Varieties of submarine failure morphologies of seismically-induced landslides in Alaskan fjords

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The Great Alaska Earthquake of 1964 caused major damage and 43 deaths in the coastal communities of Seward and Valdez. Most of these losses were caused by tsunamis that occurred immediately after the earthquake and were most likely induced by local submarine landslides. Recent NOAA multibeam bathymetric surveys near Seward and Valdez provide detailed information about the morphology of landslide deposits in both areas. High-resolution (chirp) surveys were conducted by the USGS, and sediment samples were taken over apparent landslide debris. Landslide deposits near Seward typically take the form of a series of large and small blocks lying directly off the front of the town, although there are indications of sandy and muddy debris flows occurring off river deltas. Near Valdez, landslide morphologies include at least three forms: a field of large blocks (up to 40 m high), an intricate series of gullies, channels, and talus near the fjord-head delta and a broad debris lobe that apparently flowed half-way down the fjord and stopped. The 1964 landslide tsunamis may have been composites resulting from a number of landslide events.

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Introduction

The Great Alaska Earthquake of 1964 (Mw = 9.2), the largest earthquake to occur in North America during the twentieth century, caused major damage to all of the coastal communities in south-central Alaska. Particularly hard hit were the towns of Seward and Valdez (locations shown in Fig. 1), which were struck and partly destroyed by tsunamis that propagated within the fjords adjacent to the towns. A total of 43 persons died in these communities. Although Seward was also affected by the tectonically generated tsunami, most of the damage and deaths were caused by tsunamis that occurred immediately after the earthquake and were most likely induced by local submarine landslides (Hampton et al. 1993).

Some post-earthquake investigations were conducted in the fjords in the 1960's and dramatic changes in bathymetry were observed (including up to one hundred meters of deepening below the fjord heads). Recent multibeam, high-resolution subbottom and coring surveys of Resurrection Bay (Seward; Lee et al. 2003) and Port Valdez (Valdez) provide much more information about the morphology of landslide deposits in both areas. This paper describes these recent findings.

Setting

The southern coast of Alaska has been heavily glaciated and contains numerous glacially carved fjords. Both Resurrection Bay and Port Valdez are typical of these features. They are each about 20 km long and 5 km wide; Resurrection Bay extends in a N-S direction, and Port Valdez, in an E-W direction. At peak glaciation, ice extended far above sea level, as much as 1000 m above Port Valdez (Grant & Higgins 1910) and scoured deeply into bedrock, by as much as 600 m below sea level into the floor of Port Valdez (von Huene et al. 1967). The glaciers receded about 7000 years ago in Port Valdez and likely a comparable time in Resurrection Bay. Subsequently, major rivers formed draining nearby glaciers and ice fields and discharging into the heads of the fjords. The Resurrection River flows into the head of Resurrection Bay and has built a fjord head delta that fills the upper 5 km or more of the original fjord. Similarly the Lowe River flows into the head of Port Valdez and has built a comparable delta. Sediment from the Lowe and other rivers has deposited about 350 m of sediment on the floor of Port Valdez since deglaciation. Several small fan deltas extend into Resurrection Bay as a result of deposition from smaller creeks entering the bay.

A tidewater glacier currently enters Shoup Bay a small embayment off the northwestern corner of Port Valdez. Clearly the glacier extended into Port Valdez at some time in the recent past and deposited a moraine that nearly closes the entrance to the bay. The south side of the moraine forms a steep slope that extends to the greater than 200-m-deep flat bottom of Port Valdez (Grant & Higgins 1913).

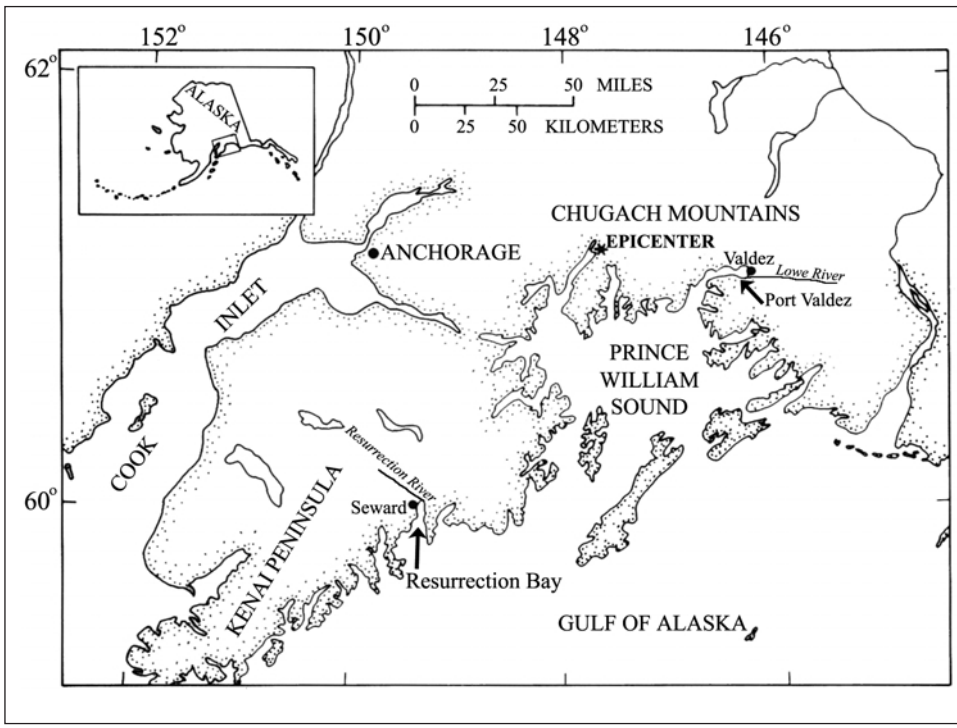

Fig 1: Location map showing Valdez and Seward, Alaska, and the epicenter of the 1964 Mw = 9.2 earthquake.

Approach

The United States National Oceanic and Atmospheric Administration (NOAA) routinely performs multibeam surveys of U.S. coastal waters. Recently, both Resurrection Bay and Port Valdez were mapped as part of this program. The availability of these new data enabled us to systematically re-evaluate the morphology and scale of submarine mass failure deposits that might be related to the 1964 earthquake. To complement these evaluations, the United States Geological Survey (USGS) conducted extensive chirp subbottom profile surveys in both locations during the summer of 2005. These results allow us to assess the three-dimensional character of landslide deposits and determine their volumes. Also, sediment cores were obtained for sedimentology and dating surficial sediment deposits using short half-life radioisotopes.

Ultimately, our goal is to better understand submarine landslide-induced tsunamis. Scientists at the University of Alaska at Fairbanks are using geometric and geologic information from the NOAA and USGS surveys as input information for a tsunami generation model. Comparisons between predicted and observed tsunamis will lead to either a validation of the models or form the basis for model improvements.

Methods

Multibeam Surveys

A recent advancement greatly improving our understanding of undersea landslides has been the development and use of multibeam echosounder systems (MBES) for seafloor mapping of bathymetry. In contrast to earlier techniques that acquired bathymetry along tracklines, multibeam systems provide complete bathymetric coverage over an area. These data can be visualized in a variety of ways including shaded relief, producing imagery that resembles aerial photography. When MBES systems are used to map seafloor landslide features, they allow us to identify morphologic details that could not be resolved with earlier techniques. Accordingly, we acquired a much improved appreciation of the characteristics of submarine landslides that cause tsunamis.

A general discussion of MBES technology is given by Hughes Clarke et al. (1996). In principle, a multibeam echosounder differs from the traditional single-beam echosounder in that the MBES records the return echoes with a contiguous series of narrow receive apertures that are precisely aimed at angles that together typically cover a swath of 60° to more than 150° of the seafloor. Each received signal is adjusted for spherical spreading, attenuation in the water column, the ship's roll, pitch, yaw, heave, and the sound-speed structure of the water column. These systems are capable of producing geodetic quality bathymetry with spatial errors of less than 1 m and vertical errors of 0.5% or less of the water depth. Multibeam data from Resurrection Bay and Port Valdez, Alaska were obtained using high-resolution MBES systems aboard the NOAA ship *Rainier*. Images of the data presented in this paper were prepared using Fledermaus software.

Fig 2: Vertical aerial photographs of the waterfront of Seward, Alaska, before (a) and after (b) the 1964 earthquake. Note the loss of shoreline and the maximum height of tsunami waves shown in the bottom figure (photographs after Coulter & Migliaccio 1966).

Chirp Profiling

High-resolution subbottom profile data were acquired using an Edgetech 512 Chirp System and recorded using Delph Seismic software. Frequencies were typically swept over the range of 500 to 7200 Hz during a 30 ms period. The output signal was adjusted as needed to achieve optimum returns. The Edgetech 512 was towed approximately 15 meters aft of the stern at approximately 15 meters below the water surface from the *R/V Montague*. Chirp technology uses multiple sound frequencies as opposed to older, single-frequency systems. Resolution (ability to image thin layers) is improved without compromising significantly the penetration.

Resurrection Bay

Damage during the 1964 Earthquake

The community of Seward, situated at the head of Resurrection Bay along the southeast side of the Kenai Peninsula was particularly hard hit during the 1964 earthquake (Lemke 1967; Hampton et al. 1993; Shannon & Hilts 1973). Much of the damage in Seward was clearly related to slope failures and the generation of local tsunamis (Wilson & Tørum 1973). Between 35 and 45 seconds after the strong shaking began, an approximately 1 km-long section of the waterfront, containing three large docks, many oil tanks, and a railroad yard, began sliding seaward as a result of large-

scale offshore landsliding. Figure 2 shows the loss of shoreline related to these failures. Pipes from the oil tanks ruptured, the tanks overturned, and the spilled oil erupted into flame. The landslide displacements caused a "mound of water" to form in the bay (Lemke 1967). Waves radiated in all directions from the mound, having a height of about 10 m as they struck near Seward. As the wave hit Seward it brought back burning oil, destroyed an 80-car freight train in the railway yard and caused 40 railway cars loaded with oil to burst into flame in a chain reaction. These waves and damage that occurred almost immediately after the earthquake were related to local coastal and marine failure. About 30 minutes later, the tectonically-generated tsunami, roughly 10 m in height, arrived from outside Resurrection Bay, struck Seward and caused significant additional damage. In all, 13 persons died in Seward, most of them as a result of wave action.

Recent surveys

The bathymetry in the northern part of Resurrection Bay shows the front of the major fjord-head delta of the Resurrection River extending completely across the northern end of the Bay (Fig. 3). Within the area mapped in Fig. 3, the fronts of three smaller fan deltas produced by tributary creeks (Lowell Creek, Fourth of July Creek, and Spruce Creek) can also be identified. These extend out into the bay, producing relatively flat areas of land and steep slopes immediately offshore. The town of Seward was built on one of these fan deltas (Lowell Creek), and it was the face of this feature that failed catastrophically in 1964, removing significant parts of the town's infrastructure (Fig. 2). The remains of this failure appear as blocky debris extending offshore for about 750 m (Fig. 3). Some blocks are 10 to 15 m high. The area immediately offshore Seward currently has a slope of about 25° decreasing to about 5° along the deeper part of the area of blocky debris. The other two small fan deltas (Fourth of July Creek and Spruce Creek) do not show comparable blocky debris although steep headwall-like topography and a deep trough south of the Fourth of July Creek fan-delta (Fig. 3) may be related to a flow failure. The face of the large Resurrection River delta is covered with chutes and gullies related to numerous smaller failures of the fjord-head-delta front that are perhaps ongoing. Attempts to core the sediment below the Resurrection River delta and the area south of the Fourth of July Creek fan-delta recovered only small amounts of sand, likely indicating sandy debris flows continuing to the present time. The Resurrection River delta front may have failed in 1964, but the bathymetric and chirp records do not constrain the hypothesis.

High-resolution subbottom profile records obtained

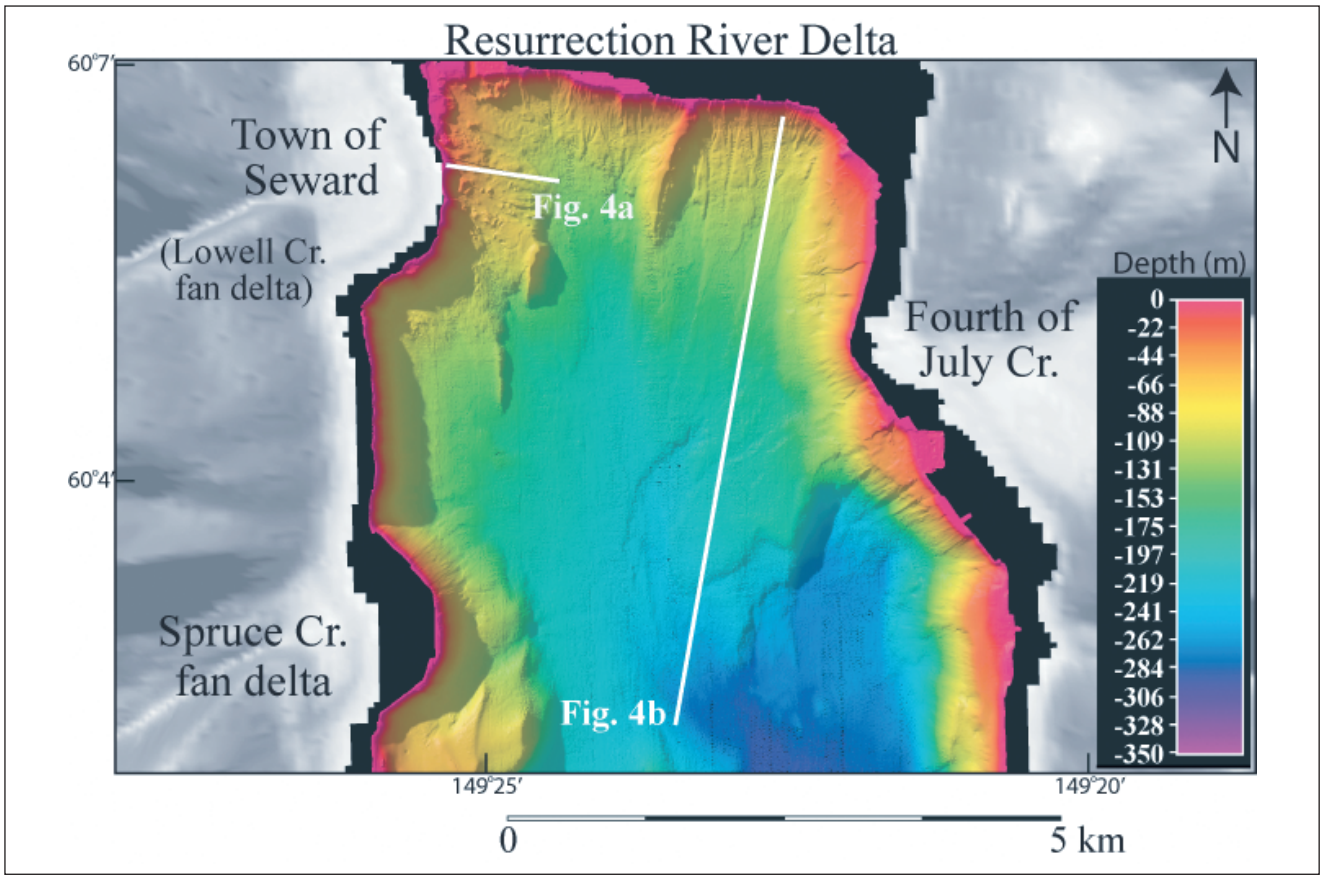

Fig 3. Shaded relief multibeam imagery of the head of Resurrection Bay in map view. Locations of seismic profile lines shown in Fig. 4 are identified.

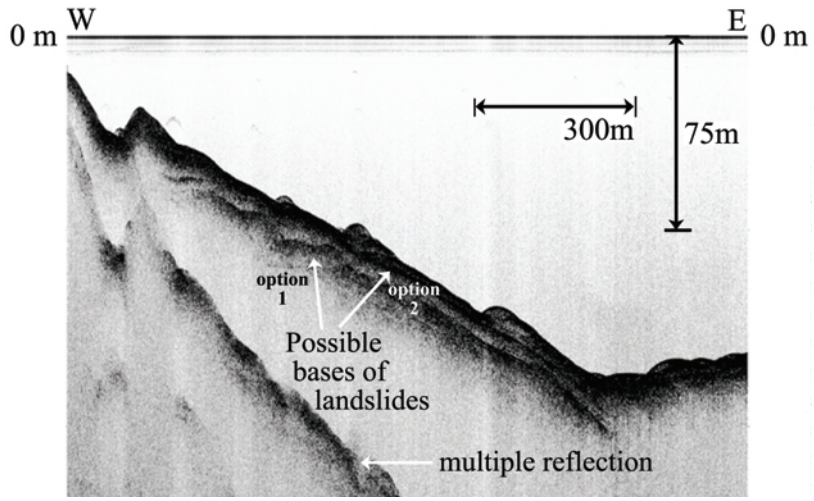

Fig 4a. High-resolution subbottom profile of blocky landslide debris east of the town of Seward (Options 1 and 2 refer to different possible bases of 1964 failed material; see text for discussion and see Fig. 3 for location of profile).

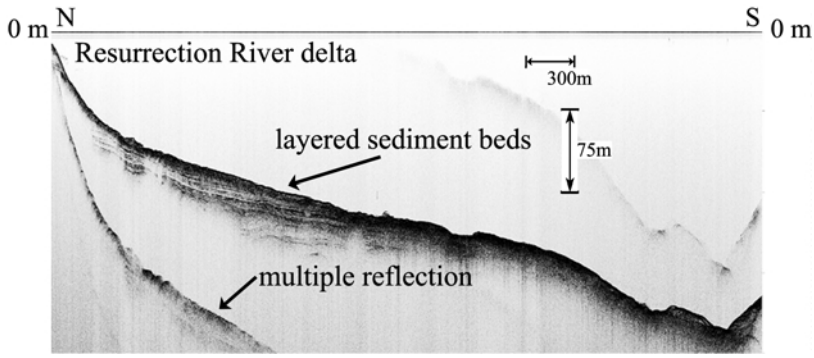

Fig 4b. High resolution subbottom profile of the front of the Resurrection River delta (See Figure 3 for location).

with the chirp system show the field of blocky debris off the Lowell Creek fan-delta (Fig. 4a). Heights of blocks appear to vary between about 5 and 15 m and the blocks may be embedded in a roughly 10 m thick matrix with a smoother seafloor expression. The base of the matrix is a more irregular surface which perhaps corresponds to the pre-landslide surface (Option 1, Fig. 4a). An alternative interpretation is that the base of the 1964 landslide material lies higher in the sediment column and includes mostly blocky material (Option 2, Fig. 4a). The presumed matrix material would, in this case, correspond to pre-earthquake sediment (Fig. 4a).

In other parts of Resurrection Bay, high-resolution subbottom profiles show significantly different records of mass movement. Thick beds of layered sediment lie off the head of the Resurrection River Delta (Fig. 4b). These could correspond to multiple fine-grained sediment flow events, not all corresponding to the 1964 earthquake. Alternatively, the layered sediment could represent hemipelagic sedimentation related to sediment plumes discharged from the Resurrection River.

South of the front of the Fourth of July Creek fan delta, there is little acoustic penetration of the bottom, and gravity coring returned only limited sand grains. We interpret these results to imply that sandy debris flows have flowed down the steep delta front slope onto the flat basin below. These debris flows could have occurred during the 1964 earthquake or subsequent to it.

In summary, the local tsunamis created in 1964 must have been related in part to the failure of the Lowell Creek fan-delta and the production of the blocky debris. This blocky debris may include the part of the town's infrastructure that collapsed into the fjord. Other failures, taking the form of muddy or sandy debris flows, possibly occurred off the Resurrection River delta and off the delta of the Fourth of July Creek. Although it is likely but not certain that failures occurred in these locations, it is clear that if failures occurred they were different in style from those of the failures that occurred in the Lowell Creek delta. Local 1964 tsunamis may have been produced by a number of different landslides and the resulting waves could be a composite of different tsunami events.

Port Valdez

Damage during the 1964 Earthquake

At Valdez, located about 70 km east of the earthquake's epicenter (Fig. 1), the greatest damage was associated

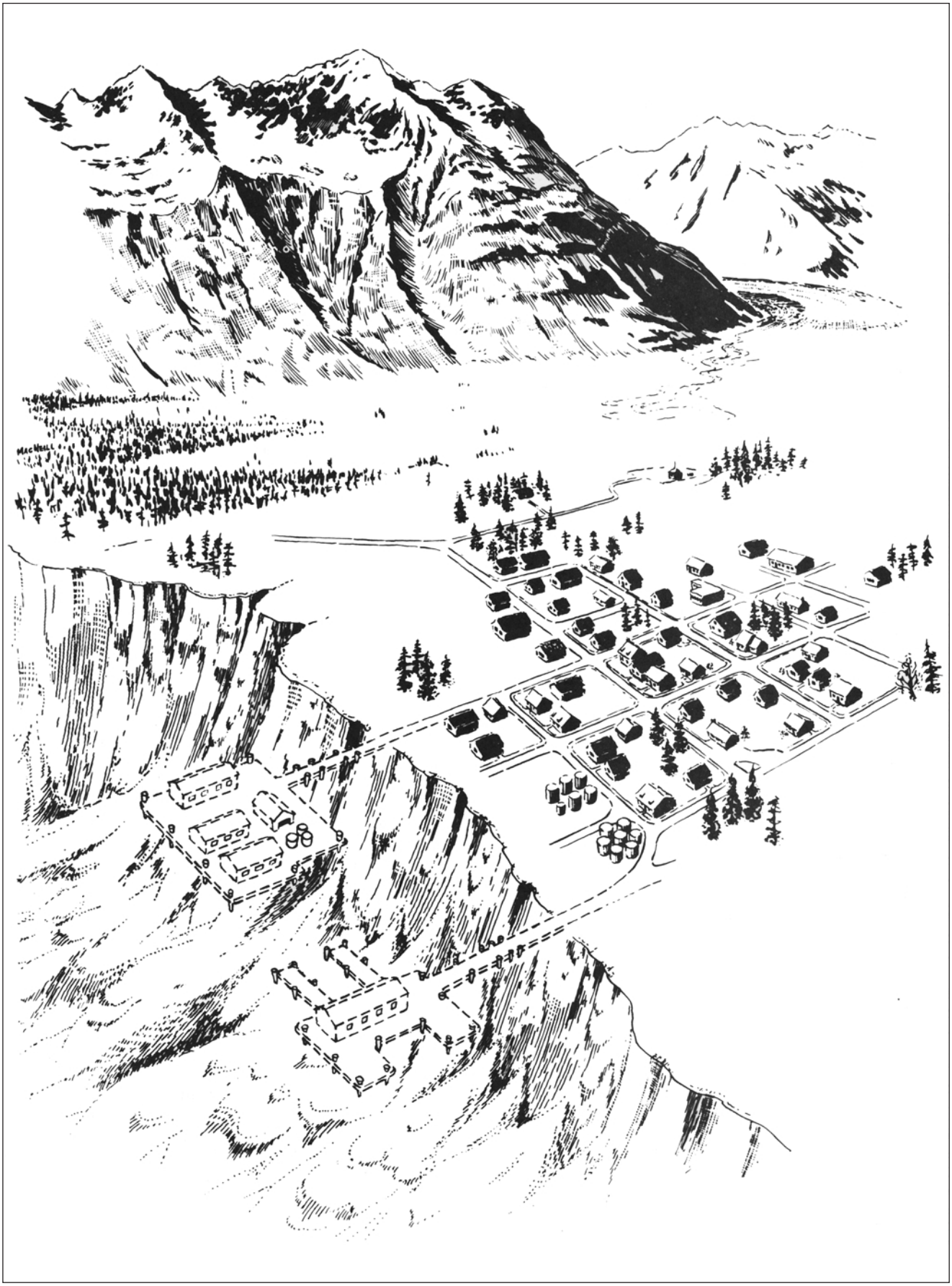

Fig 5. Submarine landslide area at old Valdez (from Coulter and Miliaccio, 1966). The dashed lines indicate the dock area destroyed by the landslide.

with a delta-front landslide involving an estimated 75 million cubic meters of sediment (Coulter & Migliaccio 1966). The landslide was first observed indirectly when, shortly after shaking began, a cargo ship unloading at the town dock began to toss violently, with vertical motion in excess of 10 m and rolls of 50°. Shoreward retrogression of the landslide soon reached the docks, causing them to vanish instantly into the turbulent water. A motion picture shot at the time showed the landslide head scarp with ocean water rushing over it (Wilson and Tørum, 1973). The entire waterfront was lost, along with warehouses, a cannery, and heavy equipment (Fig. 5). There were 31 deaths. The initial 10 m high wave, which occurred shortly after shaking began, inundated the waterfront and propagated westward down the fjord (Wilson & Tørum 1973). A wave of similar size, either generated within or reflected from the far end of the bay, struck Valdez about 10 minutes after the earthquake. Later that night, 6 and 8 hours after the earthquake, a tidally augmented seiche (an oscillation of the surface of the bay) again advanced into the town. Following the earthquake, widespread subsidence of the ground surface near the town continued for several months.

The sediment along the waterfront consists of a 7 to 10 m thick layer of sandy-gravel fill that is underlain by an unknown thickness of gravely sand outwash with interbedded layers of silt. Scientists and engineers who studied the slope failure at Valdez speculated that the delta-front liquefied in response to the earthquake and the drop in water level, then the landslide material transformed into a mobile, low-density sediment flow that spread much of the sediment as a thin deposit away from the delta (Hampton et al. 1993).

At least five previous seismic events in Valdez, between 1899 and 1925, were accompanied by submarine landslides, as evidenced by the occurrence of phenomena such as communication cable breaks and sudden water depth increases (Coulter & Migliaccio 1966). There are reports of three small submarine landslides (in the early and late 1920's and in the early 1940's) that damaged parts of the dock facilities but were not associated with earthquakes. Instead, they probably were due to loading by the docks themselves or by localized sedimentation associated with river-control projects.

According to engineering analyses (Shannon & Wilson 1964), the stability of the delta at Valdez did not seem to be increased by the landslide, and similar large slope failures are expected in connection with future earthquakes. This threat prompted the decision to move the entire town of Valdez to a more stable site 5.5 km to the west. An engineering and geological study of the fan pointed out the comparative desirability of this site.

Recent surveys

Figure 6 shows multibeam imagery of all of Port Valdez and includes point estimates of tsunami wave heights experienced during the 1964 earthquake (Plafker et al. 1969). The greatest wave heights (38-52 m) were observed near the mouth of Shoup Bay in the northwestern part of the fjord. Waves elsewhere were commonly in excess of 10 m.

The multibeam bathymetry of Port Valdez shows a number of important characteristics (Fig. 6). Perhaps

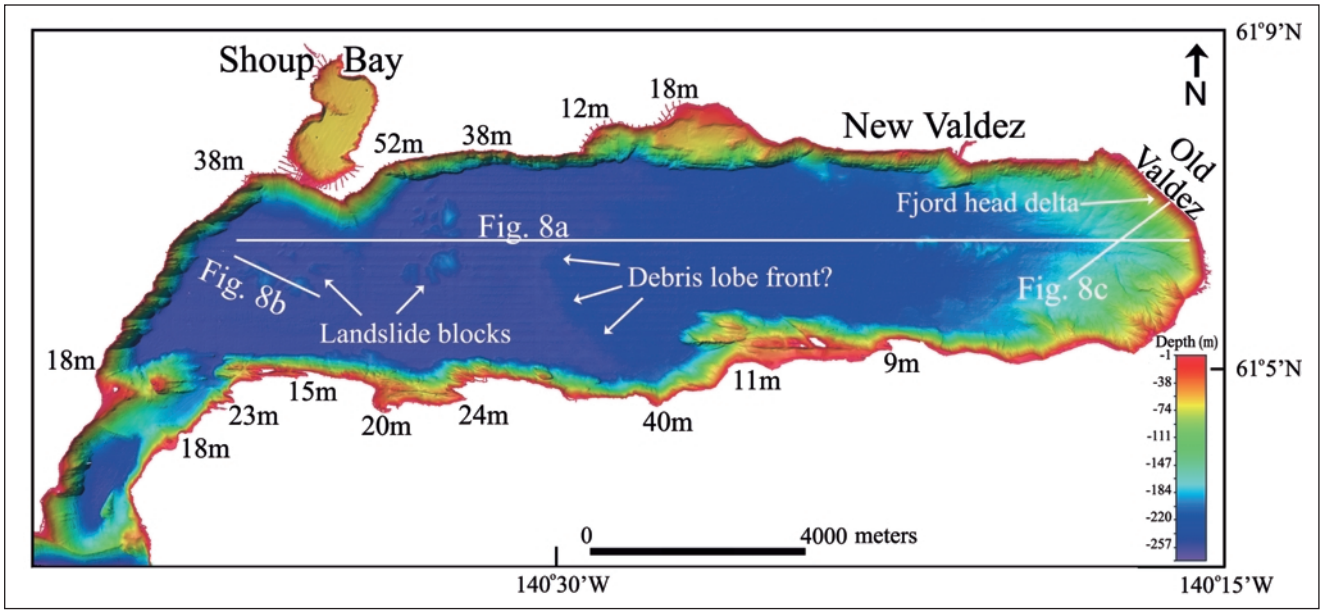

FIg 6. Multibeam imagery of Port Valdez showing landslide features discussed in the text. Labels around margin of the fjord show the estimated tsunami wave heights resulting from the 1964 earthquake (Plafker et al., 1969). Locations of seismic profile lines shown in Fig. 8 are identified.

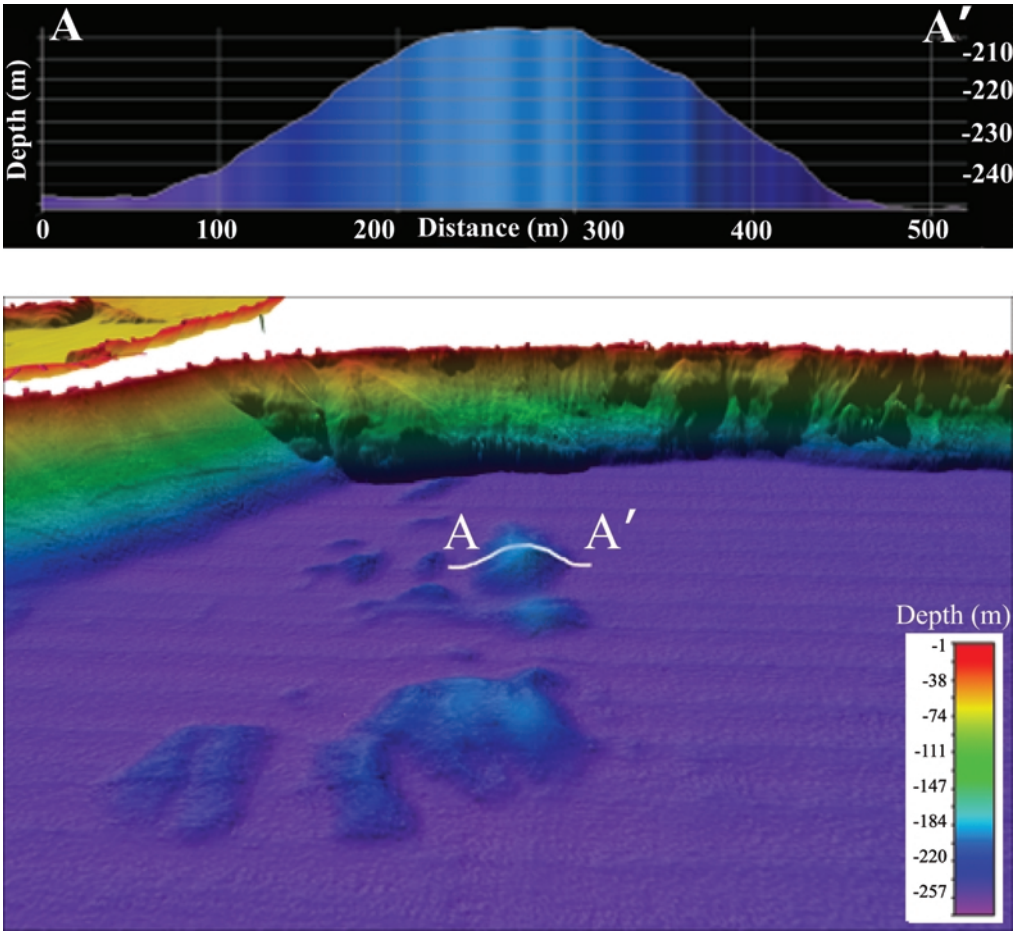

Fig 7a. Oblique view of possible landslide blocks to the southeast of the mouth of Shoup Bay. Vertical exaggeration in 2x. Profile A-A' (derived from multibeam bathymetry) shows the size of one of the blocks.

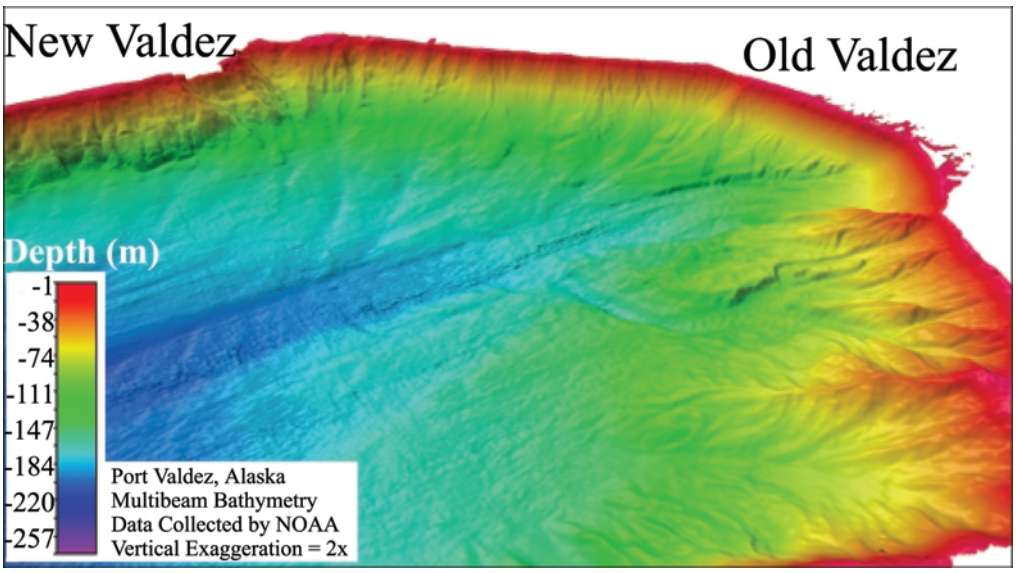

Fig 7b. Oblique multibeam image of the head of Port Valdez fjord. Image shows features associated with the fjord-head delta.

most significant are a number of large blocks found offshore of the mouth of Shoup Bay. There appear to be two sets, one southeast of the mouth and the second southwest of the mouth. An oblique view of the objects to the southeast (Fig. 7a) shows several large blocks with a profile across one of the blocks. This profiled block is about 300 m across and about 40 m in height. The morphology of the blocks strongly suggests that they were displaced during a landslide and resemble similar landslide features off the Hawaiian Islands or in Lake Tahoe (Moore et al. 1989; Smith et al. 2002; Gardner et al. 1999). The presence of these large landslide blocks near the locations of the largest 1964 tsunami waves (Fig. 6) presents the intriguing possibility that

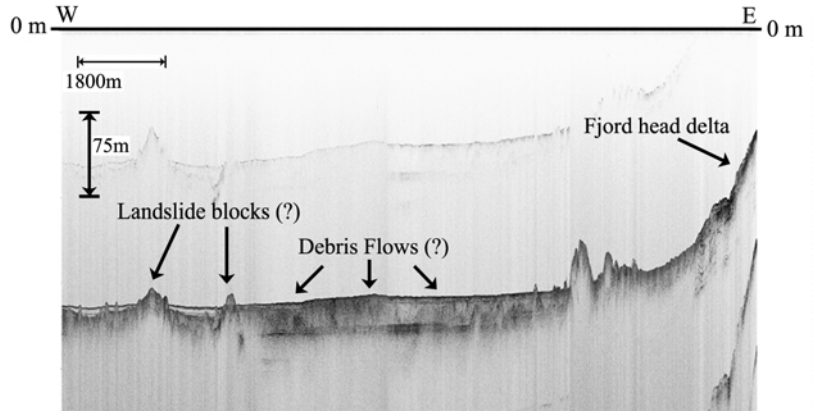

Fig 8a: High resolution subbottom profile along the entire length of Port Valdez (see Fig. 6 for location).

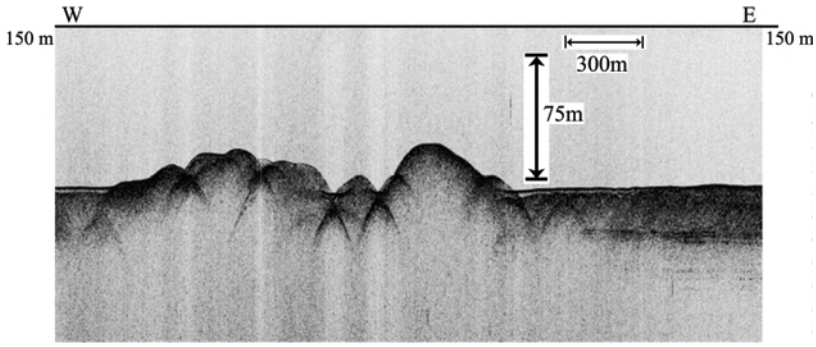

Fig 8b: High resolution subbottom profile across possible landslide blocks in the western part of Port Valdez (see Fig. 6 for location).

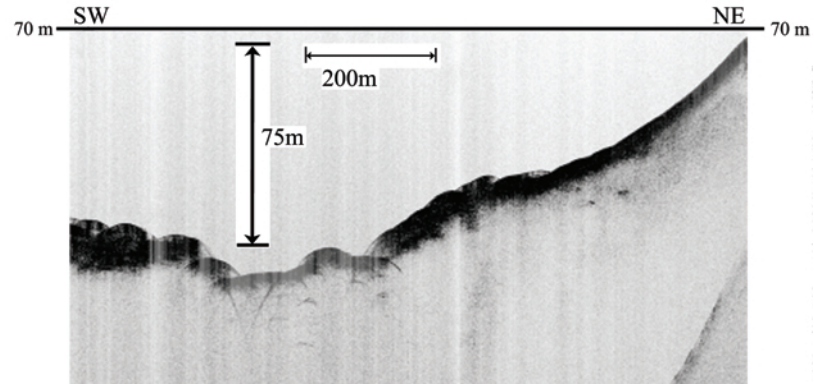

Fig 8c: High resolution subbottom profile down the face of the fjord-head delta in Port Valdez (see Fig. 6 for location).

the motions of these blocks caused the large waves. However, arguing against this interpretation are subbottom profile records across these blocks (Figs. 8a and 8b) that show that the base of the blocks extends below the seafloor. Recent (post-landslide?) sediment deposits appear to bury the lower parts of the blocks by as much as 10 m (Fig. 8a). To deposit 10 m of sediment in the 41 year time span since the 1964 earthquake, the sediment accumulation rate would need to be about 25 cm/yr. Although such a rate is very high, sediment accumulation rates in the range of 1 to 70 cm/yr have been reported in Icy Bay, Yakutat Bay, and Taylor Bay, other fjords along the southern coast of Alaska (Jaeger & Nittrouer 1999; Molnia 1979). Arguing against such rapid deposition are limited deep penetration seismic profiles (von Huene et al. 1967) that show a total thickness of sediment deposited during the Holocene of about 350 m. Such thicknesses could have been emplaced with average accumulation rates in the range of only 5 cm/yr. Perhaps more likely, sediment deposits on the floor of Port Valdez could have been augmented by debris flows travelling west after the failure of the fjord-head delta. If the blocks off Shoup Bay moved rapidly during and after the earthquake, they could have been in position by the time the debris flows reached the western part of the fjord. Accordingly, the possibility exists that the large landslide blocks off Shoup Bay correspond to the 1964 earthquake and could have produced the high tsunami runup in the western part of Port Valdez

A second important characteristic shown by the multi-

beam imagery is the morphology of the eastern end of Port Valdez, in the vicinity of old Valdez and the fjord-head delta (Figs. 6 and 7b). Most of the loss of infrastructure and human life in old Valdez was directly related to landsliding of the delta face and resulting landslide-induced tsunami waves. A comparison of bathymetric depths before and after the earthquake (Coulter & Migliaccio 1966) shows a deepening of the seafloor by as much as 100 m over a distance extending at least 1.5 km offshore. Indications of this major sediment failure are difficult to discern in the modern multibeam imagery. Rather, what is seen is a complex surface covered by chutes and gullies, similar to the face of the Resurrection River delta in Resurrection Bay (Fig. 3), with little indication of a deposit of landslide debris at the toe of the delta front. The material removed by the massive landslide appears to have been completely removed from the delta head, perhaps by mobilizing into a fluid debris flow or turbidity current. A high-frequency, high-resolution seismic reflection profile of the area off old Valdez (Fig. 8c) shows a bottom with little acoustic penetration. Attempts to core in the area recovered only traces of sand.

A final, but subtle, feature on the floor of Port Valdez is a possible debris flow lobe front slightly west of the center of the fjord (Fig. 6). Additional indications of such a lobe are apparent in the longitudinal sub-bottom profile of the fjord (Fig. 8a). If this is a debris lobe it could be the remains of the large amount of sediment removed from the fjord-head delta during the earthquake.

Summary and Conclusions

This paper shows a variety of landslide features on the floors of Resurrection Bay and Port Valdez, many undoubtedly corresponding to the 1964 earthquake. In most locations of failure, slide scars are not clearly evident in the source regions. The morphology of depositional features ranges from very large blocks in western Port Valdez, to smaller blocks off the town of Seward to dispersed debris flows that may extend from fjord-head deltas for long distances out into the fjords. The more blocky failures seem to relate to failures of sidewalls and small fan deltas, whereas the more diffuse debris flows appear to correspond to fjord-head delta failures. Potentially, a variety of failures types can occur almost simultaneously as a result of the same triggering event.

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