EOLIANITES AND EUSTASY: EARLY CONCEPTS ON DARWIN'S VOYAGE OF HMS BEAGLE

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ABSTRACT: "Eolianite" and "Eustasy" are both 20th century terms and even in their most rudimentary beginnings were not alluded to in most early 19th century treatises of geology. Darwin saw beachrock for the first time in 1832 when HMS *Beagle* stopped at Recife (Pernambuco) in Brazil, then saw raised shore terraces in Patagonia and Chile, followed by coral atolls in mid-Pacific, and examined eolianites on Ascension, S.W. Australia, South Africa and on St. Helena, during the *Beagle's* extended voyage (1831-1836).

The subsidence theory of atolls, based on studies of Capt. Fitzroy's navy charts, was formulated already before reaching Recife, and the crustal uplift in Patagonia offered a perfectly logical contrast to Pacific subsidence that eventually led to the concept of "tectono-eustasy". Although a decade or so before Charpentier, Agassiz and Geikie, the Ice-Age glaciation must have been clearly implanted in Darwin's mind, for he also reasoned on the assumption of its hydrologic implications, now known as "glacio-eustasy".

Darwin repeatedly observed lime-cemented sandstones (later to be called "eolian calcarenites" by Grabau and "eolianites" by Sayles) in coastal settings. Their steep dips and bedding orientation suggested wind-borne ("aeolian") transport from seaward, from a continental or insular shelf, now inundated by what - he reasoned - was a rise of sea level or sinking of the land. Darwin's observations of eolianites at King George's Sound in southwestern Australia in the last year of the voyage of the *Beagle* (March 1836) may perhaps have been the final "crucial experiment" that convinced him of the fundamental concept: the worldwide nature of eustasy.

INTRODUCTION

The history of science is abundantly littered with tales of serendipity: the felicitous chance. When Charles Darwin was appointed as naturalist to accompany HMS *Beagle* on its world voyage in the year 1831, he was singularly ill-equipped in an academic sense, although he had enjoyed Professor Henslow's lectures on natural history (and country walks) at Cambridge and had even served as field assistant to Charles Lyell on a trip to Wales. His background in the "nature versus nurture" stakes was to have been descended from several generations of remarkably gifted people, reasonably well-to-do and country-oriented. But the really serendipitous event was the publication of the first volume of Lyell's "*Principles of Geology*" in 1830, and this was thoroughly read before the *Beagle* dropped anchor at Pernambuco, Brazil. Volumes two and three reached him later on the voyage. In his introduction to the 1959 edition (p. vi) of "*The Voyage of the Beagle*" (1839) H. Graham Cannon points out the profound effect of the *Principles* on young Darwin, who had never previously strayed from the shores of Britain.

"Unexpected indeed were the results that followed, and in this book the reader can see for himself the gradual development of the change that came about in Darwin's mental outlook. He left England scorning geology. By the time he reached the southernmost tip of South America he had become the most ardent uniformitarian geologist. From Monte Video he was writing to his sister Caroline of '...my feelings of excessive pleasure which geology gives as soon as one partly understands the country.' It is easy to see what had happened. Armed with Lyell's *Principles* he had been able to observe for himself, in the various parts of South America, the way in which the scenery gradually unfolds itself through the ages. Later he writes to his sister Catharine from the Falkland Islands: 'There is nothing like geology; the pleasure of the first day's partridge shooting...cannot be compared to finding a fine group of fossil bones, which tell their story of former times with almost a living tongue.' This is praise indeed coming from such a sportsman as Darwin, who in his youth placed shooting in front of almost everything else."

Darwin, of course, is known primarily for his renowned work on biological evolution and its philosophical liberation of the intellectual world from the fetters and hobgoblins of creationism and fundamentalism. Less known, regrettably, is his role as a geologist, although the laurels for the recognition of physical evolution, one of the fundamental "Earth Laws" (Fairbridge 1980, 1987), have always very properly gone to Lyell. Cannon (op.cit., p.vi) wrote:

"Now, Lyell's Principles is an amazing book. In it there is the whole conception of evolution. It deals, of course, with the evolution of inanimate things, with rocks and rivers and deserts and mountains. But he left it to be inferred by the reader that these evolutionary ideas must also apply to living forms and even to man. This he admitted in reply to those two old diehards at Cambridge, Whewell and Sedgwick the elder, who taxes him with this heresy. Now, Darwin must have noted all this when he read the book on the long voyage southwards through the Atlantic, so that when he came to see the actual structure of the land masses of Patagonia, and then the Andes themselves, the light shone and he must have realized the soundness of Lyell's views."

Thus forearmed, Darwin exploited the voyage of the *Beagle* as the greatest learning experience of all time. From December 27, 1831, when she weighed anchor from Devonport, to her homecoming in Falmouth on October 2, 1836, every port of call offered new experiences, new scenery to observe, new intellectual challenges.

The theme of this essay "Eolianites and Eustasy" deals with twin concepts that grew on Darwin as the voyage progressed, although, indeed neither term had yet been promulgated. Of neither term is there much more than a hint in the voluminous works of Lyell or any other basic geological text of the 19th century. The role of wind ("aeolian" processes to Darwin) in creating coastal rock formations ("eolianites" of Sayles 1931) was in fact documented by a young officer of the Royal Navy, Lt. Nelson and published in one of the earliest volumes of the Geological Society of London (*Transactions*, v. 5, 1840). Eustasy, for its part, in the category of glacio-eustasy, emerged almost as soon as the ice age theory came to be recognized (MacLaren, 1842). The actual term "eustatic" motions of sea level had to await the vision of the great Eduard Suess (1888) and the specific category "glacio-eustasy", the pen of Henri Baulig (1935).

It was Darwin who integrated the two. On a volcanic island like St. Helena, for example, there are abundant eolianites but almost no beaches. Whence came all that sand? *Ex nihil, nihil fit.* Evidently it came from offshore, blown in from the insular shelf, at a time when either the land was higher or the sea level was lower. Fresh from his Patagonian observations, at first he quite naturally favored land uplift, but in later writings it is clearly implied that he accepted the glacial theory. (A basic, encyclopedia entry on "Eolianite" is provided in Fairbridge and Johnson 1978; see also Battistini 1964; Sanders and Friedman 1967; Sanlaville 1977; Yaalon 1967; Buchbinder and Friedman 1980).

An important diagenetic process that appears also to have been first addressed by Darwin is the role of timing in calcium carbonate cementation, a question which is intimately bound up with both eolianite formation and eustatic fluctuations. This phenomenon, so characteristic of the littoral zone in the tropics is almost unknown in the middle and upper latitudes, and so had escaped the attention of most of the 18th and early 19th century geologists. Some of the problems relating to it appear destined to persist into the 21st century (Friedman 1995).

To conclude these introductory words, one may return briefly to the theme of serendipity, when the curious vicissitudes of World War II brought Fairbridge and Teichert (1953) together in Australia, one of us (R.W.F.) via the U.K., Canada, Central Europe, and the Middle East, and the other (C.T.), from Königsberg (once, East Prussia), via Copenhagen, Greenland, and Washington, D.C. Together we studied beachrock, eolianites, coral reefs and eustatic processes (Fairbridge and Teichert 1948, 1953) and pioneered the interpretation of reefs and kindred coastal forms by the use of air photography (Teichert and Fairbridge 1948).

CALCIUM CARBONATE CEMENTATION OF BEACHROCK

One of Darwin's first experiences on South American shores was at Pernambuco (now Recife), where he observed the astonishing sandstone reef about 3m above MSL. This is classical "beachrock" (Branner 1904; Guilcher 1961). Waves beat over it, but it clearly has the structure and petrographic composition of a sandy beach, in fact, a structural pseudomorph now firmly cemented, and at an elevation that today we might well identify as "non-actualistic"; in short, we could not explain it without calling for two unusual mechanisms: recent cementation and recent change in elevation. Since that time numerous intrepid coastal tourists have "rediscovered" beachrock (e.g. Russell 1959), but have added precious little to our knowledge, and in numbers of papers transparently incorrect conclusions have been promulgated (see discussions: Alexanderson 1972; Friedman and Gavish 1971; Pytkowicz 1971; Hopley 1982).

Darwin's description of beachrock observed on Ascension Island is worth repeating (from "Geological Observations on the Volcanic Islands...": 1844; 1851/90, p.198):

"*Formation of calcareous rocks on the sea-coast.*-- On several of the sea-beaches, there are immense accumulations of small, well-rounded particles of shells and corals, of white, yellowish, and pink colors, interspersed with a few volcanic particles. At the depth of a few feet, these are found cemented together into stone, of which the softer varieties are used for building; there are other varieties, both coarse and fine-grained, too hard for this purpose: and I saw one mass divided into even layers half an inch in thickness, which were so compact that when struck with a hammer they rang like flint. It is believed by the inhabitants, that the particles become united in the course of a single year. The union is effected by calcareous matter; and in the most compact varieties, each rounded particle of shell and volcanic rock can be distinctly seen to be enveloped in a husk of pellucid carbonate of lime. Extremely few perfect shells are embedded in these agglutinated masses; and I have examined even a large fragment under a microscope, without being able to discover the least vestige of striae or other marks of external form: this shows how long each particle must have been rolled about, before its turn came to be embedded and cemented. One of the most compact varieties, when placed in acid, was entirely dissolved, with the exception of some flocculent animal matter; its specific gravity was 2.63. The specific gravity of ordinary limestone varies from 2.6 to 2.75; pure Carrara marble was found by Sir H. De la Beche to be 2.7. It is remarkable that these rocks of Ascension, formed close to the surface should be nearly as compact as marble, which has undergone the action of heat and pressure in the plutonic regions."

"The great accumulation of loose calcareous particles, lying on the beach near the Settlement, commences in the month of October, moving towards the S.W., which, as I was informed by Lieutenant Evans, is caused by a change in the prevailing direction of the currents. At this period the tidal rocks, at the S.W. end of the beach, where the calcareous sand is accumulating, and round which the currents sweep, become gradually coated with a calcareous incrustation, half an inch in thickness. It is quite white, compact, with some parts slightly spathose, and is firmly attached to the rock. After a short time it gradually disappears, being either redissolved, when the water is less charged with lime, or more probably is mechanically abraded. Lieutenant Evans has observed these facts, during the six years he has resided at Ascension. The incrustation varies in thickness in different years... Considering the position of the tidal-rocks, and the period at which they become coated, there can be no doubt that the movement and disturbance of the vast accumulation of calcareous particles, many of them being partially agglutinated together, cause the waves of the sea to be so highly charged with carbonate of lime, that they deposit it on the first objects against which they impinge."

Darwin provided a footnote, pointing to an illustration of turtle eggs encased in beachrock, in Lyell's *Principles* (1833, vol.3, ch.17). In the above extract, and in several other places, Darwin refers to a "white incrustation ... that gradually disappears". It appears to be what Tchermak (1878) once described as a new mineral *Pelagosite* (from the Adriatic island of Pelagosa (now believed to belong to Croatia). It appears instead to be an ephemeral evaporitic mixture of carbonates and other sea salts that easily redissolves in salt spray or rain (Fairbridge 1952, 1957; Revelle and Fairbridge 1957).

Beachrock, it turns out, is in many ways an ideal indicator of former sea levels (Hopley 1986); a 1000-yr-old example from 1.5-2m below present datum was recently reported from San Salvador Island, Bahamas (Kindler and Bain 1993). Failure to identify it, or to distinguish it from eolianite, leads to common errors (Dalongeville and Sanlaville 1981; Bain 1988; Friedman 1995).

DARWIN'S OBSERVATIONS OF EOLIANITE

On the homeward stretch on March 6th, 1836, HMS *Beagle* dropped anchor in King George's Sound, not far from the present site of Albany, in Western Australia. Darwin was not favorably impressed by the poor soil and sparse vegetation, but evidently fascinated by a corroboree put on by the local aborigines, who were regrettably dismissed in ignorance as "the lowest barbarians". It was here at Bald Head near the entrance to the Sound that he came face to face with eolianites on a large scale. This is on the world's largest tract of eolianites (Sanders and Friedman 1967), extending over 5000 km of coastline. In his *Voyage* (1845/1959 ed., p. 433), he says:

"One day I accompanied Captain Fitz Roy to Bald Head; the place mentioned by so many navigators, where some imagined that they saw corals, and others that they saw petrified trees, standing in the position in which they had grown. According to our view, the beds have been formed by the wind having heaped up fine sand, composed of minute rounded particles of shells and corals, during which process branches and roots of trees, together with many land-shells, became enclosed. The whole then become consolidated by the percolation of calcareous matter; and the cylindrical cavities left by the decaying of the wood, were thus also filled up with a hard pseudo-stalactical stone. The weather is now wearing away the softer parts, and in consequence the hard casts of the roots and branches of the trees project above the surface, and, in a singularly deceptive manner, resemble the stumps of a dead thicket."

There is more information in *Volcanic Islands* (1844; 1851/90, p.260-265):

"A calcareous deposit on the summit of Bald Head, containing branched bodies, supposed by some authors to have been corals, has been celebrated by the descriptions of many distinguished voyagers. It folds round and conceals irregular hummocks of granite, at the height of 600 feet above the level of the sea. It varies much in thickness; where stratified, the beds are often inclined at high angles, even as much as at thirty degrees, and they dip in all directions. These beds are sometimes crossed by oblique and even-sided laminae. The deposit consists either of a fine, white calcareous powder, in which not a trace of structure can be discovered, or of exceedingly minute, rounded grains, of brown, yellowish, and purplish colors; both varieties being generally, but not always, mixed with small particles of quartz, and being cemented into a more or less perfect stone. The rounded calcareous grains, when heated in a slight degree, instantly lost their colors; in this and in every other respect, closely resembling those minute, equal-sized particles of shells and corals, which at St. Helena have been drifted up the side of the mountains, and have thus been winnowed of all coarser fragments. I cannot doubt that the colored calcareous particles here have had a similar origin. The impalpable powder has probably been derived from the decay of the rounded particles; this certainly is possible, for on the coast of Peru, I have traced *large unbroken* shells gradually falling into a substance as fine as powdered chalk. Both of the above-mentioned varieties of calcareous sandstone frequently alternate with, and blend into, thin layers of a hard substalagmitic rock, which, even when the stone on each side contains particles of quartz, is entirely free from them: hence we must suppose that these layers, as well as certain vein-like masses, have been formed by rain dissolving the calcareous matter and re-precipitating it, as has happened at St. Helena. Each layer probably marks a fresh surface, when the now firmly cemented particles existed as loose sand. These layers are sometimes brecciated and re-cemented, as if they had been broken by the slipping of the sand when soft. I did not find a single fragment of a sea-shell; but bleached shells of the *Helix melo*, an existing land species, abound in all the strata; and I likewise found another Helix, and the case of an Oniscus." ... ."Calcareous deposits, like these of King George's Sound, are of vast extent on the Australian shores...." .... "The extent of these deposits, considering their origin, is very striking; and they can be compared in this respect only with the great coral-reefs of the Indian and Pacific Oceans...."

The present author (R.W.F.) had the good fortune to be able to explore Bald Head more than a century later, as well as numerous other eolianites around the coasts of Australia (Fairbridge and Teichert 1953) as well as others, for example, in South Africa, Madagascar, Mozambique, Southern California, Florida, Mexico (Yucatan, Baja California), Bermuda, Bahamas, the Canary Islands, Morocco, Algeria, Tunisia, Libya, Egypt, Palestine, Israel, Lebanon, Greece, Italy, Arabia, China, India and Hawaii. (For a global review, see Goldsmith 1985.) The Bald Head examples were described earlier as scenic curiosities of coral origin, by Vancouver in 1791 on his world voyage. More details on another area of Western Australia (later called Point or Cape Péron) were furnished by the French explorers Péron and deFreycinet (1807-1816, p. 75, 168-173), who recognized their eolian nature. Teichert (1947) provided a history of these discoveries.

It is thus possible to explain now that the well-bedded sets are clearly of eolian origin. These members are separated from one another by powdery layers of fossil soils, which in places contain abundant terrestrial gastropods. In Western Australia we observed that the gastropods (of the genus *Bothriembryon*) appeared to be species-specific to each paleosol layer (Fairbridge and Teichert 1953), just as Steven Jay Gould (1969) discovered later in his in-depth studies on Bermuda and the Bahamas. Amiel (1975) has described the pedogenesis of eolianite soils. The ecology of the gastropods provides a valuable insight into the paleoclimates involved. The free-drifting of sand (without human interference) requires an annual precipitation generally of less than about 100 mm; otherwise the dunes will become vegetated and sand migration will cease. The paleosols, for their part, are mostly of insoluble desert dust (silica, iron oxides, etc.) and call for a shift or reversal in prevailing wind direction, i.e. from on-shore to offshore directions. The fossil gastropods for the most part tend to cluster near the top of each paleosol and, by comparison with living environments, require a rainfall of > 200 mm. In Western Australia, we reached the conclusion that the dune-building incidents were quite brief, corresponding to intervals marked by abrupt fall of sea level that laid bare a sandy shelf area, with an arid climate but marked by onshore winds. The paleosols, in contrast reflected mainly offshore winds, but with seasonal rainfall > 200 mm. For a discussion of the Bermuda paleosols, see Ruhe et al. (1960, and Bricker and Mackenzie 1970); and those of the Bahamas, see Carew and Mylroie (1991). We will return briefly to the paleowinds, below.

Neither Darwin, nor Fairbridge and Teichert (1953), had access to modern isotopic age determinations, but geomorphic reasoning in Western Australia showed that the youngest dune series were probably the result of a series of events in the early to mid-Holocene. These deposits overlapped older, more cemented eolianites, in turn overlapping fossil reefs or marine deposits apparently belonging to the last interglacial. The latter then capped still older series of Pleistocene eolianites. In Western Australia the whole sequence has long been known as the "Coastal Limestone"; it later received a formal stratigraphic name, "Tamala Limestone (Playford 1977). These general conclusions were later confirmed by isotopic dating.

The most complete eolianite sequence in Western Australia in vertical sections is that of Rottnest Island, covering about 1900ha, situated 20 km offshore from Fremantle. It was named by the Dutch explorer Willem de Vlamingh in 1696, but it was not explored geologically until studied by Teichert (1950). It has the farthest-south coral reef in the world and its interglacial reef -- called "Rottnest Limestone" by Fairbridge (1953) -- has been dated by Veeh (1966) as about 100,000yr (see also Teichert 1967). The site was named "Fairbridge Bluff" on the geological survey map issued in 1976. An excellent guide book was prepared by Playford (with Leech: 1977; see also Playford 1983). A deep boring shows that the base of the eolianite sequence (collectively named "Tamala Limestone") reaches 70m below MSL, a total thickness of 115m. Holocene climatic and sea-level fluctuations are shown by emerged rock platforms, undercut cliffs and "raised" shell beds. Offshore, at various depths, planed-off "reefs" of eolianite correspond to Pleistocene interstadial stillstands (Carrigy and Fairbridge 1954). These can be matched elsewhere, e.g. a recent report off Grand Cayman (Blanchon and Jones 1995).

Elsewhere in Australia, eolianites are found all up the west coast for more than 1500 km to the region of Broome. Ocean-facing ridges of them reach more than 300m above MSL south of Shark Bay. Eolianites are also widespread along the coasts of South Australia, western Victoria (see, e.g. Gill 1943) and N.W. Tasmania. A slow tectonic uplift associated with late Quaternary volcanism has caused an upwarp near the S.A./Victoria border, exposing a magnificent series of them, with no less than seventeen major ridges, the inner ones being progressively more and more consolidated and karstified. Sprigg (1952, 1979), with remarkable perspicuity for that time, speculated that they represented a continuous sequence of Milankovitch cycles. Subsequent isotopic dating confirms this suggestion.

In the northern hemisphere, the most extensive development of eolianites is all along the coast of North Africa, from the Levant (Sanlaville 1970, 1977) to Malta (Paskoff and Sanlaville), to Tunisia (Paskoff, Oueslati and Sanlaville 1982; Paskoff and Sanlaville 1983), to Morocco. Isotopic dating, with associated archaeological material, notably in Morocco (Stearns 1978; Weisrock 1980; Weisrock and Fontugne 1991) suggests that their ages go back to the early Pleistocene (pebble-tool cultures). More scattered examples in the northern Mediterranean disclose interfingering relationships with cryoclastic periglacial solifluction surfaces which can be followed below sea level (Ozer and Vita-Finzi 1986). In places (e.g. Istria) the calcareous-cemented solifluction sheets contain bones of the giant Pleistocene mammals that existed during the coldest phases (Pirazzoli 1980). On the NW coast of Corsica an inhabited cave deposit ("Würmien") shows wedges of the eolianites.

In the Atlantic, volcanic islands such as St. Helena, Ascension, Cape Verde and the Canaries all have eolianite veneers, but the truly oceanic islands like Bermuda and literally thousands of members of the Bahamas are essentially built of eolianites, with minor components of marine or lacustrine origin (Nelson 1840; Sayles 1931; Lind 1973; Zankl and Schroeder 1972; Garret and Gould 1984).

The nature of the eolian grains is largely dictated by regional factors. Along continental coasts, such as Australia, South Africa, Madagascar, Western India and Mediterranean Africa, the grains are of terrigenous origin (quartz, feldspar and black minerals), generally in the range 50-90%, having been transported to the site, progressively, by rivers, waves and wind; they are therefore as a rule well-sorted, well-rounded and lightly pitted by eolian impacts. On oceanic islands, the grains are dominated by calcareous bioclastics, fragmented foraminifera, corals, small mollusca and calcareous algae; the last-named are rich in magnesian calcites which nucleate progressive dolomitization of the cements (Friedman 1975). "Regressive diagenesis" also marks climatic fluctuations (Müller and Tietze 1975).

Pleistocene eolianites are widely used for construction purposes (when freshly exposed, they are easy to cut by saw), and have therefore accumulated a wide range of local names, e.g. *kurkar* in Palestine, Israel and Lebanon.

The red paleosols in the eastern Mediterranean are known as *hamra* in Arabic or *limons rouges* in French (in the Levant, they originate from Sahara dusts blown in from the west during glacial stages: Yaalon and Ganor 1973). In Morocco, in contrast, they come from easterly or southerly winds (Delibrias, Rognon and Weisrock 1976); likewise in teh Canary Islands. In the Bahamas and Bermuda they are clearly terrigenous (Bricker and Mackenzie 1970), but, with easterly winds, could they also come from the Sahara?

Some purists will dispute the use of the term *eolianite*, first proposed by Sayles (1931) from his experiences in Bermuda. As explained by Friedman, Sanders and Kopaska-Merkel in their recent textbook (1992, p. 124), "the best classification is based on purely descriptive parameters, but into which genetic interpretations, where they can be reasonably inferred, can be judiciously blended.... Both particle size and composition must be employed." A rock that at first sight looks like a sandstone (defined by particle size), but behaves, in response to a drop of acid, as a limestone (thus defined by composition), creates a paradox. We can, however, turn to the Latin-based system of Grabau (1913), who would call it a *calcarenite*. To introduce a third parameter, bedding structure, that defines its origin, we call it an *eolian calcarenite* and for brevity, the universally known term *eolianite* ("aeolianite" of some British writers), or sometimes, *calcareous eolianite*.

Some examples of eolianite are made distinctive by peculiarities of the grains or cement. The grains may be ooids, so that *oolitic calcarenite* (or eolianite) is appropriate; or, they may be entirely of foraminifera, as in an area of western India, where a genus then called *Miliolina* led to the rock being called *miliolite* (Evans 1900, Brückner et al. 1987). Cements and diagenesis generate yet another set of labels, such as *sparite* and so on.

RHIZOMORPHS, CALCRETES AND KARST PIPES

Two of the most interesting aspects of eolianites are related to dune vegetation, diagenetic processes (cementation), surface crust (calcrete) formation and karst drainage. All the early investigators, including Darwin, noticed the bizarre landforms related to weathering and wind erosion of partly travertine-consolidated features that created a "petrified forest" or lacework of alveolar erosion and weakly cemented structures.

The solution and redeposition of $CaCO_3$ were not understood in Darwin's day and still present recurrent problems. A general consideration and bibliography is provided in Revelle and Fairbridge (1957). For his part, Darwin (*Volcanic Islands...*, p.261) wrote: "The causes which determine water to dissolve lime, and then soon to redeposit it, are not, I think, known. The surface of the substalagmitic layers [a term Darwin borrowed from Lt. Nelson] appears always to be corroded by the rain-water. As all the above-mentioned countries [he had reviewed the many examples] have a long dry season, compared with the rainy one, I should have thought that the presence of the substalagmitic [layers] was connected with the climate, had not Lieutenant Nelson found this substance forming under sea-water." Indeed, he was right about the climate connection, but in all probability, the submarine travertine seen by Nelson in Bermuda was inherited from a eustatically lowered sea-level state. In some exceptional circumstances, however, a deep-water carbonate has been observed in formation under biogenic control.

The vertical structures are clearly related to former vegetation which readily propagates across the dunes during humid climatic cycles. Their lower parts tend to be more sinuous and twisting, and have acquired the name *rhizomorphs* (i.e. root pseudo-morphs: Northrop, 1890). Another variation is *rhizoconcretion* (used in France by Ters 1961) and *rhizolith* (Klappa 1980). At Bald Head, Darwin (*Volcanic Islands...*, p. 261) says:

"The branches are absolutely undistinguishable in shape from the broken and upright stumps of a thicket; their roots are often uncovered, and are seen to diverge on all sides; here and there a branch lies prostrate. The branches generally consist of the sandstone, rather firmer than the surrounding matter, with the central parts filled, either with friable, calcareous matter, or with a substalagmitic variety; this central part is also frequently penetrated by linear crevices, sometimes, though rarely, containing a trace of woody matter. These calcareous, branching bodies, appear to have been formed by fine calcareous matter being washed into the casts or cavities, left by the decay of branches and roots of thickets, buried under drifted sand. The whole surface of the hill is now undergoing disintegration, and hence the casts, which are compact and hard, are left projecting. In calcareous sand at the Cape of Good Hope, I found the casts, described by Abel, quite similar to these at Bald Head; but their centers are often filled with black carbonaceous matter not yet removed. It is not surprising, that the woody matter should have been almost entirely removed from the casts on Bald Head; for it is certain, that many centuries must have elapsed since the thickets were buried; at present, owing to the form and height of the narrow promontory, no sand is drifted up, and the whole surface, as I have remarked, is wearing away. We must, therefore, look back to a period when the land stood lower, of which the French naturalists [Peron and Freycinet, 1807-1816] found evidence in upraised shells of recent species, for the drifting on Bald Head of the calcareous and quartzose sand, and the consequent embedment of the vegetable remains. There was only one appearance which at first made me doubt concerning the origin of the case, -- namely, that the finer roots from different stems sometimes became united together into upright plates or veins; but when the manner is borne in mind in which fine roots often fill up cracks in hard earth, and that these roots would decay and leave hollows, as well as the stems, there is no real difficulty in this case."

In his various revisions, Darwin (1851/90) had access to the work on Madeira by Macaulay (1840, p.350-351), who described a "Fossil Forest of Caniçal", already (at that time!) a celebrated tourist attraction. As in St. Helena there was no contemporary source for the sand, "only a tiny amount of mud beach".

Modern observations of vegetated dune structures have been carried out on the coast of Israel (Goldsmith 1973). On the older, i.e. Pleistocene, dune surfaces hard duricrusts are formed of calcrete (term introduced by Lamplugh 1902), which in the former swales became penetrated by vertical karst pipes; examples from Syria were described by Day (1928). The surface pipes in Western Australia (Fairbridge 1950) can be traced well below present sea level, and in the Bahamas and Bermuda are found to be linked to extensive karst cave systems associated with Pleistocene low sea level stands (Vasher 1973; Mylroie and Carew 1988; Vollbrecht and Meischner 1993). It seems likely that these pipes followed guidelines provided by the original clusters of interdune vegetation.

EUSTASY, GEODESY AND CLIMATE CHANGE

These three subjects were being discussed conceptually in Darwin's time, but even now, at the end of the 20th century, they are still "on the table" and many aspects are still highly controversial. Darwin's own contributions were not insignificant. His experiences in South America impressed upon him two fundamental aspects of the Earth's crust: (1) it possesses remarkable up- and down-mobility (epeirogeny), as shown by the warping and tilting of shore platforms, and (2) its motions may be quite abrupt, indeed potentially catastrophic, and associated with powerful seismic events and even tsunamis (although he did not use this term). The science historian may find it somewhat paradoxical that this practical argument for the Steven Jay Gould concept of punctuated evolution should have been such a feature in the experience of the future proponent of evolutionary gradualism.

It should be appreciated that the voyage of the *Beagle* took place more than a decade before the glacial theory of Agassiz and Charpentier, and before its glacio-eustatic consequence was first spelled out by MacLaren (1842). Nevertheless "raised beaches" in Scotland, Scandinavia and Canada were being observed and widely discussed. Indeed, an entire book on them "*Ancient Sea-Margins*" was written by Robert Chambers (1848), who corresponded with Darwin and who was a contemporary and friend of Hugh Miller in that remarkable Edinburgh society of interested amateurs. Chambers' book was largely descriptive (with carefully measured elevations) and compilative, but near the end he permitted himself the modest privilege of a brief speculation as to the origin of the warped strandlines he so painstakingly described -- Darwin's anticipation of tectono-eustasy (see below).

Darwin's empirical observation of uplift in Patagonia vis-à-vis his deductive assumption of downwarping to explain the Pacific atolls was very much a common-sense conclusion. In a way it could be interpreted as a forerunner to the theory of isostasy, the hydrodynamic nature of the Earth's crust. In point of fact, however, the two phenomena are totally unrelated. The uplift of the Patagonian terraces is a glacioisostatic consequence of load removal due to recent deglaciation. In contrast, the majority of Pacific atolls are built on sinking volcanic foundations, true, but not on fresh cones, alas. Most of the atolls are compound upgrowths from guyot-type volcanic stumps that were planed off already before the end of Cretaceous. And their upgrowth has been episodic (cf. the Vail eustatic curve), and superimposed on a slowly subsiding oceanic crust, sinking as it cooled off, following the mid-Cretaceous thermal crescendo, which marked the most-rapid and protracted sea-floor spreading interval of the Phanerozoic (Pitman 1978; Caldeira and Rampino 1991).

The subsiding volcano hypothesis was, of course, a generalization. On the Great Barrier Reef and elsewhere (e.g. Sahul Shelf) there are "shelf atolls" created by tectonic subsidence and eustasy (Fairbridge and Teichert 1948; Hopley 1982). In Darwin's time the subsidence hypothesis was vehemently opposed by some scientists, for example, by Murray (1888), who was over-impressed by widespread evidence of solution processes. He remarked (p. 144): "It is at once evident that the views now advocated are in almost all respects the reverse of those demanded by Mr. Darwin's theory .... it seems impossible with our present knowledge to admit that atolls or barrier reefs have ever been developed after the manner indicated by Mr. Darwin's simple and beautiful theory of coral reefs."

Darwin's atoll-foundation subsidence theory is nonetheless, in principle, correct, although it was simplistically overplayed by both critics and admirers (Steers and Stoddart 1977; Hopley 1982; Stoddart 1994). But while it has little to do with isostasy, it nevertheless provides the nucleus for what later came to be called the theory of *tectono-eustasy* (Fairbridge 1961; Rona 1995). As Darwin correctly reasoned, if a large area of the ocean basins subsided, there would indeed be a land emergence around the margins. The eustatic theory of Suess (1888) was based largely on his observations of "Mediterranean" regressions and transgressions in the Paratethys domain of eastern Europe, which he believed were due to an alternation of subsidence and sedimentary filling of the basins. The latter has received the label *sedimento-eustasy* (Fairbridge 1961), but its quantitative role is insignificant, and the sharply saw-tooth Vail "sequence curve" of the Phanerozoic is now largely attributed to episodic pulses (on a 10^6 yr scale) in sea-floor spreading and subduction (Dott 1992; Rona 1995).

On a different scale, the so-called "third order" Vail oscillations, relate to *climatic forcing* by the Milankovitch radiation mechanisms (with 10^4-10^5 yr periods). It is these that control the major fluctuations of sea level during the Quaternary Period (of the order of 100-150m) which explain Darwin's eolianites that plunge below sea level and result in the exposure of a large supply of littoral and shelf sands. If the eolianites were single-event phenomena, consideration could be given to the idea of tectonic control, but their cyclic recurrence (and isotopic dating) clearly points to the Milankovitch mechanism.

Superimposed on these third order Milankovitch oscillations are 4th, 5th and 6th order climatic-eustatic controls (Lowrie 1995), although their nature is still hotly contested in some areas. As late as the 1960's the "standard" (Shepard 1963) sea-level curve of the last 20,000yr was a smooth rise but it was opposed by the fluctuating records of Fairbridge (1961), Mörner (1976), Ters (1987) and others. It was the stepped erosion platforms of the Southwest Pacific and Australia's Indian Ocean shores that convinced Teichert (1950) and Fairbridge (1948 1950) that fluctuations were involved. These fluctuations are reflected in the eolianite paleosols, interfingering beach deposits and multiple erosion notches. It might be added that in southwestern Australia, the main river valleys e.g. the Swan and Helena were terraced during the Holocene, and, being thalassostatic (controlled by sea level), are strong evidence of eustatic fluctuation (Aurousseau and Budge 1921); pollen analysis confirms the climatic oscillations (Churchill 1959). Radiometric dating and field observations confirm the original concept (Playford 1983), though some problems remain. Nevertheless, it should be added that some scientists prefer neotectonic models (e.g. Wyrwoll et al. 1995).

Daly (1934), in his masterful book *The Changing World of the Ice Age*, not only pointed out the widespread existence of recent shore platforms up to around 3m that he observed in the Pacific (also, Daly 1924), but also considered the possible role of what Higgins (1969) later called *hydroisostasy*. This concept was based on two known facts (a) the loading that must have been applied to the world's oceanic crust by the transfer of water from melting ice sheets; and (b) the plasticity calculated to exist in the asthenosphere. Several distinguished geophysicists have recently taken up this theme and developed world-wide models (e.g. Lambeck 1990). Collectively, one and all, they have conveniently chosen to ignore the field evidence: (1) The evidence intrinsic in the eolianites, observed by Darwin and all subsequent writers, that episodes of aridity and rainfall must alternate in order to create the accumulation - solution - cementation sequences so evident in the multi-cycle eolianite complexes. (2) The steadily accumulating literature that shows that simultaneously with sea-level fluctuations, dune building, paleosol development, transgressions and regressions, elsewhere in the world, there have been rises and falls of lake levels, together with advance and retreat of mountain glaciers that reflect paleobotanically (pollen) demonstrated arid versus humid climate changes. These globally active phenomena could not act in a vacuum. Climate changes vary in expression from point to point, but their extent is planetary. The hydroisostatic models will therefore require a great deal more modification before they can be taken seriously.

There are other, and possibly more important areas of needed research that emerge from the evidence of Darwin's eolianites. For example: (1) The amplitude of Holocene sea-level fluctuations varies regionally; to what extent are these differences illusory and related to neotectonics or are they due to changes in ocean-current velocities (Coriolis effect?) or to regional shifts in the jet stream, atmospheric pressure cells and wind directions? (2) The climate switches from hyper-arid conditions to moderate (seasonal) precipitation exceed the rate and are beyond the range of presently observed variability. What are the forcing conditions? (3) The above-mentioned switches seem to imply feedback-accelerated chaotic states from one relative equilibrium to another. What are the geochemical conditions and consequences?

CONCLUSIONS

This essay, a somewhat nostalgic trip for its author back over experiences of half-a-century ago, has served to underline the importance of an historical approach to science. In saluting the "greats", as well as some of the mere "spear carriers", let us rejoice that while some of the problems have been solved, many more emerge to challenge future generations.

We observe how Darwin's experiences became gradually locked together within a dynamic-historical approach to earth science that owed more to the paleontologically guided stratigraphy of William Smith than to the fossil-systematics of Baron Cuvier or the geometric and chemical mineral systems of James Dwight Dana (see ed. 3 of his *System*). Darwin benefitted greatly from receiving Lyell's *Principles* (3 vols., 1830-1833) which evidently gave him a genuine feeling for cause and effect in physical geology: not to forget the persistent questioning by the pragmatic, if somewhat irascible Capt. Fitzroy.

REFERENCES

ALEXANDERSON, T., 1972, Mediterranean beachrock cementation: marine precipitation of Mg-calcite, *in* Stanley, D.J. (ed.). *The Mediterranean Sea*. Stroudsburg: Dowden, Hutchinson & Ross, p. 203-223.

AMIEL, A.J., 1975, Progressive pedogenesis of eolianite sandstone: *Journal of Sedimentary Petrology*, v. 45, p. 513-519.

AUROUSSEAU, M. and BUDGE, E.A., 1921, The terraces of the Swan and Helena rivers and their bearing on recent displacements of the strand line: *Royal Soc. Western Australia, Jour. Proc.*, v. 7, p. 24-43.

BAIN, R.J., 1988, Exposed beachrock: its influence on beach processes and criteria for recognition. *Proceedings, 4th Symposium on Geology of Bahamas*, San Salvador: Bahamian Field Station, p. 33-44.

BATTISTINI, R., 1964, L'extrème Sud de Madagascar: Étude Géomorphologue. Paris: Cujas, 2 vols., 636 p.

BAULIG, H., 1935, The Changing Sea Level. London: Institute of British Geographers, Publ. no. 3, 46 p.

BLANCHON, P. and JONES, B., 1995, Marine-planation terraces on the shelf around Grand Cayman: a result of stepped Holocene sea-level rise: *Journal Coastal Research*, v. 11(1), p. 1 -33.

BRANNER, J.C., 1904, The stone reefs of Brazil: *Bull. Museum Comparative Zoology (Harvard College)*, v. 44, geol. ser.7, 285 p (extended summary in 1905: *Geological Society of America Bulletin*, v. 14, p. 1 -12).

BRICKER, O.P., and MACKENZIE, E.T., 1970, Limestones and red soils of Bermuda: discussion: *Geological Society of America Bulletin*, v. 81, p. 2523-2524.

BRÜCKNER, H., et al., 1987, Miliolite occurrences on Kathiawar Peninsula (Gujarat): *Berliner Geographische Studien*, v. 25, p. 43-361.

BUCHBINDER, L.G. and FRIEDMAN, G.M., 1980, Vadose, phreatic and marine diagenesis of Pleistocene-Holocene carbonates in a borehole: Mediterranean coast of Israel: *Journal of Sedimentary Petrology*, v. 50, p. 395-407.

CALDEIRA, K. and RAMPINO, M.R., 1991, The mid-Cretaceous super plume, Carbon dioxide and global warming: *Geophys. Research Letters*, v. 18(6), p. 987-990. [follow up: Larsen, R., 1995. The mid-Cretaceous Superplume episode. *Sci. Amer.*, 82-86.]

CAREW, J.L. and MYLROIE, J.E., 1991, Some pitfalls in paleosol interpretation in carbonate sequences: *Carbonates and Evaporites*, v. 6(1), p. 69-74.

CARRIGY, M.A. and FAIRBRIDGE, R.W., 1954, Recent sedimentation, physiography and structure of the continental shelves of Western Australia: *Royal Soc. Western Australia, Jour. Proc.*, v. 38, p. 65-95.

CHAMBERS, R., 1848, Ancient Sea-Margins, as Memorials of Changes in the Relative Level of Sea and Land. Edinburgh and London: Chambers, Orr & Co., 388 p.

CHURCHILL, D.M., 1959, Late Quaternary eustatic changes in the Swan River district: *Royal Soc. Western Australia, Jour. Proc.*, v. 42, p. 3-55.

DALONGEVILLE, R., and SANLAVILLE, P., 1981, La signification morphogénétique du beach-rock (grè de plage) en Mediterranée: *Soc. Géol. France, C.R. somm.* (2), p. 60-62.

DALY, R.A., 1924, Geology of American Samoa. *Carnegie Inst.,Washington*, Publ. 340, p. 3-143.

DALY, R.A., 1934, The Changing World of the Ice Age. New Haven: Yale Univ. Press, 271 p.

DARWIN, C., 1839, Journal of Researches into the Geology and Natural History of the Various Countries visited by H.M.S. Beagle. London: Henry Colbur; 615 p' [Facsimile reprint, New York: Hafner Publ. Co., 1952. Reprint with new introduction, London: J.M. Dent, 1959.]

DARWIN, C.R., 1851, Geological Observations on Coral Reefs, Volcanic Islands and on South America, being the Geology of the Voyage of the Beagle, under the Command of Captain Fitzroy during the years 1832 to 1836. London: Smith, Elder & Co. (*Coral Reefs*, repr. of 1842; *Volcanic Islands*, 1844; *South America*, 1846); 2nd ed. by Ward, Lock & Co., 1890, 549.)

DAY. A.E., 1928, Pipes in the Coast Sandstone of Syria: *Geol. Mag.*, v. 65, p. 412-425.

DELIBRIAS, G., ROGNON, P., and WEISROCK, A., 1976, Datation de plusieurs épisodes á 'limons roses' dans le quaternaire récent de l'Atlas atlantique marocain: *Académie Sciences, Comptes Rendus* (Paris), ser. D, v. 282(7), p. 593-597.

DOTT, R. (ed.), 1992, Eustasy: The historical ups and downs of a major geological concept: *Geol. Soc. Amer. Memoir*, v. 180 (esp. Dott: Introduction, p. 1-16).

EVANS, J.W., 1900, Mechanically-formed limestones from Junagarh (Kathiawar) and other localities: *Geol. Soc. London, Quarterly Jour.*, v. 56, p. 559-563.

FAIRBRIDGE, R.W., 1948, Notes on the geomorphology of the Pelsart Group of the Houtman's Abrolhos Islands: *Roy. Soc. Western Australia, Jour. & Proc.*, v. 33, p. 1-36.

FAIRBRIDGE, R.W., 1950, The geology and geomorphology of Point Peron, Western Australia: *Roy. Soc. Western Australia, Jour. & Proc.*, v. 3 4, p. 35-72.

FAIRBRIDGE, R.W., 1952, Marine erosion: *Proc. Seventh Pacific Science Congress* (New Zealand, 1949), v. 3, p. 347-359.

FAIRBRIDGE, R.W., 1953, *Australian Stratigraphy*. Nedlands: University of W.A. Textbooks Board.

FAIRBRIDGE, R.W., 1957, The dolomite question: *Soc. of Economic Paleontologists & Mineralogists* (Tulsa), Sp. Publ. 5, p. 125-178.

FAIRBRIDGE, R.W., 1961, Eustatic changes in sea level, *in* Ahrens, L.H. et al., eds., *Physics and Chemistry of the Earth*. London: Pergamon Press, v. 4, p. 99-185.

FAIRBRIDGE, R.W., 1980, Prediction of long-term geologic and climatic changes that might affect the isolation of radioactive waste, *in Underground Disposal of Radioactive Wastes*, v. 2, p. 285-405. Vienna: Internat. Atomic Energy Agency (IAEA-SM-243/43).

FAIRBRIDGE, R.W., 1987, Climatic Variation, historical record, *in: Oliver*, J.E. & Fairbridge, R.W. eds.). The Encyclopedia of Climatology. New York: Van Nostrand Reinhold, 303.

FAIRBRIDGE, R.W. and JOHNSON, D.L., 1978, Eolianite. *In:* FAIRBRIDGE, R.W. and BOURGEOIS, J., *Encyclopedia of Sedimentology*. Stroudsburg: Dowden, Hutchinson & Ross.

FAIRBRIDGE, R.W. and OLIVER, J.E., eds., 1987, The Encyclopedia of Climatology. New York: Van Nostrand Reinhold, 986 p.

FAIRBRIDGE, R.W. and TEICHERT, C., 1948, The Low Isles of the Great Barrier Reef: a new analysis: *Geogr. Jour.*, v. 111, p. 67-88.

FAIRBRIDGE, R.W. and TEICHERT, C., 1953, Soil horizons and marine bands in the Coastal Limestones of Western Australia: *Royal Soc. New South Wales, Jour. & Proc.*, v. 86, p. 68-87.

FRIEDMAN, G.M., 1975, The making and unmaking of limestones, or the downs and ups of porosity: *Journal of Sedimentary Petrology*, v. 45(2), p. 379-398.

FRIEDMAN, G.M., 1995, The depositional and diagenetic evolution of the coastal ridges of northwestern Egypt -- discussion: *Sedimentary Geology*, v. 95, p. 133-135.

FRIEDMAN, G.M. and GAVISH, E., 1971, Mediterranean and Red Sea (Gulf of Agaba) beachrocks, *in* Bricker, O.P. (ed.). *Carbonate Cements*. Baltimore: Johns Hopkins Univ. Studies in Geology, p. 13-16.

FRIEDMAN, G.M., SANDERS, J.E., and KOPASKA-MERKEL, D.C., 1992, Principles of Sedimentary Deposits: Stratigraphy and Sedimentology. New York: Macmillan, 717 p.

GARRET, P. and GOULD, S.J., 1984, Geology of New Providence Island, Bahamas: *Geological Society of America Bulletin*, v. 95, p. 209-220.

GILL, E.D., 1943, The geology of Warrnambool: *Proc. Roy. Soc. Victoria*, v. 55(2), p. 133-152.

GOLDSMITH, V., 1973, Internal geometry and origin of vegetated coastal dune: *Journal of Sedimentary Petrology*, v. 43, p. 1128-1143.

GOLDSMITH, V., 1985, Coastal sand dunes, *in* Davis, R.A.jr. (ed.): *Coastal Sedimentary Environments*. New York: Springer-Verlag, p. 303-378.

GOULD, S.J., 1969, An evolutionary microcosm: Pleistocene and Recent history of the land snail Poecilozonites in Bermuda: *Bull., Museum Comparative Zoology*, v. 138, p. 407-532.

GRABAU, A.W., 1913, Principles of Stratigraphy. New York: A.G. Seiler & Co., 1185 p. (also Dover repr., 2 vols.)

GUILCHER, A., 1961, Le beach-rock ou grès de plage: *Annales Géographie*, no. 378, p. 113-125.

HIGGINS, C.G., 1969, Isostatic effects of sea-level changes, *in* Wright, J. (ed.), *Quaternary Geology and Climate*. Washington, D.C.: Nat. Acad. Sci., publ. 1701, p. 141-145.

HOPLEY, D., 1982, The Geomorphology of the Great Barrier Reef. New York: J. Wiley (Interscience), 453 p.

HOPLEY, D., 1986, Beachrock as a sea-level indicator, *in* Van de Plassche, O. (ed.), Sea-Level Research: A Manual for the Collection and Evaluation of Data. Norwick: Geo Gooks. p. 157-173.

KINDLER, P. and BAIN, R.J., 1993, Submerged Upper-Holocene beachrock on San Salvador Island, Bahamas: Implications for recent sea-level history: Geologische Rundschau, v. 82, p. 241-247.

KLAPPA, C.F., 1980, Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance: *Sedimentology*, v. 27, p. 613-629.

LAMBECK, K., 1990, Glacial rebound, sea-level change and mantle viscosity: *Royal Astronomic Society, Quarterly Journal*, v. 31(1), p. 1-30.

LAMPLUGH, G.W., 1902, Calcrete: *Geol. Mag.*, dec. IV, v. 9, p. 575.

LARSEN, R., 1995, The mid-Cretaceous superplume episode: *Scientific American*, v. 272, p. 82-86.

LIND, A.O., 1973, Bahamas coastal dunes: *Assoc. Amer. Geographers, Proc.*, v. 5, p. 147-159.

LOWRIE, A. and HAMITER, R., 1995, Fifth and sixth order eustatic events during Holocene (fourth order) high stand influencing Mississippi delta-lobe switching: *Journal Coastal Research*, Sp. iss. 17.

LYELL, C., 1830-1833, *Principles of Geology*. London: John Murray, [facsimile reprint, New York: Johnson Reprint Corp., 1969, introduction by M.J.S. Rudwick].

MACAULAY, J., 1840. Notes on the Physical Geography, Geology, and Climate of the Island of Madeira: *Edinburgh New Phil. Jour.*, v. 29, p. 336-375.

MacLAREN, C., 1842, The glacial theory of Prof. Agassiz: *Amer. Jour. Sci.*, v. 42, p. 46-365.

MÖRNER, N.A., 1976, Eustasy and geoid changes: *Journal of Geology*, v. 84, p. 123-151.

MÜLLER, G. and TIETZE, G., 1975, Regressive diagenesis in Pleistocene eolianites from Fuerteventura, Canary Islands: *Sedimentology*, v. 22(3), p. 485-496.

MURRAY, J., 1888, Structure, origin, and distribution of coral reefs and islands. *Royal Institution*, London (reprint, 1971: *Earth Sciences*, v. 2, p. 132-144.)

MYLROIE, J.E. and CAREW, J.L., 1988, Solution conduits as indicators of late Quaternary sea level position: *Quaternary Science Reviews*, v. 7, p. 55-64.

NELSON, R.J., 1840, On the geology of the Bermudas: *Geol. Soc. London, Trans.*, v. 5 (ser. 2), p. 103-123.

NORTHROP, J.I., 1890, Notes on the geology of the Bahamas: *New York Acad. Sci., Trans.*, v. 10, p. 4-22.

OZER, A. and VITA-FINZI, C. (eds.), 1986, Dating Mediterranean shorelines: *Zeitschrift für Geomorphologie*, NF, Suppl. v. 62, 207 p.

PASKOFF, R., OUESLATI, A. and SANLAVILLE, P., 1982, Le Tyrrhénien de Tunisie: essai de synthèse: *Bulletin Société Géologique de France*, v. 2, p. 173-178.

PASKOFF, R., and SANLAVILLE, P., 1983, Les Côtes de la Tunisie: Variations du Niveau Marin depuis le Tyrrhénien.

Lyon: Maison de l'Orient Méditerranéen (no. 14), 192 p.
PERON, F. and DEFREYCINET, L., 1807-16, Voyage de découvertes, aux terres Australes, sur les corvettes le Géographe, le Naturaliste, et la goelette le Casuarina, pendant les années 1800-1804.... Paris, 3 vols.
PIRAZZOLI, P.A., 1980, Formes de corrosion marine et vestiges archéologiques submergés: interprétation néotecto-nique de quelques exemples en Grèce et en Yougoslavie: *Annales Institut Océanographique*, v. 56(S), p. 101-111.
PITMAN, W.C.III, 1978, Relationship between eustacy (*sic!*) and stratigraphic sequences of passive margins: *Geol. Soc. Amer. Bull.*, v. 89, p. 1389-1403.
PLAYFORD, P.E., 1977, Geology and Hydrology of Rottnest Island. Perth: Geological Survey, W.A., Report 5(1), p. 1-53 (With *Hydrology* by R.E.J. Leech, p. 54-86).
PLAYFORD, P.E., 1983, Geological research on Rottnest Island: *Royal Soc. Western Australia, Jour.*, v. 66(1/2), p. 10-15.
PYTKOWICZ, R.M., 1971, Sand-sea water interactions in Bermuda beaches: *Geochimica et Cosmochimica Acta*, v. 35(5), p. 509-515.
REVELLE, R.R. and FAIRBRIDGE, R.W., 1957, Carbonates and carbon dioxide. *In: Treatise on Marine Ecology and Paleocology*. Geol. Soc. Am. Mem. 67(v. 1), p. 239-296.
RONA, P.A., 1995, Tectonoeustasy and Phanerozoic sea-levels: *Journal Coastal Research*, Sp.iss.17.
RUHE, R.V., CADY, J.G., and GOMEZ, R.S., 1961, Paleosols of Bermuda: *Geological Society of America Bulletin*, 72, p. 1121-1142.
RUSSELL, R.J., 1962, Origin of beachrock: *Zeitschrift für Geomorphologie*, NF, v. 6(1), p. 1-16.
SANDERS, J.E. and FRIEDMAN, G.M., 1967, Origin and occurrence of limestones, *in* Chilingar, G.V., Bissell, H.J., and Fairbridge, R.W. (eds.). *Carbonate Rocks*. Amsterdam: Elsevier, p. 169-265.
SANLAVILLE, P., 1970, Les variations holocènes du niveau de la mer au Liban: *Revue de Géographie de Lyon*, v. 45, p. 279-304.
SANLAVILLE, P., 1977, *Étude Géomorphologique de la Région Littorale du Liban*. Beyrouth (Lebanon).
SAYLES, R.W., 1931, Bermuda during the Ice Age: *Amer. Acad. Arts & Sciences, Proc.*, v. 66, p. 382-467.
SHEPARD, F.P., 1963, Thirty-five thousand years of sea level, *in* Clements, T. (ed.), *Essays in Marine Geology*. Los Angeles: Univ. of S. Calif. Press, p. 1-10.
SPRIGG, R.C., 1952, Stranded Pleistocene sea-beaches of South Australia and aspects of the theories of Milankovitch and Zeuner. *Int. Geol. Congr.* (XVIII, G.B., 1948), pt.13, p. 226-237.
SPRIGG, R.C., 1979, Stranded and submerged sea-beach systems of southeast South Australia and the aeolian desert cycle: *Sedimentary Geology*, v. 22, p. 53-96.
STEARNS, C.E., 1978, Pliocene-Pleistocene emergence of the Moroccan Meseta: *Geological Society of America Bulletin*, v. 89, p. 1630-1644.
STEERS, J.A. and STODDART, D.R., 1977, The origin of fringing reefs, barrier reefs, and atolls, *in* Jones, O.A. and Endean, R. (eds.). Biology and Geology of Coral Reefs, London, New York: v. 4 (Geology, pt.2), p. 21-59.
STODDART, D.R., 1994, Theory and reality: the success and failure of the deductive method in coral reef studies – Darwin to Davis: *Earth Sciences History*, v. 13(1), p. 21-34.
SUESS, E., 1885-1909, Das Antlitz der Erde, Vienna: F. Tempsky. (Engl. trans. "The Face of the Earth". Oxford: Clarendon Press, 1904-1924). 5 vols.
TCHERMAK, G., 1878, Neue Minerale: Pelagosit: *Tschermak's Mineralog. u. Petrogr. Mitth.*, n.s., v. 1, p. 174-175.
TEICHERT, C., 1947, Contributions to the geology of Houtman's Abrolhos, Western Australia: *Linnean Soc. New South Wales, Proc.*, v. 71, p. 145-196.
TEICHERT, C., 1950, Late Quaternary changes in sea level at Rottnest Island, Western Australia: *Roy. Soc. Victoria, Proc.*, v. 59, p. 63-79.
TEICHERT, C., 1967, Age of Coastal Limestone, Western Australia: *Australian Jour. Sci.*, v. 30, 71 p.
TEICHERT, C. and FAIRBRIDGE, R.W., 1948, Some coral reefs of the Sahul Shelf: *Geographical Review*, v. 38(2), p. 222-249.
TERS, M., 1961, *La Vendée Littorale, Étude Géomorpho-logique*. Rennes: Thèse, 578 p.
TERS, M., 1987, Variations in Holocene sea level on the French Atlantic coast and their climatic significance, *in* Rampino, N.R., Newman, W.S., and Sanders, J.E., eds., *Climate: History, Periodicity and Predictability*. New York: Van Nostrand-Reinhold, p. 204-237.
VACHER, H.L., 1973, Coastal dunes of younger Bermuda, *in* Coates, D.R. (ed.), *Coastal Geomorphology*. Binghamton: State Univ. N.Y., p. 355-391.
VEEH, H.H., 1966, Th^{230}/U^{238} and U^{234}/U^{238} ages of Pleistocene high sea level stand: *Jour. Geophysical Research*, v. 71, 3379-3386.
VOLLBRECHT, R., 1990, Marine and meteoric diagenesis of submarine Pleistocene carbonates from the Bermuda carbonate platform: *Carbonates and Evaporites*, v. 5, p. 13-95.
VOLLBRECHT, R. and MEISCHNER, D., 1993, Sea level and diagenesis: a case study on Pleistocene beaches, Whalebone Bay, Bermuda: *Geologische Rundschau*, v. 82, p. 248-262.
WEISROCK, A. and FONTUGNE, M., 1991, Morphogenèse éolienne littorale au Pleistocène superieur et à l'Holocène dans l'Oulja atlantique macaine: *Quaternaire*, v. 2(3/4), p. 164-175.
WYRWOLL, K.-H., et al., 1995, Holocene sea-level events in Western Australia: revisiting old questions: *Jour. Coastal Research*, sp.issue 17.
YAALON, D.H., 1967, Factors affecting the lithification of eolianite and interpretation of its environmental significance in the coastal plain of Israel: *Journal of Sedimentary Petrology*, v. 37, p. 1189-1199.
YAALON, D.H. and GANOR, E., 1973, The influence of dust on soils during the Quaternary: *Soil Science*, v. 116, p. 146-155.
ZANKL, H. and SCHROEDER, J.H., 1972, Interaction of genetic process in Holocene reefs off North Eleuthera Island, Bahamas: *Geologische Rundschau*, v. 61(2), p. 520-541.

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