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THE TORTUGAS AND FLORIDA REEFS.

BY

ALEXANDER AGASSIZ.

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MEMOIRS.

I.

Explorations of the Surface Fauna of the Gulf Stream, under the Auspices of the United States Coast Survey. — II.[1] *The Tortugas and Florida Reefs.*

By ALEXANDER AGASSIZ.

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Presented November 15, 1882.

All naturalists who have visited the Florida Reefs have felt the difficulty of applying Darwin's theory of reef formation to the peculiar conditions existing along the Straits of Florida. Agassiz, Le Conte, and E. B. Hunt have each in succession attempted to explain, from a different standpoint, the mode of formation of the Florida Reefs. Agassiz stated, and his statement was afterward confirmed by Le Conte, that the Florida Reefs had a distinctive character, and could not be explained by subsidence, to which cause Darwin had ascribed the formation of barrier reefs in general. The report of Agassiz on this subject, presented to Professor Bache in 1851, has been republished in full in the Memoirs of the Museum of Comparative Zoölogy. In this report he has shown, not only that the southern extremity of Florida is of comparatively recent growth, but that the causes by which it has for the greater part been built up are still going on, and that we have a specimen or sample as it were of the past action in the mode of growth of the present reef, keys, and mud flats. He showed that the whole southern portion of Florida is built of concentric barrier reefs, which have been gradually cemented into a continuous sheet of land by the accumulation and consolidation of mud flats between them, — a process

[1] For No. I. see Bulletin of the Museum of Comparative Zoölogy, Vol. IX. No. 7, p. 252. 1882.

which is now going on between the Florida keys and reefs from Cape Florida to the Tortugas, and must end in transforming them, in like manner, into a continuous tract, to be connected eventually with the mainland.

In Agassiz's report no attempt was made to explain the substructure of the peninsula upon which the reef corals grow. Le Conte, however, attributed this substratum to the mass of material brought along by the Gulf Stream. He believed that the Gulf Stream then ran parallel with the line of the present peninsula, and that the substratum was formed by the heaping up of these loose materials along that line. All the later investigations show, however, that the Gulf Stream never followed this course. Then, as now, it swept across, and not parallel with, the line of the peninsula, and though it undoubtedly assisted in the building up of Forida, it simply brought then, as it does to-day, the food, or the greater part of the food, consumed by the animals living on the Bank of Florida. These animals supply, by their growth and decay, the building material for the great Florida Bank. No doubt, the floating animals brought by the Gulf Stream add something beside to the mass of the bank itself; but they are chiefly consumed by the animals living upon it.

The curve of the Florida Reef (Plate VI.) along the Gulf Stream is due in great measure, as Hunt shows, to a counter current along the reef running westward. This current is known to all navigators, and, though ill-defined at Cape Florida, it becomes stronger and wider as it goes west. It has a width of at least ten miles at Key West, and of twenty miles at the Tortugas. This is clearly shown by the mass of surface animals driven along upon this westerly counter current by the southeasterly winds.

The tides set strongly across the reefs, and through the channels between the keys, the flood running north and the ebb south. When storms occur, the fine silt of the bank, made up of coral sand from the reefs, is taken into the bay back of the keys and deposited there. The counter current then carries this to the westward, and thus material has gradually been added to the flats. As Hunt has already noticed, tides and currents have undoubtedly been the principal agents here. That this material has not been brought by the Gulf Stream from the mouth of the Mississippi, is shown by the fact that no trace of Mississippi mud has ever been found in any of the innumerable soundings taken to the eastward of the Mississippi, or more than a hundred miles from its mouth. It is also probable that the action of the waves from the southeast, in forming a talus of coarser material, does not penetrate below one hundred fathoms, and everything once fixed below that depth has its final character. The line of keys seems to be formed by the waste of the exterior present reef,

rather than by the remains of an older anterior reef. At the Tortugas, the contrary seems to be the case; but this perhaps is due to the fact that the strong currents which sweep over the reefs, and have excavated the Southwest Channel, have also established conditions favorable to the growth of corals on both sides of this channel, and that the two lines of keys are due to this cause. Had the currents run only from the Southeast through the Northwest Passage, larger keys, separated by channels running north and south, would then have been formed.

I shall first show by an examination of the Tortugas how far the explanations given by Agassiz, Le Conte, and Hunt are satisfactory as regards the formation of the group of islands making the extremity of the reef, and shall then attempt, by the help of the dredging operations of the "Blake" along the Florida Bank, to reconstruct the past history of the peninsula in its southern portion. Beginning with an account of the formation of the present Reef, based upon the knowledge obtained by a careful survey of the Tortugas, I shall then proceed to the elucidation of the structure of the peninsula itself.

The Tortugas (Plate I.) are situated at the very extremity of the slope upon which the line of the Florida Reefs has been built up. They form the most recent of the cluster of Florida Reefs, and have not as yet been transformed into the normal coral reef characteristic of the whole line extending from the Rebecca Shoal and Marquesas to Cape Florida. There is as yet nothing at the Tortugas corresponding to the extensive mud flat stretching uninterruptedly a few feet below the surface of the water, to the northward of the line of keys (Plates X., XI.). The northern part of this flat, from Cape Sable to Key Biscayne, is fringed on the southeast face by the line of narrow keys reaching from Cape Florida to Bahia Honda (Plate VI.). In the oldest part of the reef, the bay to the north of the keys, the waters of which once undoubtedly covered the whole space between Pine Keys and Cape Sable, has little by little been filled up and transformed for the greater part into the wide shallow mud flats now extending over that area. Next comes, from the Pine Keys to Rebecca Shoal, a comparatively more recent portion of the reef, in which the northern extremities of the keys rise somewhat higher above the general level of the mud flats. These two adjoining regions of flats and keys run parallel to the main reef, at a distance of from one to nine miles from the outer line of reefs; the reef that is, *par excellence*, over the whole surface of which the living corals still prosper. Farther yet to the westward, at a distance of fifteen miles from the western extremity of the outer parts of the reef, rise the Tortugas. In this group a condition of things prevails at the present day, which must have been repeated over and over again from

the time when the Florida Reef formed but an insignificant point south of the line extending from Cape Sable to Key Biscayne, until it reached the extremity of the present continuous mud flat, about ten miles to the west of the Marquesas. As is well shown on the Coast Survey maps, the mud flats, keys, and reef dip as a whole to the southwest, as does also the Florida plateau to the westward of the Marquesas. It is only upon such parts of this plateau as from some cause or other have attained a sufficient elevation to allow corals to flourish, that the reef may be expected to extend. The knoll rising above the general level upon which the Tortugas have little by little been built up, is such an area, and such also is the patch to the westward of the Tortugas, upon which, as I shall show hereafter, an incipient coral reef is already forming, at a depth of a little less than twenty fathoms (Plate I.). It is not difficult to go back to a time when the great mud flats of Florida did not exist. In their place was a steep slope, such as we now find to the west of the Tortugas. Following the comparison backward, it is easy to imagine how, little by little, from the existence of the prevailing easterly winds and currents, the materials coming from the small outside reefs and held in suspense were little by little driven to the westward, accumulating finally upon what was then the extremity of the great Florida Bank. There they gave rise to knolls similar to those upon which the Tortugas have been built. From the moment these knolls attained a sufficiently favorable elevation for the growth of corals, a western reef was at once formed, holding to the small Florida Reef then existing very much the same relations as the Tortugas at the present day hold to the great Florida Reef. Again, by the same agencies, the channels which once undoubtedly ran back into the mud flats to the north of the oldest keys were gradually closed; such channels as are still open in part or wholly in the more recent and westerly portions of the reef, as, for instance, the entrance to Key West Harbor, running from the south to the north across from the reef to the mud flats. In like manner these channels and those which form an extensive strait on the most recent part of the reef between Rebecca Shoal and the Tortugas, will in time disappear, and become, in consequence of the extension of the mud flats beyond Rebecca Shoal, narrow channels, like those of Key West, of the Pine Keys, and of the Marquesas. By this time there will also have been formed an extension of the outer reefs along the twenty-fathom line, connecting the Tortugas with the present reef, and only broken here and there by passages similar to those already existing along the reef, by which vessels find free access to the middle passage between the reef and keys. These channels are kept open by the same tidal agencies as are now more powerfully at work at the Tortugas,

but which have gradually diminished in force from the Pine Key Channel to the northward. The depth of the passage between the Tortugas and Rebecca Shoal allows a larger and stronger body of water to pass through that channel than through any other.

It has been clearly proved by Hunt that the extensive flats to the northward of the keys have been formed by the agency of the tides, the whole triangular space between the Rebecca Shoal and Cape Sable being filled up with silt. The flood running in a northerly and the ebb in a southerly direction, the tides in their alternation hold in suspense the silt which they wear away from the reef or from the shores of the keys. During storms this floating silt is driven either on to the flats to the north of the keys, or on to the slope of the reef toward the Gulf Stream. An examination of the present condition of the Tortugas, and of the mud flats beyond the Marquesas, gives us a very simple explanation of the formation, and gradual extension westward to its present limits, of the small reef originally existing only as a diminutive spit, but gradually spreading to the southwest from Cape Florida until it reached its present gigantic proportions.

The Tortugas show us, as will be seen, how the reef was actually formed, while the extension of the mud flats beyond the Marquesas explains how the bottom is prepared and gradually raised to a level at which corals will flourish. One other condition was, however, essential to the development of the coral reef, that of the existence of a powerful current, such as the Gulf Stream, bringing an immense quantity of pelagic animals to serve as food for the corals found along its path. There is practically no evidence that the Florida Reef, or any part of the southern peninsula of Florida which has been formed by corals, owes its existence to the effect of elevation; or that the atolls of this district, such as those of the Marquesas or of the great Alacran Reef, owe their peculiar structure to subsidence.

It cannot be denied that the backbone of the Florida peninsula was first produced by a fold of the earth crust in an earlier geological period. Smith and Hilgard have also shown that such a fold or folds formed the axis which has raised a part of the northern base of the peninsula to a height of something less than two hundred feet, and that this axis, which has still, at the latitude of Lake Okeechobee, an elevation of about forty feet, but sinks gradually as we go south, was formed before the Vicksburg limestone age, while on either side of it are deposited the more recent limestones which have given Florida its present width. They have pointed out, moreover, as a secondary result of this folding, the formation of an immense submarine plateau directly in the track of the Gulf Stream, which has been gradually built up since that time by the

accretions of the solid parts of Mollusks, Echinoderms, Corals, Alcyonoids, Annelids, Crustacea, and the like, which have lived and died upon it, thus furnishing the limestone for the gradual completion of the peninsula. No one who has not dredged near the hundred-fathom line on the west coast of the great Florida Plateau can form any idea of the amount of animal life which can be sustained upon a small area under suitable conditions of existence. It was no uncommon thing for us to bring up in the trawl or dredge large fragments of the modern limestone now in process of formation, consisting of the dead carcasses of the very species now living on the top of this recent limestone. To the westward of the western shore line, Florida now stretches out as an immense submarine plateau, forming, as the sections show, a huge tongue coated or veneered only by coral limestone over its very top. The whole of the peninsula of Florida south of St. Augustine, as far as Tampa Bay, has probably been built up in this way, from north to south, of limestone somewhat older than the reef limestone. The plateau, judging from the inclination of the axis, has but a slight southward dip until we reach the southern extremity of the peninsula, where the fall is more rapid toward the outer reef.

The whole of the eastern and western edges of Florida consist of recent limestones, the immediate predecessors of the present limestone now forming on the western and southern slopes of the great Florida Plateau. The early dredgings of Mr. Pourtalès, in 1867 and 1868, developed on the Gulf Stream slope off the Florida reefs an extensive rocky plateau (Pourtalès Plateau) from a depth of about ninety fathoms to about two hundred and fifty fathoms. The rock of which this plateau is built consists of the same species of corals and shells as those now living upon it, to which it owes its formation. A similar sea-bottom is found on the north side of Cuba, but with a much steeper slope. These fringing limestones also formed the southern extremity of Florida at a time when the northern part of the Everglades had perhaps been built up to a level favorable for the growth of coral reef. In this northern portion of the Everglades alone can we confidently speak of the first concentric reefs, which have little by little built up Florida toward the south. It seems highly probable that on the remainder of the peninsula north of the Everglades both the newer and older limestones were built up by the same agencies as are now at work on the Florida Bank. There are to-day other submarine banks which undoubtedly owe their origin to similar agencies. The great bank to the east of the Mosquito coast, which practically extends to Jamaica, has probably been formed in the same way as the Yucatan and Florida Banks; that is, by the gradual decay of the animals subsisting in great abundance upon its slope, and fed by the pelagic materials which the currents and the

prevailing winds bring to the bank. All the reefs on the south coast of Cuba between the Isle of Pines and the shore to the east and west may have a similar origin. Among the West India Islands the barrier reefs of the windward side are built upon plateaux of a similar structure. The Basse Terre of Guadeloupe is a fine example of such a plateau, which has been elevated slightly above the level of the sea. At Barbados the whole shell of the island consists of a series of terraces, which have been successively lifted by the trachytic centre forming the nucleus of the island. These terraces are entirely composed of limestone formed of the species of Mollusks and Radiates now living in the West India seas.

While there is thus undoubted evidence that a great part of the shore line of the northeast extremity of South America has been washed away, yet there is also evidence that the lines of the bank connecting the lesser West India Islands have been built up by agencies similar to those which have formed the Yucatan and Florida Banks, except that these latter have been formed around the volcanic islands or folds extending along the eastern edge of the Caribbean Sea. In some cases these banks have been elevated after the existing condition of things was in force; in others their elevation dates back to the period when the separation of the Caribbean from the Pacific took place, at the time of the closing of the Isthmus of Panama. Evidence of this action is found in the elevated coral reefs and the raised earlier tertiary and later cretaceous deposits of the West Indies and Central America.

Nowhere do we find better examples than in the West India Islands of the formation of submarine banks in connection with volcanic peaks. A great number of peaks of volcanic origin have risen nearly to the surface of the sea, or above it, and serve as the foundation of great submarine banks. It is well known, also, that the "Challenger" and "Tuscarora" soundings have developed a number of submarine elevations, covered by deposits of Pteropods and Globigerina ooze, forming extensive banks serving as foundations for barrier reefs and atolls, while the volcanic substratum has been completely hidden. In the West Indies, as at Martinique, there are volcanic peaks rising to a height of over four thousand feet; on their windward side are extensive submarine plateaux, formed, I imagine, by agencies similar to those to which we ascribe the formation of the Yucatan and Florida plateaux. Whenever such plateaux have reached on their windward side the level at which corals prosper, there coral reefs spring up and flourish. Side by side with such conditions we find plateaux at lower levels, under a greater depth of water, covered only by the Invertebrates living upon their surface, — as is the case, for instance, in the northern extremity of the plateau of the Grenadines. These plateaux have probably never risen to the surface. We

have also the still older phenomenon of such islands as Barbados, where the terraces formed by the raised coral reefs mark the successive elevation of the volcanic cone; or we may have still another combination, like that of Guadeloupe, where a high volcanic peak forms the main island, an elevated plateau forming the Basse Terre with a growing coral reef to the windward of the latter.

The fact that these great submarine banks of modern limestone lie in the very track of the great oceanic currents sufficiently shows that these currents hold the immense quantity of carbonate of lime needed in the growth of the bank. Its amount has, besides, been actually measured by Murray. He has shown that, if the pelagic fauna and flora extend, as the experiments carried on by the "Challenger" and the "Blake" seem conclusively to prove, to a depth of one hundred fathoms, we should have sixteen tons of carbonate of lime for every square mile one hundred fathoms deep. But the greater the depth at which these plateaux begin to form, the less rapid must be their formation. The fact that the deeper part of the ocean, below three thousand fathoms, does not contain any of the larger shells of pelagic type, can be readily explained on the supposition that, being thinnest, like Pteropod shells, they present a large surface to the action of the carbonic acid, which is most abundant in deep water. Attacked as soon as they reach the bottom by this action, these shells of thinnest surface are reduced to a bicarbonate, and are carried off in solution. They do not, therefore, appear at these greater depths, and are indeed rarely to be found below two thousand fathoms. The thicker-shelled Foraminifera extend to a greater depth, not because they are of different chemical composition, but because their greater amount of substance yields less easily to the action of the acid. At shallower depths the solvent action of carbonic acid must be far less efficient, on account of the rapid accumulation of dead siliceous and calcareous shells of Foraminifera, Sponges, Hydroids, Corals, Halcyonoids, Mollusks, Polyzoa, Echinoderms, etc., which must long have lived upon the bank before they had by their accumulation brought it to a level at which coral reefs could begin to grow.

The bathymetrical sections (Plate VII.) of the peninsula of Florida to the eastward into the trough of the Gulf Stream are very different from those taken on the western side of the peninsula. Proceeding northward from Cape Florida, you pass out of the action of the current from the Straits of Bemini, where the velocity of the Gulf Stream is the greatest. As soon as you reach a latitude at which the trade winds do not blow, you come gradually upon the usual comparatively gentle slope off shore, showing less traces of disturbance either from currents or from the action of the prevailing winds. Judging from what I have seen of the east coast

of the peninsula of Florida, the shore line deposits, such as the Coquina of St. Augustine and the shelly beaches of Indian River, seem to indicate the presence in deep water of a limestone deposit formed of the detritus of Mollusks, Annelids, Starfishes, and Sea-urchins. There are but few corals, occasional patches of reef-builders, but no extensive reefs; but this is a difficult point to decide even at Key West. Indeed, all along the line of the reefs it would be difficult to decide to-day whether the reefs have been formed, like the Marquesas Keys, merely by the accumulation of detrital matter driven to the westward and northward, or whether the Mangrove Keys and the reefs really indicate the old lines of a reef similar to the one now in full activity on the northern edge of the Gulf Stream, parallel to the main line of keys. The absence of the more delicate shells from limestone in the formation of which they must nevertheless have shared, is explained by the solvent action of carbonic acid upon them, and by the deposition of carbonate of lime as a cement. A comparison of the structure of Loggerhead Key at the Tortugas with that of the Mangrove Islands and the main keys, shows us the difficulty of deciding these points. At Loggerhead Key we have a shore line made up of brecciated and oölitic coral limestone, fully as characteristic as any similar shore line on the older keys like Key West (Plate XII.). Yet we still find on the southern, eastern, and northern sides of Loggerhead an active growth of reef-building coral, while other parts of the island and some of the flats, if covered by mangroves, could not be distinguished by their structure from the genuine mangrove islands on the flats to the north of the inner line of keys along the main reef (Plates X., XI.).

We must be careful to distinguish the line of islands running from the mouth of the St. John to Cape Florida, parallel with the coast of Florida, from the line of islands forming the Florida Keys. The latter seem at first glance to be the continuation of the former; but this is not the case, their mode of formation, as well as their geological structure, being radically different. As has long been pointed out by H. D. Rogers, the line of narrow islands to the eastward of Florida belongs to the series of coast islands lying parallel to the coast from Long Island to Florida, and extending around the whole Gulf of Mexico. They all seem to have been formed by the same causes, perhaps by the action of currents along the continental shores forming lines of deposit of but little width, separated from the mainland by a shallow channel. Some of these islands have been slightly elevated at a comparatively recent period. This is especially the case with the islands along the east coast of Florida, — Anastasia Island, and those running south to Cape Florida, separating Indian River from the Atlantic Ocean. In all these we find the so-called Coquina of St. Augustine raised from ten to twenty

feet above the level of the sea at such points as Anastasia, Merritt's, and Worth Islands, showing all along the east shore of Florida a very recent formation of shell *débris* or breccia very similar to the formation now going on in the lagoons near Venice. This bed of shell breccia was probably deposited after the low backbone of the peninsula, extending from Southern Georgia and Alabama to the northern part of Lake Okechobee and the Everglades perhaps, had been raised, and when the peninsula of Florida from the St. John to the eastward was below the level of the sea at a shallow depth. At any rate, it seems plain from recent evidence that no trace of reef-building corals exists on the east coast north of Cape Florida. Mr. Dietz is inclined to look upon the formation of these islands as due to the action of the waves. But there seems to be nowhere, as is well stated by Rogers, any deposit of the kind going on now; and when such masses of shells are thrown up on beaches, the tendency is strong to consolidate from fragments to the concrete form known as Coquina.[1] The mode of formation does not, however, seem adequately explained by Rogers from the action of currents acting along the coasts. These currents must have flowed over a wide plateau, and have supplied the large amount of food needed for the development of a large and thriving bank of Mollusks and other Invertebrates. As soon as these growing colonies had risen high enough to form banks parallel to the shores, they were in their turn cut off and isolated from the shore by the action of the tides and currents, which must then have begun to deepen the channels intervening between the bars and the mainland. They must also have forced their way across to form the shifting inlets, such as Mosquito Inlet, etc., so characteristic of the channels leading into these inland waters along our whole Southern Atlantic coast. The dip of the Coquina bed to the westward is well shown by the borings of Artesian wells at Palatka. I was informed by the contractor that he met the Coquina beds at a depth of about forty feet, when he reached a mass of clay, which in its turn was underlaid by pebbles resembling the small pebbles found on flats off a rocky shore. Possibly this mass of clay was formed by the silt of the Gulf Stream at a time when it flowed over the low ridge of Central Florida, before that ridge had risen to form a dividing line between the two plateaux, which must have extended, the one to the westward much as it now is, while the other undoubtedly extended in some localities north of Cape Canaveral somewhat to the eastward of the present shore line of Florida.

All this evidence tends to show that the coral reefs had little if anything to do with the building up of the peninsula of Florida north of Cape Florida. The present

[1] Fourth Report, British Association for 1834–38, p. 11.

line of reef is indeed probably the only one which has played any important part in the formation of land south of the line of the present southern extremity of the peninsula of Florida. There seems, however, some reason to believe that a line of reefs, or perhaps two lines not very distant from each other, once stretched along the southeastern end of the Everglades before the present reef began to extend westward. Judging from the sections shown by the maps, the growth of the present reef, as fast as the mud flats were formed to the south of it, has been altogether in that direction (Plate VIII.).

The Bahamas, the San Pedro and Yucatan Banks, have probably all been formed by a similar process, — by the accumulation of limestone either upon an early fold of the earth's crust, or upon a volcanic plateau, or upon a foundation of slower growth from great depths. In Yucatan we can actually descend into the bank itself through any one of the aguadas, or caverns, found everywhere in the northern part of that country. Many of these caverns extend to a considerable depth. One of them, that of Bolonchen, has a depth of seventy fathoms, the whole formation consisting of recent limestone entirely composed of species of Invertebrates now living on the Yucatan Bank. In Yucatan, as in Florida, we find a low ridge of limestone, somewhat older than that of the coast, extending across the peninsula. The uplifting of this ridge has caused the slight undulations of level traceable throughout Yucatan, at a distance of from twenty to thirty miles from the coast, and running nearly at right angles to it. Judging from its fossils and lithological characters, the limestone of which this ridge is formed is identical with the so-called Vicksburg limestone of the central backbone of Florida. I have already attempted to show, in my letter No. 1 (Bull. M. C. Z., V., No. 1), containing an account of the great Alacran[1] Reef on the Bank of Yucatan, that we need not refer the atoll-shaped form of this reef (Plate V.) to the subsidence of the Yucatan Bank as a whole, since the action of the prevailing winds and currents would account for all the existing phenomena. The decay of the animals living upon the great plateau, added to the deposition of all the animal life brought to it

[1] The map of Alacran on Plate V., copied from one of the Hydrographic Office charts, gives an excellent idea of this magnificent reef, its eastern face forming a great arc of a length of about twenty miles, exposed to the full sway of the easterly winds. The huge breakers pound incessantly upon this steep face of the reef, and drive all the silt to the westward. This silt has already completely killed the corals on the eastern faces of the long, narrow sandy islands forming the western chord of the reef. Between them and the walls of coral heads still runs an irregular channel, varying in depth from one to six fathoms, and connected with the open water by narrow channels on the southern face of the reef. The section of the reef shows that, like the Tortugas, it has been built up from the general level of the Yucatan Plateau, rising gradually from a depth of about thirty fathoms until it reached the depth at which corals can flourish, when it shot up more vertically to form the present cone of the reef. The western slope is not so steep as the eastern, and the silt below the twenty-fathom line is deposited on a much more gentle slope than on the eastern face.

by the currents, would explain a gradually increasing elevation of the surface till the level was reached at which reef-building corals can flourish, and at which a reef would naturally be formed. Darwin has noted the close resemblance between encircling barrier reefs and atolls. It seems to me that the structure of the Marquesas[1] (Plate V.) and of Alacran proves conclusively that not one point of difference exists between a barrier reef and an atoll. Darwin has also called attention to the fact, that in shallow seas, such as the Persian Gulf and parts of the East Indian Archipelago, the reefs lose their fringing character and appear as irregularly scattered patches, often covering a considerable area; and observes that many reefs of the West Indies have been formed in like manner upon large and level banks lying a little beneath the surface, — banks which he believes to have been formed by the accumulation of sediment. Such patches of reef-building corals would seem, from their analogy with the Tortugas, to be the beginning of more extensive reefs.

Judging from my examination of the Tortugas reefs, it would seem that corals do not thrive below a depth of from six to seven fathoms. It is, of course, impossible to determine whether that is their bathymetrical limit, or whether they are killed from the accumulation of ooze in the channels and adjacent slopes. We find them confined, however, to the same shallow depths, along the whole of the main reef to the northward (Agassiz). Captain Moresby also showed that at a depth of ten fathoms in the Maldive and Chagos archipelagoes the masses of living coral are scattered at greater distances separated by patches of smooth white sand, and that at a slightly lower depth even these patches merge into a smooth, steep slope wholly bare of coral. All the evidence accumulated by Dana, Ehrenberg, Quoy and Gaimard, tends to show that the limit of reef-building corals is found at about twenty fathoms. On the Yucatan, as on the Florida Bank, the conditions favorable for coral reef growth have

[1] The plan and section of the Marquesas Keys on Plate V. show the formation of the keys on a knoll rising from the general platform of the surrounding reef plateau. This knoll has undoubtedly been built up, as were the Tortugas, from the remains of the corals which once lived upon its face and surface until the formation of the outer reef shut out the prevailing easterly winds, and the corals were killed from the accumulation of silt upon them. The filling up of a lagoon like that of the Marquesas must be a slow process, for we find the water of the inner lagoon deeper than that of any other part of the reef immediately surrounding the outer slope. We can imagine that when the outer ring of the reef surrounding the inside lagoon is once connected, or nearly so, the enclosed calm area is so placed as to be subject to but few disturbing agencies, and is practically excluded from receiving any appreciable amount of sediment from the water of the outer reef, the lagoon connecting with the surrounding waters only by the narrow passages forming the channels between the lagoon and the main channel. Whether the removal of the dead coral rock from the interior of the lagoon of an atoll by the action of the current through the narrow connecting channels, and by the solvent action of the carbonic acid, will alone explain the cause of the great depth of the interior lagoon, seems somewhat doubtful. The mud of the interior of the Marquesas atoll was found to be calcareous, as is practically all the mud which forms the extensive mud flats to the northward of the keys. This mud is, however, generally covered by a thin dark-colored layer of decomposed vegetable and animal matter. The Marquesas are covered by a thick growth of mangroves.

been produced, not by the uplifting of the continent, but by the gradual rising of the bank itself into suitable depths in consequence of the accumulation of animal *débris* upon it. That level once attained, reef-building corals would first establish themselves on such spots as were most favorably situated, with reference to currents and prevailing winds, both of which are essential to their healthy growth, and thus the reef would be begun.

How far the growth of corals is affected by such local conditions is perhaps nowhere better seen than in the smaller West Indian islands. On the eastern side, exposed to the prevailing trade winds and washed by the great equatorial currents, the corals flourish, while on the lee side they do not exist at all. The whole eastern coast of Honduras, of Yucatan, and of Venezuela, exposed to the same action and washed beside by the Gulf Stream, is studded with coral reefs. To the action of the Gulf Stream on the south coast of Jamaica and of Cuba we must ascribe the presence of extensive coral reefs, and to the same cause is undoubtedly due the great San Pedro Bank. The fringing reef which skirts nearly the whole northern coast of Cuba is in a less flourishing condition than the Florida reef on the opposite shore, which is reached not only by the main current of the Gulf Stream, but also by the prevailing winds. For a similar reason, corals are found alive only on the edges of the Great Bahama, where they are subjected to the beneficent action either of currents or of winds, driving the silt clear of the growing corals, and bringing an abundant supply of food. The same causes which have formed the great mud banks to the northward and westward of the Florida Reef have, in the case of the Bahama Banks, formed the immense sand flats and shallows which are fringed by living corals on the east and west. They owe their existence, on the one side, to the wash of the northerly trend of the great equatorial current and to the action of the trades; on the other, to the clearing action of the Gulf Stream. It must also be remembered that the Bahama Plateau was originally joined to Florida, as part of the great fold which built up the framework of that peninsula, and that it was also connected at one time with the island of Cuba. It was also united with the reefs, now elevated to eleven hundred feet, which joined the eastern and western islands in more recent geological times, and formed, before the Tertiary, the two extremities of Cuba. On the southern side the reefs are still in full activity, while on parts of the northern coast, in the vicinity of Havana, they have been elevated to a height of no less than one thousand or eleven hundred feet, while the present barrier reef of the north shore of Cuba forms an immense reef, extending nearly without break from Cape San Antonio to the eastern edge of the old Bahama Channel. The Bahama

Plateau we may also fairly assume to have been built up, little by little, from its original level, by the accumulation of limestone formed in great part from the bodies of the mass of animals which undoubtedly flourished upon the great submarine plateau at a time when the Gulf Stream found its way out of the Gulf of Mexico with less velocity than it now has as it passes through the narrow Straits of Bemini. At that time it spread itself fan-shaped over the southern part of Florida and the Bahama Bank, and flowed more gently northerly and easterly along the coast with the additional reinforcement of the westerly equatorial flowing north of the Great Antilles to the eastward of Cuba. The Bahama Banks then probably consisted of a series of banks like Salt Key Bank, separated by channels like the Santarem and St. Nicholas, undoubtedly kept open by the same currents as now form the old Bahama Channel. These channels, like those between the keys on the Florida side, have gradually become filled with the detritus driven into them by the trade winds, till the whole formed the bank in its present state of consolidation. And yet it must not be forgotten that, while in the western part of the Caribbean, the Gulf of Mexico, and Florida a dead level prevails, at Havana, Hayti, and Barbados we have reefs elevated to a great height, and others at considerable elevation on certain of the Greater and Lesser Antilles. The somewhat capricious distribution of coral reefs may perhaps be explained by the action of the great equatorial currents. The larger reefs occur in regions to which these currents bring in the track of their course abundant supplies of food for the reef-building animals. On the eastern coast of Africa, of Central America, or of Australia, for instance, extensive colonies of coral reefs flourish, while on the western coast of the same continents in similar latitudes, but not bathed by such powerful equatorial currents, the supply of food seems insufficient for more than the isolated patches of corals existing there.

Other naturalists, as Semper[1] and Murray,[2] have already attempted to explain the formation of coral reefs, in part at least, on grounds differing essentially from those to which Darwin ascribed them, and similar in the main to those here brought forward. Undoubtedly Darwin's theory of reef formation presents a sound and admirable exposition of the grander causes which have brought about the elevation or subsidence of large tracts to a level favorable for coral growth; but at the time he wrote upon this subject, the formation of these extensive limestone banks, built up by the animals living on the bottom, and constantly strengthened and increased by the attendant phenomena of winds and currents, was little under-

[1] Semper, C. Zeits. f. Wiss. Zool., 1863, XIII., p. 558.

[2] Murray, John. Proc. R. S. Edinb., No. 107, 1880, X., p. 505, On the Structure and Origin of Coral Reefs and Islands.

stood. These facts have been brought into notice and emphasized by recent deep-sea explorations. Darwin, however, when examining maps of the West Indies, had been struck by the probable connection between the areas of deposition of the great banks marked upon the charts and the course of the sea currents. He naturally explained the steep slopes abruptly dropping from comparatively shallow plateaux to great depths, by what is known to occur wherever great masses of sediment are found, and he therefore considered these plateaux to be submerged mountains. Such they undoubtedly are, in a certain sense; not wholly built, however, as Darwin supposes, of sediment, but in great part also of the remains of the innumerable animals living and dying upon them. The nucleus of these banks has probably been formed around the shores of promontories subjected to the most active play of the great oceanic currents.

At the time when Darwin wrote, and when we knew little of the limestone deposits formed by the accumulation of the *débris* of Mollusks, Echinoderms, Polyps, and the like, upon folds of the earth's crust, the basal parts of barrier reefs were difficult of explanation. The evidence gathered by Murray, Semper, and myself, partly in districts which Darwin had already examined, and partly in regions where his theory of reef formation never seemed to find its proper application, has in part removed this difficulty. It all tends to prove that we must look to many other causes than those of elevation and subsidence for a satisfactory explanation of coral reef formation. All important among these causes are the prevailing winds and currents, the latter charged with sediment which helps to build extensive plateaux from lower depths to levels at which corals can prosper. This explanation, tested as it has been by penetrating into the thickness of the beds underlying the coral reefs, seems a more natural one, for many of the phenomena at least, than that of the subsidence of the foundation to which the great vertical thickness of barrier reefs has been hitherto referred. It is, however, difficult to account for the great depth of some of the lagoons — forty fathoms — on any other theory than that of subsidence.

If, however, we have succeeded in showing that great submarine plateaux have gradually been built up in the Gulf of Mexico and the Caribbean by the decay of animal life, we shall find no difficulty in accounting for the formation of great piles of sediment on the floors of the Pacific and Indian Oceans, provided these banks lie in the track of a great oceanic current. Certainly the coral reefs of the Caribbean and the Gulf of Mexico, of Florida and the Bahamas, are distributed upon banks which lie directly in the path of the great Atlantic equatorial currents and of the Gulf Stream, which we know to have been formed by the agency of these cur-

rents. The fact that the coral reef at the extremity of Florida is the most recent of the coral formations found on the Florida shores, plainly shows that they, as well as the coral reefs of Yucatan, Cuba, the Bahamas, and the Caribbean Sea, though not all of the same age, were yet of modern origin, since we find them still in an active state of formation. Even the elevated reefs of Cuba and of the other West India Islands, though older, probably belong, nevertheless, to the most recent deposits of the kind we know. The difficulty of explaining the constant renewal of the coral faces of the atolls of the Pacific, and their present condition, on the supposition of their having lived from the time of the early Tertiaries, was one of the main causes which led Darwin to seek for some other agency, like subsidence, to explain the renovating process of the original structure. In some instances coral reefs have unquestionably been lifted. I have seen the elevated reefs of Cuba, of San Domingo, and other West India Islands, and especially of Barbados,[1] which are perhaps the most striking of these. They are too well known to need more than a passing notice here. The terraces they form show plainly the successive stages of arrest in the agency of elevation, and there is no difficulty in accounting for their existence, especially in a volcanic region like the West Indies; but that there should have been an extensive area of subsidence in which the rate of subsidence was so evenly balanced with the rate of coral growth as to create and maintain the necessary conditions for reef formation, is less easy of explanation.

In a very interesting article on the Bermudas, Rein[2] has taken very much the same view of their gradual building up, and explains the formation of the present condition of things by causes greatly differing from those adduced by Darwin as explaining the apparent atoll shape of the groups.

The islands composing the Tortugas (Plates I. and II.) are Loggerhead, Bird, Garden, Long, Sand, Middle, and East Keys. These are always above the level of the sea, while Southwest Key and Bush Key are only exposed at low water, and North Key and Northeast Key have disappeared. These insignificant islands are the outcrops of extensive submarine banks. Loggerhead Key, not more than three fourths of a mile in length, is the top of a bank extending to the three-fathom line of about five miles in length with an average width of three fourths of a mile, extensive coral sand-flats running in prolongation of the northern and southern extremities of the

[1] The trachytic cone forming the base upon which the successive terraces of Barbados have been elevated is seen to crop out on the surface in the northeastern part of the island.

[2] Rein, J. J. Beiträge zur Physikalischen Geographie der Bermuda Inseln. Bericht. Senckenb. Naturf. Gesell., 1869–70, (Mai 1870,) pp. 140–158.

key. This bank we have called in the sections (Plates III. and IV.) Loggerhead Bank. Between this and the Garden Key and Long Key Bank, there are a few shoals running more or less parallel with Loggerhead Bank, the largest of which are Brilliant and White Shoals. Garden Key and Long Key Bank form a rectangular shoal of nearly the same length as that of Loggerhead, with an average width of nearly two miles, the great sand flats of this shoal being those of the Long and Bush Key tract. The Southwest Channel, with a depth varying from ten to twelve fathoms, separates Loggerhead Bank from the Bird, Garden, and Long Key Bank. This, in its turn, is separated from the still greater North, Northeast, East, and Middle Key Bank by the Southeast Channel, with a depth of about nine fathoms, while the Northwest Channel separates Loggerhead Bank from the North Key Bank with an average depth of from seven to ten fathoms. The Eastern Bank is irregularly horseshoe-shaped, convex to the east, and partly surrounds a great interior bay, with an average depth of about seven fathoms. The flood tides run from the south through the Southwest and South Channels in a northeasterly direction, the ebb tide flowing in the opposite direction. The strongest tidal current passes through the Southwest Channel.

An examination of the sections of the Tortugas from the west to the east, on the lines parallel to *A A'*, *B B'*, etc. (Plate IV.), shows the gradual rise of the mound forming the Tortugas, as we pass from the west side of the Loggerhead Bank along the line *A A'* to a line passing through the southwest slope of the same bank, *B B'*, till we come across the main bank of the group on the line *C C'*, and again fall slowly on the eastern slope as we cut across the east end of East Key Bank on the line *D D'*, till we finally come to the low elevation forming the southeast slope of East Key Bank along the line *E E'*. The action of the Southeast and Northwest Channels in keeping open the passage between Long Key and Loggerhead Bank, and that between North Key Bank, is well shown on the sections *B B'* and *C C'*, as well as the secondary channels separating Bird Key, Garden Key, and Long Key. These channels are undoubtedly the last traces of the deeper and wider channels, probably once running parallel to the Southeast Channel. They have little by little been filled up after the sand flats of Bush Key began to form, thus preventing the free circulation of the tides through these channels. The presence of a few large heads of Mæandrinas and Astræans, as well as the luxuriant growth of *Madrepora cervicornis* near low-water mark, on the two sides of these channels, now changed into sand flats (see Plate II.), seems to indicate formerly a more active tidal circulation through them than is now taking place. An examination of the cross-sections in the direction of the prevailing winds, and in the direction of the tides along the lines 1–1′ to 10–10′

(Plate III.) shows at a glance the mound-shaped mass which forms the base, rising from the general twenty-five to thirty fathoms level, with its abrupt side facing the east on the extremities 1′–10′[1] of the section lines. There are also seen the deep furrows, more or less broad, which have been scooped out of this mass by the action of the currents, such as those passing through the Southwest Channel. (See lines 1–1′ to 6–6′, with the secondary channels cut between the Loggerhead Bank and the Brilliant and White Shoals, Bush, Garden, and Long Keys; lines 2–2′, 3–3′, 4–4′, 5–5′, as well as the primary channels formed by the Northwest Channel and the secondary between Middle and East Key, on line 7–7′ and 8–8′.) With this preliminary examination of the relief of the Tortugas, we can now pass to the examination of the distribution of the more important species of corals, and see how far we are able to explain the peculiar formation of the Tortugas from causes still in operation at the present day (Plate II.).

The corals which give to the reefs their peculiar physiognomy are the extensive patches of Madrepora (principally *M. cervicornis*), the clusters of the two common species of Porites (*P. furcata* and *P. clavaria*) more or less covering the shallow tracts of coarse sand, and *Mœandrina areolata* growing between the more or less extensive patches of marine lawns formed by a species of Thalassia, with occasional patches of Anadyomene. In other parts of the reefs large Holothurians (Mülleria) lie scattered on the bottom, or in somewhat deeper regions we find pockets filled with large Diadematidæ. Immense masses of Nullipores (*Udotea Halimedea*) and Corallines grow on the shallowest flats on the tops of the branches of Madrepores which have died from exposure to the air, either from growing up to the surface and becoming exposed by extreme low tides, or from the action of strong winds blowing the water from the flats. The destructive effect of an extremely low tide on a growing reef is well shown on the flats to the southward of Fort Jefferson, where the upper part of the branches of a certain size reaching up to a given level are frequently killed off by low tides. Exposure to the action of the sun even for a very short time is sufficient to kill them. The extreme sensitiveness of all corals to atmospheric action is well known, so that it becomes plain, as has been stated already by Darwin, Dana, and others, that no coral reef can grow above the level of the lowest tides, and that all subsequent additions of material must be due to accumulation of sediment transported by the action of the tides

[1] Loggerhead Bank itself also shows, as well as Garden, Bush Key Bank, and East Key Bank, a steep slope on the eastern face. Although an interior slope, it is yet sufficiently exposed to the same influences which have shaped the outer slopes of the more exposed banks.

and prevailing winds. Next come the clusters of coral heads, huge masses of Astræans and of Mæandrina, very limited in their distribution at the Tortugas, as well as the more or less extensive patches of *Madrepora palmata*, and finally what is known as broken ground, namely, the outer edge of the reef occupied mainly by clusters of Gorgoniæ, which also reach upward into the shallower region. Occasional patches may be seen also of Astræans, Madrepores, and other reef-builders, which have extended below the depths at which they generally flourish, and where they are soon killed or choked by the accumulation of fine coral sand, and coralline sand or ooze of the deeper waters. This sediment fills the broad and narrow flat channels dividing the three great banks which compose the Tortugas, or separate the inner shoals, banks, and islands. Finally come in the lines of broken coral heads and branches, mixed with dead corallines, shells of Mollusks, old Serpulæ tubes,[1] Gorgoniæ stalks, and the like. These form a low dike, as it were, to be little by little pounded up by the breakers into smaller fragments, and carried, either by the winds, or waves, or currents, into the interior of the reefs, there to form sand flats of more or less coarse materials, until on the western faces of the banks the finest detritus is deposited in very steep slopes, constantly shifting like those of sand dunes, and, like them, running forward and backward at the will of the winds and waves. This continues until the particles have become cemented together by the action of the carbonic acid contained in excess in the salt water surrounding the reefs, and the gluing of the slight amount of animal matter which holds these particles together. Some of the slopes (according to General Wright, of the Engineers) are as great as thirty-three degrees. All this fine material, composed of fragments of all sizes of every animal and plant with a calcareous skeleton, of course prevents the growth of corals in positions which are not well scoured, either by the action of the tides or of the prevailing winds. The corals when alive are gradually buried under this mass of material constantly passing over them, and held in suspense. They flourish therefore only where the disturbing elements are reduced to a minimum; namely, on steep banks or on the slopes which are scoured by tides, or on flats at considerable depths, over which a large body of water can freely pass, whether brought by the tides or driven by the winds. In such cases the corals can grow gradually towards the surface as fast as the sediment deposited has closed up the circulation of the lower levels. The quantity of calcareous matter held in suspense in the water in the vicinity of a reef, and on the reef itself, is very great. The breakers pounding

[1] Serpulæ often form incrusting masses of considerable extent, acting, as has been noticed by Darwin, much as the patches of Nullipores do in protecting decayed and dead corals from being too rapidly broken to pieces by the action of the waves.

upon the exposed slopes of the reefs destroy, even on calm days, large quantities of corals which have been weakened by the borings of Mollusks, Annelids, Echinoderms, and Sponges. On windy or stormy days the powdered fragments are driven far and wide, turning all the surrounding water to chalk color for a considerable distance from the reef. It is not an uncommon thing after a blow to come upon this water discolored by the fine calcareous silt it holds in suspense to a distance of six to ten miles from the outer reef. I have seen between two and three inches of fine silt deposited in the interval between two tides after a prolonged storm. The limitation of coral reef growth to shallow depths may be due to the fact that the ooze held in suspense rapidly sinks to the bottom from the top, the surface water remaining clear. The rapidity with which the corals are choked readily explains why they must of necessity have a limited vertical distribution depending upon local causes. This is well shown along the sections of Tortugas off the Marquesas, along the line of the main reef. We find corals living and flourishing at a much greater depth, and there seems to be no simpler explanation of the limited bathymetrical range than that of the baneful action of the silt held in suspense near all reefs. That the silt is carried on the bottom by currents and waves is well known, and on the bottom of the Gulf Stream to the north of the Straits of Bemini as far as Cape Hatteras, we have a huge muddy river carrying its silt to the steep slope south of Hatteras, depositing occasionally a few patches of green sand along the sides of its course, while the upper waters are perfectly clear and of the deepest blue.

Corals alone cannot supply all the sand we know to be carried by the Gulf Stream. We must add to this the silt, mud, and sand which comes from pelagic animals, and which is distributed by the winds and waves, to be spread uniformly over large areas, as is well shown from the distribution of the immense mass of calcareous ooze over the whole of the bottom between Florida and Cuba. This undoubtedly owes its origin in part to the silt the Gulf Stream brings from the southeastern edge and slope of the Yucatan Bank, in addition to the accumulation due to the pelagic fauna which it sweeps along its course. The amount of work done by the animals living upon the reef in preparation for the grinding process of the breakers is very great. All writers upon the reefs have referred to the destructive agency of boring Mollusks, Annelids, and Echinoderms riddling the coral branches and heads with holes, and preparing the way for their fracture into larger or smaller fragments.

The Echinoderms living upon the flats seem to live almost exclusively upon the organic matter and Foraminifera they find mixed with the coral sand, upon which they

feed and which fills their digestive cavity. Their action, however, while undoubtedly an important one in that they reduce the sand to a smaller size, is yet very slight as compared to the action of the breakers upon the sea face of the reef. Darwin, Dana, and others have referred to this agency as one among those at work in triturating the corals. By some observers, these animals are supposed to be simply on the living coral. This is certainly not the case either with Holothurians and Diadematidæ, or with Clypeasteroids: livingon flats, they swallow the sand as they find it. But with Cidaris and Echinometra, which dig out holes in the rock, the case is different. H. H. Guppy has also observed the Holothurians full of sand on the flats of the reefs of the Solomon Islands.

The Loggerhead, Bird, and Bush Keys Banks, which protect each other to a certain extent from the action of the strong winds opposed to the prevailing trade winds, present a more normal growth than that of the East, North Key Bank, which is particularly exposed to the full fury of the northers, which must counteract to a great extent the action of the trade winds. This can be seen on sections (Plate III.) 7–7′, 8–8′, 9–9′, which show a nearly equal slope on the eastern and western sides of the bank. The distribution of the broken ground, the position of the masses of *Madrepora cervicornis*, and the trend of the sand flats, all alike show the conflicting action to which the two slopes of this great bank have been subjected. This counterbalancing action of the northers and of the trade winds is also well shown by its effect on the position of the islands themselves. During the prevalence of southeasterly winds, East Key, Sand Key, and Middle Key extend bodily to the westward, the materials for their growth being washed from the eastern shores. The opposite takes place during the prevalence of northers. The outline of Loggerhead Key is also constantly shifting, and, according to the officers of the Lighthouse Board, none of the landmarks furnished by these islands can be relied upon in the location of buoys.

What takes place upon the shores of the islands also takes place, of course, upon the flats. Owing to the action of the winds and waves, the whole mass of the surface of the reef is kept in more or less active movement, according to the depth of the flats and to their position. The coarser materials covering the flats and shore lines, made up of large-sized fragments, are gradually changing to the coarse sand forming the flats nearer the outer edge of the reefs; and these, in their turn, are changed into the fine silt which fills the channels and eventually limits the growth of the corals to regions where they can find permanent lodging, and are not immediately under the influence of this shifting sand and silt. The quality of the sand forming the beaches at different points on the keys and flats depends entirely on its position. It will be

coarser or finer, according to the exposure of the beach, and the finest sand is found in the most sheltered places, where the silt has free chance to settle. (See Plate IX. for a view of a characteristic coral sand-beach at Key West.) The scarcity of fossils in the coral limestones of the reef has already been dwelt upon, and their absence is readily accounted for from the constant disturbance of the shore-line deposits, reducing little by little the larger fragments of shells and corals, or Echinoderms, to a breccia, or again to oölite or fine sand. This is nowhere as well seen as on the shore line of Key West to the north of Fort Taylor (Plate XII.). There the outer reef is sufficiently distant to allow waves of considerable size to break upon this coast, and then strike upon a low line of shore rocks. These rocks are completely riddled by larger or smaller cavities made by boring Mollusks, Annelids, Sea-urchins, etc., or left by fossils or fragments of corals which have fallen out. Thus weakened, large masses are easily undermined by the water, which washes around them with considerable force. They fall off, become then broken again into smaller and finer pieces, which are again reground in their turn, and are finally either resoldered into finer breccia or coarse oölite, according to the composition of the rock, or into the finest oölite or sand. This is then cemented again to the shore line, forming a new line, more or less regularly stratified, dipping towards the sea, and which, when exposed to the action of the air, soon becomes coated with a thin film of hard limestone. This hardens, and forms the ringing crust of the rocks found everywhere on the keys. This coating is formed with great rapidity, an exposure between two tides is sufficient to form such a thin coating, as I have repeatedly had occasion to observe in the deposition of finer oölitic sands which fill the rock pockets just within reach of the waves at high tide. A process of undermining similar to what has been observed at Key West takes place along all the coral rock shores which happen to be exposed to the action of the sea. From the description of Rein and others, this undermining action, acting on a very much larger scale on æolian deposits of considerable altitudes, must be the principal agent in the formation of some of the peculiarly characteristic features of the Bermuda Islands. On the east and west shore of Loggerhead, near the northern extremity, we can trace admirably the successive layers of the coral limestone which have been deposited and have had an opportunity to harden between the tides, forming what appear to be stratified beds, with their outcrops running as a general thing parallel to the bend of the shore or at a slight angle from it, and dipping on the one side to the eastward and on the other to the westward.

The bank to the west of the Tortugas has large heads of Astræans and Madrepores growing up in it at a depth of from six to seven fathoms. Gorgoniæ are

still found at a somewhat greater depth. This bank is an excellent specimen of an isolated coral patch, such as must have formed the basis of all the keys and reefs. This patch will undoubtedly in time form a new reef flush with the surface to the westward of the Tortugas. The greatest depth at which reef-building corals were observed to grow was in the Southwest Channel on the steep banks of White Shoal, and in the channel to the southwest of Bird Key, where Madrepores grow to a depth of about ten fathoms. As a general rule, however, the corals were generally choked below six fathoms by the ooze, and their place was taken by Gorgoniæ.

All estimates of the age of the southern extremity of Florida, or of the reef alone, must necessarily be very defective. The great age assigned by Professor Agassiz to the northern part of the peninsula may not be exaggerated, if it is understood as including the time at which the Vicksburg limestone forming its backbone was deposited. But the extension of the coral reefs proper so far north in Florida has never been proved. The rate of growth of the reef-builders is very rapid, and it is quite possible that the reef-builders of the Florida Reef began at once all along the line extending from Key West to Cape Florida, and quickly reached the surface, forming at first a barrier somewhat less compact than the present line of reef. Uncertain as we are respecting the time at which the various parts of the reef reached the surface, one can only say that in Florida, limiting the estimate strictly to the depth at which corals grow, it would probably take one thousand to twelve hundred years for corals to rise from the seven-fathom line to the surface. This would give us no clue whatever to the actual age of the reef, because it is difficult to determine how far the width of any coral reef is due to the growth of coral. But supposing the reef to have an average width of half a mile, and their lateral growth to be say four or five times more rapid than their vertical increase, we should get at least twenty thousand years as the age of the outer reef. It is quite possible for a great width of reef to be forming at one time, and to spread laterally with great rapidity if the plateau upon which it grows is of the right depth. Take, for instance, the width of flats upon which Madrepores flourish. A plateau at favorable depth would very soon be covered by them; they would spread rapidly until they reached the edge beyond which no corals could thrive on account of the depth.

Thus we see from the sections and a study of the distribution of the corals, that at the present day material is constantly added to the knoll forming the Tortugas; that this material is derived either from the animals and plants living upon the reef, or from the pelagic animals which die while passing through the channels, and that we can find nowhere any trace of elevation. Here the calcareous material has evi-

dently been heaped up to its highest point by the influence of the waves or winds. Furthermore, we see growing to the westward of the Tortugas a knoll similar to that which has formed the Tortugas themselves, and which will form, in the course of time, an island or a series of islands like them, to the westward. It is further evident, also, that the great Alacran Reef (Plate V.) has been built up in a similar way, and that its peculiar atoll shape is entirely due to the action of the prevailing winds and currents, and not to any subsidence of the great Yucatan Plateau.

The character of the Fauna and Flora of the Tortugas is interesting as corroborating the comparatively recent age at which the reef has been formed. We find, as we go north along the keys, that the nearer we come to the mainland of Florida, the greater do we find the number of plants characteristic of the mainland. As we reach islands more or less inaccessible, or islands merely formed by flats which have reached low-water mark, we find the vegetation to consist almost entirely of mangroves. Yet at the Tortugas, in spite of the narrow channel which separates them from the Marquesas, I saw but a single diminutive mangrove plant, while a few Bay-cedars, as they are called, a Hop-vine with a thick white flower, and Bermuda grass, have alone found their way there, in spite of the fact that the Tortugas are in the direct line of the prevailing winds from the Marquesas. One of the species of land shells common at Key West has already found its way to the Tortugas. The group is visited by pelicans, cranes, humming-birds, plovers, and a few land birds. It being the winter season, the insects were few in number. No terrestrial reptiles have as yet been found on the Tortugas, while at Key West we find many of the frogs, toads, lizards, and snakes characteristic of the southern spit of the mainland, all this showing that the Tortugas reefs have not been above the level of the sea long enough to have received as yet the fauna or flora characteristic of the more northern line of keys.

The explanation given in this paper of the formation of huge deposits of limestone from the limestone carcasses of Invertebrates, takes it for granted that the most favorable conditions for their support exist, and this condition we assume to be an abundance of food brought to them by the great oceanic currents passing over the regions where these submarine plateaux are forming. We know as yet too little of the fauna of the oceanic basins to be able to affirm how far the population of the bottom depends upon the food it receives from oceanic currents. We can only judge by analogy. No marine fauna has as yet been explored which equals in variety or in the number of its individuals that of the Caribbean and of the Gulf of Mexico from the depth of two hundred and fifty to about one thousand fathoms. It has proved

richest in the districts most favorably situated with regard to the currents and the food supply they bring in their track. It is but natural to extend this effect to other great oceanic currents, and in their track we may therefore expect to find the most favorable conditions for the support of an immense fauna. In fact, the question of food is of the utmost importance to the distribution, not only of marine, but of terrestrial animals, and the absence or presence of an abundant supply of suitable nourishment must of necessity be an all-important factor in the character and variety of the fauna of any place or period, — far more influential, perhaps, than the many obscure physical causes upon which we are so apt to explain the distribution of animal life. On the continental ledges, where the shore detritus is gradually accumulated, bringing with it a large amount of animal and vegetable food, we find the most populous fauna near the hundred-fathom line. When, in addition to the action of the influences which have accumulated the shore detritus, we have a continental shore or plateau bathed by a great and powerful current, bringing with it an abundance of pelagic life, we may expect a superabundant supply of food, and consequently a fauna of unusual richness and variety. The fauna of the Pourtalès Plateau, of the hundred-fathom slope to the westward of the Tortugas, of the northeastern slope of the Yucatan Plateau, of the windward side of the Lesser Antilles, and of the continental slope of the eastern coast of the United States below the hundred-fathom line, are all examples of such districts supporting a marine fauna of surpassing richness. In a similar way, we may expect to find in the track of the great Pacific equatorial current also the most favorable conditions for the support of a rich and varied marine fauna. The "Challenger" found, perhaps, no richer field than that off the coast of Japan, which lies directly in the track of the Japanese current, and may be considered as the Pacific counterpart of the Florida and Caribbean fauna.

In past geological times the effect of the currents in determining the distribution of the marine invertebrates must have been as marked as it is at the present day. As long as we had a great equatorial current running practically unbroken round the world, and only slightly deflected by the great continental islands of Central America and of the East Indies, which stood in the path of this great equatorial belt, it was natural that we should have a very extensive geographical range for all the tropical marine forms. It was only after the complete shutting off or comparative isolation of the Atlantic from the Pacific that different physical conditions began to exist simultaneously, which were of the greatest importance in reducing the supply of food to the animals on the west coast of the continental barriers, and in extending

towards the north, as far as the temperature would allow, a supply of food far more abundant than that with which the fauna of the eastern coast was supplied before such a break of continuity existed. As this separation of the Atlantic and Pacific probably took place late in the Cretaceous period, and was perhaps not completed till the Middle Tertiary, we shall naturally expect to find the marine fauna of the earlier geological periods of the Old and the New World to be very similar, and consisting of many identical species. These older faunæ flourished on the shores and continental shelves, either washed by the great equatorial currents or by branches extending both north and south along the then existing continents and continental islands; and where we now find rich fossiliferous deposits we may feel assured that the beds at the time of their formation lay in the track of a primary or a secondary marine current, which supplied an abundance of pelagic food indirectly necessary for the support of any rich marine fauna.

EXPLANATION OF THE PLATES.

PLATE I.

Sketch map of the Tortugas, showing the position of the reefs on the southeast extremity of the great Florida Plateau, and the commencement of the New Tortugas Reef to the westward of the Loggerhead Key. Reduced from Coast Survey charts.

PLATE II.

Colored map showing the distribution of the principal types of reef-builders, as well as the distribution of coral sand and ooze. The hydrography of this map is taken from Coast Survey Chart No. 471[a]; the original of this plate was colored on the spot.

PLATE III.

Sections across the Tortugas, prepared from Coast Survey Chart No. 471[a], along the lines marked 1–1′ to 10–10′ on Plate II. 6 fms. = $\frac{1}{3}$″.

PLATE IV.

Sections across the Tortugas, prepared from Coast Survey Chart No. 471[a], along the lines marked *A*–*A*′ to *E*–*E*′ on Plate II. 6 fms. = $\frac{1}{3}$″.

PLATE V.

Sketch map of the Marquesas. An atoll to the westward of Key West along the continuation of the line of keys, with section along the line *A B*, prepared from Coast Survey Chart No. 470. Vertical scale, $\frac{1}{8}$″ = 1 fm.

Sketch map of the great atoll of Alacran Reef, on the Yucatan Bank, with a section prepared from the Hydrographic Office Chart No. 403. Vertical scale, $\frac{1}{4}$″ = 5 fms.

PLATE VI.

Sketch map of the southern extremity of Florida, to show the lines along which the sections Cape Romano–*G*′, *S*–*G*, *T*–*S*, *M*–Cape Sable, *M*–*F* of Plate VII., and the lines Mainland to 1, 2, 3, 4, 5, 6, 7, 8, 9–9 to 13–13, as well as the line along the course of the reef of Plate VIII., have been taken. Prepared from Coast Survey charts.

PLATE VII.

Sketch map of Florida, showing the lines along which the sections of this plate have been prepared. See also Plate VI. for some of the lines extending partially across the reef. Constructed from Coast Survey charts.

PLATE VIII.

Longitudinal section along the course of the reef from off the Quicksands to off Cape Florida. Cross-sections of the reef along the lines 1–13 of the sketch map of Plate VI. Constructed from Coast Survey charts.

PLATE IX.

Coral sand beach south of the Navy Depot, Key West.

PLATE X.

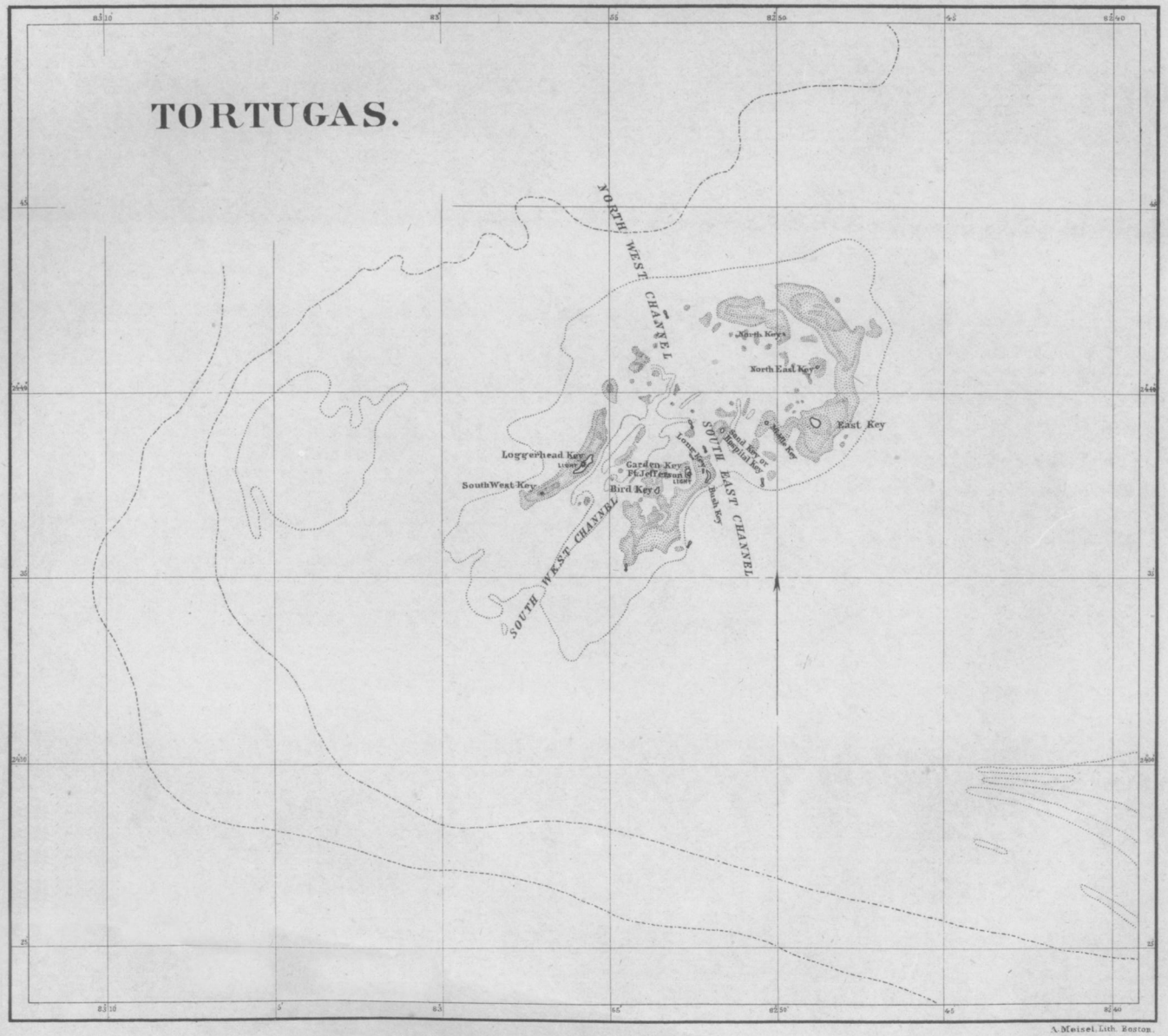
Mangrove Islands in the distance, seen from the mangrove beach north of the slaughter-house, Key West.

PLATE XI.

Lagoon formed by promontories and low islands covered with mangroves, on the northeast shore of Key West, near the slaughter-house.

PLATE XII.

Coral-rock beach north of Fort Taylor, exposed to the action of the waves of the channel between the outer reef and Key West.



A. Meisel, Lith. Boston.


83° 00'
5 8'
4 4'
4 2'
4 0'
5
4
3


NORTH WEST CHANNEL
Bellamy Shoal
8
7
6
5
4
54'
56'


52′
82° 50′
8
Y.
B.
9
NORTH WEST CHANNEL
North Key
disappear

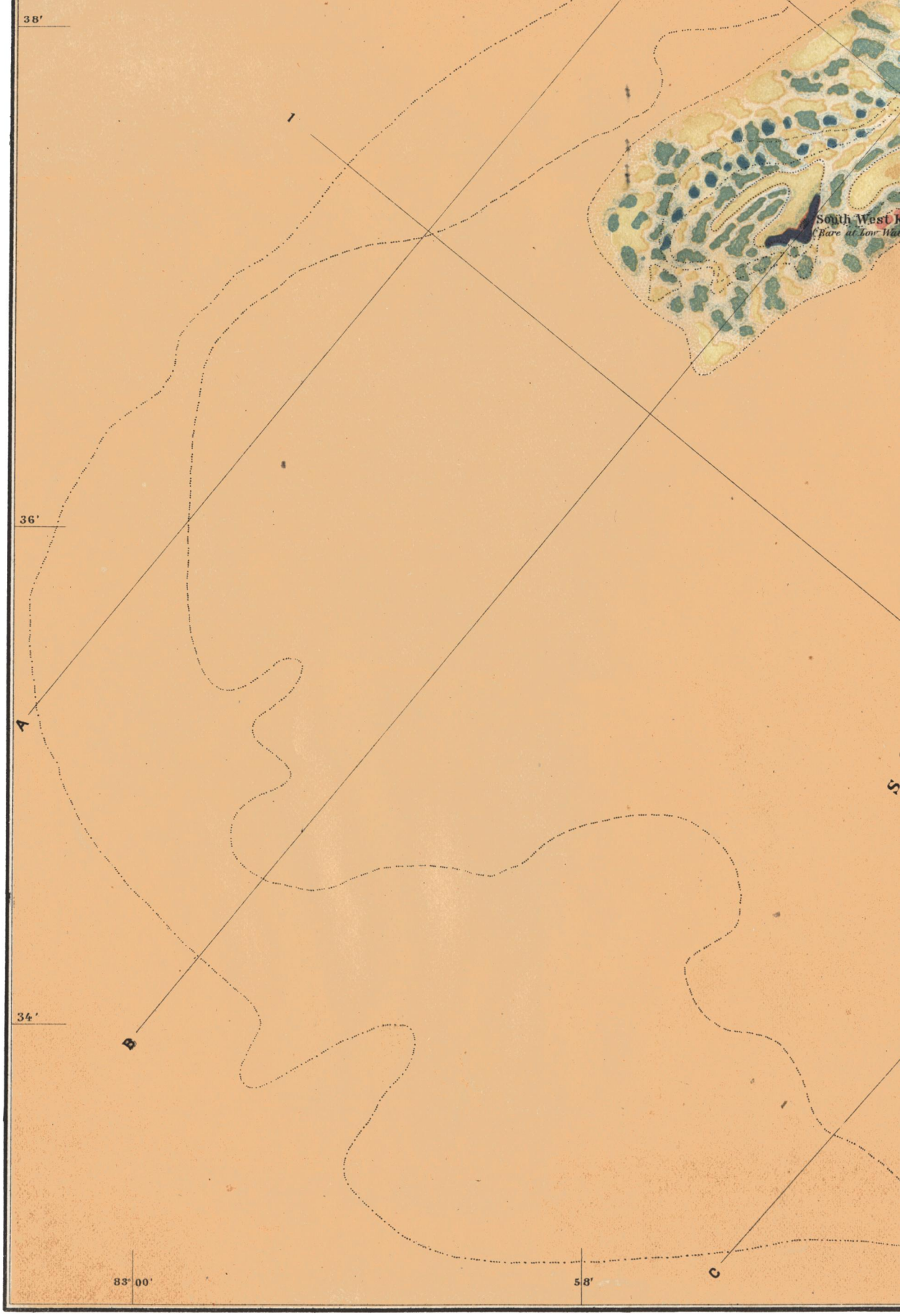

82° 50'
10
48'
C
44'
42'
D
10'
North Key
(disappeared)
North Key Harbor
North East Key
(disappeared)
24°40'
E
9'

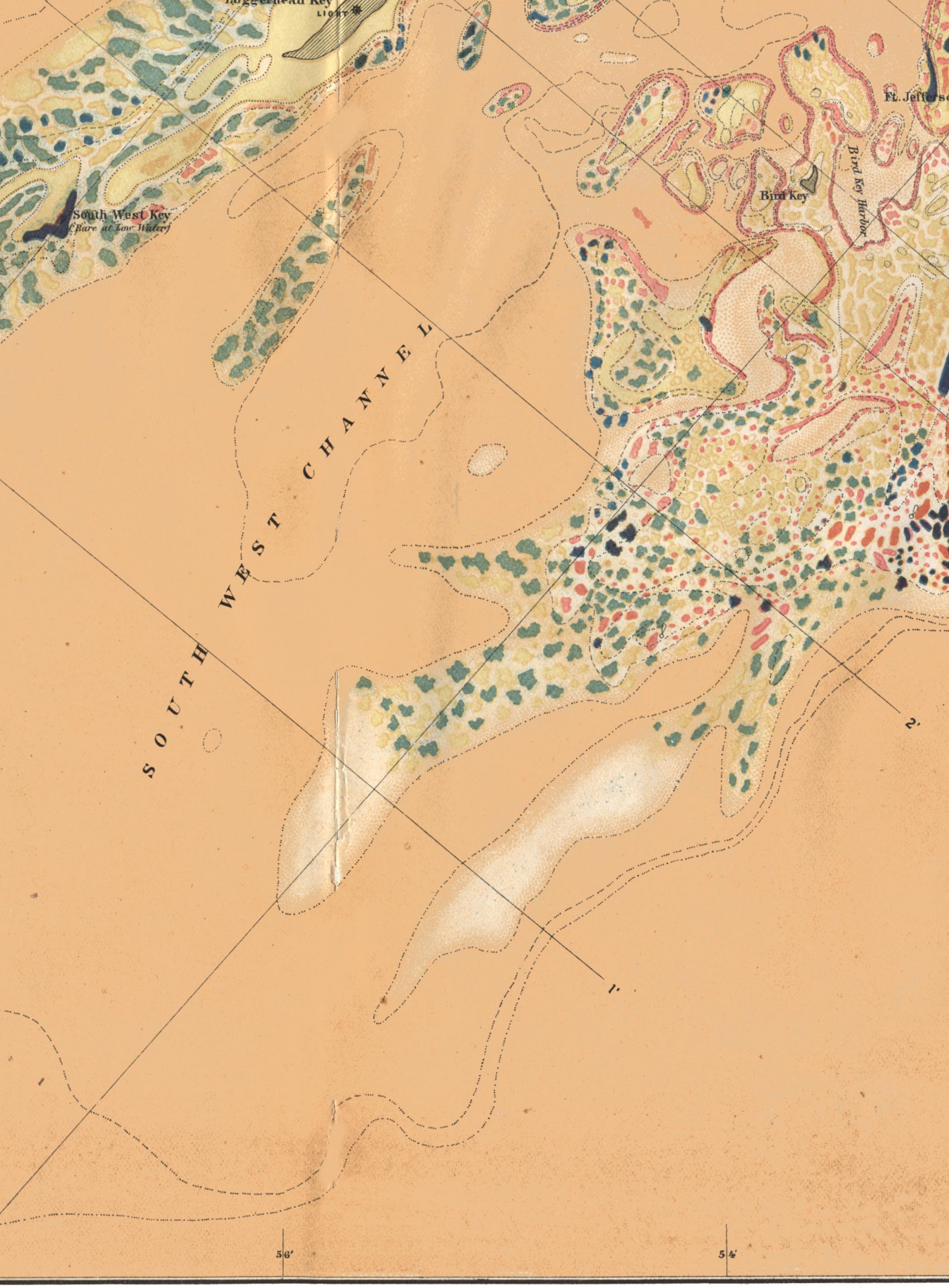

40'
38'
36'
1
2
3
4
5
South West R
Bare at Low Wat


5
4
Billiard Shoal
White Shoal
Loggerhead Key
LIGHT
South West Key
(Bare at Low Water)
Bird Key
Bird Key Harbor
Ft. Jefferson
CHANNEL


Middle Key
Sand Key or
Hospital Key
Middle Ground
Long Key Shoal
Long Key
Garden Key
Ft. Jefferson
Bush Key
Bird Key Harbor
SOUTH EAST CHANNEL
D
6'
5'
4'
3'


North Key Harbor
North East Key
(disappeared)
East Key
iddle Key
24°40'
38'
36'
10'
9'
8'
7'
6'
E'
E


38'
36'
34'
A
B
C
South West
Bare at Low Wa
83° 00'
58'


Loggerhead Key
LIGHT
South West Key
(Bare at Low Water)
Bird Key
Bird Key Harbor
Ft. Jefferson
SOUTH WEST CHANNEL
2'
1'
1
56'
54'


Long Key
Garden Key
Ft. Jefferson
Bush Key
Bird Key Harbor
SOUTH EAST CHANNEL
5'
6'
4'
3'
2'
SOUNDINGS:
1 fathoms
2 "
3 "
6 "
10 "
12 "
82° 52'
82° 50'



38'

36'

TORTUGAS

Scale $\frac{1}{40\,000}$

EXPLANATION:

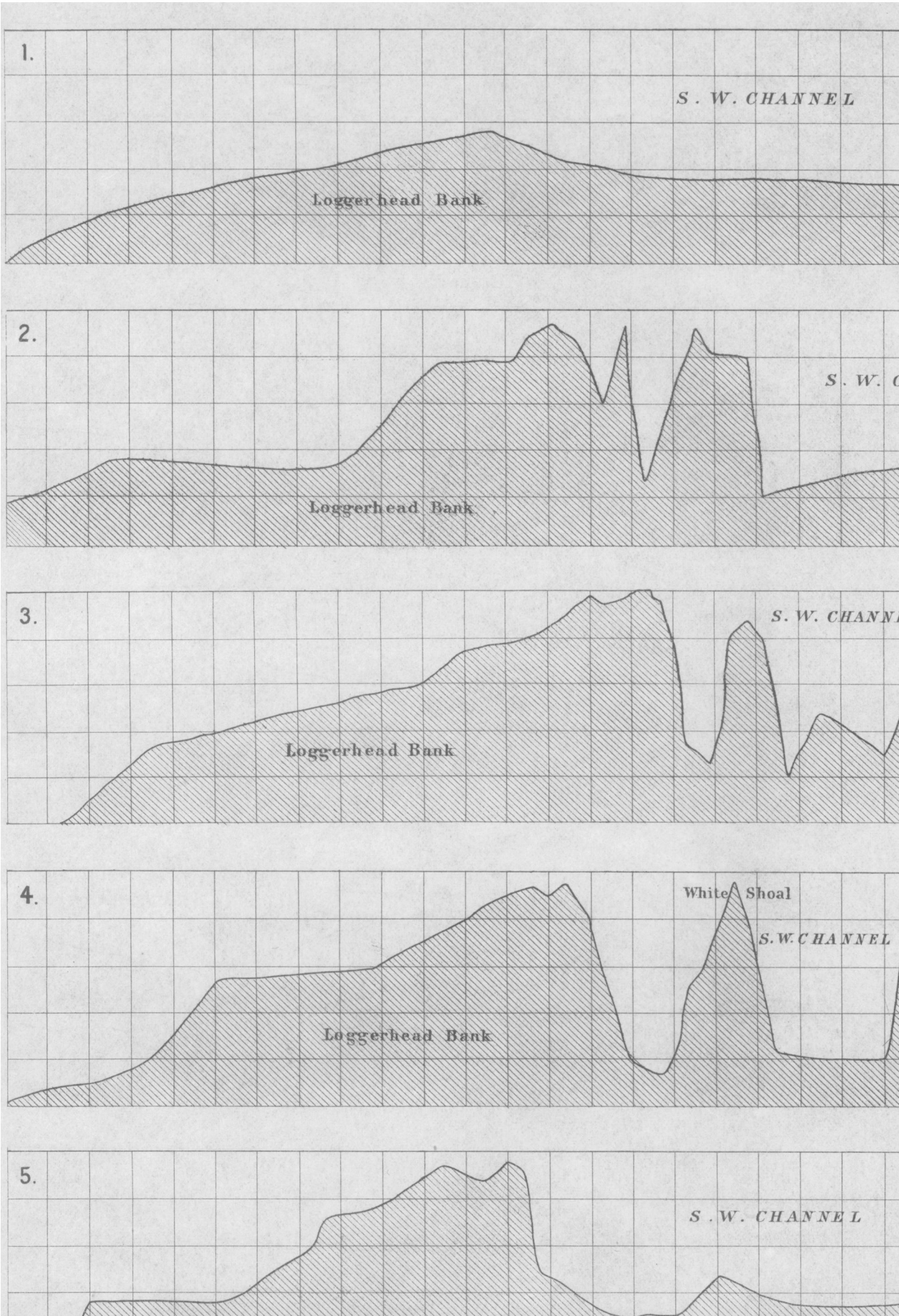
- *Land.*
- *Fine Sand and Ooze.*
- *Broken Coral heads.*
- *Large heads Astraea and Meandrina.*
- *Madrepora cervicornis.*
- *Coarse Sand on Flats above 6 fathom line.*
- *Madrepora palmata.*
- *Gorgoniae and broken ground.*
- *Coarse Sand and Porites.*

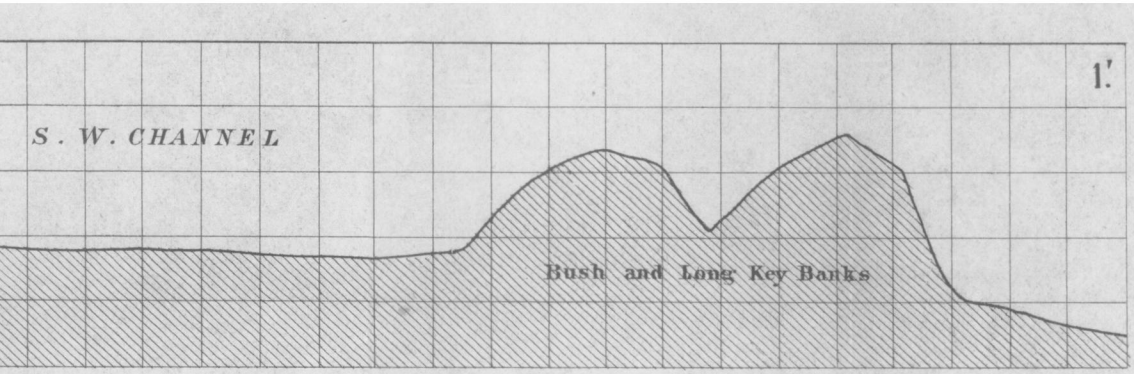
24' 34'

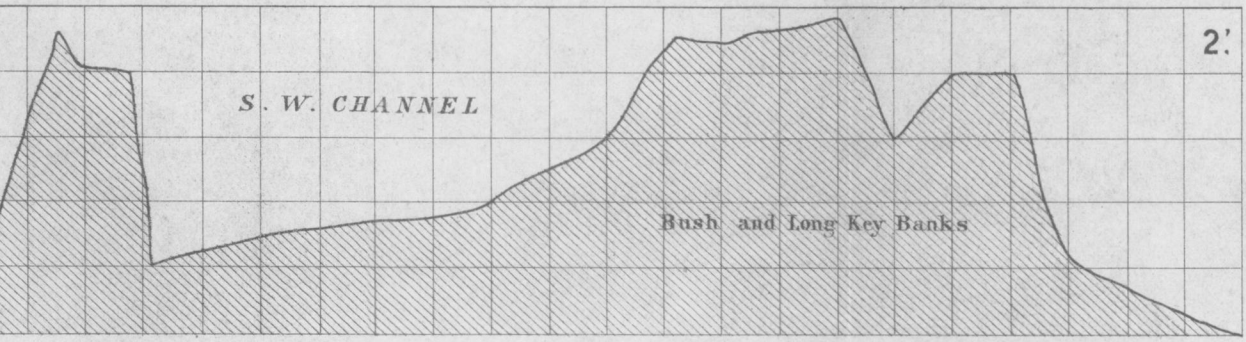
82' 50'

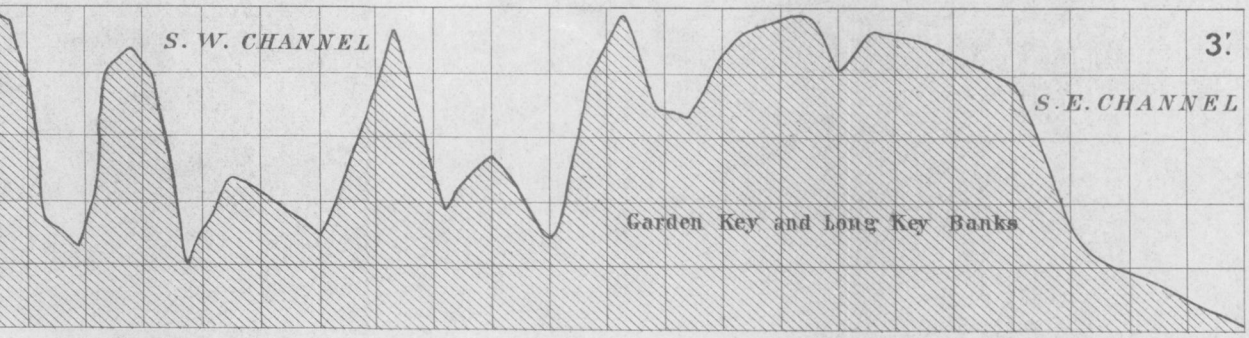
48'

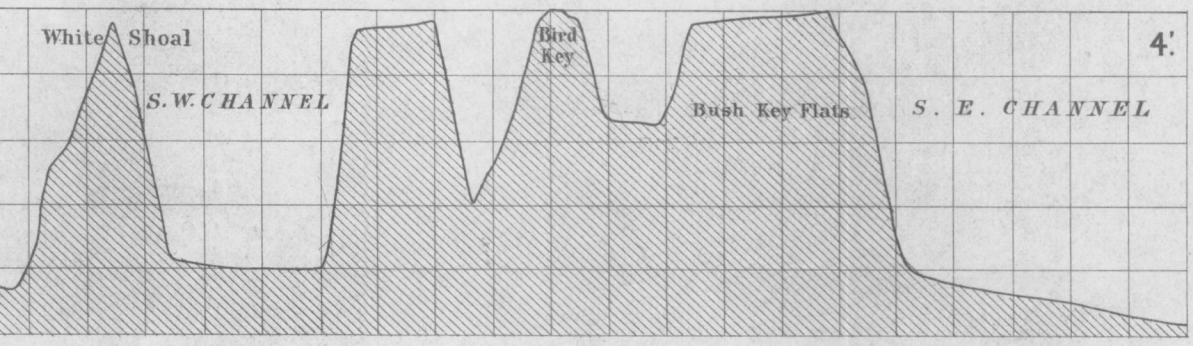
A. Meisel, Lith. Boston.

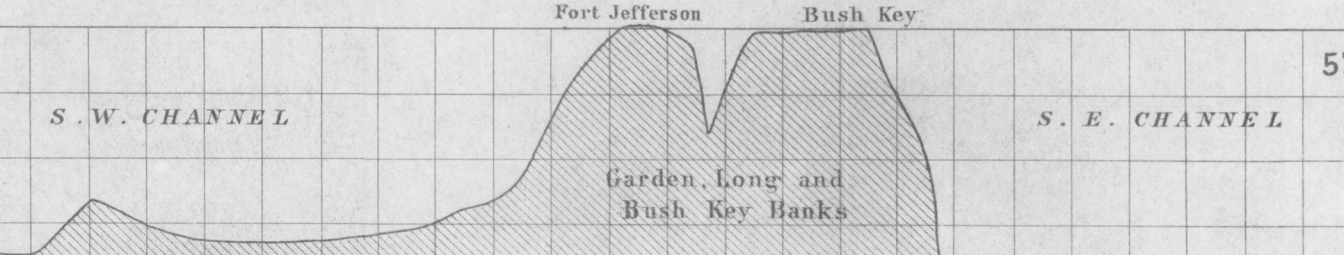

1.
S. W. CHANNEL
Loggerhead Bank
2.
S. W. C
Loggerhead Bank
3.
S. W. CHANN
Loggerhead Bank
4.
White Shoal
S. W. CHANNEL
Loggerhead Bank
5.
S. W. CHANNEL


1'
S. W. CHANNEL
Bush and Long Key Banks

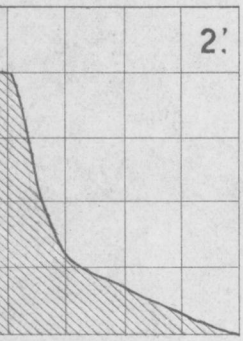

2'
S. W. CHANNEL
Bush and Long Key Banks

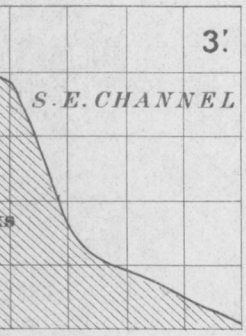

S. W. CHANNEL
3'
S.E. CHANNEL
Garden Key and Long Key Banks


White Shoal
Bird Key
4'
S.W. CHANNEL
Bush Key Flats
S. E. CHANNEL

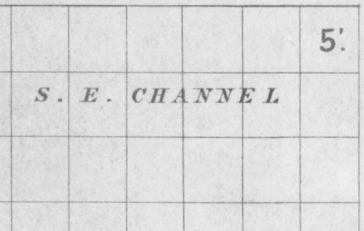

Fort Jefferson
Bush Key
5'
S. W. CHANNEL
S. E. CHANNEL
Garden, Long and
Bush Key Banks

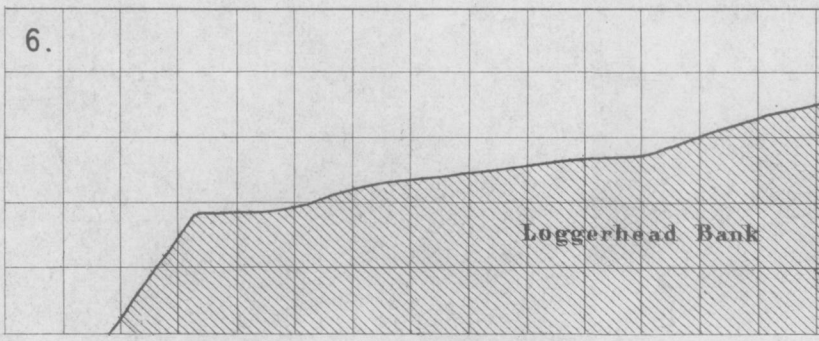

1.'

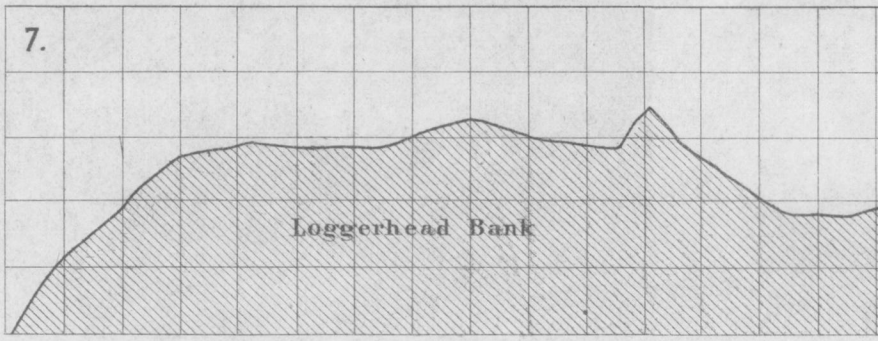

2.'

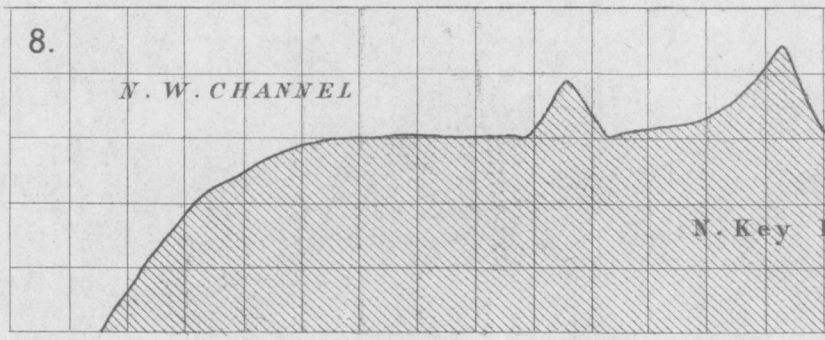

3.'
S.E.CHANNEL

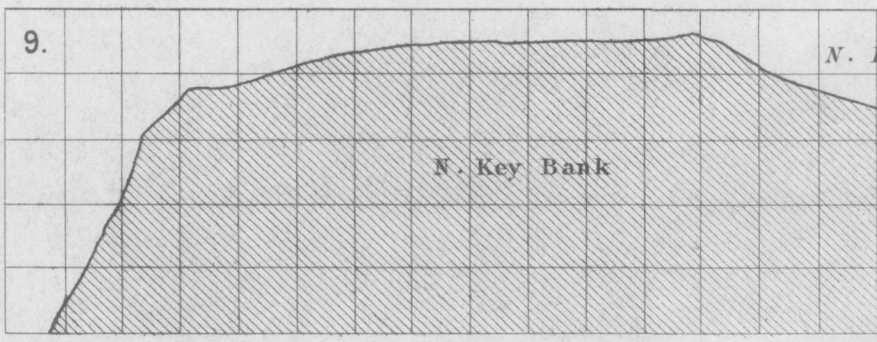

4.'
CHANNEL

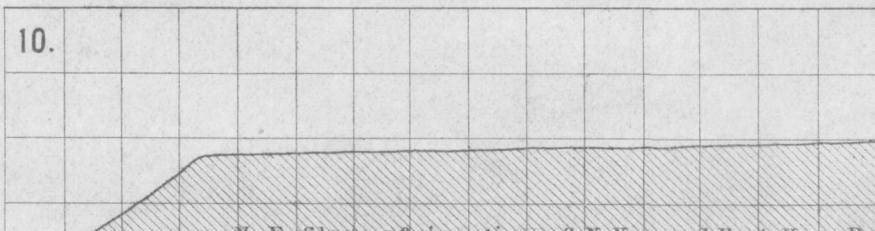

5.'
S. E. CHANNEL

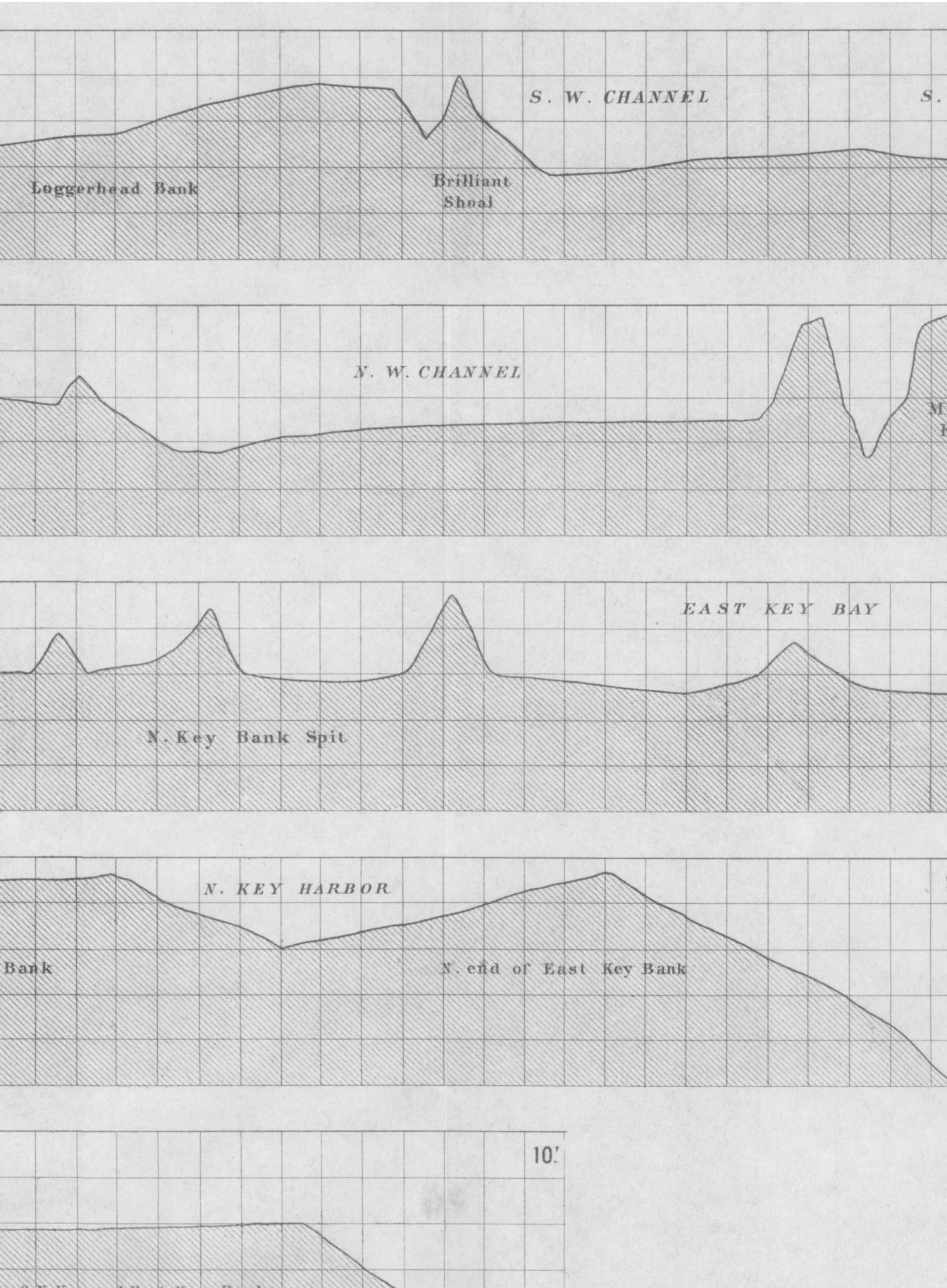

6.
Loggerhead Bank

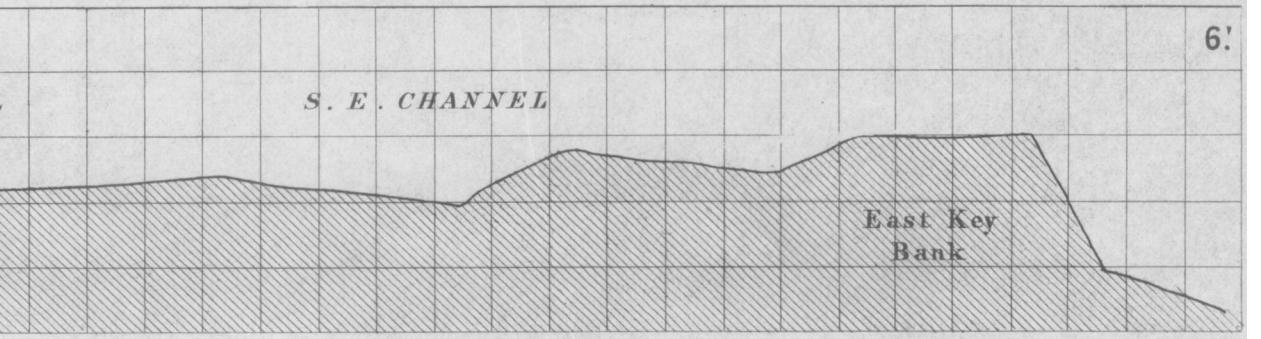

7.
Loggerhead Bank

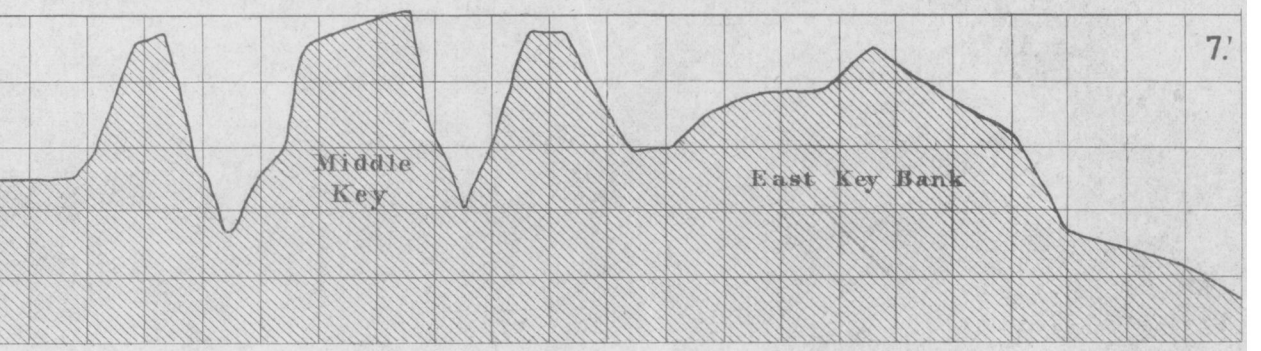

8.
N. W. CHANNEL
N. Key

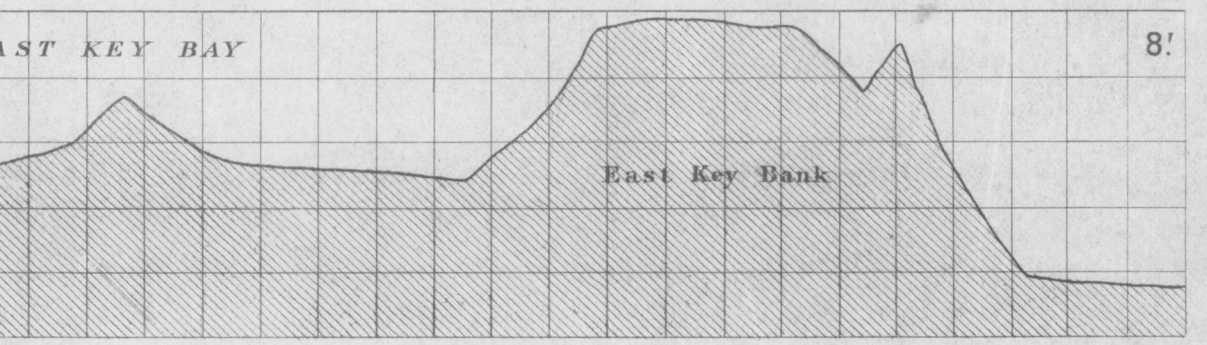

9.
N.
N. Key Bank

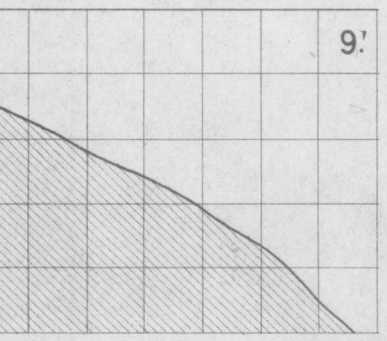

10.


S. W. CHANNEL
S.
Loggerhead Bank
Brilliant
Shoal
N. W. CHANNEL
EAST KEY BAY
N. Key Bank Spit
N. KEY HARBOR
Bank
N. end of East Key Bank
10'

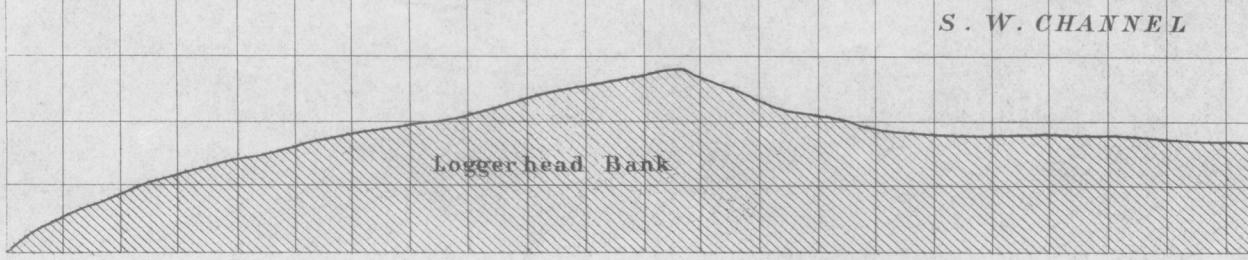


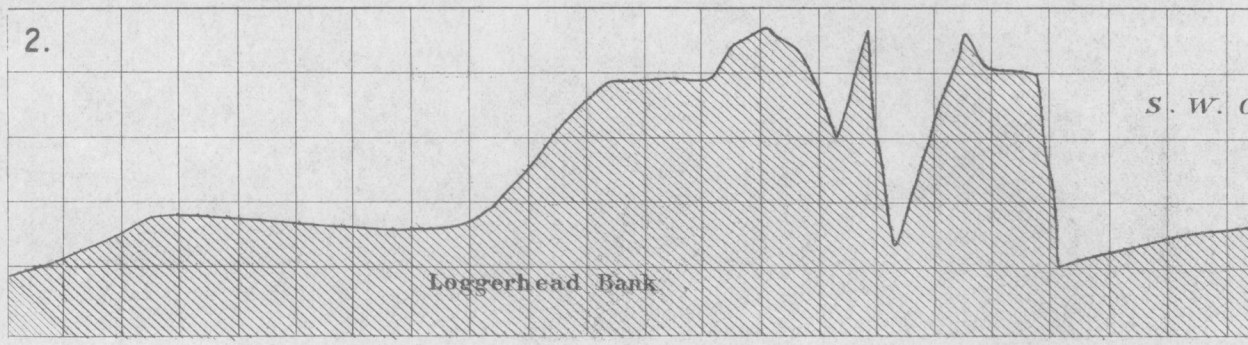


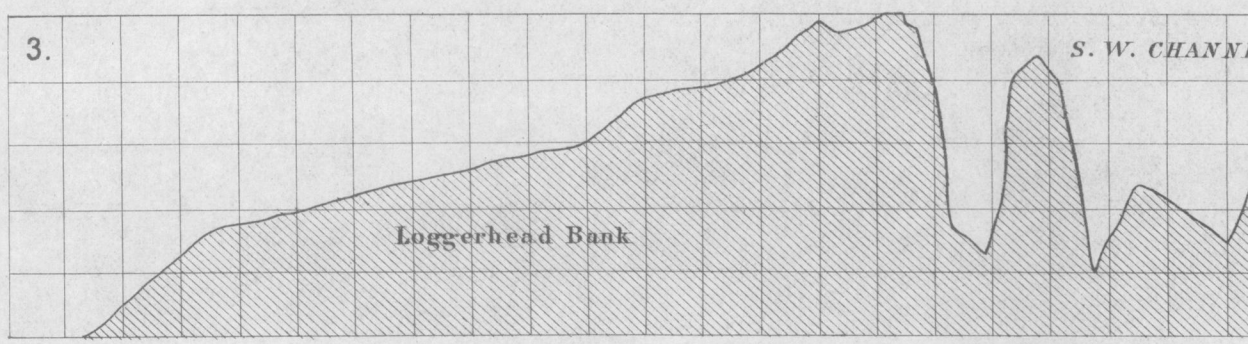


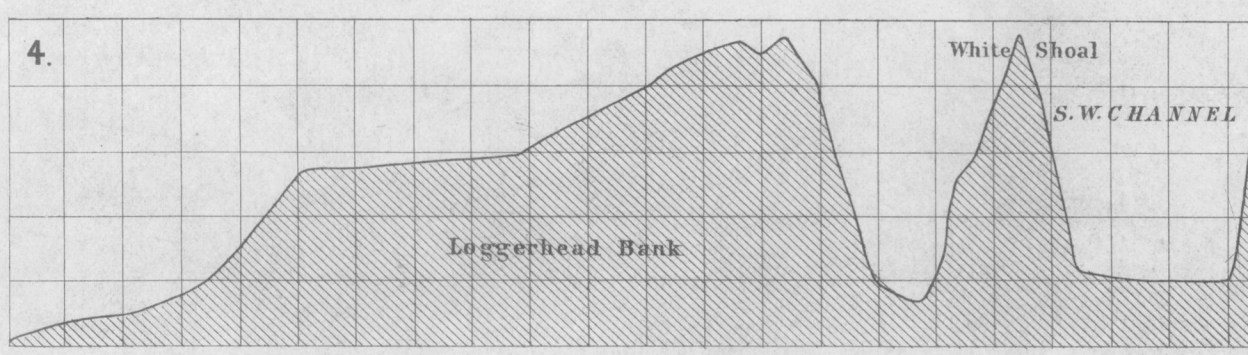


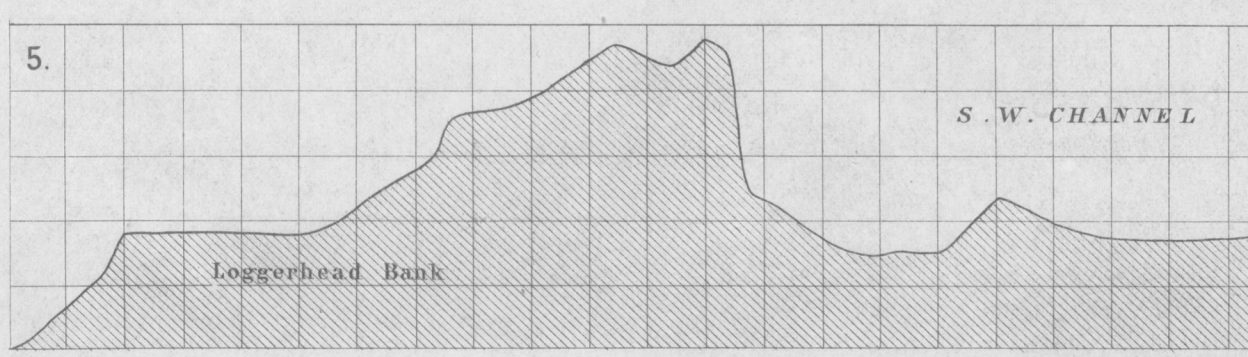
Vertical Scale 6 fathoms = ⅓ inch.

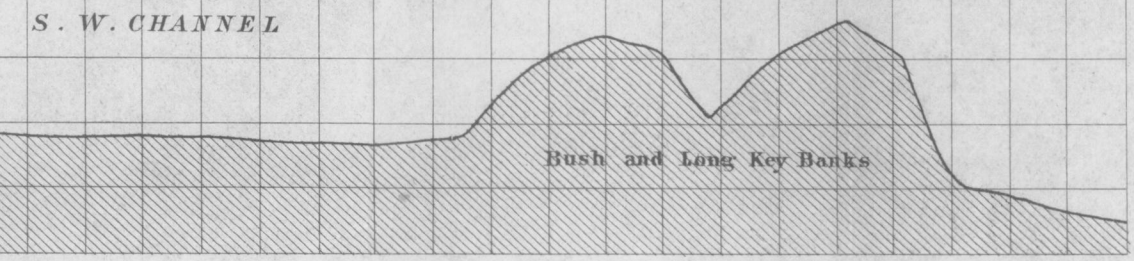

S. W. CHANNEL
Loggerhead Bank

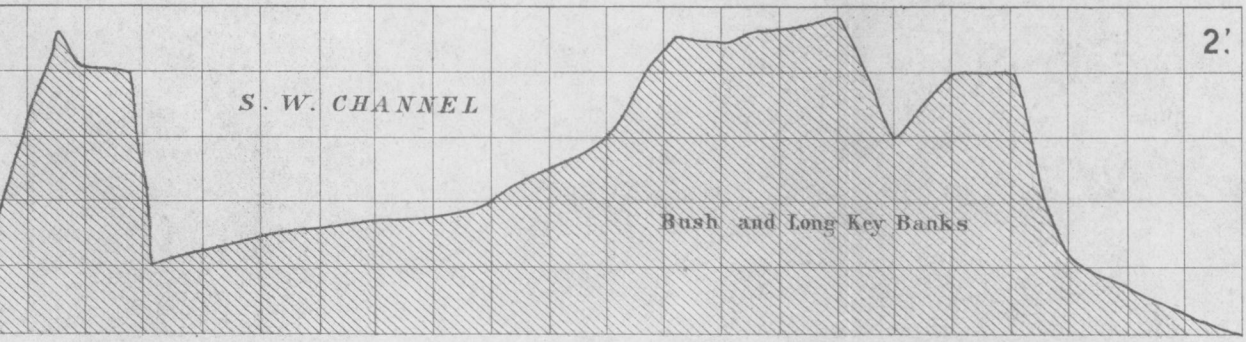

2.
S. W.
Loggerhead Bank

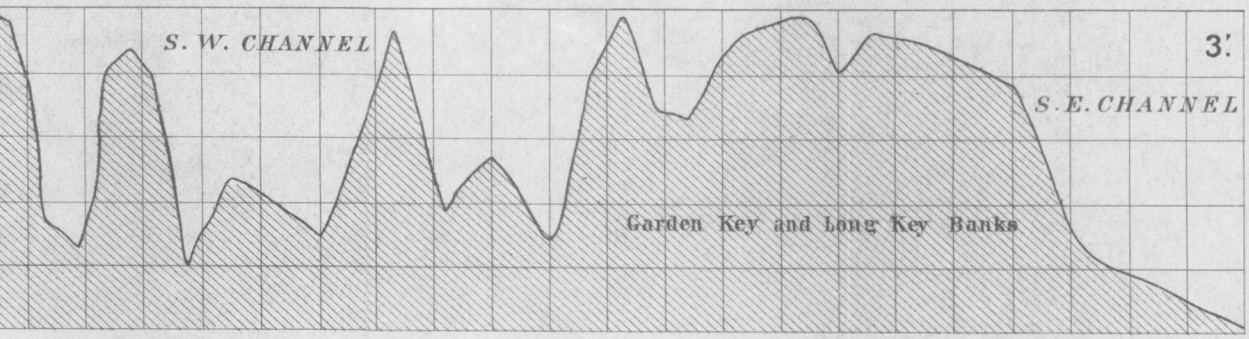

3.
S. W. CHANN
Loggerhead Bank

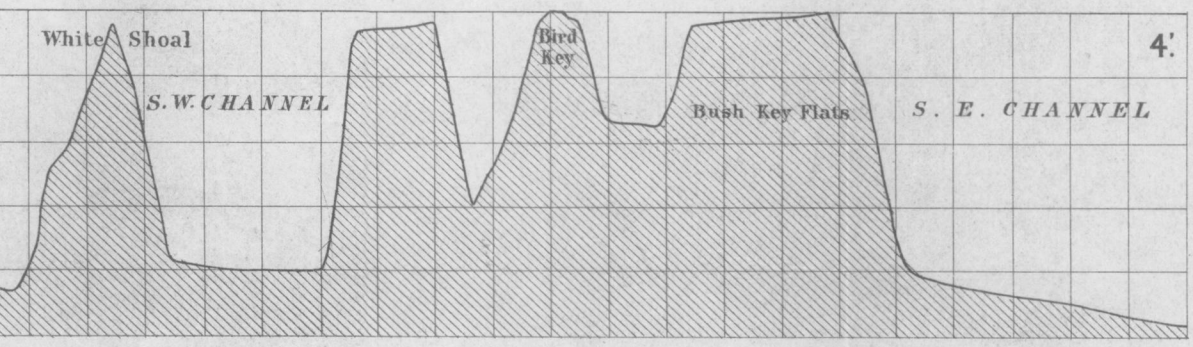

4.
White Shoal
S.W.CHANNEL
Loggerhead Bank

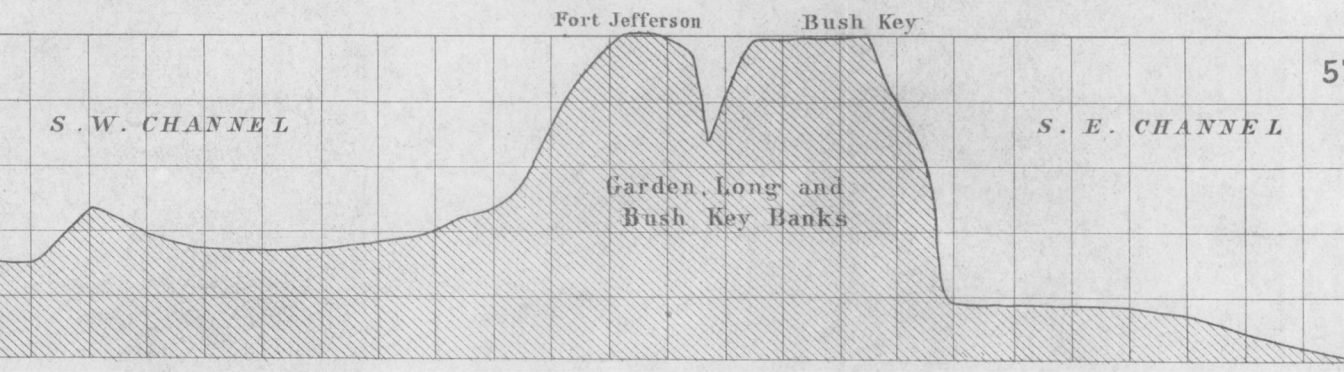

5.
S. W. CHANNEL
Loggerhead Bank


S. W. CHANNEL
Bush and Long Key Banks

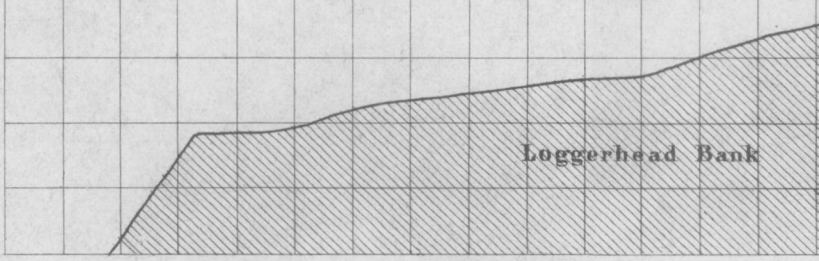

2'.
S. W. CHANNEL
Bush and Long Key Banks

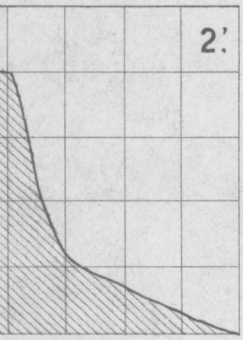

3'.
S. W. CHANNEL
S. E. CHANNEL
Garden Key and Long Key Banks

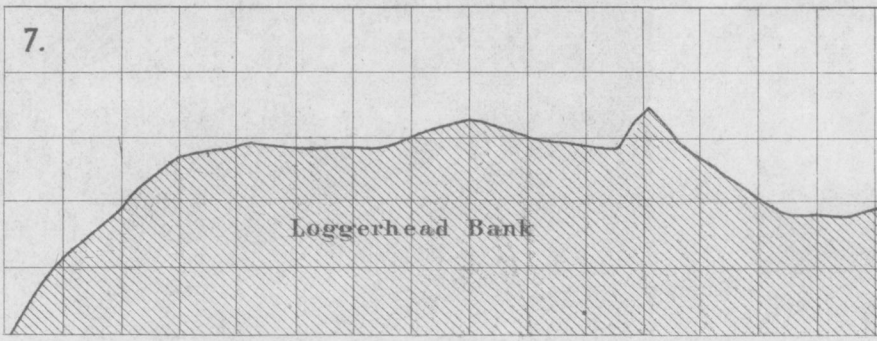

4'.
White Shoal
Bird Key
S. W. CHANNEL
Bush Key Flats
S. E. CHANNEL

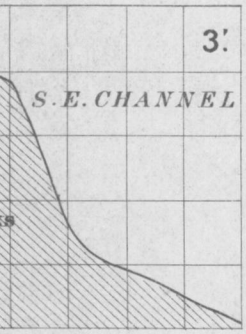

Fort Jefferson
Bush Key
5'
S. W. CHANNEL
S. E. CHANNEL
Garden, Long and
Bush Key Banks

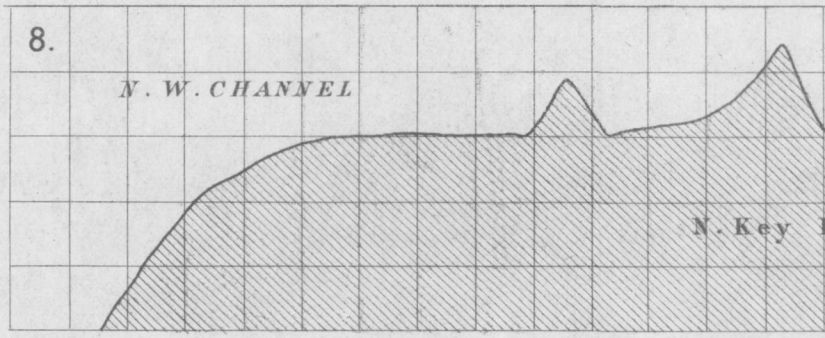



Loggerhead Bank

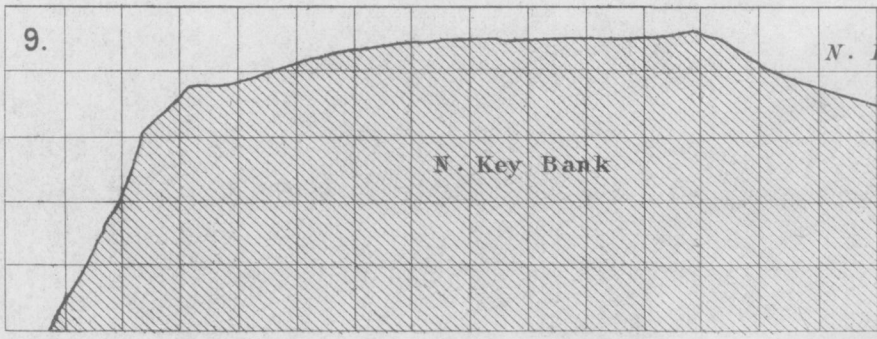

2.

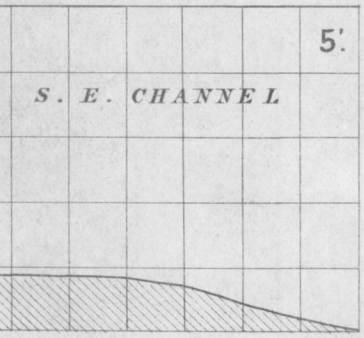

7.
Loggerhead Bank

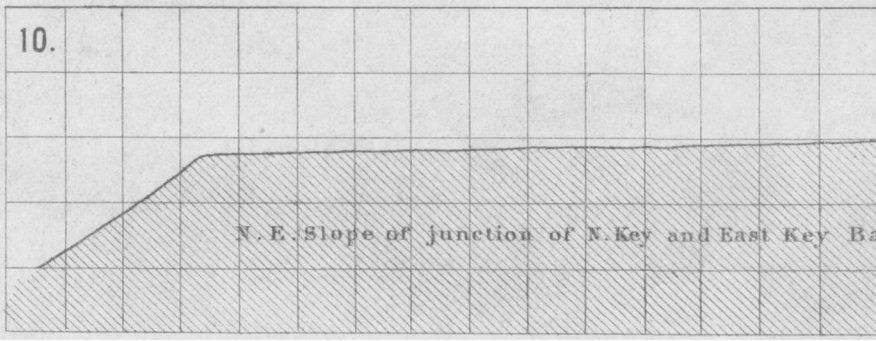

3.
S.E.CHANNEL

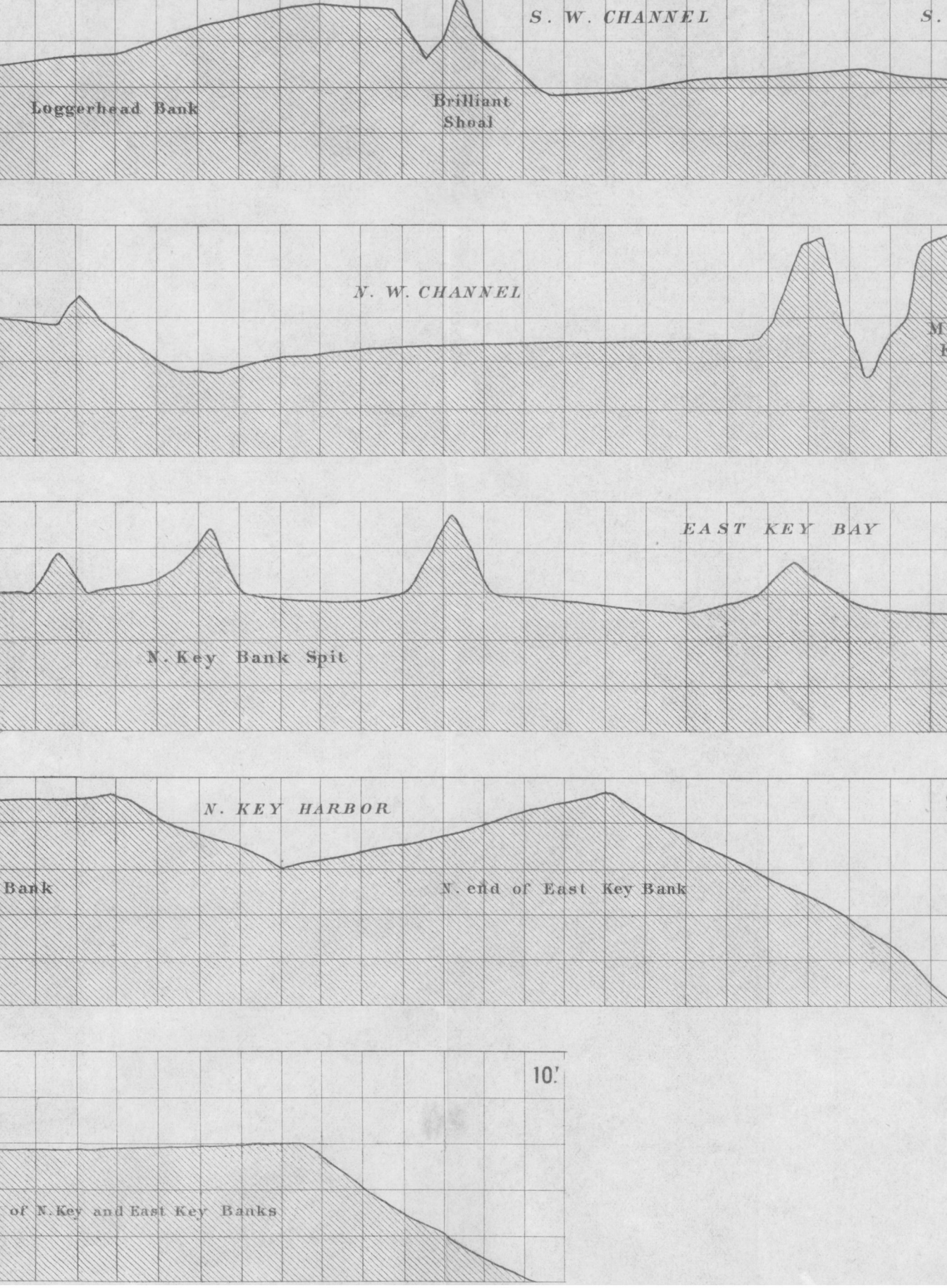

8.
N. W. CHANNEL
N. Key

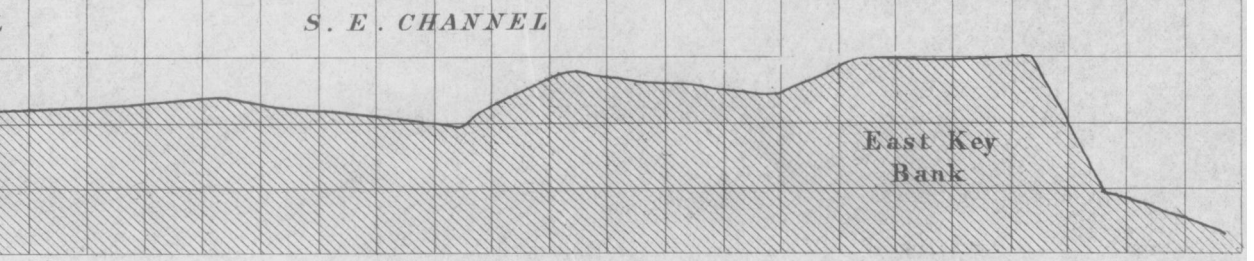

4.
CHANNEL

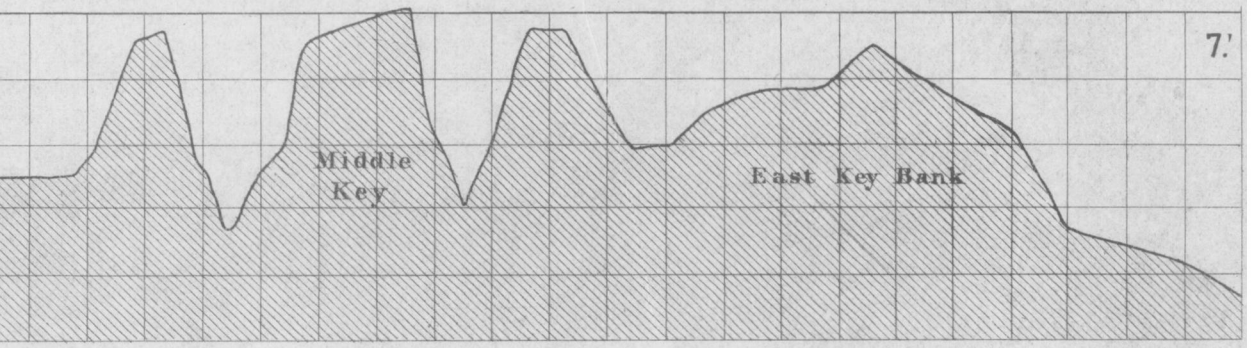

9.
N.
N. Key Bank


5.
S. E. CHANNEL

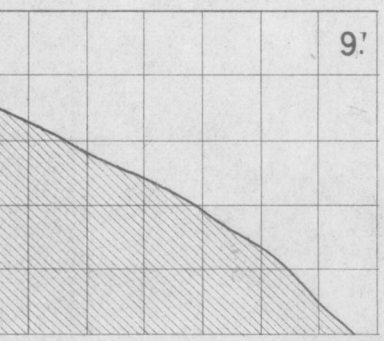

10.
N.E. Slope of junction of N.Key and East Key Ba


S. W. CHANNEL
S.
Loggerhead Bank
Brilliant
Shoal
N. W. CHANNEL
M
EAST KEY BAY
N. Key Bank Spit
N. KEY HARBOR
Bank
N. end of East Key Bank
10'
of N. Key and East Key Banks





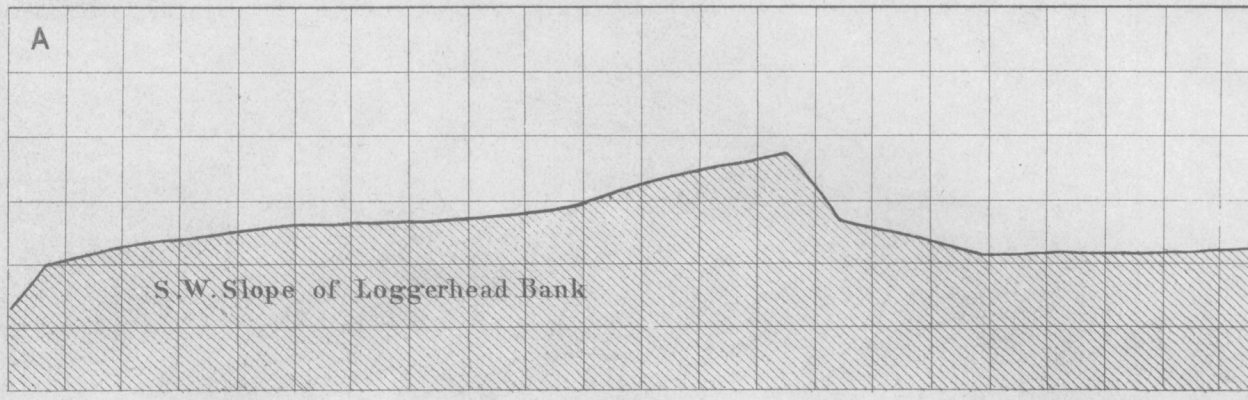


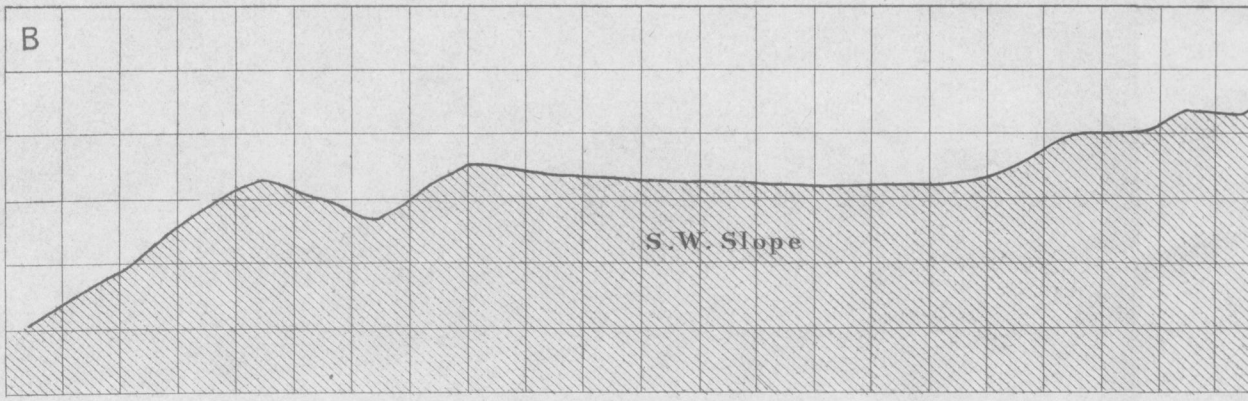


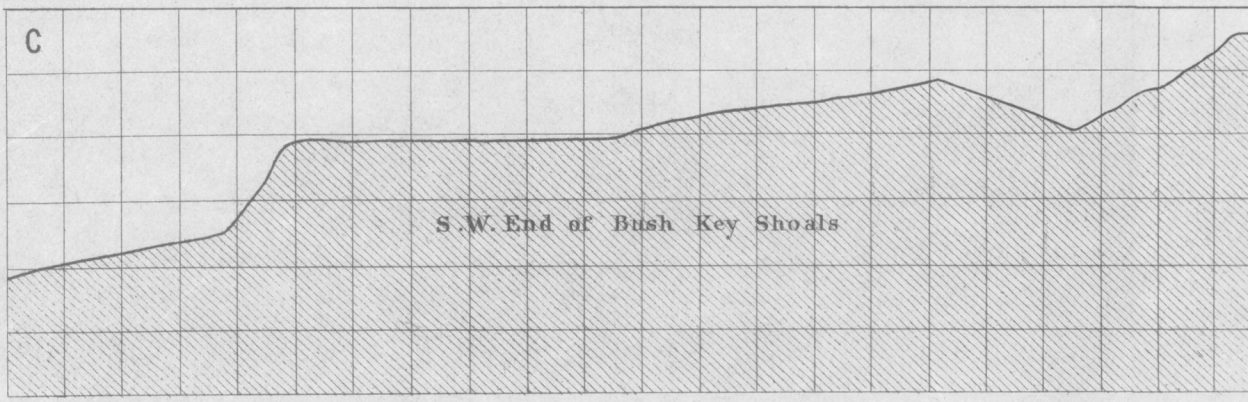
Vertical Scale 6 fathoms = 1/3 inch.

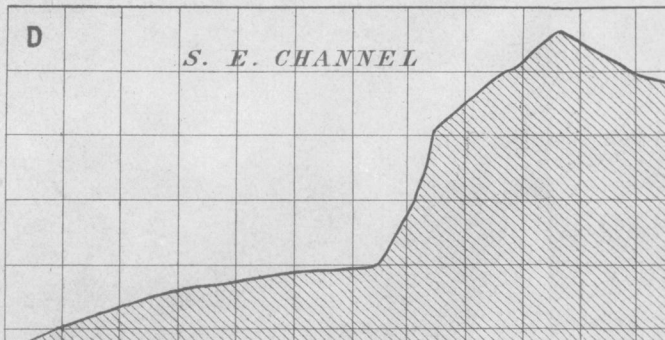
Horizontal Scale 1/40 000.

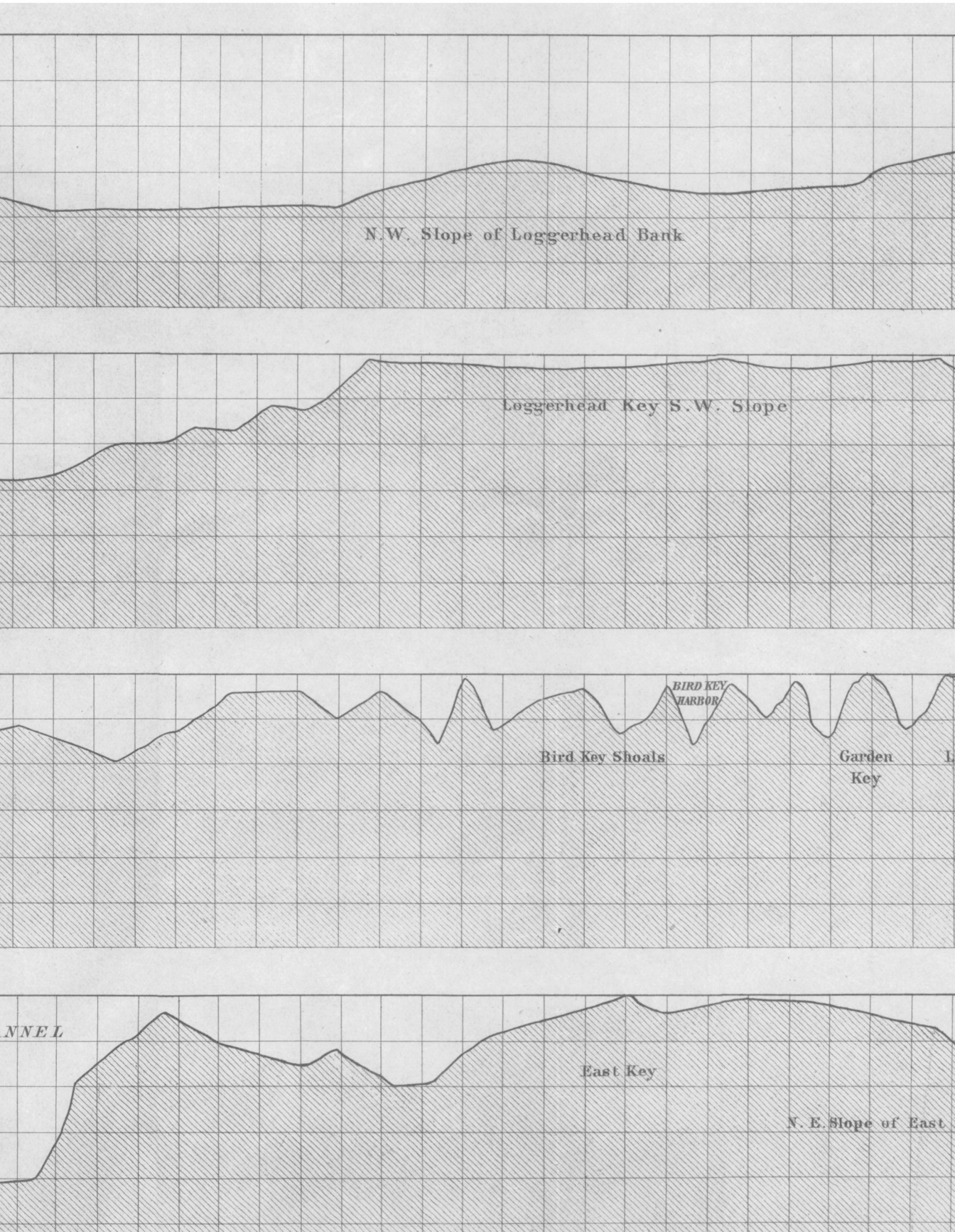
A. Meisel, Lith. Boston.

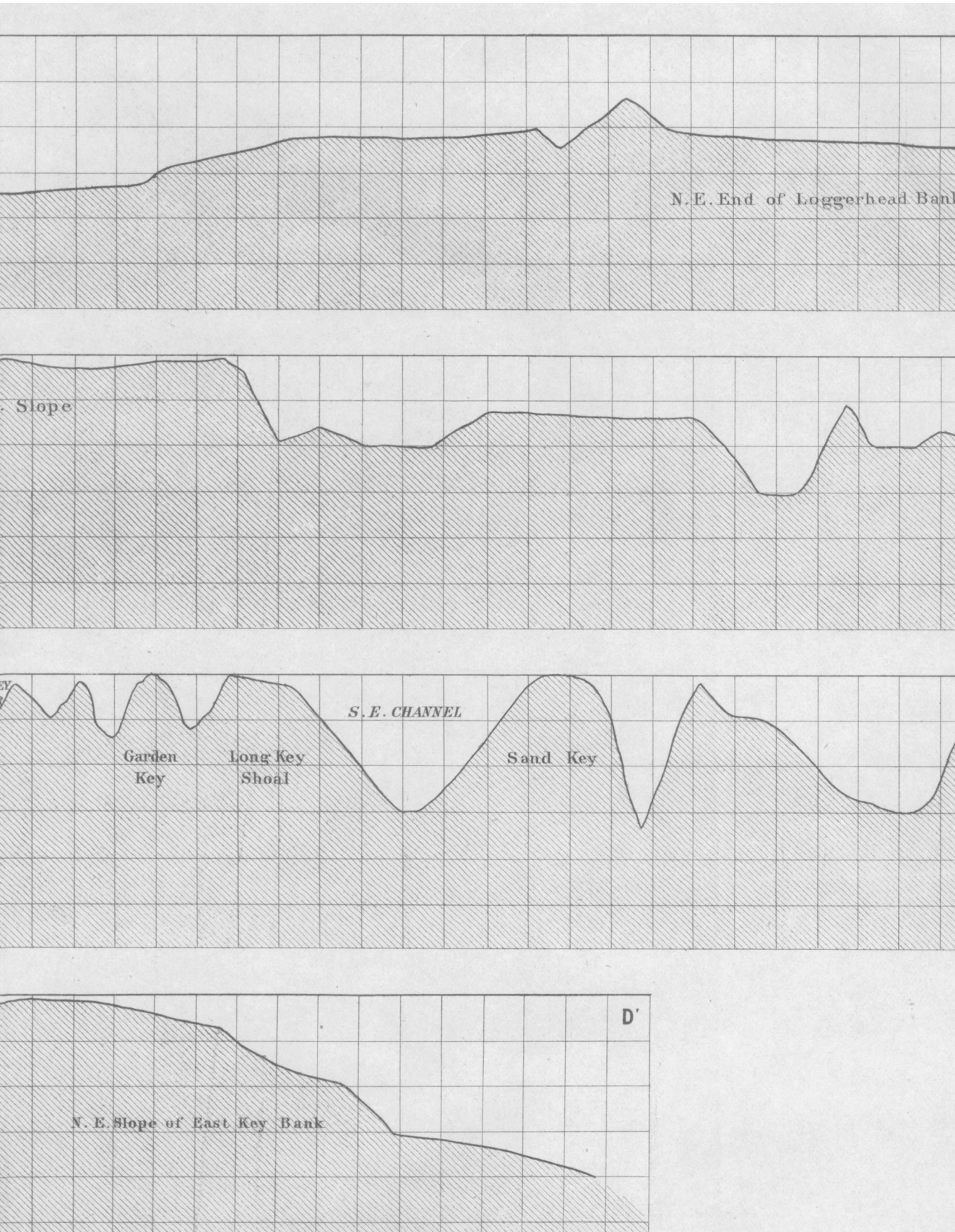

A
S.W. Slope of Loggerhead Bank

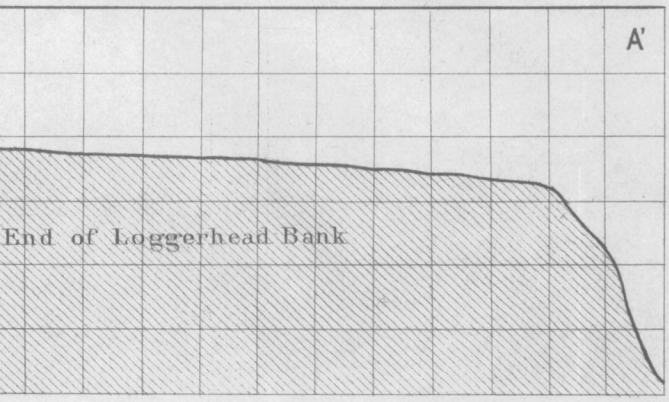

B
S.W. Slope

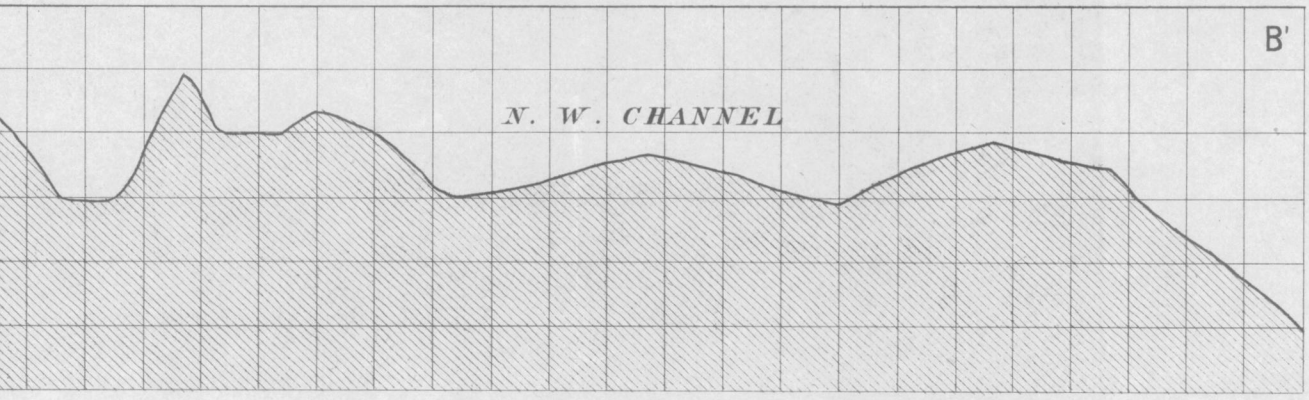

C
S.W. End of Bush Key Shoals

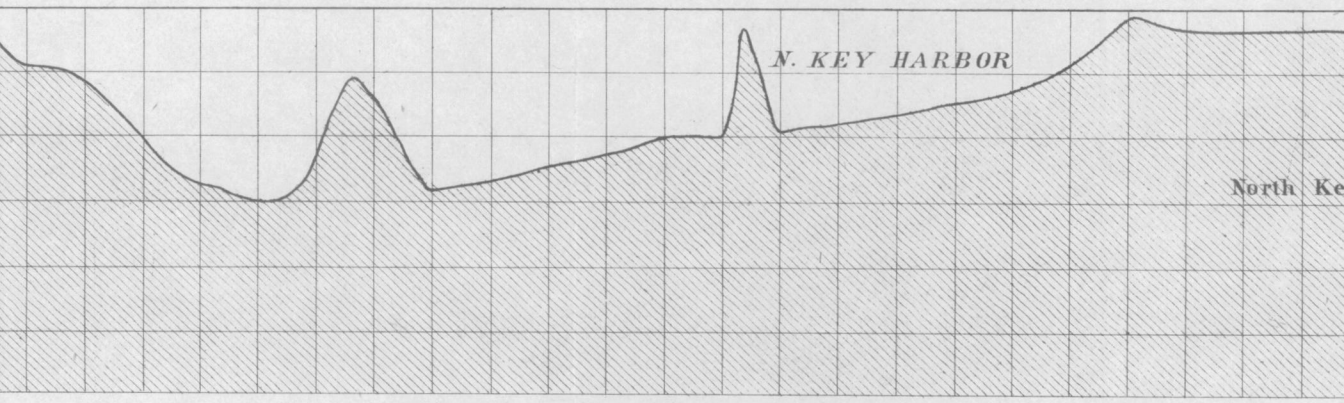

D
S. E. CHANNEL


N.W. Slope of Loggerhead Bank
Loggerhead Key S.W. Slope
BIRD KEY HARBOR
Bird Key Shoals
Garden Key
NNEL
East Key
N. E. Slope of East

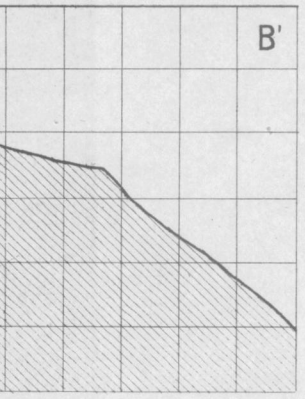

N.E. End of Loggerhead Bank
. Slope
S.E. CHANNEL
Garden Key
Long Key Shoal
Sand Key
D'
N.E. Slope of East Key Bank

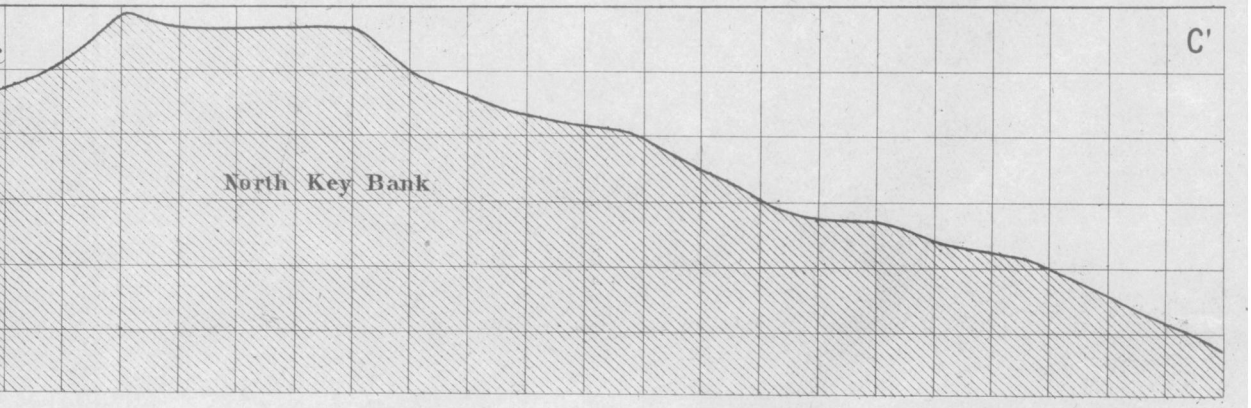

A'
End of Loggerhead Bank

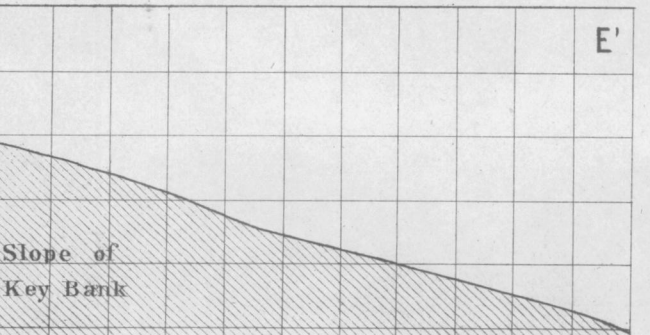

B'
N. W. CHANNEL


N. KEY HARBOR
North Ke


E
S.E. Slope of
East Key Bank

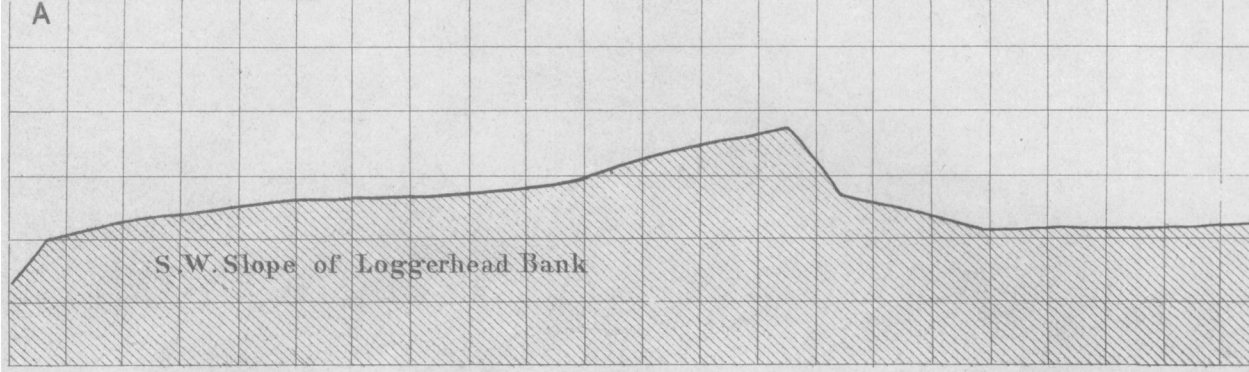


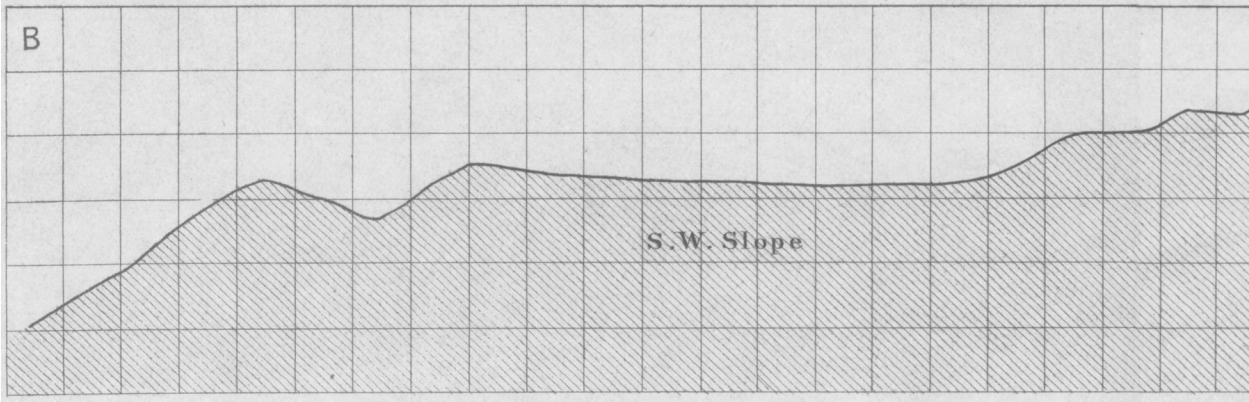


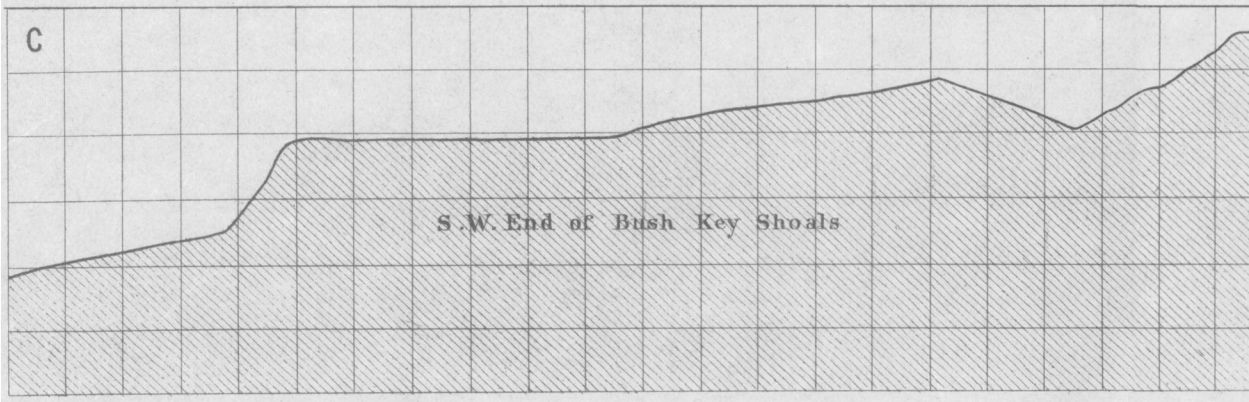


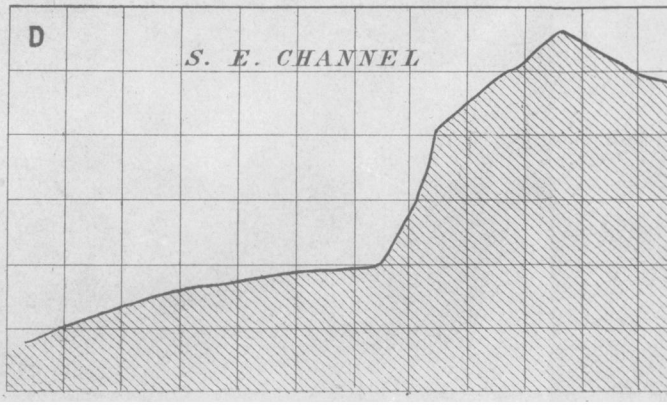
Vertical Scale 6 fathoms = 1/3 inch.

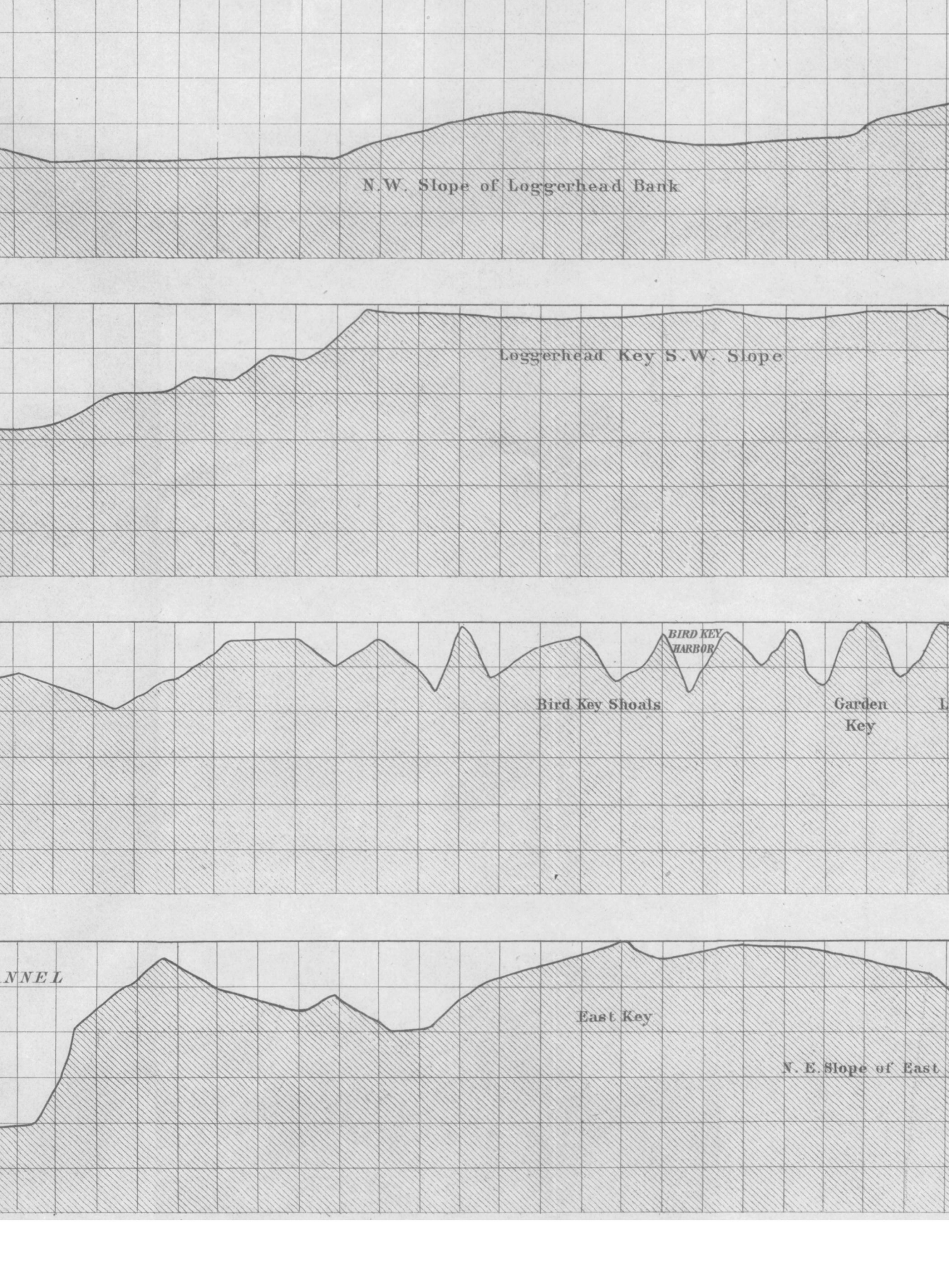
Horizontal Scale 1/40,000

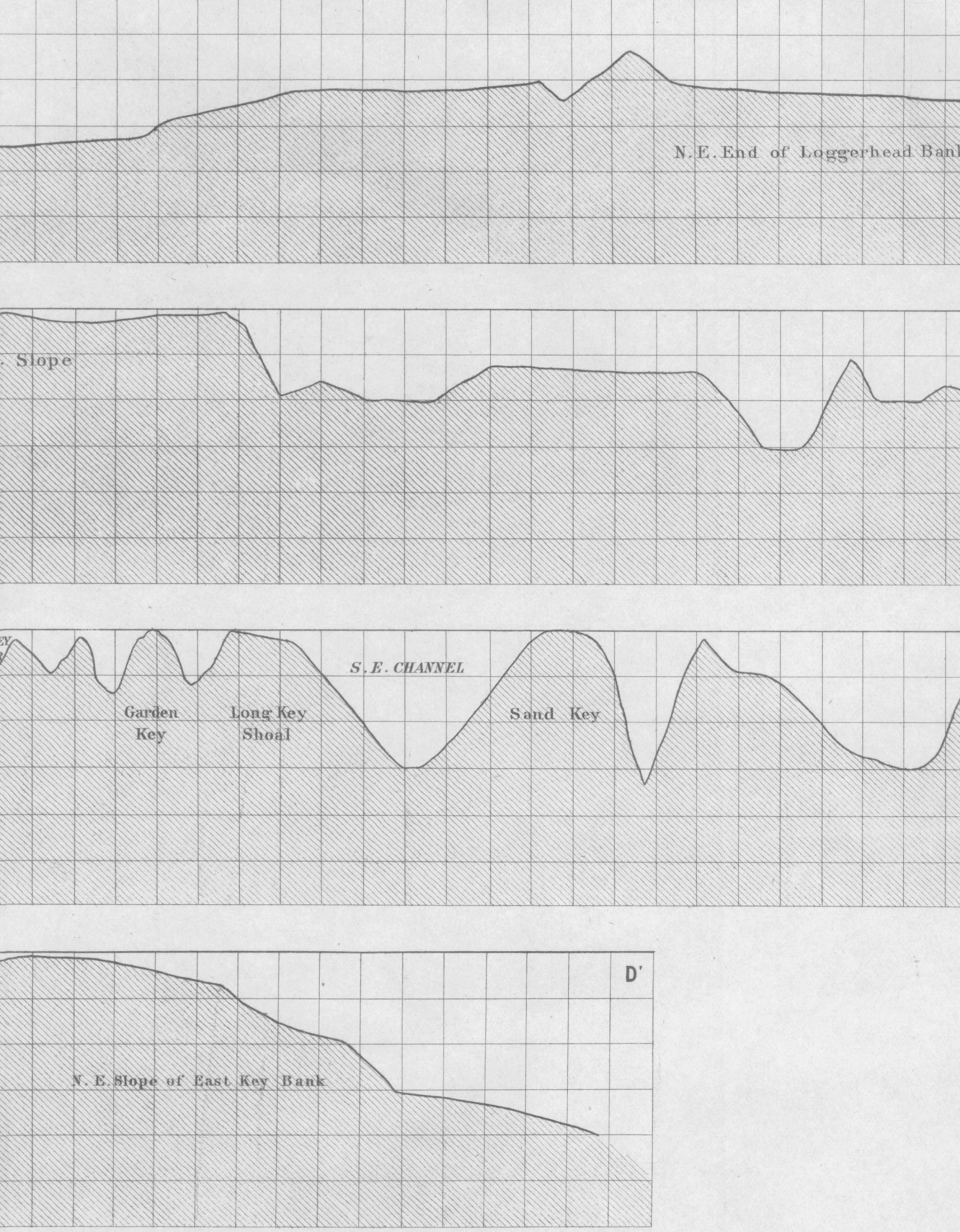

A
S.W. Slope of Loggerhead Bank

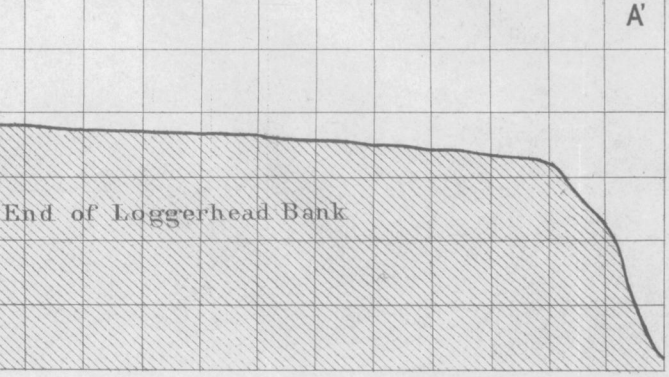

B
S.W. Slope

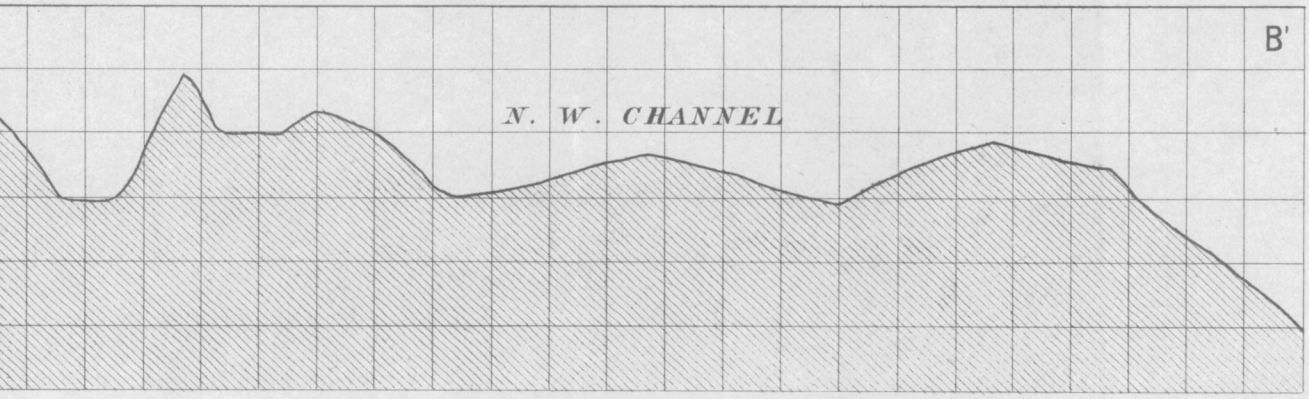

C
S.W. End of Bush Key Shoals

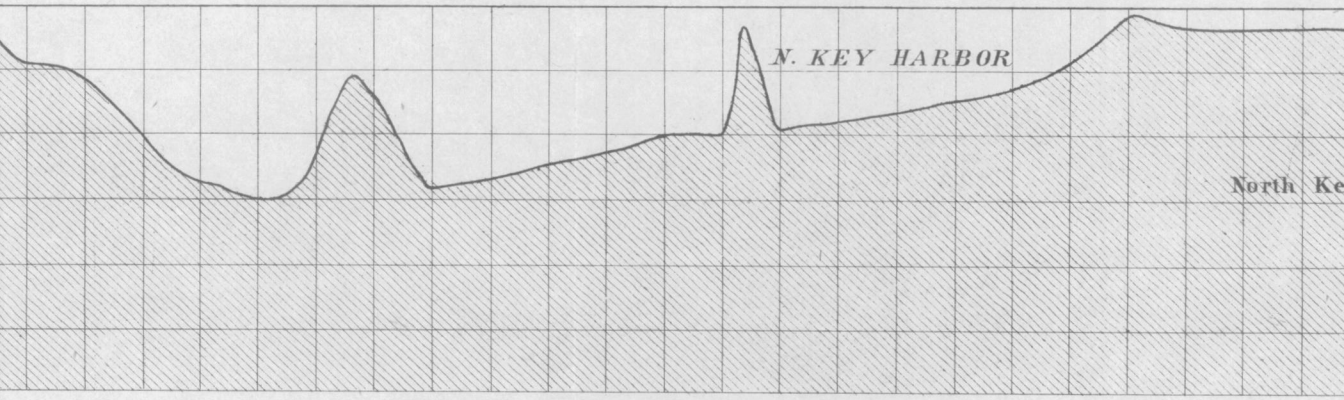

D
S. E. CHANNEL

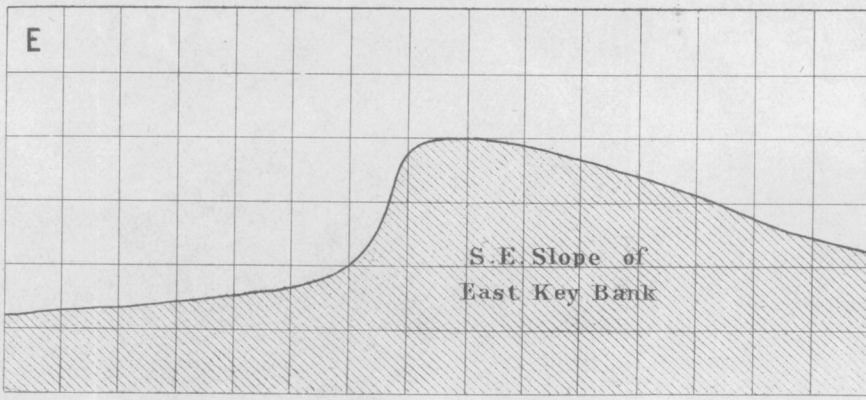

N.W. Slope of Loggerhead Bank
Loggerhead Key S.W. Slope
BIRD KEY HARBOR
Bird Key Shoals
Garden Key
NNEL
East Key
N. E. Slope of East

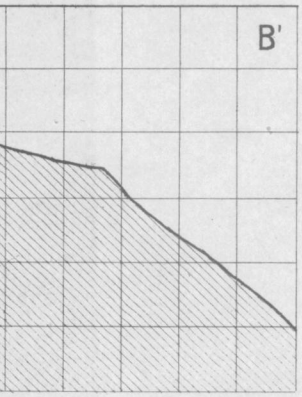

N. E. End of Loggerhead Bank
. Slope
S. E. CHANNEL
Garden Key
Long Key Shoal
Sand Key
D'
N. E. Slope of East Key Bank

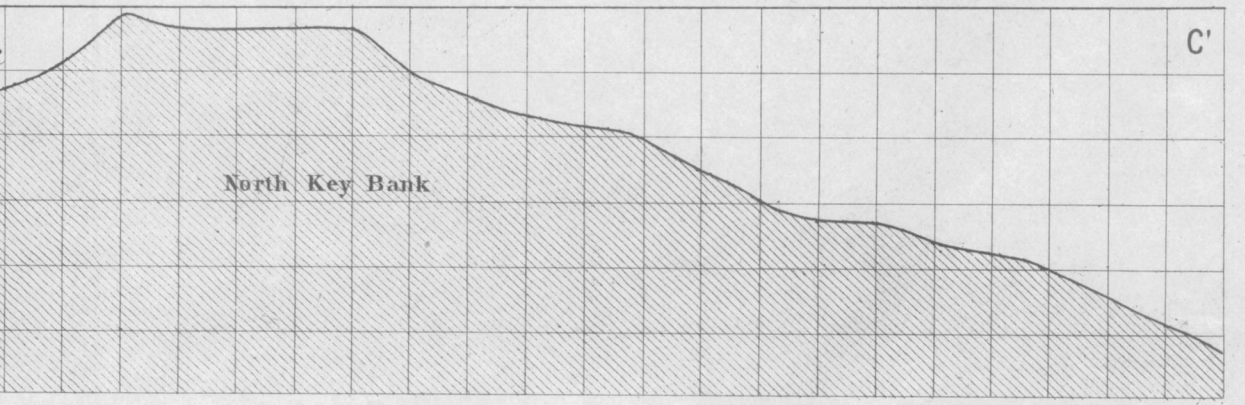

A'
End of Loggerhead Bank

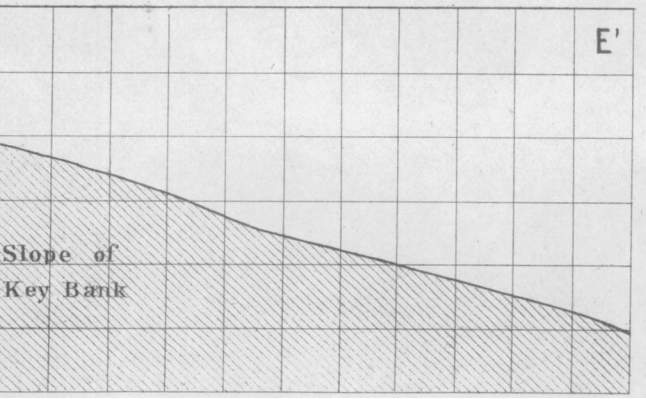

B'
N. W. CHANNEL


N. KEY HARBOR
North Ke


E
S.E. Slope of
East Key Bank



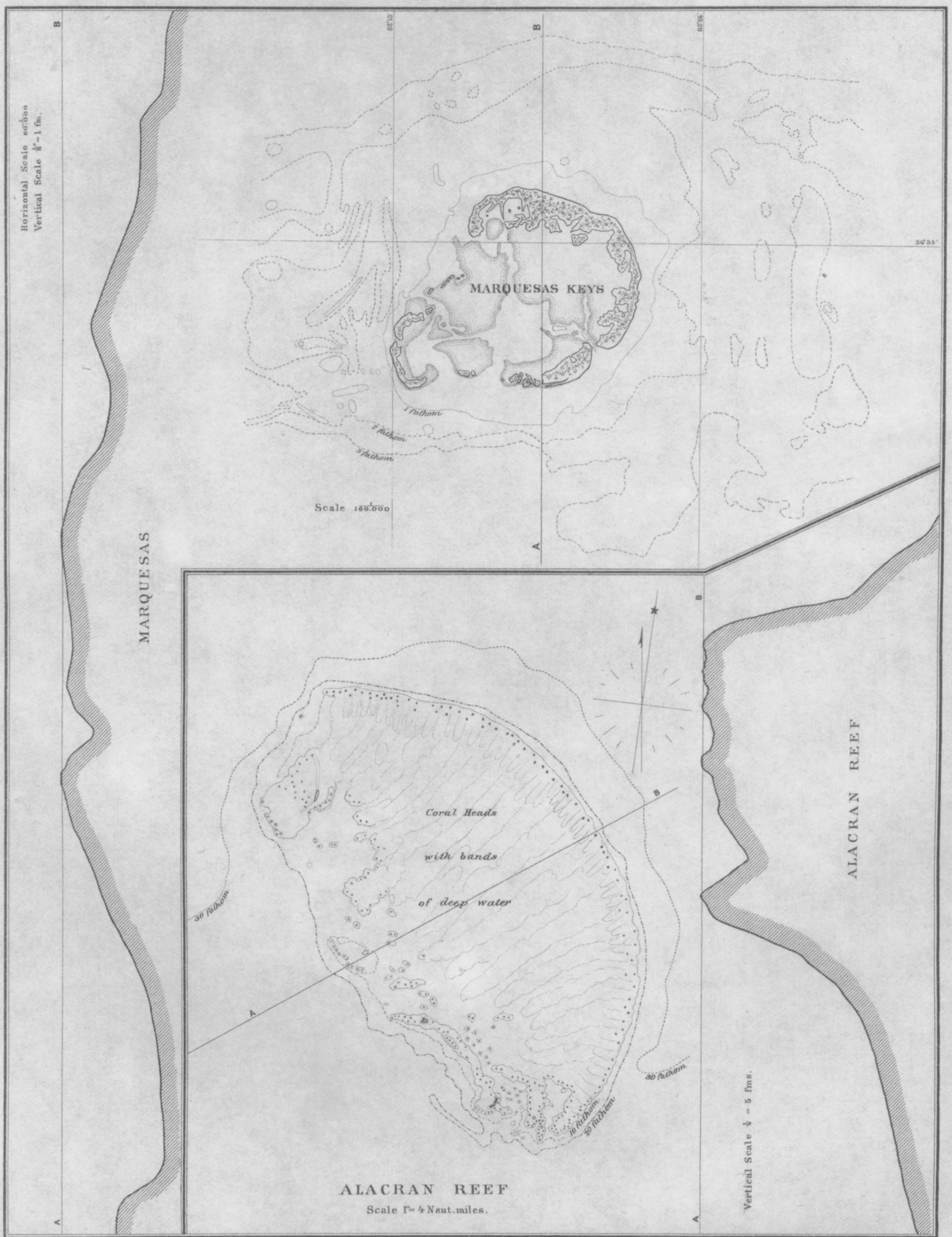




Vertical Scale 6 fathoms = 1/3 inch.

Horizontal Scale 1/40 000.

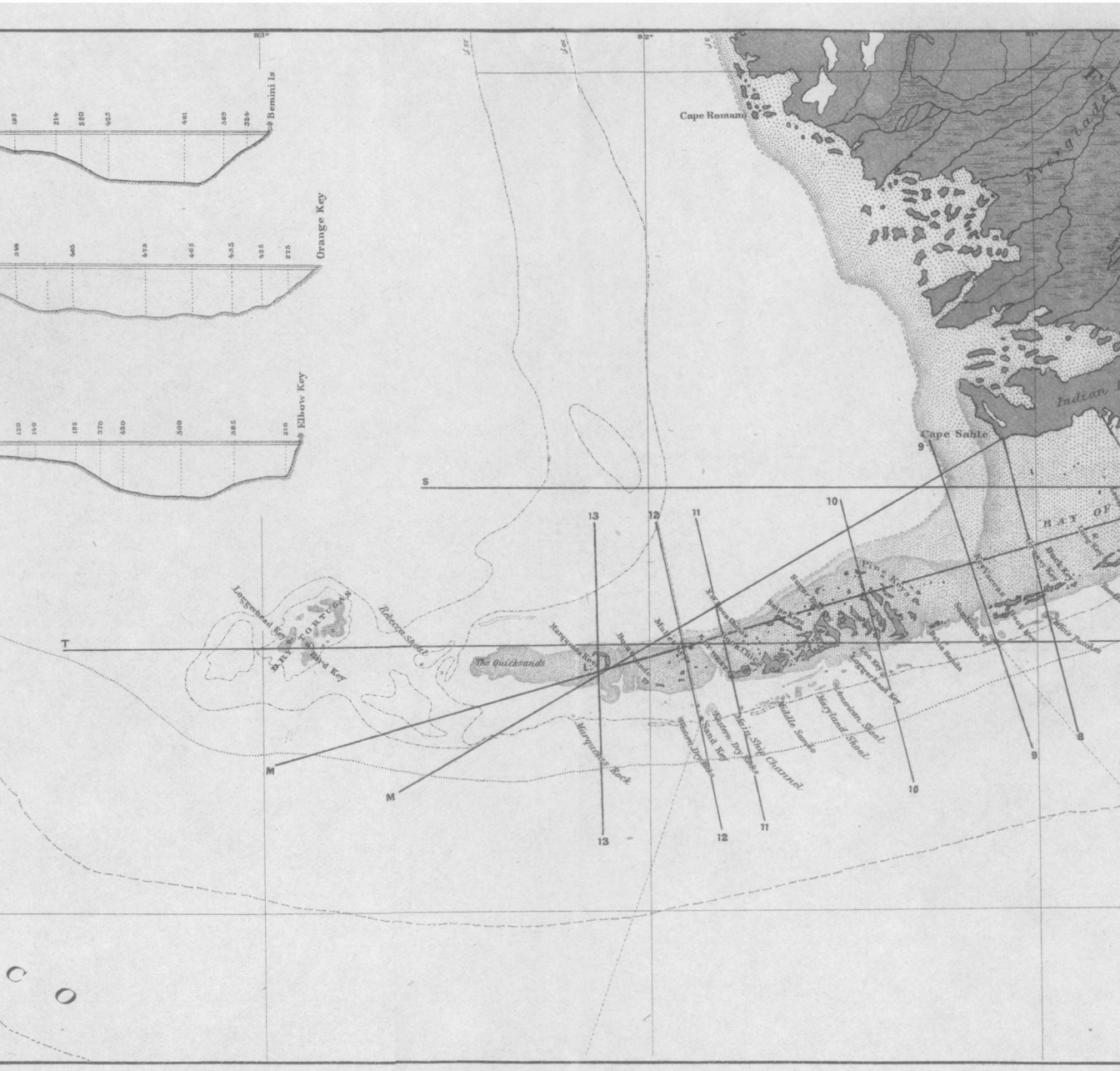
A. Meisel, Lith. Boston.



A. Meisel, Lith. Boston.

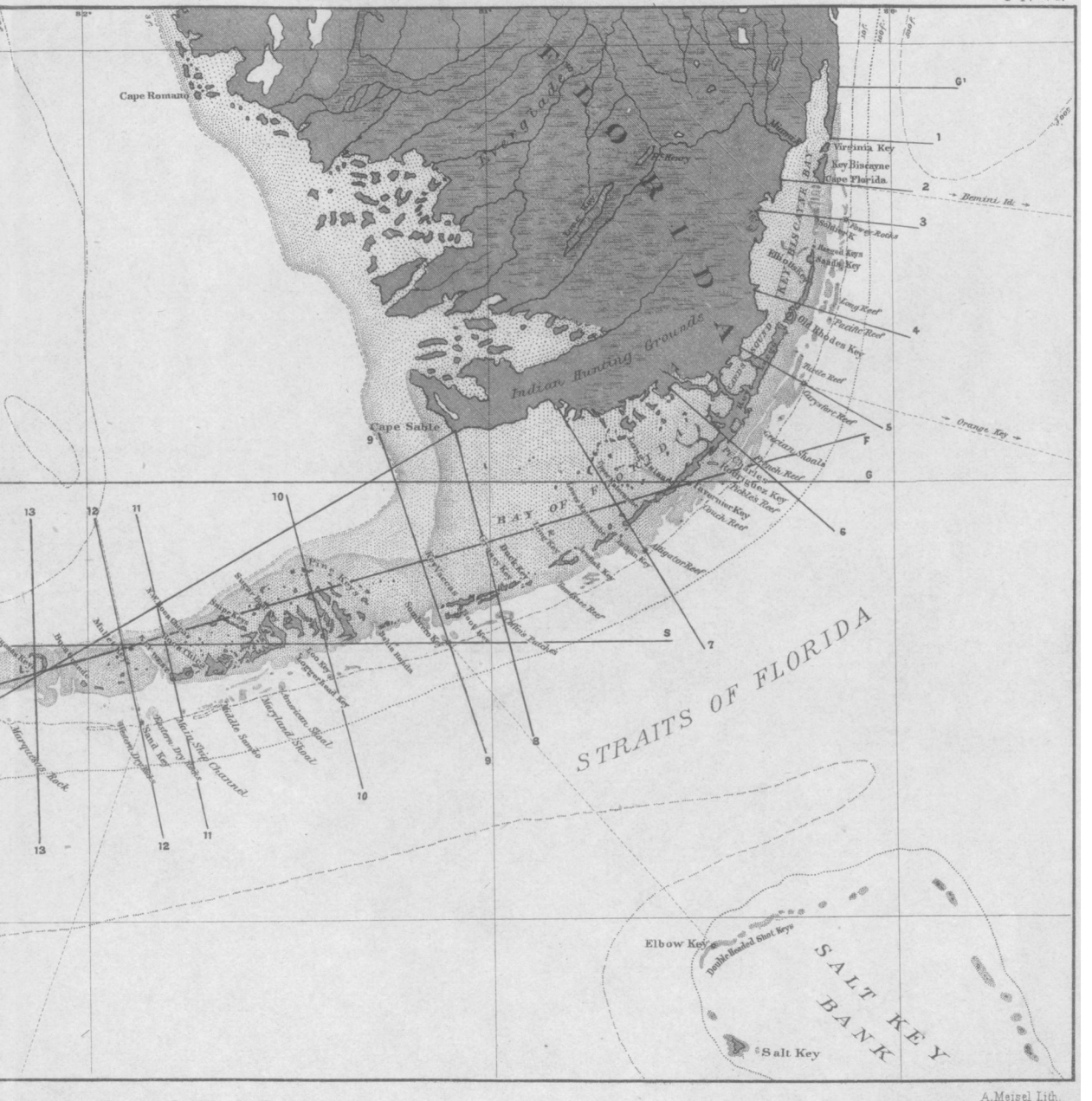
STRAITS

from Coast



STRAITS OF FLORIDA.

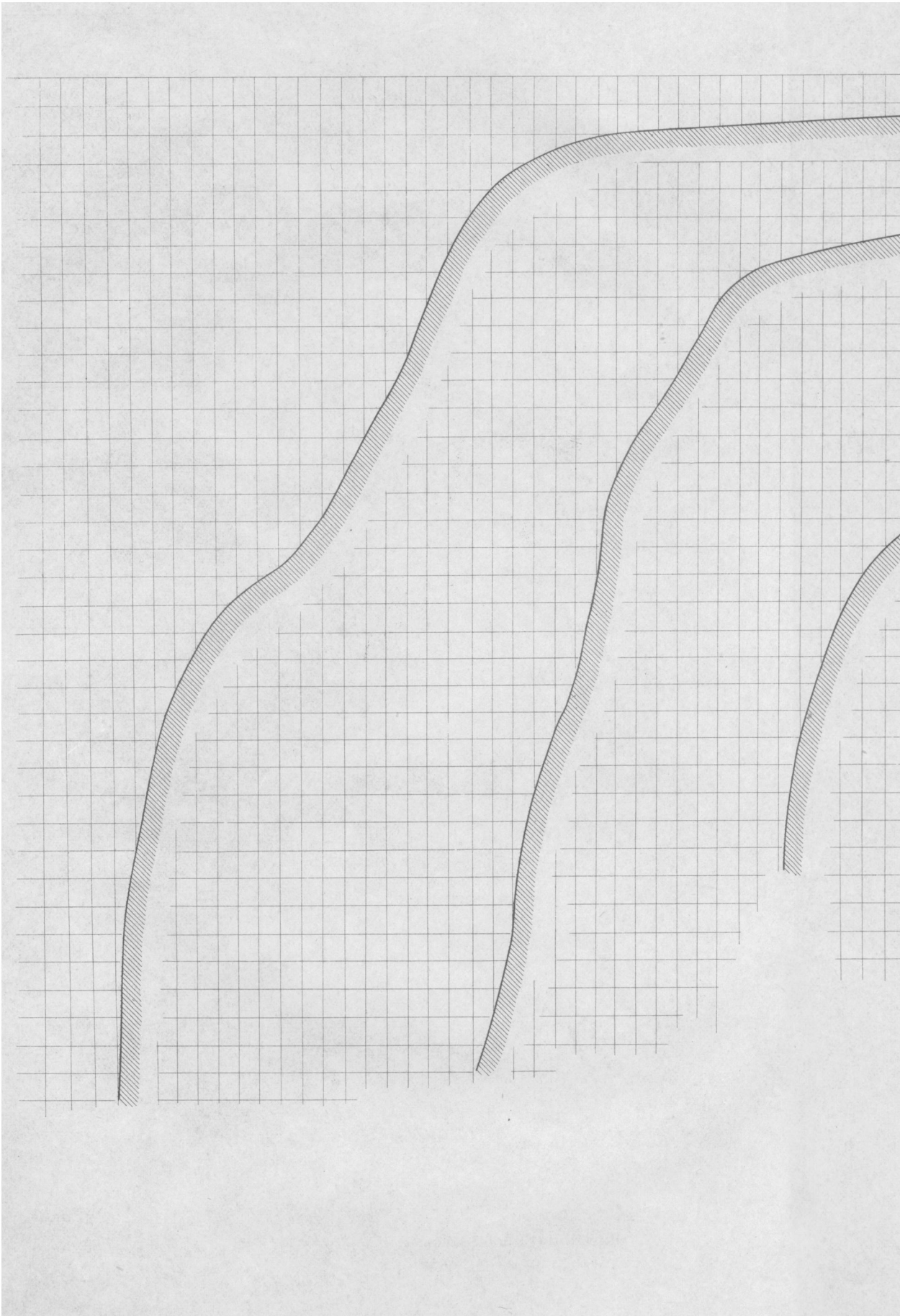
from Coast Survey Charts.



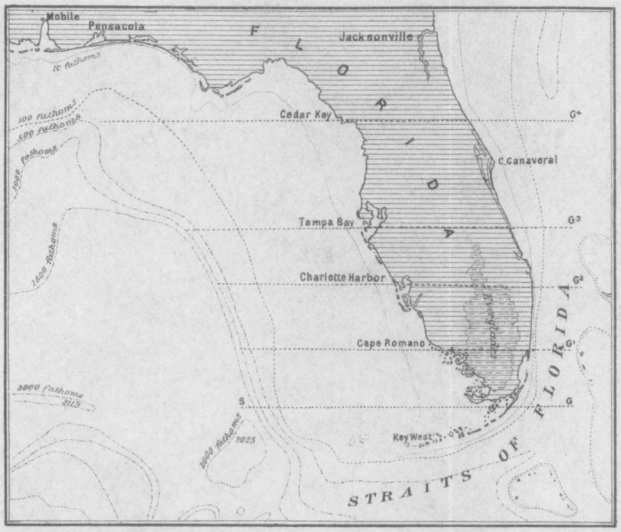
F FLORIDA.

A. Meisel Lith.

Survey Charts.




Cedar Key
Tampa Bay
Charlotte Harbor
T
S
M
Marquesas Keys
Mud Key
Snipe Key
Horizontal Sc
Vertical Scal



Charlotte Harbor

Cape Romano

S

Dry Tortugas

Rebecca Shoal

Mullet Key

Sugar Loaf Key

Sombrero Key

M

Cape Sable

Marquesas Keys

G

Long Island

Pickles Reef

F

Snipe Keys

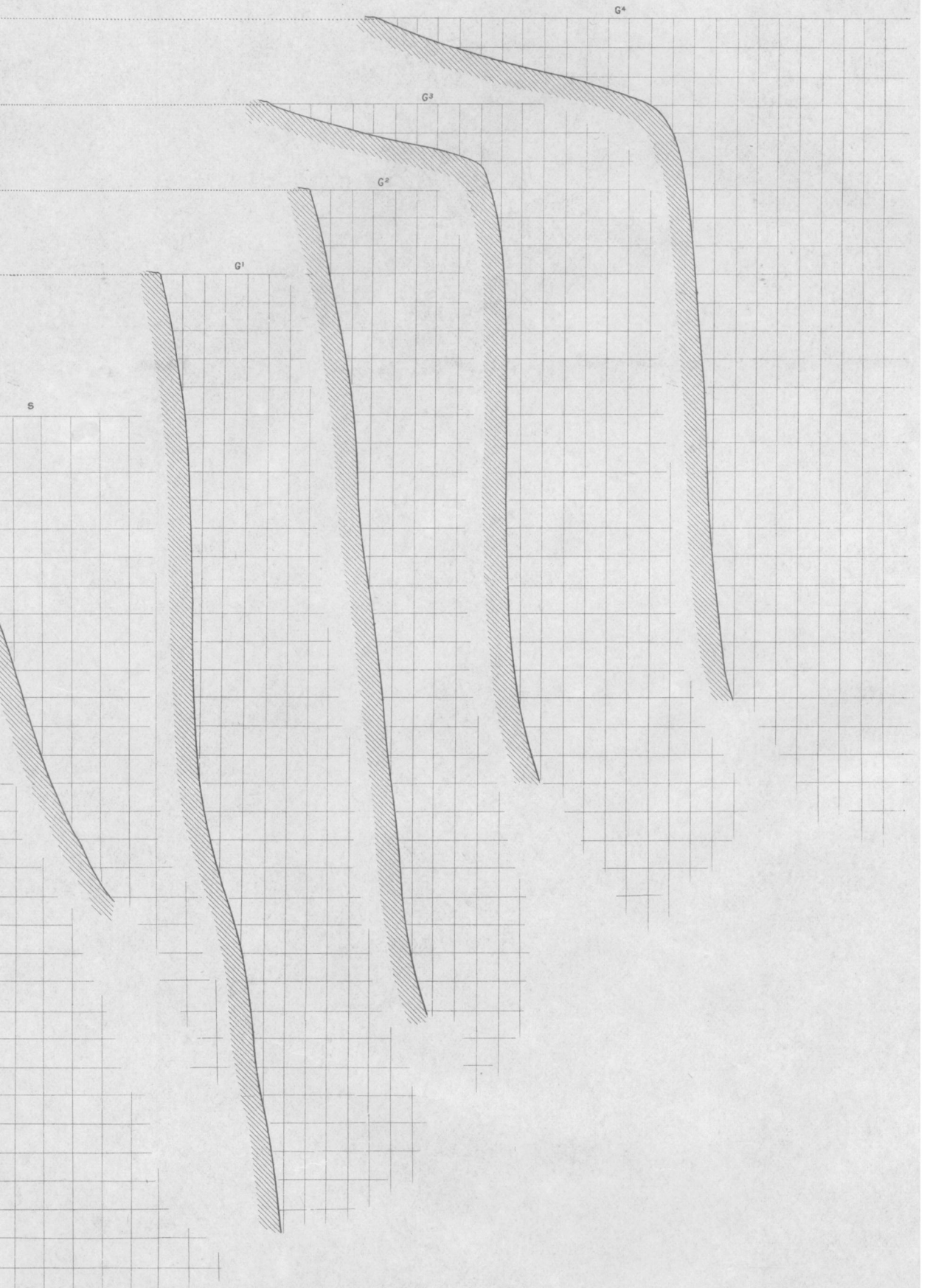
Pine Key

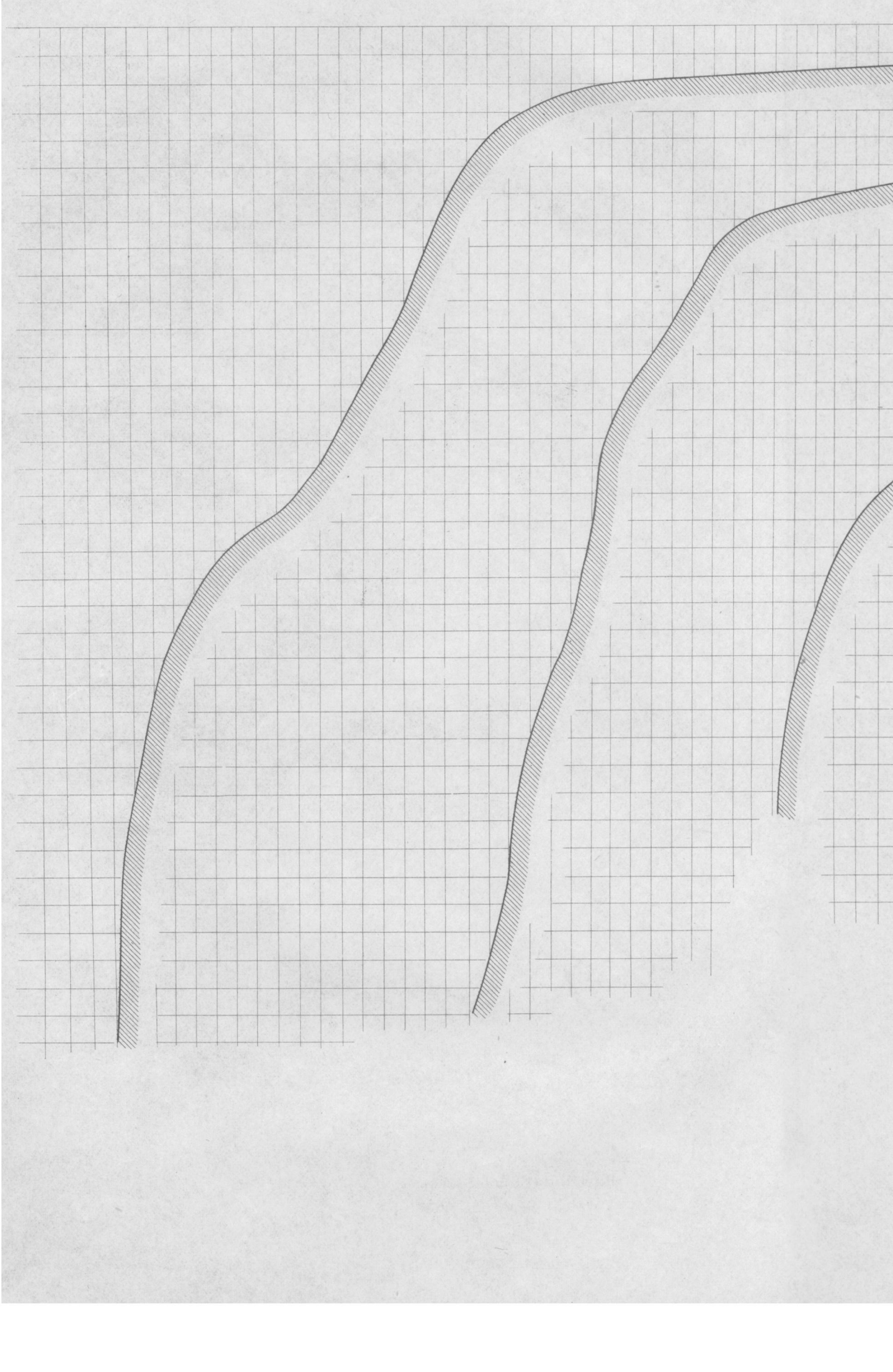
Long Island

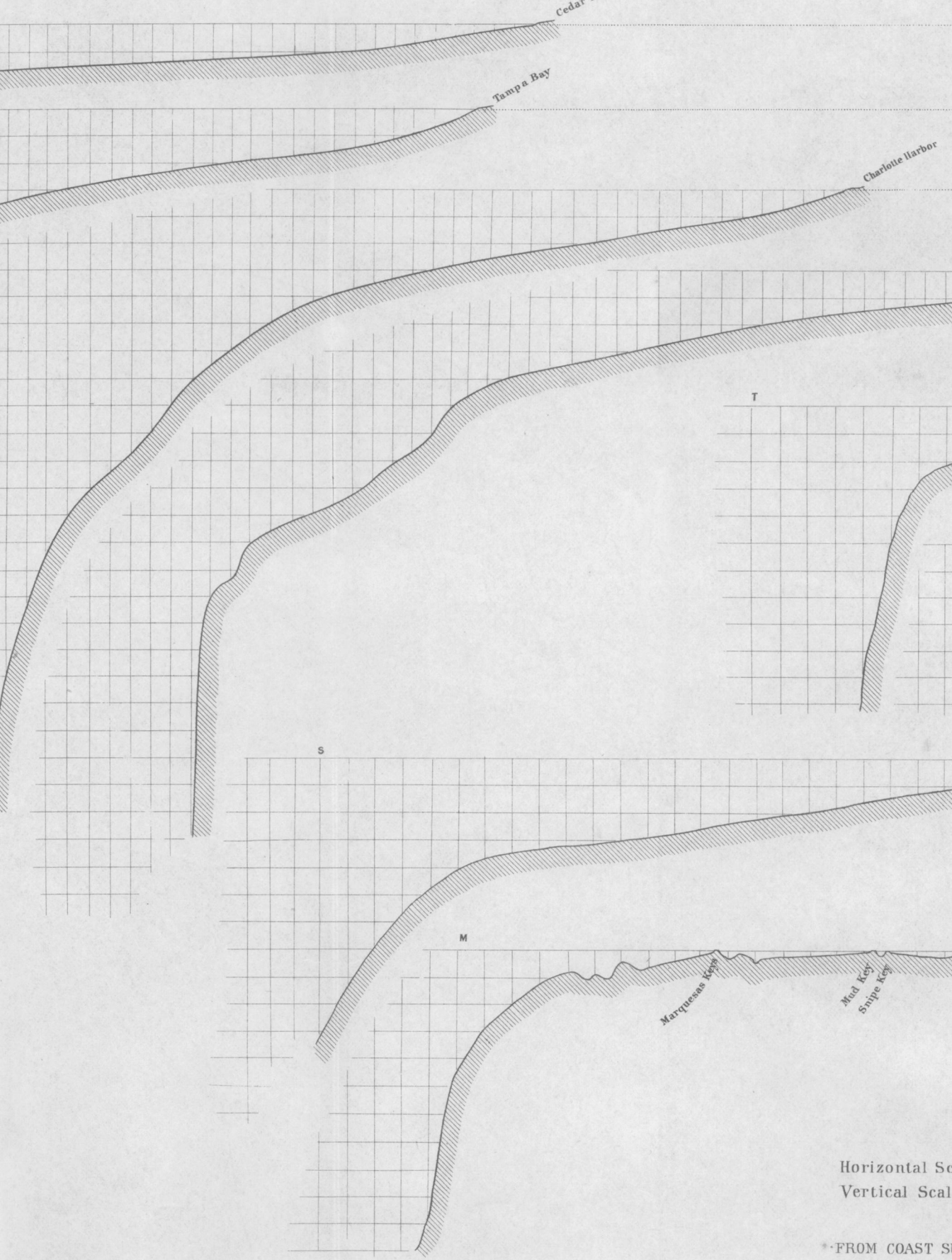
French Reef

Horizontal Scale $\frac{1}{1.600.000}$

Vertical Scale $\frac{1}{5}$" = 10 fms.

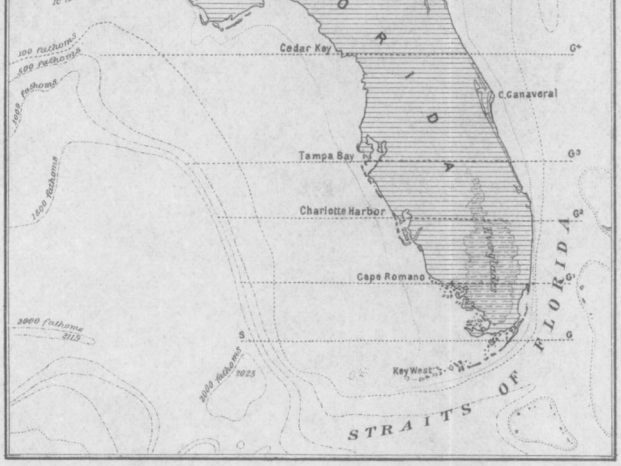

G4
G3
G2
G1
S

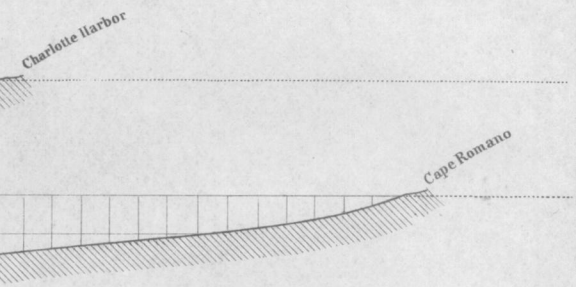


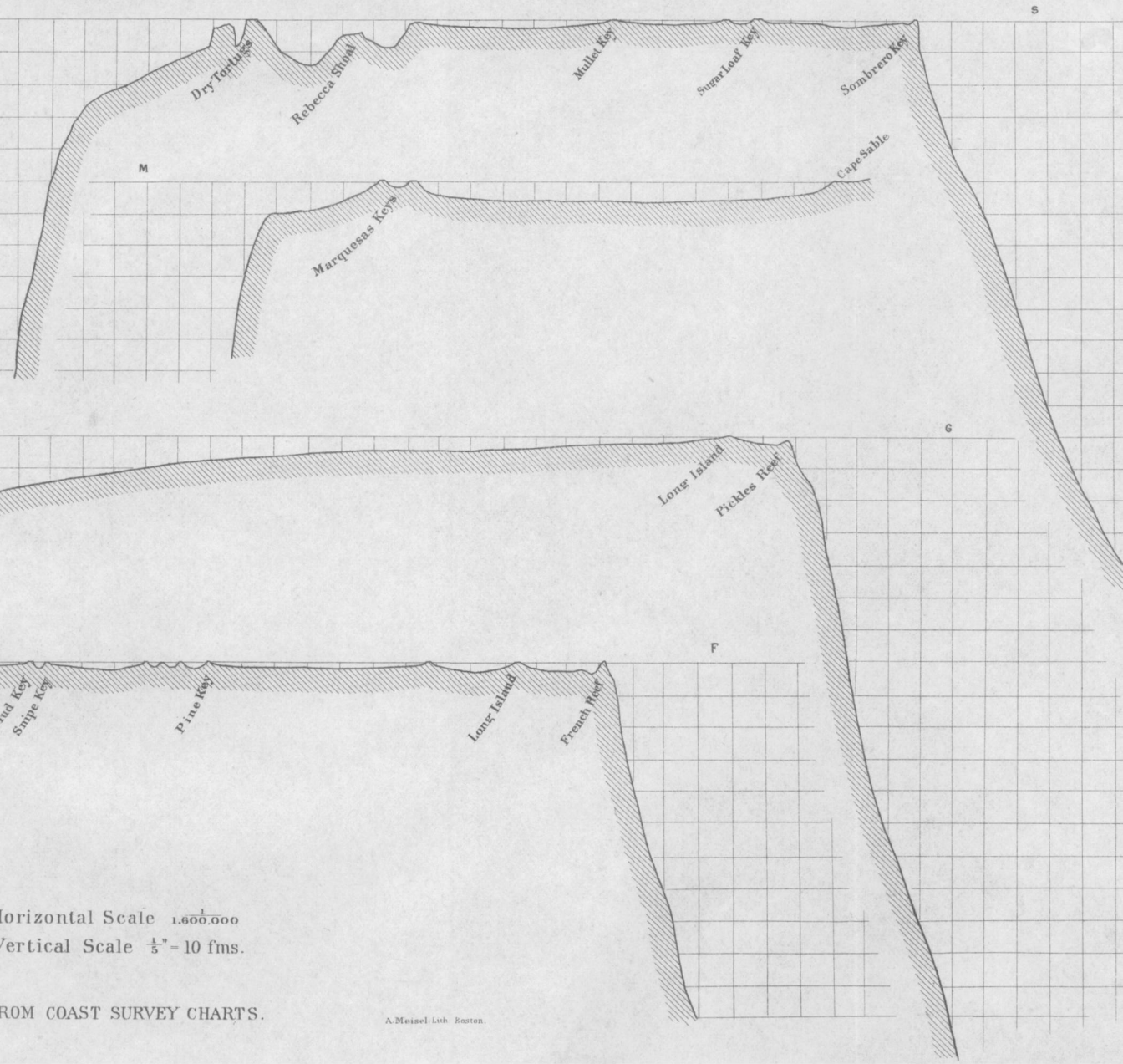


Horizontal Sc
Vertical Scal

FROM COAST S



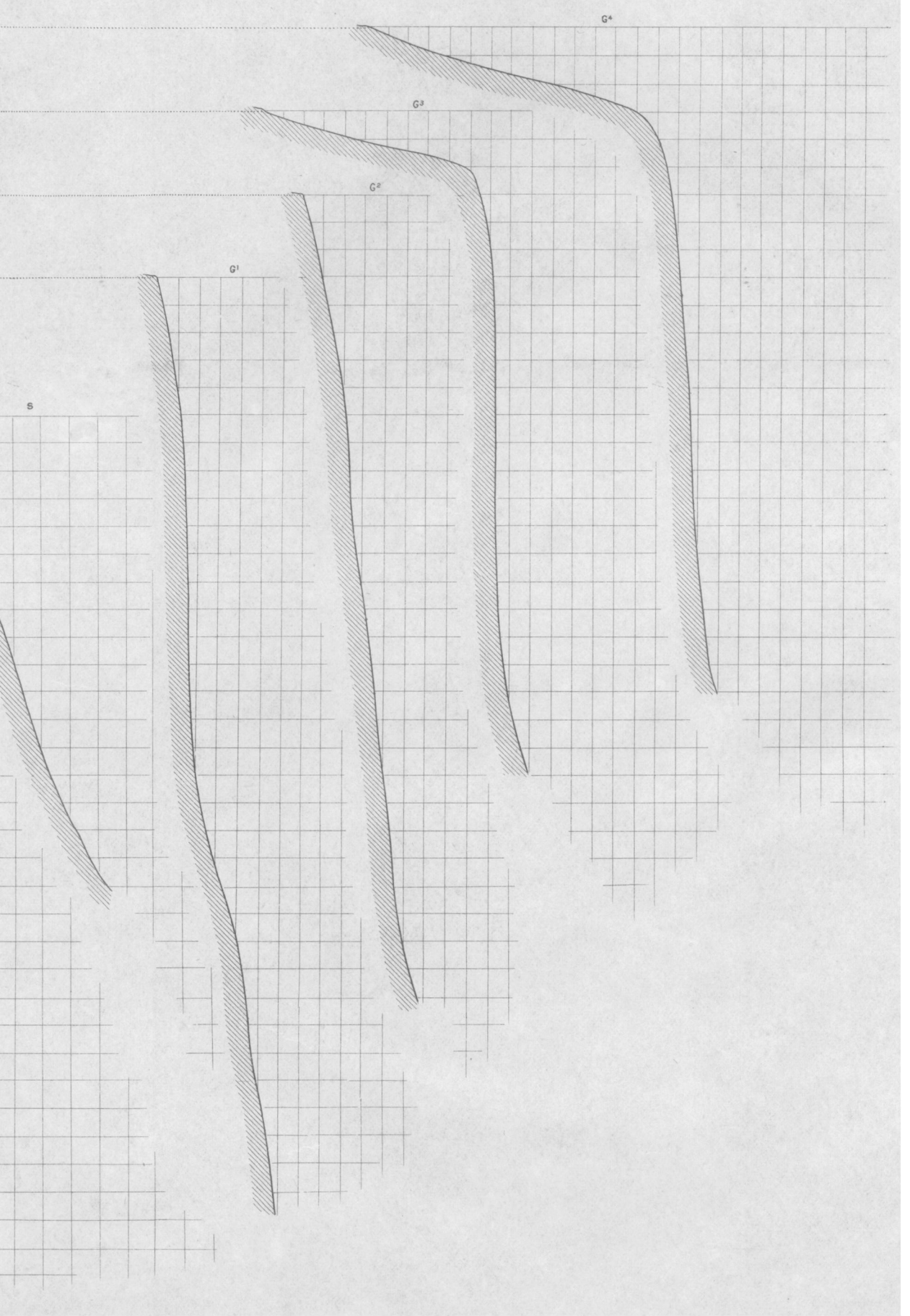


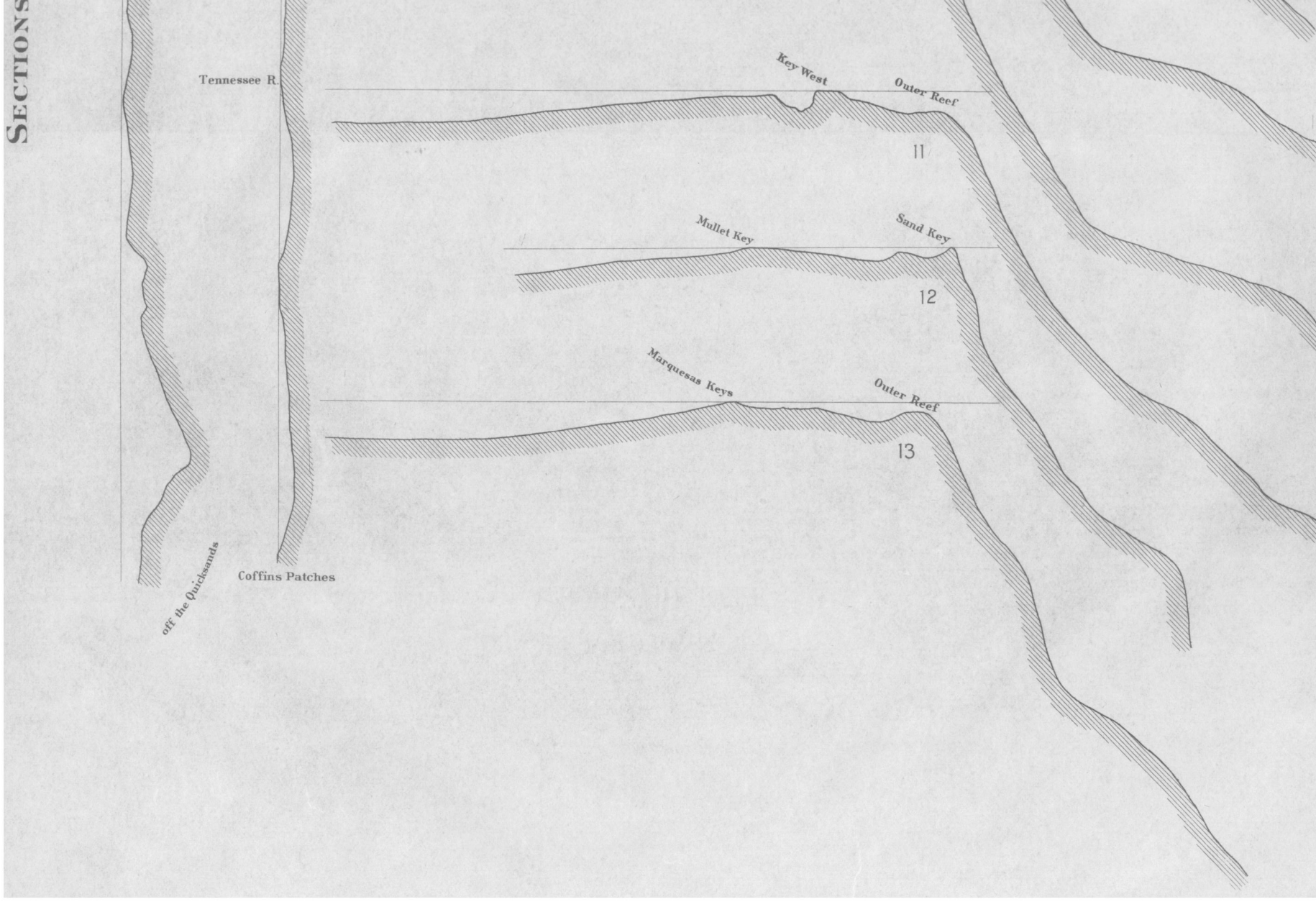


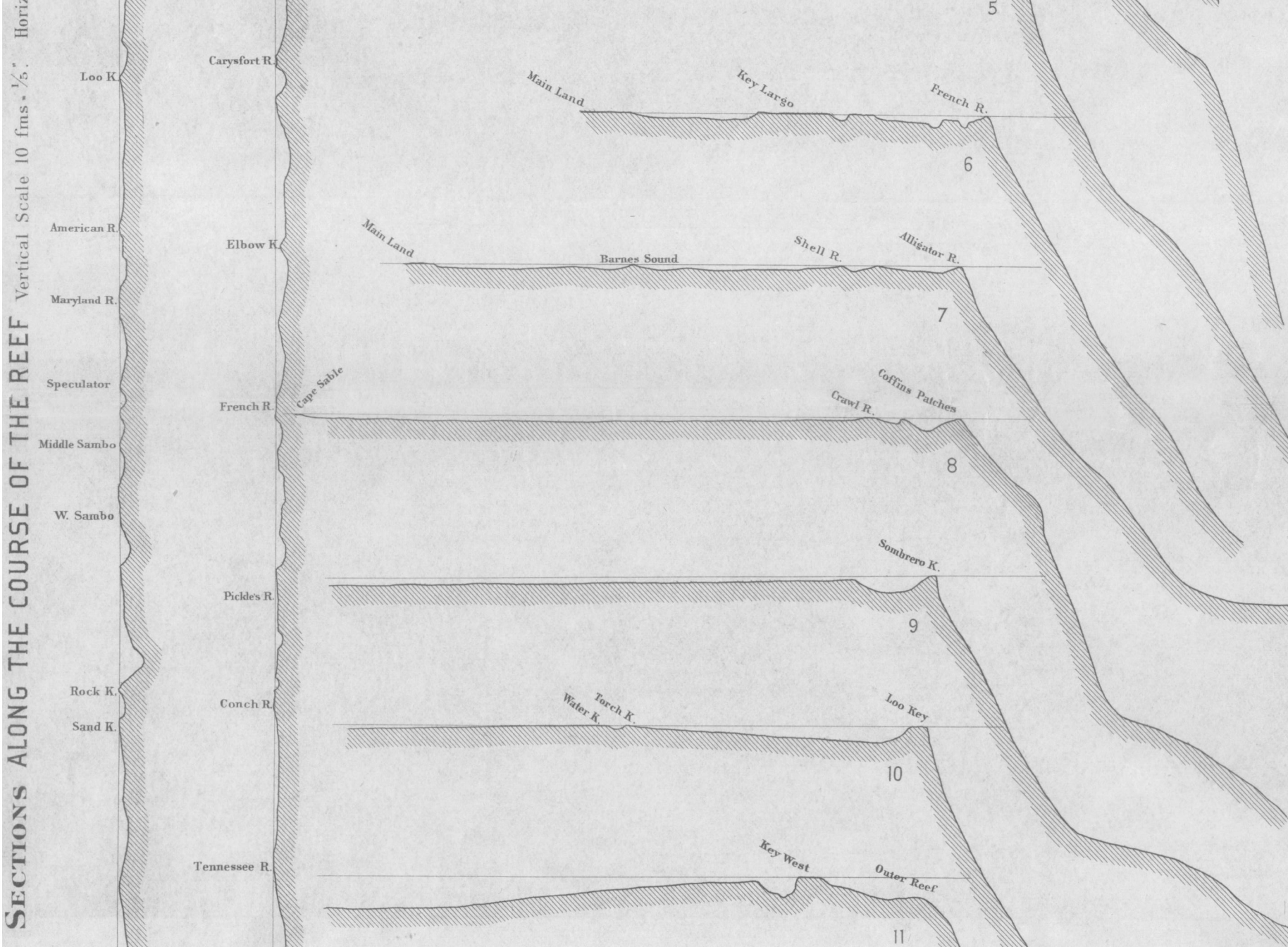
Horizontal Scale 1.600.000
Vertical Scale $\frac{1}{5}$" = 10 fms.

FROM COAST SURVEY CHARTS.

A. Meisel. Lith. Boston.


G4
G3
G2
G1
S


Sections
Tennessee R.
Coffins Patches
off the Quicksands
Key West
Outer Reef
11
Mullet Key
Sand Key
12
Marquesas Keys
Outer Reef
13


SECTIONS ALONG THE COURSE OF THE REEF Vertical Scale 10 fms - 1/5"
Loo K.
Carysfort R.
Main Land
Key Largo
French R.
5
6
American R.
Elbow K.
Main Land
Barnes Sound
Shell R.
Alligator R.
7
Maryland R.
Speculator
French R.
Cape Sable
Crawl R.
Coffins Patches
8
Middle Sambo
W. Sambo
Sombrero K.
Pickles R.
9
Rock K.
Conch R.
Sand K.
Water K.
Torch K.
Loo Key
10
Tennessee R.
Key West
Outer Reef
11

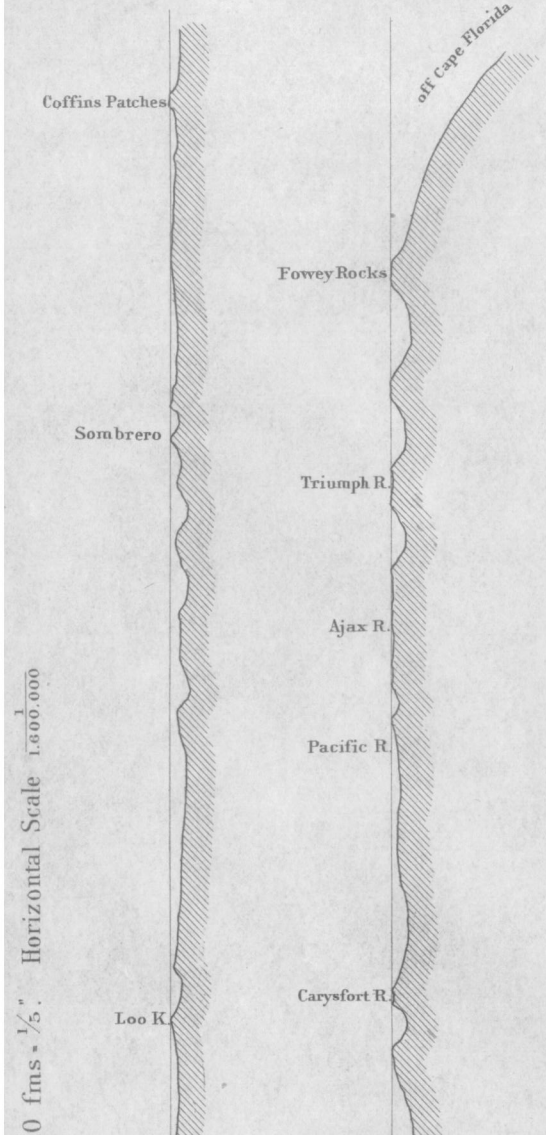
Pl. VIII.

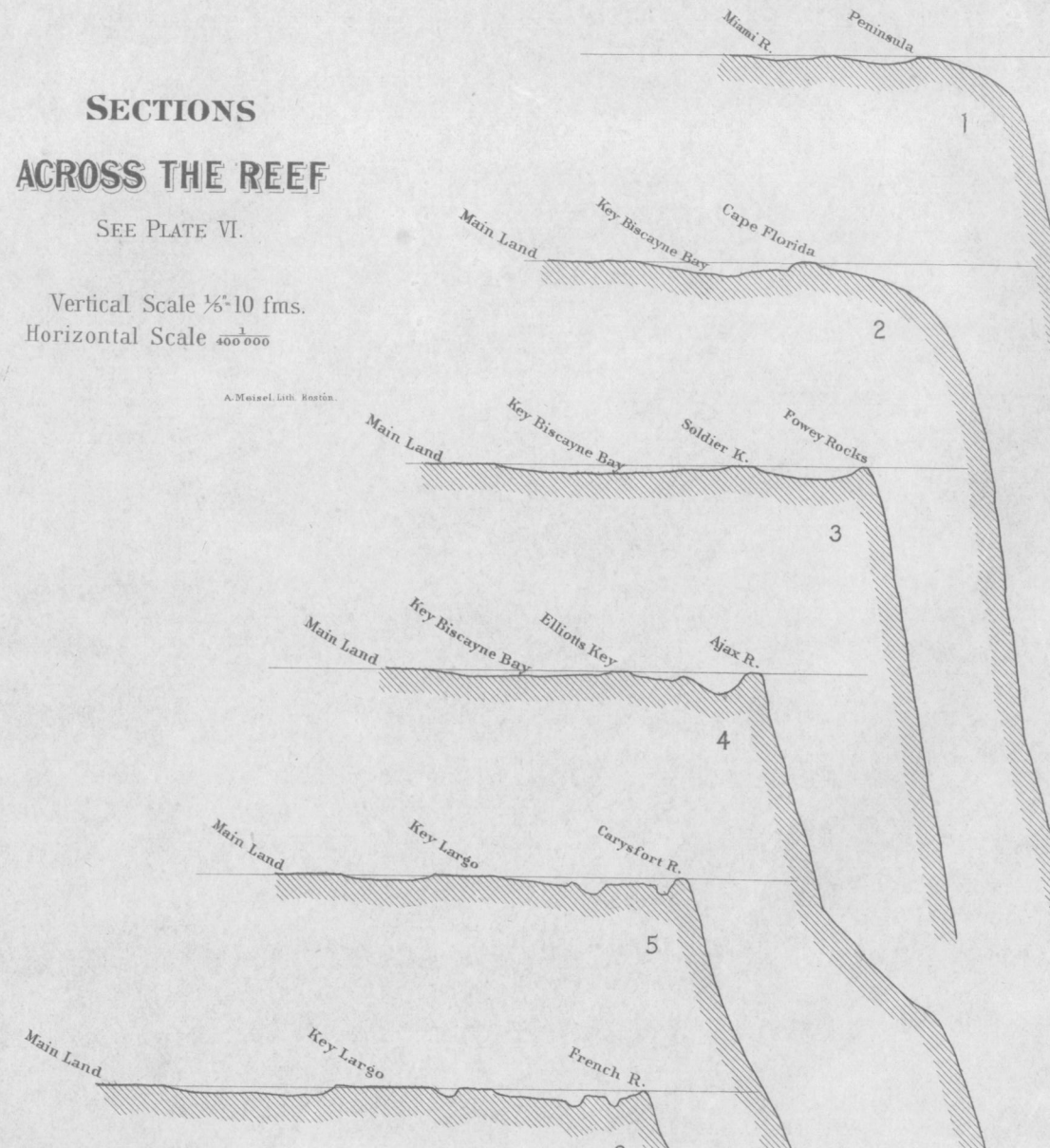
SECTIONS
ACROSS THE REEF

SEE PLATE VI.

Vertical Scale ⅕"-10 fms.
Horizontal Scale $\frac{1}{400\,000}$

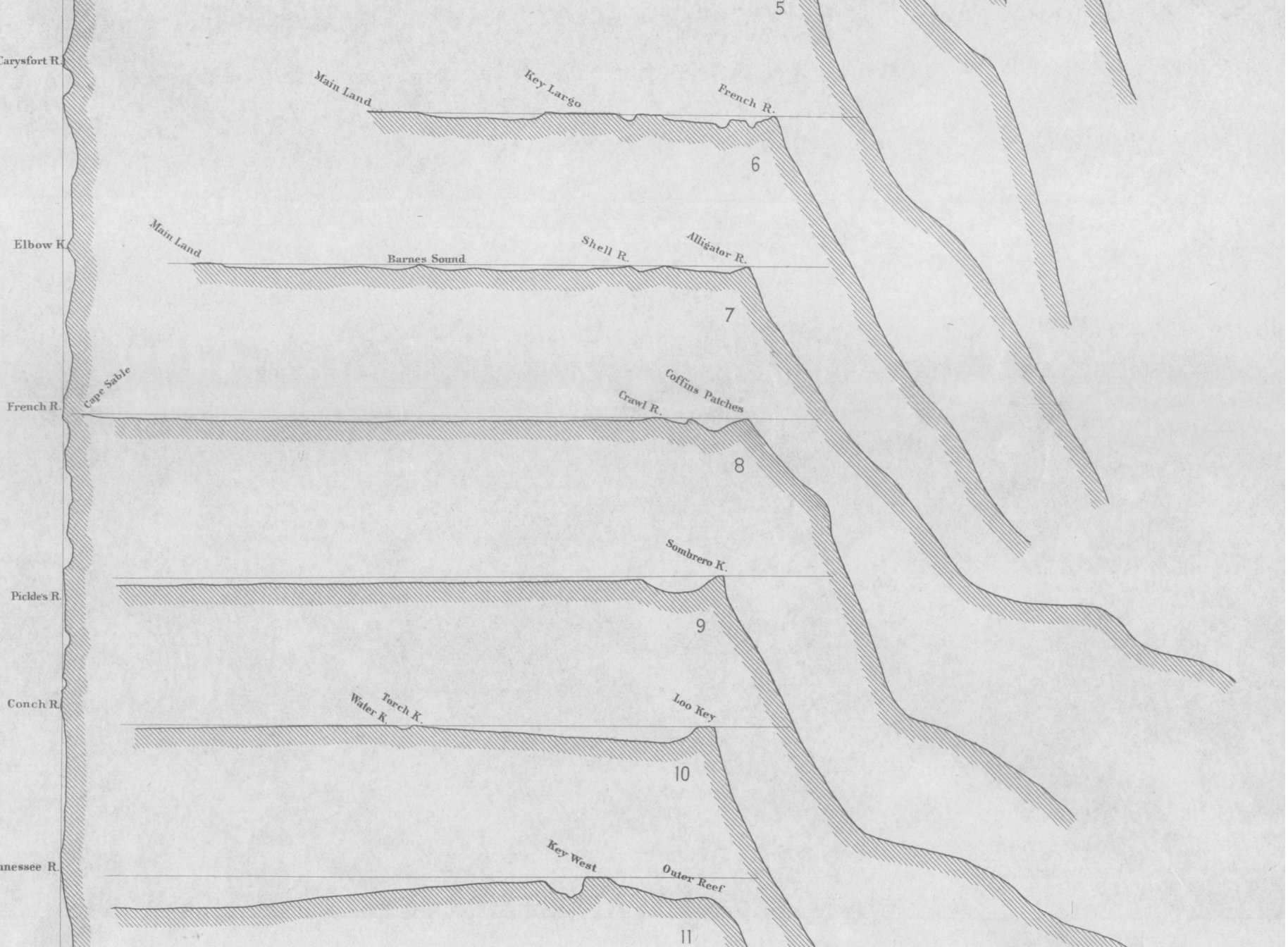
A. Meisel, Lith. Boston.





0 fms = ⅕". Horizontal Scale $\frac{1}{1.600.000}$


nessee R.
Key West
Outer Reef
11
Mullet Key
Sand Key
12
Marquesas Keys
Outer Reef
13
Coffins Patches


Carysfort R.
Main Land
Key Largo
French R.
5
6
Elbow K.
Main Land
Barnes Sound
Shell R.
Alligator R.
7
French R.
Cape Sable
Crawl R.
Coffins Patches
8
Sombrero K.
Pickles R.
9
Conch R.
Water K.
Torch K.
Loo Key
10
Key West
Outer Reef
11

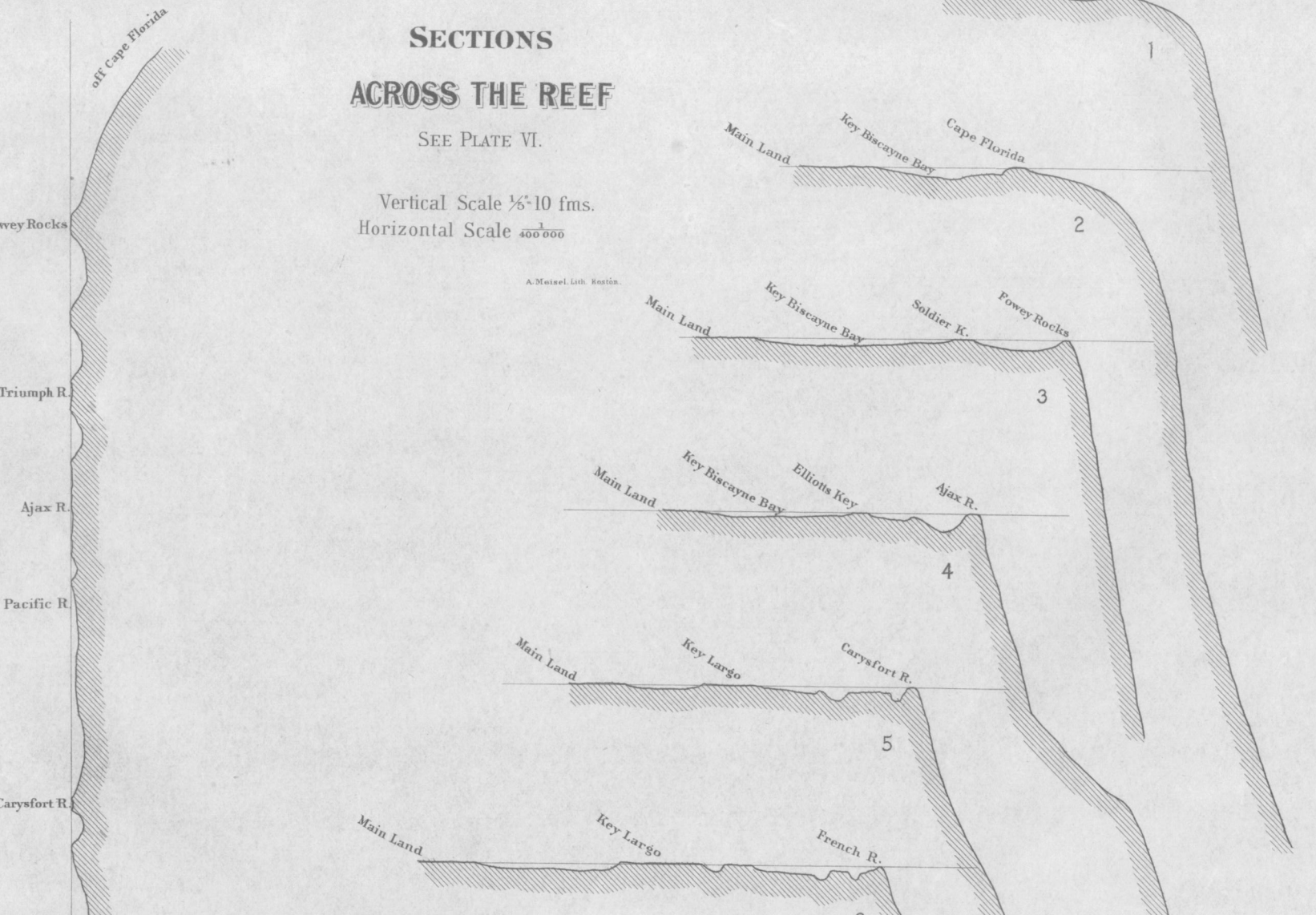
SECTIONS

ACROSS THE REEF

SEE PLATE VI.

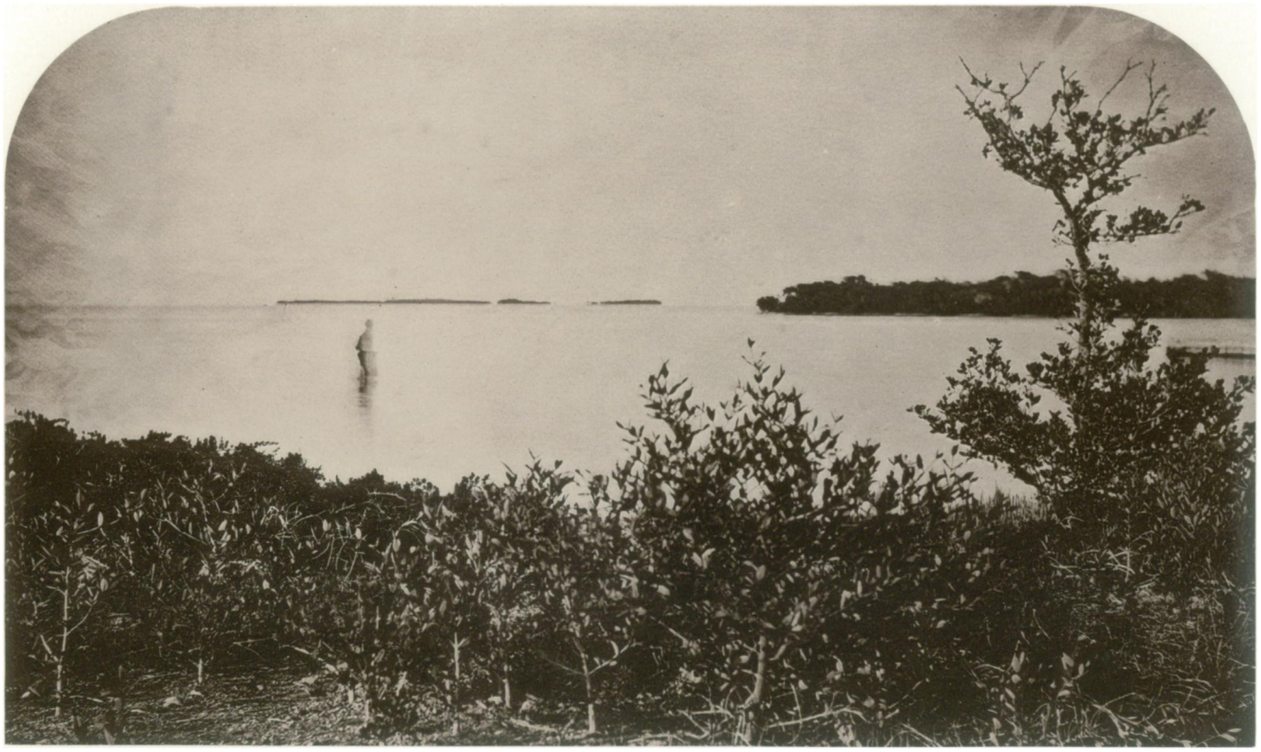
Vertical Scale 1/5" 10 fms.
Horizontal Scale $\frac{1}{400\,000}$

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