Part 2
COASTAL SEDIMENT PROBLEMS

CHAPTER 9

GEOLOGY IN SHORELINE ENGINEERING AND ITS APPLICATION TO MASSACHUSETTS BEACH PROBLEMS *

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At the outset I wish to make it clear that I am presenting this subject as a geologist, and not as a coastal engineer. I stand only on the fringe of that area of engineering science, and it would be presumptuous of me to discuss techniques of shoreline engineering. On the other hand, analysis of geologic processes that have molded and are now molding the shoreline furnishes basic terrane data of importance in the solution of coastal problems. As a geologist, then, perhaps I may properly point out the pertinency of geology to these problems, and indicate the kinds of appropriate data that are within the province of the geologist to explore and interpret. More or less an observer on the sidelines, I have for some time been impressed by the intricacies of the problems involved in coastal engineering projects. Such engineering is, of course, highly scientific and technological. But it seems to me that it is also somewhat of an art, for it is strongly tempered by experience, and the success of a calculated solution to a problem is often anxiously awaited by the engineer when the project is completed. There seems to be less of the slide-rule certainty that characterizes the planning and design of a bridge. Will the sea-wall, the jetty, or the offshore breakwater, for examples, accomplish the intended results? Sometimes they do not because of some unrealized factors. Such factors are often obscure geologic conditions - unrecognized because the geologic regimens along shores seem to be very delicately balanced with respect to several factors, and to be sensitive to even slight interferences, despite the massiveness of the natural forces that are at work. The geologic history of the coast, translated to the present, together with minutiae of existing geologic features may demonstrate such obscure factors. It behooves the engineer, therefore, to seek the offices of geologic sciences. Perhaps at this point I may be pardoned to related digression if - to employ the vernacular - I "get something off my chest".

It seems axiomatic, and yet strangely to need emphasis, that the engineer should be able to plan his work more effectively and with greater economy if he were provided with a knowledge of the compositions, properties, structures, and implications of the geologic formations and forces with which he perforce is obliged to deal so directly and so intimately. The strength, soundness, and secureness of a structure may depend largely upon these elements. This is patent whether he is dealing with highways, bridges, foundations, reservoirs, or works for shoreline control. Terrane intelligence is within the primary field of the geologist to provide and he is far better equipped than the engineer to obtain and interpret such

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basic data. He is, if well trained and experienced, aware of complex interrelations of phenomena that to the untrained may seem to have no tangible relation to each other.

To a degree this is an appeal for both geologists and engineers to recognize the fundamental correlations of their sciences. An engineer should know when to seek and how to use geologic data. His failure to do so more often is perhaps to be blamed more on the geologist than on himself, for in the past the geologist has too commonly seemed to be "long-haired", and to interest himself in the philosophic vistas of his science rather than in the pertinent and practical applications of it. The geologist should, of course, know how to select and present his data for engineering use. The fault, however, is to be charged in no small part to those engineering schools - and there are many - whose curricula and faculty make little or no provision for acquainting the engineer with the solid substance of geologic science, or perhaps make a perfunctory gesture in that direction. It is very gratifying, however, to note that engineers are taking an increasingly greater interest in geologic sciences, which, besides standard lithologic, structural, and morphologic studies, include such specialized geologic fields and laboratory techniques as geophysical studies of terranes, petrographic studies of materials, and "soil mechanics" tests. In recent years the fine work of the Beach Erosion Board and its promotion of correlative studies by geologic specialists is but one of several outstanding examples of coordination between engineering and geology. Nevertheless, there is a very common lack of awareness among engineers that geologic sciences can provide specialized basic data for their problems. Let the technical schools look to it!

What are the basic data for coastal studies that derive from geology? The science deals with processes and materials - processes that are ever striving to establish an equilibrium and rarely approach it closely over a large area, and materials that are locally varied in composition, properties, and structures. In the study of coastal processes, both the engineer and the geologist must often transgress the stricter limits of their fields and enter the domain of mathematical physics. They should both be prepared to do so. By virtue of his training, however, the geologist can do much physical analysis from observation of currently active processes, and an interpretation of the history and evolution of the land area as indicated by a study of the morphology and materials of the coastal belt. To him the marks of the past disclose the path to the present, and may predict the course of the future. He has the advantage of four dimensions with which to work, the fourth being the greatly expanded vista of time. Seemingly intangible philosophy can be transmuted into tangible facts.

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The morphology of the coastal belt reflects the recent history and evolution of the shore, and it further implies the future course of development under a continuing regimen that, through a routine cycle of geologic changes, culminates in ultimate planation, unless interfered with by uplift, downsinking, or tilting of the land area with respect to sea level. The changes are both constructive and destructive. The engineer seeks to control, interrupt, mold, or prevent some of these changes. He is dealing, then, with dynamic geologic processes and can accordingly benefit by increasing his knowledge of the regimen. Geology begins its contribution to engineering by indicating the morphologic stage of the cycle, and consequently the principal forces that are acting upon the coast. By the same token it indicates the normal path of future changes. These facts are fundamental in the analysis upon which control or remedial engineering measures are to be based.

The stratigraphy, structure, and lithology of the coastal zone subjected to wave erosion are closely involved in beach preservation and construction projects. Sea-walls are necessarily massive and heavy, and require firm foundations; the sub-surface materials and stratigraphy, therefore, must be determined and interpreted with relation to their soundness as foundation materials. Some beaches, for instance, are built on layers of peat or clay, over which they have naturally retrogressed during the normal geologic cycle. These layers, however, may be very close to the surface, so that, by depletion of the beach, they may quickly become exposed to wave action. The sea-walls then become unstable and may be undermined. Sea-walls are essentially defensive; they generally do little or nothing toward building up and preserving a beach. Indeed, they often tend to promote deterioration of the beach by sealing off natural sources of materials from replenishment of the strand. Their purpose is primarily to stabilize and preserve the backshore properties, but this objective is antipathetical to the geologic regimen, which seeks to establish a stable profile. Built generally near the normal high tide line, sea-walls are subjected to the severe buffeting of storm waves. Not only, then, must they be built of highly resistant materials, soundly integrated, but they must also rest firmly on sound foundations, and their bases must be well below any possible level of erosion. The instability of sea-walls is increased by the hydraulic surging effects of high storm tides acting upon porous, saturated, sub-surface layers.

The conditions just mentioned as affecting the design and maintenance of sea-walls are particularly critical with respect to some of the Massachusetts beaches, especially those within and north of the Boston Basin. Many of these are so-called "pocket beaches", essentially bay-head beaches, developed between either low, rocky headlands or projecting, partly submerged hills of relatively compact, bouldery, glacial till ("hard pan", and "boulder clay"). Because of the recent geologic history of the region, these beaches have been built variously upon bedrock, till, outwash sands and gravels, marine clays, and even peat. Moreover, this variability makes it impossible to closely predict the stratigraphy and structure of one beach from the next successive beach of the chain.

Each beach, then, becomes to some degree a coastal unit by itself, with its own distinctive personality, though the beaches may collectively bear the marks of family relationship. The first step, then, in the study of the coast for engineering projects is to determine the basic geologic facts of the coastal belt.

The natural sources of beach materials and the adequacy of such sources for future replenishment of the beaches are determined by this basic geologic study. Specifically, in this connection investigations are directed to details of coastal lithology, morphology of the deposits, rates of erosion of various materials (where indicated by geologic features and available statistical data), distribution of grain sizes in beach deposits (as indicative of redistribution by littoral currents and shore drift, sorting with respect to beach physiography, and variations in wave energy). In these areas of study geologic techniques are directly and highly contributory.

Natural replenishment of beach materials has become a critical factor for some of the Massachusetts beaches. The sealing off of supplies along the backshores and projecting headlands of till, necessitated by protection of properties, the retrogression of beaches over backshore marshes, and the loss of beach substance to the deeper offshore waters, have caused a permanent net loss. Rocky headlands contribute practically no materials, and even where till headlands are not fronted by sea-walls, the development of boulder pavements in front of these headlands somewhat retards and decreases the rate of supply by normal wave erosion. Such beaches may need to be artificially supplied, and to be protected against further erosion by such structures as offshore breakwaters and groins. It seems to be true that once sands are removed to the deeper offshore waters they are often forever lost, under the existing regimen of geologic forces. This is, of course, conditioned by such features as slope of the shore outward from the low tide line, the dimensions - height and length ratio - of the non-storm waves, and the consequent opportunity for the building of offshore bars. The Beach Erosion Board (1933) has made some investigation of these factors, and reached the conclusion that the offshore sea-bottom does not, in the absence of bars in the deeper waters, furnish a source of replenishment for the beach sands. In and north of the Boston Basin offshore bars are generally lacking, whereas along part of the South Shore, particularly within Cape Cod Bay, and off the Chatham area of Cape Cod, they are common.

For convenience the coastal belt of Massachusetts may be divided into three major segments that present contrasts in morphology, structure, and lithology. Consequently these segments present different problems in beach control. These three divisions of the coast are the North Shore, the Boston Basin, and the South Shore (including Cape Cod). (See index map, figure 1). Although these are essentially physiographic and geologic divisions, they are not to be completely separated, for some features of each are, of course, to be found in the others. In their broad aspects, however, the major differences are marked. I will consider only the geologic history, lithology, and natural sources of beach

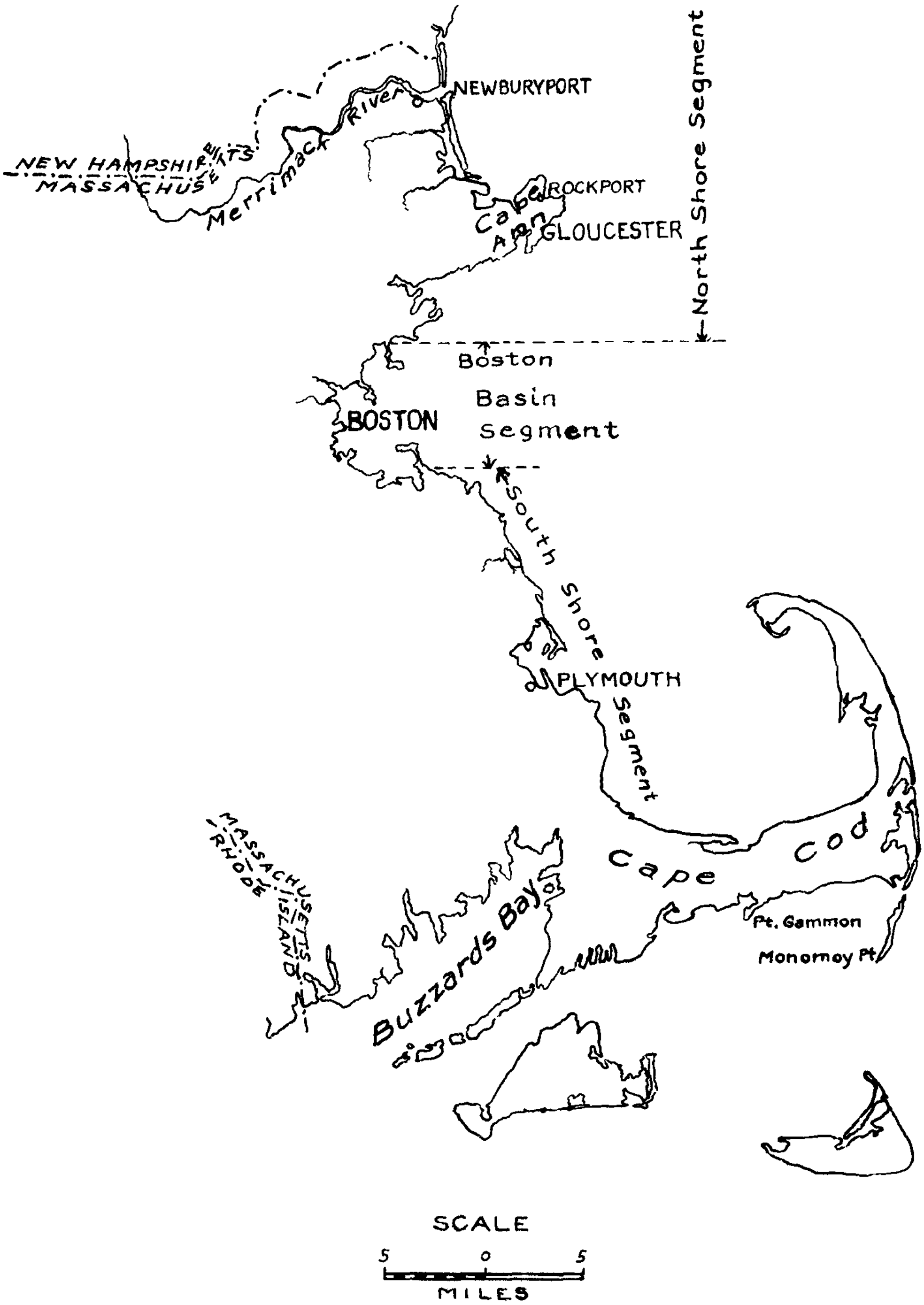

Fig. 1. Outline map of the coast of Massachusetts, indicating principal segments and features.

materials, but there are numerous other minor features that characterize individual beaches and are important to the engineer, and so need to be studied with relation to individual projects. A brief review of the geologic history will bring the beach characteristics into focus.

The coast of New England is one of submergence (Johnson, 1925), that is, the basic features have been determined primarily by a net relative depression of the coastal belt. Valleys that had been eroded in a maturely dissected upland composed chiefly of hard crystalline rocks were drowned by invasion of marine waters. A coast so developed is commonly irregular, in proportion to the degree of dissection and the magnitude of the depression, in contrast with an emerged or relatively uplifted coast, which is comparatively smooth and straight. Drowned coasts tend normally to have deeper offshore waters dotted with rocky islands; they are marked by estuarine embayments, rocky headlands, and, as in the area north of the Boston Basin, so-called "pocket beaches". If the geologic regimens are not interrupted such coasts ultimately become straightened by erosion of the headlands, and the development of sand spits, bay-mouth bars, long smooth beaches and, subsequently, offshore bars. Barrier beaches - long, straight, and smooth - form normally in the later stages, when the offshore waters become shallow enough by seaward deposition of land waste. In general, the New England shoreline is youthful; marks of the youthfulness of the Massachusetts coast, however, are somewhat more obvious in the North Shore and Boston Basin segments than in the South Shore segment (excepting the northern portion). The reasons for this are attributable to the accident of continental glaciation, which interrupted the geologic regimen of the preglacial coast, tilted the coastal belt differentially, and has masked or modified the rocky-coast features. For practical purposes, then, the coastal belt of Massachusetts is not to be classed quite so simply as a shoreline of submergence, for on it were superimposed the effects of continental glaciation. In the southern part especially these effects were so marked that much of the shoreline reflects the details of glacial processes and deposits more than the conventional features of a submerged coast. This has led to a great variety of forms that invest the Massachusetts coast not only with a visible charm, but also with a variety in beach structures and a complexity in local regimens. Clearly, the engineering problems are varied.

An ice sheet, such as traversed New England and came to rest far beyond the present shores, tends to abrade and round off the upland divides, and to deposit the abraded soil and rock materials over the entire area, but more thickly in the valleys. The deposits consist in part of till (ice-laid bouldery, heterogeneous, unsorted and unstratified debris) and in part of outwash deposits (gravel, sand, silt and clay, sorted and transported by the glacial melt waters) deposited broadly over the lowlands, partly or completely filling pre-glacial valleys. The sea came to rest against a glaciated land mass and began its work of erosion and redistribution of the thick, loose, glacial deposits. These deposits have been the principal sources of beach materials. It is true that rocky residuals of the pre-glacial land mass appear as prominent headland along part of the coast, but they are contributing very subordinately and slowly to the present strand in the North Shore segment, and not at all to the segment south of Plymouth and east of Buzzard's Bay. Where exposed, the rocks are mostly hard, crystalline varieties, and wave-cut terraces in them are conspicuously wanting. Hence, from an engineering standpoint, bedrock headlands are contributing practically nothing to the present beaches.

Appreciable natural replenishment of beach materials must therefore be derived from glacial deposits. The composition, distribution, and thickness of these deposits within the zone of wave action thus become an important part of the basic data to be provided by the geologist. It is in this connection that one of the major points of contrast between the three coastal segments mentioned above is brought out through a study of the recent geologic history.

The bevelled and deeply eroded pre-glacial land mass, with its sharply incised valleys and rounded divides, that underlies eastern Massachusetts slopes toward the southeast. In the general vicinity of Plymouth, about 30 miles south of the Boston Basin, it disappears completely below present sea level; southward and eastward from this point the old bedrock surface lies deeply buried beneath very thick deposits of glacial debris. The southernmost exposure of bedrock is in the vicinity of Plymouth; to the north, nearly to the southern limit of the Boston Basin, bedrock exposures are increasingly numerous, though small and low, as the old surface rises gradually to and above sea level. North of Boston Basin, the coast is truly "rock-bound". We have, then, a picture of the bedrock surface dominating the coast north of Boston, and gradually declining south of the Basin until it disappears below the zone of wave action to leave the soft and vulnerable glacial deposits unprotected and exposed to the full onslaught of the sea. Thus the coast has many aspects, and presents the engineers with a wide range of problems. The geologist can help materially in analyzing the natural forces currently at work and the probable future changes to be accomplished by them, through a study of the materials, land forms, morphology and slope of the beach, textural distribution of shore materials, and other features of the regimen.

The North Shore segment as far north as Rockport and Gloucester (the Cape Ann area) is clearly a drowned rocky coast that is only subordinately modified by glaciation. Along it, glacial deposits are everywhere present, in part as very thin deposits of till capping the rocky knolls and headlands, or as somewhat thicker, but local, deposits of outwash materials within the intervening valleys. Beds of silt and clay are irregularly and locally present, having been deposited post-glacially within shallow estuaries. Small, poorly drained flat areas of marsh lands form the backlands of some of the characteristic "pocket beaches". Projecting rocky headlands afford some degree of protection to these beaches, but not enough to prevent some removal of materials to the deeper offshore waters. Sands that have been so removed seem to be permanently lost to the beaches; the headlands furnish no significant substance to them, and littoral currents for the most part cannot redistribute sands from distant sources, being unable to skirt the rocky points and thence to carry the materials landward. Where the backlands consist of low, marshy areas, or the shore properties are protected by sea-walls, as they necessarily must be in places, there is no adequate source for replenishment of beach sands by natural processes. The engineering problem then becomes one of preserving the present beaches, and preventing the seaward migration along the beach itself.

From the Cape Ann area north to the State line, the coastal strip presents some features that are in marked contrast with the rest of the North Shore segment. In this belt, bedrock exposures, though numerous, do not now form projecting headlands; rather, they appear a mile or more back of the present beaches. Extensive tidal marshlands, and groups of hills composed of glacial materials - both till and outwash - lie between the low rock-knolls and the chain of barrier beaches. This 15-mile stretch of the Massachusetts coast is, then, comparatively low and flat. Unlike the coast to the south, much of it has prograded. Nevertheless, it is entirely consistent with the interpretation of a submerged shoreline, for it represents the true ria type coastal features, in which wide and deep embayments mark the drowning of the mouths of major river valleys. Two major pre-glacial streams of eastern Massachusetts entered the sea along this part of the coast. These valleys were filled with glacial deposits and recent marine clays, and along the general site of one of the valleys the present Merrimack River flows eastward to meet the sea at Newburryport. Another valley to the south is marked by a concentration of drumlins and outwash forms. The gentle and regular seaward slope of the shore zone permitted offshore accumulations of sand and silt, and ultimately the formation of offshore bars, sand spits, and barrier beaches. The beaches have been developed and nourished partly from glacial deposits, including drumlins, but they have also been nourished from offshore sources, in part, at least, provided with materials moved southward along the coast by littoral currents. The Merrimack River is the only stream in Massachusetts that now furnishes material amounts of sediments to the offshore waters. By the same token it has necessitated corrective measures by the construction of long jetties at its mouth. It has played a constructive role in the development of the gentle seaward slope of the coast here, although, as pointed out by R. L. Nichols (Chute and Nichols, 1941) this slope was also in large measure determined by deposition of marine clays, and glacial outwash sands and gravels. Thus the geologic stratigraphy and history again furnish the key to an understanding of the processes that are operating along this unique portion of the New England coast. A detailed discussion may be found in the reference cited just above.

The Boston Basin consists of a down-faulted block bordered by higher areas of crystalline rocks both to the north and south. It embraces the major indentation that comprises Boston harbor. Containing many islands of glacial till hills (drumlins) and some small knob and islands of bedrock, Boston harbor presents a very irregular shoreline. Some of its prominent beaches have been developed in large measure from the drumlins.

Some of the drumlins have been entirely worn away; some are in different stages of removal and form projecting headlands with erosional cliffs fronting the sea. Erosion of the drumlins has left partly submerged boulder pavements marking the former extents and distribution of these land-forms. The beaches are, therefore, in part tied to drumlins, but bedrock headlands are lacking in general within this segment of the coast. Protection of shore properties has required the construction of sea-walls, in places even around the ends of the partly eroded drumlins, so that natural sources of beach sands have been removed from the regimen. In places beaches have retrogressed over back-shore marshes, and are consequently underlain by peat, clay, and other materials. Some of the beaches, also, are sand bars that tie rocky islands or till hills together as tombolos. There is thus a great variety of local shore forms within this segment, and the beach engineering problems involve various kinds of geologic data. Stratigraphy, sources of materials, and processes need to be analyzed with respect to each individual beach in order that pertinent background data may be furnished the engineer.

Along the South Shore - Cape Cod segment, where the pre-glacial bedrock surface declines below the zone of wave action, a markedly different geologic set-up prevails. Here bedrock is eliminated from consideration in shore problems. Thick glacial deposits provide the materials for extensive beaches, and materials are moved for long distances by littoral currents. For the most part there are no problems relating to adequate sources, but, rather, the problems are concerned with rapid erosion of the coast - as particularly the outer shore of Cape Cod - and the prevention of coastwise translation of beach materials. In many places short groins have been effective in locally tying down and preserving the beaches. Bay-mouth bars are prominent across some of the drowned margins of glacial outwash plains, and long sand spits project in places. Submarine profiles are varied and are particularly important in the analysis of the coastline for engineering purposes. The conditions and shore processes are too numerous and complex to epitomize adequately in this short paper, but the importance of geologic investigations can, indeed, be emphasized. For details the reader is referred to the earlier cited work by Johnson on the New England - Acadian shoreline, and to two papers by N. E. Chute (1939, 1946).

In 1938 the Commonwealth of Massachusetts, through its Department of Public Works, proposed and entered into a continuing cooperative program with the United States Geological Survey for geologic investigations in the State. The principal objective is to prepare a complete and detailed geologic map of the State by quadrangle units. It was with commendable foresight that the officials specified a broad objective, namely, that the work should provide geologic data for scientific, educational, and engineering uses, for mineral resources studies, and for general information. Thus the program is to furnish all-purpose geologic maps from which basic data can be obtained for various needs. Hence the work is not directed toward any particular technical use of geology. Necessarily the engineering application has been largely in connection with highway and bridge projects, and to studies of the occurrences and distributions of construction materials.

However, special studies of shoreline segments and certain beaches hav been made upon requests by engineers, and insofar as the fiscal limitations have permitted. These studies furnish background data for shoreline engine but make no attempt to discuss the strictly engineering aspects of the prob lems, or to recommend technical engineering procedures. So far under the cooperative program in Massachusetts we have made special studies of four l segments of the shoreline, and of six beaches. Two of the longer reports a primarily concerned with erosional effects of exceptional storms on the sou shore of Cape Cod (Chute, 1939, 1946). The third, an open-file report by N Chute, discusses the development of, and recent changes along, the South Sh between Nantasket Beach and Duxbury, and the fourth report (Chute, and Nich 1941) describes the development of the northeastern coast from Gloucester t the New Hampshire line, and important geologic changes that have recently occurred within that segment.

Perhaps the function of the Geological Survey should properly be to pr vide engineers and their technical consultants with the broader terrane dat that are pertinent to the preliminary stages of their projects, and that th are otherwise not likely to acquire. As a public agency we would not feel justified in entering the technical engineering field either as practicing consultant engineers - we have neither the qualifications nor the inclinati to do this. But the general scientific study of coastal forms and shore processes as they involve geologic principles and agents, both of the past present, is properly within our field of research. Such study in the field engineering geology, could well be expanded by the Geological Survey, and c dinated with the work of other agencies to fill in the fringe area between fields of geologic science and engineering that is apt to be neglected by t geologists and engineers engaged in local coastal projects.

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