EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964 AT VALDEZ, ALASKA

The town of Valdez, part of the Valdez outwash delta, the Valdez Glacier, and the Chugach Mountains. Photograph by Bradford Washburn, 1937.

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
EFFECTS ON COMMUNITIES

Effects of the Earthquake Of March 27, 1964 At Valdez, Alaska

By HENRY W. COULTER and RALPH R. MIGLIACCIO

A description of the massive landslides, destructive sea waves, landmass displacements, and extensive ground breakage due to the earthquake at Valdez

GEOLOGICAL SURVEY PROFESSIONAL PAPER 542-C

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the Alaska earthquake of March 27, 1964, in a series of six professional papers. Professional Paper 542 describes the effects of the earthquake on communities: Anchorage (542–A), Whittier (542–B), Valdez (542–C); other chapters are in preparation on Homer, Seward, and Kodiak, and on several smaller communities. Succeeding professional papers will describe the regional effects of the earthquake; the effects on the hydrologic regimen; the effects on transportation, communications, and utilities; and the history of the field investigations and reconstruction effort.

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EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964 AT VALDEZ, ALASKA

By Henry W. Coulter, U.S. Geological Survey, and Ralph R. Migliaccio, Alaska Department of Highways

ABSTRACT

Valdez is situated on the seaward edge of a large outwash delta composed of a thick section of saturated silty sand and gravel. The earthqake of March 27, 1964, triggered a massive submarine slide, involving approximately 98 million cubic yards of material, that destroyed the harbor facilities and nearshore installations. Waves generated by the slide and subsequent strong seiches did additional damage in the downtown area. Stresses generated by the seismic shocks and the slide developed an extensive system of fissures throughout the unconsolidated deposits at the head of the fiord. These fissures plus the shocks caused structural damage to many of the buildings in Valdez and destroyed the sewer and water systems. Removal of support from the face of the delta by submarine sliding allowed some of the material to move seaward and caused parts of the shore area to subside below high-tide level.

A site for relocating the town of Valdez has been designated. It is situated on the Mineral Creek fan—an area underlain by coarse alluvial gravel. This relocation site is protected from sea waves by a series of bedrock ridges and islands that also provide a resistant buttress retaining and protecting the toe of the fan from danger of sliding or slumping. The absence of evidence of ground breakage on the Mineral Creek fan indicates that the coarse subsoils at the relocation site react favorably under seismic conditions.

INTRODUCTION

At 5:36 p.m., March 27, 1964 (Alaska standard time), a great earthquake of magnitude 8.4 to 8.6 on the Richter scale, centered at lat 61.05° N. and long 147.50° W. approximately 45 miles west of Valdez, rocked south-central Alaska (Grantz, Plafker, and Kachadoorian, 1964). The loss of life and damage at Valdez resulting from submarine slides, sea waves, and ground breakage (pl. 1) coincident upon this event were so great, and the prognosis of recurrence of such effects during possible future seismic activity so forbidding, that the decision was made to move the entire community to a safer location. The results of the geologic investigations which supplied background information for this decision are presented here. The new site chosen is about 4 miles northwest, on Mineral Creek fan—a more stable area that also has natural protection from sea waves.

Port Valdez, the northeasternmost extension of Prince William Sound, is a narrow steep-walled glaciated reentrant or fiord in the Chugach Mountains (fig. 1). The fiord trends east-west and is approximately 14 miles long and 3 miles wide. The axial alinement of Port Valdez is controlled by a strongly developed, steeply dipping foliation in the metasedimentary rocks of the Valdez Group of Late Cretaceous(?) age. Alinement of the tributary valleys is controlled by a prominent north-south joint set. The Port Valdez depression extends laterally into four subsidiary valleys—Valdez Narrows to the southwest, Shoup Bay to the northwest, Valdez Glacier valley to the northeast, and Lowe River valley and Heiden Canyon to the east (frontispiece and fig. 20.) Elsewhere Port Valdez is hemmed in by steep mountain walls rising to altitudes of 3,000 to more than 5,000 feet. Soundings in Port Valdez indicate that the high-angle subaerial slopes continue beneath the water and form a steep-sided flat-bottomed trough with maximum depths of more than 800 feet. The submarine topography shows irregularities similar to the subaerial glaciated landforms of Port Valdez, many elongate ridges displaying prominent stoss and lee morphology.

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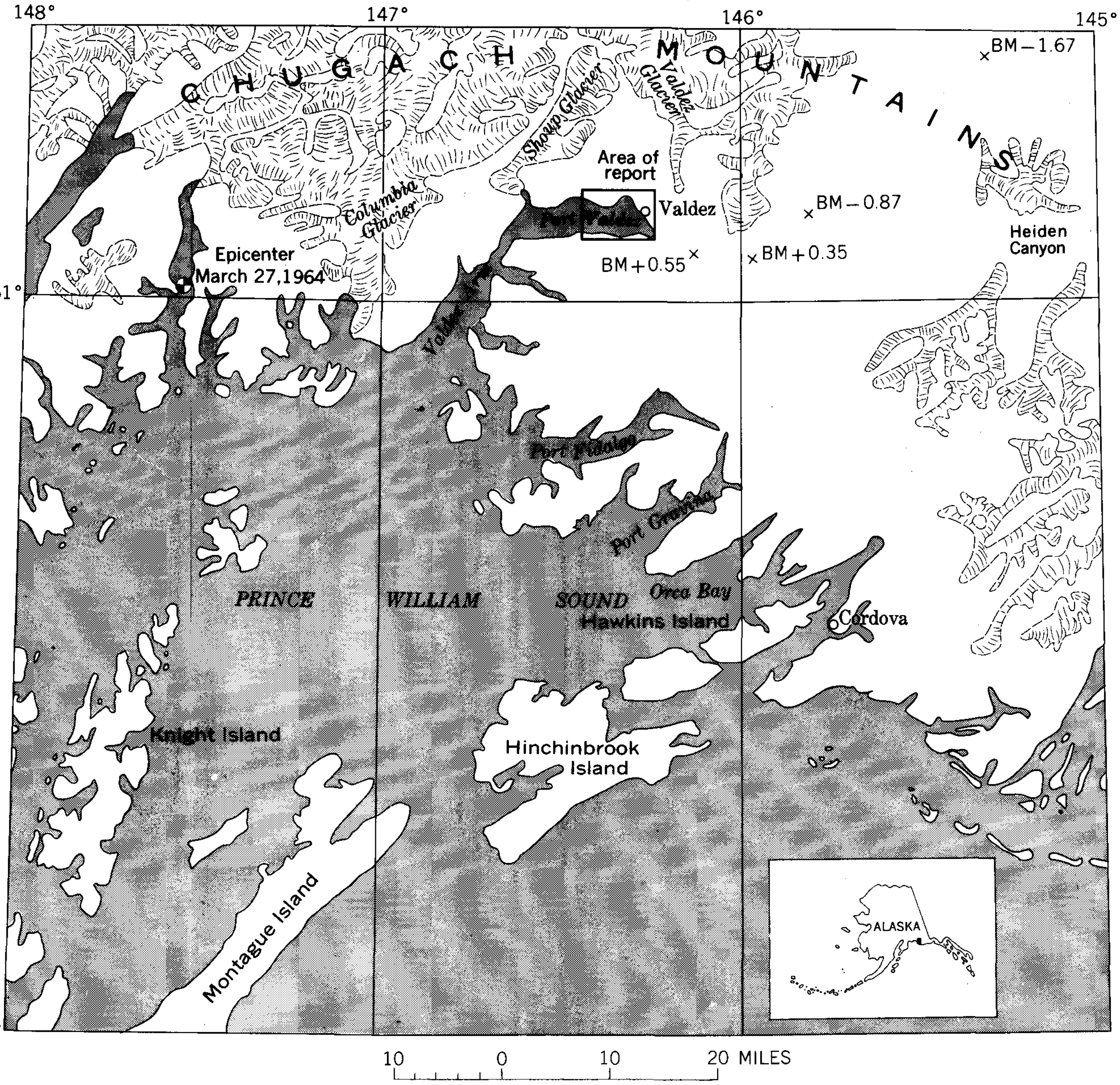


1.—Index map, Valdez area. Bench marks show change in altitude, in feet.

The eastern end of Port Valdez is being filled rapidly by an outwash delta supplied by material carried by the Lowe River, the Robe River, and the stream from Valdez Glacier. The subaerial part of this delta slopes westward from approximately 300 feet at the toe of Valdez Glacier to sea level in a distance of approximately 4 miles. The town of Valdez is situated on the seaward edge of this outwash delta.

The geographic importance of Valdez stems from the fact that it is the farthest north ice-free seaport in Alaska and is the southern terminus of the Richardson Highway—the shortest and most direct route from tidewater to Fairbanks and interior Alaska. The principal industry is shipping, and Valdez is the home port of a modest commercial and sport fishing fleet. The population given for Valdez in the 1960 census is 555, but during the heaviest shipping season a maximum population of 1,000 is estimated by the Alaska Department of Health and Welfare (1964).

ACKNOWLEDGMENTS

Many individuals and organizations contributed time, effort, and information in support of this investigation. Mayor Bruce Woodford and the people of Valdez extended all possible assistance to us, as did the Fairbanks Committee for Alaska Earthquake Recovery through the agency of their representative, Acting Valdez City Manager, Ed Martin. Ralph Taylor, American Institute of Architects, of the Fairbanks Committee, supplied valuable data on the nature and extent of damage to buildings. District Engineer Nels Kjelstad, Assistant District Engineer William Whitnal, and the Valdez District staff of the Alaska Department of Highways were most cooperative. Charles H. Clark, geologist, Alaska Department of Highways, prepared a detailed map of the fissure distribution within the city and supervised the waterfront drilling program, and Robert Felland and Gordon Brunton, geologists, Alaska Department of Highways, supervised the drilling program at the Mineral Creek townsite. Charles H. Blake, U.S. Army Corps of Engineers, supplied detailed information on the damage to sewer and water supply systems. The late Capt. F. J. Bryant, U.S. Coast and Geodetic Survey, supplied preliminary data on altitudes and harbor soundings, and R. M. Chapman, U.S. Geological Survey, made preliminary observations in Valdez on April 1 and 2, 1964, and supplied pertinent information.

GEOLOGIC SETTING

The distribution and nature of the deposits in the vicinity of Valdez are shown on figure 2. For purposes of this discussion, they are most conveniently subdivided into one bedrock unit and three depositional complexes of unconsolidated sediments.

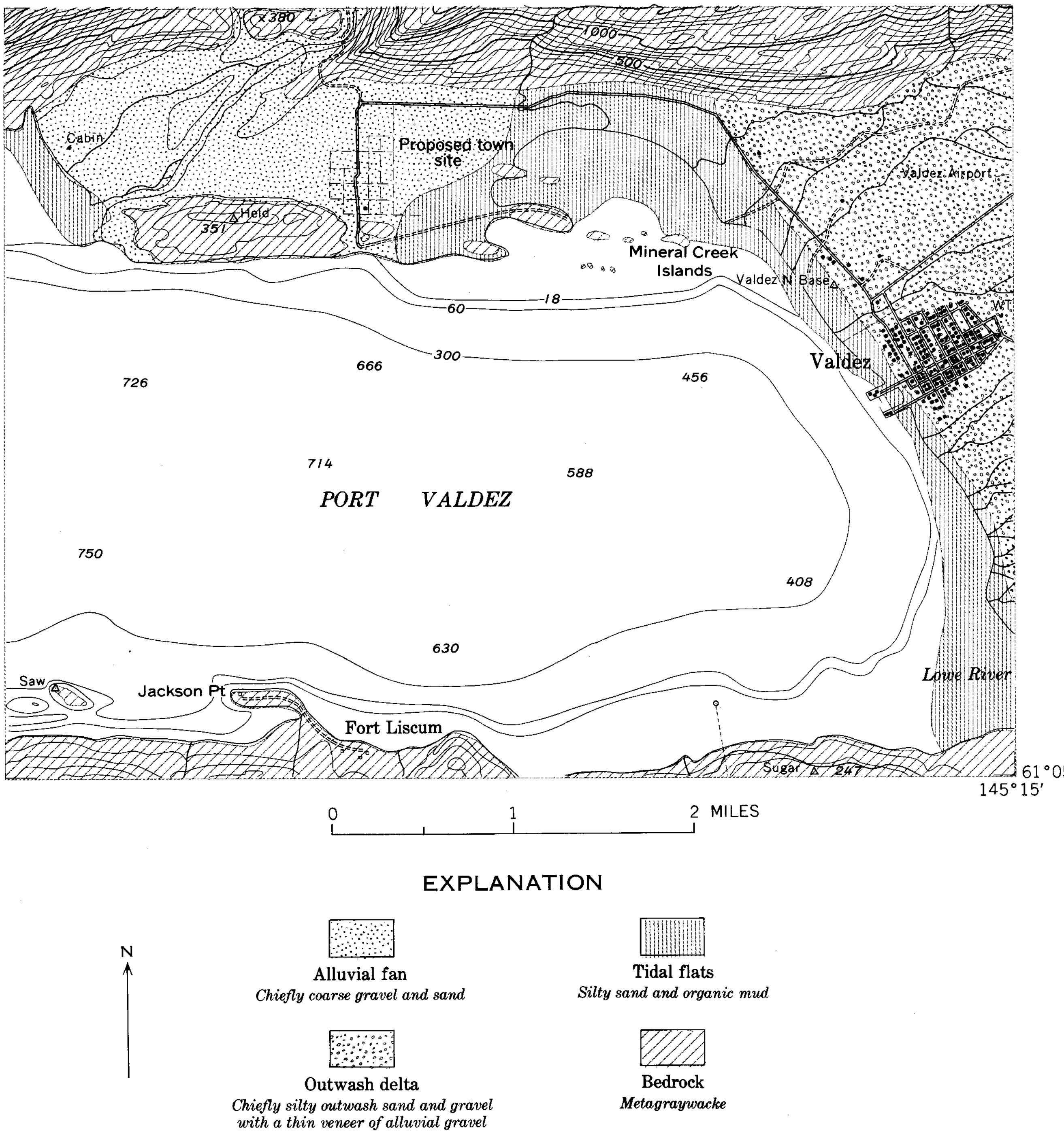
Port Valdez lies within the outcrop belt of the Valdez Group of Late Cretaceous(?) age. These rocks have been described by Moffit (1954) as: "Interbedded slate and graywacke prevailingly in thick beds. Includes minor amounts of argillite, arkosic sandstone, and conglomerate. Closely folded and subschistose to schistose."

In the vicinity of Valdez, the rocks of the Valdez Group have a well-developed foliation which strikes east-west and dips steeply to the north. They are also strongly jointed, the most prominent joint set being oriented perpendicular to the foliation. These two structural trends in the bedrock determine the topographic grain in the region. The southern flank of the Chugach Range, underlain by rocks of the Valdez Group, has been subjected to repeated episodes of intense glacial erosion, which has imposed a topography characteristic of ice-scoured areas on the entire region. It is into and against these glaciated bedrock landforms that the recent sediments have been, and are being, deposited.

At the eastern end of the Port Valdez fiord, the outwash plains of the Robe River, the Lowe River, and the stream from Valdez Glacier coalesce to form a broad delta, the surface of the delta slopes westward from approximately 300 feet msl at the toe of Valdez Glacier to sea level in a distance of approximately 4 miles. Although the deepest well in this outwash delta penetrates only to a depth of 250 feet, the configuration of the bedrock valley and the depth of water in Port Valdez suggest that this section of unconsolidated deposits may be as much as 600 feet thick near the shoreline.

The prequake and postquake configurations of the seaward face of this deltaic complex are shown on plate 2. Subsurface investigations by the Alaska Department of Highways indicate that the delta is composed of a thick section of poorly consolidated silt, fine sand, and gravel (pl. 3 and table 1). The silt and fine sand occur as beds and stringers within the section and also are widely disseminated throughout the coarser fractions. The surficial beds of stream-deposited outwash gravels dip gently to the southwest, but more steeply dipping deltaic foreset beds probably occur at depth. The water table lies within a few feet of the surface throughout this outwash delta complex, so the entire section is saturated.

The Mineral Creek alluvial fan lies approximately 4 miles northwest of the town of Valdez. It was deposited in an elongate depression between the main valley wall and a parallel outlying bedrock ridge that forms a series of ribs and islands along the north shore of Port Valdez (see figs. 20 and 21, p. C34). This bedrock ridge serves to confine and contain the Mineral Creek fan on the seaward side. The fan slopes from approximately 60 feet above msl at the mountain front to sea level. The braided flood plain of Mineral Creek occupies the western margin of the fan, and the eastern margin and a short segment along the southwest shore are covered by tidal-flat deposits.



2.—Ground conditions at Valdez.

TABLE 1.—*Grain-size analyses of test-boring samples from the Valdez delta*

[*LL*, liquid limit; *PL*, plastic limit; NV, no value; NP, nonplastic]

Boring	Sample	Sieve analysis, percent passing—												Atterberg limits		Moisture content (percent)	Specific gravity
		3 in.	2 in.	1¼ in.	1 in.	¾ in.	½ in.	No. 4	No. 10	No. 40	No. 200	0.02 mm	0.005 mm	*LL*	*PL*		
1	1	100	100	100	100	100	100	100	94	64	36.2	0	0	16	NP	9.7	----------
	2	100	100	100	100	100	100	100	100	100	96.1	0	0	21	NP	17.7	----------
	3	100	100	100	100	100	100	100	24	12	4.5	0	0	NV	NP	12.6	----------
	4	100	100	100	100	100	100	100	56	19	6.0	0	0	NV	NP	12.4	----------
	5	100	100	100	100	100	100	100	65	27	7.2	0	0	NV	NP	12.7	----------
	6	100	100	100	100	100	100	100	63	29	7.7	0	0	NV	NP	13.4	----------
	7	100	100	100	100	100	100	100	75	40	14.0	0	0	NV	NP	14.0	2.80
	8	100	100	100	100	100	100	100	78	46	14.3	0	0	NV	NP	16.3	2.73
	9	100	100	100	100	100	100	100	79	54	19.2	0	0	NV	NP	17.5	2.74
	10	100	100	100	100	100	100	100	74	36	8.4	0	0	NV	NP	14.1	2.73
	11	100	100	100	100	100	100	100	74	34	8.9	0	0	NV	NP	14.7	2.73
	12	100	100	100	100	100	100	100	77	23	5.6	0	0	NV	NP	17.5	----------
	13	100	100	100	100	100	100	100	71	27	7.0	0	0	NV	NP	13.8	----------
	14	100	100	100	100	100	100	100	51	26	9.6	0	0	NV	NP	11.2	----------
	15	100	100	100	100	100	100	100	4.0	3.0	1.8	0	0	--------	--------	19.6	----------
	16	100	100	100	100	100	100	100	17	8	3.3	0	0	--------	--------	7.9	----------
2	1	100	100	100	100	100	100	100	44	21	10.1	0	0	NV	NP	8.4	----------
	2	100	100	100	100	100	100	100	41	20	9.3	0	0	NV	NP	12.2	----------
	3	100	100	100	100	100	100	100	2.0	1.0	.8	0	0	--------	--------	15.0	----------
	4	100	100	100	100	100	100	100	42	18	6.7	0	0	NV	NP	14.4	----------
	5	100	100	100	100	100	100	100	76	17	3.4	0	0	NV	NP	21.3	----------
	6	100	100	100	100	100	100	100	77	37	6.8	0	0	NV	NP	16.7	----------
	7	100	100	100	100	100	100	100	61	25	8.5	0	0	NV	NP	12.1	----------
	8	100	100	100	100	100	100	100	80	43	7.9	0	0	NV	NP	16.9	2.74
	9	100	100	100	100	100	100	100	77	41	7.4	0	0	NV	NP	18.0	2.73
	10	100	100	100	100	100	100	100	83	55	14.0	0	0	NV	NP	18.7	2.73
	11	100	100	100	100	100	100	100	81	58	19.0	0	0	25	NP	14.6	2.75
	12	100	100	100	100	100	100	100	63	28	7.7	0	0	NV	NP	12.2	2.71
	13	100	100	100	100	100	100	100	75	39	7.7	0	0	NV	NP	14.5	----------
	14	100	100	100	100	100	100	100	71	33	6.7	0	0	NV	NP	14.5	----------
3	1	100	100	100	100	100	100	100	46	18	6.4	0	0	NV	NP	10.7	----------
	2	100	100	100	100	100	100	100	45	15	7.6	0	0	NV	NP	13.9	----------
	3	100	100	100	100	100	100	100	37	17	7.5	0	0	--------	--------	12.9	----------
	4	100	100	100	100	100	100	100	54	24	7.2	0	0	NV	NP	11.2	----------
	5	100	100	100	100	100	100	100	50	15	4.6	0	0	NV	NP	11.6	----------
	6	100	100	100	100	100	100	100	64	26	7.0	0	0	NV	NP	13.5	----------
	7	100	100	100	100	100	100	100	92	66	11.2	0	0	--------	--------	24.4	----------
	8	100	100	100	100	100	100	100	68	29	6.3	0	0	NV	NP	13.9	----------
	9	100	100	100	100	100	100	100	70	36	9.8	0	0	NV	NP	12.9	----------
	10	100	100	100	100	100	100	100	58	28	8.6	0	0	NV	NP	13.8	----------
	11	100	100	100	100	100	100	100	75	36	7.1	0	0	NV	NP	15.0	----------
	12	100	100	100	100	100	100	100	78	45	14.2	0	0	NV	NP	12.3	----------
	13	100	100	100	100	100	100	100	54	27	9.9	0	0	NV	NP	13.4	----------
	14	100	100	100	100	100	100	100	73	42	12.1	0	0	NV	NP	12.1	----------
	15	100	100	100	100	100	100	100	62	46	18.1	0	0	NV	NP	9.2	----------
	16	100	100	100	100	100	100	100	88	60	39.2	0	0	17	NP	15.0	----------
	17	100	100	100	100	100	100	100	80	43	14.2	0	0	NV	NP	11.6	----------
	18	100	100	100	100	100	100	100	73	32	5.6	0	0	NV	NP	14.3	----------
	19	100	100	100	100	100	100	100	99.7	99.4	84.2	36.8	18.5	18	18	23.0	----------
	20	100	100	100	100	100	100	100	80	51	16	8.1	3.6	NV	NP	11.3	----------
4	1	100	100	100	95	82	72	51	47	23	7.2	0	0	--------	--------	----------	2.76
	2	100	100	100	95	93	84	61	40	14	5.1	0	0	--------	--------	----------	2.73
	3	100	100	100	100	86	78	51	35	23	7.0	0	0	--------	--------	----------	----------
	4	100	100	100	100	81	74	59	37	11	3.3	0	0	--------	--------	----------	----------
5	1	100	100	100	100	73	71	62	54	30	8.0	0	0	--------	--------	----------	2.64
	2	100	100	100	100	80	67	42	26	12	5.6	0	0	--------	--------	----------	----------
	3	100	100	100	96	91	76	57	42	21	8.4	0	0	NV	NP	----------	2.68
	4	100	100	100	100	86	65	45	29	11	3.7	0	0	--------	--------	----------	----------
	5	100	100	100	84	82	72	55	39	18	8.0	0	0	--------	--------	----------	2.76
	6	100	100	100	100	97	83	61	42	19	8.2	0	0	NV	NP	----------	2.61
	7	100	100	100	100	97	88	67	50	22	4.3	0	0	NV	NP	----------	2.71
	8	100	100	100	100	100	100	95	90	56	26.1	0	0	NV	NP	----------	2.75
	9	100	100	100	100	100	99	91	83	57	14.4	0	0	NV	NP	----------	2.70
	10	100	100	100	96	96	91	77	63	28	2.6	0	0	NV	NP	----------	2.69
6	2	100	100	100	100	100	100	93	82	55	16	0	0	NV	NP	----------	2.68
	3	100	100	100	100	92	90	78	68	41	9.6	0	0	--------	--------	----------	2.74
	4	100	100	100	100	92	81	60	43	18	6.1	0	0	--------	--------	----------	2.68
	5	100	100	100	100	93	89	77	64	45	8.8	0	0	--------	--------	----------	2.70
	6	100	100	100	96	93	88	72	50	22	4.1	0	0	NV	NP	----------	2.68
	7	100	100	100	92	83	79	61	42	32	25.9	0	0	NV	NP	----------	2.63
	8	100	100	100	100	85	77	59	44	17	6.0	0	0	NV	NP	----------	2.80
	9	100	100	69	66	64	59	44	34	18	9.3	0	0	NV	NP	----------	2.65
7	1	100	100	100	100	100	100	100	84	72	42.4	24.6	10.2	NV	NP	18.0	2.69
	2	100	100	100	100	100	100	100	63	40	16.0	9.0	5.0	NV	NP	12.5	2.73
8	1	100	100	100	100	100	100	100	36	20	8.7	6.6	3.4	NV	NP	2.8	2.73
	2	100	100	100	100	100	100	100	56	31	15.7	11.0	5.6	NV	NP	13.2	2.67
	3	100	100	100	100	100	100	100	54	40	22.1	13.5	6.1	NV	NP	13.4	2.69
9	1	100	100	100	100	100	100	100	83	66	34.5	18.5	7.4	NV	NP	25.3	2.68
	2	100	100	100	100	100	100	100	95.4	86	52.7	23.6	8.8	NV	NP	26.2	2.73
	3	100	100	100	100	100	100	100	90.3	77	38.6	19.0	8.0	NV	NP	24.0	2.71
10	1	100	100	100	100	100	100	100	71	32	12.4	9.0	5.3	NV	NP	7.4	2.73

A comprehensive subsurface investigation was made of the central part of the Mineral Creek fan—the area selected for the new location of the town of Valdez. The investigation was initiated by the U.S. Geological Survey and the Alaska Department of Highways under the sponsorship of the Alaska State Housing Authority and the U.S. Army Corps of Engineers. Responsibility for the final phases of the investigation was assumed by Shannon and Wilson, Inc., of Seattle, Wash., under contract to the U.S. Army Engineer District, Anchorage, Alaska. Studies were made of 27 test pits ranging in depth from 7 to 12 feet, of 7 solid auger borings ranging in depth from 20 to 33 feet, and of 8 rotary borings ranging in depth from 37 to 121 feet.

The subsurface data show that the Mineral Creek alluvial fan is underlain by more than 100 feet of medium dense to very dense cobble gravel in a matrix of medium to coarse sand. Where exposed in the test pits, this gravel consists primarily of elongate tabular pebbles and cobbles of graywacke and some quartz showing a pronounced interlocking texture. The gravel is overlain by a thin layer of sand and silt and an organic mat 6 to 8 inches thick. In some places, along abandoned stream channels, the sand and silt may be as much as 4 feet thick, but the average thickness is about 1 foot. The complete results of the subsurface investigations are included in a report prepared by Shannon and Wilson, Inc. (1964).

Because of the relatively high tidal range (about 17 feet) and the large volume of finely comminuted rock particles carried by the glacial streams, broad tidal flats composed of silt, fine sand, and organic muds are being deposited at the seaward edge of the Valdez outwash delta and at the seaward edge of the Mineral Creek alluvial fan. These deposits are probably quite similar to, and in fact coextensive with, those being deposited as foreset beds along the face of the Valdez outwash delta.

At the time of the earthquake the ground at Valdez was frozen down to the water table, that is, to depths ranging from 4 to 6 feet below the surface; approximately 5 feet of snow lay on the ground. The predicted low tide for March 27, 1964, was −0.6 feet at 6:19 p.m., and the predicted high tide for March 28 was +12.4 feet at 12:42 a.m.

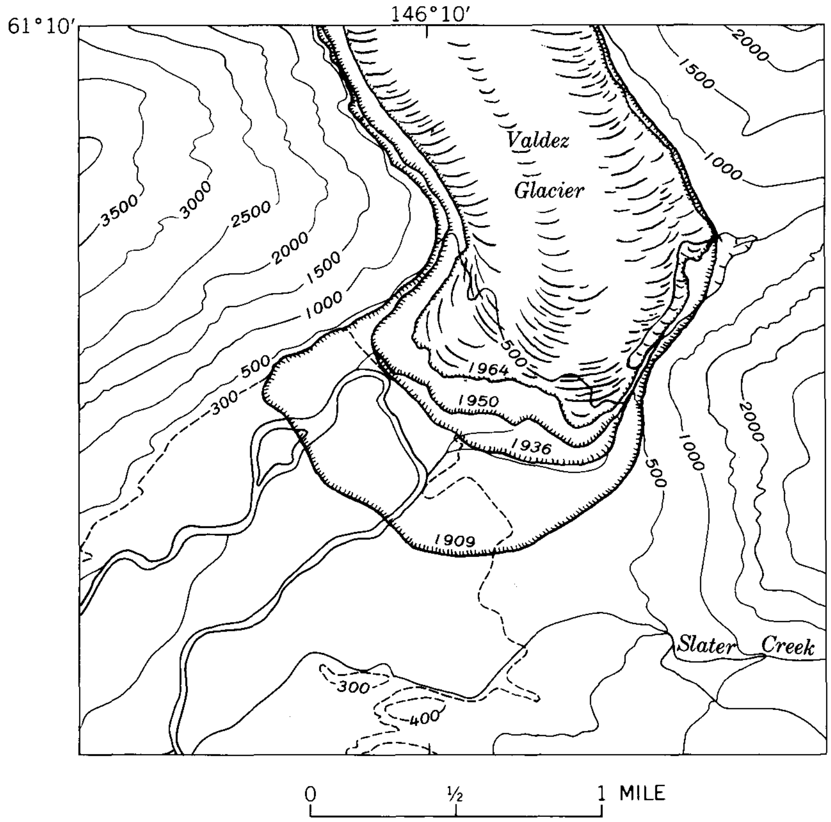
DRAINAGE

The town of Valdez has always been subject to intermittent flooding by the stream from Valdez Glacier (frontispiece). The first appraisal of this problem on record was made by Edward Gillete, an engineer in the party, led by Capt. W. R. Abercrombie, that surveyed the route from Valdez to Copper Center in 1899. Mr. Gillete wrote (in Abercrombie, 1900):

> Where the small town of Valdez has been hastily built there is danger at any time of having the buildings swept into the Bay by swift and quickly changing channels formed by the numerous streams flowing from uncertain and everchanging parts of the immense Valdez Glacier situated some 4 miles north of town.

At present the channel of the stream from Valdez Glacier is artificially confined by levees, and the town itself is protected by a dike. The continued retreat of the terminus of Valdez Glacier over the past 50 years (fig. 3) into the mouth of its bedrock canyon has made the problem of channel control progressively less difficult. However, an unusual advance of Valdez Glacier, such as occurred along the coast after the 1899 Yakutat earthquake (Tarr and Martin, 1914, p. 168–194), could change the present drainage system enough to bypass the levees and cause damage to the highway and town.

Three large and several smaller ice-dammed lakes along the flanks of Valdez Glacier constitute another potential flooding hazard to the highway and town. Possible development of new crevasse systems in the glacier, such as might be caused by an earthquake, could result in a sudden release of large volumes of water from one or more of these lakes and consequent flooding in the lower drainage system.



3.—Recorded positions of the terminus of Valdez Glacier since 1909.

SEISMIC HISTORY

Approximately 70 earthquakes of recorded or estimated magnitudes of 5 or greater have been reported from Valdez since 1898 (Davis and Echols, 1962; Heck, 1958). Of these, five in particular warrant special attention here because reinterpretation of the historical accounts suggests that these quakes were in fact accompanied by submarine landslides similar to the one triggered by the March 27th earthquake.

At the time of the Yakutat earthquake (Sept. 3, 1899), at Valdez the shaking was reportedly so strong "that men were made dizzy and could not stand, houses and forests were disturbed, and there were earthquake water waves in Port Valdez" (Tarr and Martin, 1912, p. 66).

There is also a fugitive report that a ship which had anchored off the mouth of the Lowe River in 40 feet of water in 1898 was unable to reach bottom with 200 feet of cable in the same spot late in the fall of 1899.

The second of the five relevant earthquakes took place on February 14, 1908, at 1:41 a.m. local time. It was variously reported by eyewitnesses to have lasted anywhere from 3 seconds to about 2 minutes. Several witnesses who were former residents of San Francisco stated that it seemed to be as violent as any of the shocks felt there April 18, 1906. The most interesting aspect of this quake, however, is the record of submarine cable breaks. These breaks were described and interpreted by Tarr and Martin (1912, p. 98):

> * * * both the Valdez-Sitka and Valdez-Seward cables were interrupted close to the city of Valdez, and well inside Valdez Narrows * * *. A short length of the cable was covered by the upheaval of the sea bottom, so that it had to be abandoned.
>
> A map by Lt. Paul Hurst, of the United States cableship *Burnside* (Pl. XXVII), shows the places where the cables were broken. The Valdez-Seward cable was broken in four places three-eighths to 1½ miles apart, while the Valdez-Sitka cable was broken in seven places five-eighths to seven-eighths mile apart. This later report

shows that the cables were buried not in one place but in three, the outermost being 1½ to 3 miles from shore in 700 feet of water.

The United States Geological Survey party, under the direction of U. S. Grant, which worked in the region in 1908, did not discover actual faults running ashore nor changes of level of the land; one stretch of coast, however, along Valdez Inlet near the cable breaks, was not examined by them. Prof. Grant says:

"While at Valdez I went out to the Valdez Glacier and also walked westward from the town for about a mile and a half. On both of these trips I had in mind the possibility of earthquake cracks but saw no evidence of such. I think that cracks of any size made in February ought still to be visible the following summer. I also examined the south shore of Valdez Inlet from Fort Liscum westward to Entrance Island. This examination was done from a small gasoline launch which was practically everywhere within a few rods of the shore. When farther away I used a field glass. I saw no evidence of earthquake cracks along the shore, and I think that any displacements of a foot or so could easily be recognized. Neither did I see any evidence of elevated or depressed shore lines, although of course the shore was not examined in great detail.

"There was fire in the cable office at Valdez on the night of my arrival there and the maps and records of the earthquake of February 1908, were destroyed. I did not get [the] map showing the breaks in the cable until almost time to start home and so had no opportunity to study carefully the shore opposite the breaks."

The hypothesis that the pairs of breaks in parallel cables three-eighths to three-fourths of a mile apart are caused by faulting is of decided interest. The Coast Survey chart shows that this cable lies in soft mud under 280 to 800 feet of water where the breaks occurred. At these depths the alternate hypothesis of breaking of the cables by masses of silt sliding down the steep submerged delta front near Valdez does not seem plausible, for the soundings show no slopes down which the mud could slide to cause several of the breaks. Nor does a hypothesis of breaks a mile or more apart caused by jellylike shaking of the fiord-bottom deposits during the earthquakes seem applicable. It is far more likely that the cables were broken at the points shown (Pl. XXVII) by actual fault movements during the earthquakes.

It was further stated that the steamer *Northwestern*, which was approaching the dock at Valdez, encountered a "tidal wave" and "felt as though the ship struck on the bottom."

In a subsequent report, Grant and Higgins (1913, p. 12), made the following statement concerning the 1908 quake:

* * * It seems quite probable that the slumping is taking place occasionally along the seaward edge of the delta. On February 14, 1908, an earthquake of considerable magnitude visited this district and broke in several places both the Seattle-Valdez and the Valdez-Seward cables, which run east and west through Port Valdez. Accompanying the earthquake there seems to have been a slumping of the delta front which buried sections of the cables. The cause of the earthquake is not known, but it is thought to have been minor faulting, for one of the cables was broken in deep water on the flat bottom of the fiord 11 miles from Valdez. The slumping of the delta front at this time was therefore probably a result rather than a cause of the earthquake.

The third of these five relevant earthquakes took place on September 21, 1911, and was described by Tarr and Martin (1912, p. 100):

A. H. Brooks, geologist in charge of the division of Alaskan mineral resources of the United States Geological Survey, has given one of the best accounts of the earthquake as follows:

"The record in my notebook shows that on September 21 I noted four earthquakes between 7 and 8:30 p.m. I was at that time at the camp of the Ibex Mining Co., on the west side of Valdez Glacier, about 8 miles from the town of Valdez. I corrected my time observations in accordance with the clock at the Signal Corps station at Valdez upon my return. The correction shows the shocks to have been as follows:

"The first one was at 7:01 p.m. This lasted 20 seconds by my observation. As, however, I was sitting across the tent from the candle and as I did not recognize it as an earthquake at once, I think it safe to add 5 or 6 seconds to this observation.

"The second shock came at 7:13 and lasted between 5 and 10 seconds. The third shock came at 7:28 and lasted 3 to 5 seconds. The fourth shock came at 8:38 and lasted about 2 seconds. The earth movement seemed to be from west to east. I had no means of measuring the intensity of the shock, but it did not seem to have been sufficient to upset anything on the shelves where I was. I was told that at Valdez some articles were thrown from shelves and that a heavy glass bowl was moved, so that it was in danger of falling from a sideboard. The clock at the Signal Corps station at Valdez stopped at two minutes past 7.

"So far as I know, there was no perceptible earthquake wave at Valdez, but of this I have no definite information. It would seem that there should have been a wave there when the cable was broken. Curiously enough, the operator at Valdez told me that the cable was not broken immediately, but that communication was kept up with Sitka some seconds after the earthquake shock. He was telegraphing to Sitka at the time of the shock. The shock at Valdez was sufficient to frighten the people very badly. Nearly everyone rushed out on the street. I did not learn, though, that it had done any damage whatsoever.

"As I had never before felt an earthquake shock I had no basis for comparison. The tent in which I was sitting was located on a little spur jutting out from a steep slope about 1,000 feet above the Valdez Glacier, and the rumbling of the earthquake was confused with heavy falls of boulders down the talus slopes. The talus slopes on both sides showed considerable movement after the earthquake shocks."

During this earthquake the submarine cable from Valdez to Sitka was broken just north of Fort Liscum, at a point 3³⁄₁₆ miles west of the dock at Valdez, near latitude 61°06′08″ N., and longitude 146°19′23″ W., and was buried for 1,650 feet. This is almost exactly at one of the points (Pl. XXVII) where the cable was broken during the earthquake of February 14, 1908, when twice as great a length of cable was buried near this break. The water here is 700 to 750 feet deep and the slope of the fiord bottom is less than 50 feet to the mile. The break at this same point in 1911 seems to verify our suggestion made in 1908 (p. 98), that a fault exists there. Mr. Brooks' statement that cable communication was not interrupted until several seconds after the shock may tend to show that there was slight flowage of fiord-bottom mud along a fault scarp, resulting in the burial of a great length of cable. We do not think that the earthquake shaking alone, without actual displacement by faulting, could have caused sufficient flowage on the flat fiord bottom to break the cable.

A. J. Burr, a former Valdez resident states: "* * * that was the first time that we had ever observed Valdez Bay so literally covered with dead fish as a result of the concussions in the water so that in most of the patches the dead fish were so thick it was difficult to see much of the water" (written commun., July 29, 1964).

Records of the fourth of this series of relevant earthquakes, with which submarine slides appear to haxe been associated, are less detailed than for those of 1908 and 1911. The fourth earthquake took place on January 31, 1912, at 8:11 p.m. local time. The epicenter was recorded as lat 61° N., long 147½° W.; the focal depth was 80 km and the magnitude 7¼. The submarine cables were again broken in Port Valdez.

The fifth of these quakes occurred on February 23, 1925, at 1:55 p. m. local time and is remembered by many present residents of Valdez. Many electric lines were broken, and the front wall of the vacant Valdez Brewery collapsed. More significantly a part of the dock collapsed; an unusual wave accompanying the tremors tore up a section of the boardwalk along Water Street, and the submarine cables were again broken (Gov. William A. Egan, oral commun., August, 1964).

Thus, the record shows that on at least five occasions in the past 70 years, submarine slides—and associated turbidity currents—have accompanied earthquakes at Valdez. To this extent, the combined effects of the earthquake of March 27 were in no way abnormal. Instead, they typify a reaction pattern under seismic conditions that may be expected in the prism of saturated fine-grained deposits that make up the Valdez delta.

SUMMARY OF EVENTS OF THE 1964 EARTHQUAKE

The following description of the events of the March 27 earthquake at Valdez has been constructed from interviews with eyewitnesses, responses to questionnaires, and unpublished reports submitted to various agencies.

The first tremors were felt in Valdez at approximately 5:36 p.m. The shocks lasted from 3 to 5 minutes and were reported to have been accompanied by a low-pitched rumbling sound. The one observation on which there is any semblance of unanimity was that the ground had a rapid rolling motion. Jarring also was reported by many. The ground surface was reported to have been "heaving in much the same manner as a ground swell in the open ocean, except that the swells were much more rapid and frequent." Large fissures could be seen opening and closing along the streets and in areas cleared of snow. Water and suspended silt and sand spurted from many of the fissures. Ground water augmented by water from broken mains and sewers was ejected from the fissures and was trapped between snow berms along the streets; in many places the water attained a depth of 18–24 inches. Trees pitched wildly as if buffeted by a strong wind; several were split but none was broken across. Cars parked in gear or with brakes set moved back and forth, and drivers of moving cars were forced to stop to avoid losing control.

Within buildings, bric-a-brac and lamps were overturned, large heavy objects were shifted, and cans and bottles were thrown down from tables and shelves.

Structural damage to buildings is described in another section of this report (see p. C30).

The most detailed report of the effects of the earthquake in town was made by Charles H. Clark of Valdez. Mr. Clark is a geologist with the Alaska Department of Highways and an experienced aircraft pilot. Hence, he is not only a trained observer of natural phenomena but also possesses the proven ability to judge distances and depths quickly and accurately. His observations are as follows:

The writer was in Valdez at the time of the quake and the following is an attempt to describe the earthquake as it occurred.

The first tremors were hard enough to stop a moving person and shock waves were immediately noticeable on the surface of the ground. These shock waves continued with a rather long frequency which gave the observer an impression of a rolling feeling rather than abrupt hard jolts. After about one minute the amplitude or strength of the shock waves increased in intensity and failures in buildings as well as the frozen ground surface began to occur. Cracks in the roadway surface opened and closed again as the troughs and crests passed the failure. These cracks opened as much as three feet but the most frequent failures were only opened several inches. As these cracks closed due to passing of a shock wave trough, water from both ground water sources and broken sewers and water pipes squirted in a spray about twenty feet into the air. These occurred at intervals several seconds between sprays, but no other timing of the waves was attempted by the writer. The amplitude of waves was estimated by observance of a boy standing about 410 feet away. This boy is the writer's son, stands 6 feet tall and was in plain sight during most of the earthquake. As a crest would pass him, he would appear in full sight with one depression between himself and the writer. As he entered a trough, he would appear to sink out of sight up to about one foot below belt line. This would indicate that he rose and fell about 3 to 4 feet, and that the waves had a fairly large amplitude. Other features in the vicinity viewed by other qualified observers seem to substantiate this sort of estimation.

After about 2 to 2½ minutes, failures of buildings became apparent and power poles began going down. After about 3½ minutes the severe shock waves ended and people began to react as could be expected.

Many things occurred during the brief few minutes of the severe earthquake. Buildings of a wooden frame construction swayed and rocked as if on a high sea. The frame structures evidently were flexible enough to give and sway with very little structural damage. Damages to foundations occurred under these structures, but in general they held together very well for a shock of this intensity and duration. Structures of concrete block or other masonry construction suffered severe damage to both bearing walls and foundations. Glass breakage was very limited. Also, it should be noted that the cracks mentioned previously extended under almost every building in town and caused damage to plumbing as well as foundations.

The single most disastrous event caused by the earthquake at Valdez was the submarine landslide which occurred on the waterfront (fig. 4). This slide and its concomitant waves were responsible for the loss of 30 lives. The slide also caused much of the property damage in the city as well as the destruction of all docks and associated facilities (figs. 5 and 6).

The slide occurred so rapidly and with such violence that eyewitnesses on the shore were overwhelmed. Most of them have very little recollection of what actually occurred directly beneath their feet. The SS *Chena*, a converted liberty ship some 400 feet long, was discharging freight at the Valdez dock when the quake struck. The *Chena* first rose 20–30 feet, then bottomed, rose, bottomed, shot forward, bottomed again, and was lifted clear. Men on the ship say it heeled over at least 50° before being righted by waves. Witnesses on shore state that the bow rose until it could be seen well above the dock warehouses, then fell and the stern rose until the ship's propellers were exposed. Two men on the ship were killed by falling cargo, and another died of a heart attack. By this time the ship was under way and moved to deep water and safety.

As the *Chena* was rising, the Valdez dock was in violent motion. Within seconds of the first tremors, the dock broke in two and the warehouses flipped forward and vanished into an extremely turbulent sea. *Chena* crewmen watched men, women, and children on the dock struggling desperately to get off or to find something to hold on to. None had time to escape.

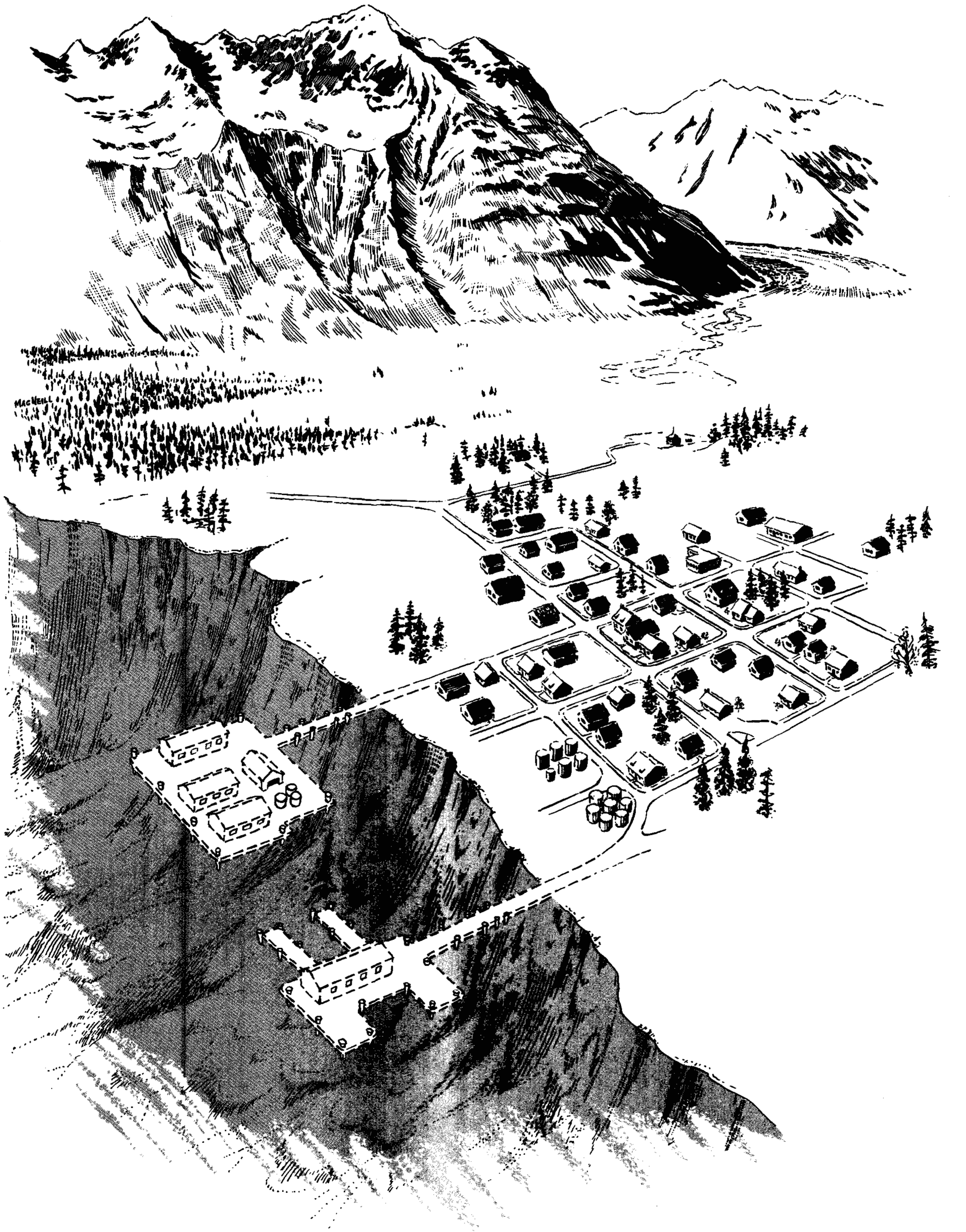
The following account of events as seen from the deck of the SS *Chena* was recorded by Capt. M. D. Stewart, master of the vessel.

The *Chena* arrived at Valdez at 1612 hours, March 27. About 1731 o'clock, 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.

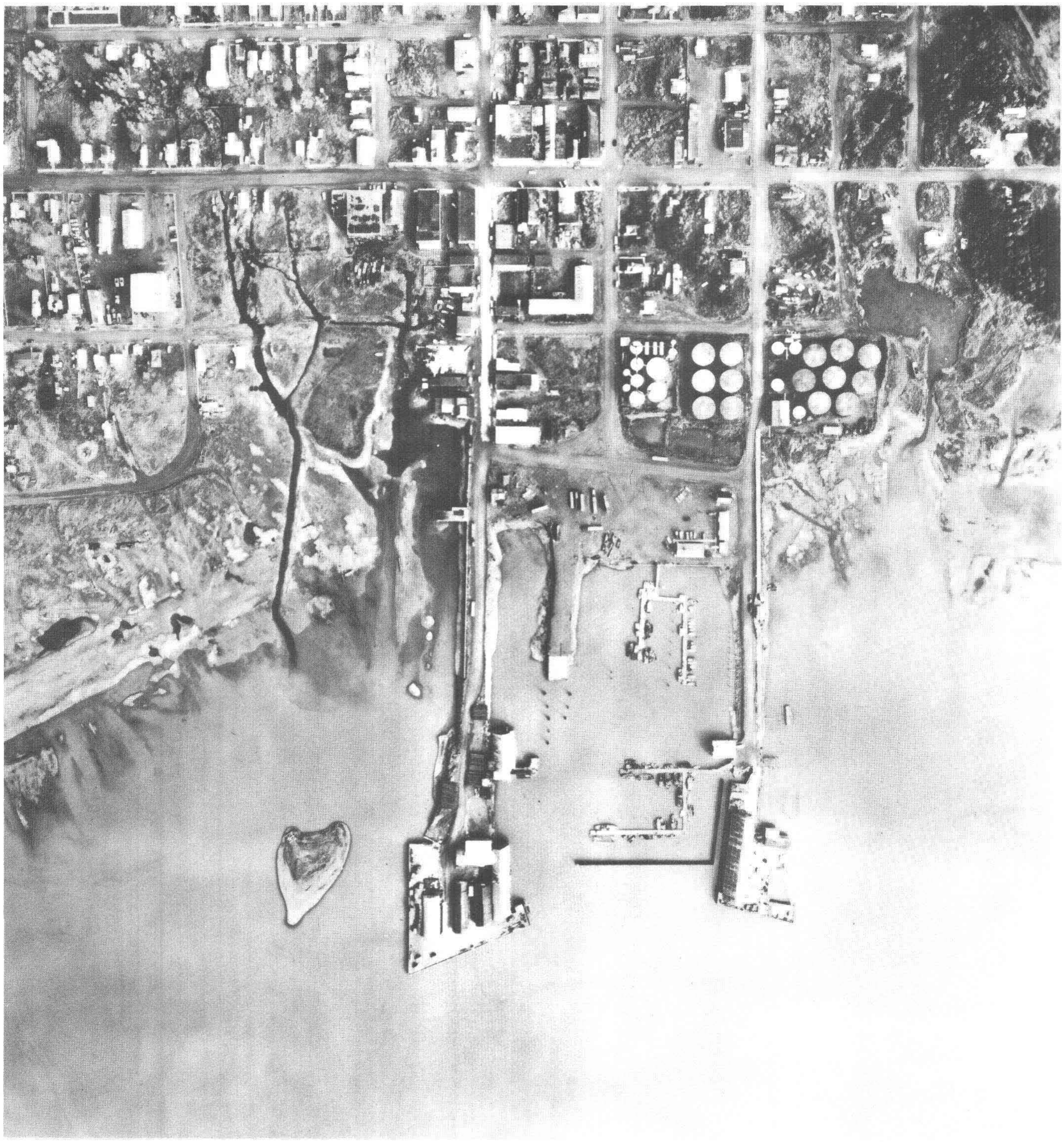
The Valdez piers started to collapse right away. There was a tremendous noise. The ship was laying over to port. I had been in earthquakes before, but I knew right away that this was the worst one yet. The *Chena* raised about 30 feet on an oncoming wave. The whole ship lifted and heeled to port about 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 there was an ungodly backroll to starboard. 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 piling, rocks, and mud.

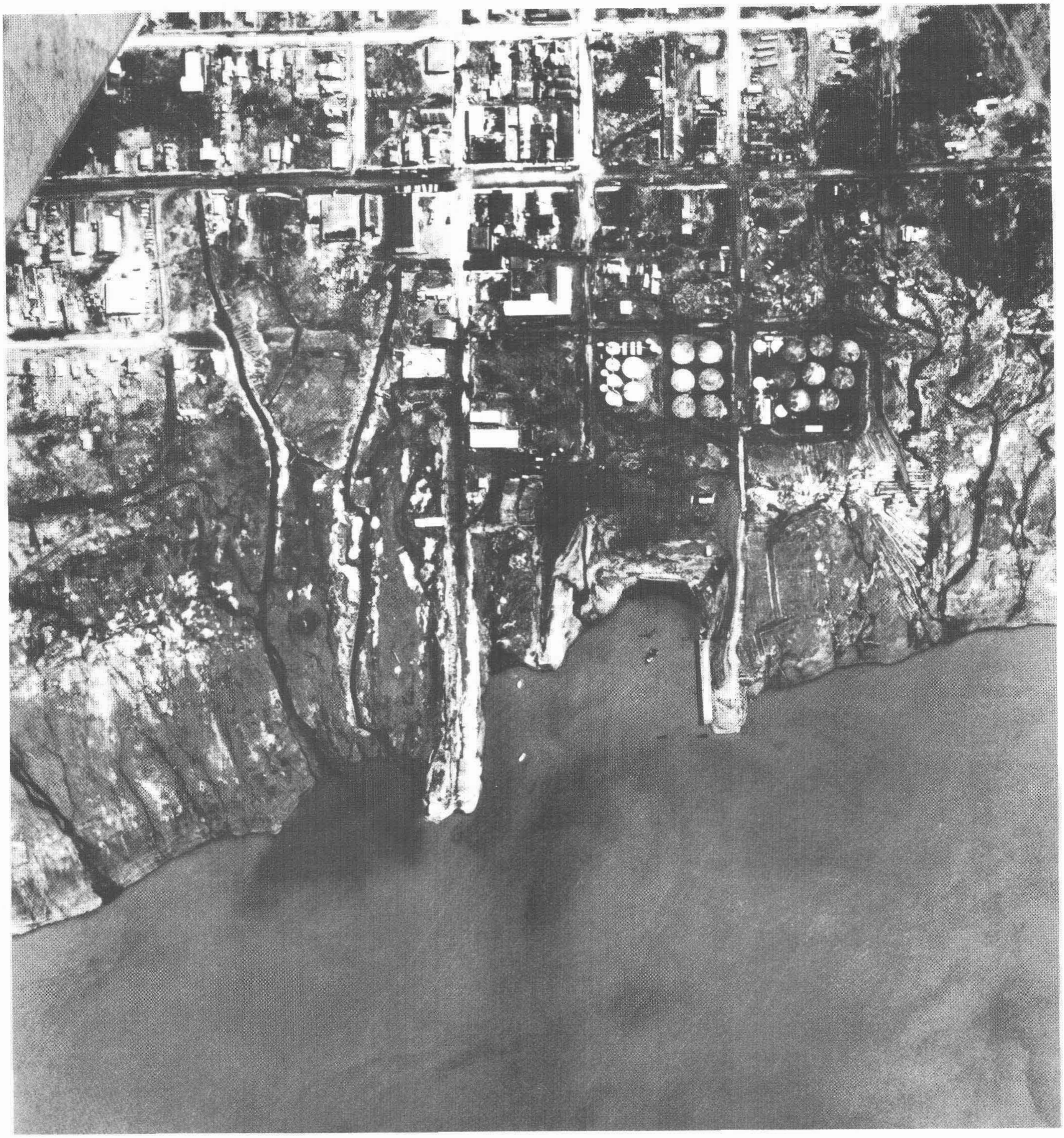
I signaled to the engine room for power and got it very rapidly. I called for "slow ahead," then "half ahead" and finally for "full." In about four minutes, I would guess, we were moving appreciably, scraping on and off the mud (bottom) as the waves went up and down. People ashore said they saw us slide 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 10 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 had to stop. The condensers were plugged with mud and



4.—Submerged slide area at Valdez. Dashed lines indicate dock area destroyed in earthquake. Sketch by David Laneville.



5.—Valdez dock area, September 23, 1965. Photographed by U.S. Bureau of Land Management.



6.—Valdez dock area, June 13, 1964. Photograph by Air Photo Tech, Inc.

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.

Exact details of the wave sequence at Valdez have been difficult to determine; however, four major waves have been distinguished. During the first two waves, most eyewitnesses state, the turbulence in the harbor area generated a mist or haze that obscured the bay beyond the shoreline. In addition, the gyrations and maneuvers of the SS *Chena* during the first wave were so remarkable that few recall seeing anything else at that time. Later in the evening, general apprehension concerning the possibility of a tsunami was sufficient cause for the absence of observers in the waterfront area.

Apparently there was no major surge of water from Prince William Sound through Valdez Narrows into Port Valdez. The reason for this conclusion is the dearth of evidence of wave or high-water effects in Sawmill Bay, a reentrant at the mouth of Valdez Narrows whose alinement and configuration are such that damage there from an incoming surge would have been extreme. Furthermore, the high-water marks and runup effects at the north end of Valdez Narrows (see fig. 20) indicate outward flow of water only. This conclusion is in agreement with Van Dorn's analysis (1964, p. 166) that "the tsunami source was somewhat directional radiating energy preferentially to the southeast." He believed that wave effects in the fiords in northern Prince William Sound were the results of slumping of deltas and strong seiching action.

The first major wave at Valdez closely followed the submarine slide. Without doubt, it was caused by the sudden transfer of approximately 98 million cubic yards of unconsolidated deposits from the face of the delta out into the bay. This wave, estimated to have been from 30 to 40 feet high, surged onto the Valdez waterfront with destructive violence. A component of this slide-generated wave seems to have been propagated westward down the bay and to have caused the extreme runup to 170 feet above sea level at Cliff Mine. It probably caused the outward surge of water through Valdez Narrows that was reported by Mr. Red Ferrier, a Valdez fisherman who rode out the wave on his boat in the Narrows. This down-bay wave may have been reinforced by subsidiary slumps off small deltas along the flanks of Port Valdez.

The second major wave to strike the waterfront at Valdez arrived approximately 10 minutes after the strong ground motion ceased; it has been described as a violent surging wave only slightly smaller than the first. Presumably, this wave was the return surge from the first wave reflected back from the opposite end of the bay.

The seismic energy plus the submarine landslides seem to have generated a complex multinodal seiche in Port Valdez that persisted until early the following morning.

At approximately 11:45 p.m. and 1:45 a.m., just before and just after high tide, waves three and four, described as rapidly moving tidal bores, advanced into the town. These two waves are presumed to have been the result of the coincidence of long-period seiche waves with the high tide.

The late evening seiches may have been reinforced by the effects of one or more of the strong aftershocks, or possibly by the arrival of greatly attenuated tsunami.

SUBMARINE LANDSLIDE

DIMENSIONS

Precise dimensions of the submarine slide are impossible to obtain because measurements depend upon a comparison of prequake and postquake soundings, and the prequake soundings were taken in 1959, nearly 5 years before the earthquake. Accurate modern prequake soundings below 360 feet are not available, and there is no way in which the interim changes in bottom topography can be determined. However, the total volume of material transferred between 1959 and 1964 is more than 100 million cubic yards (pl. 2). It is probable that some of this transfer took place before the earthquake and that additional material was carried down by waves flowing over the newly formed scarp. The entire face of the delta was affected, and the volume of material directly involved in the March 27 slide is estimated to be approximately 98 million cubic yards.

SUBSURFACE CONDITIONS

The sediments underlying the eastern end of Port Valdez have not been studied enough to warrant a detailed description of the entire submarine slide area. Insofar as is known, three exploratory borings put down by the Department of Highways are the only deep borings ever made on the Valdez waterfront or, for that matter, along the entire eastern shore of Port Valdez. Several deep water wells have been drilled in the city of Valdez, but they are approximately 1 mile from the waterfront area. The records of these early wells are not considered to be of great value because the samples were not tested, and apparently no geologist or soils engineer was present during the drilling. The records are much too general for identifying accurately the stratigraphic units.

The drilling by the Department of Highways was done with a truck-mounted rotary drill, using water and bentonite as the circulation medium. Samples were taken at 5-foot intervals or wherever a change of lithology occurred. The borings were all in the Valdez dock area, and thus the information obtained applies only to that area.

These three borings, which reached depths of 105, 82, and 132 feet, show a remarkable degree of horizontal continuity and vertical uniformity (see pl. 3, logs 1, 2, and 3). There are two distinct layers. The first, or surface layer, is a loose to medium-dense sandy gravel with cobbles and silt. This layer is 20 to 30 feet thick. Conversations with local residents and examination of old photographs indicate that this material is fill moved in during the development of the harbor facilities.

The gravel layer is underlain by an undetermined thickness of loose to medium-dense gravelly sand containing thin lenses of silt. This zone persists to the maximum depths drilled.

Standard penetration resistance (relative density), particle-size distribution, and natural-moisture content are fairly uniform throughout both layers.

The shape of individual particles varies from subangular to rounded. The majority of sand-size particles are subangular, whereas the gravels and cobbles are rounded. The original faces and edges of the coarser fractions have been almost completely destroyed, but most of the particles show at least one flat surface.

Ground-water levels were measured in all borings after a 24-hour period to allow for equalization of drilling fluid and ground water. All measurements showed ground water within 6 feet of the ground surface in the locations drilled.

The geologic environment suggests that sediments from the northern extremity of the delta to some point between the stream from the Valdez Glacier and the Lowe River should be similar in composition and particle-size distribution to those in the dock area, except, naturally, the layer of coarse fill material in the dock area. Inasmuch as materials carried by the Lowe River have been transported much farther than those on the rest of the delta, presumably they would generally have a finer grain or particle size. This finer material represents the only probable departure from overall uniformity of sediments in the upper 100 feet in the Valdez delta.

MECHANICS OF THE SLIDE

That certain soils, particularly loose water-saturated sand, may suffer a loss of bearing capacity when subjected to seismic shock has long been recognized (Terzaghi and Peck, 1948, p. 100). The geologic environment at Valdez provides optimum conditions for this phenomenon and bears many similarities to other liquefaction flow sites described by Terzaghi (1956, p. 23–34).

During the earthquake, several factors apparently combined to produce the slide. First, the actual shocks or ground vibrations were of the critical intensity and duration required to create a condition of spontaneous liquefaction in the loose to medium-dense saturated sand. During liquefaction an increase in pore-water pressure, in effect, transformed a normal sediment into a concentrated suspension with a minimal shear strength. Second, the water withdrew from the beaches almost simultaneously with the initial shocks, according to eye witnesses. The withdrawal may have been accompanied by a sudden decrease in hydrostatic head. The net result would have been an immediate increase in the weight of the upper soil layers and a corresponding decrease in support at the toe of the slide due to the sudden drop in sea level. The situation was further aggravated by the fact that the slide occurred at low tide. All these factors, together with the seepage pressures that existed in the area, presumably combined to produce a slide of large proportions.

The slide was probably very similar in shape to the classic sandflows common in subaerial sediments. This shape cannot be accurately determined because receding waves removed enough material from the root of the slide to mask its original configuration. In addition, the mound normally located at the toe of a slide is absent. However, once the sand particles had been placed in a state of suspension and had begun flowing downslope, they probably would not have come to rest in a large pile or mound. The tendency would be to spread laterally, with a consequent thinning of the sliding mass. Movement would probably continue until the suspension reached an area which was nearly flat, where gravity and friction would slow and ultimately stop the rapidly moving soil suspension. If this interpretation is correct, the soil suspension could accurately be described as a turbidity current, a theory that seems to be borne out by the description of the earthquake which struck the Valdez area on September 21, 1911. Of particular interest is the fact that some 1,650 feet of cable was buried. The breaks and cable burial apparently occurred several seconds after the tremor some 3 miles west of the Valdez waterfront. During the February 19, 1908, earthquake, the Valdez to Sitka submarine cable was broken at a point identical to that just described, and the length of buried cable was nearly twice as great.

The 1908 and 1911 cable breaks were considered, at that time, to have been caused by faulting on the floor of Port Valdez. This mechanism is now considered unlikely for several reasons. First, there was no evidence of any faulting visible along the shores of Port Valdez after either the 1908 or the 1911 earthquake. Second, it seems unlikely that any faulting would have occurred after the earthquake. The fact that communication was maintained during the entire 1911 earthquake and was not disrupted until several seconds after the tremors stopped argues strongly against the faulting theory. More probably, the tremors triggered a submarine slide that began moving during the tremors and took several seconds to reach and break the submarine cables.

The fact that numerous cable breaks occurred during or immediately after the 1908, 1911, and 1925 earthquakes adds support to the theory that submarine landslides caused the cable breaking. Even though the breaks occurred at many points, sliding cannot be ruled out as the cause.

In addition to the Valdez outwash delta, there are at least five other locations in Port Valdez where streams have built relatively large deltas: (1) Mineral Creek, (2) Gold Creek, (3) the stream from Shoup Glacier, (4) Sawmill Creek, and (5) Allison Creek. All these streams enter Port Valdez from the north or south. Thus, any slides which occurred on their respective deltas would most likely move in a north-south direction. The magnitude of the turbulence which would be created by five or six masses of liquefied soil moving in different directions, particularly when two or more crossed paths, would break any cable within range.

Cable service to Valdez has long been discontinued, and consequently this means of comparison between previous earthquakes and the 1964 earthquake no longer exists.

PRESENT STABILITY OF THE VALDEZ WATERFRONT

The Valdez waterfront has proven to be unstable under seismic conditions. Records of slides which have occurred during previous earthquakes make any additional elaboration unnecessary. It is important, however, that an attempt to assess the static stability of the Valdez waterfront be made. This assessment is important not only for the Valdez area, but for all harbor facilities located on the numerous deltas throughout south-central Alaska.

Slides have occurred on the Valdez waterfront without any acceleration caused by earth tremors. Because the damage caused by these slides was relatively light and no lives were lost, the events received little, if any, attention from the general public and were not described in the scientific literature. Three separate incidents of slides on the waterfront were related to us by Valdez residents.

The first slide occurred in the early 1920's. A cargo of large spools of cable had been off loaded onto the north dock. At some time during the night, the section of dock upon which the cable was resting sheared away from the rest of the dock, carrying the cable with it. The cable was never recovered. Reportedly the piling supporting the failed section was not broken but was carried out by a sliding mass of soil. A diver reported that he had difficulty working on the delta face after the slide because of the steepness of the slope. In this case, apparently the subsoils simply did not have sufficient strength to support the concentrated weight of the dock and cable. The slide was localized, and the other sections of the dock were not damaged.

The second dock failure occurred in the late 1920's and is illustrated by figure 7. In this failure there is no record of heavy loads on the dock at the time of failure. Note that the failed section is tipped shoreward.

Sometime between 1942 and 1945, a third slide occurred beneath the cannery dock. Although its exact dimensions are unknown, the slide affected the entire dock and was estimated to have been at least 100 feet wide. Oddly enough, the dock, although badly damaged, was not carried away, probably because it was tied together rather rigidly.

7.—Dock failure in late 1920's. Note that failed section has tipped shoreward. Photograph courtesy of James Derringer.

The reason for these two later slides is not as clearly understood as the first slide described. The dock was empty when the last two slides occurred, and there was no noticeable seismic action. Because both seismic action and heavy loads can be ruled out, other factors were undoubtedly responsible. It should be emphasized that these slumps were small localized features.

The most probable cause of these local slides would appear to be oversteepening of the delta face during the natural processes of deposition and erosion. Terzaghi (1956) described two prevalent causes of oversteepening in this type of environment, either or both of which may be applicable to these slides: (1) the intercalation of cohesive strata within the deltaic sequence and (2) artificial interference with the natural depositional and erosional patterns.

Clayey silts have been found in the Valdez waterfront borings (see pl. 3, log. 3), in the Mineral Creek townsite borings (Shannon and Wilson, Inc., 1964, borings No. B–5A, B–6), and in the deep well at Valdez (see Waller and Tolen, 1962, table 2, well 1). Hence, local oversteepening from intercalation of cohesive strata is a possibility.

Artificial interference with the natural environment along the Valdez waterfront, however, is a more probable cause of local oversteepening. Since the construction of the dike around Valdez in the early 1900's, distributary channels across the delta have been denied access to the Valdez waterfront area, and since construction of the levee system, beginning in the 1930's, the distributaries have been entirely restricted to the southern half of the delta. Construction of the docks and the breakwater system has also seriously disrupted the natural-wave and longshore-current pattern across the northern part of the delta face. This situation appears to be similar to that described by Terzaghi (1956) as contributing to the submarine slope failure at Howe Sound, British Columbia. There, interference with the natural processes allowed accumulation of a perched body of fine-grained concentrates to a point where the critical slope value was exceeded and failure in the dock area ensued.

The absence of evidence of past large-scale slides occurring along the face of the Valdez delta under static conditions indicates that massive slides along the relatively stable delta are not likely to occur under ordinary circumstances. The evidence that the postquake slope of the delta face is practically parallel to the prequake slope lends support to this conclusion.

Calculations were made in an attempt to assess the static slope stability of the delta face. Because shear-test data were not available, assumed angles of internal friction derived from the angle of repose of the materials involved and from the standard penetration indices recorded during the waterfront drilling program were used in the computations. In view of the assumptions involved, the computed safety factors can be considered relative only; consequently no attempt is made to state them in numerical terms.

If the present average slope of the delta face of 16° is used in the calculations, the delta face appears to be relatively stable against massive failure under static conditions. If the slope angles of 20°, 33° and 45°, which represent the locally oversteepened condition on the upper part of the delta only, are used in the calculations, the stability against slumping on the upper part of the delta ranges from marginal to critical.

All available evidence indicates that the face of the Valdez delta is fairly stable under static conditions, insofar as massive slides involving large sections of the waterfront are concerned. Small slumps occurring at frequent intervals involving the upper part of the delta face only are considered highly probable. Neither of these conclusions takes earthquake acceleration into consideration.

Under seismic conditions, the subsoils underlying the Valdez waterfront are susceptible to spontaneous liquefaction and subsequent failure. Because the Valdez area lies in a zone of high seismic activity, numerous quakes with a wide range of intensities will occur. If the intensity and duration of a shock are sufficient, large blocks of the Valdez delta will liquefy and slide. This fact looms over all considerations which suggest that an incipient failure condition under the local oversteepened case exists even without earthquakes.

GROUND DISPLACEMENT

VERTICAL DISPLACEMENT

Valdez appears to lie on the hinge line—or line of zero tectonic altitude change—separating the zone of regional uplift to the south and east from the zone of regional subsidence to the north and west. The two closest bench marks set in bedrock, on the Coast and Geodetic Survey first-order level line[1] south of the town at mile 5 and mile 10 on the Richardson Highway show displacements of +0.55 feet and +0.35 feet, respectively. The first two bench marks, set in bedrock on the first-order line north of the town at mile 19 and mile 46 on the Richardson Highway, show displacements of −0.87 feet and −1.67 feet, respectively. The distribution of these changes in altitude strongly suggests that the Port Valdez valley—and its continuation into Heiden Canyon—lies on the dividing line between the area of tectonic uplift and subsidence (see fig. 1).

Because of the direct evidence of differential displacements resulting from landsliding, fissuring, sand ejection, and possibly compaction within the unconsolidated sediments of the Valdez delta, the changes in level of individual bench marks there apparently do not adequately reflect the nearshore deleveling. These movements within the unconsolidated deposits are strictly local readjustments in contrast to the regional deleveling indicated by changes in altitude of bench marks set in bedrock.

An index of the amount of subsidence in the waterfront area can be gained from a comparison of the prequake and postquake highway profiles along Alaska Avenue measured by the Alaska Department of Highways (pl. 1). These profiles are comparable as far west as Hobart Street and diverge progressively from there to Water Street where the indicated subsidence is 9 feet. An estimate of subsidence west of Water Street to the remaining end of the ramp of the main dock suggests an additional 10 feet of deleveling. This estimate is based on the present submergence at high tide of the dock gatepost, which formerly stood at approximately 18 feet above high water.

The nature and extent of flooding of areas formerly above high tide confirm the observations that deleveling as just estimated above has in fact taken place. Furthermore, continued progressive en-

[1] Preliminary Coast and Geodetic Survey first-order level data released November 9, 1964.

croachment of high tides suggests that some component of the factors that caused the initial rapid subsidence has continued to affect the area for as long as a year after the earthquake.

No detailed prequake measurements are available in the shore area south of the town; however, study of prequake and postquake photographs indicates a comparable steepening of the beach profile and drowning of drainage channels across the entire face of the delta.

Apparently the major component of the deleveling in the waterfront area was a response to submarine sliding which removed support from the face of the delta and thereby allowed some of the material to move seaward and caused parts of the shore area to subside. The observation that some of the pile-supported structures near the waterfront have subsided less than the surrounding ground surface suggests that some compaction of the subsoils has taken place. The generally poor consolidation of the subsurface materials indicated by the low penetration resistances recorded in the waterfront exploratory borings (pl. 3, Nos. 1–3) suggests that compaction cannot have been extensive.

LATERAL DISPLACEMENT

Observations of horizontal separation across fissures in the unconsolidated deposits throughout the town indicated that seaward lateral displacement of considerable magnitude coincided with the submarine slide and resultant removal of support from the delta face. Prequake horizontal control networks were not sufficiently detailed to establish the amount of movement. Measurements of the separations across fissures along Alaska Avenue from the waterfront to the east end of town totaled more than 80 feet. However, because some differential displacement and tilting of the blocks were obviously involved, this figure is not an true indication of the amount of lateral displacement.

Measurements that do appear to reflect actual lateral displacement became available during the reconstruction work; accurate records were kept of the horizontal separations of waterlines throughout the town. Separations on the four main lines were measured between 7th Street and McKinley Street (table 2 and pl. 1).

TABLE 2.—*Water-line separations*

[C. H. Blake, U.S. Corps of Engineers, written commun., 1964]

Street	Separation between Sherman and 4th	Separation between Hobart and McKinley	Minimum individual separation	Maximum individual separation	Total separation between McKinley and 7th
Wickersham Avenue			3 in.	1 ft	10 ft 3 in.
Alaska Avenue			3 in.	1 ft 4 in.	12 ft 6 in.
Broadway	5 ft 3 in.				13 ft 1 in.
Keystone Avenue		6 ft 4 in.		1 ft 10 in.	16 ft 2 in.

Besides the measurements of these displacements, accurate measurements of the distance between the prequake and postquake positions of the bulkhead at the small-boat harbor at the foot of Keystone Avenue indicate a lateral displacement of 25 feet, as shown on a postquake map made by the Corps of Engineers. The total measurable seaward displacement along Keystone Avenue from 7th Street to the waterfront is 41 feet 2 inches.

Other measurements of lateral displacement were reported by M. L. Wilson of the Alaska Department of Highways (written commun., 1964):

> Some lateral movement was noted in the stretch of road going southeasterly out of Valdez, with the movement being associated with the earthquake of March 27, 1964. The most severe shift was located about 1,100 feet past the concrete bridge over Glacier Stream #3, towards Glennallen.
>
> As-built plans and a survey made in 1962 for the City Streets project tied the original centerline of the roadway to U.S.C. & G.S. triangulation station Knife. The same triangulation was repeated in June 1964 in connection with project ER-13(1).
>
> Assuming that station Knife has remained fixed in the same location, the horizontal distances from the road to Knife before and after the quake indicate the following:
>
> That a shift of about 1.5 feet towards the bay has occurred on the road near the ball park. The shift continues and increases to an apparent maximum deflection of 5.3 feet at the point 1,100 feet past the bridge. The deflection then decreases to nil around 2.2 mile. Isolated segments of displacement of smaller magnitude were noted past 3 Mile.
>
> Visual examination of the movement past the bridge tends to verify our calculations, and we should be fairly close in the order of magnitude.

Further evidence of lateral displacement was found in the rupture and offset of the casings in water wells.

Beneath the powerplant building at 5th and Broadway, a 6-inch well casing was broken during the quake at a depth of 15 feet 8 inches below the surface, and the upper part of the casing was offset to the west (shoreward). The well point was also bent at a depth of 20 feet 8 inches below the surface, but this damage may have occurred during removal of the point from the ruptured casing.

The casing of the auxiliary water-supply well at the northeast end of town was also damaged during the earthquake. However, the main well there appeared to have been undamaged and the internal pipe and well point moved freely inside the casing on March 27. During a strong aftershock on June 16, 1964, the casing of the main well was bent at a depth of 28 feet below the surface and the casing of the auxiliary well was ruptured at a depth of 48 feet. The casing of the main well was bent again at an undetermined depth during an aftershock on September 22, 1964, and the well had to be abandoned. In each of these wells the direction of movement of the bends and breaks in the well casings was westward (shoreward).

The postquake condition of powerlines throughout the town supplied additional confirmation of seaward lateral extension. West of McKinley Street, most lines were broken and many utility poles were down. East of McKinley Street along streets at right angles to the waterfront, powerlines were stretched tightly and lines on many blocks had to be slacked off to prevent breakage. In general, along streets parallel to the waterfront the lines maintained a normal amount of sag.

Without doubt, lateral displacements comparable to those described above took place in the shore area south and west of the town, but there are no fixed reference points in that area to indicate such displacements.

GROUND BREAKAGE

The theory of formation of earth fissures, sand vents, and allied phenomena has been elucidated by several authors (Oldham and Mallet, 1872, p. 264–268; Thomas Oldham, 1882; R. D. Oldham, 1899; Davis and Sanders, 1960, p. 248–250; and Imamura, 1937, p. 70–77). These phenomena characteristically occur in areas where thick sections of saturated, incompetent, predominantly fine-grained deposits overlain by more coherent surficial strata have been subjected to stresses generated by a high-magnitude earthquake. The following are the better known of the historic documented earthquakes from which the particular set of physical circumstances necessary to produce the widespread broken-ground phenomena have been described:

- New Madrid (Fuller, 1912)
- Cachar (Thomas Oldham, 1882)
- Charleston (Dutton, 1889)
- The Great Indian Earthquake of June 12, 1897 (R. D. Oldham, 1899)
- California (Lawson and others, 1908)
- Bihar-Nepal (Roy, 1939)
- Fukui (Tsuya, 1950)
- Alaska, April 7, 1958 (Davis, 1960)
- Alaska July 10, 1958 (Davis and Sanders, 1960).

Oldham (1899, p. 86) makes a clear distinction between fissures which "start at the surface and penetrate down to the depths," and fractures which "may be taken to have been propagated upward from below." Fissures are considered to be "a result more or less indirect of the wave motion which has been set up elsewhere and traveled to the place where the fissures are formed." Fractures on the other hand "must be regarded as a cause and as surface manifestations of the deeper seated fracture by whose formation the wave motion was originated." Fissures are subdivided by Oldham (1899, p. 87–90) into two genetically distinct categories. Those of the first category are attributed to lateral spreading toward an unconfined face. This type of fissure has often been attributed to a rather loosely defined phenomenon termed "lurching" (see Richter, 1958, p. 124). Fissures of the second category are formed on level ground where the unconfined-face effect does not obtain. They are attributed to "visible undulations of the ground induced by the earthquake which traveled as independent quasi-elastic or purely gravitational waves. Such waves traversing the alluvium would throw each part into alternate compression and extension as the surface was bent into a concave or convex curve and in a compressible material decidedly lacking in elasticity this might easily lead to the formation of fissures" (Oldham, 1899, p. 89). Ejection of water, silt, sand, and even coarser particles may accompany the formation of either of these types of fissures.

The occurrence during earthquakes of low-velocity, short-wavelength, high-amplitude surface waves—variously called "earthquake waves" (Freeman, 1932, p. 769), "visible waves" (Richter, 1958, p. 129), "visible undulations of the ground" (Oldham, 1899, p. 89), and "gravity waves" (Imamura, 1937, p. 28)—has been accepted by many seismologists and has been questioned by others. Such waves have been observed and recorded from dynamite and nuclear blasts (Leet and Leet, 1964, p. 181). The major arguments against occurrence of such waves associated with earthquakes are: (1) that they are characteristically not recorded on instruments (Heck 1936, p. 22; Eiby, 1957, p. 26), and (2) that there is a stated disparity between the damage such waves would be expected to do and the damage actually done in areas where the waves have been reported (Freeman, 1932, p. 770). Insofar as the seismic records are concerned, apparently neither the normal calibration of the instrumentation nor the normal geologic environment of instrumentation is such that waves of this nature would be recorded. In this context, Swain's (1962, p. 240) reports of Gutenberg's observations that lead to the "rule of thumb under which the multiplication of displacement from rock to alluvium or fill could be expected to be two to ten times" and Gutenberg's (1957, p. 221) further assessment that "at sites on alluvium, relatively strong shaking lasts several times as long as at those on crystalline rock" seem particularily pertinent. Insofar as the damage is concerned, until instrumental records become available for analysis, the damage potential from such waves cannot be adequately assessed. Doubtless, as pointed out by Richter (1958, p. 130–132), many erroneous and mistakenly exaggerated reports have been made about this phenomenon; however, judgments concerning these visible ground waves must still rest on the purely qualitative information from eyewitnesses and from secondary analysis of effects.

FISSURES

At the time of the quake, the ground at Valdez was frozen down to the water table at depths of from 4 to 6 feet, and hence it could be expected to react somewhat like a rigid pad suspended on saturated granular subsoils. A snow cover approximately 5 feet deep also lay on the ground.

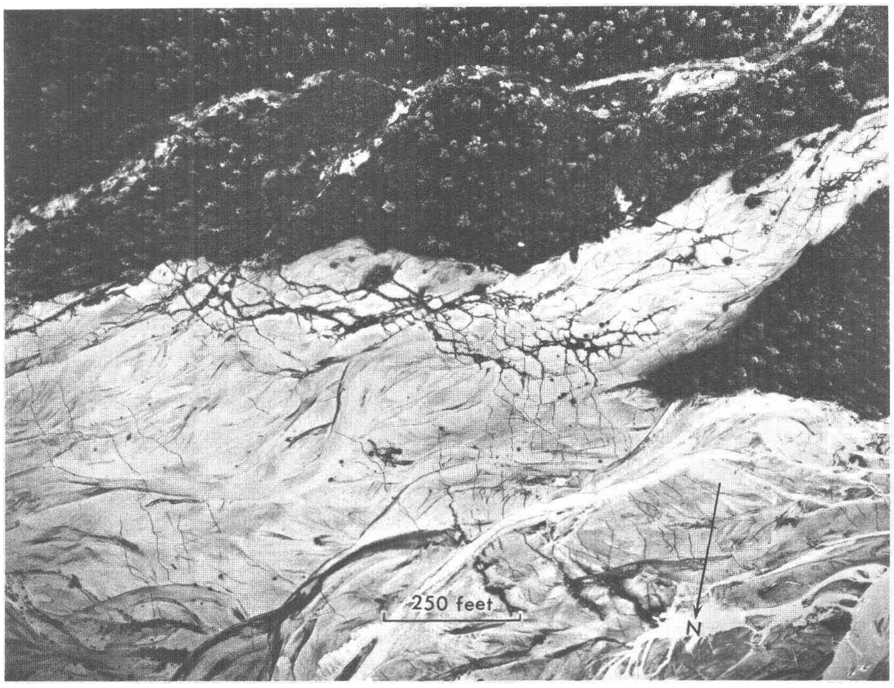
During the earthquake and while the slide was taking place along the waterfront, an extensive system of fissures developed across the Valdez delta. Some of these fissures reportedly were opening and closing during the tremors, and considerable volumes of water and suspended silt and sand were pumped from many of them. Within the town the pattern of this fissure system is complicated by refraction of fissures across deeply frozen zones under plowed streets and by the tendency of individual fissures to follow thawed zones over pipelines, sewers, and into foundation pits and cellars. On the open flood plain southeast of town, however, two distinct fissure sets could be recognized (figs. 8 and 9).

TRANSVERSE FISSURES

The first of the two sets of fissures on the flood plain, hereafter called the transverse set or transverse fissures, has a general trend of N. 30° W., approximately parallel to the waterfront. The width of the transverse fissures ranges from a few inches to more than 2 feet. No accurate appraisal of the original depth of the fissures could be gained although they probably lost their identity as discrete voids at the water table. The maximum length of any individual segment of the transverse set is approximately 1,000 feet although a broad zone of subparallel segments, which overlap in plan, extends across the entire breadth of the delta from north of Airport Road to the mouth of Robe River. In general, both the width of individual fissures in this set and their number per unit area decreases away from the shore. Aerial photographs taken within a few days of the quake show that minor quantities of silt and sand were ejected from some of the transverse fissures near the shore. Evidence of this ejected material was obliterated by the effects of subsequent high tides. Elsewhere, evidence of pumping along transverse fissures is uncommon. Only four of the transverse fissures observed showed much vertical displacement. The maximum displacement recorded was 6 inches, and in all four fissures the relative movement was west side down. No suggestion could be discerned in the pattern of these transverse fissures of the stepped, tilted, tread-and-riser arrangement typical at the heads of block-gliding-type landslides nor of the concentric, crescentic fractures typical of arcuate slip failures. Instead, the physical characteristics and the spatial arrangement of the transverse fissures suggest that they originated as tension breaks in response to the lateral displacement and the imposition of a seaward camber on the distal part of the frozen delta surface coincident upon removal of support from the delta face by seismically triggered submarine landsliding. Thus, the transverse fissures belong to Oldham's first category (lateral spreading toward an unconfined face).

LONGITUDINAL FISSURES

The second prominent set of fissures on the flood plain, hereafter called the longitudinal set or longitudinal fissures, displays more complexity and diversity than the transverse set. In general, the trend of the longitudinal set is oriented at right angles to the transverse set and to the waterfront, although many individual fissures depart from this orientation. The longitudinal fissures



8.—Vertical aerial photograph showing fissures on the flood plain of the stream from the Valdez Glacier. Photograph by Air Photo Tech, Inc.

9.—Transverse fissures (foreground) and longitudinal fissures (in the middle distance). Ridges of ejected material (silt and sand) border the longitudinal fissures.

are concentrated in, but not confined to, swales and depressions in the flood plain of the delta where the thickness of the frozen layer and the depth to the water table were least. Only transverse fissures were found on the higher and older surface of the low terrace remnants although the thick brush cover on the terrace remnants hindered accurate observations and precluded accurate plotting there.

The largest individual longitudinal-fissure segment observed was located 1,500 feet east of Dike Road and 800 feet north of Richardson Highway. It was 6 feet wide, 4 feet deep, and approximately 250 feet long (see fig. 10). Although some parts of the walls of the fissure apparently had collapsed during the spring thaw, the overall width does not appear to have been increased appreciably. A large volume of fine sand and silt was ejected from this fissure.

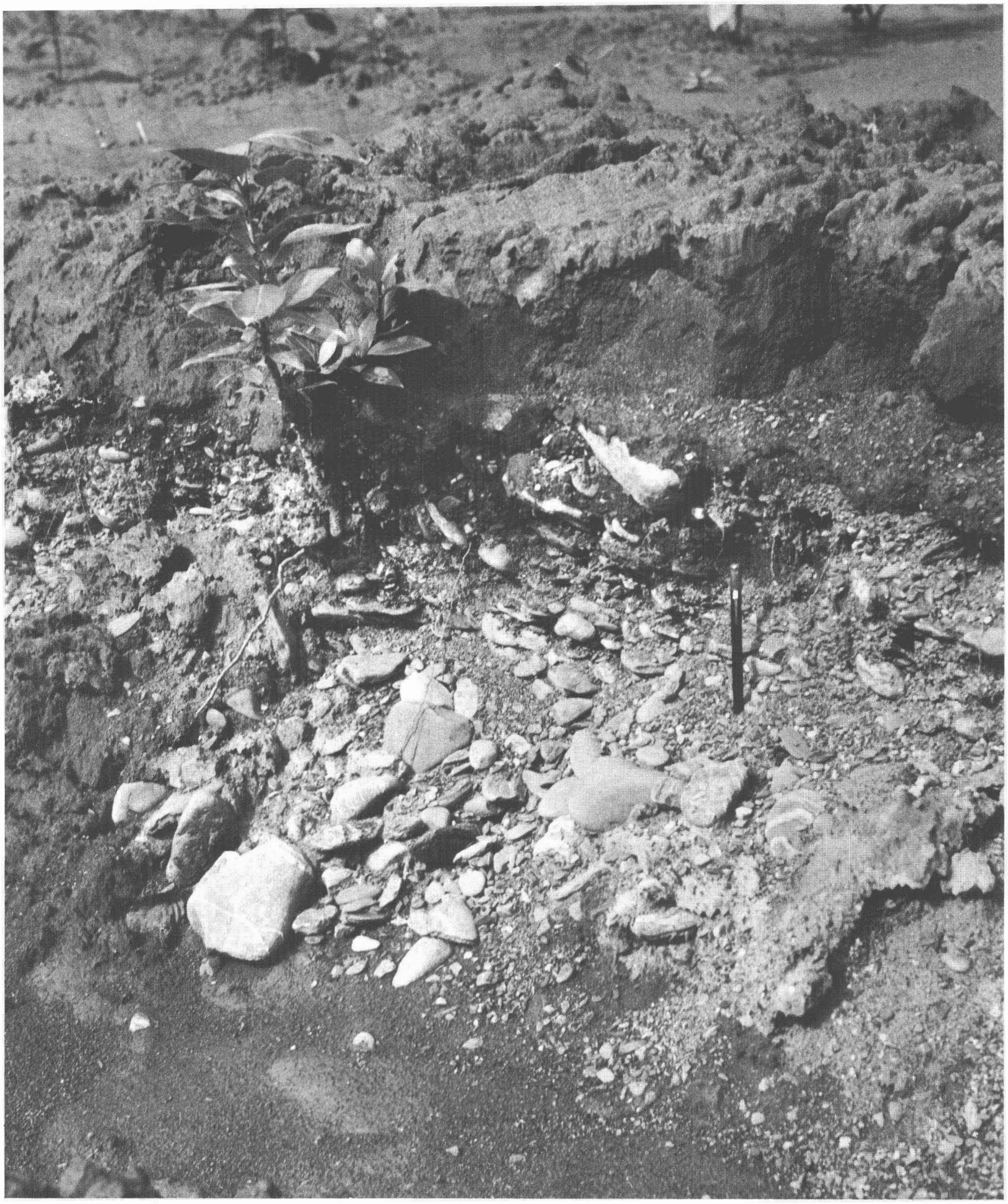
10.—Large longitudinal fissure. Surrounding area covered by ejected sand and silt. Carpenter's rule across fissure is 6 feet long; vertical scale below it is 1 foot high.

Figure 11 shows the fissure wall and approximately 2 feet of ejected material overlying the original surface. The thickness of this blanket of ejecta decreases away from the fissure on both sides to a featheredge approximately 100 feet from the centerline of the fissure. The volume of material ejected is roughly estimated as 2,000 cubic yards.

The distribution of ejected material from this fissure on the Valdez flood plain differs in several respects from that of similar features elsewhere. Commonly a steeper lip or ridge borders this type of fissure, and circular scour pits, attributed to the rapid return flow of water at the cessation of seismic shaking, occur along the fissures (Davis and Sanders, 1960; Oldham, 1899). On the Valdez flood plain, however, the thick blanket of snow covering the surface at the time of the quake apparently exercised a strong control on the somewhat atypical distribution of the ejecta. It also impeded the return flow of water enough that circular scour pits were not formed nor was much ejected material washed back down into the fissures.

In several areas, the largest of which measured approximately 300 by 900 feet, the entire surface was blanketed by a layer of silt and fine sand as much as 3 feet thick which completely obscured the fissure complex from which it was ejected.

Trenches were dug across several of the longitudinal fissures in an attempt to determine their subsurface configuration and relationships. In each trench, fines were concentrated at the bottom of the fissure, but the identity of the fissure was lost completely at the water table from 1½ to 3 feet below the bottom of the void. Examination of these trenches suggests that features comparable to the discrete sand dikes described by Fuller (1912, p. 52) will not be preserved here. As stated earlier, the physical relationships required for the formation of these features comprise a thick section of poorly consolidated, predominately fine-grained, saturated deposits overlain by a more competent stratum. In the examples cited in the literature, the stratigraphy of the area has included a pronounced lithologic break—for example, sandy alluvium overlain by a well-developed soil, sand overlain by clay, or a similar lithologic break—and the material of the underlying saturated unit was carried up into and through the overlying competent unit. On the flood plain at Valdez, the lithology



11.—Longitudinal-fissure wall showing concentration of fines in ejected material. Original surface at pencil top.

is relatively homogeneous (see pl. 3 and table 1), and the break was between units having different physical states (that is, between frozen and unfrozen strata) rather than between units having different lithologies. Thus, at Valdez, the finer fractions were elutriated from the underlying unfrozen deposits and carried up into and through the overlying frozen deposits, but the transported material is indistinguishable from the fine-grained beds and interstitial material of the frozen deposits.

RELATIONSHIP BETWEEN TRANSVERSE AND LONGITUDINAL FISSURES

An area, at the zone of intersection of a transverse-fissure complex and a longitudinal-fissure complex, which illustrates many of the commonly developed characteristics of the fissures at Valdez is shown on figures 12 and 13. This area lies along the zone of swales and abandoned channels parallel to and west of the low terrace remnant south of Dike Road. The transverse fissures furthest away from the longitudinal pattern are clean but, as they approach the longitudinal fissures, more and more ejected material appears along them (see fig. 14). At the point of intersection, the exact relationships become obscured by the large volume of ejecta, but in general the trends of the transverse fissures are deflected or terminate at longitudinal fissures. Within the longitudinal pattern itself, there is a general linear trend, but many segments intersect complexly. Some of these segments display a roughly conjugate arrangement, whereas others anastomose without any apparent systematic alinement. Large volumes of ejected silt, sand, and in some places pebbles characterize the central part of the longitudinal complex. On each flank of the longitudinal complex, and parallel to it, are a series of clean fissure segments which show vertical displacement and which cut both the longitudinal- and transverse-fissure segments. The displacement ranges from 2 to 8 inches and the downdropped side is always interior, forming a graben with the longitudinal-fissure complex on the down-dropped block. Late-stage collapse pits are associated with these border faults (figs. 15 and 16). Collapse pits were still forming as late as August 1964.

ORIGIN OF LONGITUDINAL FISSURES

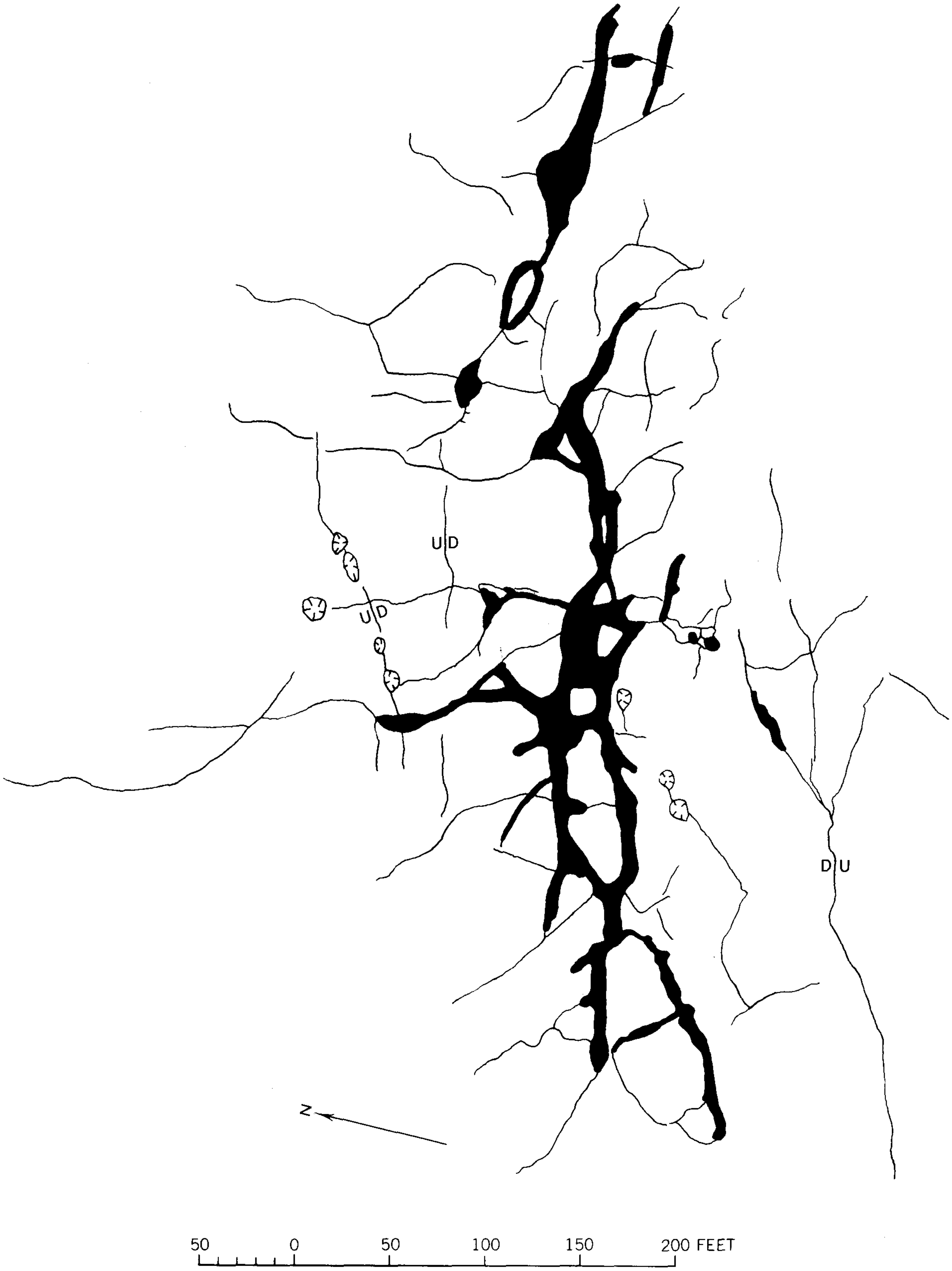
The process whereby the longitudinal fissures originated is visualized as follows, and the fissures correspond closely to Oldham's second category: As seismic energy was transmitted from the surrounding bedrock walls into the thick alluvial fill at the head of the fiord, the displacements were augmented until large-amplitude slow-moving visible surface waves were being excited in the alluvium. These waves increased in size until the strength of the frozen surface layer was exceeded, characteristically in areas where that layer was the thinnest, and rupture occurred. Continued wave action subjected the underlying saturated materials to alternate compression and tension, and water containing suspended silt and sand was pumped up through the zones of rupture and out onto the surface. Removal of relatively large volumes of subsurface materials in this manner allowed subsidence to take place along the flanks of the longitudinal fissure zones, and the border faults and, ultimately, the late-stage collapse pits were formed. Because the transverse fissures are deflected by or terminate at longitudinal fissures, many of the transverse fissures must have formed later than the longitudinal fissures. However, the evidence of pumping of material along transverse fissures at localities where they approach longitudinal fissures indicates that the formation of the transverse fissures must have taken place prior to the cessation of strong ground motion.

Two minor features associated with the fissures are discussed below.

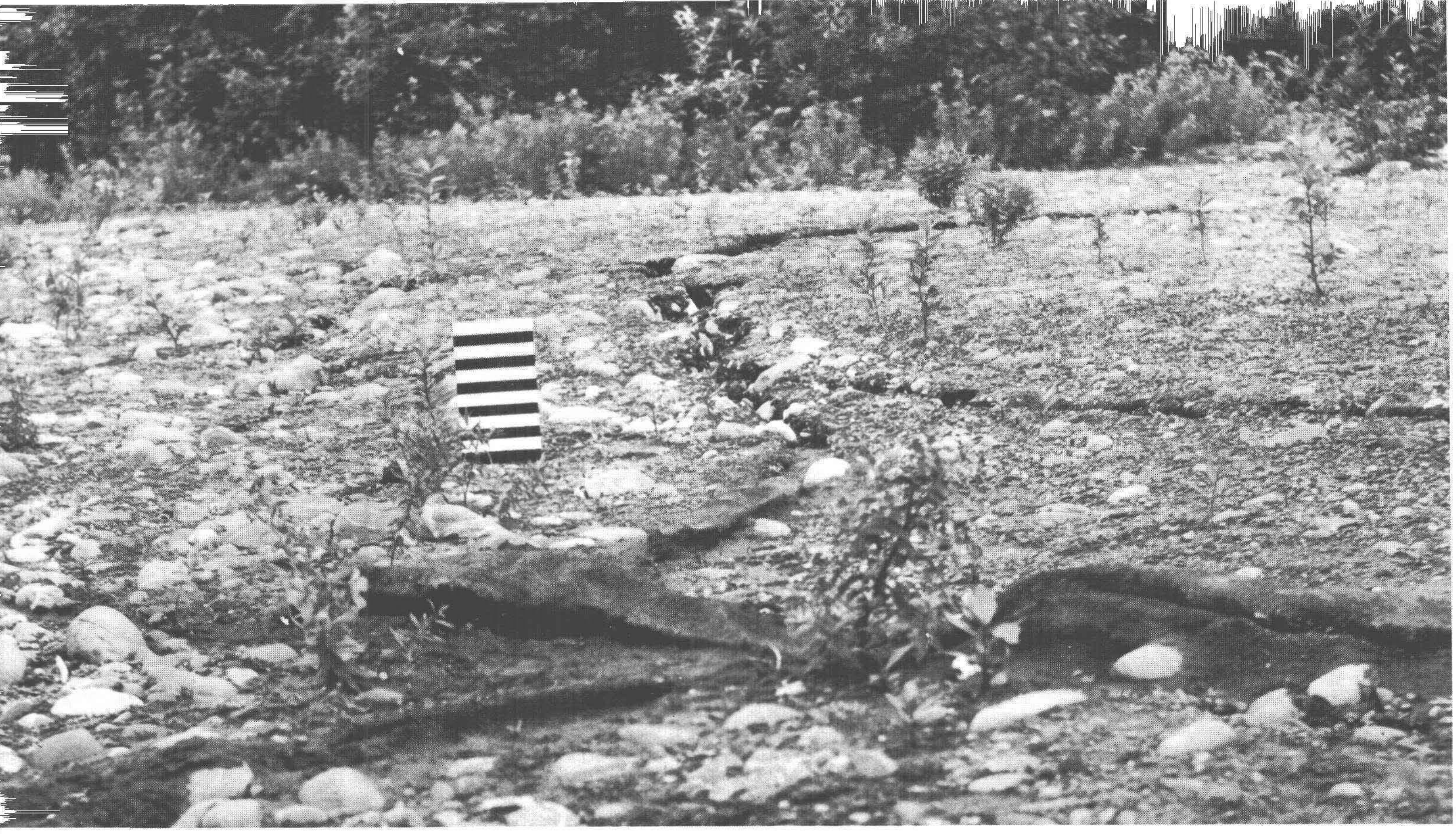
Tabular ridges of silt and sand stand in relief along some of the narrower fissures (fig. 14). These ridges were at first interpreted as extrusions indicating final compressive stress along these particular fissures. However, the fact that many of these ridges intersect almost at right angles argues against their origin by compression. The absolute lack of plasticity of the granular materials comprising these ridges also militates against this explanation; it appears that the ridges are not extrusions but are accumulations of ejected material deposited in fissures that were propagated up into the snow cover; and that the ejecta were left standing in relief after the snow melted.

An early interpretation on the height to which water and suspended silt and sand squirted into the air was later proven incorrect. Eyewitnesses reported that individual jets of water reached as high as 20 feet. These jets were observed only along plowed streets and cleared areas within the town in places where an increased hydrostatic head from broken water mains could be expected. Elsewhere in a few localities the water broke through the snow cover but did not go much above the cover. In an area of heavy brush north of the airport road, however, where little ground was broken, mud splashes and clots

12.—Flood plain of the stream from the Valdez Glacier showing the intersection of a set of transverse fissures with a set of longitudinal fissures. The longitudinal set appears darker because of ejected silt and sand.



13.—Map showing details of fissures shown on figure 12.



14.—Zone of intersection between longitudinal fissures (foreground) and transverse fissure (background). Note increasing evidence of sand ejection along transverse fissure as it approaches longitudinal-fissure complex. Scale is 1 foot.

15.—Collapse pit in a graben on the flank of a set of longitudinal fissures. Scale is 1 foot.

16.—Collapse pit on the flank of a set of longitudinal fissures. Scale is 1 foot.

were observed on alder branches 25 to 30 feet above the ground, but it was eventually recognized that the mud spots were only on the ends of branches which had been weighted down to the ground by the heavy snow cover and, hence, were not related in any way to the height of water jet.

DAMAGE TO STRUCTURES

To facilitate the discussion of the effects of the earthquake on manmade structures, four somewhat arbitrary categories will be used. The cause-and-effect relationships among the various categories are generally complexly interrelated. The four categories are:

1. Effects to structures on or near the waterfront resulting from the submarine slide.
2. Effects to structures resulting from waves and (or) high water.
3. Effects to structures resulting from ground breakage under or near them.
4. Effects to structures resulting from strong ground motion.

The damage to structures resulting from the submarine slide are so graphically illustrated by figures 4, 5, and 6 that little elaboration of this category is necessary, other than the enumeration of some salient dimensions to portray the scale of the effects.

Approximately 500 feet were lost off the end of the north dock. The ship berth on the north and the west face of this dock each measured 325 feet. The dock held six large buildings, each approximately 50 feet wide, having an aggregate length of nearly 700 feet, and numerous smaller sheds, platforms, and related structures. Almost 400 feet were lost off the end of the south dock, including a berth at the west face 200 feet long. The dock held one large building 200 by 50 feet, one smaller building, and an extensive bank of freezer units. Several large trucks and semitrailers, cars, and numerous pieces of heavy-cargo-handling equipment were lost with the docks. A 500-foot L-shaped bulkhead between the two docks and 900 linear feet of floats in the small-boat harbor were also destroyed.

Wave and water damage (category 2) was areally restricted but severe. The violent surging wave which struck the shore within minutes of the slide did additional damage to the dock ramps and destroyed three of the four buildings at the head of the small-boat harbor and another building along the north-dock ramp. This wave also completed the wrecking of the small boats and the fishing fleet. One fishing boat was carried approximately 150 feet inland, and wave-carried debris damaged the installations in the Standard Oil Co. tank farm. One of the asphalt storage tanks was presumably punctured at this time. The runup from this first wave reached beyond McKinley Street at several points.

Apparently the down-bay component of this first slide-generated wave caused the extensive damage at the western end of Port Valdez. In the bight between Shoup Spit and the steep north wall of the fiord, the wave attained its maximum runup height and completely obliterated the abandoned installations at Cliff mine. Small submarine slumps off Shoup Spit and elsewhere probably augmented the wave in this vicinity. On the steep valley wall above Cliff mine, the high-water marks on the snow reached 170 feet above msl. Slopes were stripped of vegetation up to altitudes as high as 70 feet along parts of the west wall of the fiord, and the navigation light standing on a concrete pylon approximately 25 feet above msl in Valdez Narrows was carried away. On the south side of the fiord, the cannery building at Jackson Point was torn from its foundations and drifted several miles down the bay; the runup in Anderson Bay reached 70 feet and destroyed an occupied dwelling.

The second wave, presumably the return surge from the first wave, crossed the waterfront at Valdez approximtaely 10 minutes after the first wave, carrying much debris. Water from this wave is reported to have reached a depth of 18 inches in the Valdez Hotel on McKinley Street, but elsewhere its effects cannot be differentiated from those of subsequent higher waves.

At approximately 11:45 p.m. and again at 1:45 a.m., respectively, the third and fourth waves advanced. The third reached as far as Hobart Street and was reported to have been 2½ feet deep in the Valdez Hotel. Water from the fourth and final wave was 5–6 feet deep in buildings along McKinley Street and 2 feet deep on Hobart Street (see fig. 17) and was responsible for most of the water damage to buildings, homes, and merchandise and supplies in the commercial establishments

17.—High-water mark from the early-morning wave, about 1:45 a.m., March 28, 1964, on a building on the east side of North Front Street between Rudolph Alley and Dike Street.

along McKinley Street and west of it. Large volumes of silt were deposited in and around buildings by the wave. Some of the wooden structures floated free during the high water, and an empty storage tank in the Standard Oil Co. tank farm was toppled. The final wave evidently advanced and receded with considerable speed because the high-water marks left by it on building exteriors are in most places several inches higher than the interior high-water marks. Furthermore, much wreckage and many damaged boats were swept off the waterfront, and considerable scour and gullying around buildings and other obstructions occurred during the recession of the final wave.

The apparent sporadic distribution and the many anomalous effects of the final wave can be explained in large part by the existence in the town of high snow berms and a deep snow cover which channeled the water and restricted its distribution.

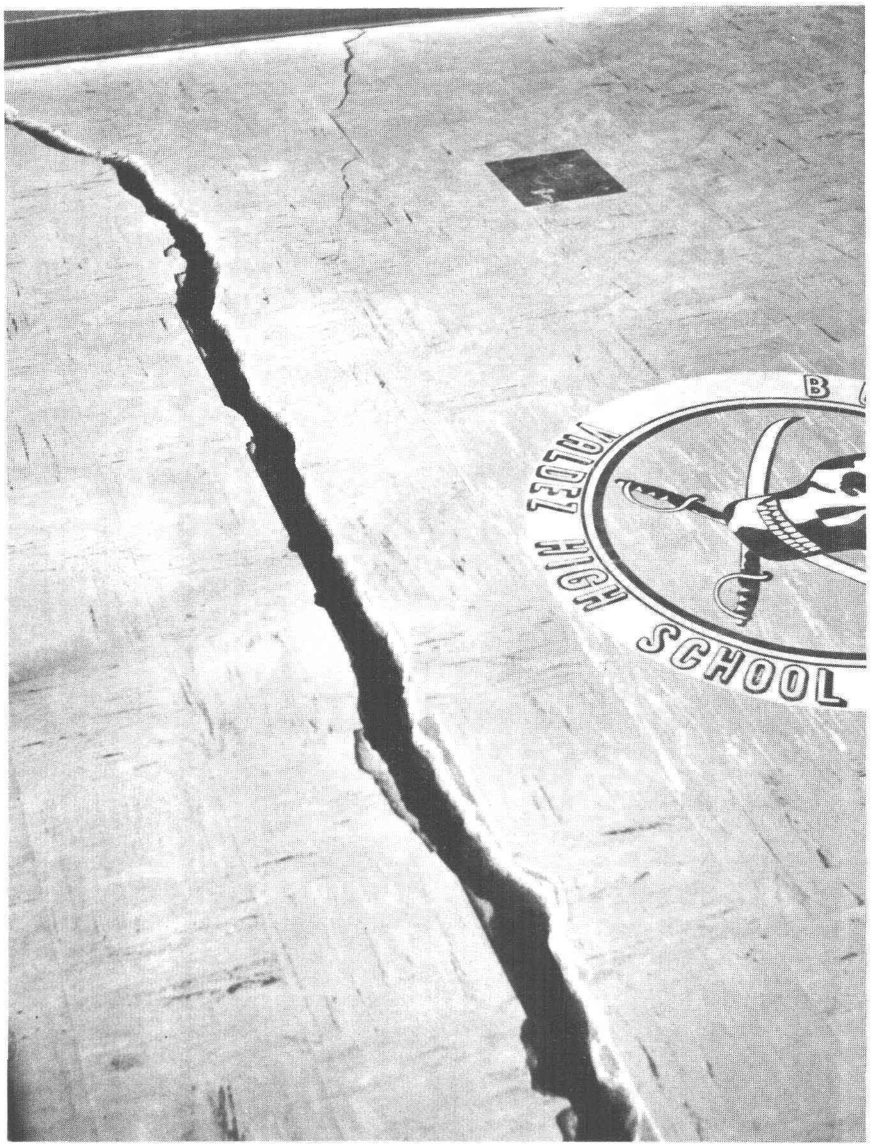
The principal cause of damage to manmade structures away from the waterfront was ground breakage. Approximately 40 percent of the homes and most of the larger commercial buildings in Valdez were seriously damaged by fissures extending under or near them. The effects to wooden buildings—the predominant type—are not readily apparent from the outside, but extensive foundation damage, which completely destroyed the structural integrity of the building, occurred in every unit intersected by fissures. The breakage of the foundations in most houses was accompanied by fracturing of floor joists, buckling of floors, and warping and cracking of interior walls. In many houses, intersec-

18.—Damage to the Alaskan Hotel on McKinley Street between Alaska Avenue and Broadway. The foundation of this building was intersected by four fissures. Photograph by T. L. Péwé.

tion of the foundations by fissures resulted in the pumping of large volumes of silt and sand into the cellars and crawl spaces. The effects on the commercial cinder-block structures are more apparent (fig. 18).

Simple rectangular buildings having heavily reinforced-concrete pad foundations—such as the Highway Department maintenance shop at North Front Street and Rudolph Alley, the powerplant at Broadway and 5th Street, and the Post Office at Alaska Avenue and Hobart Street—were not affected by fissures, although some differential settlement of the Post Office building appears to have taken place. Foundations of multicomponent structures having less heavily reinforced-concrete pad foundations—such as the hospital at Hobart Street and Wickersham Avenue, the high school at Empire Avenue and Sherman Street, and the Harborview complex at 6th and Wickersham Avenue—were damaged owing to intersection by fissures (fig. 19); these buildings also showed evidence of differential movement between their various elements.

The west abutment of the concrete bridge that crosses the stream from Valdez Glacier at 0.8 mile from Valdez was fractured, had dropped about 16 inches, and showed evidence of rotation toward the stream channel. There was partial failure of all three bridge approaches between town and mile 3, leaving steps between the approaches and the bridge decks. The characteristic damage to road embankments, particularly where the road is flanked by deep borrow pits, in the section between town and mile 3 included wide fissures along the flanks of the embankment and concomitant sags in the pavement; this damage suggests lateral spreading of the embankment.



19.—Transverse fissure through the concrete foundation slab of the Valdez High School, Sherman Street and Empire Avenue.

Waterlines were broken by fissuring in at least 150 places throughout the town, and service was disrupted within one block of the water tower (Waller, Thomas, and Vorhis, 1965, p. 126). Comparable damage was done to the sewerage system.

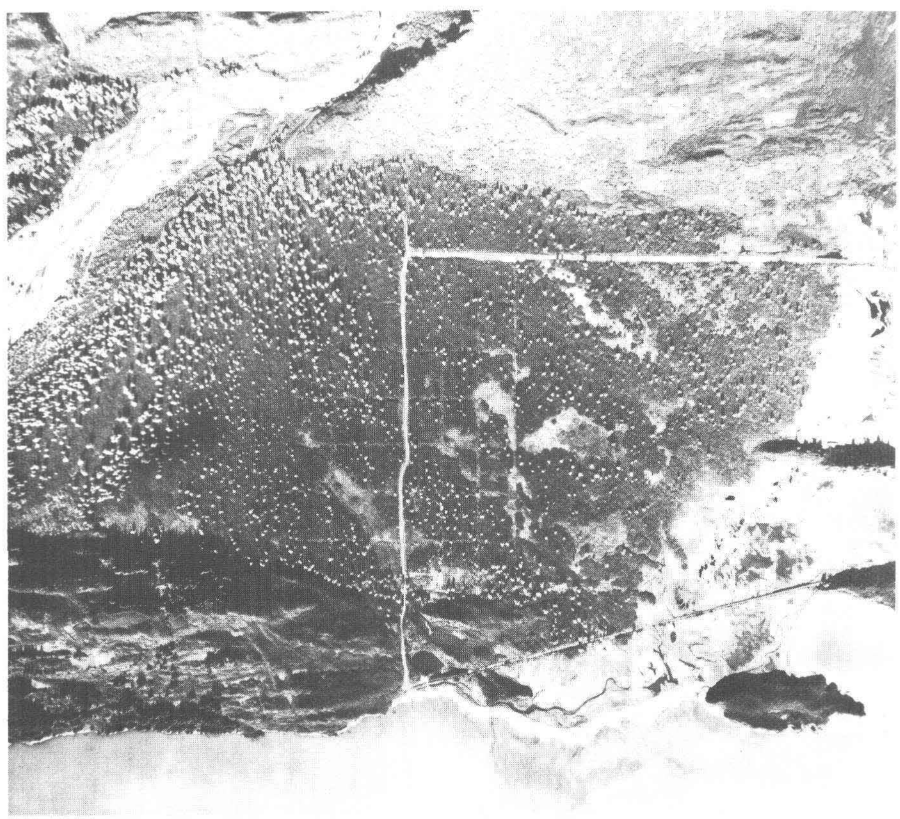
Damage to structures that can be directly attributed to strong ground motion was not widespread. Many brick, fieldstone, and cinder-block chimneys were damaged or destroyed. Loose items on tables and shelves were upset, tumbled, and thrown down. The riveted steel tanks in the Union Oil Co. yard, unlike the welded tanks in the Standard Oil Co. yard, ruptured, but the subsequent fire and explosions obscured any evidence of the exact cause of rupture. At the powerplant the heavy 200-kw generators

20 (above).—Oblique aerial photograph showing Mineral Creek fan and Mineral Creek islands (foreground), the western end of Port Valdez, Shoup Spit, and Valdez Narrows (background). Photograph by U.S. Air Force.

were rocked out of alinement and approximately three-fourths of the water from two cylindrical 3,500-gallon water tanks was sloshed out. No damage or loss of water from strong ground motion occurred at the 200,000-gallon city water tank, which is supported by a heavily cross-braced wooden tower, although the tank drained rapidly through water-main breaks. The exact contents of the tank at the time of the quake cannot be established. The legs of the 60-foot steel radio mast at the Alaska Communications System station at Alaska Avenue and McKinley Street were bent, but the tower was prevented from falling by heavy steel-cable guys.

The financial losses to the Valdez community are summarized in detail in the reports of the Federal Reconstruction and Development Planning Commission (1964).

The absence of evidence of wave damage, of ground breakage and fissures, and of vibration damage to the single dwelling on the Mineral Creek Fan (figs. 20 and 21) indicates a more stable environment there under seismic conditions than exists on the Valdez Delta.



21 (below).—Vertical aerial photograph showing the new location for Valdez on the Mineral Creek fan. Photograph by U.S. Bureau of Land Management.

CONCLUSIONS

Valdez is located on the seaward edge of a large outwash delta composed of saturated silty sand containing some gravel. The March 27, 1964, earthquake triggered a massive submarine slide, involving approximately 98 million cubic yards of material, which destroyed the harbor facilities and nearshore installations. Waves generated by the slide and subsequent strong seiches did additional damage in the downtown area. Stresses generated by the seismic shocks and the slide developed an extensive system of fissures throughout the fine-grained saturated deposits of the delta. These fissures plus the shocks caused structural damage to most of the buildings in Valdez and destroyed the sewer and water systems. Removal of support from the face of the delta allowed some parts of the delta to move seaward and caused parts of the shore area to subside below high-tide level. Continued progressive encroachment of high tides and fracturing of well casings strongly suggest that subsidence and lateral movement were still active many months after the quake. Furthermore, the drainage from Valdez Glacier continuously threatens the artificial dike and levee system protecting the town and the access road.

In summary, Valdez is unsuitable as a habitation site or port facility in the following respects:

1. Poor foundation conditions on saturated fine-grained materials which are unstable under seismic conditions.
2. Exposure to slide or seismically generated sea waves.
3. Exposure to serious floods.

In contrast with the unfavorable geologic conditions at the present site of Valdez, the conditions at the new Mineral Creek townsite are very suitable for habitation and port facilities. The Mineral Creek site is situated on an alluvial fan confined on the seaward side by a series of bedrock ridges and islands (figs. 20 and 21). It is underlain by coarse tabular cobble gravel having an interlocking bedded texture which will provide excellent foundation conditions. The bedrock configuration at the mouth of Mineral Creek effectively prevents the stream from swinging eastward into or near the townsite.

In summary, the Mineral Creek townsite has the following advantages:

1. A series of bedrock ridges and islands which act as a resistant buttress retaining and protecting the toe of the alluvial fan from danger of sliding or slumping. This bedrock buttress plus the higher elevation of the Mineral Creek site also provides protection from slide or seismically generated sea waves.
2. A stable foundation anchor on bedrock for a major dock facility, favorable offshore conditions, and a protected locality for a small-boat harbor.
3. Good foundations conditions. On the basis of the absence of ground breakage and fissures, and of vibration damage to the single dwelling there, the coarse alluvium of the Mineral Creek site appears to be relatively stable under seismic conditions.
4. Excellent natural protection from floods.

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