The Alaska Earthquake March 27, 1964: Regional Effects

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 543

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

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By KIRK W. STANLEY

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of its investigations of the Alaska earthquake of March 27, 1964, in a series of six Professional Papers. Professional Paper 543 describes the regional effects of the earthquake. Other Professional Papers in the series describe field investigations and reconstruction and the effects of the earthquake on communities, on the hydrologic regimen, and on transportation, utilities, and communications.

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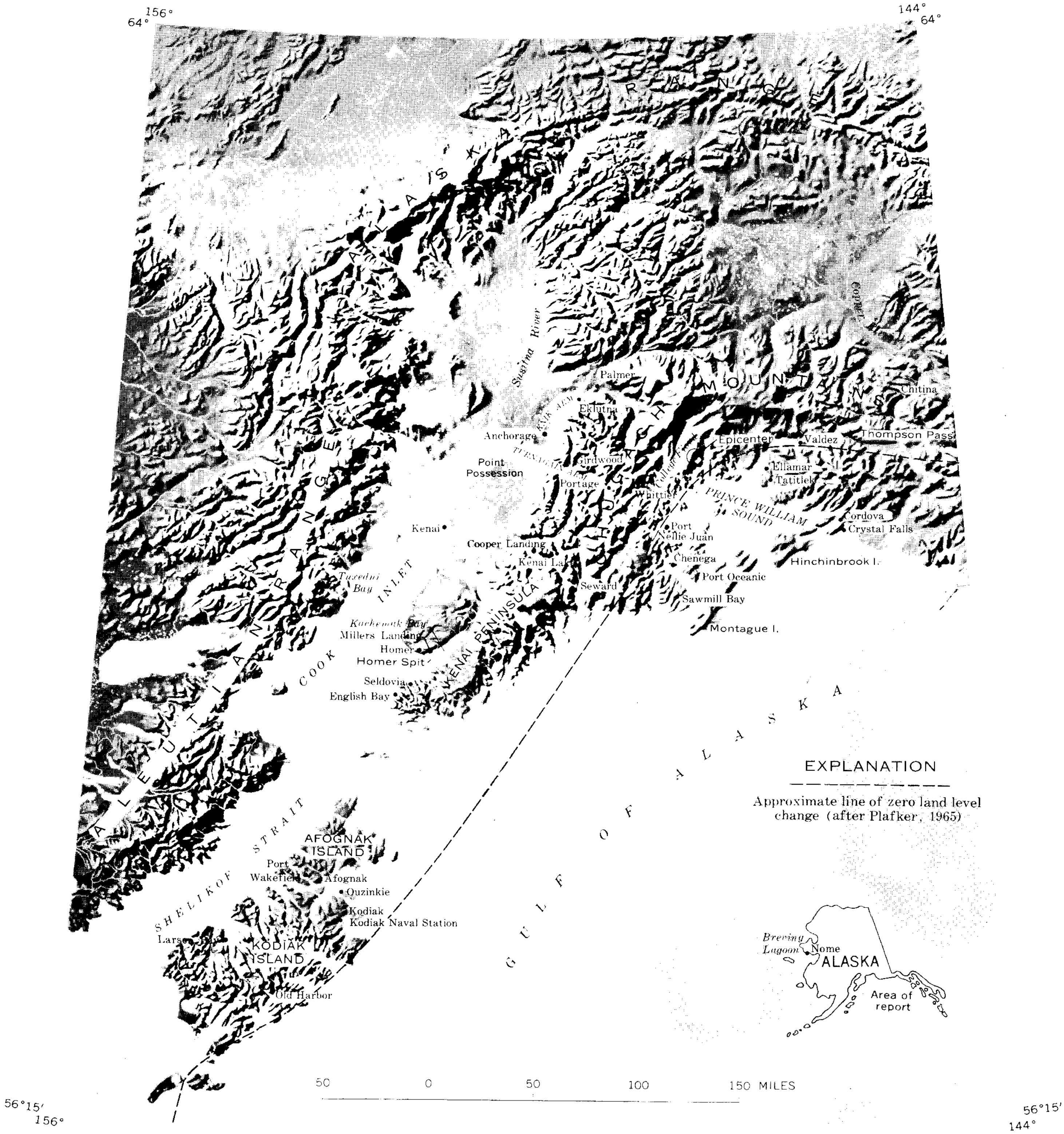

1.—South-central Alaska showing coastlines affected by the earthquake. Land to left of zero land-level change was generally lowered; land to right was raised.

EFFECTS OF THE ALASKA EARTHQUAKE OF MARCH 27, 1964, ON SHORE PROCESSES AND BEACH MORPHOLOGY

By Kirk W. Stanley [1]

ABSTRACT

Some 10,000 miles of shoreline in south-central Alaska was affected by the subsidence or uplift associated with the great Alaska earthquake of March 27, 1964. The changes in shoreline processes and beach morphology that were suddenly initiated by the earthquake were similar to those ordinarily caused by gradual changes in sea level operating over hundreds of years, while other more readily visible changes were similar to some of the effects of great but short-lived storms. Phenomena became available for observation within a few hours which would otherwise not have been available for many years.

In the subsided areas—including the shorelines of the Kenai Peninsula, Kodiak Island, and Cook Inlet—beaches tended to flatten in gradient and to recede shoreward. Minor beach features were altered or destroyed on submergence but began to reappear and to stabilize in their normal shapes within a few months after the earthquake. Frontal beach ridges migrated shoreward and grew higher and wider than they were before. Along narrow beaches backed by bluffs, the relatively higher sea level led to vigorous erosion of the bluff toes. Stream mouths were drowned and some were altered by seismic sea waves, but they adjusted within a few months to the new conditions.

In the uplifted areas, generally around Prince William Sound, virtually all beaches were stranded out of reach of the sea. New beaches are gradually developing to fit new sea levels, but the processes are slow, in part because the material on the lower parts of the old beaches is predominantly fine grained. Streams were lengthened in the emergent areas, and down cutting and bank erosion have increased.

Except at Homer and a few small villages, where groins, bulkheads, and cobble-filled baskets were installed, there has been little attempt to protect the postearthquake shorelines. The few structures that were built have been only partially successful because there was too little time to study the habits of the new shore features and to design appropriate protection measures. Emergence of large areas that were once below water and permanent submergence of once-useful land areas have led to many problems of land use and ownership in addition to the destruction or relocation of wildfowl, shellfish, and salmon habitats.

INTRODUCTION

One of the strongest earthquakes ever reported occurred in Alaska on March 27, 1964, at 5:36 p.m. Alaska standard time. The epicenter was at Unakwik Inlet in Prince William Sound (fig. 1). The magnitude of the main shock was 8.4–8.6 on the Richter scale (Wood, 1966). The area of land and sea bottom affected by the earthquake is at least 70,000 square miles and may exceed 110,000. Forty thousand square miles was lowered as much as 7½ feet and 25,000 square miles was raised as much as 33 feet (Plafker, 1965, 1967). The coastlines affected by the earthquake are shown by figure 1.

Definite limits of the coastal area of Alaska affected by the earthquake have not been determined. Most authorities, however, agree that it is bounded by Yakataga (just southeast of the area shown in figure 1) on the east and the Kodiak group of islands on the southwest (Plafker, 1965). If all the shoreline irregularities of the mainland and the islands affected by the earthquake are included, the shoreline within the area exceeds 10,000 nautical miles.

Certain changes in beach forms occurred as a result of relative changes in sea level caused by uplift or subsidence of the land during the earthquake. These changes were abrupt and thus cannot be unconditionally compared to a gradual change in sea level, but they did provide much information regarding normal shore processes. Because sea-level changes were not only abrupt but also permanent, months were afforded for observations, which other-

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wise—as during storms—would have been limited to hours or at the most several days.

No attempt is made in this paper to present a detailed description of changes in beaches throughout either the submergent or emergent areas. A study of this type might have provided some interesting and descriptive material, but, considering the great distances and the general remoteness of much of the shoreline involved, such a study would have been impractical. This paper is therefore restricted to descriptions of specific areas and problems. These limited observations do not réflect all conditions and processes that occurred within the area affected by the earthquake, but they do provide a basis for understanding the general processes that occurred.

The chief objective of this report is to compare pre- and post-earthquake processes. For this reason, Homer Spit is used as an example for much of the descriptive matter; it happens to be one of the few places for which considerable preearthquake information is available. Descriptions of coastal erosion primarily involve examples along Cook Inlet because (1) much of the shoreline there is eroding and (2) the area is more densely populated than elsewhere.

The earthquake not only caused physical changes which have left their marks upon the beach; it also had certain significant economic and legal consequences. These sociological effects have an interconnection with the physical effects and are considered worthy of mention.

SHORELINES OF THE EARTHQUAKE-AFFECTED REGION

The line of zero land movement, (fig. 1) trends southwest from the epicenter on Unakwik Inlet at the head of Prince William Sound, along the east shore of Kenai Peninsula, to Kodiak Island. West of this line the land subsided; to the east it was uplifted. Anomalous areas of submergence, particularly along deltas and at the heads of bays, occur in both regions and were caused by compaction and settlement of sediments. Compaction of sediments in the uplifted area reduced the overall upward change in some localities; compaction in the subsided areas accentuated submergence.

The landmass bordering the coastal area affected by the earthquake is mountainous, and both it and the shoreline are characterized by glacial or periglacial features. The shoreline from Yakataga northwestward to the Copper River Delta is characterized by long sweeping beaches broken by wide-mouthed rivers and resembles a ria coast (Lobeck, 1939). The shoreline features were formed in part of outwash deposits from the Bering and other large glaciers. Westward from the Copper River Delta the shoreline is glacially carved and is highly irregular, deeply incised, and fringed by numerous offshore rocks and reefs. The offshore area, particularly between the mouth of the Copper River and Cordova, is shallow and has numerous shoals, barrier islands, and spits. Active glaciers occupy the heads of many bays in the region, particularly in Prince William Sound.

Along Kodiak Island the shoreline is characterized by fiords in classic forms. The bays, particularly along the Shelikof Strait side of Kodiak Island, have deep depressions at their heads and submarine threshholds of either rock or unconsolidated material at their mouths—a feature that, according to Guilcher (1958, p. 160), denotes a true fiord. The walls of the bays are usually steep, and many headlands are characterized by cliffs. Beaches are generally poorly developed and are composed of medium to coarse shingle. Sandy beaches and constructional costal forms occur along the heads of bays, however, and well-developed sand-shingle beaches tens of miles in length are present along the southwesternmost part of the island.

Along the southern Kenai Peninsula and the western part of Prince William Sound, the shoreline resembles that of Kodiak Island in its irregularity, although bayhead depressions and submarine rock ramparts at the bay mouths are less well developed. However, the presence of active glaciers along the shoreline indicates that many of the indentations are true fiords. Here also the walls of many of the bays are steep, and cliffs are more numerous than along Kodiak Island. Narrow, relatively steep beaches consist predominantly of shingle. Sandy beaches occur along the sides and heads of inlets and bays but are less well developed than along the eastern shoreline of Prince William Sound.

Contrasting sharply with the irregular shorelines of Kodiak Island and Prince William Sound is the more uniform one of Cook Inlet. Cook Inlet extends into the mainland more than 175 miles and narrows and shallows towards its head. The backshore, particularly east and north of the inlet, consists of low gently rolling glacial outwash plains. Wave-cut bluffs as high as several hundred feet occur in that area, and the adjacent beaches are generally well developed. At the head of Cook Inlet the waters are shallow, and broad silty tidal flats are common. South of Tuxedni Bay, on the west shore of Cook Inlet, the low coastal plain pinches out, and mountains rise abruptly from the sea.

Much of the shoreline affected by the earthquake presents seemingly contradictory evidence of both uplift and subsidence—a contradiction that perhaps is not surprising when viewed in the light of the complex tectonic history of the region. The high Chugach Mountains, Saint Elias Mountains, and Fairweather Range are obvious manifestations of strong tectonic uplift. Raised beaches along some coasts indicate more recent uplift, also, but the drowned fiordlike character of much of the shoreline, combined with numerous offshore islands, skerries, and reefs, suggest coastal subsidence and submergence.

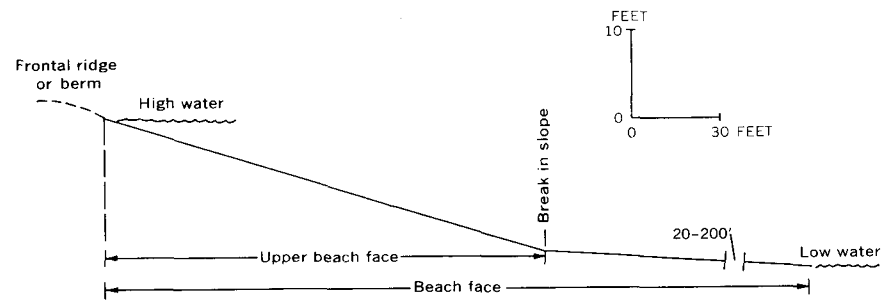
Reconnaissance studies of the displaced shorelines, paced by numerous radiocarbon dates, have brought out a general similarity between the pattern of earthquake displacements and the long-term trend of Holocene coastal emergence or submergence, as well as a remarkable widespread submergence during the past several centuries over much of the zone that was uplifted during the earthquake, and at least part of the zone that subsided (Plafker and Rubin, 1967; Plafker, 1968, in press). Thus, according to Plafker, the tectonic movements that accompanied the earthquake were but one pulse in a long-continuing trend of diastrophic deformation that has resulted in regional emergence of parts of the continental margin, simultaneous submergence of the Kenai-Kodiak Mountains belt, and either relative stability or emergence along the shores of Cook Inlet and parts of Shelikof Strait.

COASTAL FEATURES AND EARTHQUAKE EFFECTS

BEACHES

The beach face is the area between high and low water (fig. 2). It is an ever-changing feature, but normally the changes are subtle and become noticeable only during severe storms.

During the earthquake of 1964, rapid changes in land elevation caused obvious changes in shore processes and beach-face morphology. These changes were comparable in magnitude to changes that normally are caused by centuries-long fluctuations in sea level—or, paradoxically, to sudden changes caused by severe storms. Thus, changes in the beach face following the earthquake are important both to the study of fluctuating sea level as it affects a beach and to the engineering problems that might be met along the beach face as a result of changes caused by storms.



2.—Diagram illustrating beach features.

CHANGES IN PROFILE AND GRADIENT

Obvious changes in profile and gradient occurred along shingle beaches within the submergent areas. In those areas, changes were noticed within 1 week after the earthquake. The most noticeable change was a flattening of the gradient and a recession of the beach face.

Many shingle beaches within the submergent areas range in gradient from 1:8 to 1:30 and are characterized by a break-in-slope 50–200 feet seaward of the high-water line. The break-in-slope marks the location where waves act longest at high tide (King, 1959). The beach face (fig. 2) shoreward of the break (termed the "upper beach face") has a steeper gradient and coarser material than does the lower beach face. The break-in-slope shown in figure 3 is typical of those on many shingle beaches in Alaska.

3.—Sharp break-in-slope between upper and lower beach faces extends from midforeground to midcenter of photograph, just to right of man. These features, here seen in Kachemak Bay at low tide, are common to many shingle beaches.

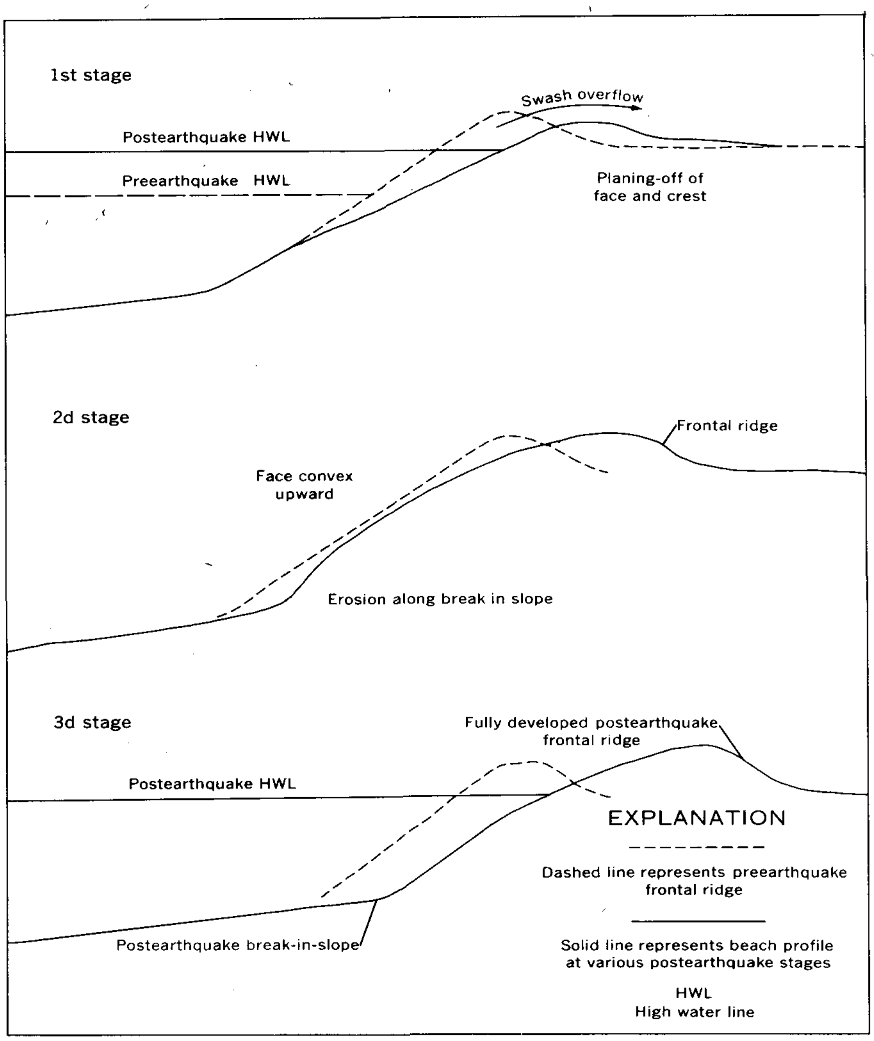
After earthquake-caused subsidence, waves reached higher on the beach face and caused severe scour erosion of the upper face; the break-in-slope gradually shifted shoreward. The upper limit of the swash was also extended at some places, and the frontal ridge, or berm, was overflowed. Part of the material eroded from the beach face was thus carried by the swash over the frontal ridge and was deposited along the landward side.

A good example of profile and gradient changes along a shingle beach within the submergent areas was afforded by beaches along Homer Spit. Adjustment of the Homer Spit beaches to the new high-water level was gradual but can be described as occurring in three stages (fig. 4). The first stage was characterized by severe erosion and planing off of the beach face and crest by wave and swash overwash. Part of the eroded material was carried across the beach crest and onto the spit. The second stage was characterized by active erosion along the break-in-slope and the development of a new postearthquake frontal ridge. During this stage the beach became noticeably convex upward because material from near the break-in-slope moved toward the upper beach face. The third stage was characterized by development of a well-defined break-in-slope that had gradually shifted landward. Erosion and recession of the beach face continued until the slope approached the preearthquake gradient. During the third stage the new frontal ridge increased noticeably in height and eventually retarded overflow. During this stage also, some of the material carried by the longshore drift began to accumulate along the lower beach face near the break-in-slope. The observed erosional and depositional effects of a relatively raised sea level on the Homer Spit beaches are in agreement with suggestions made originally by Bruun (1962) and partly tested by Schwartz (1965) with small-scale laboratory experiments. Bruun concluded in part that a raised sea level is followed by shoreward displacement of the beach profile as the upper beach is eroded and that the amount of material eroded from the upper beach is equal in volume to that deposited on the nearshore bottom. Thus the rise of the nearshore bottom that results from this deposition will ultimately equal the original rise in relative sea level.

Along beaches protected from severe storm waves, adjustment to subsidence differed somewhat from that on exposed shingle beaches such as Homer Spit. Within the protected areas, for example those along the south side of Kachemak Bay and certain shores of Kodiak Island, recession of the beach face was more uniform and the convex-upward profiles were less noticeable because wave action was less turbulent. Erosion along the new break-in-slope and swash action along the beach crest were also less severe. Thus, the rate of beach-face recession along the beaches not acted on by large waves was more uniform and less rapid than along exposed beaches.

Even less noticeable changes occurred along sandy beaches, probably because their gradient is usually flatter than that of shingle beaches and because sand is less readily moved by wave action than is shingle.

One area of subsidence where sandy silty beaches predominate is upper Cook Inlet. That region is characterized by an estuarine environment where the beach material consists largely of silt-sized particles derived from glacier-fed streams (Karlstrom, 1964). Storm waves seldom exceed 4 feet in height. The beach gradient is as low as 1:500 and, because the beach is acted upon by a tidal range of 35 feet, silty mud flats several



4.—Sketch of three stages that characterized the postearthquake changes of beach configuration in the submergent areas. Sketch is based on behavior of the beach on the Cook Inlet side of Homer Spit, but applies to many other beaches.

miles wide are exposed during low water. Subsidence of the region was not uniform but was as much as 2 feet. Some beaches examined shortly after the quake showed no noticeable change in profile or gradient, but by mid-1967, 3 years after the earthquake, subtle changes in profile had occurred.

The action of shore processes following subsidence of the coastal region and the resultant effects on the beaches were similar to the effects of a severe storm. However the changes resulting from subsidence must be measured in years, whereas the maximum destructive action of a storm is usually measured in hours.

Within the emergent areas, as along the Copper River Delta, the profile and gradient of the uplifted beaches remain unaffected with respect to wave action. The changes that have taken place are related to abandonment and stranding of the former beach faces above high water, and to exposure to the normal processes of subaerial erosion. In time, of course, new beaches will develop below the abandoned ones to fit the postearthquake high-water lines.

MINOR BEACH FEATURES

Minor beach forms including cusps, small beach ridges, and steps began to reappear on all submergent beaches within a few weeks after the earthquake. The new beach cusps were generally poorly developed and irregularly spaced upon the beach. Some of the hollows were overly large—being 30–40 feet wide as compared with preearthquake forms 5–15 feet wide. The outlines of the forms were vague, and at some places one horn was two to three times longer than the other. In all known examples, however, when the beach face itself began to revert to the preearthquake form, the cusps also began to develop gradually into preearthquake forms.

On beaches where the gradient was lowered by initial postearthquake processes, cusps did not reappear until the gradient had steepened, possibly because lack of mobility of the materials retarded the formation of the beach cusps. On beaches where the gradient was initially steepened after the earthquake, poorly defined cusps formed early, that is, within 3 months after submergence. These cusps were alternately destroyed and rebuilt by large storm waves, however—a process that suggests that beach cusps will not form, or at least will not persist, if the gradient of the beach flattens below a critical gradient. Along Homer Spit, this gradient apparently is about 1:20 for shingle beaches.

Prior to the earthquake, small beach ridges and steps occurred along the upper beach face of most shingle beaches. Submergence destroyed or greatly altered both features. However, the ridges and steps began to develop in approximately the same location on the postearthquake beach face about 3 months after subsidence. Unlike beach cusps, the ridges and steps became stable within 1 year after submergence.

LOW-WATER FEATURES

The most prominent low-water features on beaches are ridges, runnels, and submarine sandbars. All three forms were modified by the earthquake, and the changes observed give some insight into the movement of material and the development of such forms.

RIDGE AND RUNNEL

Ridges and runnels occur along most beaches of low gradient where sand is available and where the tide range is large enough to expose several hundred feet of beach face at low water. Good examples are found along many beaches of Alaska but they are especially conspicuous at Cook Inlet.

The ridges are composed chiefly of sandy material; the runnels, or troughs, are floored with gravel. The runnels provide channels which drain the beach on the ebbing tide. King (1959) suggests that a correlation can be made between the most persistent ridges and the position at which the tide will stand for the longest period during the tidal cycle. The ridges along the Alaska coast are usually fairly stable, particularly those that are alined parallel to the coast and perpendicular to the direction of the dominant wave approach.

In profile the normal sand ridge is asymmetrical, not unlike a ripple mark, but on a much larger scale; seaward-facing slopes are steeper than shoreward-facing ones. In general, individual ridges near the low-water line are higher than those farther up the beach face.

In the areas of land subsidence, a noticeable scouring of sand occurred in the runnels within a few weeks after the earthquake, and at numerous places exposed a much coarser bed material. During the same period the ridges became rounded and more symmetrical in profile. The heights of many ridges increased a foot or more. At many places where the preearthquake ridges were hard enough to support the weight of a man without appreciable indentation, the postsubsidence ridges were soft. Approximately 30 days after the earthquake, many of the ridges had widened, some to as much as several hundred feet, from previous widths of a few scores of feet. During the widening process the adjacent runnels were partly filled, and low basins were left in some areas to serve as drainage channels. Ridges and runnels that were particularly conspicuous prior to the earthquake were modified to broad, somewhat undulating sand flats without definitely recognizable features.

The landward shifting of the ridges was not a simple process of individual ridge migration. Instead, the ridges were first rounded then widened, and finally were coalesced—a process which often obscured and obliterated the intervening runnels. No appreciable seaward migration of material occurred. The predominant landward migration seems to bear out King's statements (1959) that seaward of the plunge zone, or break-in-slope of the beach face, there is a definite landward migration of material.

One year after the earthquake, most of the ridges and runnels had stabilized in approximately the same configurations as those before the earthquake.

The landward migration of the ridges apparently is not a simple process of removal from the seaward side of the ridges and deposition on the landward side, such as that by which a new frontal ridge forms along the crest of a beach. Instead, the process seems to be one of flattening and spreading of the material followed by a landward movement of material en masse. As the landward migration of sand is slowed by its deposition at a higher elevation on the beach, runnels begin to form. Water draining from the beach contributes to the process by eroding sand from the channels. The eroded sand is thereafter transported to the lower beach face where part of it is eventually carried downbeach by littoral currents. For this reason there was a persistent meandering and relocation of the runnel courses during the first year following subsidence, something that had not been observed before the earthquake. The meandering process is a result of the larger quantity of available sand and its increased movement along the low-water areas; part of the sand was deposited by the runnels themselves.

On new beaches within the uplifted areas, particularly along the Copper River Delta, incipient ridges and runnels became noticeable about a year after the earthquake. They were poorly developed, perhaps because the newly formed lower foreshore had not yet stabilized with respect to gradient and profile. In part, material in the ridges was transported landward and deposited on the upper beach face or on frontal ridges along the new high-water line. A few preearthquake sand ridges and runnels were partly stranded above the high-water line and so were altered or destroyed by storm waves.

SUBMARINE SAND BARS

Limited observations indicate some relocation of submarine bars.

This relocation is suggested by previously reported hard bottoms in anchorages that, after the earthquake, were composed of soft sand. This condition was particularly noticeable along Homer Spit where scuba diving showed that preearthquake areas of hard-packed sand were characterized by soft loose sand within a year after the earthquake.

In some areas, particularly in Prince William Sound, submarine sand bars apparently were altered or destroyed by seismic sea waves or by local waves. G D. Hanna (written commun., 1965) states that soft sediments were scoured from many shallow bottom areas. Elsewhere submarine bars were altered even though tsunami effects were not evident along the shoreline.

MODERN BEACH RIDGES

Beach ridges (also referred to as "beach storm berms") occur along many of the beaches of Alaska; in the submergent areas many of these ridges were altered during the earthquake. Observations since the earthquake have provided information on the formation of beach ridges as well as their adjustment to relatively higher sea level.

Beach ridges of south-central Alaska are more perfectly formed along shingle beaches than along sand beaches where most are smaller and less well developed. Most constructional coastal forms, such as cuspate forelands, spits, and tombolos, are formed and enlarged by the development of successive beach ridges along the shoreline.

The usual beach ridge consists of a mound or windrowlike deposit along the beach immediately above the high-water line. King (1959, p. 353) considers the ridges to be the product of steep storm waves which throw debris above the reach of normal waves. The larger ridges along the Alaska coast are composed of shingle, often with minor amounts of sand. A beach ridge along the present shoreline is generally referred to as a modern or frontal ridge, whereas the ridges farther inshore are referred to as ancient or old ridges.

Most individual ridges are 5–6 feet above high water and 8–10 feet wide, but some are as high as 20 feet and their bases may be as wide as 200 feet. Most ridges eventually become stabilized by vegetation that establishes itself on the landward slope.

Frontal ridges grow gradually in both height and width by the deposition of material carried onto and across the ridge crest by waves and swashes during storms. As the ridges increase in height, the ability of the overwash to carry debris across them decreases. Thereafter material will accumulate along the seaward side of the ridge; as the accumulation of debris progresses, a second ridge, seaward of the earlier one, will begin to form. The entire process may then be repeated.

The time span between development of successive ridges is variable, being about a year or less along certain narrow stable beaches (a "stable" beach being defined as one not enlarging seaward or retreating landward) but several hundred years or more along such large forms as cuspate forelands and spits.

It is generally accepted that coastal forms, such as cuspate forelands and spits, widen seaward by the development of successive parallel and subparallel beach ridges. The landward parts of such coastal forms are usually characterized by a series of old vegetation-covered beach ridges that represent former shorelines that trend parallel or subparallel to the present shoreline.

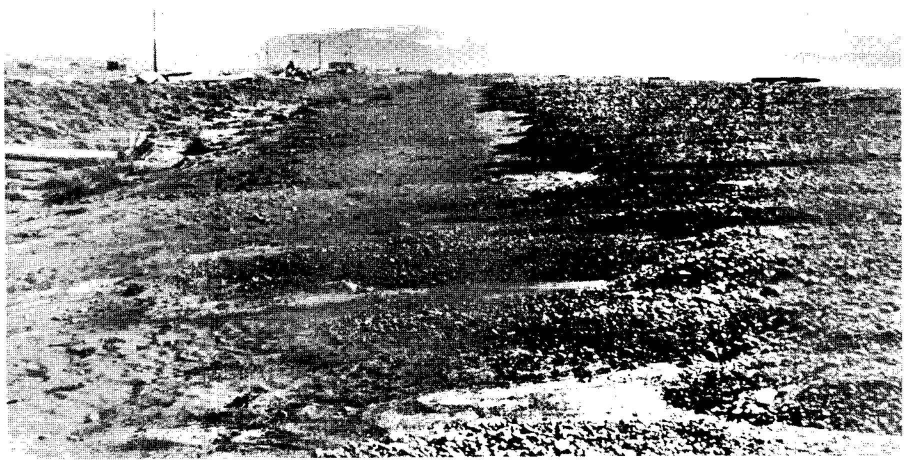
RESPONSE TO SUBSIDENCE AND UPLIFT

Changes in beach ridges occurred in many submergent areas. The magnitude of the changes depended on (1) the extent to which the land was submerged, (2) the geographic location of the beach with respect to storm waves, (3) the slope of the beach face, and (4) the type of beach material. In sheltered areas where submergence was only about 1–2 feet, changes were minor, but in areas of greater subsidence and exposed sea conditions the changes were often major.

In some areas, such as along Homer Spit, subsidence caused waves to reach as much as 6 feet higher on the beach face than before the earthquake, and swashes overflowed the crest of the frontal ridge. Material along the upper beach face, which was formerly above all but the highest waves and swashes, was scoured and eroded. Part of the eroded material was carried by the swash across the crest of the frontal ridge and deposited along the landward slope (fig. 5).

As overflow of the frontal ridges continued, material eroded from the beach face, including the face of the frontal ridge, was carried onto the backshore and deposited there. Continued overflow and erosion of the preearthquake frontal ridges reduced the crest height and caused the eroded material to spread out along the backshore.

The beaches along Homer Spit (Stanley, in Waller, 1966a) are good examples of postearthquake beach-ridge development. Within approximately 30 days after the earthquake, the beach face in some areas had receded as much as 15 feet, but the frontal ridges had increased as much as 30 feet in width and 2–3 feet in height. As the frontal ridges widened, coarse debris



5.—Overflow of the crests of some beaches caused material to be carried and spread out along the backshore, left half of picture. Gradually the material accumulated into a new and higher frontal ridge. View along Homer Spit, looking southeast.

was deposited near the crest and the finer material was carried toward the backshore. Along the crest and the seaward side of the ridge, the material was poorly sorted because of the severe scour. On the landward slope of the frontal ridges, the sorting was generally better and the grain size decreased. Along the extreme landward edge of the frontal ridge, the overflow material was delicately layered in fanlike forms and consisted of silt, sand, and pea-sized gravel.

Continued overflow and the transfer of material from one side of the frontal ridges to the other caused the ridges to migrate toward the backshore. The transfer of material from one location to the other led to a net loss along the seaward side and a net gain along the landward side. Thus the process of landward ridge migration was accomplished by the transfer of material within the ridge proper.

During overflow of the frontal ridges a greater volume of coarse material was deposited along the crest than along the landward side; the height of the ridges thus gradually increased. When the ridges had increased sufficiently in height to prevent overflow, migration stopped and the ridges stabilized.

Observations of the migration of beach ridges after the earthquake suggest an explanation as to why some ridges appear to migrate even under conditions not necessarily related to a rise in sea level. As stated above, beach ridges along Homer Spit migrated landward under conditions of relatively higher sea level, the migration being brought about by the process of overflow. Migration of the ridges ceased, however, when the width of the ridge was sufficient to further the heightening by deposition of material along the crest. It is concluded, therefore, that a beach ridge will stabilize if there is sufficient backshore area upon which the overflow material can accumulate.

If a barrier beach fronts a lagoon, then there is no platform for buildup of material, and landward migration of the beach ridge may continue indefinitely. This condition is exemplified by the barrier beach at Breving Lagoon, on the Seward Peninsula, far from the area where shorelines were affected by the earthquake (fig. 6). This barrier beach has a maximum width of 500 feet and is separated from the mainland by a shallow lagoon as much as a mile across. The beach is migrating landward, apparently because of storm-wave action and the resultant process of overflow. Material eroded by storm waves from the seaward side and transferred by overflow to the landward side of the barrier beach is carried into, and spread out on the floor of, the lagoon. Because the lagoon affords no platform on which overflow material can accumulate there can be no appreciable widening of the barrier beach, and therefore, the height of the beach cannot be increased. Hence under normal storm conditions the beach will continue to migrate landward; the landward migration is not dependent on a rise in sea level.

Unlike the large ridges along shingle beaches at such places as Homer Spit, beach ridges along sandy beaches on the east shore of Cook Inlet were destroyed in many areas, particularly along the toes of low bluffs. In such areas the widths of beaches between the high-water line and the bluff toes prior to the earthquake ranged from 25 to 150 feet. After subsidence the beach widths were decreased and the small beach ridges—those from 1 to 4 feet high—were destroyed. The relatively narrow width of such beaches prevented overflow material from accumulating, and thus the beach ridges could not retreat landward when acted on by a sea level as much as 2 feet higher

6.—Part of the barrier beach at Breving Lagoon, Seward Peninsula. Lagoon is north of (above) beach; Bering Sea is south of (below) beach. The lagoonward migration of the barrier beach is shown by superposition of the overflow upon the cuspate spit. Most beaches in the earthquake-affected part of Alaska migrated landward only short distances because they were backed by land platforms that allowed overwash material to accumulate. Photograph by Alaska Highway Department.

(fig. 7). Thus, the material, instead of accumulating higher on the beach (as it did along Homer Spit) was dissipated by wave action and was transported away from the site by the longshore drift. As the bluffs in such areas erode and recede, the beaches will eventually regain their preearthquake widths, and new beach ridges similar to those that existed before the earthquake should develop.

In the uplifted areas the old frontal ridges are abandoned and stranded above high water. New ridges have formed in some places, and rather rapidly. In most areas, however, the growth of new ridges has been slow, probably because the predominantly fine material

7.—Submergence caused the high-water line to shift to a higher elevation on this beach on the eastern shore of Cook Inlet. The establishment of a new high-water line caused undercutting and sloughing of bluffs. Note absence of beach ridges.

along the preearthquake lower beach face does not form stable beach ridges as readily as does shingle. The old ridges in the uplifted areas will gradually be covered by vegetation and will then assume the character of the typical old beach ridges of many coastal areas. New ridges along the lower high-water line will begin to develop as material continues to be worked by waves. However, the new ridges probably will require several years to stabilize, mainly because of a lack of coarse source material.

ANCIENT BEACH RIDGES

Postearthquake studies of subsided coastal forms afford an explanation for the fact that the crests of some ancient beach ridges are uniformly lower than the modern or frontal ridge. In some areas this condition is sufficiently pronounced to result in a basin-shaped area between the frontal ridge and the mainland. This habit of Alaska beach ridges has also been noted elsewhere (Bird, 1964; Johnson, 1919).

Johnson (1919), Fisher (1955), and Zenkovitch (1959) attribute the relatively lower crest elevation of the older ridges to a continuous rise in sea level whereby each successive frontal ridge builds higher. This is well illustrated along Homer Spit; as a result of the earthquake-caused rise in relative sea level, the frontal ridge here has been built higher than the older ridges. If a rise in sea level is the only factor at work, however, the profile between the frontal ridge and mainland should have a gentle landward slope rather than the commonly observed basin-shaped profile.

Studies by the author after the earthquake suggest that compaction and settlement of sediments by seismic shaking may also contribute to a change of coastal forms. The 1964 earthquake caused compaction and settlement of sediments in many parts of south-central Alaska (Kachadoorian, 1965; Coulter and Migliaccio, 1966; Waller, 1966a). Coastal forms must have been subjected to similar compaction processes many times: During the past 50 years that official records have been kept, hundreds of earthquakes have occurred along the Alaska coast (U.S. Coast and Geodetic Survey, 1964, p. 23).

As new beach ridges develop, the coastal form widens seaward with a corresponding increase in thickness of the column of sediment. The coarsest material is usually near the mainland and the smaller particles along the seaward side. If the mass of this sediment is repeatedly subjected to seismic and microseismic shocks, the sediments—particularly the finer particles—will lose bearing capacity and settlement will follow (Terzaghi and Peck, 1948). In some kinds of sediments, vibration can lead to spontaneous liquefaction which would cause additional settlement.

Even though the coastal form nearest the mainland is oldest and hence has been subjected longest to seismic action, the sediment layer there is thinnest and the size of the particles is coarsest. Compaction by seismic shaking, therefore, would be less in such areas than in the seaward part of the landform where the sediment is thicker and the particle size is smaller.

Although the modern frontal ridge has been subjected to fewer earthquakes than have the ancient ridges, sediment compaction does occur there also. However, any decrease in height caused by compaction would perhaps be offset by the addition of new material brought in by waves. Maximum decrease in height from compaction and settlement, therefore, probably would occur between the modern frontal ridge and the mainland and would lead to the typical basinlike profile that characterizes so many coastal constructional forms along the south-central coast of Alaska.

STREAM-MOUTH CHANGES

Stream mouths were changed throughout the areas of uplift and subsidence. In uplifted areas, streams were lengthened and incised into the elevated beach face. In the submergent areas, streams were shortened and drowned.

SUBMERGENT AREAS

Stream mouths were drowned throughout the submergent areas. Maximum drowning occurred mostly at the mouths of low-gradient streams that flowed across low-flying backshores composed of water-laid sediments. Within such areas, subsidence is attributed both to tectonic movement and compaction of the sediments (Kachadoorian and Plafker, 1967, p. F27; Kachadoorian, 1965, p. B2), and the extent of stream drowning is a function of both.

The most notable examples of stream-mouth drowning are along the shores of Kodiak Island and the southern Kenai Peninsula where subsidence of the land was 5 feet or more in some locations (Alaska Dept. Fish and Game, 1965). Several excellent photographs of drowned streams on Kodiak Island are shown in a report on that area by Plafker and Kachadoorian (1966).

During the earthquake many bays along Kodiak Island were hit by seismic sea waves. Spits, bay-mouth bars, and barrier beaches at or near stream mouths were altered or destroyed. Some of the lower of these landforms were overwashed, eroded, and reduced in height. New outlets formed where the tsunamis tore channels through ridges and spits. In all examples known to the writer, stream mouths that were acted upon by tsunamis were widened by scour and erosion.

Since the earthquake, erosion by normal wave and swash overflow has gradually caused many coastal features such as spits and barrier beaches to flatten in profile and recede landward. Thus, the effect of the tsunami and of normal wave action has reduced many once-conspicuous forms to flattened, poorly defined deltalike features. In some areas of active shore drifting, material eroded by wave action from the stream mouths has replenished the beach along the downdrift side. In areas of weak or inactive shore drifting the eroded material is merely spread out on the lower beach face.

In certain streams of low gradient and velocity, the shores were subjected to strong wave action when the land subsided, and material eroded from the unconsolidated deposits along their banks, such as deltas and outwash fans, was transported by waves into the stream mouths. This process is particularly noticeable along Turnagain Arm in upper Cook Inlet, where mud is accumulating in drowned stream mouths.

In some areas the drowning of streams has decreased the supply of material for natural beach nourishment. By reducing stream gradients, submergence has led to prograding rather than degrading of channels. Stream erosion therefore is less effective than it was before the earthquake, and the reduced quantity of debris carried by the streams diminishes the quantity of material available to the longshore drift. The extent to which the beaches will be affected by the decreased supply of material is not yet clear; however, because of a decrease in stream-borne material, because wider stream mouths will retard longshore drifting and by-passing of material, and because of continuing wave action, beach erosion probably will characterize many drowned stream-mouth areas for many years to come.

8.—Tectonic uplift created new lands permanently above high water, such as this area along the Copper River Delta. View at high tide, several months after the earthquake. The preearthquake high-water line is shown approximately by the dashed line. Photograph by U.S. Forest Service.

UPLIFTED AREAS

Changes at the mouths of streams in the uplifted areas are related to stream-course lengthening and downcutting (fig. 8). These changes range from minor alterations along shorelines of little uplift to major changes along gently sloping, easily eroded beaches in areas that were appreciably uplifted.

The effects of tsunamis on stream mouths in the uplifted areas varied widely. In many places, sand and silt were scoured from the mouths and carried with other debris into the upper reaches of the streams. Such deposition caused considerable silting in stream mouths and channels, and in some streams caused a temporary damming or blocking. Spits and barrier ridges at stream mouths were generally altered by the tsunamis. Many of the lower beach forms were appreciably changed, and material was redistributed along the beach into the stream mouth. Such redistribution of the material even obliterated some stream courses.

Along appreciably uplifted shorelines composed of sand and silt, rapid gullying occurred at stream mouths (fig. 9). Along the Copper River Delta, an area of readily eroded sand and silt that was uplifted several feet, gullying commenced within hours after uplift (Reimnitz and Marshall, 1965). Rapid headward erosion produced small waterfalls 1–2 feet high.

9.—Rapid gullying and sloughing caused by headward stream erosion along the uplifted coast on the Copper River Delta. Photograph by U.S. Forest Service.

Along beaches of mixed sand and shingle, stream adjustments were slower. Small riffles formed at stream mouths along such beaches.

Kirkby and Kirkby (1968) described in detail stream-mouth adjustment along elevated intertidal zones composed of sand and shingle at Montague Island, where uplift was as much as 33 feet. As on the Copper River Delta, stream adjustment began immediately after uplift had occurred.

Along some elevated shingle beaches, streams disappeared into the gravel of the uplifted intertidal zone. Generally this condition was temporary, and after several months the streams developed new courses across the intertidal zone.

Most uplifted stream courses showed evidence of degradation and bank erosion within a few days after the earthquake. Slumping of bank material and debris deposited by seismic sea waves also contributed material. In addition, after spring breakup, the normal increase of streamflow made deposition of material all the greater. The overall result was an increase in material carried by the streams and deposited at their mouths.

Along some stream mouths the newly deposited material has retarded channel development and has led to meandering. Along the larger streams the process has been mainly silting and dissection of newly formed deltas and spits.

Although evidence indicates an increase in sediment carried by the streams, the length of time the increased load was carried probably was short. By the fall of 1964, 6 months after the earthquake, the stream-carried sediment load was normal (Waller, 1966b).

COASTAL EROSION AND MOVEMENT OF MATERIAL

EROSION

Coastal erosion is active along all shorelines within the area affected by the earthquake except on the rocky platforms. The shorelines most affected are those composed of unconsolidated material within the submergent areas.

Of the shorelines modified by wave erosion, none were affected more than the east shore of Cook Inlet from Kachemak Bay to Turnagain Arm—a distance of more than 170 miles (fig. 1). There the entire shoreline is eroding. As already mentioned, the shoreline is a relatively uniform sandy beach with slopes as low as 1:300. The tidal range is about 22 feet along the southern section but increases to more than 30 feet near Turnagain Arm. Because of the low beach gradient and high tidal range, several thousand feet of tidelands are exposed at low water. The beach is backed by a line of bluffs about 200 feet high in most places, but locally as high as 600 feet in the Homer area. Most of the bluffs are of unsorted glacial material that is easily eroded.

Prior to the earthquake, wave action was undercutting the bluffs in many areas. Most of the sandy fraction of the sloughed material drifted away, but part of the coarser material remained along the high-water line in the form of shingle on beach ridges. The ridges, which were as high as 8 feet, protected the toes of the bluffs from all but the larger storm waves.

During the earthquake the shoreline subsided as much as 3½ feet along the southern section near Homer and as much as 1 foot near Point Possession at the mouth of Turnagain Arm. Prior to submergence the width of beach between the high-water line and the toe of the bluff was generally less than 100 feet, and in some areas less than 20 feet. Submergence decreased these widths and, after the earthquake, storm waves, particularly along the southern section, acted directly upon the toes of the bluffs. Many beach ridges that had previously protected the toes of the bluffs were exposed to waves of even, moderate height (fig. 10).

10.—Undercutting and sloughing of bluffs caused by tectonic subsidence, eastern shore of Cook Inlet. Driftwood along toe of bluff indicates the position of post-earthquake high-water line.

11.—Serious bluff erosion caused by subsidence along the waterfront of the town of Kenai. View looking northwestward, about 30 days after the earthquake.

By 1967, 3 years after the earthquake, the bluff line in some areas had receded sufficiently to provide a width of beach that afforded protection from all but the larger storm waves. Elsewhere intermediate-size storm waves still (1967) erode the toes of the bluffs. Until the bluff line recedes enough to provide a sufficient beach to prevent wave runup to the toe, erosion and recession will continue.

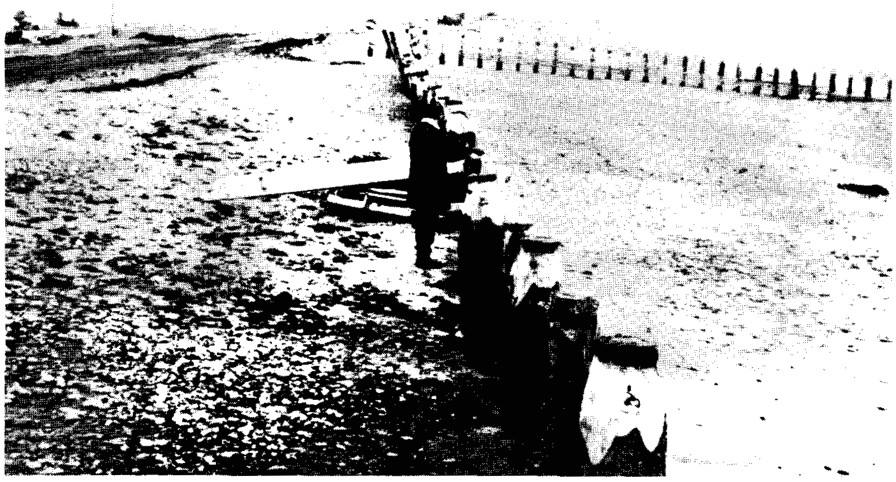
The two communities along this shoreline most seriously affected by bluff erosion were Kenai and Homer. Kenai is at the mouth of the Kenai River, a tidal estuary. During the earthquake the area subsided 12–18 inches. South of the town, bluffs as much as 150 feet high consist of readily eroded glacial material and alluvium. After regional subsidence, the preearthquake accumulation of sloughed debris along the toe of the bluffs was quickly removed. Undercutting by waves and by the river began a few days after the earthquake, and within 3 months the bluffs had receded as much as 20 feet (fig. 11).

In the Homer area the regional subsidence was about 3½ feet. Particularly damaging wave erosion occurred in the Millers Landing area, toward the east end of Homer on Kachemak Bay, along a low line of bluffs composed of peat, sand, and silt. After the earthquake, undercutting caused serious sloughing; within 6 months, the bluff line had receded as much as 8 feet.

SHORE PROTECTION MEASURES

Except at Homer and a few small villages, no serious effort has been made to construct erosion-preventive works anywhere in the earthquake-affected area. Along the Cook Inlet side of Homer Spit, erosion on the lee side of the groin farthest downdrift became critical. Retreat of the beach was jeopardizing the spit highway. In July 1964, a seawall and two additional groins were constructed. Two hundred feet of the wall was constructed to a height of 1–2 feet above the high-water line, and one section was built 5 feet higher above the high-water line. Figure 12 shows the timber bulkhead and the additional groins a short time after construction. Figures 13 and 14 show the same area 6 and 16

12.—Timber seawall and new groins along west side of Homer Spit as constructed 3½ months after earthquake-caused subsidence.



13.—Seawall shown in figure 12, approximately 6 months after construction.

14.—Seawall shown in figure 12 some 16 months after construction. Note that the bulkhead and one of the groins were completely destroyed during this period owing to their excessive height.

15.—Cobble-filled wire-mesh fence under construction at Larsen Bay, Kodiak Island, shortly after the earthquake and resultant subsidence of 2 feet. Most of the fence was destroyed by a storm before it could be completed.

months later, respectively. Sixteen months after construction, the high timber bulkhead between the fifth and sixth groin had been destroyed, as had the last groin (fig. 14). Similar high bulkheads were constructed in other areas but most were destroyed within several months, or at most within a year, after the earthquake. Failure is attributed to the fact that the bulkheads were too high and were anchored in unstable beach gravel.

Elsewhere wire-mesh baskets filled with cobbles were placed along the beach to serve as bulkheads. Such baskets appeared to function well along Homer Spit, even though they were pounded by waves as high as 10 feet. Erosion, moveover, occurred on neither the updrift nor the downdrift side. A similar cobble-filled wire-mesh fence was started at Larsen Bay on Kodiak Island (fig. 15), but most of it was destroyed by storm waves before it could be completed.

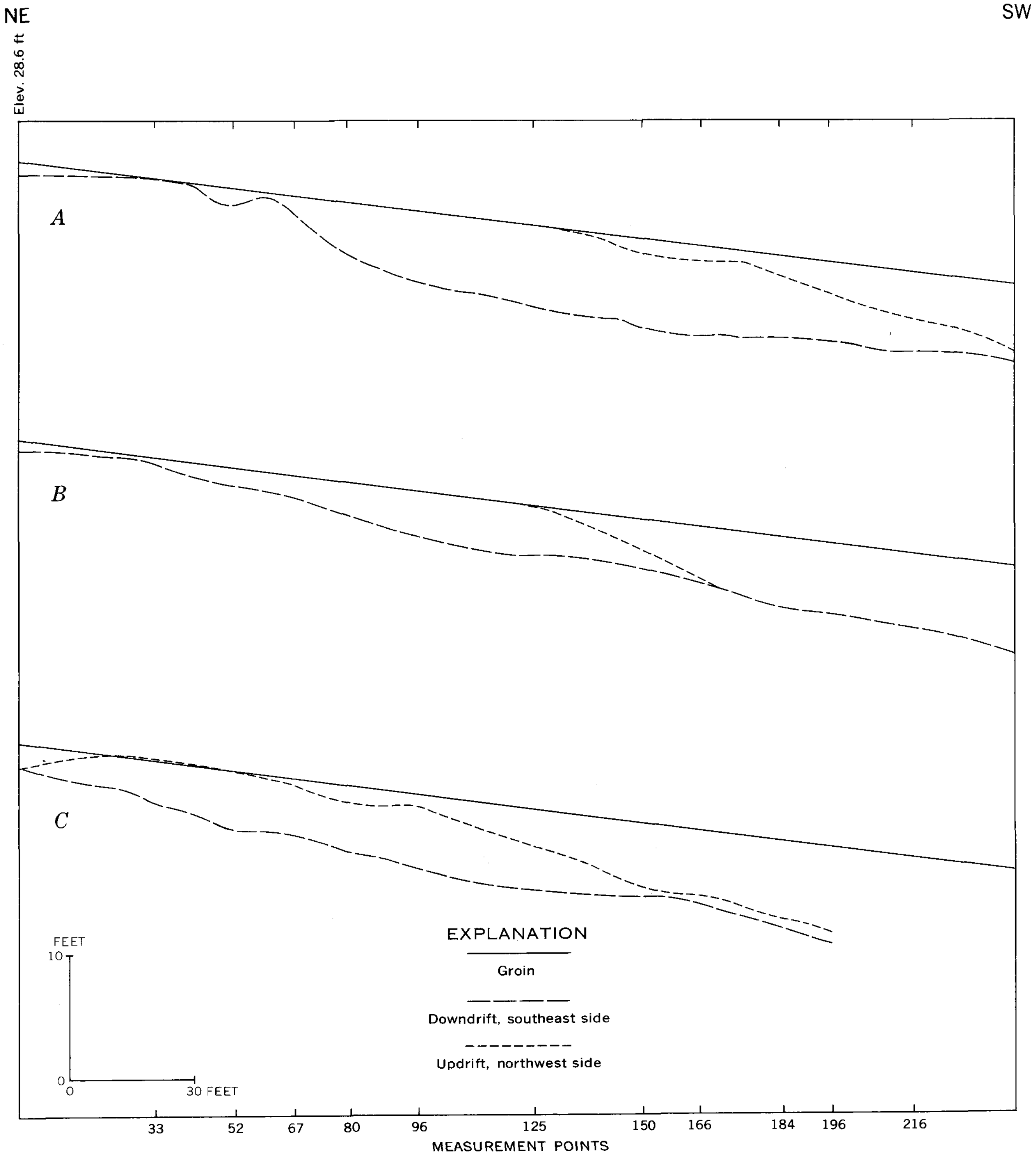
Wave erosion of landslides caused by the earthquake was rapid, particularly along Cook Inlet where the frontal edges of the slides were greatly modified within 2 years. Many slides consisted of sandy-silty material. Silty-mud beaches have developed gradually, particularly on the downdrift sides.

Erosion within the uplifted areas is evident along the post-earthquake lower high-water line. Wave erosion along most of the uplifted area is not serious so far as loss of land is concerned; most streams across elevated tidal flats are incising channels.

LONGSHORE MATERIAL MOVEMENT

No significant changes resulting from the earthquake are known or reported for the directional habit of the longshore drift. The changes that have occurred are only in the quantity of material carried. Along most shorelines affected by the earthquake, more material has entered the longshore drift than before.

The additional material began to enter the sea immediately after the earthquake. This fact was made obvious along many shorelines by a broad band of muddy water that was several miles wide



16.—Profiles of updrift and downdrift fill of groin at Homer Spit, measured (*A*) on March 2, 1964, a few weeks prior to the earthquake; (*B*) on August 28, 1964, 4 months after submergence; and (*C*) on September 30, 1965, 18 months after submergence. The change in configuration of the groin fill was caused by submergence and the resultant higher level of water on the fill. Note, however, that the gradient at 18 months approximates the preearthquake gradient.

in some areas, but no direct effect, such as the formation of new berms by the deposition of the material, was observed along beaches until several weeks after the earthquake. A good example of the effect of a delayed longshore drift is described by Stanley (in Waller, 1966a, p. D24). At Homer Spit the additional quantity of material that had entered the longshore drift in the source area, 2–6 miles west of the spit, did not reach the spit until about 30 days after the earthquake.

Accelerated shoreline erosion in the submergent areas caused more material to enter the drift than had been entering before the earthquake. However, in the same areas, material contributed by rivers and streams decreased. The converse was true in the uplifted areas. What effect the change in balance of the source and supply of material will have on the character of the longshore drift is not yet known. In planning future coastal projects the possible changes in source and supply that have occurred since the earthquake must be taken into consideration.

UPSLOPE MATERIAL MOVEMENT

Only one limited study of material movement was made within the first year following the earthquake (Stanley, in Waller, 1966a). Significant changes in material movement may therefore have passed unnoticed.

The study was made by the Alaska Division of Lands along the west side of Homer Spit at a system of filled groins that had been studied prior to the earthquake. After submergence the high-water line rose 3.5 feet. Within 5 days after submergence, 1–2 feet of material had accumulated along the landward end of the groins and had spread inland to a width of 30–50 feet. The newly deposited material was first thought to have been carried in by the longshore drift. However, the first profiles made 7 days after submergence indicated that the intergroin fills had actually receded and flattened and all had undergone a net loss of material (fig. 16*A*). Inasmuch as the material lost from the intergroin fill area about equaled the newly deposited material along the landward end of the groins, the material probably was derived from the adjacent interfill area rather than from some distant source.

Additional profiles were made at about 15-day intervals for the next 60 days (fig. 16*B*, *C*). Within the first 30 days the intergroin fills receded as material continued to accumulate along the landward ends of the groins (fig. 16*B*), but about 30 days after the earthquake the intergroin fills began to enlarge, and thereafter the enlargement increased noticeably. The material causing the increase probably was brought there by the longshore drift.

Observations indicate that during the 30-day period following the earthquake, the material deposited along the beach crest came from the lower-upper beach face of the groin fills and was carried upslope. Erosion along the lower-upper beach face continued until a new profie of equilibrium had been established. The dominant movement of material during the 30-day period following subsidence was upslope because the waves were reaching higher up the beach face. Waves running higher up the beach face shorten the travel distance of the swash and thus increase its carrying capacity.

The increased shoreline erosion throughout the area unquestionably increased the supply of material to the longshore drift; after about 30 days a noticeably increased quantity of material was drifting alongshore, but during this first 30-day period following submergence the dominant motion of material was up the beach rather than along it.

BIOLOGIC EFFECTS OF SHORELINE CHANGES

FISH

At the time this report was written (1967), the most comprehensive discussion of the effects of the earthquake on the Alaska fisheries was the one compiled by the Alaska Department of Fish and Game (1965). Although a complete analysis and assessment of damage to this resource has not yet been made, the environment and habitat of the salmon is known to have been drastically changed in some areas.

Part of Prince William Sound was uplifted as much as 33 feet, and great changes in the environment and habitat of pink and chum salmon resulted. Similarly, in the submergent areas, such as Kodiak Island, important intertidal spawning grounds were inundated.

G. Y. Harry, Jr. (written commun., 1964), reported, 5 months after the earthquake, that the greatest damage to the salmon in Alaska was probably in Prince William Sound; here 75 percent of the pink and chum salmon production comes from the intertidal spawning areas. Thorsteinson (1964) states that within Prince William Sound the runs of pink salmon range from 3.2 to 8.7 million fish and the chum salmon from 0.4 to 0.6 million fish.

Compounding the permanent damage caused by uplift and submergence of the intertidal spawning grounds was the temporary effect of tsunamis and local waves. In parts of Prince William Sound, the waves caused considerable scour, and debris and silt were carried upstream for several hundred feet. Some biologists believe that many salmon eggs were scattered by the movement of debris. When, all contributing factors in Prince William Sound are taken into account, the salmon loss caused by the earthquake and its subsidiary effects is thought to be about one-quarter of a million salmon (Noerenberg and Ossiander, 1964).

In the Kodiak Island area, where submergence was as much as 6 feet, widespread flooding of the intertidal spawning areas occurred. In some places flooding of the intertidal area was helpful to the salmon in that waterfalls which formerly obstructed their upstream migration were eliminated. Along other streams, submergence and flooding increased the size of the intertidal area. Removal of waterfalls in some areas and enlargement of other areas, thus increased the size and availability of certain intertidal salmon-spawning grounds.

W. L. Sheridan (written commun., 1965) stated that the changes in the intertidal spawning habitat and environment have not been fully assessed, but that future production will decrease. Although some intertidal spawning areas have increased in size, Sheridan indicates that many of the preearthquake lower areas are now characterized by excessive quantities of sediments that decrease the survival rate of salmon eggs and alevins.

SHELLFISH

One of the more important habitats of shellfish, particularly the razor clam, is along the Copper River Delta. The delta was uplifted as much as 8 feet, and, because of the low offshore gradient, extensive intertidal areas were permanently elevated above high water. This area supported a large population of razor clams. The widespread death of these and other bivalves throughout Prince William Sound was evident within a few weeks after the earthquake (G. B. Haven, written commun., 1965). Many of the clam beds are now above high water and are lost, but clam beds formerly below lower low water were elevated and are now accessible to clam diggers. In some areas of Prince William Sound, particularly along the western part, subsidence at the bayheads was caused by local compaction of the sediments. Consequently, clam beds which were once readily accessible are now from 2 to 4 feet below low water and out of reach to conventional methods of harvesting.

There is no general consensus as to what long-term ecological effect either submergence or emergence has had upon the general clam or bivalve population within the affected areas. Certainly the initial mortality rate was high—especially in the uplifted areas—as was proved by the skeleton. In the submergent areas the greater depth of water now present over the outermost clam beds has also resulted in bivalve mortality.

WILDFOWL

Ordinarily submergence or emergence would not be considered to affect waterfowl adversely, but, according to P. E. K. Shepherd (written commun., 1966), there has been an indirect effect. In the feeding ground of the dusky Canada goose in the Copper River Delta, the preferred food of the goose is a type of vegetation referred to as "forb-grass." This grass—actually a combination of herbs and grasses—apparently requires occasional inundation by marine waters and usually grows along the sides of tidal sloughs and other areas regularly inundated by the highest tides. Because of changed tide levels, the forb-grass is dying, and before it is reestablished at a higher elevation, the dusky Canada goose is likely to have changed its habitat. Shepherd indicates that the habitat of the goose may be further changed because its former nesting grounds will become overgrown with conifers or other plants when the salt is leached out of the soil. To some extent these same changes are affecting the habitats of the dabbling and diving ducks and the trumpeter swans.

Brakish-water lagoons and sloughs are particularly favored as nesting or feeding grounds by some wildfowl. Uplift drained some of these areas or made them less brackish because of the inflow of fresh water. Thus, changed environments, whether caused by uplift or submergence, may ultimately contribute to a decrease in the wildfowl population in specific areas. Whether new wildfowl communities will spring up in areas made more favorable by the earthquake will not be known for some years.

EFFECTS ON PROPERTY VALUES AND MANMADE STRUCTURES

Earthquake-caused uplift and subsidence—and the consequent changes in coastal processes—affected the legalities of land ownership, and also led to many changes in property values and necessitated reconstruction or relocation of many coastal installations. A few of the resultant problems are touched on here.

SUBMERGENT AREAS

As already mentioned, coastal erosion is occurring in many of the submergent areas, and in some areas—such as on the Kenai Peninsula—the rate of bluff recession is several feet per year. In other areas, erosion may still become a problem although the process is not yet noticeable. One such area is along upper Cook Inlet where submergence was less than 2 feet. The dramatic effects seen in areas of greater submergence are not present in this area, but there is unquestionably a gradual retreat of the shoreline. This retreat is occurring in some of the more densely populated areas where land values are high.

At Turnagain Arm, wave erosion has damaged road and railroad embankments that were raised after the earthquake. Wave erosion in that area will probably continue, and the embankment will require constant surveillance and maintenance. In Homer, wave action has already damaged sections of the newly constructed Homer Spit highway.

Some shore installations that escaped severe damage at the time of the earthquake were, because of the higher stand of the sea, endangered by flooding a few weeks after the earthquake when tides were high. Several cannery wharves and loading platforms had to be raised. In some places, such as at the Wakefield Cannery at Port Wakefield on Kodiak Island, complete relocation of the cannery was necessary.

In some submergent areas, wave scour has moved large quantities of gravel under or away from canneries and other facilities built over the high-water line. For example, a cannery at Larsen Bay on Kodiak Island, which was built in a seemingly ideal location and was adequately protected before the earthquake has incurred considerable storm damage since the earthquake. Erosion of gravel from the adjoining beach has endangered some of the cannery buildings.

EMERGENT AREAS

Some of the immediate effects of emergence that necessitated economic and engineering consideration were related to small-boat harbors. In the Cordova area the land was elevated about 8 feet. There emergence necessitated dredging and enlarging the small-boat harbor. Some of the channels of the Copper River Delta that had formerly been accessible to fishing boats required considerable redredging in order to afford access after the earthquake. In some uplifted areas, individuals who formerly had access to the sea by shallow channels or tidal sloughs found it necessary to dredge their access routes. In other areas, landing facilities, such as docks and wharves, could no longer accommodate deep-draft vessels and had to be enlarged or relocated.

In Cordova, because of the 8 feet of emergence, it has also been necessary to relocate the installations upon which barges, scows, and fishing boats are stored in off-season months. At the beginning of the 1964 fishing season, following the earthquake, some craft had to be pulled from their storage areas onto the tidal flats by tractors before they could be refloated.

LEGAL PROBLEMS

Because the State of Alaska has jurisdiction over the bottoms of all navigable waters, legal problems have arisen wherever land raised or lowered by the earthquake abuts navigable waters. In Alaska the boundary of tidal waters is the line of mean high tide.

A person whose Alaskan property abuts the line of mean high tide is called an "upland owner." By common-law principles the upland owner enjoys all littoral rights and privileges afforded him by the location of his land. Such rights and privileges include, among others, free and unobstructed ingress and egress to the sea.

The line of mean high tide thus is the legal boundary that separates the upland owner's private property from the State-owned tidelands. The line of mean high tide remains fixed unless the shoreline is altered by accretion or erosion. If these processes result from natural causes and the shoreline changes are gradual and imperceptible, the legal boundary will change location to match the line of mean high tide. However, if the changes are natural but sudden in character and wholly perceptible, the process is termed "avulsion," and the legal boundary remains fixed even though the mean high tide line has been displaced.

Movement of the land during the earthquake was abrupt, certainly occurring within a matter of hours if not of minutes, and flooding or withdrawal of waters from the land was equally abrupt. On September 14, 1964, the attorney general for the State of Alaska described this process as one of avulsion and therefore the legal boundary line—the line of mean high tide—remains fixed as it was the instant before the earthquake (State of Alaska Attorney Gen. Opinion 6, Sept. 14, 1964).

Along the uplifted coasts many private parcels of land abutted the line of mean high tide before the earthquake; afterwards, however, the natural line of mean high tide was shifted seaward, in some places several hundred feet. Because withdrawal of the water has been defined as avulsion, the private ownership cannot follow the retreating line of mean high tide but must instead remain fixed to the line existing the instant before the earthquake. Thus those persons who enjoyed all the rights and privileges afforded them as upland owners before the earthquake now find themselves unable to exercise their littoral rights and privileges. The opposite has occurred in the submergent areas. There, owners of land that abutted the line of mean high tide prior to the earthquake now find their boundary line (that is, the preearthquake line of mean high tide) some distance seaward of the natural mean high tide line. These persons in fact own tidelands but the lands are legally described as uplands.

NEED FOR FURTHER STUDIES

One danger in attempting to rectify coastal-erosion problems is that protective measures are often taken without a clear understanding of littoral conditions. This problem has already manifested itself at various localities where installations that were constructed to protect the land have in fact destroyed it.

Some of the later damage to roads and embankments may perhaps be explained by the rather hurried reconstruction effort immediately following the earthquake. The necessity for haste probably did not allow for full consideration of design methods with respect to unnatural slopes; such slopes can promote wave erosion. Time did not always allow for adequate investigation of nearshore conditions, such as wave runup and current direction; consequently, adequate safeguards to insure maximum protection against coastal erosion were not designed. Certainly, in the submergent areas the sea has encroached upon the land establishing a new profile of equilibrium. When artificial impediments are placed in such areas, the result more often than not promotes rather than retards wave erosion.

The installation and construction of shore protective works will undoubtedly become necessary long before a profile of equilibrium develops and stabilizes—a profile which will itself eventually retard shoreline erosion. Therefore, the economic ramifications of coastal erosion not now readily noticeable may, within the next few years, become a problem which must be dealt with if valuable areas of land are to be saved.

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