated with colluvial silts (*limons rouges*) and eolian sands. The bay of Palma de Mallorca proved to be particularly suitable for such a mixed lithostratigraphy by virtue of its low-energy conditions, slow uplift, and an absence of faulting. Here Cuerda (1957) and Muntaner-Darder (1957) were able to demonstrate that Tyrrhenian beaches had different faunal assemblages in different lithostratigraphic contexts. This double-faceted approach, developed over several years of painstaking fieldwork and molluscan inventorization, was based on two independent criteria:

- (1) Identification of full faunal assemblages had demonstrated that there were many, locally extinct Senegalese species in the several Tyrrhenian beaches of Mallorca and that such species varied in frequency as well as in terms of presence/absence in distinctive temporal assemblages;
- (2) The faunal assemblages also varied according to sedimentary facies, reflecting different water depths and shore environments, and they formed part of facies sequences usually comprising beach sands or conglomerates, terrestrial silts, and dune sands.

These authors argued effectively that not all beaches at similar levels were of the same age, citing differences in faunal assemblages, beach facies, and under/overlying continental deposits. Equally impressive was the parallel work of Gigout (1960) in the Atlantic sector of Morocco, and the independent development of a similar lithostratigraphic approach by Bretz (1960) on Bermuda. The complexity of the Mallorquin sequence, and its unique resolution in regard to the Tyrrhenian substages (Butzer and Cuerda, 1962a, b), subsequently secured its acceptance in the international literature (see Flint, 1966).

Radiocarbon dating, with its effective limits of 20,000 or 30,000 years for carbonates, had repeatedly provided spurious results for Pleistocene beaches because even minimal recrystallization of 100,000 year old shells simulated finite ages of 35,000 BP or so. A major chronometric revolution came with the application of the putative uranium-series method ( $^{230}\text{Th}/^{234}\text{U}$ ,  $^{234}\text{U}/^{238}\text{U}$ ,  $^{231}\text{Pa}/^{235}\text{U}$ ) to shoreline chronometry. One of the very first such applications was to Mallorquin samples (Stearns and Thurber, 1965, 1967): despite some jarring discordances due to problems with uranium migration between the open-system chemistry of mollusca and their bounding environment, the Th/U dates initially appeared to confirm Cuerda's bio- and lithostratigraphy (Butzer, 1975).

By the early 1970s the uranium-series technique had been applied to coral from several other world shoreline sequences. The advantage of Barbados, New Guinea, and Bermuda was that coral provided a more stable geochemical system than did mollusca, while large suites of juxtaposed coral reefs on Barbados and New Guinea provided ideal vertical transects for systematic dating by well-funded multidisciplinary teams. Within a short time these new sequences were correlated with the detailed oscillations of the deep-sea  $^{18}\text{O}/^{16}\text{O}$  curves, and presented as a global stratigraphic framework. Now that a number of such schemes have been published in reasonable detail, it is possible to examine them more critically.

## MAJOR GLOBAL SEA LEVEL STRATIGRAPHIES

One of the most impressive shoreline sequences has been established north of Finschhafen, on the Huon Peninsula of northeastern New Guinea. The data and supporting references are listed in Table 1. Th/U dates are given in ka (kilo anno = 1000 yr) as means, with standard deviations, as well as stated limits of laboratory accuracy. The standard error quoted is a mean of all the errors, to which the standard deviation of the errors has been added. Standard deviations and error ranges increase in proportion to the number of available dates and the relative age of the formation.

The New Guinea shorelines represent stepped tiers of uplifted coral reefs, with samples generally dated from the reef crests. The stages are consequently based on morphostratigraphic units, with due attention to respective lithofacies. Differential elevations along six transects have been used in connection with the ages obtained to calculate uplift rates through time. These in turn have been used to estimate the original elevation of the associated paleosea levels. This tectonic argument is complemented by measurements of  $^{18}\text{O}/^{16}\text{O}$  isotopic deviation which, by a complex set of adjustments and assumptions, can purportedly be converted into an index of glacial meltwater dilution of oceanic oxygen and hence glacio-eustasy (Aharon *et al.*, 1980; Shackleton and Matthews, 1977). The discrepancy of the tectonic and isotopic reconstructions for stage VIIb is tenuously explained by a massive (? Antarctic) ice surge at a time of higher sea level. In general, the below-modern sea levels at 77 ka and 107 ka are compatible with the deep-sea isotopic curves, which indicate that ocean waters were as warm as or warmer than today during only one episode (substage 5e) of 'last interglacial' time. Stages II to IV are less familiar, but reflect global ice-volume fluctuations recorded on New Guinea because of the rapid, local uplift rates.

TABLE 1. Uranium-series chronostratigraphy of raised coral reefs, Huon Peninsula, New Guinea (after Bloom *et al.*, 1974; Bloom, 1980; Chappell, 1974a; Chappell and Veeh, 1978; Aharon *et al.*, 1980).

Stage	Mean age in ka	( $\pm \sigma$ )	(Error range)	No. of assays	Modern elevation (m)	Initial elevation (from uplift rates/from $\delta^{18}O$ ) (m)
I	8.2	(1.9)	(0.8)	6	+2.5 to 15	0
II		( <sup>14</sup> C 28.9 $\pm$ 1.4)		2	+7 to 30	-41
IIIb	40	(4.7)	(3.5)	6	+10 to 70	-38
IIIa	51	(2.8)	(3.0)	2	+42 to 90	-30 (?)
IV	57	(6.0)	(4.5)	4	+28 to 125	-28
V	76	(11.5)	(4.0)	4	+60 to 190	-13
VI	107	—	(9.5)	2	+93 to 250	-14
VIIb <sup>1</sup>	117.5	(2.1)	(9.0)	2	+120 to 330	-9
VIIa	136.5	(4.9)	(10.0)	2	+135 to 275	-41
VIII <sup>2</sup>	185	(7.1)	(17.5)	2	+210 to 330	+8
IXb	218	(10.5)	(30)	3	+220 to 350	+5
IXa	250			2		

<sup>1</sup> Atauro, Timor, dates for terrace complex VII are 131 (16.5) (11.2) ka.

<sup>2</sup> Modern elevation ranges for stages VIII and IX are given for two transects only.

The New Guinea data set is frequently linked with that from Atauro Island and East Timor, some 2400 km farther west. The argument for distinguishing stages VIIa and VIIb is based on distinct reefs in New Guinea and on the more abundant Atauro dates, although the latter are published as an undifferentiated set for 'Terrace 2' (which includes VIIa and VIIb with an apparent unconformity) (Chappell and Veeh, 1978). On these grounds it is argued that the date scatter supports a high sea level over 10–15 ka, interrupted by an oscillation of 7–15 m and cumulatively representing isotopic substage 5e. Further, assuming constant uplift rates through time, the higher terraces of Atauro are then matched with the deep-sea isotopic curve (which itself is dated on an assumption of constant sedimentation rates since the Matuyama–Brunhes paleomagnetic reversal) to date earlier major transgressions at 220 ka, 240 ka, 440 ka and 700 ka.

The Barbados sequence is based on Th/U dates for stepped coral reefs of the southern and southwestern coastal sectors of that island, with initial elevations inferred from  $^{18}\text{O}$  deviations (Table 2). Dates and field correlations for the Worthing, Ventnor, and Rendezvous Hill stages are consistent and, as a group, these dates have the lowest standard deviations for any world coastal sequence. The older reefs, although of great interest, are difficult to link from one area to the next, and the dates are internally inconsistent and also do not correspond to the He/U dates. There evidently are residual field problems, both in regard to the continuous Kingsland–Aberdare Ridge (considered as distinct stages but marked by inconsistent dates) and a possibly greater complexity of the Kendal Hill and Kingsland stages, as suggested by unusually great standard deviations. The  $\delta^{18}\text{O}$ -derived paleosea levels also are too low, compared with the essentially modern level inferred for Atauro ca. 200 ka.

Bermuda lacks an uplifted mountain block and the Pleistocene record consists of coralline beach deposits, transgressional eolianites, and cave dripstones (speleothems) both above and below modern sea level (Table 3). The critical Devonshire 'high' beach is consistently dated at 125 ka but the scattered outcrops of conglomerate ascribed to the Spencer's Point Formation apparently span two stages, recalling the equally great spread of dates for reefs and coral rubble on the low terrain of the Bahamas (Newman and Moore, 1975). Amino acid racemization dates (D-alloisoleucine:L-isoleucine) complement the chronostratigraphic framework for Bermuda, although there appears to be a tendency to sort out eolianites according to their apparent ages, rather than their stratigraphic relationships.

The Coastal Plain of the southeastern United States potentially provides another key sequence, of barrier beaches complemented by associated terrestrial pollen and littoral ostracode studies (Cronin *et al.*, 1981). However, there are major stratigraphic and chronometric problems. The uranium dates on corals are few and units are assembled by dates, not on lithostratigraphic criteria; systematic study of amino acid ratios shows that the uranium dates are inconsistent and perhaps generally too young, while at the same time interpretative problems are apparent for the amino acid data (Wehmiller and Belknap, 1982; McCartan *et al.*, 1982). The significance of the results lie in the ostracodes which indicate that four high sea level stages spanning much or most of the Pleistocene all converge at a similar elevation, only a little higher than today, whereas the pollen assemblages from the same deposits show considerable variation from cool-temperature to subtropical.

TABLE 2. Uranium-series chronostratigraphy of raised coral reefs of Barbados (after Mesolella *et al.*, 1969; James *et al.*, 1971; Matthews, 1973; Shackleton and Matthews, 1977; Fairbanks and Matthews, 1978; Bender *et al.*, 1979; Harmon *et al.*, 1979).

Stage	Mean age in ka	( $\pm \sigma$ )	(Error range)	No. of assays	Modern elevation (m)	Initial elevation (from uplift/from $\delta^{18}O$ ) (m)
(Cliffs Bay)	61	(2.3)	(2.8)	4	0 to +4.5	
Worthing	82	(2.1)	(4.5)	4	+3 to 20	-15
Ventnor	105	(4.0)	(5.8)	9	+6 to 30	-16
Rendezvous Hill	124	(3.3)	(7.3)	7	+37 to 61	+ 6
(Regression)						
Kendal Hill/ Durants	212	(50)	(48)	9	+49 to 67	-82
Kingsland/ Cave Hill	240	(He/U 163 $\pm$ 36) (38)	(45)	5	+79 to 85	-12
Aberdare/ Thorpe	222	(He/U 180 $\pm$ 10) (7.6)	(30)	3	+67 to 94	-32
Adam's Castle	>300	(He/U 217 $\pm$ 6) (He/U 235 $\pm$ 34)			+91 to 107	

TABLE 3. Uranium-series chronostratigraphy of beaches, collianites and speleothems of Bermuda (after Harmon *et al.*, 1978, 1981, 1983).

Formation/Soil Zone	Mean age in ka	( $\pm \sigma$ )	(Error range)	No. of assays	Modern elevation (m)	Initial elevation (Submerged speleothems) (m)
Southampton (collianite)	(racemization: 87)					
St. George's (paleosol)	109	(16.5)	(8.5)	10	—	-15 to -20 below -20
Spencer's Pt. (beach conglomerate)					+1 to +11	-15 to -20
Pembroke (collianite)	(racemization: 105)				—	-10 to -20
Harrington (shore-near lime sand, speleothems)	115	(3.2)	(12)	3	—	-6
Devonshire (marine conglomerate, dune calcarenite)	125	(3.8)	(10)	11	+2 to +6	+4 to 6
(Eolianite)	(racemization: 134)				—	above -20 below -20
Shore Hills (paleosol)					—	above -20
Belmont (beach, dune calcarenite)	215	(13)	(24)	4	+1	below -20
(Pre-Belmont collianite)	>300 (?)			1	(?)	above -20

Seen as an ensemble, these major sequences (Tables 1 to 3) as well as a number of less detailed, partially-dated coastal stratigraphies from the Pacific Ocean area and North America (data summarized by Moore, 1982), Morocco (Hoang *et al.*, 1978), and southern Italy (Dai Pra and Stearns, 1977), now allow a critical appraisal that was not possible as recently as 5 years ago. It requires no emphasis that an imposing sea level stratigraphy has been constructed since 1965, and that the basic elements of that framework are sound. It is equally apparent that significant problems of dating and interpretation remain, and that the details are by no means as precise or uncontroversial as is commonly assumed:

(a) Date averages for the first major 'high' paleosea following the isotope stage 6 regression vary from 139 to 118 ka (Stearns, 1982). Such a range of 23,000 years is unacceptable for isotope substage 5e, or for the Eemian Interglacial, which had a duration of less than 10,000 years on the basis of the deep-sea isotope curve and varve counts for the Eem Interglacial (Butzer, 1974; Turner, 1975; Heusser and Shackleton, 1979). On the logical grounds that isotope stage 5e and the associated sea level recovery should be essentially synchronous, either the dating framework is inadequate or understanding of isotope stages 5 and 6 faulty. Comparison of Tables 1 to 3 shows that New Guinea-VII, Barbados-Rendezvous Hill, and Bermuda-Devonshire all overlap in terms of scatter deviations and error ranges, so that the uranium-series framework does not contradict the high probability that they are indeed synchronous. Quite apart from the inherent problems of faulty stratigraphies and poor sample selection, published Th/U error ranges are quoted as  $\pm 0.02$ , but interlaboratory calibration suggests that  $\pm 0.04$  would be more realistic (Harmon *et al.*, 1979). As Stearns (1983) points out, this implies  $\pm 15$  ka at 125 ka. To this should be added uncertainty as to the exact age of the isotope stage 6/5e switch, somewhere between 128 ka and 145 ka (Kominz *et al.*, 1979), while a deep-sea core in the Gulf of Mexico shows an isotopic anomaly ca. 140 ka — prior to the point of maximum stage 6 glaciation — followed by another anomaly at ca. 125 ka, coincident with rapid deglaciation (Falls and Williams, 1980).

These chronometric problems serve to show that uranium-series provides dating approximations that must be anchored within and consistent with stratigraphic frameworks first established in the field. An isolated beach 'dated' even by consistent Th/U assays at 105 ka might just as well be 120 ka and, if the scatter deviation is high, the true age might range between 82 ka and 128 ka. Multiple, dated shorelines, such as the reefs of New Guinea and Atauró, further show that global correlation may be no easier: if Chappell and Veeh (1978) are indeed correct that stage VII spans 15,000 years and includes a 7–15 m negative oscillation, then it is equally possible that they have identified isotope substages 5e, 5d and 5c, and that their younger stages require reinterpretation. Such limitations of relative stratigraphies, floating within only broadly defined chronometric limits, are peculiar to exclusively marine facies: direct interdigitation with littoral and continental deposits would certainly clarify many ambiguities.

(b)  $\delta^{18}\text{O}$  measurements cannot be simultaneously used to infer both water temperatures and initial beach elevation without substantial ancillary data. The 'initial' sea level estimates, to eliminate the effects of vertical displacement, differ from one coast to another, and are inconsistent where different criteria are available. So, for example, if we assume that the 105 ka shorelines were coeval, then the associated 'corrected' sea levels would be  $-15/20$  m (Bermuda, submerged dripstone),  $-16$  m (Barbados, constant uplift inferences).

–28 m (Barbados,  $\delta^{18}\text{O}$  on mollusca), –43 m (Barbados  $\delta^{18}\text{O}$  on coral), –14 m (New Guinea, constant uplift inferences), –9 m (New Guinea,  $\delta^{18}\text{O}$  on coral), and +6.5 m (South Carolina, ostracodes). Evidently there are flaws in the assumptions concerning the  $\delta^{18}\text{O}$  deductions, as shown by Dodge *et al.* (1983), while local tectonic histories were somewhat more complex (Stearns, 1976). Curiously lacking, too, in these discussions of Pleistocene sea level traces are the sophisticated concepts of differential, hydroisostatic readjustment (Chappell, 1974b) and geoid change (Mörner, 1976), which imply that differences in apparent sea level are to be expected in different areas (Clark *et al.*, 1978).

These problems of delineating an absolute sea level trace of global validity should caution against attaching uncritical confidence to any one technique (and its inherent assumptions) or to any one regional sequence (and its peculiar crustal history). Nonetheless, the deep-sea isotope curve implies that substage 5e should have had a slightly more diluted world ocean and hence a sea level a little higher than at present, whereas substages 5c and 5a reflected a slightly greater world ice volume with sea level a little lower. The sequences reviewed here support this, but the exact global sea level for each substage is not only uncertain, but perhaps impossible to determine except within broad limits (at least  $\pm 5$  m). Given the flexibility of dating, the horizontal stratigraphic uncertainties associated with almost all localities, and the contradictory vertical coordinates of the sea level trace, shoreline stratigraphies continue to be dependent on the chronostratigraphic framework provided by the deep-sea isotopic record; they do not yet provide independent support for that chronometric record.

It is in the prevailing abstraction of the littoral record from its terrestrial milieu that shoreline studies render themselves so vulnerable to divergent explanations. Continental stratigraphers have repeatedly used marine transgressions as marker horizons to sort out tills, periglacial slope deposits, or coastal dunes. In so doing they have recognized the reciprocal value of interdigitated marine and continental deposits. The littoral zone should logically provide the means of interlinking the deep-sea and the continental records, rather than an independent confirmation of the isotopic stratigraphy.

Contrary to the initial exuberance of Mesolella *et al.* (1969) and Veeh and Chappell (1970), sea level curves do not confirm the Milankovitch radiation theory; nor, despite the increasingly evident linkage between Milankovitch ‘forcing’ and global ice-volume cycles (Ruddiman and McIntyre, 1981), do the orbital parameters provide an acceptable chronometric framework for sea level curves. Until and unless a more reliable form of shoreline dating is devised, such as by means of complementary amino acid studies, using non-linear kinetic models (Wehmler and Belknap, 1978, 1982), sea level traces will continue to provide a sorry crutch for astronomical interpretation of Pleistocene stages. And vice versa, a very incomplete understanding of cause and effect relationships in Pleistocene climatic controls (see Kominz *et al.*, 1979) means that the orbital variables provide a deductive hypothesis that, in scientific terms, cannot be used to arrange empirical data except as an explicit hypothesis. Zeuner’s (1946) deductive-hypothetical approach for several decades bedevilled objective evaluation of fresh, inductive results in Quaternary stratigraphy, and the earth sciences must remain vigilant that theory does not become the tail that wags the dog.

## SHORELINE SEQUENCES WITH CONTINENTAL INTERDIGITATIONS

The basic purpose of examining marine and continental interdigitations is to distinguish transgressive and regressive deposits and, in the process, to reconstruct the geomorphic processes dominant in the contemporary littoral zone (however broadly defined). Such information is then liable to stratigraphic and paleoclimatic interpretation.

A number of littoral contacts can be singled out as potentially productive examples.

(a) In the Canadian Arctic and along the Scandinavian margins of the Baltic Sea, marine transgression created beach ridges immediately after deglaciation, with repeated replication as shorelines readjusted during the course of progressive isostatic readjustment. Such beaches developed on glacially-scoured terrain veneered with thin tills, as well as in more massive moraines. In the areas mentioned, these shorelines have, for two generations of research, helped to date deglaciation, to calibrate isostatic rebound during the last 12 ka (see, for example, Andrews and Tyler, 1977) or, more recently, to challenge traditional concepts of ice-sheet build-up (Andrews *et al.*, 1983).

(b) Along the southeastern margins of the North Sea, mid- and late Pleistocene tills are divided by fossiliferous, transgressive beaches in many localities. Traditionally attributed to the Holsteinian and Eemian interglacials (Woldstedt, 1958), such marine interbeds are in fact more complex (Bowen, 1979) and richly deserve further attention, e.g., racemization assays.

(c) Along the cliffed coasts of southwestern Britain and northwestern Spain, particularly in non-carbonate bedrock, it is common to see screes, cones or fans of frost-weathered rubble. Such late Pleistocene detritus, sometimes dated by  $^{14}\text{C}$  and containing polliniferous peaty interbeds, can be observed over polygenetic interglacial platforms with beach shingle and, in some cases, as infillings of wavecut caves (Butzer, 1967; Mary *et al.*, 1975; Andrews *et al.*, 1979). Unfortunately, interglacial wave action has selectively undercut and removed most but not all vestiges of mid-Pleistocene detritus, so that information is commonly limited to the later Pleistocene record.

(d) Calcareous environments of the Mediterranean Basin, southwestern Spain–Portugal, and Morocco probably provide the most complex littoral sequences, especially along low-gradient coasts. The typical sedimentation cycle shifts from a transgressive beach — possibly with an interbeach, argillic paleosol, to a colluvial silt, incorporating reworked red soil derivatives and possibly interfingering with alluvium, to a regressive, upward-fining eolianite of bioclastic debris, interrupted or followed by pedocal or caliche formation (Butzer, 1974; see Muhs, 1983, for a similar facies sequence on the California Channel Islands). Transgressive dunes are, of course, also present on some coastal plains in low-lying islands, such as Bermuda (Table 3) or South Africa (Butzer and Helgren, 1972), while beach, dune and soil sequences are locally found along the shores of other, semiarid-subtropical environments in Africa, North America, and Australia. Such records may have been repeatedly truncated, but in some areas they potentially span much or most of the Pleistocene.

(e) Some of the major coastal plains, especially in humid-subtropical environments such as the southeastern U.S.A., have well developed bar-and-lagoon coasts, exposing a complex

interfingering of beach, dune, lagoon, and stream facies, with potential pollen preservation (see Cronin, 1980; McCartan *et al.*, 1982). Multiple barrier bars are relatively rare in semiarid settings but may occur there too, e.g., west of the Nile Delta (Butzer, 1960).

(f) Coral coasts are primarily found along warm-water shores of lower latitudes, where there is little or no turbid discharge from coastal rivers. The important Th/U-dated reefs of Barbados, Curaçao, Jamaica, Florida, Hawaii, Western Australia, New Guinea, Timor, Atauro, and the Ryukyu Islands fall into this category. A more informative continental component may be included along desert coasts, where stepped coral reefs are interbedded with shingle bars and interlinked with coarse fluvial detritus, e.g., along the Red Sea coast (Butzer and Hansen, 1968, pp. 395–430), to provide sequences with multiple facies.

These examples point to environments where further research should greatly expand our understanding of the interdigitation of marine and continental records. The unusually complete record of Mallorca, outlined in Table 4, serves as an example. The chronometry remains inadequate, but P.J. Hearty has recently collected a suite of samples for racemization assays. In the interim, the faunas and lithostratigraphy, even in default of the questionable Th/U dates on mollusca (Stearns, *in preparation*) nonetheless permit a firm relative sequence, precisely because of the complex interdigitation of transgressive and regressive facies. This, in turn, allows a reasonable, if unverified, comparison with the oxygen isotope curve.

TABLE 4. Beaches and regressional colianites of Mallorca (after Butzer, 1962, 1963, 1975; Cuerda, 1957, 1975; Butzer and Cuerda, 1960, 1962a, b, c, 1983). (Plio-Pleistocene record omitted.)

Marine/Continental Hemicycles	Modern elevation (m)	Fauna (Continental facies)	Inferred Isotopic stage
Z A	+2 to 4	(Dunes, early Roman) Common fauna, prehistoric to Medieval	1
Y3 B	+0.5 to 3	(Eolianite, 3 generations) Rudimentary thermophile fauna	4–2 5a
Y2	+1.5 to 2	(Argillic paleosol at modern sea level)	5b
Y1	+9 to 15	Partial <i>Strombus</i> fauna	5c
X2 C	+6.5 to 8.5	(Eolianite, 2 generations) Impoverished <i>Strombus</i> fauna	5e 6 7a
X1	+2 to 4.5	Full <i>Strombus</i> fauna	7c
W2 D	+4 to 8	(Eolianite, 2 generations) Common fauna	8 9 (?)
W1	+22 to 25	(Argillic paleosol at modern sea-level) <i>Patella ferruginea</i> fauna	(?)
V E	(below +11)	(Eolianite, 5 generations)	
U F		(No data) (Eolianite, 3 generations)	
T G	+14 to 15	<i>Patella ferruginea</i> (large subspecies) fauna	
	+15 to 19	(Eolianite, 2 generations) <i>Patella longicosta</i>	

## CONCLUSIONS

In concluding, the implications of this paper can be restated:

- (1) The past 15 years of Pleistocene coastline research have revolutionized the data base, originally developed in the Mediterranean Basin, by establishing new sequences from stepped beaches on other world coasts that are now fixed by elaborate chronometric frameworks.
- (2) Nonetheless, a critical review of four key sequences shows that the fundamental uranium-series chronology allows over 20,000 years of leeway in dating of the highest sea level of the last interglacial interval (isotope substage 5e). This implies that multiple dates must be obtained in sequences of several shorelines before safe correlations can be made with deep-sea isotope stages. Wider application of the refined racemization dating technique may also help resolve part of this problem.
- (3) Reconstructed 'initial' sea levels, obtained by different techniques and on the basis of different assumptions for five major sequences, indicate that 'high' sea levels generally dated between 75 ka and 115 ka, and correlated with isotope substages 5a and 5c, were somewhat lower than those of today, implying more extensive, residual ice-sheets. There is no unanimity as to the details of the mid- to late Pleistocene sea level trace, in part for methodological reasons, in part because hydroisostatic readjustments and geoid changes remain to be considered.
- (4) The best dated and most consistent sea level stratigraphies come from stepped coral reefs, but these sequences have a major drawback. There are no interdigitated continental sediments to place the shoreline stratigraphy into a multidimensional context, that allows evaluation of the complexity and significance of the regressional hemicycles. Lithostratigraphic resolution of superposed marine and continental facies, complemented by painstaking biostratigraphic work, consequently retains its importance in the search for a valid model for Pleistocene shoreline geochronology. An expansion of systematic study to marine interbeds of the European tills, to other sections of the U.S. Coastal Plain, to the coral reefs of desert coasts such as the Red Sea, and to new and old sectors of the Mediterranean Basin would indeed be desirable.
- (5) The available sea level framework, however substantial, continues to depend on the established deep-sea stratigraphy for confirmation. It is not yet sufficiently robust to provide an independent corroboration for that deep-sea stratigraphy nor to support the astronomical radiation curves.

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## REFERENCES

- Aharon, P., Chappell, J. and Compston, W. (1980). Stable isotope and sea-level data from New Guinea supports Antarctic ice-surge theory of ice ages. *Nature*, **283**, 649–651.

- Andrews, J.T., Bowen, D.O. and Kidson, C. (1979). Amino acid ratios and the correlation of raised beach deposits in south-west England and Wales. *Nature*, **281**, 556–558.
- Andrews, J.T. and Tyler, K. (1977). The observed postglacial recovery of Quebec and Nouvelle Québec since 12,000 BP. *Géographie Physique et Quaternaire*, **31**, 389–400.
- Andrews, J.T., Shilts, W.W. and Miller, G.H. (1983). Multiple deglaciation of the Hudson Bay Lowlands, Canada, since deposition of the Missinaibi (Last Interglacial?) Formation. *Quaternary Research*, **19**, 18–37.
- Bender, M.L., Fairbanks, R.G., Taylor, F.W., Matthews, R.K., Goddard, J.G. and Broecker, W.S. (1979). Uranium-series dating of the Pleistocene reef tracts of Barbados, West Indies. *Geological Society of America Bulletin*, **90**, 577–594.
- Bloom, A.L. (1980). Late Quaternary sea level change on South Pacific coasts: a study in tectonic diversity. In: Mörner, N.A. (ed.), *Earth Rheology, Isostasy and Eustasy*, pp. 505–516. Wiley, Chichester.
- 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  $^{230}\text{Th}/^{234}\text{U}$  dates from the Huon Peninsula, New Guinea. *Quaternary Research*, **4**, 185–205.
- Bowen, D.O. (1979). Quaternary correlations. *Nature*, **277**, 171–172.
- Bretz, J.H. (1960). Bermuda: a partially drowned, late mature Pleistocene karst. *Bulletin, Geological Society of America*, **71**, 1739–1754.
- Butzer, K.W. (1960). On the Pleistocene shorelines of Arabs' Gulf, Egypt. *Journal of Geology*, **68**, 626–637.
- Butzer, K.W. (1962). Coastal geomorphology of Majorca. *Annals, Association of American Geographers*, **52**, 191–212.
- Butzer, K.W. (1963). Climatic-geomorphologic interpretation of Pleistocene sediments in the Eurafrian subtropics. *Viking Fund Publications in Anthropology*, **36**, 1–27.
- Butzer, K.W. (1967). Geomorphology and stratigraphy of the Paleolithic site of Budiño (Prov. Pontevedra, Spain). *Eiszeitalter und Gegenwart*, **18**, 82–103.
- Butzer, K.W. (1974). Geological and ecological perspectives on the Middle Pleistocene. *Quaternary Research*, **4**, 136–148.
- Butzer, K.W. (1975). Pleistocene littoral-sedimentary cycles of the Mediterranean Basin: a Mallorquin view. In: Butzer, K.W. and Isaac, G.L. (eds), *After the Australopithecines: Stratigraphy, Ecology and Culture Change in the Middle Pleistocene*, pp. 25–72. The Hague, Mouton.
- Butzer, K.W. and Cuerda, J. (1960). Nota preliminar sobre la estratigrafía y paleontología del Cuaternario marino del sur y S.E. de la Isla de Mallorca. *Boletín, Sociedad de Historia Natural de Baleares*, **6**, 9–30.
- Butzer, K.W. and Cuerda, J. (1962a). Coastal stratigraphy of southern Mallorca and its implications for the Pleistocene chronology of the Mediterranean Sea. *Journal of Geology*, **70**, 398–416.
- Butzer, K.W. and Cuerda, J. (1962b). Nuevos yacimientos marinos cuaternarios de las Baleares. *Notas y Comunicaciones, Instituto geológico y minero de España*, **67**, 25–70.
- Butzer, K.W. and Cuerda, J. (1962c). Formaciones cuaternarias del litoral este de Mallorca (Canyamel-Porto Cristo). *Boletín, Sociedad de Historia Natural de Baleares*, **7** (1961), 3–30.
- Butzer, K.W. and Cuerda, J. (1983). Pleistocene sea-level stratigraphy of Mallorca. *Revue de Géologie Méditerranéenne*, **XX**, 259–270.
- Butzer, K.W. and Hansen, C.L. (1968). *Desert and River in Nubia*. Madison, University of Wisconsin Press.
- Butzer, K.W. and Helgren, D.M. (1972). Late Cenozoic evolution of the Cape coast between Knysna and Cape St. Francis, South Africa. *Quaternary Research*, **2**, 143–169.
- Chappell, J. (1974a). Geology of coral terraces on Huon Peninsula, New Guinea. *Geological Society of America Bulletin*, **85**, 553–570.
- Chappell, J. (1974b). Late Quaternary glacio- and hydro-isostasy on a layered Earth. *Quaternary Research*, **4**, 429–440.
- 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.
- Clark, J.A., Farrell, W.E. and Peltier, W.R. (1978). Global changes in postglacial sea level: a numerical calculation. *Quaternary Research*, **9**, 265–287.

- Cronin, T.M. (1980). Biostratigraphic correlation of Pleistocene marine deposits and sea levels, Atlantic Coastal Plain of the southeastern United States. *Quaternary Research*, **13**, 213–229.
- Cronin, T.M., Szabo, B.J., Ager, T.A., Hazel, J.E. and Owens, J.P. (1981). Quaternary climates and sea levels of the U.S. Atlantic Coastal Plain. *Science*, **211**, 233–240.
- Cuerda, J. (1957). Fauna marina del Tirreniense de la Bahía de Palma (Mallorca). *Boletín, Sociedad de Historia Natural de Baleares*, **3**, 30–76.
- Cuerda, J. (1975). *Los tiempos cuaternarios en Baleares*. Diputación Provincial de Baleares, Palma de Mallorca.
- Dai Pra, G. and Stearns, C.E. (1977). Sul Tirreniano di Taranto, datazioni su coralli con il metodo del  $^{230}\text{Th}/^{234}\text{U}$ . *Geologica Romana*, **16**, 231–242.
- 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.
- Fairbanks, R.G. and Matthews, R.K. (1978). The marine oxygen isotope record in Pleistocene coral, Barbados, West Indies. *Quaternary Research*, **10**, 181–196.
- Falls, W.F. and Williams, D.F. (1980). Glacial meltwater inflow into the Gulf of Mexico during the Illinoian glacial and Sangamonian interglacial. *EOS Transactions American Geophysical Union*, **61**, 258.
- Flint, R.F. (1966). Comparison of interglacial marine stratigraphy in Virginia, Alaska, and Mediterranean areas. *American Journal of Science*, **264**, 673–684.
- Gigout, M. (1960). Nouvelles recherches sur le Quaternaire marocain et comparaisons avec l'Europe. *Travaux, Laboratoire Géologique, Faculté de Sciences de Lyon*, N.S. **6**, 1–158.
- Harmon, R.S., Schwarcz, H.P. and Ford, D.C. (1978). Late Pleistocene history of Bermuda. *Quaternary Research*, **9**, 205–218.
- Harmon, R.S., Ku, T.L., Matthews, R.K. and Smart, P.L. (1979). Limits of U-series analysis: phase I results of the uranium-series intercomparison project. *Geology*, **7**, 405–409.
- Harmon, R.S., Land, L.S., Mitterer, R.M., Garrett, P., Schwarcz, H.P. and Larson, G.J. (1981). Bermuda sea level during the last interglacial. *Nature*, **289**, 481–483.
- Harmon, R.S., Mitterer, R.M., Land, L.S., Schwarcz, H.P., Garrett, P., Larson, G.J., Vacher, H.L. and Rowe, M. (1983). U-series and amino acid racemization geochronology of Bermuda: implications for eustatic sea level over the past 250,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **37**, in press.
- Heusser, L.E. and Shackleton, N.J. (1979). Direct marine-continental correlation: 150,000 year oxygen isotope–pollen record from the North Pacific. *Science*, **204**, 837–839.
- Hey, R.W. (1978). Horizontal Quaternary shorelines of the Mediterranean. *Quaternary Research*, **10**, 197–203.
- Hoang, C.T., Ortlieb, L. and Weisrock, A. (1978). Nouvelles datations  $^{230}\text{Th}/^{234}\text{U}$  de terrasses marines "ouljiennes" du sud-ouest du Maroc et leurs significations stratigraphique et tectonique. *Comptes Rendues, Academie des Sciences, Paris* 286 (D), 1959–1962.
- James, N.P., Mountjoy, E.W. and Omura, A. (1971). An Early Wisconsin reef terrace at Barbados, West Indies, and its climatic implications. *Bulletin, Geological Society of America*, **82**, 2011–2018.
- Kominz, M.A., Heath, G.R., Ku, T.L. and Pisias, N.G. (1979). Brunhes time scales and the interpretation of climatic change. *Earth and Planetary Science Letters*, **45**, 394–410.
- Matthews, R.K. (1973). Relative elevation of late Pleistocene high sea level stands: Barbados uplift rates and their implications. *Quaternary Research*, **3**, 147–153.
- Mary, G., Médus, J. and Delibrias, G. (1975). Le quaternaire de la côte asturienne (Espagne). *Bulletin, Association française pour l'Etude du Quaternaire*, **11** (42), 13–24.
- McCartan, L., Owens, J.P., Blackwelder, B.W., Szabo, B.J., Belknap, D.F., Kriasakul, N., Mitterer, R.M. and Wehmiller, J.F. (1982). Comparison of amino acid racemization geochronology with lithostratigraphy, biostratigraphy, uranium-series coral dating, and magnetostratigraphy in the Atlantic Coastal Plain of the southeastern United States. *Quaternary Research*, **18**, 337–359.
- 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.
- Moore, W.S. (1982). Late Pleistocene sea-level history. In: Ivanovich, M. and Harmon, R.S. (eds). *Uranium Series Disequilibrium: Applications to Environmental Problems*, pp. 481–496, Oxford, Clarendon.

- Mörner, N.A. (1976). Eustasy and geoid changes. *Journal of Geology*, **84**, 123–151.
- Muhs, D.R. (1983). Quaternary sea level events, northern San Clemente Island, California. *Quaternary Research*, **18**, in press.
- Muntaner-Darder, A. (1957). Las formaciones cuaternarias de la Bahía de Palma (Mallorca). *Boletín, Sociedad de Historia Natural de Baleares*, **3**, 77–118.
- Neuman, A.C. and Moore, W.S. (1975). Sea level events and Pleistocene coral ages in the northern Bahamas. *Quaternary Research*, **5**, 215–224.
- Ruddiman, W.F. and McIntyre, A. (1981). Oceanic mechanisms for amplification of the 23,000 year ice-volume cycle. *Science*, **212**, 617–627.
- Shackleton, N.J. and Matthews, R.K. (1977). Oxygen isotope stratigraphy of late Pleistocene coral terraces in Barbados. *Nature*, **268**, 618–620.
- Stearns, C.E. (1976). Estimates of the position of sea level between 140,000 and 75,000 years ago. *Quaternary Research*, **6**, 445–450.
- Stearns, C.E. (1983). Uranium-series dating and the history of sea level. In: Mahaney, W.C. (ed.), *Quaternary Dating Methods*, Norwich, GeoBooks, in press.
- Stearns, C.E. (in prep.).  $^{230}\text{Th}/^{234}\text{U}$  ratios in Mallorcan mollusca revisited. Homenaje a Juan Cuerda, Universidad de Valencia, in prep.
- Stearns, C.E. and Thurber, D.L. (1965).  $^{230}\text{Th}/^{234}\text{U}$  dates of late Pleistocene marine fossils from the Mediterranean and Moroccan littorals. *Quaternaria*, **7**, 29–42.
- Stearns, C.E. and Thurber, D.L. (1967).  $^{230}\text{Th}/^{234}\text{U}$  dates of late Pleistocene marine fossils from the Mediterranean and Moroccan littorals. *Progress in Oceanography*, **4**, 293–304.
- Turner, C. (1975). The correlation and duration of Middle Pleistocene interglacial periods in Northwest Europe. In: Butzer, K.W. and Isaac, G.L. (eds), *After the Australopithecines: Stratigraphy, Ecology and Culture Change in the Middle Pleistocene*, pp. 259–308, The Hague, Mouton.
- Veeh, H.H. and Chappell, J.M.A. (1970). Astronomic theory of climatic change: support from New Guinea. *Science*, **167**, 862–865.
- Wehmiller, J.F. and Belknap, D.F. (1978). Alternative kinetic models for the interpretation of amino acid enantiomeric ratios in Pleistocene mollusks. *Quaternary Research*, **9**, 330–348.
- Wehmiller, J.F. and Belknap, D.F. (1982). Amino acid estimates, Quaternary Atlantic Coastal Plain: comparison with U-series dates, biostratigraphy, and paleomagnetic control. *Quaternary Research*, **18**, 311–336.
- Woldstedt, P. (1958). *Das Eiszeitalter II: Europa, Vorderasien und Nordafrika im Eiszeitalter*. Enke, Stuttgart.
- Zeuner, F.E. (1946). *Dating the Past: An Introduction to Geochronology*, 1st Ed, Methuen, London.