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ART. XXX.—*Reef Formations of the Northeast Coast of Brazil*; by GERALD A. WARING. With Plate IX.*

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LOCATION AND CHARACTER OF THE REGION.

LYING wholly within the tropic zone, northeastern Brazil forms the shoulder of the South American continent. To the northwest is the Amazon region, noted for its abundant rains and tropic vegetation. To the south also the country is well supplied with water; but the region between about 3 and 15 degrees S. lat. is arid and is subject to periods of great drought. Few rivers drain this area, and except for a narrow belt along the coast, water is scarce during the greater part of the year. All of this coastal extent is low. For many miles the shore is bordered by sand dunes, which extend back a few miles to a gently rising plain, covered with a stunted forest of tall brush and cactus, and interrupted here and there by small isolated peaks and mountains. There are few settlements other than fishing villages along this barren stretch of coast. Nearly all the streams that enter the ocean discharge water only during

* The writer is indebted to Dr. J. C. Branner for encouragement in the preparation of this article.

periods of storm, and are hence of uncertain flow; for as is true in other arid regions, the rainfall of northeastern Brazil is very irregular in amount and distribution.

CALCAREOUS SANDSTONE.

REEFS. *General features.*

At certain places along this coast there are sandstone reefs whose character and appearance is considered by scientists and others who have seen them to be almost unique. The only other known occurrences of a similar formation appear to be at a few places along the eastern shore of the Mediterranean and on the borders of the Red Sea, and little information is available concerning the reefs of these localities. The best known reef on the Brazilian coast is that which protects and in fact forms the harbor of Pernambuco, in about 8 degrees south latitude. This reef has been described or mentioned by numerous writers. In 1836 Charles Darwin in writing of it said that "at first sight it is difficult to credit that it is the work of nature and not of art."*

Dr. J. C. Branner, President of Stanford University and head of its geological department, who has worked on the geology of Brazil for many years, has published an exhaustive study of the reefs.† The principal features of the reef have also been summarized by him in a later paper,‡ and may be stated as follows:

The reefs are long, narrow, and nearly straight, and are situated in most instances near the mouths of streams and nearly parallel to the present beach. At some places where reefs have been formed, the reef is not connected with the land; in other places one end is exposed on the beach or is buried beneath the sands, while in still others the reef lies as a whole along the present beach. The axis of each reef is practically horizontal and lies at about high-tide level. Its top, however, slopes gently seaward and in section the material also exhibits bedding planes that dip at low angles toward the sea. While the better-developed reefs are as a rule nearly continuous, in many places they are cracked, broken and undermined by the surf, and many of the smaller reefs have been greatly broken up by this means. The lithified material is only ten or fifteen

* Journal of Researches into the Geology and Natural History of the various countries visited by H. M. S. Beagle . . . from 1832 to 1836. London, 1839, p. 593.

† The Stone Reefs of Brazil, their geologic and geographic relations, with a chapter on the coral reefs, Bull. Mus. Comp. Zoology, vol. xlv, Geol. Series vii, Cambridge, 1904.

‡ Stone Reefs on the Northeast Coast of Brazil, Bull. Geol. Soc. Am., vol. xvi, pp. 1-12, Feb., 1905.

feet thick at most, and is underlain by the usual coastal sands and clays. The outer edge of a reef is in many places nearly vertical, due to the breaking off of masses which now lie beside it in inclined positions and partly protect the exposed face from the force of the surf. The inner face is commonly broken much less, but its edge is irregularly etched. In many places the surface of the reef is also deeply etched into fantastic points and pinnacles, and contains shallow pools; but ordinarily it is fairly smooth and is partly covered by organic growths, which are more abundant near the seaward edge.

The material is a sandstone that contains quartz grains, with occasional beds of pebbles, a little mica, and shells and other organic remains in varying amounts, all being firmly cemented together by lime carbonate. The material is mainly so hard that it rings under the hammer and fractures across the quartz grains and pebbles; but in some places it is relatively soft. The shells appear to be those of kinds at present living in the adjacent water, and the other constituents of the rock are those of the present beaches.

Mode of formation.

Difference in hardness seems to be the only important feature that distinguishes the material of the reefs from that of the beaches. The conclusion, therefore, is that the reefs are beaches or sand spits lithified in place. This origin of the reefs and their mode of formation was worked out by Dr. Branner after a detailed study of the various reefs south of the port of Rio Grande do Norte. The various phases of the problem are treated fully in his publication on the subject,* and his conclusions can only be summarized here. The main features brought out by his study are as follows:

The reefs are in reality hardened beaches or spits, that have been encroached upon from both sides by the sea. Their straightness implies that the original beaches or spits were straight, and seems to be well accounted for by the usual process of straightening of an irregular shore line by the cutting down of headlands and the filling of embayments. The natural features of the coast, notably the lack of good harbors, the presence of low headlands which protect shallow bays, and of stream mouths partially or wholly closed by sand bars, are some of the factors which point to this conclusion. The reefs are therefore believed to be portions of mature, nearly straight, beach lines. The lime carbonate that hardened these beaches appears most probably to have been dissolved from calcareous beach sands by streams entering behind them, and to have been redeposited along the zone of contact with the salt water as the fresh water percolated seaward through these

* Bull. Mus. Comp. Zool., Geology, vii, 1904.

sands. The solvent action of the fresh water for lime carbonate was increased by organic acids derived from decaying vegetation, and the redeposition of the lime was mainly due to the inability of the increasingly salty water to hold it longer in solution.

The conditions necessary to such an hypothesis are all present along the coast where the reefs exist. The annual rainfall is so irregular in amount and distribution that the streams carry little or no water during a large part of the year and their outlets become partially or wholly closed by drifting sand. Vegetation, especially the mangrove and the water hyacinth, grow luxuriantly in the tidal portions behind many of these closed river mouths, and the decay of dead leaves and other fragments of vegetation doubtless charges the water with organic acids. This water gradually escapes to the sea by percolation through the sands that block the way, and at times by flowing long distances around the ends of sand bars. The sand contains many fragments of shells, coral and other calcareous animal remains, so that it may easily yield the requisite lime carbonate for the cementing process. Studies made by the Challenger expedition have shown that the ocean water is unusually dense in an area that borders the Brazilian coast approximately along the portion where the reefs are found.* This greater density of the ocean water tends to cause more rapid deposition of the lime, due to the inability of the dense water to readily hold it in solution, and is believed to be another important factor which caused the formation of the reefs.

Reefs north of Rio Grande do Norte.

The structure and the mode of formation of the reefs have been thoroughly discussed by Dr. Branner, and the present paper is not written in an attempt to add anything to his conclusions in those respects. Dr. Branner's studies, however, were confined to the reefs at and south of Rio Grande do Norte, and as in February, 1913, the writer traversed a portion of the coast north of that port, the following notes concerning the region are presented. These notes are intended mainly to record the calcareous sandstone reefs noted, but observations on the other kinds of reefs seen are also given.

The harbor at Rio Grande do Norte is formed by an especially well-developed reef, descriptions of which have been published.† Since no reefs equalling it in development were seen farther north, the illustration (fig. 1) is here presented, for

* Challenger Reports, Physics and Chemistry, vol. i.

† The stone reef at the mouth of the Rio Grande do Norte, by Dr. J. C. Branner and C. E. Gilman, *American Geologist*, Dec., 1899, pp. 342-344. The stone reefs of Brazil, by J. C. Branner, *Bull. Mus. Comp. Zool., Geol. Series vii*, pp. 35-39, 1904.

together with the representation of this reef on Plate IX, it well brings out two characteristics of the better-developed reefs, i. e., their relations to present beach lines, and their positions relative to stream mouths.

North of Rio Grande do Norte the first typical calcareous sandstone was found at the mouth of Rio Ceará-Mirim, where a double reef of the material is exposed at low tide (fig. 2). The two reefs are parallel, about 100 yards apart and curve

FIG. 1.

FIG. 1. Reef at mouth of Rio Grande do Norte.

gently with the present beach. The inner reef is the shorter, and some parts of it project only a few inches above the sand of the flat beach that is laid bare by the receding tide. Its rock is brighter in color and softer than the usual pale yellow to gray material, but otherwise it has the appearance of the typical reef rock. It is the most probable example noted of a recently formed deposit. A tidal lagoon, fringed with mangrove, is formed behind a bar which separates it from the beach. The outer reef consists of the usual hard, gray material. About 450 yards beyond the place where its northern end disappears beneath the water, another stretch of the same material, probably its continuation, appears close to the shore and extends around a gently curving beach, gradually receding and disappearing beyond the surf.

Proceeding northward, the reef rock next appears as a few scattered blocks in the surf about one mile south of a low point near the village of Pitangy. About 500 yards beyond these blocks, the material is exposed as a continuous reef, with bed-

ding planes dipping 3 degrees seaward, and lies partly as a barrier, partly along the beach, suggesting that a little bay has been washed out behind it as shown in fig. 3*a*. Its northern end is buried in the beach.

Near the village of Jacumá, a few miles northward, a small reef of the rock extends from the beach into the surf. At a low point beyond, a similar reef, which first appears in the water, extends in a straight line in such a direction that it

FIG. 2.

FIG. 2. Bird's-eye view of reef at mouth of Rio Ceará-Mirim.

passes for some distance along the beach and then disappears in the water beyond the point (fig. 3*b*).

No signs of a calcareous sandstone reef were found near the mouth of Rio Maxaranguape, $4\frac{1}{2}$ miles farther north, though this stream has a small perennial flow and contains much mangrove in its lower portion. The South Atlantic equatorial current flows westward from Africa and divides at Cabo São Roque, part going northward and part southward along the Brazilian coast. The southward-flowing current may have been of influence in preventing the formation of a calcareous sandstone reef at the mouth of the Maxaranguape, which is only one mile south of the cape. The position of the Maxaranguape, near a projecting part of the coast, also appears not to be favorable to the formation of a calcareous reef, for nearly all of the prominent reefs described by Dr. Branner extend along inward-curving beaches, northward from river mouths.*

* This characteristic is well brought out by the several detailed maps of reefs accompanying Dr. Branner's report (Bull. Mus. Comp. Zool., vii, 1904). The northward discharge of river mouths, produced by drifting sand, is mentioned by Olaf Pitt Jenkins, *Geology of the Region about Natal, Rio Grande do Norte, Brazil*, Proc. Am. Phil. Soc., vol. lli, No. 211, p. 4, Sept.-Oct., 1913.

The first observed occurrence of the typical reef rock north of Jacumá is near the mouth of Rio do Fogo, 2½ miles away in a direct line. About one-half mile north of the mouth of this small stream a reef of the usual material appears off-shore and trends N. 20° W. (mag.) while the beach trends N. 6° W. Hence after a short distance the reef attains the beach, at a

FIG. 3.

FIG. 3. Positions of calcareous sandstone reefs relative to the present beach: *a*, near Pitangy; *b*, near Jacumá; *c*, near Rio do Fogo; *d*, north-west of Ponta Reducto.

place where the beach turns a little more to the west (fig. 3*c*). At this place the reef also turns, but at an angle instead of in the nearly universal gentle curve, and bearing N. 16° W., extends for about six-tenths of a mile in a straight line nearly parallel with the beach, finally disappearing in the surf. A reef which is exposed for a width of 200 or 300 yards at low tide and extends for some distance southward from the mouth of Rio do Fogo, appears to consist of quartz grains cemented

by calcareous material. It is pale yellow in color and is possibly an example of recent cementation, though it does not closely resemble the more typical reef north of the stream's mouth. Rio do Fogo has only a slight flow during the dry season, and at present does not support a growth of mangrove; but a bed of black clay exposed in the beach near its mouth resembles the material of mangrove swamps. The relative positions of the stream mouth, the bed of clay and the typical reef to the north suggest that the stream formerly entered the ocean somewhat farther north, while the wide reef of calcareous sandstone to the south suggests that more recently its water may have sought the ocean in that direction. Sand dunes now crowd the stream channel back from the shore and absorb most of its water, which reappears in part nearer the beach in the form of small springs.

Two miles north of Rio do Fogo, large slabs of the typical rock are exposed at low tide, lying upon iron-cemented sands at a small point near the village of Peroaba, while two reef fragments 200 or 300 yards long are seen respectively $1\frac{1}{2}$ and $1\frac{1}{4}$ miles northward, at about half-tide level, partly buried in the beach.

Continuing along the beach, a few other masses of the rock are to be seen in several places firmly cemented to red, iron-cemented sandstone that forms fringe reefs, but the next typical reef is met near Ponta Reducto, a number of miles farther to the northwest. The rock here appears abruptly in the surf and owing to the slight curve of the shore soon reaches the beach. Thence the reef rock extends along the beach, in large part as broken slabs piled up beyond ordinary high-tide level, for a distance of $1\frac{1}{4}$ miles, to the southeastern end of the point, where at low tide it is seen to be firmly cemented to the red sandstone at the base of the bluff. In the cove beyond the point a few slabs of the rock appear, and again at a wide curve of the low beach $1\frac{1}{4}$ miles farther northwest. Near the next curve of the beach, one mile beyond, the material appears on the shore above high tide, extends along the upper border of the beach as a succession of broken slabs, and disappears beneath a small sandy point. It reappears on the other side of this point, however, and continuing partly in the water but mainly along the upper part of the beach, it finally disappears landward (fig. 3*d*). The total length of this reef, including the portion hidden by the sandy point, is fully 3 miles.

The calcareous sandstone is next seen 5 miles westward, at a place called Queimadas. Here from an inward curve of the beach line, a narrow reef extends into the water for perhaps 300 yards. It appears for a few yards on shore as a confusion

of broken slabs, while bands of shells and disintegrated fragments of the rock in the sand back from the beach mark the buried eastward continuation of the reef. Westward also, beyond the extremity of the reef, shells and disintegrated fragments of reef rock may be found at a distance of 50 to 100 yards from the present beach, for a couple of miles along the undulating sandy plain.

About $3\frac{1}{4}$ miles west of Queimadas the reef rock begins again abruptly on the beach within reach of the tide. A spring of fresh water gushes up from beneath its extremity, and 450 yards beyond this spring another rises through the beach sand at about half-tide level, probably from beneath a buried block of the reef. Thence the reef continues, principally as great loosened blocks and slabs, along the beach at half-tide to high-tide level, for $1\frac{1}{2}$ miles to the eastern end of the series of cliffs known as Tres Irmãos (Three Brothers). In the cove between the eastern two headlands and also at their bases a few blocks of the reef rock are visible at half-tide, the gray or pale yellow of the latter contrasting with the dark red sandstone of the cliffs.

A few miles west of Tres Irmãos and $1\frac{1}{2}$ miles east of Caiçara light, in the sandy plain 80 yards from the beach and approximately parallel with it, there is an exposure of disintegrated calcareous reef rock, part rust-colored, part bleached, about 5 yards wide and 50 yards long. It is perhaps the best example that was seen of an inland remnant of a reef. About one-half mile westward from this remnant the rock reappears as broken slabs half-buried in the beach, but soon becomes a continuous beach-reef, with blocks of the material piled in confusion along its landward edge. The Caiçara light post is erected on a concrete foundation built on the reef at high-tide level. A small headland that rises to a height of 20 or 25 feet just west of the light is composed of fluted and craggy, lime-cemented sandstone that resembles the calcareous reef rock, while over the sandy knolls behind the headland are scattered many shells, fragments of coral, and pieces of lime carbonate that resemble calcified brush roots. From among these knolls a low ridge of gray to rust-colored, disintegrated lime-cemented sandstone, with many loose shells lying along its course, leads westward down to a small reef that disappears in the water of a little bay. On the far side of this bay, a short distance west of the fishing village of Santa Maria, the reef again appears in the surf. The beach thence to Ponta Caiçara, a distance of $1\frac{3}{4}$ miles, is very nearly straight. The reef rock, however, after attaining the beach and following it for 550 yards, swings a short distance inland and becomes nearly buried for 100 yards. It then returns and again forms

a beach-reef for 850 yards farther (see fig. 4), and then swings landward and is lost, though its course may be traced for some distance farther by scattered and disintegrated fragments 25 to 50 yards back from the beach. The relation of the reef to the beach along this stretch is shown by figure 5. Ponta Caiçara is formed of fresh-looking, pale-yellow, very hard stone which closely resembles the reef rock. The exposure at this place has not the usual long and narrow form of the typical

FIG. 4.

FIG. 4. Lithified beach near Ponta Caiçara.

reefs, however. The material extends from the base of a large dune down to the surf, where it exposes a steep face to the beach for a few yards. The western end of the lithified mass terminates abruptly in a vertical face 6 or 8 feet high that trends straight inland and disappears beneath the drifting sand 100 yards from the beach. The dip of the material here exposed seems to be about 10 degrees to the northeast, while the beach-reef farther east dips at low angles uniformly northward, into the sea.

The reef or lithified beach that extends almost uninterruptedly from some distance east of Caiçara light to the point of the same name, appears to be the westernmost area of any considerable extent of the typical calcareous reef formation.

By reference to the general map of Plate IX it will be seen that no streams of importance drain the area between the courses of Rio Ceará-Mirim and Rio Salgado (which enters tide water at Macáu). None of the small streams that enter the ocean between these two rivers have calcareous sandstone reefs at their mouths. The reefs that are present along this

part of the coast, however, are in several places situated in suggestive relation to existing areas or lagoons or marsh land, shut off from the sea by dunes of sand. This seems to be shown near Rio do Fogo (fig. 3*c*), and also near Ponta Reducto. At the latter place the present position of lagoons, as shown by figure 6, is evidently determined by the shifting sands; and conditions might easily have been such as to cause the water to find outlet in the vicinity of the present reef.

All of the well-developed reefs noted by Dr. Branner south of and including Rio Grande do Norte are opposite the

FIG. 5.

FIG. 5. Relation of lithified beach to present beach, near Ponta Caiçara.

mouths of rivers of considerable flow. In the light of the origin of the reefs, the absence of such well-developed off-shore reefs farther north may, therefore, be safely ascribed chiefly to the absence of suitable streams for their formation; for the weak flow of fresh water seaward has apparently been able to harden masses of sand only along the beach. In some places, however, these consolidated beaches have been encroached upon by the sea, so that they now form off-shore reefs.

The apparent greater frequency of reef remnants along the shore northwest of Touros than southward from that place is perhaps due directly to the curving of the coast line in this vicinity to a more northwesterly course. This brings the beach line more nearly parallel with the direction of the prevailing wind and hence induces slight alteration of the beach line by the drifting sand. The best example of this phenomenon that was noted is in the vicinity of Ponta Caiçara, and has been already described.

OTHER OCCURRENCES OF CALCAREOUS SANDSTONE.

Although the materials of the headland near Caiçara light and of Ponta Caiçara are similar in composition to those of the well-developed reefs, they resemble hardened masses of sand rather than elongated spits, and this character is exhibited by other occurrences that were noted farther west.

The first one of these occurrences is 6 miles west of Ponta Caiçara, at Ponta Jacaré. Here the typical gray, lime-cemented sand with layers of gravel and shells is exposed for about 100 yards along the beach; but instead of forming a reef or a lithified beach, the rock extends from the base of a

FIG. 6.

FIG. 6. Region near Ponta Reducto, showing relation of lowlands to the reef.

great sand dune to the water 25 yards away, where it forms a ledge 5 or 6 feet above half-tide level and dips 8 degrees to the north, seaward. This is the westernmost exposure of the reef rock that was seen along the beach in the journey between Rio Grande do Norte and Macáu. It could not be definitely learned by inquiry whether or not rock is exposed along any part of the coast between Ponta Jacaré and Macáu; and this portion of the coast, which is low and intersected by tidal inlets, was not traversed. It is believed, however, that no reefs are present along this stretch of dunes and tidal inlets.

At a few places west of Macáu the calcareous sandstone was observed near ports that were visited on coasting steamers, the first one west of Macáu being Areia Branca. Along the ocean east of the entrance to this port the beach is bordered

from an inlet know as Barra do Upanema nearly to the Areia Branca lighthouse, a distance of $1\frac{1}{4}$ miles, by gray, lime-cemented sandstone. This is composed mainly of coarse sand and small pebbles. No shells were seen imbedded in it, though a few seams are filled with lime-cemented shells and pebbles. While it resembles the usual reef-forming material, at many places it extends from the bases of dunes for a number of yards to the surf, and therefore is not considered typical reef rock. A few fragments of the rock, more or less disintegrated, are also exposed between the dunes.

FIG. 7.

FIG. 7. Undercut cliff of lime-cemented sand near Fortinho.

Morro Thibáu is a hill which borders the shore about 6 miles northwest of Areia Branca. Part of its coastal side is bordered by a cliff 15 to 30 feet high, behind which sandy slopes rise to a maximum height of 160 feet. A number of small springs of fresh water issue along the upper border of the consolidated layer that forms the cliff. This layer is composed of gray to red-brown sand in which are occasional chalky masses the size of an egg. A reef of the same material borders the cliff, and though it does not closely resemble the typical lime-cemented reef sandstone, it appears to have a similar mode of origin and to be comparable with the small cliffs at Pontas Jacaré and Caiçara and at Caiçara light.

At Fortinho, the port of Aracaty, gray, lime-cemented sandstone underlies cliffs of red, sandy clays, partly as a shelf at about high-tide level, and partly as a low cliff which is deeply undercut at one place (see fig. 7.) The lighthouse at the

entrance to this harbor is built on low slopes of brick-red sandstone, but at the beach about a mile beyond the light there is a cliff, 15 or 20 feet high, whose material from a distance resembles the gray rock at Fortinho. Although this calcareous sandstone of the port of Aracaty does not form the typical low, narrow reefs, it does resemble the sandstone of Ponta Caiçara.*

The presence of a sandstone reef in the harbor of Fortaleza is mentioned in a report on the betterment of the port, published in 1875.† The reef described is apparently in the locality now occupied by a breakwater that was built in an unsuccessful attempt to form a quiet harbor. No evidence of a reef was seen along this wall in 1913, but small areas of iron-cemented sand and gravel along the neighboring shore indicate that the reef is of this material rather than of calcareous sandstone. At two places along the beach between Fortaleza and Ponta Mucuripe, 4 miles to the east, however, small masses of fine-grained, very firmly-cemented gray to pale-yellow beach sand were seen, partially buried at about half-tide level; while near the point, similar small masses of hard, fine-grained sandstone are firmly cemented to the red iron-sandstone in cavities and seams, where the sand has evidently been blown from the adjacent dunes by the wind. It would appear that under favorable conditions small masses of beach sand deposited on the iron-cemented sands may become firmly consolidated by calcareous material.

On the western side of the harbor of Camocim several blocks of the typical calcareous sandstone are exposed on the beach $\frac{3}{4}$ to 1 mile north of the northernmost shipping pier. Although it is situated well within the river mouth which forms the harbor, the material very closely resembles the typical reef material in texture and composition. It does not form banks or cliffs, as does the calcareous material at Fortinho. The occurrence of calcareous sandstone at Camocim is the westernmost that was seen by the writer. There is none for a distance of 8 miles farther west along the coast from this city, and though small patches may exist beyond, inquiry among the fishermen at Camocim failed to yield any information on the matter. The material was not observed at the harbors of Amaração, Tutoya and Maranhão, respectively 60, 100 and 250 miles west of Camocim.

* At several places on the beach behind the sand bar which prevents small coasting steamers from entering the harbor at Fortinho except on the highest tides, black clay, the remnant of a mangrove area, is exposed, and resembles at a short distance a low reef.

† *Melhoramento dos Portos do Brazil*, Relatorio de Sir John Hawkshaw, pp. 89-91, Rio de Janeiro, 1875.

IRON-CEMENTED SANDSTONE.

CLIFFS.

Practically the entire coast northward from Rio Grande to Norte is bordered by the red and parti-colored sands and sandy clays, probably of Tertiary age, which also border the coast for many miles southward from that place. Along perhaps the greater part of the coast to the north these colored sediments are obscured by drifting beach sands, but in many places they form cliffs which, though ordinarily less than 50 feet in height, are prominent features of the low coast line. The limestone which underlies these sediments and is exposed a few miles inland, is seen near the beach at only two localities. One locality is near Fazenda As Moças, 25 miles east of Macáu and $1\frac{1}{4}$ miles from the beach, where a flat surface of hard, gray, fossiliferous stone is exposed over an area several hundred yards in diameter, beyond the extremity of a tidal inlet. The other exposure is 8 miles farther west, in the channel of another tidal inlet, at the base of a low bluff of the colored sediments.

In several places, notably at Tres Irmãos, the sedimentary cliffs form headlands against which the surf beats, but in other places they are not prominent features on the map. In the reëntrant a few miles northwest of Cabo São Roque, cliffs of the red sediments rise from the surf to heights of 20 to 30 feet, but at the cape itself there is no cliff. Large knolls of light-colored sand, partly brush-covered, trend uniformly northwest at this place, while the beach around the cape is protected by a wide fringe reef of iron-cemented sand. The material of the coastal cliffs varies in character from place to place and in the several layers exposed in a single cliff. The various shades of yellow and red-brown due to iron prevail, but in some places the material has a mottled appearance caused by small patches of white or pale-yellow sandy clay in the mass. It seemed to the writer that the prevailing color of the cliffs north of Rio Grande do Norte is considerably darker than is that of the cliffs south of this port. It is worthy of especial note that no shales were seen at any part of the coast north of Rio Grande do Norte, though shales are found at numerous places farther south.

The cliffs northwest of Cabo São Roque expose sections approximately as shown in figure 8*a* and *b*, while a low cliff 22 miles in a direct line northwest of the cape, between the villages of Peroaba and Carnaubinha, exposes cross-bedded sands as shown in figure 8*c*. Other cliffs northward, notably those at Touros, Ponta Reducto and Tres Irmãos, do not show distinct beds, the material being consolidated as a whole with only local differences in color, hardness and texture. These

local differences induce weathering into more or less fluted columns and into caverns.*

The highest cliff along the northeast coast of Brazil is that of Ponta Mel, between Macáu and Areia Branca, the lighthouse which stands on the point being nearly 300 feet above the sea. The cliff itself forms only the upper half of the point, rising above great dunes and winrows of sand, as is

FIG. 8.

FIG. 8. Cliff sections: *a*, $1\frac{1}{2}$ miles northwest of Cabo São Roque; *b*, $2\frac{3}{4}$ miles northwest of Cabo São Roque; *c*, $2\frac{1}{2}$ miles northwest of Peroaba.

shown in figure 9. The section exposed is approximately as in figure 10. Ponta Redonda, a few miles farther west, is only 25 or 30 feet high. It is of mottled sandstone, mainly purple in color, but with markings of lemon-yellow and of yellow bordered by white. Caverns have been formed in the material,

*The cliffs at these places are similar to those near Natal, which have been described by Olaf Pitt Jenkins (Geology of the region about Natal, Rio Grande do Norte, Brazil; Proc. Am. Phil. Soc., vol. lii, No. 211, pp. 23-25, Sept.-Oct., 1913).

and the resulting protected surfaces are studded with subangular quartz pebbles up to an inch in size. Fallen blocks form a breakwater along the front of the cliff (fig. 11). These blocks contain numerous seams which are filled with pebbles and shells cemented together with lime carbonate, while a few seams $\frac{1}{2}$ to 4 inches wide are filled with small, silvery-white mollusk shells closely matted together as if they had grown thus.

On the slopes behind the cliffs at Tres Irmãos the surface is dotted with fragments of calcified brush roots and branches.

FIG. 9.

FIG. 9. Ponta Mel as seen from a coasting steamer.

Some of the fragments attain the size of a man's arm, and many can hardly be distinguished by sight alone from the associated fragments of wood. This form of petrification appears to have been effected while the bushes were covered by dune sand, which has now drifted past and left them exposed again. Some calcareous matter has also penetrated downward into the sandstone of the cliff and is seen as lighter-colored masses. In the dune areas near Ponta Reducto and Ponta Mel similar calcified fragments were seen, less well-developed, and in a wide expanse of dun-colored dunes and sand knolls about halfway between Ponta Jacaré and Macáu, beyond the inland reach of the tidal inlets, considerable areas are dotted by whitened and sand-worn conch shells and by bone-white fragments of lime carbonate that resemble roots and twigs.

REEFS.

In practically every place where cliffs have been formed along the coast, a fringe-reef of the same material extends out into the water. In a few places there is very little difference

FIG. 10.

FIG. 10. Section of cliff at Ponta Mel.

Feet.	
15 +	Red, sandy gravel.
11 1/2	Rusty quartz gravel.
13	Red, sandy gravel.
3	Rusty quartz gravel.
3	Coarse, mottled sandstone.
11 1/2	Purple sandstone.
16	Red, gravelly sandstone.
13	Reddish-purple sandstone.
21 1/2	"Patterned sandstone."
21 1/2	Reddish-purple sandstone.
11 1/2	"Patterned sandstone."
5	Reddish-purple sandstone.
6	"Patterned sandstone."
10	Reddish-purple sandstone.
6	"Patterned sandstone."
10	Reddish-purple sandstone.
20	Purple sandstone.
160 ±	Probably brick-red and mottled sandstone, but obscured by dune sand. The lower slopes have many fragments of shells and of lime carbonate. A reef of mottled sandstone is exposed at low tide.
289 1/2	

The "Patterned sandstone" differs from the usual mottled sandstone in having a mottling that somewhat resembles the crystal pattern on a polished surface of meteoric iron. The colors are lemon-yellow, white and pink, in a ground of bluish-purple. It is softer than the reddish-purple sandstone.

in texture and hardness between the material of the reefs and that of the cliffs; but in most places the reef-forming portion is harder, heavier and more nearly rust-color, and it appears that concentration of the iron has taken place in those places subjected to the action of the sea-water. In many places where the red sandstone is not in evidence as cliffs, reefs of the material are exposed along the shore, and probably the greater number of the reefs along the northeast coast of Brazil are of

FIG. 11.

FIG. 11. Blocks of iron-cemented sandstone at Ponta Redonda.

this material. The approximate extent of these reefs along the portion of the coast under consideration is indicated on the general map of Pl. IX. They are also present farther to the north and to the south. In many places the material is an iron-cemented gravel, rather than a sandstone; but it appears to be made up of fragments of the coastal sandstone, recemented together. The wide distribution of the iron-cemented reef-forming material is notable. It is exposed at the base of a cliff of light-colored sediments on the north side of the harbor of Maranhão, 250 miles west of Camocim, and extends far toward the channel of the harbor at low tide. At the immediate base of the cliff there are boulders in which the iron is heavily concentrated. Even along the Amazon River the concentration of the iron at or about tide level seems to have taken place in the red sediments, as is shown notably at the base of a bluff on the north bank, 700 miles above the river's mouth, between the villages of Parintins and Itacoatiara.

In a few places, notably at Touros, Ponta Reducto and Tres Irmãos, the layer or zone that has been hardened by the concentration of the iron rises a number of feet above sea level, but in most places the hardened layer is only a little above high tide limit, as is shown in a reef near São José. The prevalence of the hardened material and its presence only at about sea level suggest that the concentration of the iron in the iron-cemented sandstone has taken place in similar manner to that of the lime carbonate in the calcareous sandstone reefs. In the case of the latter Dr. Branner has shown* that the lime is deposited along the zone of contact of the fresh with the salt water. Similarly, when fresh water that has percolated down-

FIG. 12.

FIG. 12. Iron-cemented sandstone reef near São José.

ward through the iron-impregnated sediments and dissolved a slight amount of the iron comes in contact with the salt water of the ocean, it probably drops its iron, which thus becomes concentrated at about sea level. It seems that some such action must have taken place in order to produce the extensive fringe-reefs of the material that are in evidence at places where landward the sediments are obscured by drifting sand. The fact that such concentration and cementing is still going on at about sea level appears to be shown at numerous reefs which are dotted with fragments of sandstone, all firmly cemented to the reef surface.†

At a few places a layer that has been hardened by concentration of the iron is also found in the red sediments some distance inland from the beach. Ponta Morego, 2 miles southeast of the center of Natal (Rio Grande do Norte), is of iron-cemented sandstone in which the iron has been concentrated, and within

* The stone reefs of Brazil, *Bull. Mus. Comp. Zool., Geol.* vii, p. 193, 1904.

† This feature has been mentioned by Jenkins (*Geology of the region about Natal*), *Proc. Am. Phil. Soc.*, Sept.-Oct., 1913, p. 24.

the city itself irregular masses of the material several feet thick are exposed in low bluffs near the harbor, a short distance above tide level. The material was also encountered at approximately sea level in nearly every one of about 50 wells that had been drilled in the upper part of the city prior to 1913; but so far as could be determined by examination of the well records, the material is thinnest in the wells most distant from the harbor. It was not encountered in wells sunk in the lower part of the city (below the exposures in the bluffs); neither was it met in a well sunk in the lowland across the harbor channel,* nor in excavations made to depths of more than 50 feet in the channel itself for the piers of a railroad bridge. At the farther side of a wide flat across the harbor from Natal the hard, iron-cemented material is exposed near the base of a red sandstone bluff, but a bed which appears to be a continuation of the material exposed in the bluff is seen to thin out landward, along a railroad cut which ascends the slope. About 20 miles south of Natal, in bluffs bordering a tidal inlet or lagoon, broken masses of the iron-cemented sandstone show the presence of a layer 2 or 3 feet thick, but on tracing it inland by occasional fragments along a railroad cut, their decreasing size indicates that the hardened layer rapidly thins.

A few miles east of Fortaleza much indurated iron-sandstone is exposed on the shore as low bluffs and fringe reefs. About $1\frac{1}{4}$ miles inland the material was encountered in a well at a depth of 6 feet, which well was continued to a depth of 16 feet without passing through it. This well is 300 yards from the margin of a tidal lagoon. The material is also exposed in a pit 100 yards nearer the lagoon, at a depth of only 2 feet, and although it was not found along the border of the lagoon, springs of fresh water issue a few feet above the margin, probably from about the upper surface of the impervious material.

The eastern side of the harbor of Camocim is bordered by large sand dunes that are continually encroaching on the water and effectually cover the underlying formation. To the west, however, the immediate coast is low, though backed by dunes, and is bordered for several miles by a nearly continuous reef of iron-cemented sandstone. Springs of fresh water issue at numerous places along the beach below high-tide level. There is a wide fringe reef of the sandstone along the beach near the Camocim lighthouse, but at the light, which is 175 yards back from the beach, good water is obtained at approximately sea level in a shallow well in which rock was not encountered. The well, however, is possibly not deep enough to determine

* A record of the materials encountered in this well is given in Jenkins' paper, *Proc. Am. Phil. Soc.*, No. 211, pp. 28-29, 1904.

whether or not the iron-cemented rock exists at this place. Two wells that were drilled to depths of more than 50 feet at Camocim, 2 or 3 miles from the ocean and several hundred yards from the harbor, did not encounter iron-cemented material.

Although the evidence here advanced is slight, it is believed by the writer that the iron-cemented material which forms most of the fringe reefs and probably some of the off-shore reefs as well, is not a definite bed in the Tertiary coastal sediments, but is a hardened phase in them produced by the concentration of the iron; and that this concentration and hardening is limited to approximately sea level and extends only a short distance back from the shore.

CORAL REEFS.

In addition to living coral reefs which exist off-shore between Rio Grande do Norte and Macáu, a few reefs that now join the land have their upper portions, at least, composed of dead coral material. These reefs are here noted chiefly to extend northward the records of Dr. Branner on the presence of such reefs and the evidence that they furnish of a comparatively recent slight elevation of the coast. The corals can have grown only when they were under the ocean water most of the time, and the presence at some places of their remains entirely out of water shows that the coast at those places has been uplifted a sufficient amount to bring the corals into their present position relative to sea level.

An organic formation that is not coral but which seems worthy of mention is a soft stone formed by worms that cement together grains of beach sand. This material was observed at only two places: on blocks of iron sandstone on the beach at Ponta Morcego, and to lesser extent on rocks at Ponta Genipabú a few miles northward. Dr. Branner mentions having observed the material farther south, it being especially well developed near Bahia Formosa, 45 miles south of Ponta Morcego.

The outer portion of the fringe reef at Ponta Genipabú is overlain by flat-topped masses that are covered to a thickness of several inches with brown, calcareous tubes and the remains of other forms of sea life. It is the only reef where such material was seen. The main part of the reef is, however, of the common iron-cemented sandstone.

About three miles westward from the village of Cajueira a bluff which rises at the upper edge of the beach to a height of 8 or 10 feet exposes for several yards a cream-colored to rust-colored rock that apparently consists of quartz grains cemented

together by the remains of coralline animals. A smaller amount of this same material was noted on the surface of a wide reef of iron-cemented sandstone about two miles farther northwest, within the reach of high tide. Similar material forms a reef near Marcas, 16 miles farther west, but at this latter place it is more firmly consolidated.

Ponta Santo Christo is bordered by a low reef of compact, pale-yellow coral that joins the beach and is uncovered for a width of several hundred yards at low tide. No iron-cemented sandstone was seen at the point, but within the cove westward from it the usual sandstone is exposed.

The point near the little settlement of Marcas is fringed by a wide reef of hard, pale-yellow to cream-colored rock that appears to be of quartz grains and pebbles cemented by coralline remains. No other rock was noted beneath it. At low tide the material is uncovered for fully half a mile westward from the beach, in a small cove or bay, and stands about two feet above the water. Beyond the cove the reef reappears along the shore for several hundred yards and extends 200 or 300 yards seaward at low tide. This western portion consists of compact pale-yellow coral containing a few fossil shells* and a very little sand. It is the westernmost coral formation that was seen along the coast.

SUMMARY.

In addition to the observations on various reefs north of Rio Grande do Norte which are given in the preceding pages, an attempt has also been made to incorporate those points of wider interest which were noted concerning the geologic features exhibited. These may be summarized as follows:

1. Off-shore reefs of calcareous sandstone are less well-developed north of Rio Grande do Norte than they are south of that place. The principal cause for this absence of prominent calcareous reefs in the northern region is believed to be absence of streams of considerable size entering the ocean. Beach reefs or lithified beaches, however, are more common northward, for the fresh water that slowly percolates from the land to the shore encounters the salt water at the beach. The tendency has therefore been for it to deposit its lime in the beach sands, and this action has taken place on a considerable scale where lithified beaches have been formed.

2. Beyond where the coast swings from a northerly to a westerly course, inland remnants of reefs and lithified beaches become more common, as the prevailing westerly wind there

* The two best-preserved shells were kindly identified by Dr. W. H. Dall as *Leptothyra albida* Watson, and *Botula cinnamomea* Lamarck, both being of species living at present in the Antilles.

becomes more effective in making slight alterations in the beach line, and in some places has built out the beach beyond what its position was at the time of its lithification.

3. Ponta Caiçara marks the western limit of the typical reefs or lithified beaches, but at a number of localities farther west similar hardening has taken place.

4. The iron-cemented Tertiary sands and clays border the coast for practically the entire distance between Rio Grande do Norte and Camocim. (They also extend along the coast for many miles beyond these points.) At a number of places the sediments form relatively low but prominent cliffs, but for long stretches they are obscured by beach sands. The limestone that underlies the sandy sediments was observed in only two places, near each other. Shales were not seen at all.

5. Dead coral reefs attached to the land were seen at a few places, the westernmost being a short distance beyond Marcos. They furnish unquestionable evidence of slight elevation of this portion of the coast.

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