sels. The water was reported to have continued oscillations at 3- to 4-minute intervals until dusk. A high wave at about 21:00 AST swept away some skiffs (Figure 78*a*).

At Port Nellie Juan, a wave about 5 ft higher than the dock swept away pilings and toppled two buildings.

In Culross Passage, a violent current surged south and then north soon after the earthquake started. The current changed three or four times during a half-hour period. The surge had the form of a bore 8 to 10 ft high (Chance, 1966).

As reported by two brothers living on an isolated bay on Perry Island, the water "ruffled" and went down to about 8 ft below low tide. Approximately 8 minutes after the earthquake started, a wave came in and rushed up 26 ft above MLLW (Berg and others, 1971; Chance, 1966).

Mrs. Clock, who lives with her family in a cove on Peak Island, reported that the water rose and "boiled furiously" along the shore and that spray went high into the trees. Then the water dropped almost 15 ft from low-tide level and it was "eerie calm." About 4 to 5 minutes after the earthquake, a wave of water "five feet higher than normal moved in from the lagoon" and struck the shore. Mrs. Clock said that the water "came back and forth for at least an hour." (See Figure 78*b*.)

The fishing boat *Roald* was anchored in Port Wells at the time of the earthquake. The captain reported that the water withdrew about 20 minutes later. Then after another 10-15 minutes it returned like a tidal bore from the south and carried the anchored boat, along with rocks and debris, into its mainstream.

At the head of Pigot Bay, Port Wells, the water receded about ¼ to ½ mile from the shore after the earthquake ended. As it receded, the water whipped violently back and forth. Then the water returned to shore like a fast-rising tide without any violent surge. About 10 minutes after the earthquake ceased, the water became calm at normal tide-water level. Between 21:00 and 21:30 AST the sea rose to a height of 8 ft above extreme high tide. It then receded about 2 ft. At about 23:00 it reached again to about 8 ft above extreme high tide (Chance, 1966) (see Figure 78*c*).

In Hobo Bay, north of Pigot Bay, the water receded during the earthquake and exposed sea bottom that is normally below lowest tide. When the water returned, it rose to about 4 ft above high tide. After the earthquake ceased, small waves came in rapid succession every 2 to 3 minutes. As darkness fell, the sea became very calm. Shortly after dark, however, the water began to rise and within 1½ hours had reached 9 ft above high-tide level. The water then receded about 4 ft before another wave came in. For a period of 2 hours the water advanced and withdrew three times (Chance, 1966) (see Figure 78*d*).

The fishing vessel *Quest* was in Unakwik Inlet at the time of the earthquake. One of the crew members reported that a big swell moved in while the earth was shaking. The water sloshed back and forth in an east-west direction and ran up approximately 100 ft in some places; when it withdrew, it exposed the sea bottom about 4 or 5 fathoms deep. Large waves swept into the inlet at 23:00 AST and then again at about 02:00 in the night (Chance, 1966).

A crew member of another fishing vessel that was about 1 mi inside the mouth of Unakwik Inlet at the time of the earthquake reported that the water started to oscillate during the earthquake, washing high on the north shore and then withdrawing an unusually great distance offshore. The oscillations continued throughout the earthquake with a period of approximately 1 minute. Immediately after the earthquake ended, the water started to recede, a regression that continued for about 2½ hours. Within 3 hours after the earthquake, the water started to rise to a level higher than high water; by 21:00 it was again receding. At about midnight another wave brought the water level to about 3 ft higher than the normal tide for that time (Chance, 1966) (see Figure 78*e*).

At Tatitlek the water receded 15 ft and then returned 17 to 18 ft above MLLW. At 21:00 AST a high wave rose to within 7 in. of the preearthquake 15-ft level; 45 minutes later, there was a wave with a height of 5.3 ft above the normal tide of that time (Chance, 1966).

At Boswell Bay, Hinchinbrook Island, it was reported that the water receded initially. The regression was followed by two waves within 3 hours after the shock. Between 24:00 and 01:00 AST, the water rose 8 to 12 ft above the high-tide level (Chance, 1966).

The maximum tsunami runup at Zaikof Bay, Montague Island, was about 33 ft above postearthquake MLLW.

At an unidentified place on Montague Island, five waves at about 5-minute intervals were observed traveling parallel to the shore; the first one, with a height of 12 ft, arrived at about 18:05.

TSUNAMI WAVES IN PORT VALDEZ

The disaster that befell Seward had something of a parallel at Valdez, situated in Prince William Sound, at the head of a long fiord comprising Valdez Arm and Port Valdez (Figure 79). The similarity of earthquake and tsunami effects is rendered more interesting because of a similarity of location of the towns with respect to bays of rather similar shape and size. In fact, the schematic representation of a coupled system of basins shown in Figure 52*b* applies in the same sense to the Valdez fiord, which is seen to comprise two basins connected by a constricted channel of shallower water (Figure 79). Even the dimensions are quite similar. The difference, in the relative situations of Valdez and Seward, is that Valdez Arm opens on Prince William Sound, a virtually closed basin, whereas Resurrection Bay opens on the sea. Valdez, of course, was much closer to the

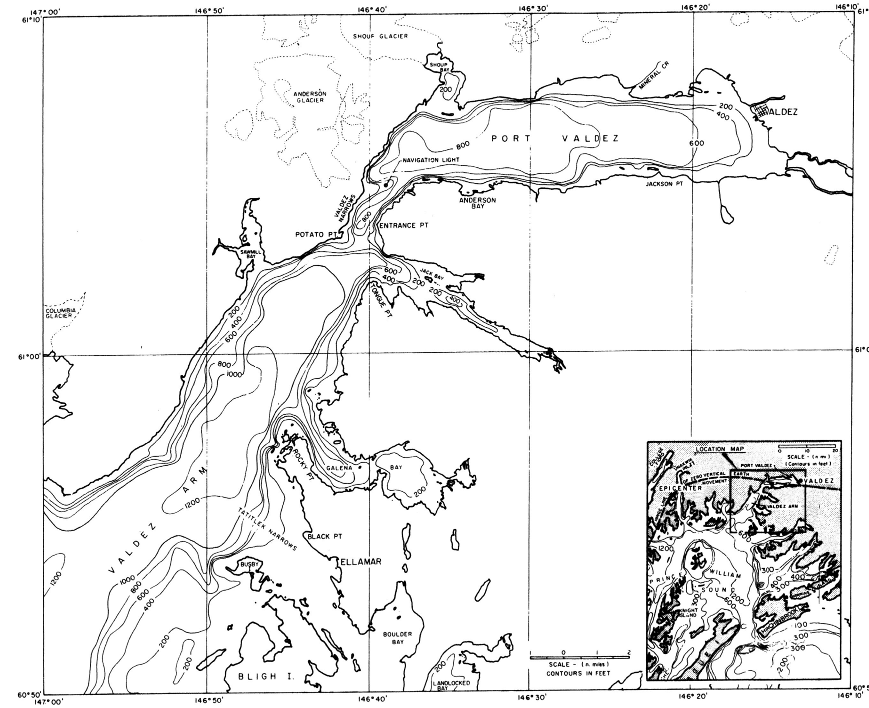


FIGURE 79 Bathymetry of Port Valdez and Valdez Arm.

epicenter of the earthquake and was located close to the hinge line of zero vertical earth motion (Figure 70, inset).

We investigate the oscillating properties of Valdez Arm and Port Valdez as a chain-basin system represented schematically by Figure 52*b*. In this case, basins I, II, and III have the approximate dimensions given in Table 8. By the impedance principle of Rayleigh as employed by Neumann (1948), we find the eigenperiods T_n ($n = 1, 2, 3, 4, \ldots$) for the first four modes of free oscillation of the system to be

$$T_n \simeq 39;\ 18;\ 11;\ 7;\ldots \text{ minutes.} \tag{9}$$

Comparison of the period sequence in equation (9) with that of equation (8) suggests that the Valdez embayment

TABLE 8 Dimensions of Interconnecting Rectangular Basins Simulating Valdez Arm and Port Valdez

Basin	Length L (nautical miles)	Breadth b (nautical miles)	Depth d (ft)
I	11.35	2.01	700
II	2.00	0.76	600
III	10.52	2.66	1100

would not provide resonance for the expected fundamental period of the tsunami waves generated at the mouth of Prince William Sound. However, in view of the implication that the Sound might well develop oscillations corresponding to the higher modes of its triangular shape, some degree

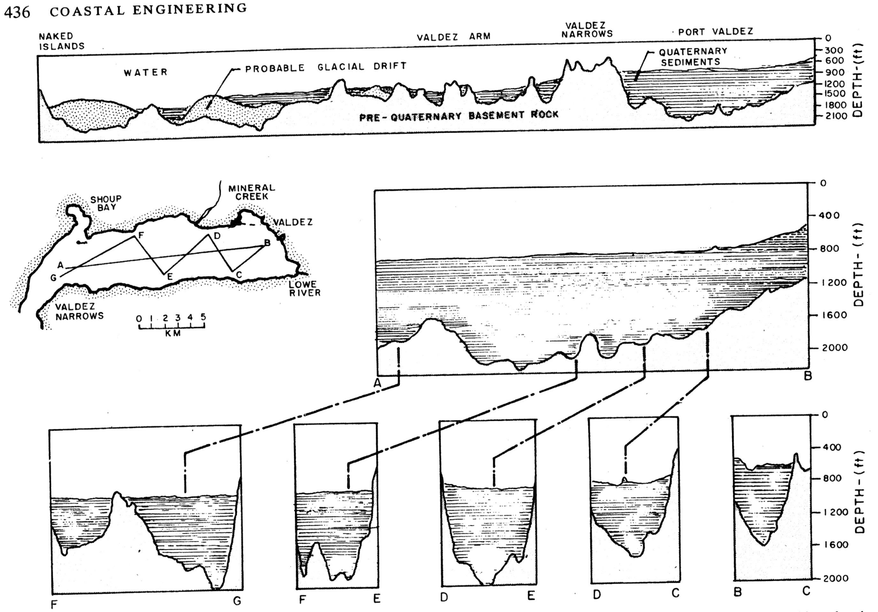


FIGURE 80 Seismic reflection profiles along the axis of Valdez Arm and Port Valdez and along various section lines in Port Valdez, showing basement structure and sediments. (Adapted from von Huene, Shor, and Reimnitz, 1967.)

of resonance or pseudoresonance could amplify the effects of oscillations of period less than 50 minutes.

Figure 80 gives the results of seismic reflection profiles of the Valdez embayment obtained in field surveys since the earthquake (von Huene and others, 1967). The basement rock profile has an average depth in Valdez Arm of about 1,200 ft; it is deeper (about 1,800 ft) in Port Valdez. In Valdez Narrows, the rock forms a sill virtually free of sediments. Because of the elbow bend formed between Valdez Arm and Port Valdez, the latter is capable of functioning effectively as a closed basin for any water oscillations generated within it. The profile AB in Figure 80 is not quite complete in showing the rise of sediments beyond B. The water-depth profile, however, may reasonably well be taken as being semiparabolic over the basin length of 11.35 nautical miles, with its maximum depth of 850 ft at the west end.

The manner in which this basin would oscillate by itself longitudinally may be found by considering it joined with its mirror-image basin. Applicable modes from the solution of the double basin are only those that will yield an antinode at the center. From Wilson (1966), then, we find the fundamental and second-mode periods of oscillation (longitudinally) for Port Valdez to be

$$\left.\begin{array}{l}\text{(i) } T_1 \simeq 17.8 \text{ minutes}\\ \text{(ii) } T_2 \simeq 9.8 \text{ minutes}\end{array}\right\}. \qquad (10)$$

No tide gage was operating at Valdez Harbor; if there had been, it could not have provided any information because of the total destruction of the harbor. As in the case of Seward, we are dependent on eyewitness accounts and the studies of other investigators for an interpretation of what happened in Port Valdez. We shall refer to many sources of information, notably, Grantz and others (1964); Brown (1964); Berg and others (1971); U.S. Coast and Geodetic Survey (1964a); Denner, personal communication (1964); Plafker and Mayo (1965); Spaeth and Berkman (1965, 1967, and this volume); Coulter and Migliaccio (1966, and Geology volume); and numerous unpublished materials to be cited.

Valdez is situated at the eastern end of Port Valdez on the seaward edge of a large outwash delta composed of a thick section of saturated silty sand and gravel. Its general location is shown in Figure 79, and details of the layout of the city and harbor are given in the preearthquake plan in Figure 81. The city was entirely contained within a V-shaped levee which prevented inundation from the frequent rampages of the Valdez River draining from the Valdez Glacier. Figure 82 shows the appearance of the waterfront at an earlier time before the development of the small-boat harbor in the tidal zone area between the north and south arms of the docks.

Valdez is the northernmost all-weather port in Alaska, but, unlike Seward and Whittier, it is connected with the interior only by road links. Its population of 1,200 was mainly active in the shipping and fishing industries, and its position as the "Switzerland of Alaska" favored a developing tourist trade. The earthquake brought overwhelming disaster to Valdez. The entire docks and waterfront were totally destroyed, and tsunamis penetrated deep into the heart of town. Figure 83 is an aerial view of the city after the earthquake with the limit of tsunami runup delineated. Because of the unstable sediments upon which the city is founded, it was condemned as a hazard (Coulter and Migliaccio, 1966; Eckel, 1967) and has been vacated in favor of a new townsite at Mineral Creek, founded on stable rock (see sections DE and DC of Figure 80).

Most authorities who have reported on the wave phenomena that destroyed Valdez have mentioned four waves as primarily responsible for the destruction; two of these appeared during and shortly after the earthquake, and two occurred many hours later. However, although the first waves are attributed to massive submarine slumping of the sediments at the waterfront, there is not unanimous agreement on just how the waves were generated. It is curious that eyewitnesses make no specific mention of a major boil of water as having developed in the bay (in the way it had been observed at Seward); yet this perhaps is understandable because the relative flatness of Valdez does not afford a commanding view of the bay, and the remarkable gyrations of the ship *Chena* distracted the attention of observers. Grantz and others (1964) and Plafker and Mayo (1965) are the only sources we can find that specifically mention mounds or boils of muddy water; yet eyewitness accounts, reported by Berg and others (1971), Brown (1964), Bryant (1964b), Chance (1966), Bracken (1964), Chapman (1964), Migliaccio (1964), and Coulter and Migliaccio (1966), make no direct reference to these boils, except in the sense of purely localized mounds hitting the ship *Chena* (reported by the ship's captain) and the development of a "wall of water" out in the bay, sometime after the occurrence of the first waves (reported by Forest Sturgis, Alaska State Highway engineer). We raise this matter not because there is any question of the occurrence (which is indisputable) of a submarine slide to which the mounds and boils are attributable, but because there is the possibility that the first wave or waves may have had other association, as we shall discuss.

To explain what happened at the waterfront at Valdez, allowing some degree of conjecture to fit the facts, it is possible to infer that water level fluctuated in approximate accord with the marigram presented in Figure 84. We shall try to justify the inference as we proceed.

The first wave to strike Valdez occurred during the earthquake and was remarkably sudden. The time sequence of the waves is confused, owing to the disastrous conditions that prevailed. People who watched the water had their attention drawn to the erratic behavior and violent movement of the Alaska Steamship Company vessel *Chena*, a 10,815-ton cargo ship moored to the north dock when the earthquake started. Captain Merrill Stewart of this ship has given the following account of his experience (Coulter and Migliaccio, 1966):

> The *Chena* arrived at Valdez at 16:12 hours, March 27. About 17:31, while discharging cargo, we felt a severe earthquake followed almost immediately by tidal waves. There were very heavy shocks about every half a minute. Mounds of water were hitting at us from all directions. I was in the dining room. I made it to the bridge (three decks up) by climbing a vertical ladder. God knows how I got there.
>
> The Valdez piers started to collapse right away. There was a tremendous noise. The ship was laying over to port. I had been in earthquakes before, but I knew right away that this was the worst one yet. The *Chena* rose about 30 feet on an oncoming wave. The whole ship lifted and heeled to port about 50°. Then it was slammed down heavily on the spot where the docks had disintegrated moments before. I saw people running—with no place to run to. It was just ghastly. They were just engulfed by buildings, water, mud, and everything. The *Chena* dropped where the people had been. That is what has kept me awake for days. There was no sight of them. The ship stayed there momentarily. Then she came upright. Then we took another heavy roll to port. I could see the land (at Valdez) jumping and leaping in a terrible turmoil. We were inside of where the dock had been. We had been washed into where the small-boat harbor used to be. There was no water under the *Chena* for a brief interval. I realized we had to get out quickly if we were ever going to get out at all. There was water under us again. The stern was sitting in broken pilings, rocks, and mud.
>
> I signaled to the engine room for power and got it very rapidly. I called for "slow ahead," then "half ahead" and finally for "full." In about four minutes, I would guess, we were moving appreciably, scraping on and off the mud (bottom) as the waves went up and down. People ashore said they saw us slide sideways off a mat of willow trees (placed as part of the fill material in the harbor) and that helped put our bow out. We couldn't turn. We were moving along the shore with the stern in the mud. Big mounds of water came up and flattened out. Water inshore was rushing out. A big gush of water came off the beach, hit the bow, and swung her out about ten degrees. If that hadn't happened, we would have stayed there with the bow jammed in a mud bank and provided a new dock for the town of Valdez!! We broke free. The bow pushed through the wreckage of a cannery. We went out into the bay and

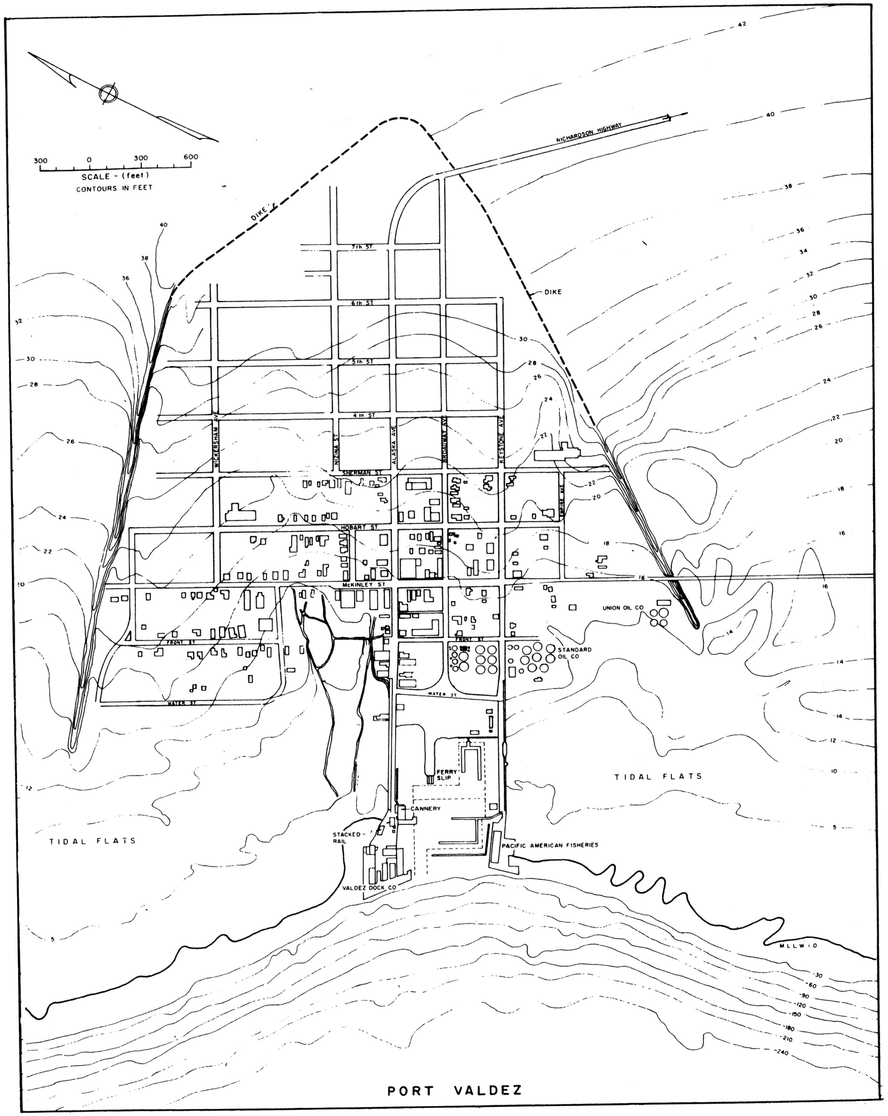
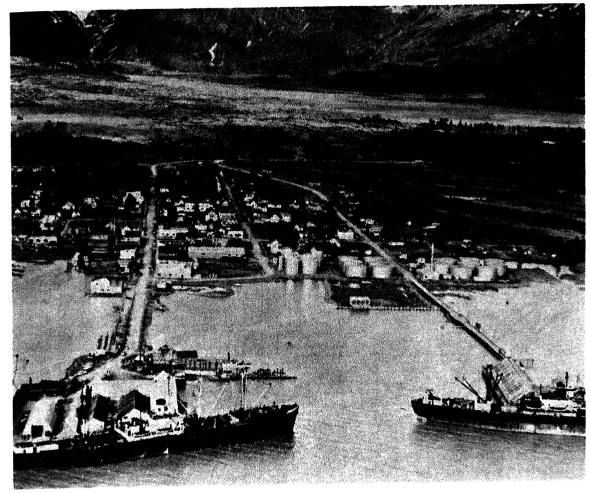


FIGURE 81 Plan of Valdez before the earthquake.



Mac's Foto

FIGURE 82 Aerial view of the waterfront at Valdez several years before the earthquake.

U.S. Army

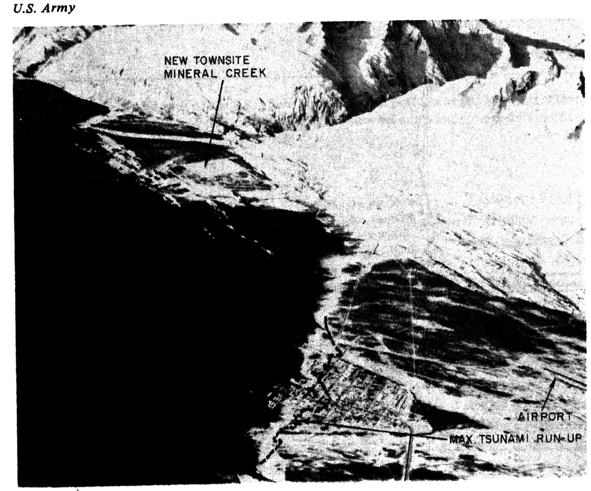


FIGURE 83 Valdez after the earthquake showing approximate extent of inundation from the tsunami.

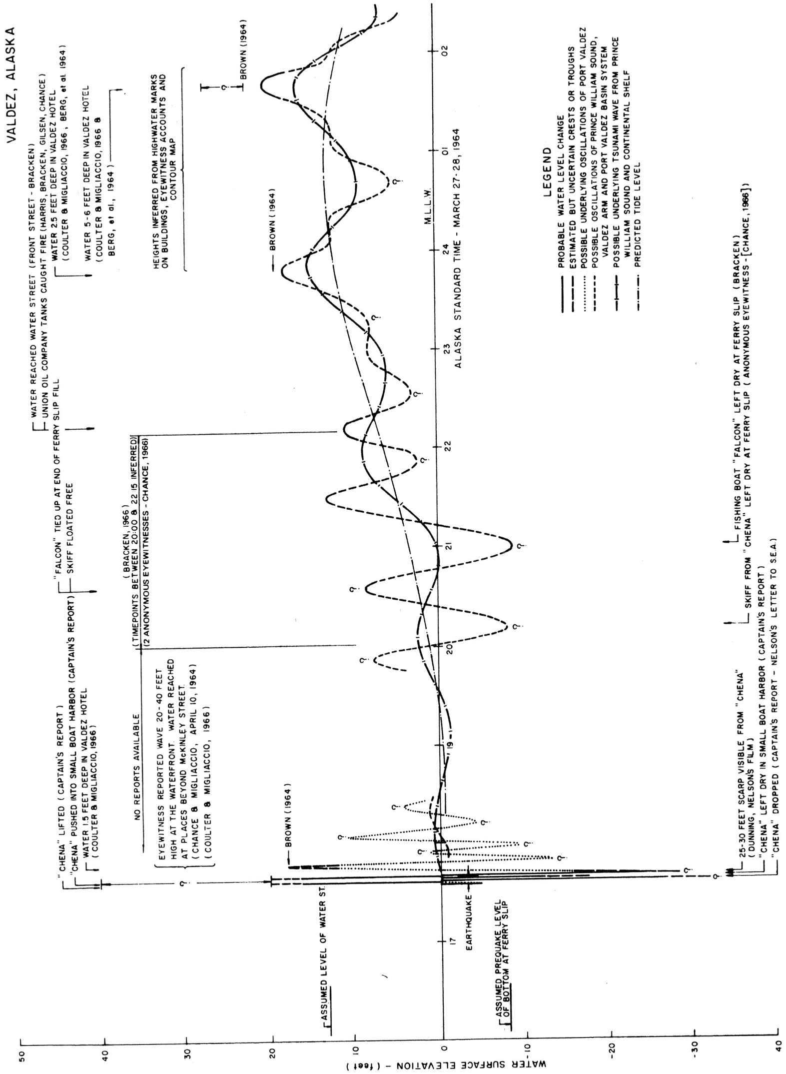


FIGURE 84 Inferred marigram for Valdez, based on accounts by eyewitnesses and on inductive reasoning.

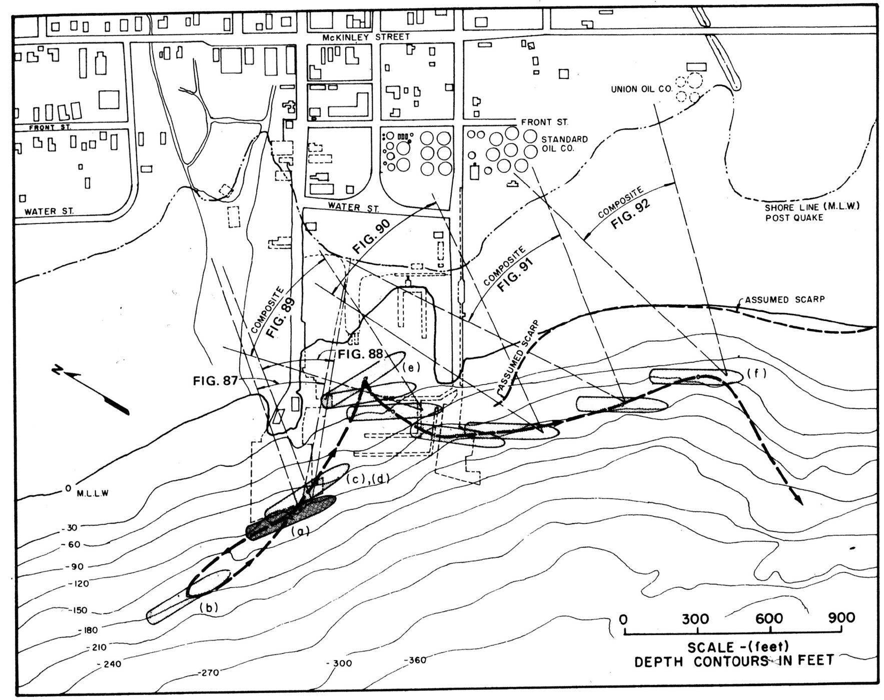


FIGURE 85 Inferred path of the S.S. *Chena* from an initial position at the North Arm Dock, Valdez Harbor, during and after the earthquake. Successive positions of the *Chena* are based on eyewitness accounts and interpretation of color motion pictures photographed from the ship by F. Numair and E. Nelson.

had to stop. The condensers were plugged with mud and pieces of the dock. The chief mate, Neal L. Larsen, checked to see then if we were taking water. We were taking none. It was unbelievable after what the ship had been through. We had the lifeboats all manned and ready. I didn't think she would float in deep water. Maybe the soft mud bottom made the difference.

Captain Stewart's impressions of the tsunami were reported by Berg and others (1971), Denner (personal communication, April 1964), Chance (1966, and in press), and the magazine Alaska Construction (1965); collectively, these sources add further important information, as do interviews that we had in 1966 with former crew members Dunning, Harding, Nelson, and Numair.

It appears evident, for example, that immediately after the start of the earthquake the *Chena* went astern in a northwest direction and either slipped or fractured her mooring lines. Sturgis, on the third floor of the Valdez Hotel, with a view seaward down Alaska Avenue (Figure 81), was in an exceptionally good position to observe this initial movement (compare Berg and others, 1971; Bryant, 1964b; Chance, 1966, and in press) which was also confirmed by Dunning and Numair. The implied movement of the *Chena* is thus shown in Figures 85*b* and 86*b*. This first movement of the *Chena* appears to have been part of a water withdrawal which accompanied the initial subsidence of the docks during the first minute of the earthquake. The earth slump at the harbor (Figure 86*b*) was at first more in the nature of compaction and partial sliding on the fairly

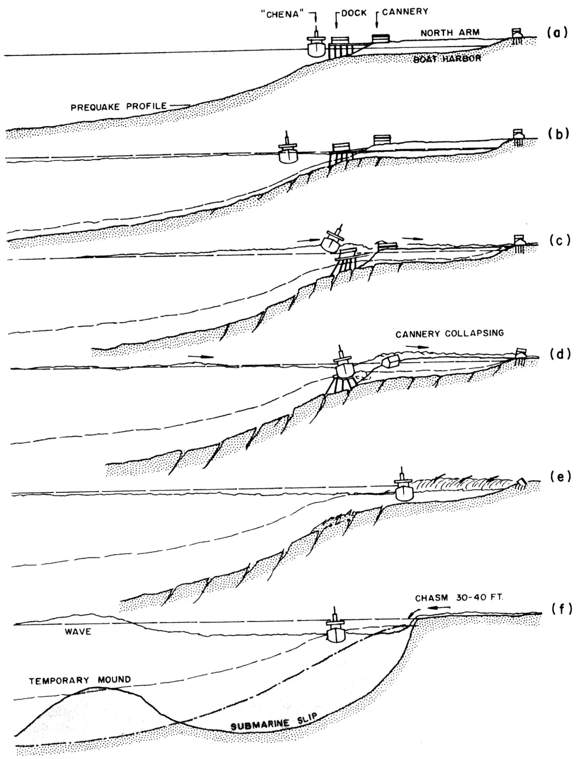
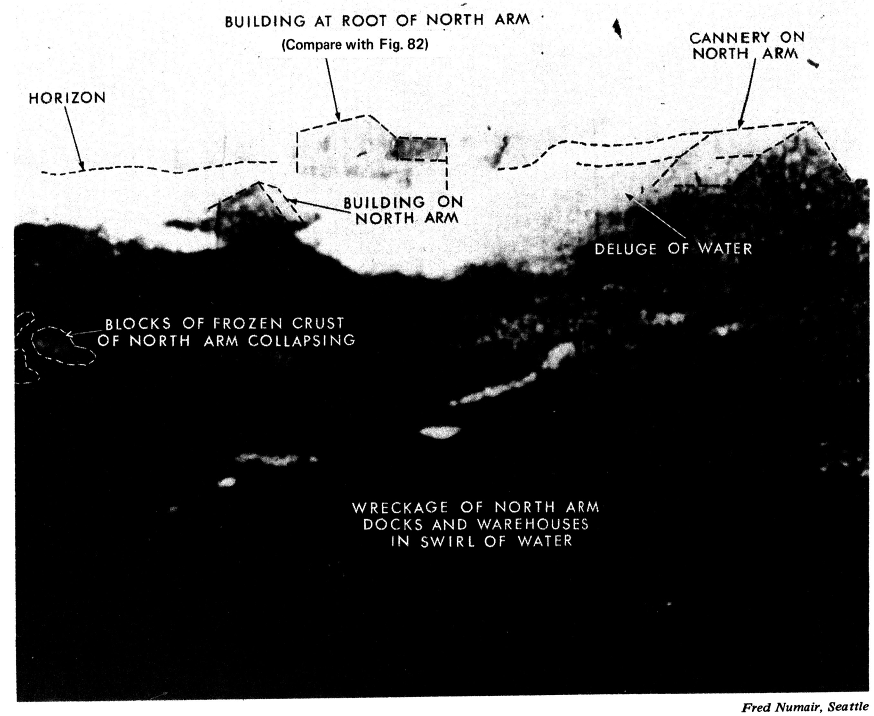


FIGURE 86 Sequence of schematic diagrams illustrating the inferred movements of the S.S. *Chena* and the destruction of the harbor at Valdez (compare with Figure 85).

flat slope of the sediments at the east end of Port Valdez. It could not have been a complete and sudden failure because the *Chena* returned on the crest of the first wave (Figures 85*c* and 86*c*) and was deposited on the wreckage of the docks. Further, although the docks had disappeared by this time, the portion of the North Arm at the approach to the docks, along with the cannery, was still intact, as proved by Figure 87. This is enlarged from a single frame (No. 110) of the 8-mm motion-picture film, photographed by Fred Numair, crew member of the *Chena*, from the approximate location of Figure 85 (*c* and *d*) or Figure 86 (*c* and *d*). Figure 87, which shows the cannery engulfed by the passing wave, should be compared with Figure 82. Numair's film (frame 184, Figure 88) shows the disintegration of the cannery moments later as the wave rushes over the North Arm from the northwest. (Figures 87 through 92 are enlargements from 35-mm color film, reproduced from original 8-mm color motion-picture films. Because the original films were not of the best quality, definition in the photographs is unavoidably poor, dashed lines in black and white and suitable annotations have been added, where necessary, to indicate features of interest or importance.)

According to his account published in *Alaska Construction*, Captain Stewart said of this happening that "the *Chena* heeled over 70° to port and crunched down hard on the spot where the pier had disintegrated moments before. I felt the hull shudder as the ship ground into the rocks and mud and broken pilings on the harbor bottom and I thought



Fred Numair, Seattle

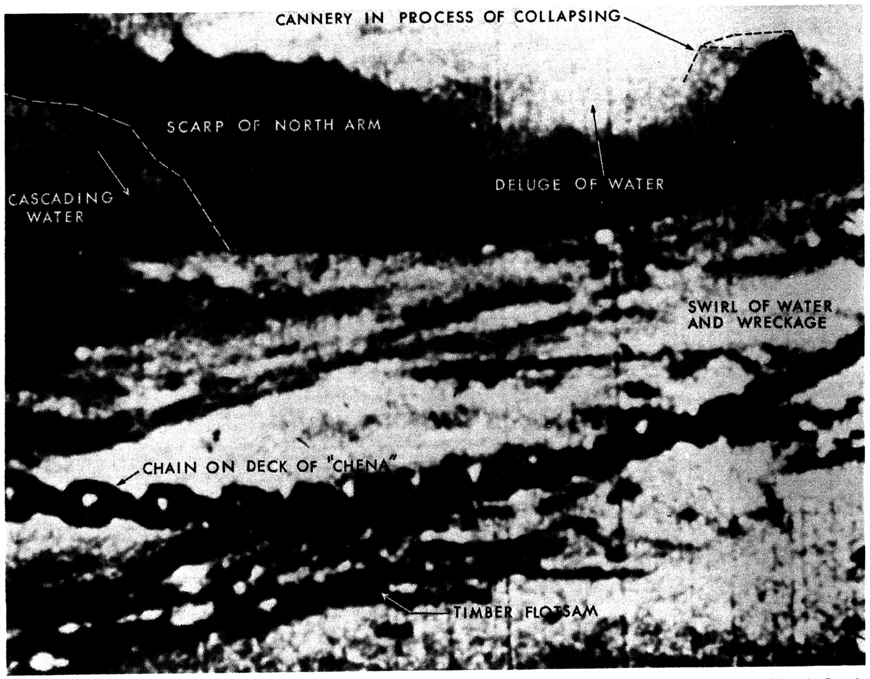
FIGURE 87 First tsunami wave engulfing the cannery on the North Arm of Valdez Harbor, as photographed from the *Chena* (enlarged from frame 110). Compare with Figures 81 and 82. (Location in Figure 85).

she was done for. No ship can stand that kind of battering."

The *Chena* at this stage took a violent roll to starboard, presumably as a result of a trough following the wave and her entanglement in the wreckage, but with additional smaller waves which apparently followed in the wake of the first crest she was prized free and carried into the boat harbor (Figures 85*e* and 86*e*). Here she was momentarily aground with her stern in the wreckage of the piling of the North Arm cannery. According to Sturgis (Chance, 1966; Bryant, 1964b), her bow was up (presumably on the mud flats) 20° to 30° above the stern. The *Chena* now took a violent roll to starboard before the boat harbor began to fill with the great volume of water pouring over the North Arm (apparently still from the first wave). All this apparently took place during the period of the earthquake, the duration of which has been variously given as 3½ to 5 minutes (prior to the final 30 seconds of the earthquake, according to Sturgis).

The following further reconstruction of what may have happened is the result of weighing all the evidence by eyewitnesses along with the factual motion-picture records by Numair and Ernest Nelson (another crew member), taken from the *Chena*.

A flux of water from the south now filled the boat harbor and carried boats and buildings, dislodged by the first wave, toward the Valdez Hotel. It lifted the *Chena*, which by now had acquired power, and enabled her to float free. This moment is believed to have been captured in Figure



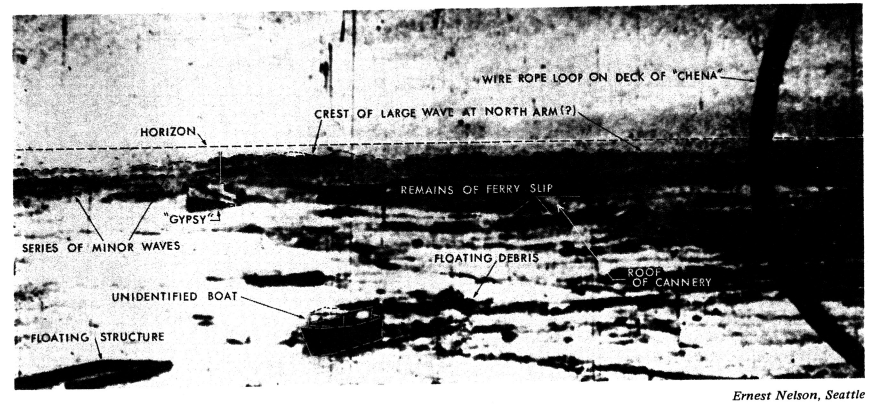
Fred Numair, Seattle

FIGURE 88 Another view (from the *Chena*) (enlarged from frame 184) of the first tsunami wave destroying the cannery on the North Arm of Valdez Harbor (for location see Figure 85).

89 (see also Figure 85), which shows the wreckage in the boat harbor. (The authors found that Nelson's film, which had been borrowed soon after the earthquake by one or more organizations, had been cut in many places and re-spliced in incorrect time sequence. Nelson, in a personal interview in 1966, was greatly upset over this treatment of his film.) The dark spur is believed to be the remains of the ferry slip and the parallel "wave" beyond to be the remnant of the North Arm. The *Gypsy*, the largest yacht in the boat harbor, is just visible off the ferry slip. In the course of the whirlpool-like movements of water between the north and south arms of the harbor, the *Gypsy* had apparently caromed off the sides of the *Chena* while the latter was still stuck in the mud. In Figure 89 the North Arm cannery roof is believed to be floating alongside the ferry slip. Subsequently, it was found entrenched in mud flats *north* of the harbor (see Figure 85).

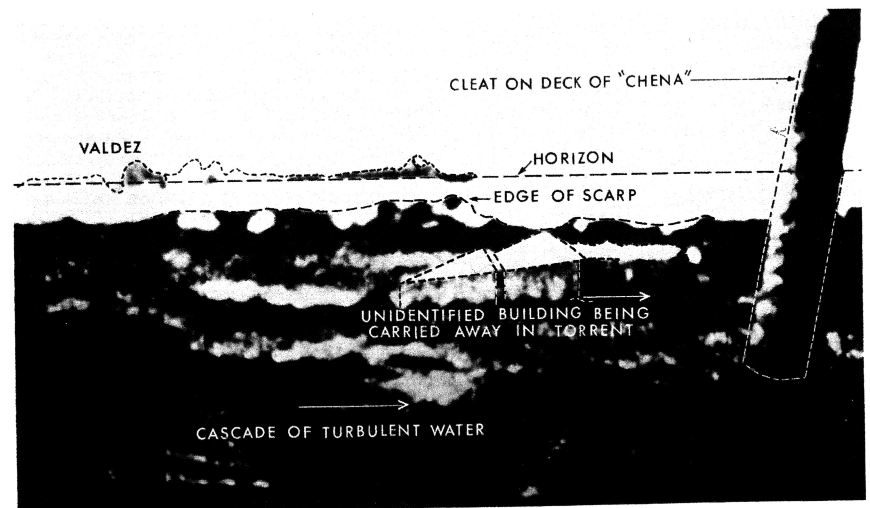
The water now began to drain from the boat harbor, and a strong movement of water from northwest to southeast along the shore began. This at first helped the *Chena* clear the stub of the South Arm and pass over where the south pier and cannery had been (see Figure 85). According to Dunning (personal interview), the deck of this pier had been swept southeast by the first wave that carried the *Chena* into the boat harbor, and surrounding piles showed bolts bent in that direction. Bracken (1964), moreover, records that a trailer frame was swept south from this pier.

The *Chena*, now under her own power, came also under the influence of a strong southerly current, which, despite her bid for deep water, carried her close alongshore as in a



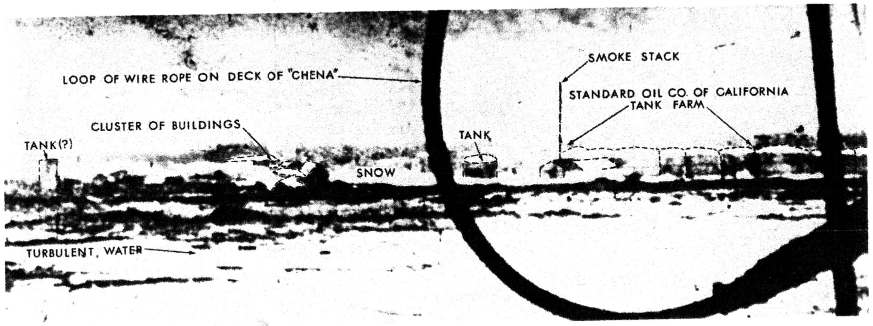
Ernest Nelson, Seattle

FIGURE 89 Momentary quiet in the ruins of the boat harbor at Valdez (panoramic composite view from the *Chena*). Yacht *Gypsy* is in left center field. Boat in foreground is unidentified. Cannery roof is believed to be floating in center field (for location see Figure 85).



Fred Numair, Seattle

FIGURE 90 View from the *Chena* while it was being swept southwestward along the coast off Valdez (from frame 246). Unidentified building being cascaded by the torrent of water down a collapsing shoreline (for location see Figure 85).



Ernest Nelson, Seattle

FIGURE 91 Panoramic composite from the *Chena*, south of the harbor of Valdez, showing water draining from the coast under the effects of the submarine slide (for location see Figure 85).

jet stream. Of this period, Captain Stewart records in the *Alaska Construction*, "The *Chena* was moving but she couldn't steer away from the beach as mounds of water continuously swept against the ship forcing her to a course next to the shore." Two observers who saw her at this time remarked on the jetlike speed of the movement (for example, see Bracken, 1964). The motion pictures by Numair and Nelson confirm this flow. Figure 90 is believed to have been taken from the approximate location shown in Figure 85. An unidentified building floats southward as it descends a cascade formed apparently by the final failure of the sediments in a major slump south of the harbor. The approximate location of the developing chasm wall formed by the slump is shown in Figure 85.

Moments later, Nelson, looking back toward Valdez, photographed this fantastic withdrawal of water and recorded the scene reproduced from several frames of his film as a panoramic composite view (Figure 91), with the direction and location of the picture as in Figure 85. Mud flats were forming behind the ship as it hurtled south. The awesome nature of the chasm formed by the submarine slide (see Figure 86*f*) is shown in Figure 92, photographed

Ernest Nelson, Seattle

FIGURE 92 Panoramic composite view (from the *Chena*) of the chasm formed by the submarine slide south of the harbor at Valdez (from three frames about 70 frames apart). Water is cascading from the land (for location see Figure 85).

U.S. Army

FIGURE 93 Aerial view of the devastation of the waterfront at Valdez in the vicinity of the Standard Oil Company tank farm. Note the relatively undamaged building in left center field (it can be identified in Figure 91). Remains of the south pier are at lower left.

from the approximate position (*f*) in Figure 85. It is believed that the location of the scarp formed by the slump is revealed in the lower right-hand portion of the aerial photograph (Figure 93) taken within a few days of the earthquake.

Figure 86*f*, which envisions the submarine slide, also suggests the formation of a wall of water on the seaward side of the *Chena*. This "wall," reported by Sturgis (Bryant, 1964b; Chance, 1966, and in press), was observed by Dunning, a longshoreman who survived disaster in the *Chena's* hold and reached the deck. This slide and the attendant wave effect almost certainly occurred after the earthquake and were probably promoted by the major drawdown of water, shown in Figure 84 to have occurred about 5 to 6 minutes after the start of the earthquake.

The submarine slide was massive; approximately 98 million yd^3 of material slumped away, according to an estimate by Coulter and Migliaccio (1966). Comparative contours of water depth in the vicinity of Valdez are shown in Figure 94, and typical profiles along cross sections *OA*, *OB*, and *OC* are shown in Figure 95. Off the delta to the south of Valdez, depth changes exceeding 300 ft are seen to have taken place; off Valdez itself the change is less, but still of the order of 100 ft. The major part of the slide thus took place off the Lowe River delta, but a substantial part consolidated and slid away at the Valdez waterfront and along the shore north of the town.

The *Chena* escaped to deep water before the next large wave rolled in over the demolished waterfront and reached to a level of 18 in. in the Valdez Hotel (Coulter and Migliaccio, 1966; Brown, 1964). The nature of these early waves now demands some explanation, particularly in regard to the directionality of the flow effects. A seemingly plausible explanation for the effects might be as follows. It is supposed that the sediments off the Lowe River delta and Valdez Glacier outwash, very much finer than those found off Valdez, were liquefied at an early stage of the earth vibration and caused a slide in the southeast corner of Port Valdez. Simultaneously, the entire basin of Port Valdez (see Figure 6, p. 131) was being jerked horizontally to the southeast parallel to the coastline of Valdez. The net effect of this would be to pile water to the north near Mineral Creek (Figure 79) and draw it from the south shore. Off Valdez itself, there could arise a pseudonodal situation in which a flow of water would take place to the northwest without a great deal of recession. This would have pulled the ship *Chena* to the northwest; alternatively, if the horizontal land thrust were sudden enough, the harbor would have been pushed southeast relative to the *Chena* (which momentarily remained fixed in space) with the same relative effect.

If this supposition is at all correct, a transverse seiche would have developed and thrown an edgewave southward along the Valdez shoreline. Taking the velocity c of the edgewave to be that given by equation (5) and assuming the period T of the seiche for a rectangular transverse vertical profile of width L at the head of the bay to be

$$T = 2L/c\,, \qquad (11)$$

we find the period of the edgewave to be [on elimination of c between equations (5) and (11)]

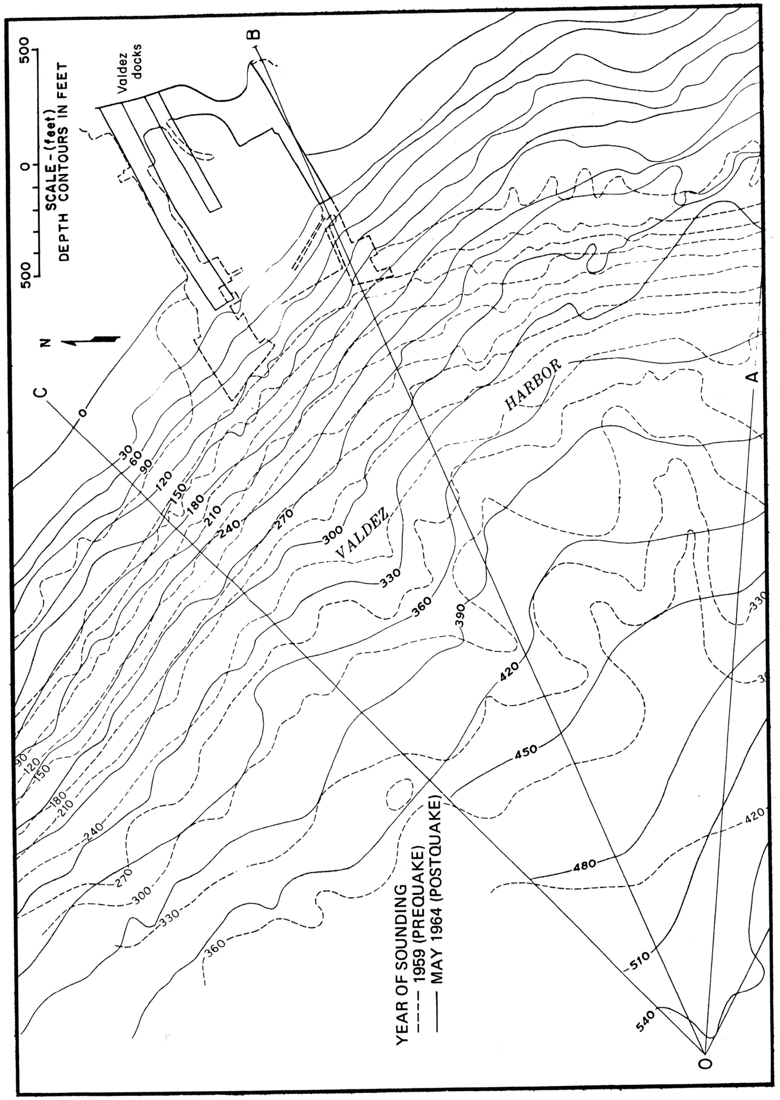


FIGURE 94 Preearthquake and postearthquake soundings at Valdez. (After Coulter and Migliaccio, 1966).

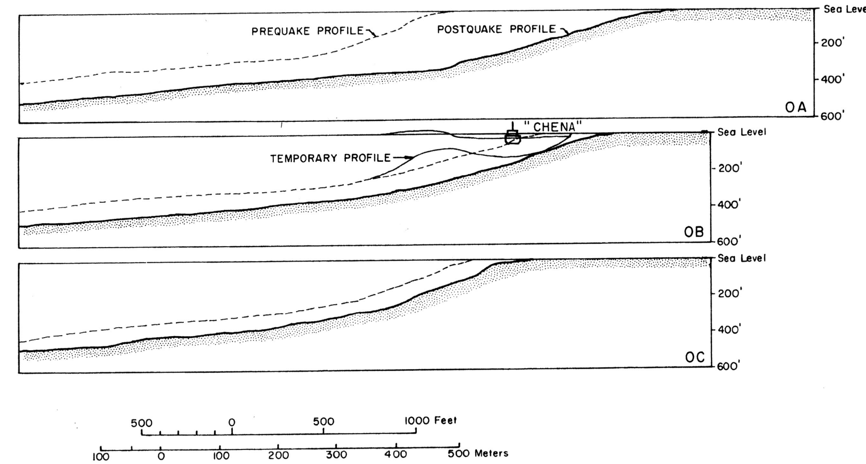


FIGURE 95 Profiles of the sea bed near Valdez before and after the earthquake. Section lines are shown in Figure 94. *Chena's* approximate position when scarp was visible is indicated schematically in profile *OB*. Dashed lines represent preearthquake profiles, and solid lines denote postearthquake profiles.

$$T = (4\pi L / g \sin\theta)^{1/2}. \quad (12)$$

For a bottom slope of about 1 in 11 and a width $L \simeq 2.94$ nautical miles, the wave period is calculated to be

$$T \simeq 4.4 \text{ minutes},$$

which could mean that the edgewave struck Valdez (midway between the north and south shores of Port Valdez) within 1.1 minute of the start of the earthquake. As an edgewave it would have had the directional effect of sweeping the *Chena* southeast onto the collapsing docks and causing the extraordinary flow of water which carried away the south pier and the cannery from the North Arm.

The returning edgewave, which would have come about 2.2 minutes later, presumably filled the boat harbor, freed the *Chena*, and caused the northward flow, which may have carried small boats and debris in that direction, as observed by Sturgis.

There would then have followed the returning nodal flow in a southeast direction which could account for the jetlike evacuation of the *Chena* and, upon the suction-like withdrawal of the water table, the sudden failure of the sea bed as envisioned in Figure 86*f*. There is no particular report that the wall of water observed by Sturgis and Dunning ever hit the Valdez waterfront as a big destroying wave.

The origin of the third big wave that hit the town and came in approximately 10 minutes after the earthquake ceased is not known with certainty. The earliest interpretation was that it was one of the waves generated by slides at the Valdez waterfront, returned as a reflection from the western end of Port Valdez. The travel time for a long wave to propagate to the Valdez Narrows and return, however, would be 17.8 minutes, according to equation (10i), and this could not explain the observations. Later investigations emphasized the idea that the wave was generated by a major slide along the steep shore of the west end of Port Valdez (Plafker and Mayo, 1965). The travel time would then accord with equation (10ii)—namely, 9.8 minutes—and meet the situation shown in Figure 84.

Figure 96 shows that the waves generated at the west end must have been singularly powerful to have produced the tremendous runup recorded at different places (Plafker and Mayo, 1965). From this it is assumed that there were two submarine slides at the mouth of Shoup Bay, one near the abandoned Cliff Mine and one on the west side of the entrance of Shoup Bay. Shoup Bay occupies a hanging valley whose floor is more than 500 ft above the bottom of Port Valdez. The Shoup Glacier has left a high deposit of glacial debris that blocks the entrance to Shoup Bay. This material is presumed to have slumped. The first wave obliterated all the sizable buildings at the Cliff Mine site, left

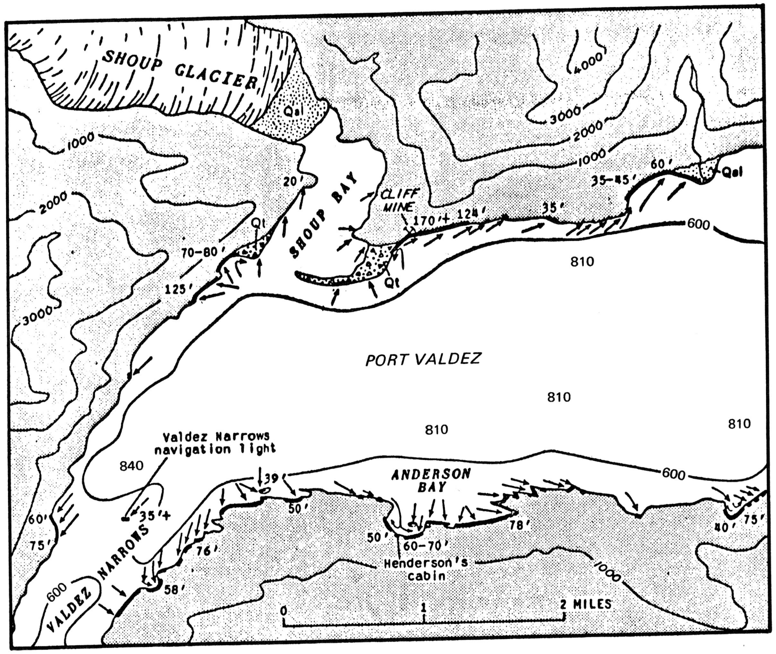


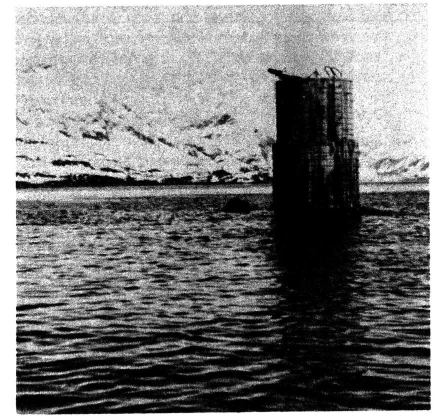
FIGURE 96 Heights and inferred directions of local waves in the western part of Port Valdez. Heavy line along shore indicates distribution of damage; numeral is measured maximum runup. Shaded pattern, bedrock; dotted pattern, alluvium and intertidal mud; triangular pattern, terminal moraine of the Shoup Glacier. Contour interval on land is 1,000 ft; submarine contour interval is 600 ft. (From Plafker and Mayo, 1965).

driftwood at 170 ft above lower low water, and splashed silt and sand up to elevations of 220 ft. From the vicinity of Cliff Mine it moved east and probably south with gradually diminishing height.

The wave generated on the west side of Shoup Bay apparently rushed up to an elevation of 125 ft near its inferred source (Plafker and Mayo, 1965).

These two slide-generated waves caused considerable runup on both the west and south sides of Port Valdez, as is evident in Figure 96. It is believed that the large wave that hit Valdez about 10 minutes after the earthquake (Figure 84) was one of these waves. Further parts of the waves propagated throughout the Valdez Narrows, destroying the navigation light on top of the lighthouse 35 ft above lower low water (Figures 96 and 97).

The fishing boat *Falcon* at Potato Point (see Figure 79), near the mouth of the Narrows, was lucky to survive this wave. As recorded by Chance (1966), two crew members were on shore when the earthquake started. When they headed in their skiff for the anchored 30-ft boat, a drawdown of the water suddenly left the skiff beached while the fishing boat disappeared out of sight behind a break in the bottom of the Narrows. Within moments, turbulent water rose again and flushed the skiff out of control. It appears to have been extraordinary luck for the boatmen that their skiff came sufficiently close to the *Falcon* that they could dive across and pull themselves out of the water onto the larger boat. After they had started the engine, they saw a huge wave (approximately 5 minutes after the earthquake) building up behind the lighthouse and heading out of the Narrows. It overtopped the lighthouse about 2 minutes later. They estimated this wave to have been 35 to 50 ft high in the Narrows and filled with mud, timber, and other debris. The *Falcon* was overtaken by the wave just outside the Narrows, but by then, fortunately, the wave had spread laterally into Jack Bay and Valdez Arm (Figure 79) and attenuated in height, thus enabling the boat to ride over the top. Later they saw many large waves, one right after the other, in the vicinity of the mouth of the Narrows and Jack Bay (Chance, 1966).



Henry Coulter

FIGURE 97 Concrete pylon of the navigation light located at the entrance to Port Valdez (for location see Figures 79 and 96). The light was destroyed by a huge wave that passed southward out of Valdez Narrows. Steel reinforcing rods at an elevation of about 37 ft above MLLW were bent in the direction of flow.

It is believed that Valdez (Figure 84) was subject at about this time to a combination of successive waves which were probably the fundamental and binodal seiches for Port Valdez, embodying the periods of 17.8 and 9.8 minutes [equation (10)]. Since the fundamental period for Port Valdez is about the same as the second-mode period (18 minutes for the entire Valdez Arm, Narrows, and port basin system [equation (9)], we should expect that these waves gradually set the system rocking in its fundamental mode of about 39 minutes. Figure 84 also expresses our belief that the first crest of the main tsunami, generated at the mouth of Prince William Sound, would have reached Valdez within about 30 minutes with rather insignificant amplitude. However, the development of oscillations from within and from without the embayment may be assumed to have developed a strong system of beat oscillations (suggested in Figure 84). The fundamental tsunami wave on the shelf, meanwhile, in tune with the fundamental period ($T \simeq 110$ minutes) of Prince William Sound, may be presumed to have built up the amplitude of oscillations (of about this period) which penetrated into the Valdez embayment. These conditions are revealed in the marigram, which has been constructed basically from eyewitness observations of the later waves, but with a foreknowledge of the probable oscillating characteristics of the regime.

After the first 25 minutes, the waves reaching Valdez on the low tide were not high enough to draw special attention and presumably failed to reach even normal high-tide level. As the tide rose, however, the oscillations in the Sound increased in amplitude, and Valdez faced further destruction (Figure 84).

Two very large waves reached Valdez on the high tide during the night. There is some discrepancy between reports as to their arrival times (see, for example, Berg and others, 1971; Chance, 1966; Coulter and Migliaccio, 1966; Migliaccio, 1964; Dunning and Gilson, personal interview, 1966). The reported crest times for the first wave vary from 22:30 AST to midnight, and for the second wave from 00:30 to 01:45. However, the most likely times of occurrence of the waves' crests are 23:45 and 01:35, as suggested in Figure 84.

The damaging wave that came in like a fast-moving tide at about 23:45 and reached as far as Hobart Street (see Figure 81) was reported to have been 2½ ft deep in Valdez Hotel.

Water from the waves that came in at about 01:35 was 5 to 6 ft deep in buildings along McKinley Street and 2 ft on Hobart Street. Although it was not a smashing wave, it evidently advanced and receded with considerable speed, because the high-water marks left by it on buildings were in most cases higher outside than inside the buildings. The reason for this is suggested in Figure 84, which supposes that peak level represented the combination of two waves, one of approximately a 2-hour period and the second of about a 40-minute period, representing the primary oscillations for Prince William Sound and the Valdez embayment, respectively. In terms of height, each constituent appears to have had an amplitude of about 5 ft.

It is not possible to differentiate in detail the runup for each particular wave. The last wave caused the highest runup, and from water marks it has been possible to trace approximately the runup within the city. The runup distribution was sporadic, and the many apparently anomalous effects reported can generally be explained by the existence of high snow berms and a deep snow cover, which channeled the water and restricted its distribution (Coulter and Migliaccio, 1966).

Figure 98 contains our interpretation of the runup levels attained by the highest waves. This is based on aerial photographs, careful examination of ground photographs, and

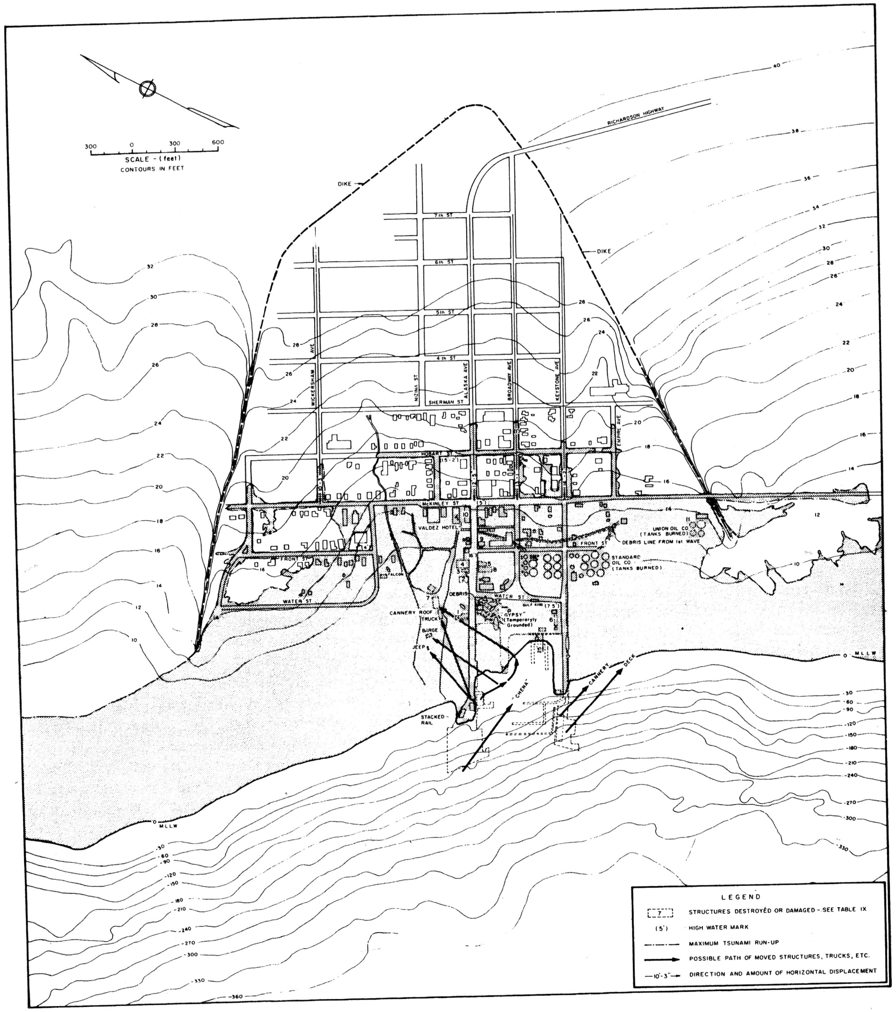


FIGURE 98 Plan of Valdez after the earthquake and tsunami, showing postearthquake contours and extent of inundation.

consideration of eyewitness accounts. Contours of land level in this figure, referenced to MLLW, are based on a preearthquake survey in 1953 undertaken by Thomas Bourne Associates of Alaska, Inc., Anchorage, for the Alaska Public Works Division. They have been adjusted for a regional subsidence of 1 ft at Fifth Street in Valdez and for proportionally larger subsidences approaching the waterfront, based on postearthquake observations of buildings at the waterfront by Kajiura and Kawasumi (Berg and others, 1971; Berg, personal communication, 1966). Contours check well for consistency with water-level measurements on numerous buildings throughout the town and with our observations in 1966.

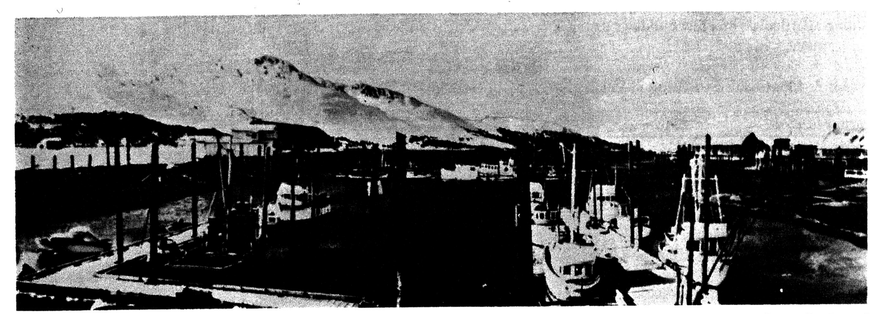
Before the above-mentioned highest waves, there was other wave activity throughout the whole evening. At about 20:00 AST a lifeboat from the *Chena* came in and was able to tie up at the ferry slip (Figure 98). Sometime later (about 20:15), this boat was found high and dry where the water had receded. While efforts were being made to launch it, the boat was floated free again by an incoming wave and was able to return to the *Chena* (Bracken, 1964). It appears that at or around 20:30 the *Falcon* returned from its sensational experience in the Valdez Narrows and tied up at the ferry slip. By 21:00, withdrawal of water left the *Falcon* beached at this point. Then, at about 21:30 (Chance, 1966) another higher wave reached as far as Water Street on Alaska Avenue (Figure 98). This wave, according to Bracken (1964), was like a fast-rising tide which he could only evade by walking rapidly ahead of it. Still another, but a lesser wave, rolled in at about 22:15 and apparently started a fire at the Union Oil Company tanks (Bracken, 1964; Chance, 1966; Gilson, personal interview, 1966). The large yacht *Gypsy* at this time was lodged alongside the ferry slip and, according to Bracken, had an open seam near her keel. In the later waves of that night she was to become a total loss. The *Chena* sighted her as she was sinking far out in Port Valdez; by dawn only her cabin was floating. (Bracken, 1964).

TSUNAMI WAVE DAMAGE AT VALDEZ

Most of the damage at the Valdez waterfront was caused by the submarine landslides, while the principal cause of damage away from the waterfront was ground breakage. Approximately 40 percent of the homes and most of the larger commercial buildings in Valdez were seriously damaged by ground heaving and fissures extending under or near them.

The slides caused the disappearance of the two docks with their warehouses and canneries of the breakwater protecting the small-boat harbor (compare Figures 99 and 100).

The whole town subsided because of the compaction of the deltaic materials during the tremors. The subsidence was largest at the waterfront area, gradually decreasing away from the shore. Figures 81 and 98 may be compared for post- and preearthquake contours in the waterfront area. Water Street subsided as much as 9 ft near Alaska Avenue. This has a bearing on the wave damage in the waterfront area and is symptomatic of the disappearance of the docks. In addition to the subsidence, the waterfront area moved laterally. The concrete bulkhead at the head of the small-boat harbor apparently moved 25 ft seaward (Coulter and Migliaccio, 1966; Wilson and Tørum, 1968; see also Figure 6, p. 131).



Loren St. Amand

FIGURE 99 Composite view (looking seaward) of the small-boat harbor and docks at Valdez just a day or two before the earthquake. The ferry slip shows at right center field with the cannery behind it. Near the entrance on the right are the North Arm docks and warehouses where the *Chena* was moored. In left center field is the cannery on the South Arm. The *Gypsy* may be seen in the background just to the left of the closest pile in center foreground (compare with Figure 81).

FIGURE 100 Aerial view of the Valdez waterfront after the earthquake and tsunami. Compare with Figures 82 and 98.

U.S. Army

The initial waves caused damage to the whole waterfront and the downtown area as far as the runup line shown in Figure 98. A wave, presumably the one that came in about 2½ minutes after the earthquake started, damaged almost all the boats and boat floats in the small-boat harbor. Many of the boats were beached temporarily and were washed into the bay by the higher waves later in the evening.

This wave also destroyed three of four buildings at the head of the small-boat harbor and another building along Alaska Avenue (see Figures 85 and 101). The buildings, like most of those in Valdez, were light wooden-frame buildings. Particulars of a few buildings damaged or destroyed are given in Table 9; their location is identified by number in Figure 98.

Some heavy trucks from the docks were also washed inland (see Figures 98 and 103). The roof of the cannery from the inner end of the north dock was partly sunk in mud flats northeastward of the North Arm (Figures 98, 100, 102, and 103).

One of the asphalt storage tanks at the Standard Oil Company tank farm was punctured during the earthquake, probably by floating debris. The escaping asphalt (Figure 104) contaminated a large area of Port Valdez. There was also gasoline leakage from the tanks, and at

TABLE 9 Identifiable Structures in Valdez Destroyed or Damaged in the Earthquake, March 1964

Structure	Type of Structure	Damage
1 Village Morgue Saloon	Wood frame	Destroyed by fire
2 Valdez Transfer Company (with residence of owner on second floor)	Wood frame	Fire damage first–wave damage later
3 Storage building used by Dieringer Chevron Station for machinery, equipment, etc.	Wood frame	Fire damage first–wave damage later
4 Dieringer Chevron Station	Concrete block or masonry	Wave damage
5 Jo's Place (café)	Wood frame	Fire damage
6 Marine Ventures	Wood frame with outer log covering	Freighter driven through building by waves caused initial collapse; subsequent waves disturbed debris.
7 Roof of cannery	Wood frame with sheet metal covering	Swept by waves from site
8 Beals' Hotel	Wood frame with sheet metal siding	Destroyed by fire
9 Club Café	Wood frame	Wave damage
10 State Highway Office, Valdez District Office	–	Building survived (destroyed by man)
11 Union Oil Tank Farm	Riveted steel tanks	Destroyed by fire

FIGURE 101 View east along Alaska Avenue.

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FIGURE 102 Eroded approach ramp to the North dock.

FIGURE 103 Cannery roof and upturned truck on mud flats north of harbor.

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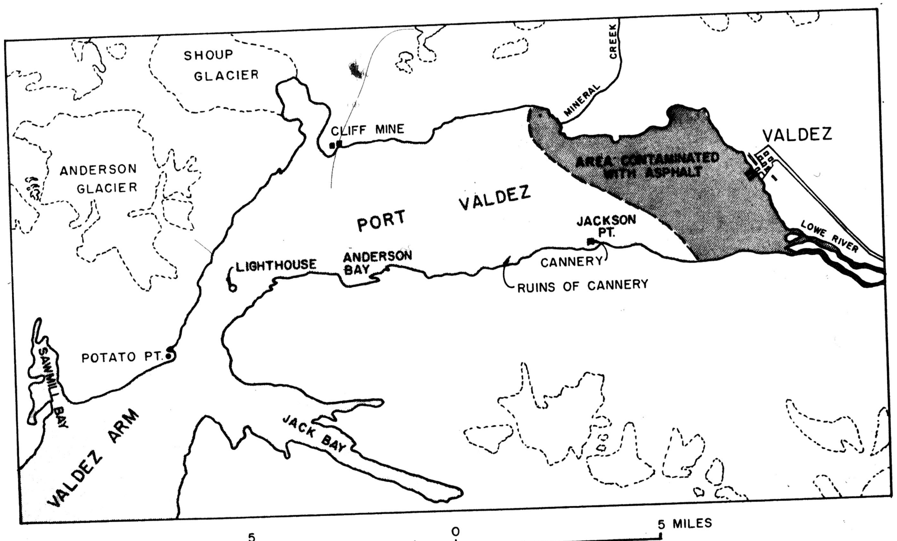

FIGURE 104 Map of Port Valdez, showing the area contaminated by asphalt from damaged oil tank farm. (From F. MacNamara, 1964).

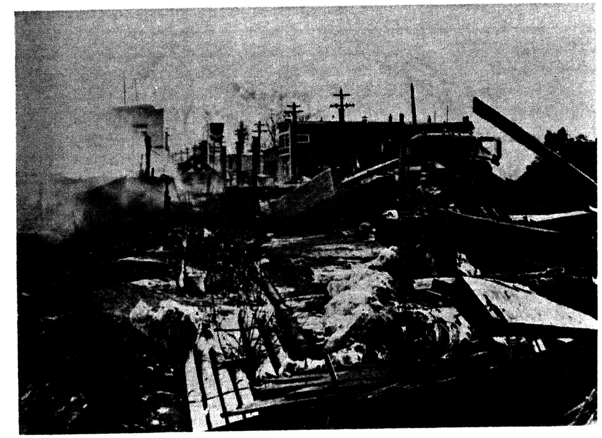

FIGURE 105 View east on Alaska Avenue before cleanup.

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FIGURE 106 View south on Water Street.

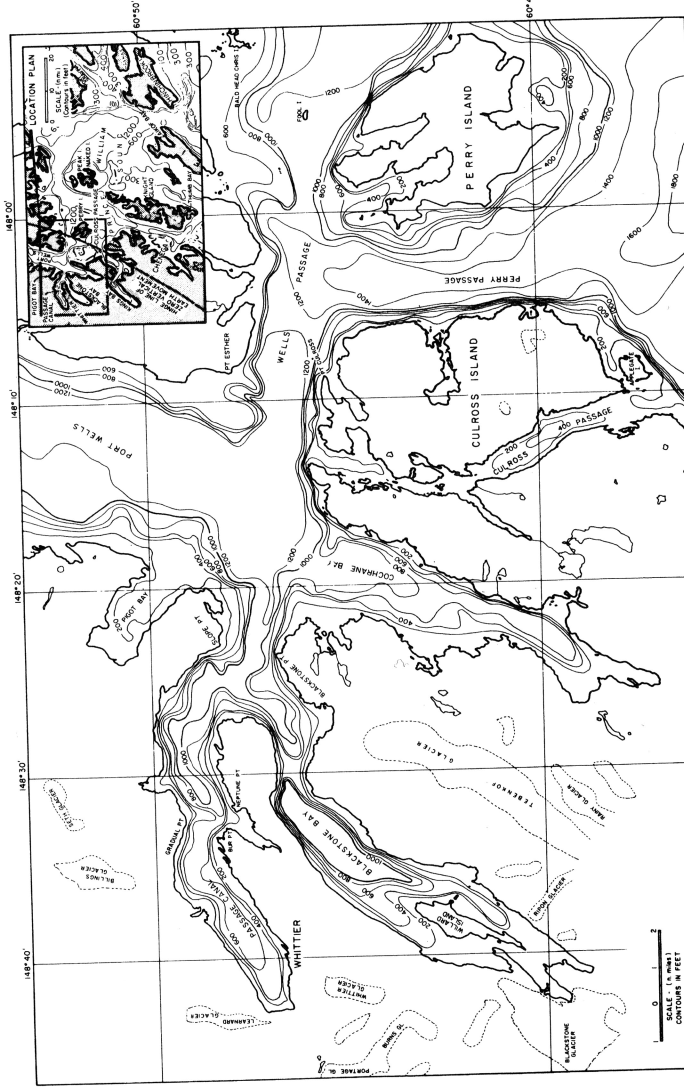

FIGURE 107 Bathymetry of Port Wells and tributary fiords, including Passage Canal and Whittier.

about 22:15 AST on the day of the earthquake, the Standard Oil tanks caught fire, probably by electric wire short-circuiting caused by water. Shortly afterward, the Union Oil tank farm also caught fire (Bracken, 1964).

The high waves that came in at about 23:45 and 01:35 during the night apparently had no smashing effects. However, they refloated boats and debris; some of the wooden structures were also floated free but were apparently not moved very much. These two waves were responsible for most of the wetting damage to buildings, homes, merchandise, and supplies in the commercial establishments along McKinley Street and west of it. The water was heavily silt-laden, and large volumes of silt were deposited in and around buildings. The backwash of the last wave had a strong current, and debris and beached boats were washed out into the bay. Some of the general melee on the waterfront is well illustrated in Figures 105 and 106.

At Jackson Point, a cannery was swept off its foundation by a wave that rushed up 32 ft. Parts of the cannery were afterward found floating a couple of miles west of Jackson Point (see Figure 104).

An inhabited cabin in Anderson Bay was completely swept away by the waves generated in the Cliff Mine area.

According to Spaeth and Berkman (1967), 31 persons lost their lives at Valdez as a result of the earthquake and tsunami, the highest number of fatalities of any community in Alaska. It has been stated that, if the earthquake had occurred just half an hour earlier while the dock was still crowded with townspeople, the death toll would have been many times greater.

The estimate of property damage caused by the waves is $12,568,000, of which $8,453,000 was privately owned and $4,115,000 publicly owned (Spaeth and Berkman, 1967, and this volume). Relative to population, Valdez suffered more acutely than Seward, although damage losses at the latter place were higher.

TSUNAMI WAVES AT WHITTIER

Whittier, located at the western end of Passage Canal (Figure 107), was built in 1942-1943 to provide a second all-weather terminal in addition to Seward, for The Alaska Railroad. The town is owned and operated by the U.S. Government, specifically by The Alaska Railroad of the Department of the Interior; some of the land has been leased to private enterprises. At the time of the earthquake 70 people were living in Whittier, and 13 of them lost their lives as a result of the earthquake.

Figure 107 shows that Port Wells and its tributary fiords are a relatively deep and intricate system of connecting basins whose oscillating characteristics are likely to be complex. No attempt has been made to determine these characteristics. Whittier lies on the northwest side of the hinge line of zero vertical earth movement running through Prince William Sound (Figure 107, inset).

The delta upon which Whittier rests and also the southern part of the delta at the head of Passage Canal (Figure 108) are formed by unconsolidated deposits consisting of outwash and stream gravels. They are composed predominantly of coarse, subangular-to-subrounded gravel in a matrix of coarse sand (Kachadoorian, 1965, and Geology volume). Whittier's rather limited area on the fan delta is well illustrated in Figure 109.

The extensive damage suffered by Whittier was caused by (1) seismic shock, (2) submarine landslides, (3) waves, (4) fracturing and compaction of fill and unconsolidated sediments, (5) fire, and (6) a 5.3-ft subsidence of the land masses. The port was rendered totally inoperative by the earthquake and tsunamis and for a time was without rail communication (Eckel, 1967).

The destructive waves that lashed Whittier were undoubtedly generated by submarine landslides (Figure 110). Data on which to base an inferred marigram (Figure 111) were extremely limited because there were not many eyewitnesses. Some of those who watched the water (see Bryant, 1964b; Kachadoorian, 1965, and Geology volume; Chance, 1966) reported that approximately 1 minute after the earthquake started, the water in Passage Canal in the vicinity of the town rose rapidly to about 30 ft above tide level for that time, which was about 1 ft above MLLW. The water was glassy and did not contain any debris.

The water immediately receded and the "glassy hump" apparently did not encroach on the shore as a wave above normal maximum tide level. The first damaging wave struck Whittier at 1 to 1.5 minutes after the glassy hump occurred. This wave was muddy and contained much debris which radiated from a boil halfway across Passage Canal. The crest of the wave was 34 ft above water level when it reached The Alaska Railroad depot (see Figures 110 and 112). It struck the depot 8 to 10 ft above ground level.

About ½ to 1 minute after the first damaging wave (second rise of water), another damaging wave rolled in on Whittier. Its crest reached about 30 ft above tide level at The Alaska Railroad depot (Bryant, 1964a).

No waves other than the two that struck during the earthquake were reported. Here it is interesting to note that the high waves which reached Cordova and Valdez late in the evening and which also had been reported in Pigot Bay, close to Whittier (see Figure 78*d*), apparently were not felt or noticed at Whittier. The reason for this is not known and will probably remain unexplained as one of many apparently anomalous wave patterns within Prince William Sound during and after the earthquake.

There were apparently no eyewitnesses to the waves in parts of the town other than at The Alaska Railroad depot.