THE STONE REEF AT PERNAMBUCO

STONE REEFS ON THE NORTHEAST COAST OF BRAZIL.*

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INTRODUCTION

It is proposed to give very briefly in this paper the results of studies of the stone reefs on the northeast coast of Brazil, which were made in connection with a general geological and geographical investigation of that region.

LOCATION, ORIGIN, AND STRUCTURAL FEATURES OF THE REEFS

The stone reefs of Brazil are mostly in an out-of-the-way part of the world. They lie along the northeast coast of that country, between

*A detailed description of these reefs is published in the Bulletin of the Museum of Comparative Zoology, VII, Geological series.

south latitudes 3 degrees 43 minutes and 16 degrees 30 minutes. Only one of these reefs is where it is readily accessible to trans-Atlantic steamers, and that is at the port of Pernambuco. The others are scattered along a coast which has no commodious harbors, and are therefore but little known outside of Brazil.

These stone reefs are unique or almost unique geologic phenomena. Darwin, who saw the one at Pernambuco, says of it that he doubts "whether in the whole world any other natural structure has so artificial appearance." Wonder at these structures is greatly increased when one finds them repeated along the coast for more than a thousand miles. Perhaps the clearest idea of them will be conveyed in fewest words if it is stated at the outset that the reefs are lithified marine spits or beaches that have been encroached on from both sides until their edges are more or less broken and angular and their surfaces swept clean of the loose, unconsolidated portions. This theory of their origin appears to be supported by the great bulk of the data collected. Only a few of the more important features of the reefs, however, can be mentioned in this place.

Where exposed at the surface the reef rock is sandstone, often almost as hard as a quartzite and ringing under the hammer like a clink-stone, but sometimes, and locally, it is only moderately hard. It contains abundant shells and other remains of animals and calcareous plants, apparently of the same species as those now living in the ocean alongside. The beach sands in the vicinity of the stone reefs invariably contain similar remains and abundant small fragments of shells, corals, and of other lime-secreting organisms. Except in the matter of hardness and compactness, the rock of the reef is therefore scarcely distinguishable from the present beaches. The cementing material of the hard rock is lime carbonate, which sometimes contains a little iron also. The rock has a remarkably fresh appearance and the shells imbedded in it usually retain their bright colors.

A section across a reef invariably shows the beds dipping toward the ocean at an angle varying from 2 to 20 degrees; the lower angles are the more common. In the gross structure no difference is apparent between the beds on the ocean side and those on the landward side.

In 1874 three drill holes were put down by the Brazilian government on the stone reef in front of the city of Pernambuco under the direction of the English engineer, Sir John Hawkshaw. The records of these holes furnish the only data we have of the thickness of the hard sand rock and of the nature of the underlying strata. The deepest hole had a depth of 17 meters.

SANDSTONE REEF AT RIO GRANDE DO NORTE

As seen from a fort on the reef. The seaward dip of the beds is well shown by this reef

SOUTH END OF CAPE SANTO AGOSTINHO STONE REEF WHERE IT JOINS THE LAND

There is a long pool on top of the reef

Record of a Boring on the Pernambuco Stone Reef

	Meters
Hard reef rock.....	2.95
White sand.....	1.22
Shells.....	1.10
Gray sand.....	0.65
Broken rock.....	1.22
Dark sand.....	2.10
Mottled clay.....	1.80
Yellow clay.....	0.70
Gray sand.....	3.50
White sand.....	2.20

In another bore the hard reef rock at the top was found to be about 4 meters thick; otherwise the records of the two other holes closely resemble this one. It is not known what is meant in the record by

FIGURE 1.—Bird's-eye View of the Region about Traição and the Mouth of Rio Mamanguape.
Showing the relations of the stone reef to the shore.

"broken rock." In none of the holes was there any repetition, at greater depth, of the hard top rock; the underlying materials were either clays or they were loose and fragmental.

The reefs are off the shore a little way and approximately parallel

with it. Usually they have one end connected with the land, at least during low tide, while the free end stands across the mouth of stream, embayment, or estuary; sometimes, however, they are not connected with the shore at all, at any stage of the tide. At high tide they are about flush with the surface of the water, while at low tide they are exposed like long, low, flat-topped walls or breakwaters. In width they vary from a few paces to 450 feet; in length they are from a few hundred feet to $8\frac{1}{2}$ miles, the total length being concealed by sand, which covers one end. Commonly they are almost straight; when they curve at all the curves are gentle and only perceptible when one looks along them lengthwise or when they are carefully mapped.

These remarkable natural walls of sandstone accompany the shores of northeastern Brazil, with many interruptions, from Ceará to Porto Seguro, a distance of 1,250 miles. With unimportant exceptions, they do not occur beyond these limits.

FACTORS IN THE FORMATION OF THE REEFS

IN GENERAL

Having stated the broad theory of the origin of these stone reefs, I shall not weary the reader with the tedious process of elimination by which the accepted conclusions were reached, but shall invite attention directly to their history as finally worked out in a study of the problem which has been carried on with various interruptions for nearly thirty years.

HISTORY OF THE COAST

It will be necessary first to briefly outline the geologic and geographic history of this particular coast. The greater part of the rocks of the coast region are marine sedimentary beds, apparently of Eocene age. During Miocene times the coast seems to have stood several hundred feet higher than it does at present, and narrow valleys were cut in the Eocene beds, mostly at right angles to the coastline. This period of erosion was followed by a depression, when many new bays were formed by the valleys which lie near the coast. There have been some changes of level since this period, but they have not been great, the evidence nowhere suggesting a movement exceeding 30 or 40 feet. In the meantime the strong on-shore waves and the in-shore currents rapidly cut away the soft Eocene sediments of the headlands and threw them into the reentrant angles of the coast. This process continued until the mouths of the bays were completely or nearly closed and the entire coast made as nearly straight as it is possible for as long a coast to be. Streams flowing into these narrow bays silted them up from the upper ends. Marine erosion was so vigorous, however, that several such bays were almost completely closed long before the land sediments filled them up.

THE CUNHAHU STONE REEF AT LOW TIDE

PORTO SEGURO REEF

View taken from a steamer behind the reef at high tide. The surf line is in outer face of the reef

In this way were formed the coastal lakes of the state of Alagôas, which are brackish water lakes lying between watersheds from 200 to 500 feet high and separated from the ocean by low sand spits.

FIGURE 2.—Coastal Lakes of the State of Alagôas, Brazil.

CLIMATE OF THE INTERIOR

It is necessary at this point to direct attention to certain climatic and drainage peculiarities of this northeastern corner of Brazil which affect the problem of the stone reefs.

If the reefs of northeast Brazil are but little known outside of that country, the climate of the interior along this coast is even less known. Everyone has heard of the great amount of rainfall about the mouth of the Amazon, and every writer on Brazil has something to say of the abundant rains of Rio de Janeiro. At one station of the edge of the plateau, south of Rio, the annual rainfall amounts to 11.7 feet. As the region of the stone reefs lies between Rio and the mouth of the Amazon

and is entirely within the tropics, it appears to the casual observer that it must also be a region of great rainfall. As a matter of fact the country about cape Saint Roque and for hundreds of miles west, southwest, and northwest of there is a region of devastating drouths.

PERIODICITY OF THE STREAMS

Ordinarily the rains fall during two or three months of the year, but some years the annual rains do not come, and the dry season is drawn out to an entire year, to two years, or even to five or six years. At such times all vegetation away from streams is parched, the streams disappear, cattle die of thirst, and sometimes the people themselves are compelled to leave the region. When the rains do fall they are frequently torrential, and the precipitation even in this region of drouth is in fact much larger than at Pará, and many other notoriously wet places. The result of these conditions is that the streams of the region are strongly intermittent, some of them being big enough to float an ocean steamer at one time, and completely disappearing during the ordinary dry seasons, to say nothing of years of severe drouths.

The Rio São Francisco is the only large perennial river along this entire strip of coast, and that river rises, not in the drouth region of northeastern Brazil, but about latitude 21 degrees south, far to the west and south of the highlands of Minas Geraes and more than 1,000 miles from its mouth. On the maps many other rivers are shown, to be sure, but they are all more or less intermittent. Under such circumstances it follows that the intermittent streams flow boldly into the ocean only during the season of rains, while during the dry season they become so enfeebled that the waves of the ocean throw their own silts and the beach sands back into their mouths, and in some cases complete barriers are thus built between the land water and the sea water. These processes have been in operation along the northeast coast of Brazil ever since the land took on its present approximate form.

CLOSED STREAMS

My studies of the stone and coral reefs have been carried on partly in small boats and jangadas or rafts, but I have also walked several hundred miles along the beach for the purpose of examining them and of seeing their geographic and geologic surroundings. Naturally one traveling along the beach would expect to find difficulty in crossing the streams, but as a matter of fact during the longest trip made on foot and at the end of the rainy season only two streams were found that could not be waded in a distance of something over 200 miles. At the mouths of several rivers there was connection between the ocean and the streams only during high tide, and at several other places where streams were to

THE MAMANGUAPE STONE REEF

Taken at low tide from the port on the landward side

LOW TIDE ON THE MAMANGUAPE STONE REEF

be expected, there were what are known in that country as "rios tapados" or shut up streams—that is, streams whose mouths are completely closed by bars across them. At one place a stream was waded that was cutting through a sand bar and running from the ocean landward; at two places gaps were found that had been cut in this way, but as they were passed at low tide, there was no water flowing through the breaks. The disposition of the sand, however, left no doubt about the water having flowed from the ocean toward the stream.

VEGETATION

Another important fact is that the region under consideration is in the tropics, and wherever there is fresh water, vegetation is rank. The banks of streams are everywhere overgrown with a dense jungle, bodies of fresh water are covered and filled with aquatic plants, while the densest of mangrove swamps cover the tide flats of the region of salt and brackish water.

DENSITY OF THE SEA WATER

The other element of the problem is the density of the ocean water along the part of the Brazilian coast on which the stone reefs occur. In volume I of the Challenger reports, "Physics and chemistry," data have been brought together and a chart constructed showing the oceanic areas of different densities of the surface waters. This chart shows that the areas of the highest densities are in the Red sea and the Mediterranean sea; these, however, are land-locked basins. The highest densities in the open ocean form two areas in the Atlantic: one being near the middle of the ocean, lying between northern Africa and the West Indies; the other being in the south Atlantic and hugging the coast of Brazil from cape Saint Roque to south of Rio de Janeiro.

It is worthy of note that the area of high Atlantic density as represented in the Challenger chart does not quite fit the area of the stone reefs. The map seems to show the dense area to be too far to the south to suit the theory of the reefs here put forward. This is probably due in part to a lack of density data, especially for the dry season, along the coast of Brazil northwest of cape Saint Roque, and extending half way from there to Pará. The southern limit of the high density lies south of Rio de Janeiro and far beyond the southern limit of the stone reefs. The absence of reefs in this direction is readily explained by the fact that rainfall on this part of the coast is very much larger than it is farther north, and the streams are therefore able to keep their mouths open. In connection with the subject of climatic conditions it should be noted that the long dry season which enfeebles the streams and permits the waves to dam them back must likewise be the season of the highest density of the sea water. The South Atlantic equatorial currents flow west-

ward from near the coast of Africa and split on cape Saint Roque. In the season of drouths the surface density must be considerably increased, especially near the land and the shallow continental shelf.

Attention is called to the absence of reefs between Bahia and the mouth of Rio São Francisco. This is attributed to the influence of the large body of fresh water discharged by the São Francisco. The reefs begin a short way north of the mouth of that stream, but the currents set southward and shoreward along this part of the coast. This permits the formation of reefs north and prevents it south of the stream.

CALCAREOUS SANDS

One more factor is this: The ocean alongside is warm and teems with marine tropical life. There are many coral reefs along the coast, and everywhere are shell-bearing mollusca, ichinoderms, crinoids, crustacea, worms, corals, calcareous algae, and other lime-secreting organisms. All of these organisms contribute abundantly to the beach sands.

THE COURSE OF EVENTS

With this data in hand, we may now observe the course of events on the coast under consideration. We have an old coastline with long, nearly straight, sandy beaches. The sands are rather coarse and are commonly mixed with fragments of calcareous skeletons of the animals and plants living in the ocean. Across old embayments the sands have been thrown back landward by the waves until in many places the weak drainage is partly or entirely shut off from the ocean by banks of sand. In and about the pools, lakes, or sluggish streams thus formed, abundant aquatic and semi-aquatic plants live and die. The fresh water is thus rendered acid by the presence of large quantities of carbon dioxide produced by organic decomposition. The acid water on the land side percolating through the embankment of sand at low tide attacks the calcareous matter in the sand and passes seaward with it in solution, but as it comes in contact with the dense sea-water on its way through the sand, the lime carbonate in solution is deposited in the interstices between the sand grains. In time the interstices are completely filled, and the sand bank is hardened and so solidified that the water can no longer soak through it. The process must then of a necessity come to a halt at that particular place, and percolating waters must either seek other loose sands or they must be turned aside by the now hardened and impervious spit and compelled to flow through the open channels. The percolation of fresh and salt waters would be very much the same whether the fresh waters to landward were completely damned in or were separated from the sea by a long spit, around which it had to flow at ebb tide. Thus the streams by the help of the sea build of

SAND SPIT AT TRAIÇÃO ENCROACHED ON BY THE SEA

There is a lake to the left of the spit

ETCHED SURFACE OF A STONE REEF

the loose sands a rock barrier against the onslaught of the sea itself. It is now clear why the hard rock occurs only at the top of the reef and why it is not thicker. It is because the seaward percolation of the fresh water is not likely to occur at a depth exceeding or much exceeding the depth of the stream behind the sand spit, and it seems probable for this reason that the hard top stratum varies somewhat in thickness and in width, the stronger streams having the thicker and broader reefs in front of them and the weaker ones having the thinner and narrower reefs.

COAST CHANGES

A coastline is never quite at a standstill. The shore currents average a little different one year from those of another. Coral reefs and the average of the winds during a given season help on some of these changes. The result is that there is always a tendency to cut a little more at one point and to fill a little more at another. In the case of such a spit as has been described these changes may in time either bury it under new accumulations of sand or its unconsolidated edges may be undermined on either side or on both sides until its edges break down. If the hardening process has not proceeded far enough at the time of encroachment the entire structure may be broken up. It is evident that many reefs have thus been attacked by the sea and partly destroyed before the consolidation was completed. Broken lines of fragments mark the position of many such reefs along the Brazilian coast. Even the strongest of the reefs are undermined here and there, so that the tides ebb and flow beneath them, or natural arches so formed have been broken down, and their angular fragments fill the gaps. Some reefs are buried or partly buried beneath loose sands. At Rio Formoso the reef passes through a sandy cape and sticks out on both sides of it. Several reefs are buried at one end and exposed at the other, while still others are exposed their entire length.

PROTECTIVE AGENTS

But while some reefs are broken up by the surf many others have resisted for hundreds of years, perhaps for thousands, without showing, during historic times at least, any marked signs of change. When a reef is partly undermined, especially on the seaward side, the fragments that break off fall with their outer margins considerably lower than the inner margins. These pieces, on sinking to the bottom, so lie as to afford protection to the rest of the reef. Waves striking these flat blocks glide up their sloping surfaces and lose their force before hitting the main reef.

Another important factor in the preservation of the reefs is organic life. The seaward faces of the reefs are everywhere covered with *serpulæ*,

sponges, seaweeds, mollusks, and the many other forms of life so abundant in tropical seas. These plants and animals form a protective coating that successfully resists the most violent waves. It is true that sea urchins occasionally bore into the reef rock, but the wearing done in this way is insignificant when compared with the protection afforded by other animals and plants.

UNIFORM WIDTH OF THE REEFS

The nearly uniform width of a reef appears to be due to the ebb and the flow of the tides and the approximate uniformity of the distance the seepage water can move through the sands between tides. The ebb and the flow of the tides are repeated in the sand barriers in so far as the sand will permit ebb and flow. Some reefs are wider than others; this is probably due, in part at least, to the fact that a larger estuary has to discharge more water in a given time than a small one. There is therefore more head and more hydrostatic pressure within the sands, so that the water flows farther in a given time when the estuary is larger. As waters flowing from the larger estuaries must move faster, channels having the same width must have a greater depth, and it follows from what has gone before that the hard strata of the reefs in front of the larger bodies will also be thicker.

CAUSE OF THE STRAIGHTNESS OF THE REEFS

The straightness of the reef has never been satisfactorily explained, for there are few beaches or spits on this part of the Brazilian coast as long and straight as the reefs. This straightness is thought to be due to their having been solidified in the early part of their history as spits in front of estuaries, at the time when the spits were narrow and approximately uniform in width. It is believed, however, that some of the reefs are more nearly straight than were the beaches and spits from which they were found. This will appear if we imagine a long beach with a few gentle curves in it and behind it a stream or estuary approximately parallel to the beach, but somewhat more crooked. The waters from both sides of such a spit will meet along a line equidistant from the two water margins, and this line will be more nearly straight than the crooked stream behind or the curved beach in front. If the beach in such a case were straight the reef would be slightly crooked.

STONE REEF MAKING STILL IN PROGRESS

The process of stone reef formation is believed to be still in operation. The new reefs, or perhaps it would be better to say the conditions favorable to forming new reefs, are now to the landward of the old ones. At

SANDSTONE REEF ROCK BURROWED BY SEA URCHINS

Traição, for example, the conditions favor the formation of a new reef behind or landward of the old one where the waters from Lagôa de Sinimbu percolate through the sand neck that separates the lake from Traição bay.

At other places the new reef may be outside or seaward of the old one, but in these places the old reef is invisible, being buried beneath the later accumulations of sand. In the city of Pernambuco one hears of rock like that of the stone reef having been struck in digging wells, nearly or quite a mile landward of the present reef. If these are buried reefs they are considerably older than the one now in front of the city.

SIMILAR REEFS OUTSIDE OF BRAZIL

It was stated at the outset that these stone reefs were unique or nearly so. Nowhere have I either seen or been able to learn of such phenomena save at a few places on the coast of Asia Minor in the Mediterranean sea. From the descriptions, the reefs at Jaffa appear to be one of the best of those of the Mediterranean. The climatic conditions and the density of the sea water lead one to expect similar reefs along the shores of the Red sea, but thus far it has not been possible to ascertain whether such reefs exist there.

In southern California the climatic conditions are favorable on the side of the land. Sands have been thrown back across the mouths of the streams until many of them are completely closed nearly the year round by a beautiful series of sand embankments. The water of the ocean alongside, however, is not so dense as that of the northeast coast of Brazil, nor is there a tropical climate with its rank vegetation; but as far as can be seen these are the only elements lacking for the formation on that coast of lithified spits or reefs of sandstone. On the coast of Brazil the reefs are formed under a remarkable combination of geographic forms and climatic conditions on the land and on the sea—a beautiful illustration of the nice balancing of the forces of nature.

LITERATURE OF THE STONE REEFS

A great many people have had something to say about the reef at Pernambuco, but most of the references to it are simply of the nature of exclamations at its appearance and commercial importance. Most writers state that it is a coral reef, probably getting their information on this subject from the officers of the vessels on which they chance to be traveling, and the officers in turn taking it from Findlay's "Sailing directory for the South Atlantic ocean." It is certainly remarkable that the book mentioned—a standard work for sailing masters—down to the edition issued in 1898 states that the Pernambuco reef is coral.*

* Gabriel Soares de Souza first pointed out in 1851 that 317 years ago this reef was sandstone. This was satisfactorily confirmed by Von Olfers in 1832, by Charles Darwin in 1841, and by later writers.

The writings of early travelers on this subject have at least this value, they show that there have been no marked changes in the elevation or appearance of the reefs during the last 250 years or more. Only four or five persons have written short articles of value upon the geology of the Pernambuco reef; these are Darwin, Hartt, Rathbun, and Hawkshaw, and perhaps Liais. With the exception of the two reefs south of Bahia, described by Hartt, little was known of the other stone reefs prior to the personal examinations made by the present writer.

The theories of the origin of the reefs put forward by these authors are all more or less correct so far as they go, but none of them take into consideration the fundamentally important factors in the case, namely, (1) the age and submarine topography of the coastline; (2) the concentration of the rainfall and periodicity of the streams; (3) the influence of a tropical climate; (4) the aridity of the interior; (5) the density of the sea water; and none of them account satisfactorily for the straightness, uniform width, or the shallowness of the lithified portions of the reefs or for their peculiar and restricted geographic distribution.

COMMERCIAL IMPORTANCE OF THE REEFS

Inasmuch as the northeast coast of Brazil is without large bays, excepting that of Bahia, these stone reefs have played an important part in the commerce of northern Brazil. They form small harbors, behind which the little cities have grown up, or where the coasting vessels load and unload, or take refuge during stormy weather. The largest city built behind a reef is Pernambuco, and that is a city of 190,000 inhabitants. The rock of the reef was formerly extensively quarried for building purposes. Nearly all of the old dwelling houses, stores, churches, monasteries, fortifications, and occasionally the sidewalks of the cities along the coast are made of stones taken from the reefs. Of late years, however, the Brazilian government, realizing the danger of injury to the ports, has wisely prohibited the quarrying of the reef rocks.

ANTIQUITY OF THE ARID CLIMATE

Since Cretaceous times there have been important geographical changes in the Amazon Valley region, but about the northeast corner of Brazil there have been no such changes. It is highly probable, therefore, that the fatal drouths common in Ceará and the adjoining states of Brazil have been characteristic of that region since Cretaceous times, and they must continue to occur as long as the present geographic conditions remain. It follows also that reefs like the existing stone reefs have characterized this coast certainly as far back in the history of the continent as Eocene times and probably somewhat earlier.

PERNAMBUCO REEF

As seen from the north end. A brick wall which has been built along the reef is in the foreground