UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

TECTONIC DEFORMATION, SUBAQUEOUS SLIDES AND DESTRUCTIVE WAVES ASSOCIATED WITH THE ALASKAN MARCH 27, 1964 EARTHQUAKE; AN INTERIM GEOLOGIC EVALUATION

By

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[1] Tectonic deformation, subaqueous slides and destructive waves associated with the Alaskan March 27, 1964 earthquake: an interim geologic evaluation

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ABSTRACT

The great earthquake which struck Alaska on Good Friday, March 27, 1964, caused severe damage to the coast of south-central Alaska mainly through vertical tectonic displacements, subaqueous slides, and destructive waves of diverse origins.

Notable changes in land level occurred over an area in excess of 50,000 square miles in a broad northeast-trending belt more than 500 miles long and as much as 250 miles wide, which lies between the Aleutian Trench and the Aleutian Volcanic Arc. The northwest part of this belt, which includes most of the Kenai Peninsula and the Kodiak Island group, sank as much as 7½ feet, bringing some roads, rail lines, docks, and settlements within reach of high tides and producing a fringe of salt-water-killed vegetation along the drowned coasts. The area to the southeast, including most of Prince William Sound and the adjacent continental shelf as far south as southern Kodiak Island, rose generally 4 to 8 feet, and locally at least 33 feet. Some beaches and surf-cut platforms were permanently raised above the reach of tides, resulting in mass extermination of intertidal faunas and floras and impaired usefulness of harbors, channels, and many shoreline installations.

Surface faulting was confined to Montague Island, and was dominantly vertical and subsidiary to regional uplift. Of the two known faults one has been traced more than 16 miles on land and about 15 miles in the submarine topography to the southwest of the island. Maximum measured vertical fault displacement on land was 16 feet on one fault and about 18 feet on the other.

Submarine uplift of the continental shelf generated a train of long-period large-amplitude seismic sea waves, the first of which struck the outer coasts of the Kenai Peninsula and Kodiak Island between 19 and 30 minutes after the initial shock. The highest waves inundated shorelines locally to elevations of 35 to 40 feet, causing 20 deaths and damage to property all along the coast of the Gulf of Alaska, especially in those areas that had been lowered relative to sea level by tectonic subsidence. The sea waves were recorded on tide gauges throughout the Pacific Ocean and resulted in casualties and local damage at points as distant as British Columbia, Oregon, and California.

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[1] Paper presented to the Fifteenth Alaskan Science Conference, Fairbanks, Alaska on September 3, 1964.

The earthquake caused widespread subaqueous sliding and sedimentation in Prince William Sound, along the south coast of the Kenai Peninsula, and in Kenai Lake. These slides carried away the port facilities of Seward and Valdez and the small boat harbor at Homer. Local violent surges of water, many of which were generated by known subaqueous slides that occurred during the earthquake, left swash marks as much as 170 feet above water level and caused heavy damage and took 85 lives at Seward, Valdez, Whittier, Chenega, and several smaller communities in Prince William Sound.

INTRODUCTION

This paper is a status report on the U. S. Geological Survey's field investigations of the tectonic deformation, subaqueous slides, and the destructive local waves and seismic sea waves that accompanied the great Alaska earthquake of March 27, 1964, which had a Richter magnitude of 8.3 to 8.4. Its purpose is to summarize the major aspects of these phenomena as known at the end of the 1964 field season (late August). Details of these studies and additional data to be obtained during the 1965 field season are to be published later in the U. S. Geological Survey's series of Professional Papers on the Alaska earthquake.

The field work on which this paper is largely based was carried out by Arthur Grantz, Reuben Kachadoorian and George Plafker between March 29 and April 9 and by Plafker, Kachadoorian, L. R. Mayo, D. S. McCulloch, J. B. Case, and G. A. Rusnak, between May 18 and August 31. The U. S. Coast and Geodetic Survey made available preliminary post-earthquake bathymetric charts of submarine slide areas; data on measured land-level changes at 14 tide-gauge stations and along a line of first-order levels between Seward, Valdez, and Anchorage; and a fathometer profile southwest of Montague Island. Invaluable data on changes of land level and the sequence of wave activity in coastal areas have been provided by numerous Alaskans in reply to form questionnaires immediately after the earthquake, and in interviews with the writers and other Survey geologists during the course of the field investigations.

In the following description, earthquake effects are considered under three major topical headings: 1) tectonic uplift, subsidence, and faulting; 2) seismic sea waves; and 3) subaqueous slides and locally generated waves. The first section describes the unprecedented tectonic warping that accompanied the earthquake throughout much of south-central Alaska, and the surface faults on Montague Island in Prince William Sound. The section on seismic sea waves describes the destructive train of long-period waves that apparently were generated in the Gulf of Alaska by uplift of the sea bottom; it also includes some tentative inferences regarding the configuration of the source area drawn from the wave arrival times and heights at the adjacent shores. The final section describes the major features of the numerous earthquake-triggered subaqueous slides in Prince William Sound and on the Kenai Peninsula, and the destructive local waves that accompanied many of these slides. It also covers descriptions of damage caused presumably by local waves of unknown origin in these same general areas.

TECTONIC UPLIFT, SUBSIDENCE, AND FAULTING [1]

Tectonic land-level changes associated with the Good Friday earthquake occurred over at least 50,000 square miles of south-central Alaska--an area larger than the state of North Carolina (fig. 1). South of a line extending

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Figure 1 near here

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from the southeast shore of Kodiak Island through the western part of Prince William Sound to the vicinity of Valdez (the inferred tectonic hinge zone of Figure 3, U.S. Geological Survey Circular 491, April 1964), the land was raised locally at least 33 feet. To the north and west of this line the land has been regionally depressed as much as 7½ feet. The zone of uplift dies out between Kayak Island and Yakataga. Its seaward extent is not known but probably coincides approximately with the belt of epicenters of the major aftershocks. This belt includes most of the continental shelf between Kayak Island on the northeast and the Trinity Islands on the southwest. There have been no reports of land-level changes along the southeastern coast of the Alaska Peninsula, indicating that the regional subsidence probably dies out somewhere between this peninsula and the northwest shorelines of the Kenai Peninsula and the Kodiak Islands group.

The region in which land-level changes occurred includes an extremely long and irregularly embayed coastline, thereby providing a unique opportunity to use the surface of the sea as a datum plane for quantitative measurement of the amount and direction of land-level change. Certain species of sessile organisms inhabiting the littoral zone along this coastline are closely controlled in vertical distribution by the local range of tides. Consequently, a technique was worked out with the aid of Dr. G Dallas Hanna of the California Academy of Sciences whereby the approximate land-level changes were determined from displacement of these organisms above or below their normal ecological niches. The common acorn barnacle, *Balanus Balanoides*, was particularly suitable for this purpose because it is widely distributed along the coastline, and its upper limit of growth is generally sharply terminated (fig. 2). At tidal bench marks for which the exact amount

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Figure 2 near here

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of land-level change was known, it was found that the upper limit of barnacle growth generally coincides closely with mean high water. By measuring the height of the barnacle line above water level at known stages of tide, the approximate amount and direction of change from the pre-earthquake position could be determined. Where barnacles were unavailable for measurement the common olive-green rockweed, *Fucus*, which has its upper growth limit near mean high water, and the black algae *Ralfsia*, which occupies the splash zone immediately above mean high water, were used for measuring land-level changes, but neither of these plants proved to be as restricted in vertical range as the barnacles.

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[1] More detailed data on the tectonic aspects of the earthquake have been published in a paper by Plafker (1965).

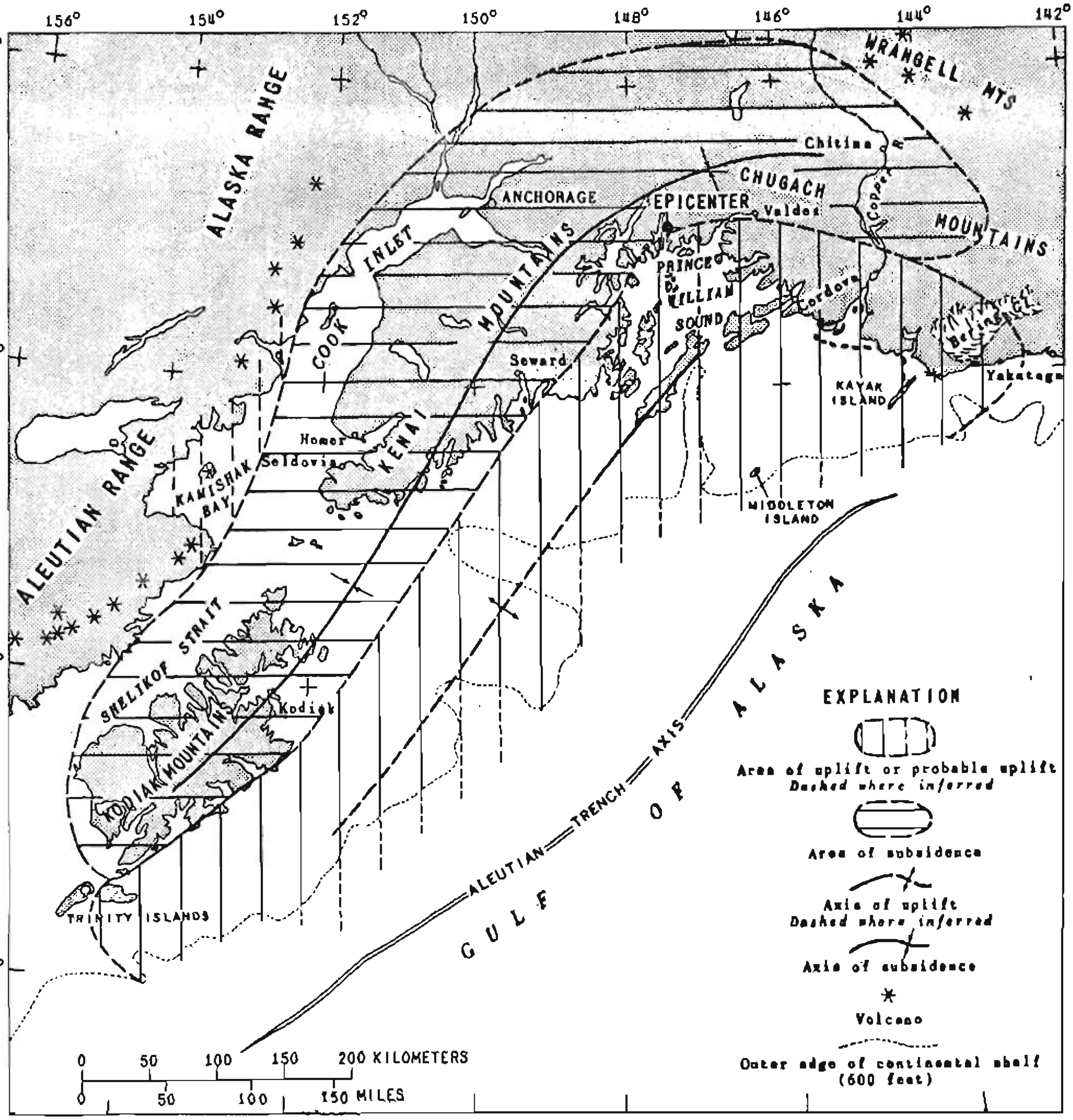

Figure 1. Major areas of tectonic uplift and subsidence in south-central Alaska.

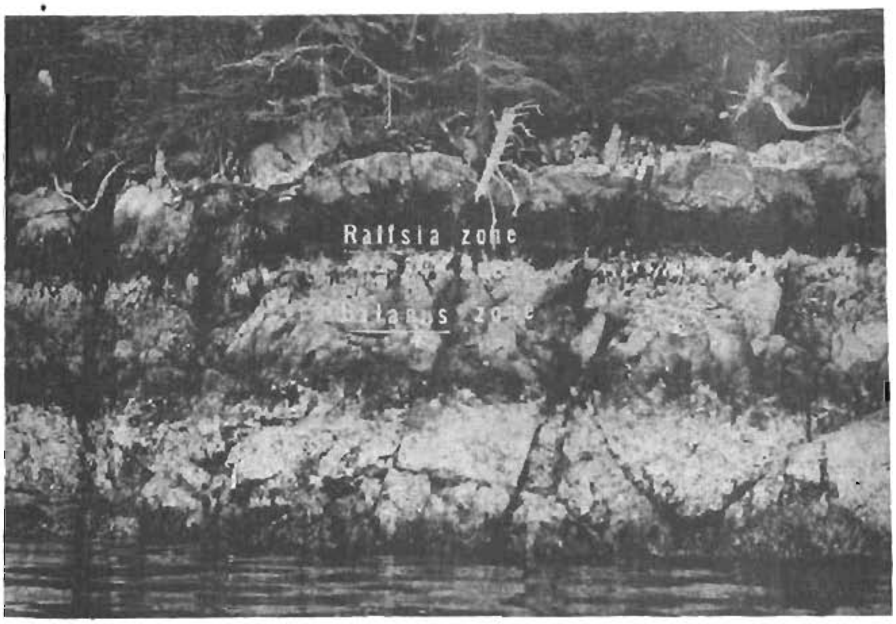

Figure 2. Sharply zoned intertidal marine organisms in Prince William Sound. The upper limit of barnacle growth is at the contact between the upper black zone of Ralfsia and the middle gray zone of barnacles. The white zone below is dominated by calcareous organisms.

Figure 3. Algae (Fucus) along the shore of Galena Bay. The dark upper zone of dead algae has been elevated above the reach of most tides by about 1½ feet of uplift.

About 800 measurements of elevation of intertidal organisms were made during our reconnaissance survey, approximately 600 of which were in Prince William Sound. The values obtained by using this technique can be considered as only an approximation of the actual amount of movement that had occurred, because of local irregularities in the degree of perfection of faunal zoning, departures of the barnacle line from mean high water, and deviation of tides from predicted levels. However, comparison of the amounts of land-level change indicated by using this technique with the available data from resurveyed U. S. Coast and Geodetic Survey tidal bench marks and, wherever possible, from local residents in this sparsely inhabited area, indicates that most values obtained on sheltered shores of Prince William Sound are probably accurate to within plus or minus 1 foot. Even under the least favorable conditions they are probably accurate to within 2 feet.

A direct measure of the approximate amount and direction of land-level changes was obtained in uplifted areas by the height of the zone of dead algae and barnacles (fig. 3). In many localities within the subsided area a new

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Figure 3 near here

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post-earthquake barnacle line has been established above the line defined by the pre-earthquake barnacle line (fig. 4). In such instances, a rough measure

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Figure 4 near here

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of the minimum amount of subsidence is provided by the difference in elevation between the two barnacle lines.

Qualitative indications of subsidence are also present in the form of vegetation killed by salt-water immersion (fig. 5), the building up of beaches

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Figure 5 near here

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and deltas to new higher base levels, and conversion of low-lying freshwater lakes into tidal lagoons. Similarly, uplifted areas show newly exposed reefs and islands along their shores as well as such features as uplifted sea cliffs, surf-cut platforms, sea caves, and drained intertidal lagoons (fig. 6).

Figure 6 near here

Regional warping has adversely affected many navigable waterways and harbors, as well as transportation routes and installations along the coast. Throughout the eastern part of Prince William Sound, docks and piers are above water level at most stages of tide so that they must be lengthened in order to reach deep water. The boat harbor and channel leading to it at Cordova require dredging in order to provide access by boats at other than highest tides. Many homes

Figure 4. Prominent white band of post-earthquake barnacles along the shore of Kizhuyak Bay, Afognak Island. The difference in elevation between the upper growth limit of the yearling barnacles in the photograph and the pre-earthquake barnacles which are at water level, indicates at least 3 feet of tectonic subsidence.

Figure 5. Spruce trees near the mouth of Resurrection Bay being killed by salt water immersion in an area subject to slightly more than 3 feet of tectonic subsidence. Adjustment of the beach berm to the new relatively higher sea level has narrowed and raised the gravel beach, thereby undermining and burying trees along the water's edge. Photo taken at a 9-foot tide, July 10, 1964.

Figure 6. Surf-cut platform 1200 feet wide, near the southwest end of Montague Island which was exposed by about 30 feet of tectonic uplift.

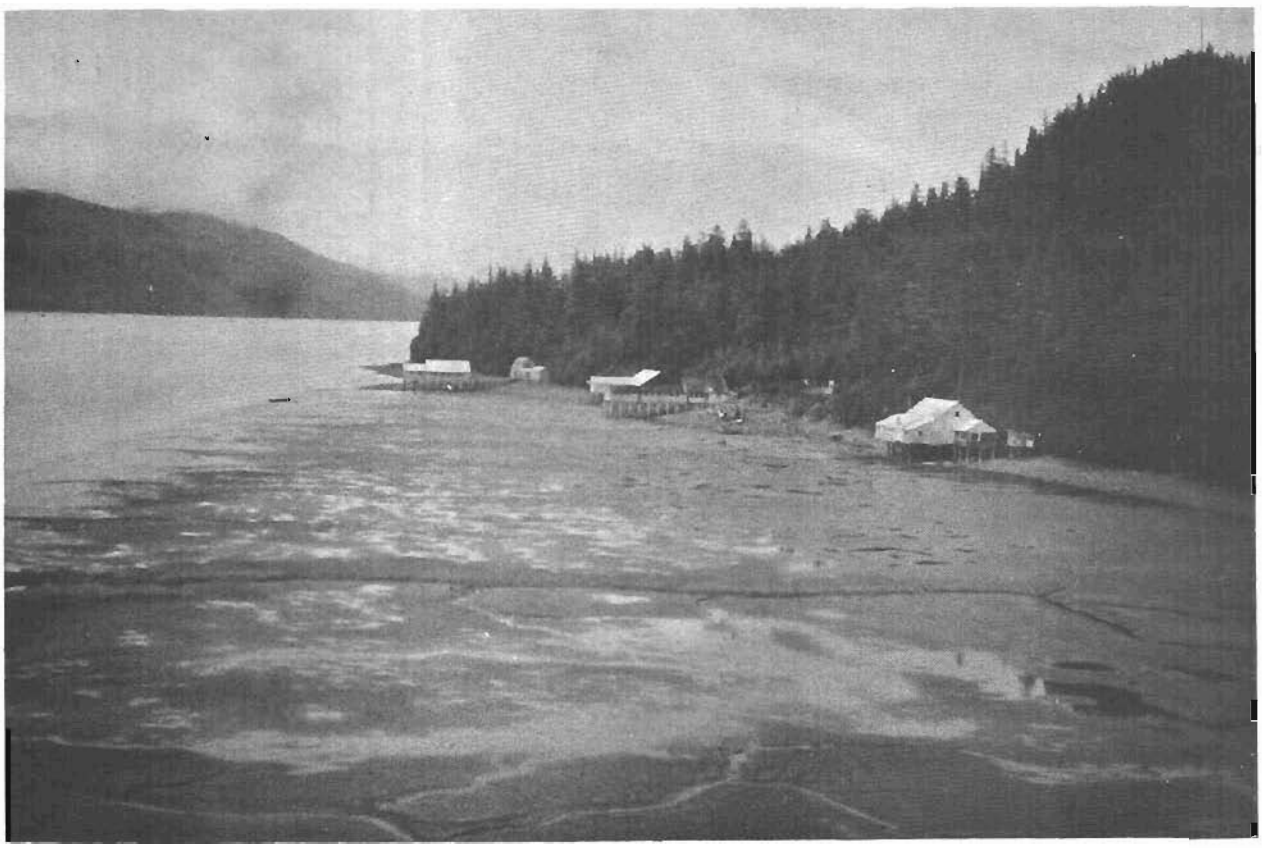

Figure 7. Canneries and fishermen's homes along Orca Inlet in Prince William Sound now above the reach of most tides due to 6 feet of uplift. Photo is taken at a 9-foot tide on July 27, 1964, which would have reached beneath the docks prior to the earthquake.

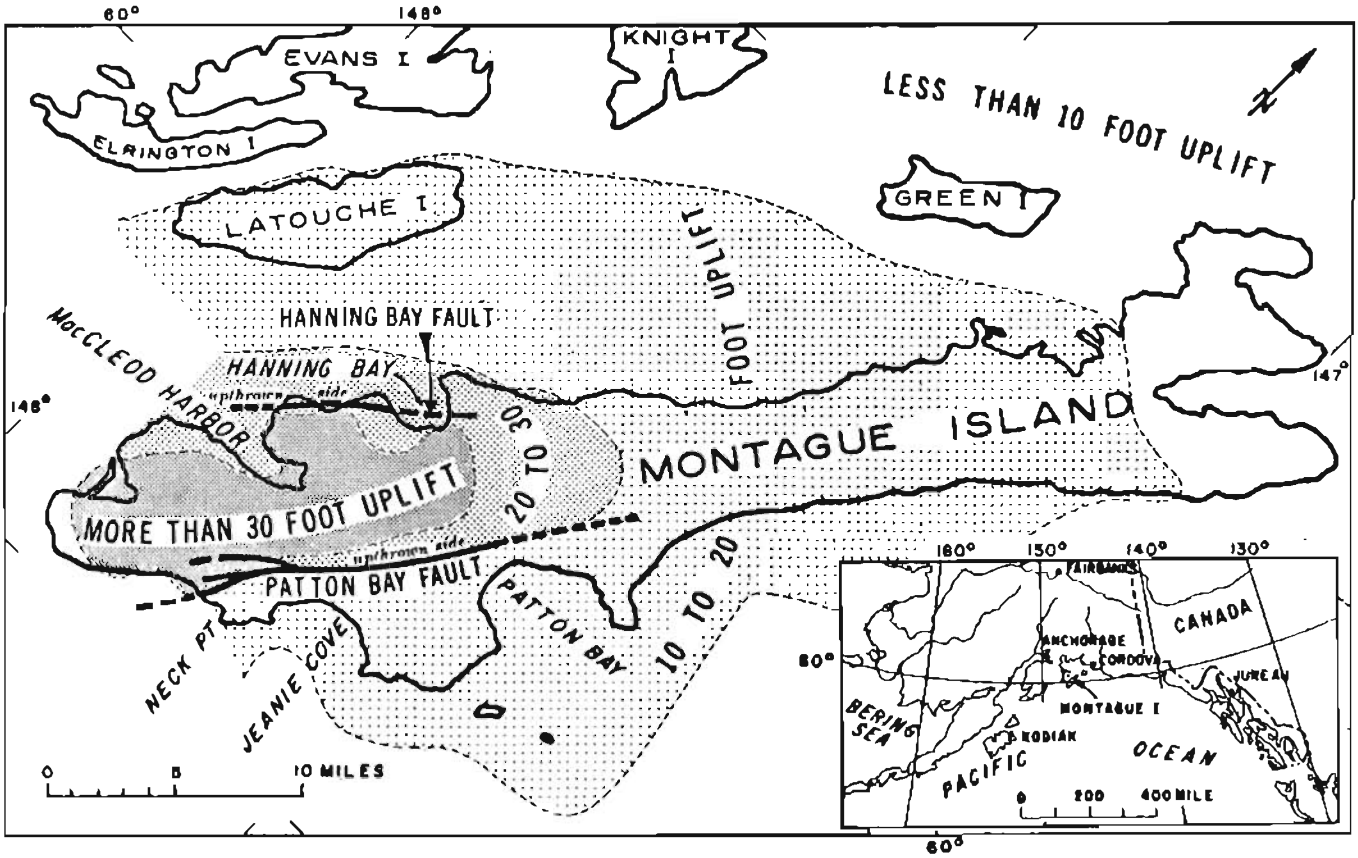

Figure 9. Tectonic uplift and faulting on Montague Island, Prince William Sound.

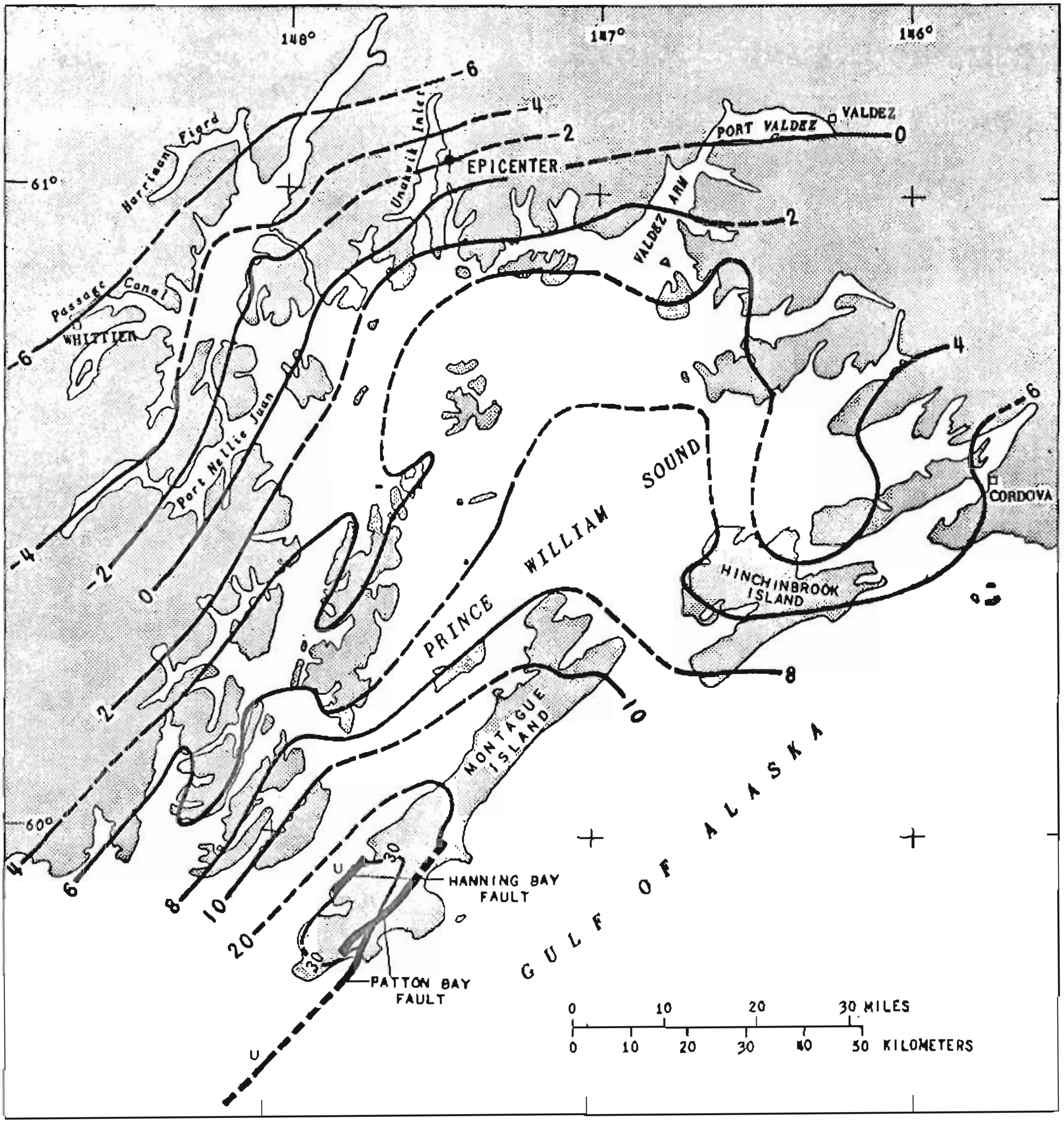

Figure 8. Isobase contours showing tectonic land-level changes in Prince William Sound. Contour interval is 2 feet between -6 and +10 feet, 10 feet between +10 and +30 feet.

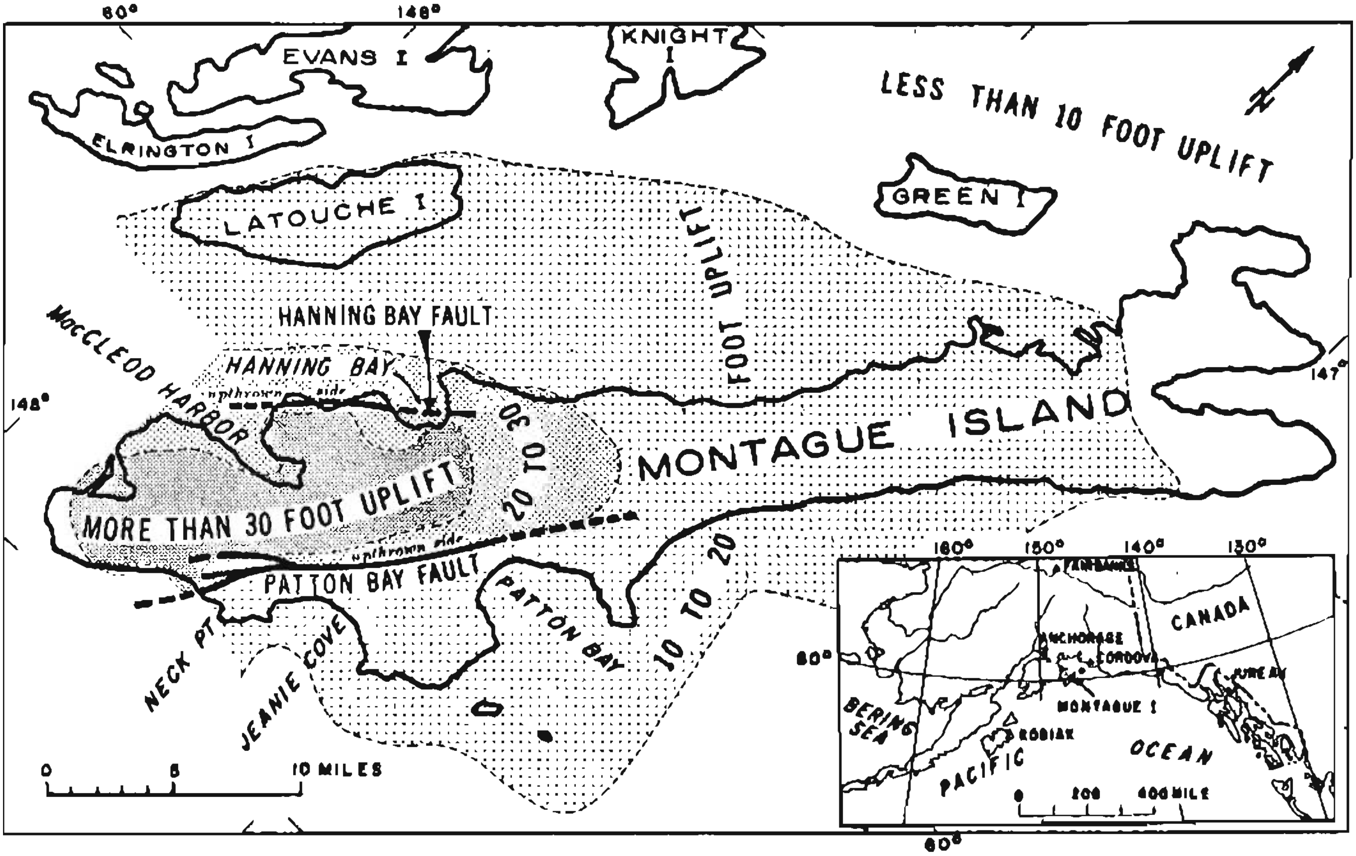

Figure 9. Tectonic uplift and faulting on Montague Island, Prince William Sound.

The longer of the two, the Patton Bay fault, can be traced on the ground for 10 miles from a point near Patton Bay westward to Neck Point, where it strikes out to sea. It is marked by a discontinuous line of landslides along the slopes and by gaping fissures on level ground. At its intersection with the coastline 18 feet of vertical displacement was measured with the northwest block upthrown. About 8 feet of this movement is attributable to actual faulting as indicated by a scarp cutting the beach gravels and reef along the shore. The remainder of the vertical offset is due to a pronounced seaward bending of the upthrown block within 1,000 feet of the fault. The fault trace is vertical where it can be seen in the sea cliff and no evidence of lateral displacement was found during the brief reconnaissance examination of the fault trace. The fault dies out at its northeast end in the vicinity of Patton Bay. From the point where it strikes out to sea, it has been traced an additional 15 miles southwestward in the submarine topography by the U. S. Coast and Geodetic Survey as a prominent scarp (Malloy, 1964, p. 1048).

The shorter of the two faults found on Montague Island is exceptionally well exposed for a distance of 3 miles from the south shore of Hanning Bay almost to MacLeod Harbor (fig. 10). As with the Patton Bay fault, the

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Figure 10 near here

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northwest side is upthrown and the fault plane dips steeply or is vertical wherever exposed. Vertical displacement ranges from about 5 feet at the shore of Hanning Bay to a maximum of 16 feet at the cove between Hanning Bay and MacLeod Harbor (fig. 11). The fault dies out to the south before reaching

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Figure 11 near here

MacLeod Harbor, and it cannot be traced north of Hanning Bay. A small left-lateral strike-slip component of movement amounting to less than one-half foot was observed near the south end of the fault. Inland from the coast the fault trace is marked by a continuous line of toppled trees, ponded streams, landslides, and fissures.

<u>Conclusions</u>.--It is still too soon after the event to fully assess the tectonic significance of the changes in land level that accompanied the Good Friday earthquake. Clearly, the zones of uplift and subsidence are the results of crustal warping and the local surface faults on land were subsidiary to the regional uplift. The parallelism of the belts of uplift, subsidence, and aftershocks to the Aleutian volcanic arc and its zone of earthquake epicenters indicate that the Good Friday earthquake and its associated land-level changes were tectonic processes genetically related to the Aleutian Arc (Grantz, Plafker, Kachadoorian, 1964, p. 2).

Figure 10. Air view toward the southwest of the Hanning Bay fault where it crosses a small cove between Hanning Bay and MacLeod Harbor. The northwest block (right) is relatively upthrown. The surf-cut platform is bleached white by the remains of calcareous organisms that normally live below mean tide level.

Figure 11. View of the Hanning Bay fault scarp looking northeast showing about 13 feet of vertical displacement in rock in the foreground and about 16 feet of displacement at the beach ridge in the background.

A noteworthy aspect of the deformation is that the belt of uplift and inferred uplift coincides closely in areal distribution with the zone of aftershocks whereas the adjacent zone of subsidence is, in general, northwest of the limits of the zone of aftershocks. This coincidence of the uplift and aftershocks suggests that the rupture along which the Good Friday earthquake occurred lies within the zone of uplift and that the subsidence is beyond the limits of, and is secondary to, the postulated faulting within the zone of uplift.

The available geologic data must be integrated with the results of seismological, gravity, and geodetic investigations of the earthquake by the U. S. Coast and Geodetic Survey and others before we can hope to fully evaluate the tectonic forces that caused the earthquake and its accompanying land-level changes.

SEISMIC SEA WAVES

Introduction.--Most major earthquakes in coastal areas that involve vertical tectonic displacements beneath the sea are accompanied by seismic sea waves (tsunamis or "tidal" waves), and the Good Friday earthquake generated one of the larger seismic sea waves of recent times. The waves took 20 lives and caused destruction all along the Alaskan coast between the southern tip of Kodiak Island and Kayak Island. They were especially destructive in areas, such as the Kodiak Islands and the Kenai Peninsula, that had been lowered relative to sea level by tectonic subsidence or by tectonic subsidence and compaction of unconsolidated deposits during the earthquake. In addition, the sea waves, which were recorded on tide gauges throughout the Pacific Ocean, caused 15 deaths and major damage in British Columbia, Oregon, and California.

The wave train in the Gulf of Alaska.--The first wave of a train of at least 7 large-amplitude seismic sea waves with periods of 55 to 90 minutes was reported at Cape Chiniak on Kodiak Island at 6:10 p.m.--34 minutes after the quake (fig. 12). It was not preceded by a warning withdrawal of water as

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Figure 12 near here

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so commonly occurs in tsunamis. The wave is described as a cresting breaker at Narrow Cape on the exposed southeastern coast of Kodiak Island, and as a fast-rising tide in the Kodiak area. At Narrow Cape the first wave reached farthest inland, whereas at the city of Kodiak the fourth wave (between 11:16 p.m. and 11:20 p.m.), which almost coincided with high tide, rose the highest, cresting at about 23 feet above tide level (Grantz, Plafker and Kachadoorian, 1964, p. 22). In the Kodiak Islands group, the city of Kodiak, the Kodiak Naval Base, and a number of small communities--most notably the native villages of Kaguyak, Old Harbor, and Afognak--low-lying areas were severely damaged by the waves and 18 people were drowned, or are missing and presumed dead. The small native village of Kaguyak was obliterated, and the villages of Old Harbor and Afognak require extensive repairs. The entire waterfront area of the city of Kodiak was destroyed and many fishing boats -- the mainstay of the local economy -- were lost or damaged.

Along the shores of Shelikof Strait and Cook Inlet the seismic sea waves, which were less than 5 feet high, caused rapid tide changes that were accompanied by swift erratic currents. However, the waves barely reached above the level of highest tides, which in this area of large tidal range exceeds 18 feet as a rule, and they did not cause any property damage.

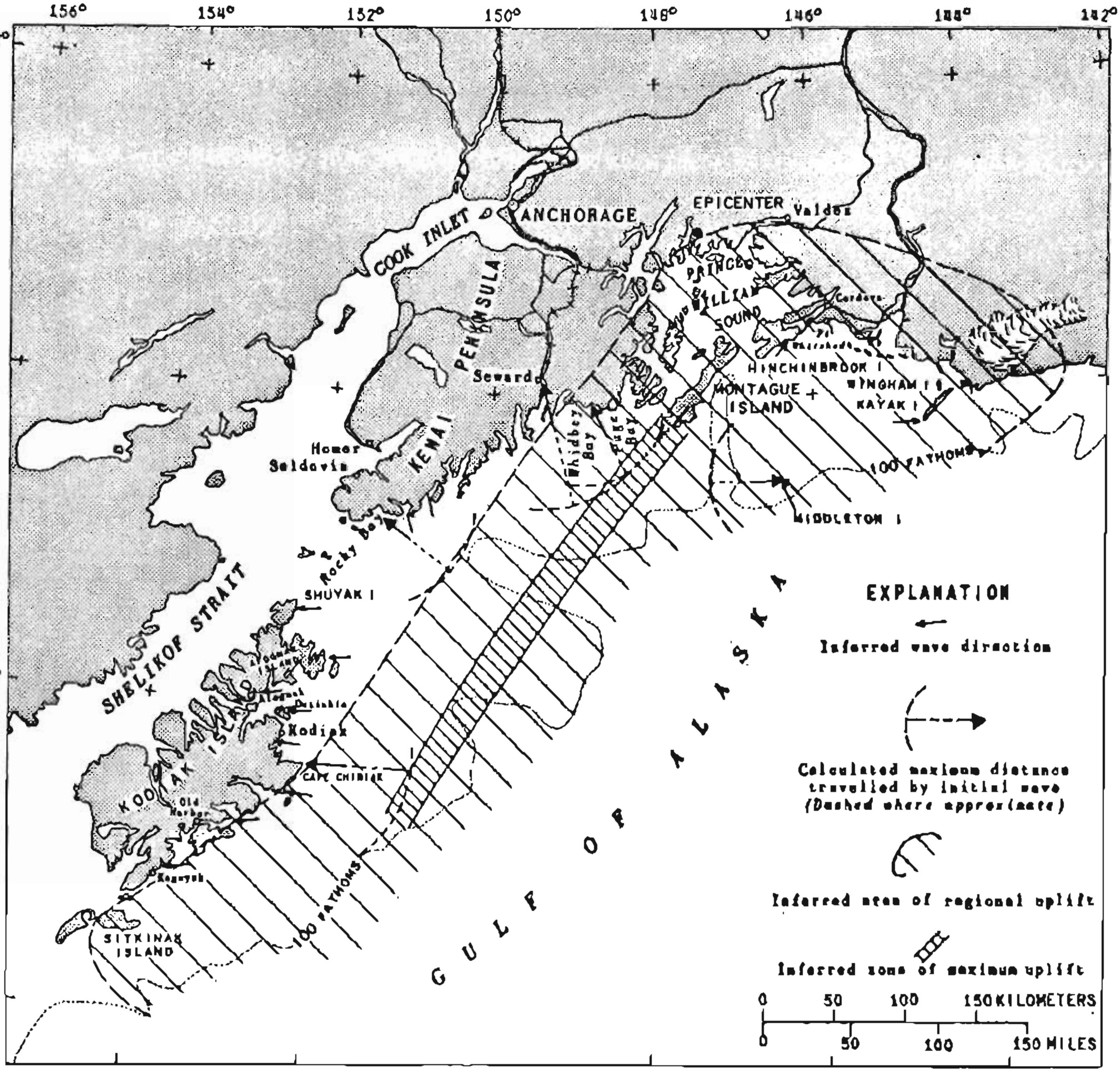

Figure 12. Inferred source area of seismic sea waves generated during the March 27th earthquake.

Seismic sea waves struck the south shore of the Kenai Peninsula, resulting in heavy property losses to Seward at the head of Resurrection Bay and at 3 isolated logging camps along this otherwise uninhabited stretch of coast. Except at the head of Resurrection Bay, all these areas experienced a train of waves which came in as large swells but did not break. The first waves reached the logging camps at Whidbey Bay and Puget Bay on the southeast coast of the Kenai Peninsula (fig. 12) between 19 and 20 minutes after the earthquake began. The highest wave at Whidbey Bay was the second one, which followed 10 to 12 minutes after the first wave and ran up to an estimated elevation of 35 to 40 feet above lower low water. Within approximately 30 minutes after the start of the tremors, the first waves arrived at the logging camp at Rocky Bay near the southwest tip of the Kenai Peninsula (fig. 12) and were breaking near Seward at the head of Resurrection Bay. Contrary to the initial water motion everywhere else, the first wave at Rocky Bay reportedly was preceded by a withdrawal of about 18 feet. The highest wave, which came in on the high tide after midnight, left swash marks 11 feet above tide level.

The seismic sea waves probably attained their maximum amplitude at the head of Resurrection Bay where they inundated low-lying areas of Seward, the flats at the head of the Bay, and Lowell Point to an estimated height of 25 and 35 feet above lower low water. The initial wave destroyed The Alaska Railroad docks and swept many houses and boats in the vicinity of the small boat harbor into the lagoon north of Seward and onto the flats at the head of Resurrection Bay. It also tossed box cars, and even a locomotive, into windrow heaps. Estimates of the height of the highest wave, which crested at about 11:00 p.m. near high tide, and the amount of withdrawal that preceded it, indicated that it may have had an amplitude of as much as 70 feet near Seward (Grantz, Plafker and Kachadoorian, 1964, p. 16).

In Prince William Sound the seismic sea waves are everywhere described as fast-rising tides with associated strong currents. The first wave, which reached Boswell Bay on Hinchinbrook Island at about 6:00 p.m., was about 12 feet high. Throughout the Sound the highest waves were recorded close to high tide between midnight and 1:00 a.m. They inundated shorelines in the eastern and northern parts of Prince William Sound to a maximum of about 17 feet above tide level. The highest wave floated away some houses and boats along the waterfront of Cordova and Orca Inlet and caused local damage to piers and docks. One person was drowned who had returned to his cabin after midnight at Port Whitshed near Cordova, believing that the danger from waves had passed. Elsewhere in Prince William Sound, the seismic sea waves did not result in loss of life, although waves 6 to 10 feet above normal tide level repeatedly inundated low-lying areas of Valdez which had settled differentially during the earthquake, and shorelines in those parts of northwestern Prince William Sound that had been significantly lowered by tectonic subsidence.

Seismic sea waves were also experienced at remote localities east of Prince William Sound on Middleton Island, at the Cape St. Elias lighthouse, on Kayak Island, and by a fishing boat that was anchored on the east side of Wingham Island. At the Cape St. Elias lighthouse on the southwest tip of Kayak Island, one of four Coast Guardsmen was drowned and the remaining men at the station narrowly escaped drowning by the initial seismic sea waves which inundated a low-lying sand bar adjacent to the lighthouse at about 6:15 p.m. The first seismic sea wave reached the west shore of Middleton Island an estimated 20 minutes after the earthquake began, but it did not rise above the tectonically elevated higher high-water line. At Wingham Island, the fishing boat ROALD experienced swift and erratic currents, with rapid fluctuations in water level which began approximately half an hour after the earthquake. The current at Wingham Island was reportedly strong enough to move boulders along the shore.

Origin of the waves.--The reported arrival times of seismic waves, as given by eye-witnesses, and the directions from which they struck the shoreline of the Gulf of Alaska, clearly indicate that the waves were generated on the continental shelf and slope in the Gulf of Alaska within the zone of uplift (figure 12). With one possible exception, the initial water motion reported was upward, suggestive of a positive displacement of the source area. There is abundant evidence for significant vertical displacement of the sea floor in this zone during the earthquake both by crustal warping and local faulting.

The southwest tip of Montague Island was elevated as much as 33 feet relative to sea level, with at least 18 feet of vertical displacement along the Patton Bay fault on land. The fault has been traced seaward as a prominent scarp in the ocean floor for at least 15 miles southwest of Montague Island, and uplifts of as much as 50 feet were identified southeast of the Patton Bay fault on fathograms made by the U. S. Coast and Geodetic Survey (Malloy, 1964). Arrival times of the initial large wave, which struck the shores of the Kenai Peninsula within 19 minutes and Kodiak Island within 34 minutes after start of the earthquake, suggest further that the wave crest may have originated along one or more lines within the elongate belt shown on Figure 12 that extends southwestward toward Kodiak Island from the axis of maximum uplift on Montague Island.

SUBAQUEOUS SLIDES AND LOCAL WAVES

Introduction.--The intense and prolonged ground shaking during the Good Friday earthquake triggered many subaqueous slides (submarine "landslides") along the seacoast and lake shores of south-central Alaska. A substantial portion of the property damage resulting from the earthquake is attributable directly to subaqueous slides which carried away the port facilities of Seward and Valdez, the small boat harbor at Homer, and possibly segments of the railroad and fuel docks at Whittier. Numerous other slides are known to have occurred in the sparsely inhabited epicentral area of Prince William Sound and the adjacent Kenai Peninsula; most of those that occurred entirely underwater undoubtedly have gone unrecognized.

Violent local waves[1/] generated by subaqueous slides caused major damage to adjacent shorelines and loss of life in the cities of Seward, Valdez, and Whittier. Many other localized waves not specifically identifiable with submarine slides caused comparable damage in these same general areas. The local waves, and combinations of local waves and subaqueous slides, were responsible for 85 of the 114 fatalities in Alaska that resulted from the earthquake.

Physiographic setting.--Prince William Sound and the Kenai Peninsula to the west are regions of high rugged mountains that are indented by long, narrow glacier-scoured fiords that make good natural harbors. The rocky shores of many of these fiords drop off precipitously to depths of 600 feet to more than 2,000 feet. Subaerial and subaqueous bedrock slopes commonly exceed 35 degrees and locally may be nearly vertical. Similar glacier-scoured valleys and basins on the mainland are occupied by deep lakes, the largest of which is Kenai Lake.

At places, especially at the heads of the fiords, streams have built prisms of poorly consolidated alluvial and glacial deposits, which provide almost the only large level sites for buildings, docking facilities, and railroad yards. At other localities, submarine deposits of intercalated moraine and outwash form low crescentic bars or shoals across the fiords that mark the terminal positions of recent glacial advances. Marginal glacial

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[1/] As used in this report, "local wave" refers to water waves, generated either along the coast or in lakes during the earthquake, that affected areas of limited extent. The waves were originated at or close to the shoreline mainly by subaqueous slides, but possibly also by other mechanisms such as subaerial landslides, seiches, or tectonic warping. The term local wave is used to distinguish these waves from the train of long-period seismic sea waves that first struck the coast of the Gulf of Alaska 19 to 20 minutes after the earthquake began. According to some definitions, all of these earthquake-generated waves are "tsunamis".

deposits that accumulated along the sides of the valley glaciers occur along the fiords of eastern Prince William Sound. Although apparently absent at the surface elsewhere, in northern and western Prince William Sound and the Kenai Peninsula such deposits probably occur locally under water, because depressed cirque levels in these areas indicate that the shorelines of the northern part of Prince William Sound and much of the Kenai Peninsula have been drowned since the last major glaciation (Grant and Higgins, 1910, p. 17-18; 1913, p. 57).

Distribution of slides and local waves.--Most of the known subaqueous slides and localized waves were concentrated along the rugged coasts of northern and western Prince William Sound, at Resurrection and Aialik Bays on the south coast of the Kenai Peninsula, and along the shore of Kenai Lake (fig. 13). Only the locations of the larger slides and shorelines damaged by

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Figure 13 near here

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the waves with run-up in excess of 40 feet above lower low water (the stage of tide at the time of the earthquake) are shown; a great many smaller slides and waves also occurred in these same general areas and elsewhere in south-central Alaska.

Shorelines damaged by the waves show no preferred orientation. This is contrary to the impression gained from interviews and observations during the preliminary reconnaissance study that there was a general northward surge of water in Prince William Sound (Grantz, Plafker, and Kachadoorian, 1964, p. 12). One of the most striking characteristics of the waves is their highly localized and seemingly erratic distribution along the shorelines. An excellent example of this occurs along the north shore of Jack Bay in northeastern Prince William Sound. At that locality a 600-foot long section of shoreline was stripped bare of timber to a maximum elevation of 39 feet by a violent surge of water; yet this small area and a nearby cove are the only segments along the north shore of Jack Bay that show evidence of wave damage.

Wave effects.--The extent of wave damage to shorelines ranges from the splashing of mud and sea shells above high-water line, to the stripping of vegetation and soil from swaths of shoreline. The affected region is one of moderate climate and high rainfall so that a dense forest of conifers crowds the shoreline except in recently deglaciated areas or places where cliffs are too precipitous for the trees to gain a foothold. As a consequence, wave damage to shorelines is best recorded by scarred, broken, or uprooted trees and brush. Muskeg and soil are locally stripped from the bedrock and muskeg, and seashells, driftwood, and beach deposits up to boulder size may be thrown up above the level of the highest tides.

In the absence of eyewitnesses, the direction of motion for the larger waves could generally be determined from the orientation of the damaged shorelines, and the directions in which limbs and trunks of trees and brush are scarred, bent, or broken off. On shores bare of vegetation, only the orientation of the affected shoreline and the distribution of displaced driftwood and beach deposits could be used as directional indicators.

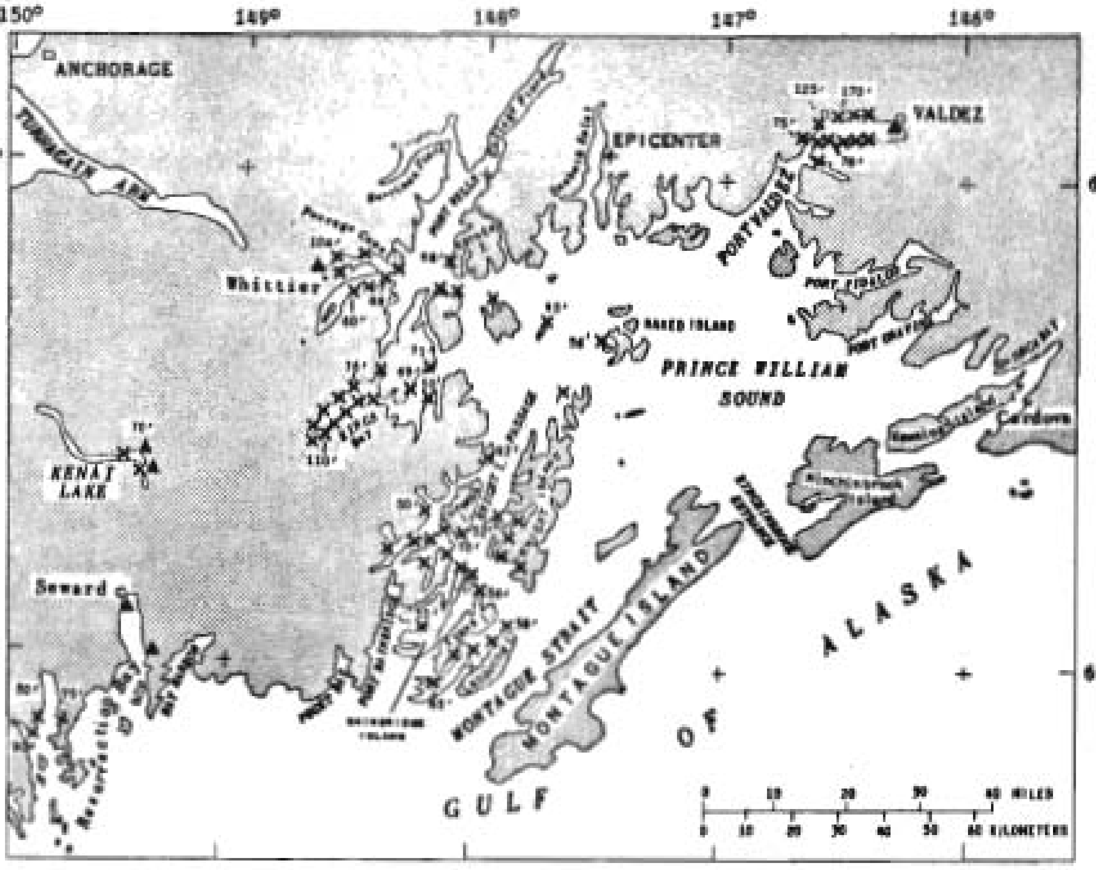

Figure 13. Generalized distribution of larger destructive local waves and known subaqueous slides in Prince William Sound and part of the Kenai Peninsula. Shorelines damaged by waves with run-up heights in excess of 40' above lower low water are indicated by an "X" - numerals are the measured maximum run-up heights. Solid triangle indicates known subaqueous slide.

The earthquake occurred almost at a zero tide (lower low water). Consequently, effects of the localized waves along the coast were visible only where the waves were high enough to reach above the extreme high tide line, which is approximately 10 to 15 feet above lower low water.

Time and sequence of waves.--An important characteristic of the damaging local waves, where observed by eyewitnesses at ten widely scattered localities in Prince William Sound, Resurrection Bay, and Kenai Lake, is that a single large wave struck during the earthquake or within minutes after it ended. Much smaller waves immediately preceded or followed the large wave, but run-up from these waves rarely rose above extreme high-tide level. By the time the initial crest of the train of seismic sea waves reached the outer coast of the Kenai Peninsula 19 to 20 minutes after the earthquake began, the strong water disturbances generated by the local waves had largely subsided.

Subaqueous slides and slide-generated local waves.--Subaqueous slides were observed during the earthquake at Seward and Thumb Cove in Resurrection Bay, and at Valdez. The sequence of events reported from these places clearly demonstrates the instability of unconsolidated deposits under strong seismic shock, and the ability of such submarine slides to generate destructive waves. A smaller slide was witnessed at the small boat harbor on Homer Spit in Kachemak Bay (not shown on fig. 13), but it was not accompanied by damaging waves.

Seward.--At Seward, a 4,000-foot-long slide of alluvium and man-made fill carried with it the docking facilities and part of the railroad yard within 30 seconds after the earthquake began (Grantz, Plafker, and Kachadoorian, 1964, p. 15-16, figs. 9 and 10). Downward movement of the submarine slide mass drew water from the former shoreline and created one, possibly two, "boils" of debris-laden muddy water at a distance from shore estimated by various witnesses to be several hundred feet to half a mile. Large waves were generated at the boil or boils and radiated from them at high speed, striking the Seward waterfront and the adjacent shorelines of Resurrection Bay before the earthquake stopped. Thirteen people who were in the waterfront area were lost in the waves. At the north side of Lowell Point, almost 2 miles south of the slide, the largest wave broke limbs of spruce trees to a height of 32 feet above lower low water and had sufficient force to move heavy machinery and vehicles along the shoreline.

Valdez.--A submarine slide along the Valdez waterfront 4,000 feet long and 600 feet wide was triggered almost as soon as the earthquake was felt (H. W. Coulter, written communication, May 1964). The slide occurred near the front of the Lowe River delta, which had a seaward slope of 15° near shore. A remarkable amateur movie taken from the heaving deck of the freighter M. V. CHENA, which was tied up to the city dock at the start of the earthquake, includes a glimpse of a distinct scarp, estimated to be 20 to 30 feet high, at the presumed head of the slide and the movement of water and wreckage from the former shoreline toward the scarp and the depression above the landslide mass. Eyewitness accounts indicate that shortly thereafter, a "boil" of muddy water appeared offshore, and a destructive wave reportedly 30 to 40 feet high rushed back to inundate the waterfront area and lower portion of Valdez. The slide and wave resulted in the tragic loss of 30 lives before the violent shaking had subsided.

The effects of the wave generated at Valdez are not visible along the adjacent shore west of the Lowe River delta. Damage to the shores in the western two-thirds of Port Valdez resulted from much larger waves that were generated near Shoup Bay, probably at about the same time that the slide occurred along the Valdez waterfront.

Passage Canal.--Multiple submarine slides occurred at the head of Passage Canal, along the front of the alluvial delta on which the port city of Whittier is situated, and on the deltas and terminal moraine at the head of the bay (fig. 14). Comparison of pre- and post-quake bathymetry (profiles

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Figure 14 near here

A-A', B-B', C-C', fig. 14) shows that slides have removed as much as 200 feet of material from the moraine-outwash-delta complex at the head of the fiord, and as much as 75 feet of material from the delta at the Whittier waterfront. The heads of the slides are oversteepened scarps that dip seaward at angles locally in excess of 30°. The submarine slide at the northwest end of Passage Canal carried away the former tidal mud flat that was about 75 feet wide, and part of the shoreline, including the end of a railroad spur and the foundation of an unoccupied building (fig. 15). Slides along the Whittier waterfront

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Figure 15 near here

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may have undermined parts of the railroad and fuel docks. Erosion debris from the slides was deposited as hummocky masses in the axial portion of the fiord.

Within 4 minutes of the start of the earthquake a series of three waves inundated much of the shoreline at the head of Passage Canal to a maximum elevation of 104 feet above lower low water. These waves took 13 lives at Whittier and caused extensive damage to waterfront installations at the port and at the head of Passage Canal. No waves reached above the extreme high water line after the end of the earthquake. From eyewitness accounts and the inferred directions of wave motion along the shoreline, it is reasonably certain that the wave which damaged the sawmill and other structures at the head of Passage Canal, and demolished the sawmill and fuel-tank farm in Whittier, originated at the site of the submarine slide at the northwest end of Passage Canal (figs. 14 and 15). A smaller wave from an unknown source struck Whittier from the northeast almost simultaneously. The latter wave caused damage mainly to the small boat harbor, the railroad terminal building, and other installations along the east end of the Whittier waterfront. The first wave was reportedly a calm rise to 26 feet above lower low water, the cause of which is unknown. It may be related to the general northwestward tectonic tilting of Prince William Sound which resulted in six feet of subsidence at the head of Passage Canal (fig. 8).

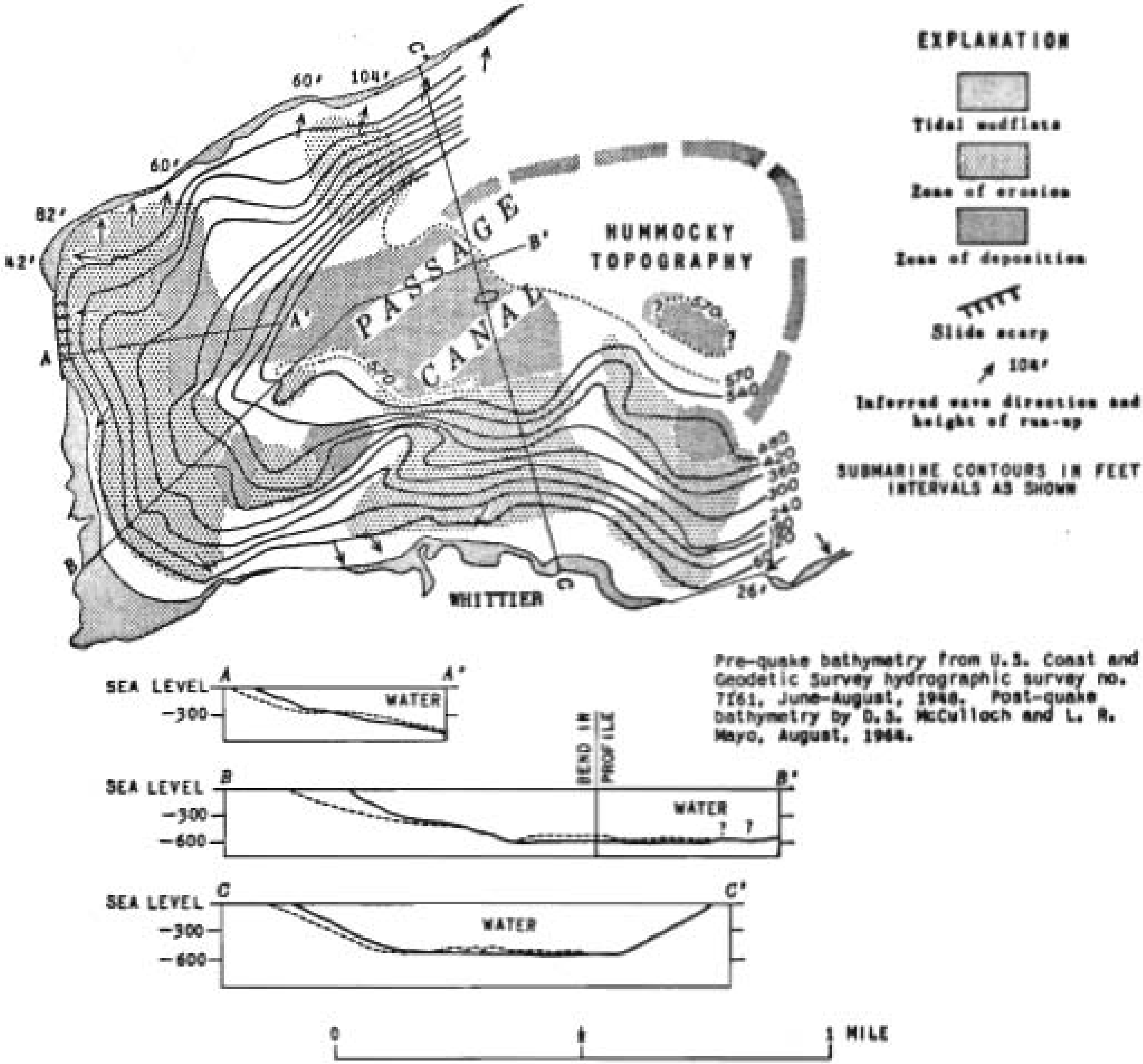

Figure 14. Distribution of submarine slides and local waves at the head of Passage Canal. Profiles show approximate bottom topography prior to (solid), and following (dotted) the earthquake.

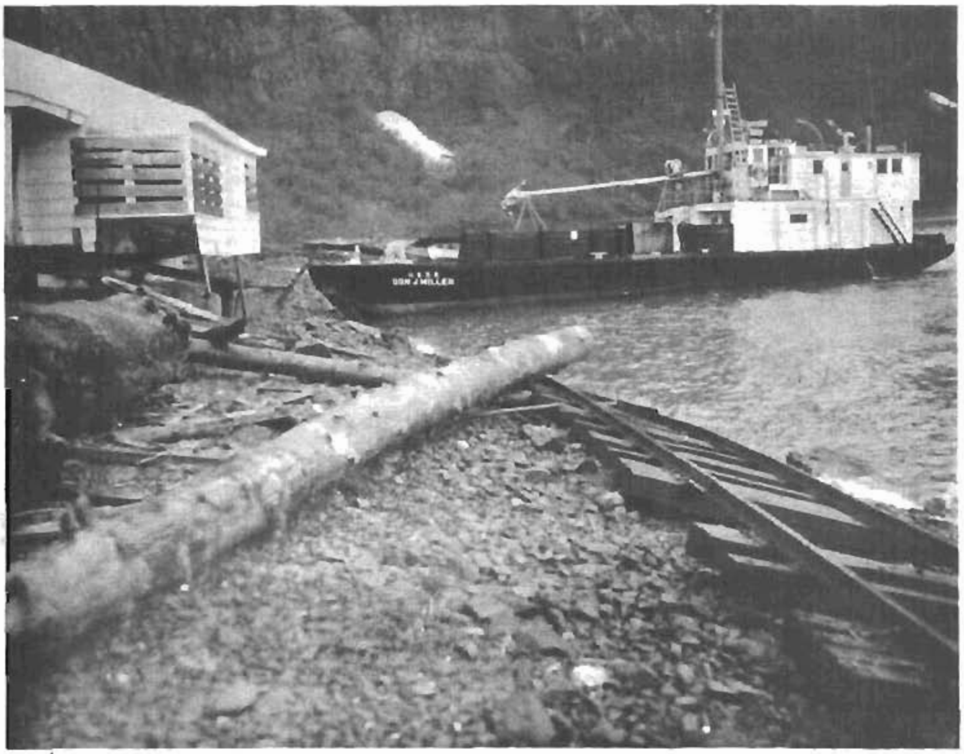

Figure 15. Slide scarp in terminal moraine-outwash-delta complex at the head of Passage Canal. The submarine slide carried away a portion of the railroad spur in the right foreground and partially undermined the abandoned house shown at the left. Water depth beneath the stern of the boat is 63 feet, indicating a submarine slope of 32 degrees. Prior to the earthquake the tidal mud flats extended 75 feet out from shore at this point. Photo by G Dallas Hanna.

Kenai Lake.--Two large subaqueous slides of alluvial deposits at Kenai Lake (fig. 13) have characteristics comparable in all important aspects to those that occurred along the coast. Their locations on land are marked by missing segments of shoreline - including a section of Alaska Railroad track - and clear evidence of damage to adjacent areas from waves or from ice floes carried by the waves. Detailed bathymetric mapping at these localities by McCulloch and Mayo shows typical slide scars and deepening of water near shore, and hummocky landslide deposits spread over the adjacent lake floor.

Local waves of uncertain origin.--Wave damage occurred along large segments of the shoreline of northern and western Prince William Sound and locally along the south shore of the Kenai Peninsula (fig. 12). This damage is comparable in all major aspects to that which accompanied known submarine slides. At some of these localities the pattern of wave damage and the submarine topography suggest that the waves were generated by subaqueous slides. In others, the available information is too scanty to justify speculation on the mode of origin of the waves that caused the observed damage. The more likely possibilities include: 1) submarine slides; 2) regional northwestward tectonic tilting; 3) seiching generated by ground vibration during the earthquake; 4) local submarine faulting; and 5) subaerial landslides.

Local waves in western Port Valdez.--The general source areas of some of the local waves could be determined by mapping the location of wave-damaged shorelines, run-up heights, and their inferred direction of movement.

Figure 16 illustrates one of the many areas in which the distribution of

Figure 16 near here

shoreline damage, inferred directions of local waves, and heights of run-up were plotted. At least two exceptionally large waves were generated close to the north wall of Port Valdez on either side of the mouth of Shoup Bay--a bay which occupies a hanging valley whose floor is more than 500 feet above the bottom of Port Valdez. At this locality Shoup Glacier has left a crescentic deposit of glacial debris that blocks the entrance of Shoup Bay except for a narrow channel that cuts through the deposits near the west side of the bay.

One of the waves, which originated near the abandoned Cliff mine obliterated all of the sizable mill buildings at the mine site, deposited driftwood at 170 feet above lower low water and splashed silt and sand up to an elevation of 220 feet. From the vicinity of the Cliff mine it moved east and probably south, with gradually diminishing height.

Another wave, which was generated on the west side of Shoup Bay, attained a maximum elevation of 125 feet near its inferred source, from which it moved southwestward toward Valdez Narrows and probably southward to the opposite shore of Port Valdez. To the west of Shoup Bay the wave surged to more than 125 feet above lower low water. The wave, which was traveling from east to west, broke several 24-inch-diameter trees at elevations between

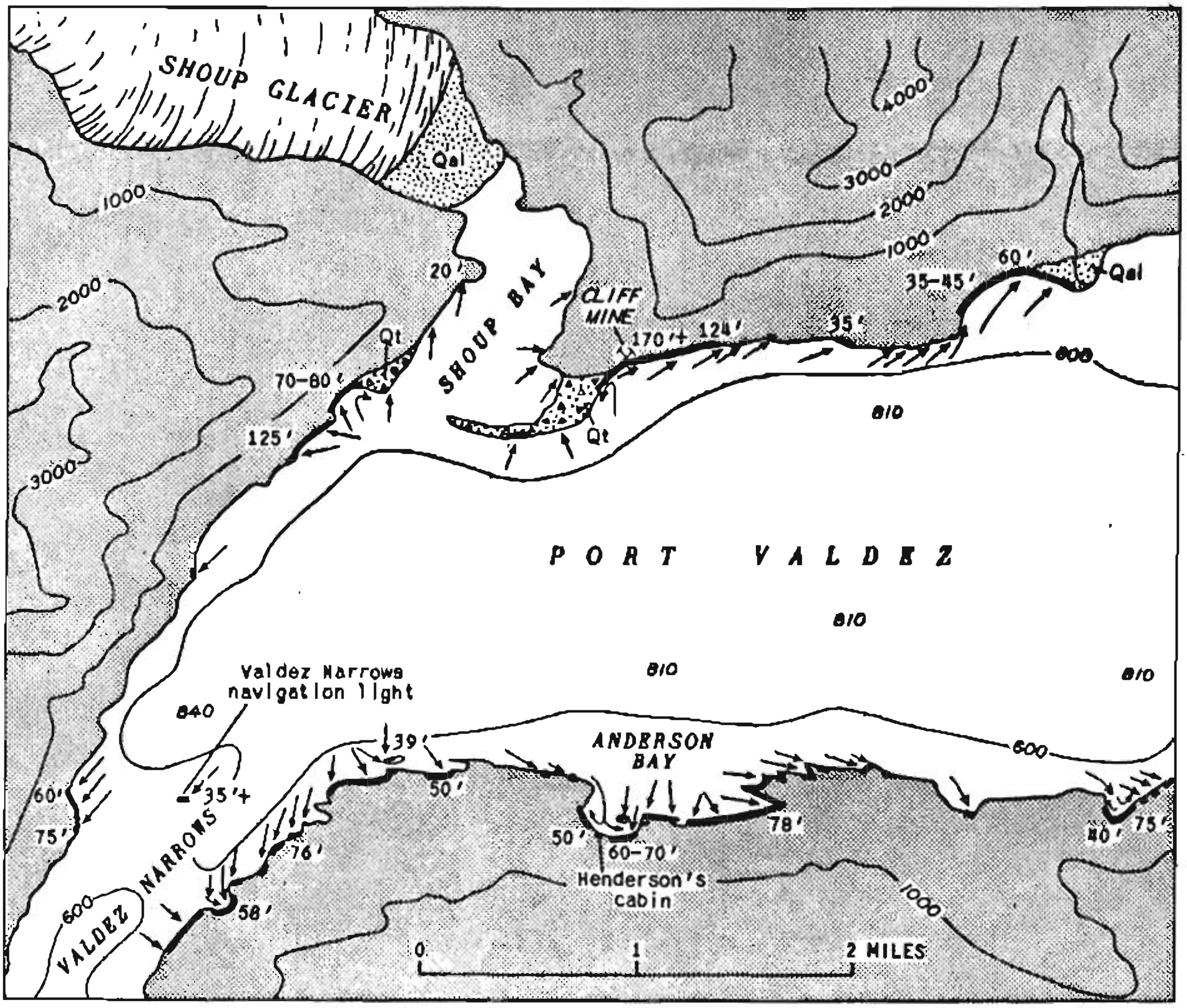

Figure 16. Heights and inferred directions of local waves in the western part of Port Valdez, Prince William Sound. Heavy line along shore indicates distribution of damage; numeral is measured maximum run-up. Shaded pattern, bedrock; dotted pattern, alluvium and intertidal mud; triangular pattern, terminal moraine of the Shoup Glacier. Contour interval on land is 1,000 feet; submarine contour interval is 600 feet.

88 and 101 feet and deposited barnacle-covered boulders estimated to weigh 1,700 pounds 88 feet above lower low water (figs. 17, 18, 19). This

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Figures 17, 18, and 19 near here

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particular surge was so violent that even at the entrance to Port Valdez, 3 miles to the southwest, it left a trimline 75 feet high and broke off spruce trees 18 inches in diameter. It also overtopped and destroyed the Valdez Narrows navigation light which was situated on a reinforced concrete pedestal 35 feet high.

On the south shore of Port Valdez violent surges of water that probably came from the two source areas near Shoup Bay caused almost continuous damage for approximately a mile along the shore of Anderson Bay. Harry Henderson, who was at his cabin on the opposite side of Port Valdez from Shoup Bay (fig. 16), is missing and presumed lost, and his cabin site is marked only by some foundation piling driven into the ground.

On the basis of a brief examination of the wave effects at two localities in Port Valdez shortly after the earthquake, it was inferred that the shoreline damage was caused by a wave that entered the Port from the west (Grantz, Plafker, and Kachadoorian, 1964, p. 12). Detailed examination of the damage distribution during the follow-up studies clearly indicates that the waves originated at the sites of large submarine slides of segments of the terminal moraine that blocks the mouth of Shoup Bay rather than outside of Port Valdez. The largest slides probably originated near the Cliff mine and at the west side of Shoup Bay near the point marked "70-80" on figure 16. Precipitous downslope movement of such masses triggered by the earthquake must have forced a sudden withdrawal of water from the area which they had occupied. Water moving into the surface depressions created high-velocity surge waves that first struck the immediately adjacent shores and then spread radially outward with gradually diminishing intensity.

Two eyewitnesses to the event who were in a small boat outside Valdez Narrows saw one of these waves coming from the direction of Shoup Bay approximately 5 minutes after the earthquake began and they watched the wave overtop and destroy the Valdez Narrows navigation light. Although the wave dissipated rapidly outside Valdez Narrows, the boat barely rode it out without swamping. On their way to Valdez, at 8:00 p.m., 2½ hours after the earthquake these same two men saw large numbers of dead red snappers of exceptional size floating in the water near Valdez Narrows. The red snappers, which normally inhabit deep water and are extremely sensitive to rapid pressure changes, probably were killed when they were forced up off the bottom by turbulence caused by the inferred submarine slides. Significantly, large numbers of red snappers were seen floating on the waters of Knight Island Passage whose shorelines were extensively damaged by surge waves the day after the earthquake.

Figure 17. Spur west of Shoup Bay that was overtopped by a local wave travelling from right to left. Trees and branches are broken to an elevation of more than 100 feet above lower low water.

Figure 18. Living spruce trees 2 feet in diameter that were snapped off by a local wave at elevations between 88 and 101 feet above lower low water.

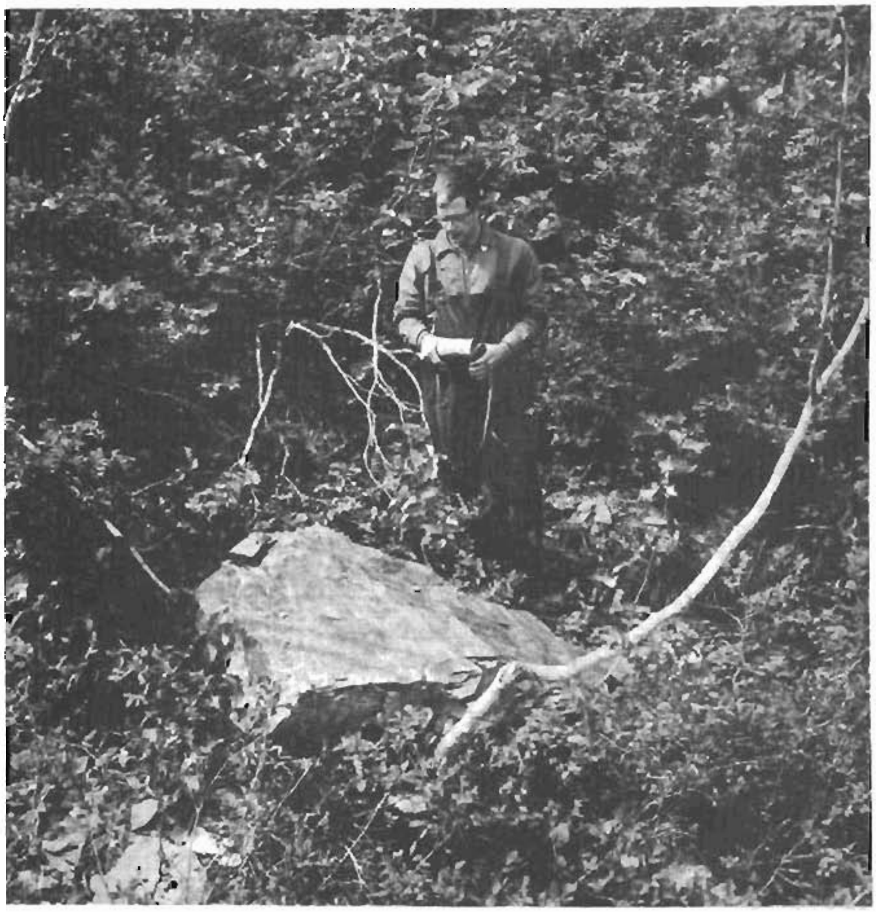

Figure 19. Boulder estimated to weigh 1,700 pounds thrown up to 88 feet elevation from the shoreline by a local wave.

Origin of the waves.--In several instances, most notably at Seward, Thumb Cove, Whittier, Blackstone Bay, Valdez, and Kenai Lake the local surge waves can be specifically identified with subaqueous slides along the margins of unstable alluvial deltas and moraine-outwash complexes. Fathometer profiles show typical slide scars near shore, and hummocky topography presumably formed by deposition of slide debris at the base of the slopes in deep water. Near Shoup Bay in Port Valdez, Icy Bay in western Prince William Sound, and Aialik Bay on the Kenai Peninsula, the wave distribution strongly suggests sliding of submarine moraine-outwash complexes.

At most of the localities where surge waves struck extensive segments of rocky shoreline, such as at the native village of Chenega and other places along Knight Island Passage, no subaqueous or subaerial slide source for the waves was identifiable. However, because the waves were generated during or immediately after the earthquake wherever there are surviving witnesses, were extremely localized in distribution, bore no systematic relationship to known areas of faulting, and generally were higher and more violent than the seismic sea waves that followed, it is entirely possible that many, if not all of them, may also have been generated by subaqueous slides.

Detailed marine geologic studies are planned by the U. S. Geological Survey for the 1965 field season with the objective of defining the environmental factors that gave rise to the known earthquake-triggered slides and their associated waves as well as the cause of the local waves whose origin is as yet uncertain. Such studies are essential for evaluation of the susceptibility of existing communities and installations to further subaqueous sliding or wave damage, and as a basis for the selection of future building sites in earthquake-prone coastal areas in south-central Alaska.

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