Earthquake, Landslide and Tsunami Hazards in the Port Valdez area, Alaska: Consultation to the Prince William Sound Regional Citizen's Advisory Council

Prepared for:

Prince William Sound RCAC Regional Citizens' Advisory Council

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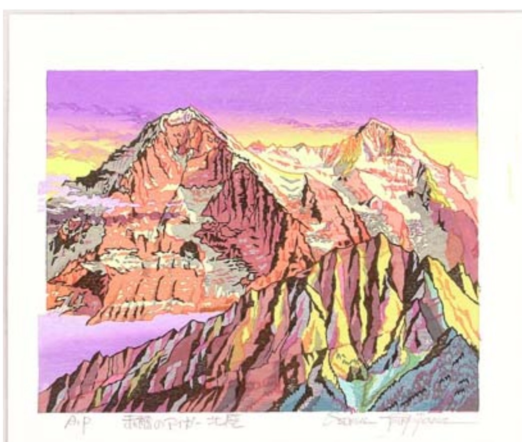

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EXECUTIVE SUMMARY

The 1964 earthquake demonstrated that the Valdez area is subject to enormous earthquakes and coeval tsunamis. The geologic record of prehistoric earthquakes and tsunamis in the Valdez area has not previously been studied.

Historic and prehistoric paleotsunami deposits were identified during this study at sites near Shoup Bay, at Saw Island in the Valdez Marine Terminal, and at a site near Solomon Gulch. Paleotsunami deposits are distinctive sediments found in certain geologic settings that record deposition by large prehistoric tsunamis. Large tsunamis are usually coeval with great earthquakes, and the history of tsunamis in the Valdez area is interpreted as a proxy record of past great earthquakes. Multiple accelerator mass spectrometry radiocarbon dates and conventional radiocarbon dates indicate major prehistoric earthquakes also created large tsunamis in the Valdez area ca. 950-1000 yr B.P., ca. 3800 yr BP. and ca. 4300 yr BP. A large landslide near the VMT dated to 5800 yr BP may have been triggered by a still older earthquake.

The tsunami dated to ca. 950-1000 yr BP was higher and affected a larger inland area at the eastern end of Port Valdez than the historic 1964 tsunami. The 950-1000 yr BP tsunami was probably caused by submarine landslides from the Shoup Bay Moraine and the Valdez Glacier Stream and Lowe River fan deltas. Some of the extensive submarine landslide deposits on the floor of Port Valdez appear to pre-date the 1964 earthquake, and may be correlative with the 950-1000 yr BP event. The tsunamis at 3800 and 4300 yr BP may also have been larger than the 1964 event, but were not as large as the 950-1000 yr BP event. The 950-1000 yr BP earthquake may have been significantly larger than the 1964 earthquake. Little could be determined about the magnitude of a possible earthquake that may have caused a large landslide dated to 5800 yr BP.

Prior estimates of seismic hazards in the Valdez area have been based on an assumption that future earthquakes will resemble the 1964 event, and an educated guess that such events will recur only every few thousand years. The actual duration between great earthquakes in the Valdez area has apparently varied between ca. 500-2800 years, with some previous earthquakes and tsunamis being larger than the 1964 event. The discovery and documentation of records of four great earthquakes within the last 4300 years and possibly as many as five earthquakes in 5800 years shows that the duration of quiet intervals between large earthquakes in the Valdez area is variable and can be shorter than assumed in prior seismic safety evaluations. Even assuming a repeat of the shortest interval found between prehistoric earthquakes, another giant subduction zone earthquake similar to the 1964 event is unlikely to occur for hundreds of years. A small but real possibility exists, however, that a local earthquake on a different fault or a large but distant earthquake might cause submarine landslides and generate dangerous local tsunamis in Port Valdez.

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INTRODUCTION

The dangers of seismic hazards and tsunamis were brought home to Alaskans when the “Good Friday” Earthquake struck south-central Alaska on March 27, 1964. This earthquake had a magnitude of 9.2, and is the second largest earthquake ever measured with modern instruments. The earthquake caused severe damage along the coast of south-central Alaska due to shaking, regional and local effects of uplift and subsidence, landslides and subaqueous landslides, and tsunamis.

Since 1964 significant increases in population and major construction of infrastructure has occurred in some areas that were affected by the 1964 earthquake. In the Valdez area, construction from 1974 to 1977 resulted in the completion of the southernmost part of the Trans-Alaska Pipeline System (TAPS), designed to bring oil south from Prudhoe Bay to the Valdez Marine Terminal (VMT). Efforts were made in conjunction with the construction to evaluate seismic hazards that might affect the TAPS and the VMT in the Valdez area. Purely theoretical models, based on assumptions about the behavior of faults in Alaska were used at that time to roughly estimate the recurrence interval of large earthquakes similar to the one that occurred in 1964.

Since 1964, new methods, approaches, and technologies for reconstructing the actual past behavior of faults and the history of earthquakes have been developed. In some cases it is possible to use geologic data to reconstruct the actual timing of past events. By using real data on the actual past history of earthquakes for a given region, it is possible to make estimates of seismic hazards that are more reliable and rigorous than those based simply on assumptions about fault behavior.

In the spring of 2006 I was asked by the Prince William Sound Regional Citizens’ Advisory Council (PWSRCAC) to make a new evaluation of potential seismic hazards that might affect the TAPS and the VMT in the Port Valdez area. During the summer of 2006 I examined aerial photographs and satellite images and made a field study in the Port Valdez area to independently evaluate potential seismic hazards. I employed modern approaches and newly available technology, including studying satellite imagery, using GPS location equipment, and utilizing newly developed techniques for the identification and sedimentologic and stratigraphic studies of prehistoric tsunami deposits. I then applied tephrochronology and accelerator mass spectrometry (AMS) radiocarbon dating methods to age date the newly discovered prehistoric tsunami deposits produced by ancient earthquakes.

This approach has produced valuable new data on the timing, frequency and effects of prehistoric earthquakes in the Valdez area. This in turn allows realistic information, rather than theoretical assumptions, to be applied to a new evaluation of the seismic hazards from future earthquakes in the Port Valdez area. This report summarizes the data and my interpretations resulting from this study.

SCIENTIFIC BACKGROUND TO THIS STUDY

Geology of the Valdez Area

The rocks that make up the mountains surrounding Valdez are composed of a variety of sediments, metasediments, small intrusions and volcanic rocks, and consist mainly of graywacke, siltstone, shale, slate, pillow basalt, lesser sheeted dikes, gabbro, and ultramafic rocks that are broadly assigned to the Late Cretaceous Valdez Group (Crowe and others, 1992; Nelson and others, 1985; and Nelson and Nelson, 1993; Schrader, 1900). The Valdez Group is part of an enormous assemblage of Mesozoic accretionary complex rocks called the Chugach terrane (Jones and others, 1987) that extends around much of the northern Gulf of Alaska.   Similar but slightly younger rocks of Paleogene age found farther south in Prince William Sound are assigned to the Orca Group, which in turn is part of an accretionary complex called the Prince William terrane (Plafker, 1969, 1971; Tysdal and Case, 1979).

The Valdez Group and the Orca Group were mainly created by the erosion of ancient volcanic islands (Phillips, 1996; Dumoulin, 1987) although some of the sediments appear to have been derived from coastal areas of Canada (Farmer and others, 1993), including the mainly basaltic Wrangellia and Peninsular terranes (Phillips, 1996). The two rock groups are separated by the Contact Fault, which crosses Prince William Sound south of Port Valdez (Winkler and Plafker, 1981; Bol and Gibbons, 1992).

Both the Valdez Group and the Orca Group rocks are intruded by plutonic rocks with reported age dates of 50 to 54 Ma (Plafker and Lanphere, 1974; Nelson and others, 1985; Haeussler and others, 1995). Locally, even younger plutons dated to 32-38 Ma occur (Barker and others, 1992; Bradley and others, 1993; Lanphere, 1966; Nelson and others, 1985; Nelson and others, 1995).

The rocks of the Chugach Terrane and the Prince William Sound terrane accretionary complexes have been warped into tight folds on a kilometer-scale. Valdez lies near the hinge of an enormous orocline which comprises much of the coastline area of south-central Alaska (Grantz, 1966). Near Valdez the regional strike of bedding changes by about 90. The plutons in the Valdez area are locally offset by faulting related to the oroclinal bending, suggesting that the deformation occurred during or soon after intrusion of the plutons (Haeussler and Nelson, 1993). The Contact Fault separates rocks of the Valdez Group sedimentary rocks from the Orca Group rocks to the south and cuts across Valdez Narrows (fig. 1).

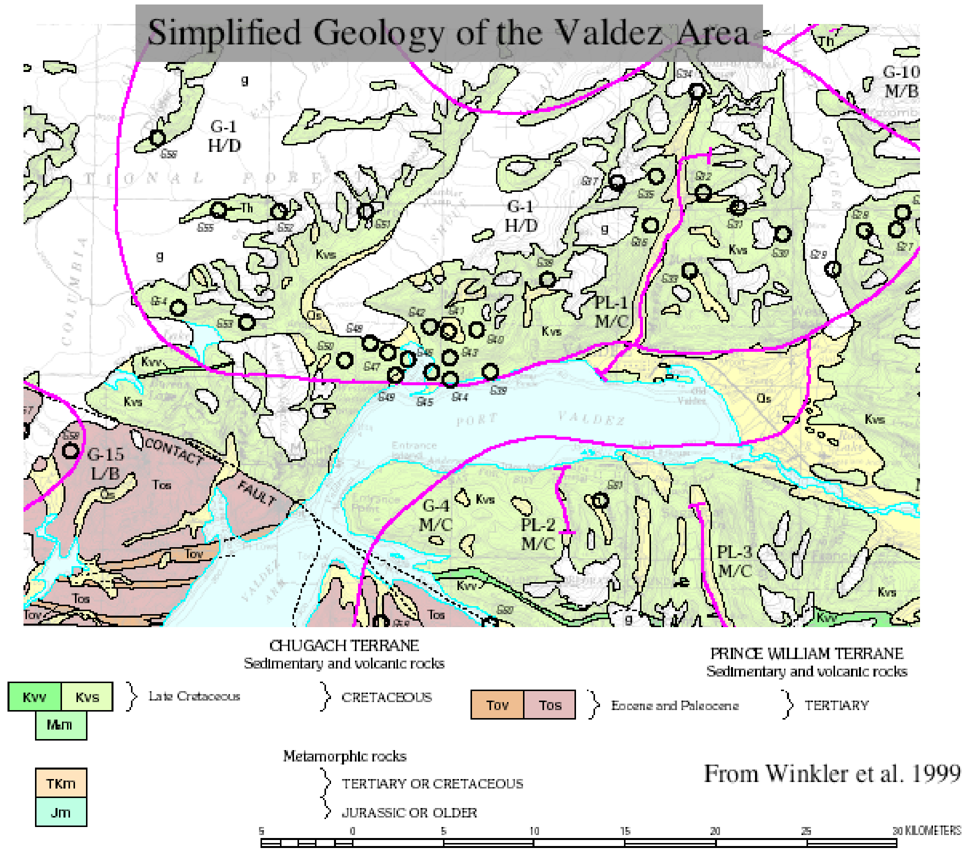

Figure 1. Simplified Geologic Map of the Valdez Area, from Winkler et al. (1999). The NW-SE trending Contact Fault separates Late Cretaceous rocks of the Valdez Group fo the Chugach Terrane from Eocene and Paleocene rocks of the Prince William Terrane. The Contact Fault zone has been deeply eroded, especially at Jack Bay, but there is no evidence that the Contact Fault is active.

There is no evidence the Contact Fault is active. Many smaller faults and lineaments cross Port Valdez and show a strong east-west or E-W orientation (see section on aerial photo mapping below). The lineaments express themselves as parallel ridges and valleys in the bedrock on either side of Port Valdez. Displacements are apparently minor along these small features since no significant offsets of geologic contacts have been observed. Strike-slip displacements of several kilometers are permissible on a few larger faults that juxtapose different sedimentary facies within the accretionary complex, but there is currently no evidence that any of the faults exposed in surface rocks around Port Valdez are active today.

Glaciation of these rocks during the Pleistocene Ice Ages produced the modern topography that form Port Valdez and Valdez Arm. The faults, lineaments, and other structural features, together with any zones of softer and weaker rocks within the surrounding metasediments have been extensively eroded by glaciers during multiple Quaternary glaciations, producing a distinctive corrugation in the topography parallel to the direction of Port Valdez. Saw Island at the VMT and virtually all the other islands in Port Valdez are notably elongate due to differential glacial erosion. Little is known about the precise number of glaciations that have affected the Valdez area, because any deposits left by the older glaciations have been eroded by subsequent ice advances. The most recent glaciation occurred during the late Wisconsin ca. 25-14,000 years ago when the Valdez Glacier and other alpine glaciers from the Chugach Mountains north of Valdez merged with greatly expanded glaciers fed from the mountains around Port Valdez, and flowed more than 100 km south to the edge of the continental shelf (Fig. 2). The glacier flowed over the islands of Prince William Sound to beyond Kayak Island. As this glacier retreated at the end of the last ice age ca. 14,000 years ago it locally left glacial deposits on the bottom of Port Valdez. Minor readvances of glaciers have occurred several times during the last 10,000 years, most recently during the several-hundred-year-long "Little Ice Age" which ended at the beginning of the 20th century. The terminal moraine at the end of Shoup Bay, the moraines impounding Solomon Lake, and many other geomorphic features in the Valdez area were formed during the Little Ice Age. The Shoup Bay Glacier, the Valdez Glacier, and virtually all other glaciers around the Port Valdez area have undergone massive retreat since the start of the 20th century.

Large fluvial deltas, especially at the Lowe River, have been constructed into Port Valdez since the end of the last Ice Age. Fine-grained clastic sediments from the rivers and from glacial-marine sedimentation at Shoup Bay has accumulated on the seafloor in Port Valdez, producing a flat-bottomed estaurine basin (Hood et al., 1973; Shaw and Hameedi, 1998). Submarine landslides, submarine gravity flows and turbidites are interbedded with the marine and glacial marine sediments on the floor of Port Valdez (Sharma and Burbank, 1973; Sharma, G. D. 1979; Naidu and Klein, 1988).

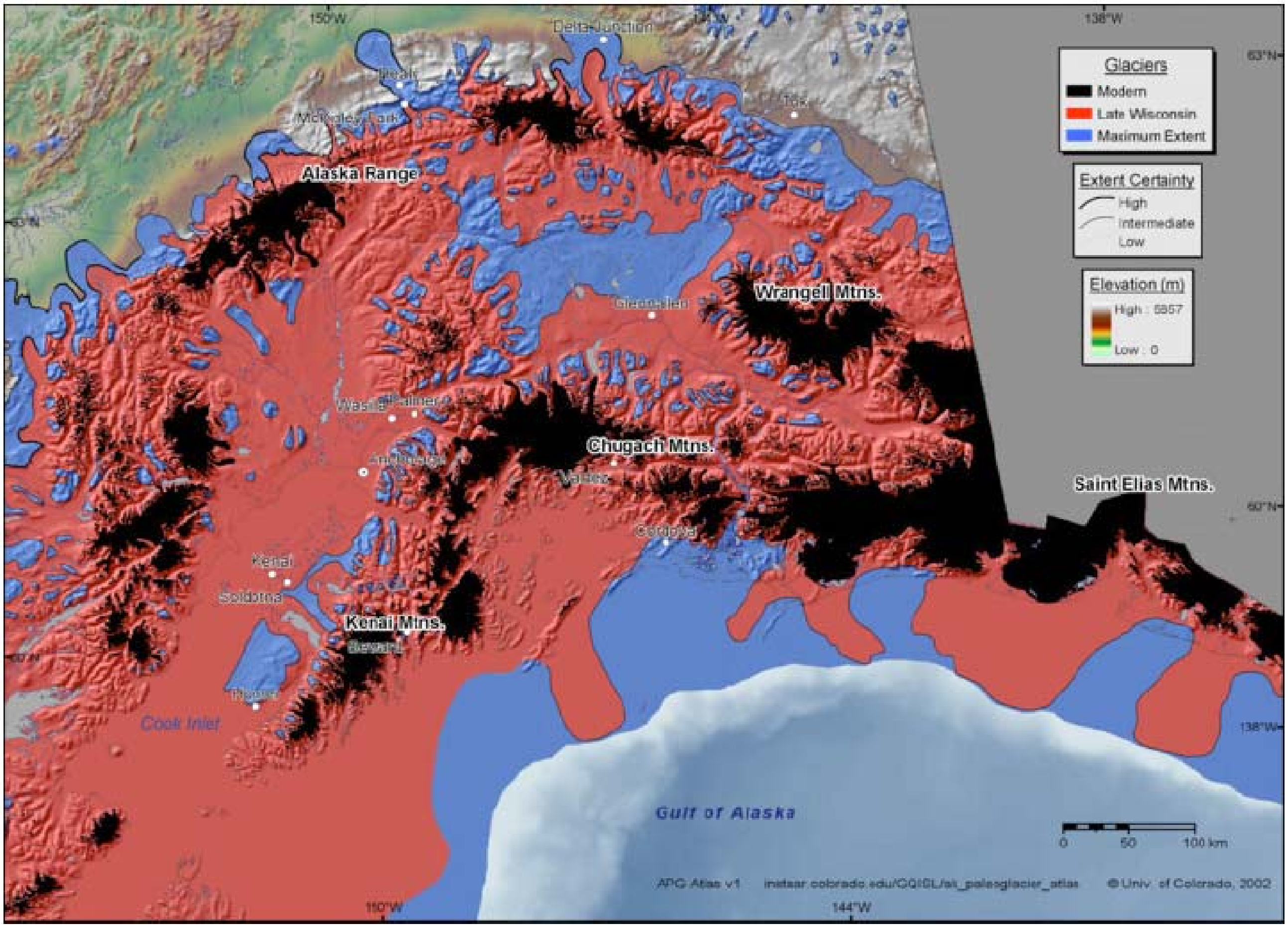

Figure 2. Extent of late Wisconsin glaciation and the maximum glaciation in the Valdez area and other parts of south-central Alaska. (from the Alaska Paleoglacier Atlas, a composite glacial map of Alaska with data contributed by W. Manley, D. Kaufman, T.A. Ager, Y. Axford, N. Balascio, J.E. Begét, J.P. Briner, P. Carrara, T.D. Hamilton, D.J. Lubinski, R.D. Reger, H.R. Schmoll, R.M. Thorson, C.F. Waythomas, F.R. Weber, A. Werner, and F.H. Wilson.) Glaciers repeatedly filled Valdez Arm and Prince William Sound during the Pleistocene, sometimes extending out to the margin of the continental shelf. The deeply eroded topography in this area is primarily due to the effects of glaciation.

The 1964 Earthquake

The 1964 Good Friday earthquake was caused by subduction of a segment of the northernmost part of the Pacific Plate beneath south-central Alaska. The earthquake lasted about four minutes, and produced deformation over a huge area of south-central Alaska covering more than 125,000 square kilometers. Parts of the Kenai Peninsula and the Kodiak Islands sank 1-2 m, while many areas in Prince William Sound were uplifted 1-2.5 m. Overall, the 1964 earthquake produced uplift across a broad zone close to the subduction zone and subsidence in areas farther inland. Valdez lies near the hinge between the zones of uplift and subsidence, and so experienced little direct tectonic deformation, but shaking produced significant settling and collapse in fan deltas.

The only known surface faulting was on Montague Island in southernmost Prince William Sound, where two known faults broke the surface and produced uplift of 5-6 m.

Displacement of the seafloor under the Gulf of Alaska during the earthquake produced tsunamis that took just 20-30 minutes to travel from the source areas in the Gulf of Alaska to the Pacific coast of the Kenai Peninsula and Kodiak Island. The wave runup locally reached 10-13 m along the outer coast of Alaska. The tsunamis also propagated southwards, and produced damage in British Columbia, Oregon, California and Hawaii.

The four minutes of shaking during the earthquake also caused many submarine landslides and concomitant tsunamis in coastal communities like Seward, Whittier, Chenega, and Valdez.

1964 Tsunami in Port Valdez

The highest tsunami runup that occurred anywhere during the 1964 earthquake was 67 m measured in Port Valdez near the Shoup Bay Moraine. The tectonic tsunami produced in the Gulf of Alaska arrived almost 30 minutes later and was much smaller.

Later studies showed that the unusually high tsunami near Shoup Bay and numerous other local tsunamis generated at sites around the Prince William Sound area were caused by subaqueous mass movements of large volumes of unconsolidated sediment that resulted in displacement of seawater. Field studies showed that most local tsunamis were generated by submarine landslides, but some also occurred where sub-aerial landslides flowed into the sea and at sites where mud flows and slumps of fan deltas and alluvium in bays and fjords were triggered by shaking during the earthquake.

The generation of local tsunamis in response to the interaction of earthquakes, landslides and water is complicated. Tectonic tsunamis are generally formed in deep water, can have a large area of origination, and can cause damage even after traveling hundreds or thousands of kilometers from the earthquake zone. In contrast, local tsunamis originate as water is displaced by submarine mass movements, so that several tsunamis can be created by different landslides at different sites in a single fjord. The interaction of multiple tsunamis within a narrow fjord can produce composite waves that are higher than any single wave, and the local geometry and bathymetry of the fjords can also play a role in locally amplifying wave heights. The 1964 earthquake occurred almost at a low tide, and in some fjords the local tsunamis created resonating oscillations and surges that lasted for hours, with the maximum inundation in some places not occurring until high tide, hours after the earthquake (Grantz and others,1964).

The most damaging tsunami in the Valdez area was generated when a large slump caused about 1300 m of the waterfront area of the original Valdez town site to collapse into the waters of Port Valdez. The slump displaced a huge volume of seawater, and a destructive wave propagated back towards Valdez. This tsunami was 10-13 m high and destroyed parts of the waterfront of Valdez, but had minimal effects away from the town site. In particular, it produced no damage along the shoreline south of the Lowe River delta.

Even larger tsunamis were generated by submarine landslides from the Shoup Bay moraines, a composite glacial delta-moraine deposit at the mouth of Shoup Bay, but these tsunamis affected mainly undeveloped areas. One tsunami traveled east and destroyed the Cliff mine, leaving deposits up to 67 m above sea level. A second tsunami went westward, and was locally more than 40 m high near Shoup Bay. These tsunamis also caused extensive damage in Anderson Bay on the other side of Port Valdez.

FIELD RECONNAISANCE OF PORT VALDEZ

In early July I made a reconnaissance visit by boat to areas around the shoreline of Port Valdez in the company of Dr. Thomas Kuckertz of the Prince William Sound Regional Citizens' Advisory Council. On this trip we used binoculars to examine coastal exposures for evidence of past landslide and rockfall deposits, and to identify sites that might be at risk from future landslides or that might warrant additional fieldwork. This reconnaissance trip also provided a useful overview of the geography and features of the Valdez area.

We did not identify any large prehistoric landslide deposits on the slopes around Port Valdez on this reconnaissance trip. These results are consistent with previously published geologic maps of the Port Valdez area that had not located large landslides in this area, and also with my analyses of

Figure 3. Steep cliffs and well-developed joints characteristic of rocks on the northwest side of the Valdez Narrows to the northeast of Mt. Thomas. Note the presence of light colored patches of rock on the cliffs, showing the sites of recent rockfalls. These prominent joint sets constitute potential failure planes for rockfalls and large landslides.

Figure 4. Huge, active talus fans fed by rockfall extend down to sea level below the summit of Mt. Thomas on the northwest side of the Valdez Narrows. These talus cones are fed by rockfalls and landslides from the steep cliffs above that are cut by well-developed jointing planes.

satellite and aerial photographic images of the Valdez area (see below).

One site was identified where there appears to exist some potential for large rockfall avalanches in the future was located along the northwest side of the Valdez Narrows. While virtually all of the slopes around Port Valdez are forested, extensive steep unvegetated cliffs rise directly from tidewater for several kilometers along the northwest side of the Valdez Narrows.

Several factors suggest these cliffs are potentially hazardous. These include (1) these cliffs are the steepest and highest of any found around Port Valdez and (2) the cliffs are cut by large joints that provide potential failure planes for future landslides (Fig. 3). (3) The steep cliffs are being undercut by wave action. (4) Several large talus cones along the base of the cliffs in this area show that rockfalls are common in this area (Fig. 3, 4). (5) A major fault (the Contact Fault) cuts across these cliffs just outside of the Valdez Narrows area. This fault is not considered to be active, but it has caused extensive fracturing of rocks around it as shown by the trench and scarp system found along it.

The cliffs at the narrows are being undercut by wave erosion, and the presence of numerous large joint sets in the face of the cliff suggests that this area could be the site of a future large landslide. The relief of this area is similar to that around Lituya Bay, where an earthquake produced a landslide and tsunami during an earthquake in 1958, and some potential may exist for a similar event to occur in this area. However, no large prehistoric landslide deposits were identified in this area during the field reconnaissance. Similarly, no landslide deposits were mapped using aerial photography and satellite data, and no large submarine landslide deposits occur at the base of these cliffs on the floor of Port Valdez (see bathymetric DEM data in section below). These results suggest that the likelihood a large landslide without an earthquake trigger is probably very low, and the fact that even large earthquakes like the 1964 event did not produce a large collapse suggest this area may be relatively stable.

This trip also provided an introduction to the Shoup Bay area and the Shoup Bay Moraine. This area was visited and studied in detail as part of the boat fieldwork carried out in August (see below).

SATELLITE IMAGERY AND AERIAL PHOTOGRAPHY OF PORT VALDEZ

Aerial photographs and satellite images were studied and mapped as part of this project (figs. 5, 6, 7, 8, 9). A digitized set of the aerial photographs purchased for this study is attached with this report (Appendix one). All of the remote sensing imagery was obtained at the Geodata Center of the Geophysical Institute of the University of Alaska. Satellite images were obtained at no charge from Google Earth. This section will concentrate on the data from the aerial photographs, as they provide the best data on the regional tectonic structures in

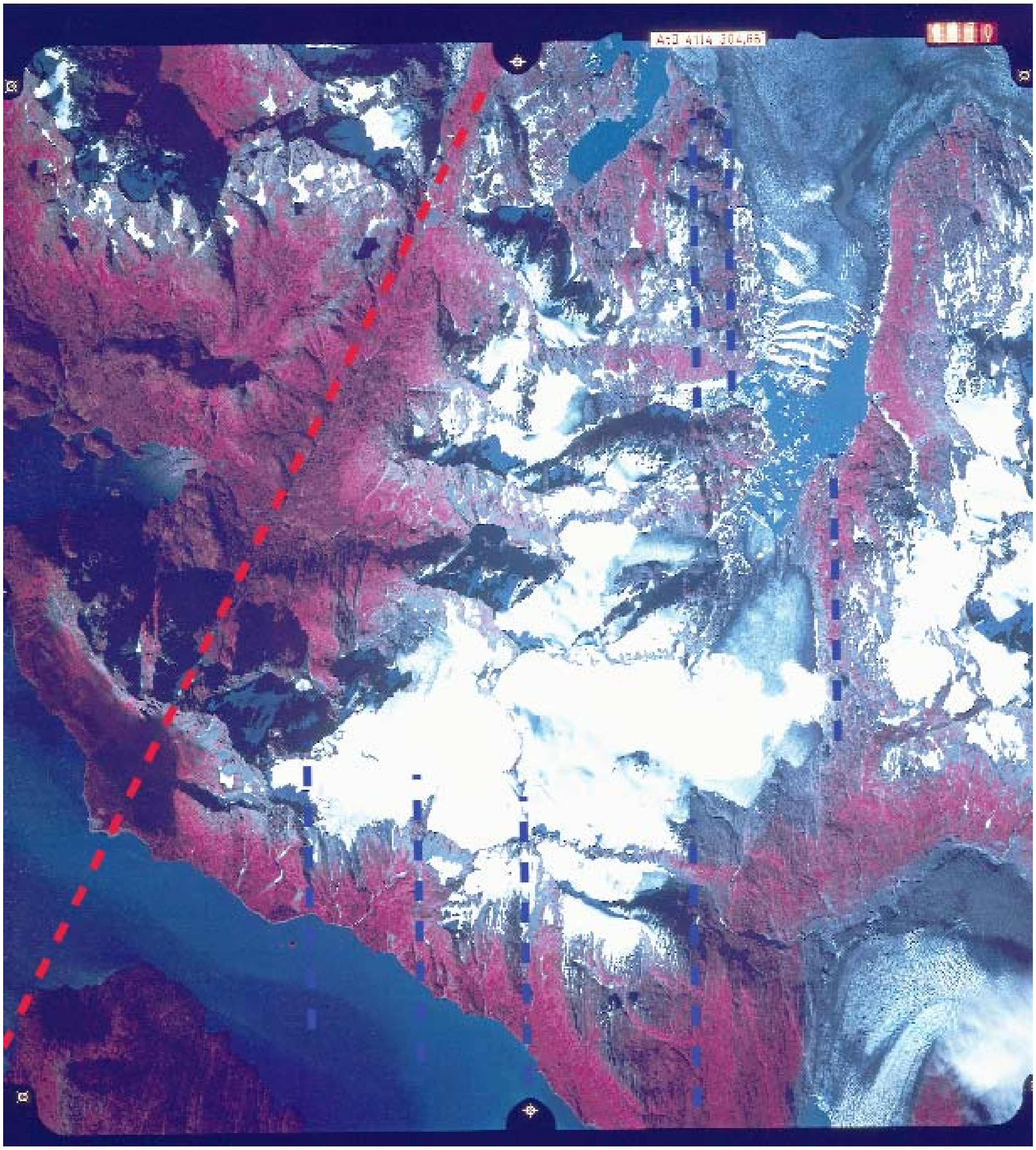

Figure 5. Location of the Contact Fault (red dashed line) and E-W trending lineations in the Valdez Narrows area. Lineations with a similar trend are visible on the south side of the Contact Fault, consistent with previous findings that the fault is inactive. Examples of the numerous lineations are shown by blue dashed lines.

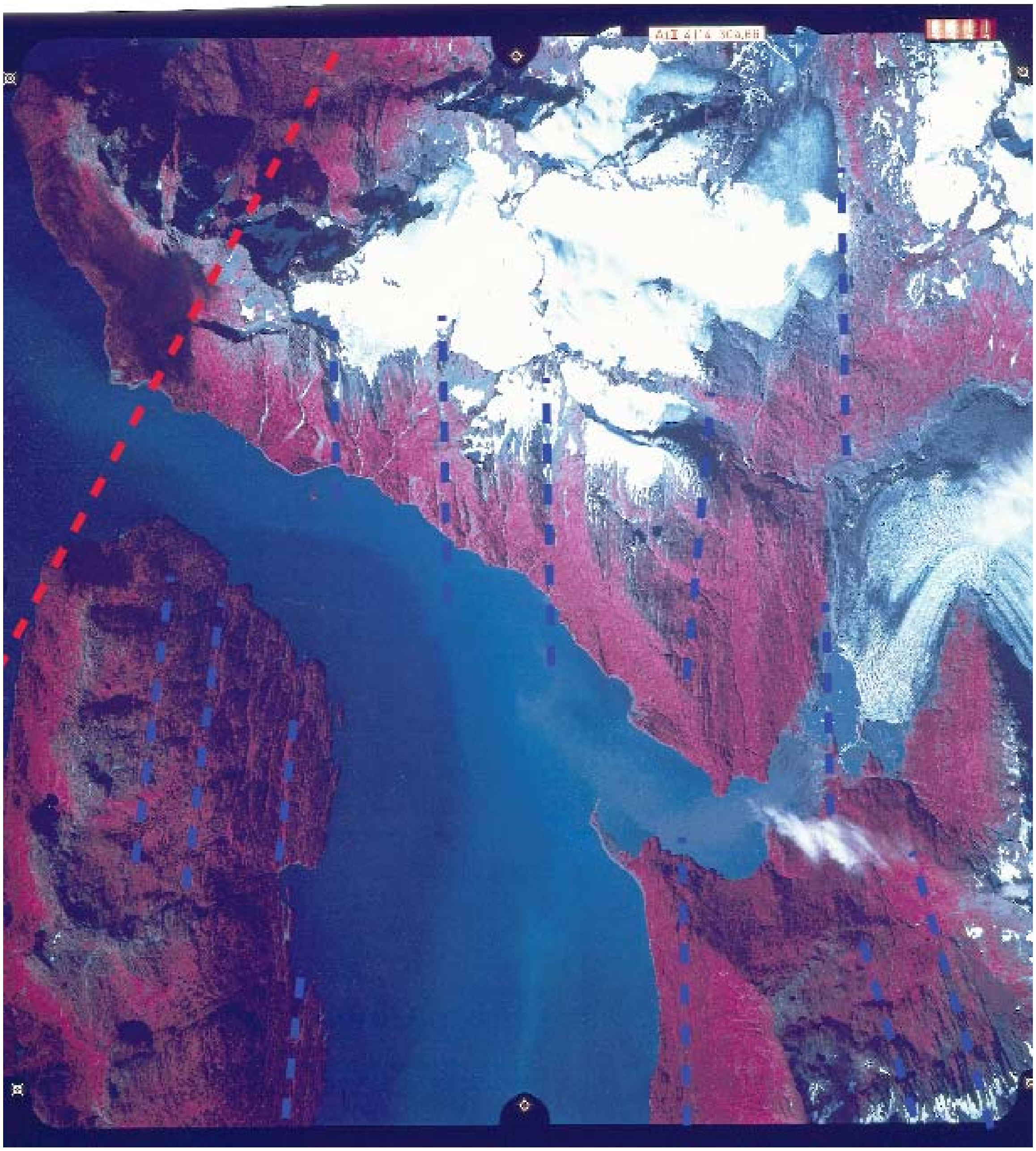

Figure 6. Location of the Contact Fault (red dashed line) and representative E-W trending lineations (blue dashed lines) in the Valdez Narrows and Shoup Bay areas.

Figure 7. Orientation of representative structural lineations in rocks in the central Port Valdez area (blue dashed lines). Virtually all lineations are parallel throughout this region, suggesting that no major structural discontinuities are present.

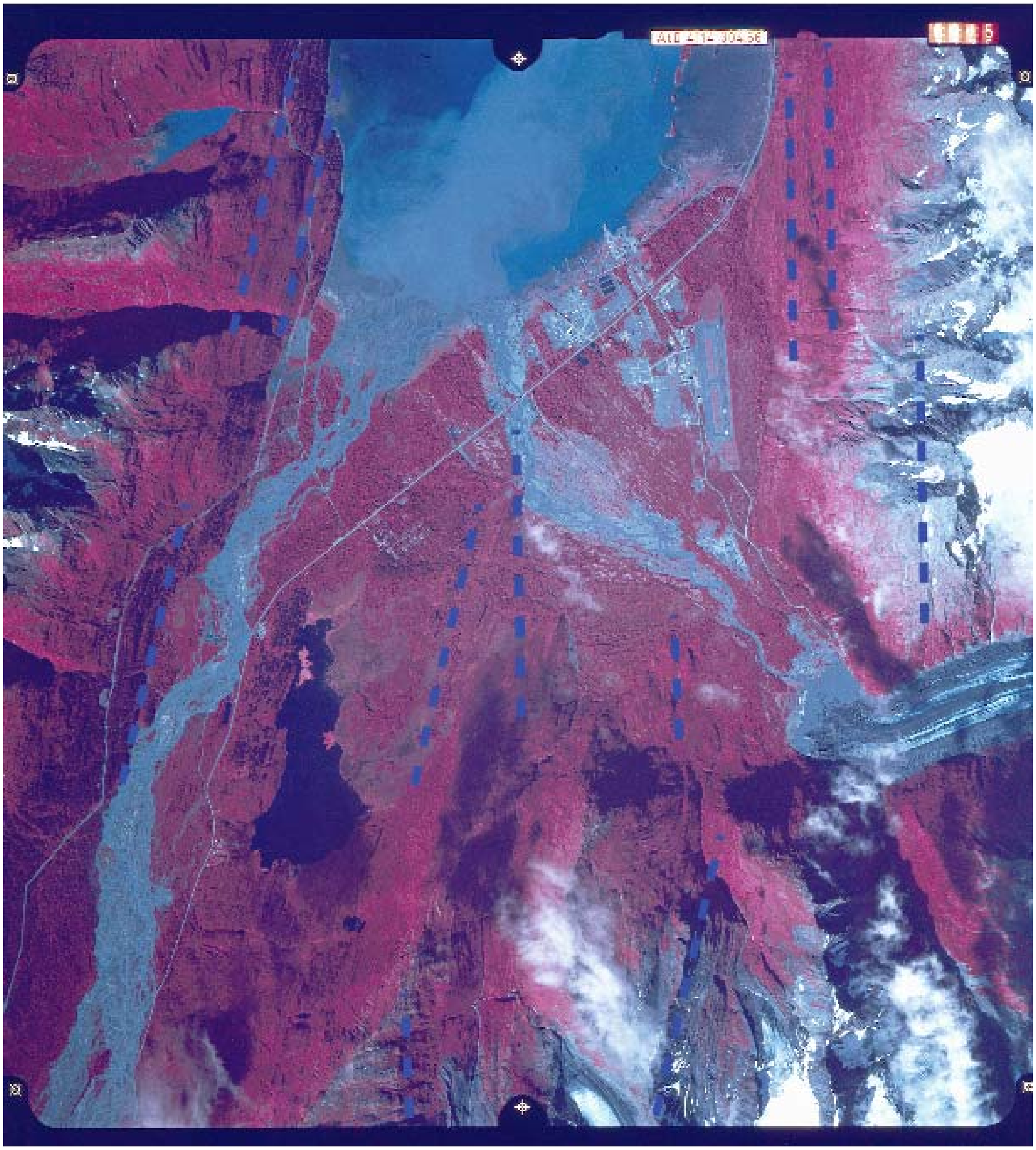

Figure 8. Orientation of representative lineations present in rocks in the upper Port Valdez and Lowe River Delta areas (blue dashed lines). Virtually all lineations are parallel throughout this region, suggesting there are no major structural discontinuities are present.

Figure 9. A slight flexure in the regional trend of the bedrock lineations occurs between rocks forming the middle region of Port Valdez and rocks farther to the east in the Lowe River Delta areas (representative lineations shown by blue dashed lines). However, no significant structural discontinuities occur in the Port Valdez area near the town of Valdez or at the VMT.

the Valdez area because they are at a much larger scale than the satellite data.

The predominant structural feature visible on aerial photographs of the Port Valdez area is a set of major lineaments that trend E-W through the entire Valdez area. Figures 5, 6, 7, 8, and 9 show the distribution of these lineaments in the bedrock on the north and south sides of Port Valdez. The lineaments are easily visible in the aerial photographic images, indicating they were readily eroded by Pleistocene glaciers that traveled down-valley roughly along the trend of the major set of E-W trending lineaments. These structural features produce a readily visible “grain” in the topography of the Port Valdez area. The modern hill slopes on either side of Port Valdez show numerous cliffs, gullies and other alignments of topographic features that parallel the trend of Port Valdez and all reflect this regional structural trend. The structural lineament appears to be a major joint set, reflecting regional tectonic stresses, but may locally include some foliation and lithologic contacts.

Using the aerial photographic images, we also identified two other joint sets in this area. These are most visible in mountains behind the Valdez townsite, and in mountains east of the VMT. Both of these sets are oblique to the major set of lineations, and presumably record two additional minor joint sets.

No active faults or previously unrecognized landslides were found during study of the aerial photography. The previously mapped but inactive “Contact Fault” is visible in the remote sensing imagery, forming a series of aligned linear features and topographic trenches that include Jack Bay just outside the Valdez Narrows and the linear Clear Creek valley west of Mount Thomas (Figs. 5 and 6).

Geochronology of a Large Landslide near the Valdez Marine Terminal

A large landslide deposit is present on the southern side of Port Valdez near the east boundary of the Valdez Marine Terminal. The TAPS access road and pipeline cross the landslide deposit a few kilometers east of the VMT (Fig. 10). Exposures along the access road show the landslide deposits consists of a complex diamicton that locally includes numerous large heterolithic clasts in a fine-grained silt-sandy matrix. The landslide is locally 5-8 m thick, but the overall thickness is very poorly constrained, as it is exposed in only a few places. A very rough estimate of of its volume, based on the width, length, and average thickness of the landslide deposit in the sites where it is exposed by roadcuts, is ca. 80,000-200,000 m^3. The diamicton is interbedded with alluvial sands and colluvium, and is overlain by a thin paleosol and peat.

The landslide deposit was previously identified during construction of the TAPS road and pipeline to the VMT, but no information was obtained at that time on the extent, volume, origin, or age of this deposit. Landslides are often produced by earthquakes, but the possible connection of this landslide to paleoseismic events has not previously been investigated.

Field mapping by Beget and Jason Addison found that the deposit is more

Figure 10. Exposure of large landslide deposit in road cut constructed for the TAPS system 1.5 km east of the VMT. The landslide deposit is more than 5 m thick in this area.

extensive than previously thought. It can be traced for more than 200 m along the trend of the pipeline in exposures created by road construction, and at the west end of the road exposures, the deposit can be traced for another 120 m down the access road towards Port Valdez. We determined that the landslide deposit terminates in the forest and did not reach saltwater. We were unable to climb up the landslide to its source. However, examination of topographic maps and the aerial photography indicates that there is no cliff, mountain, or other rockface that might have been the source of the landslide in the area upvalley from the deposits. There were no distinctive scars or embayments in hillslopes or rockfaces to indicate where the slide originated.

In order to determine the age of this landslide, a radiocarbon sample was collected at a site where pods of organic material were present within the landslide diamicton. A date of 5210 ± 100 yr BP was obtained on a pod of peaty material that had been incorporated within the landslide debris (Table 1).

Some radiocarbon dates are known to deviate from calendar ages by as much as 5-10% because of natural variations in the production of the radio-isotope ^{14}C through time, so this report will use the standard scientific convention that all radiocarbon ages dates are reported as years BP (i.e. before present) to distinguish radiocarbon years from calendar years. The differences between radiocarbon years and calendar years for the radiocarbon samples discussed in this study are not large enough to affect the interpretations of this report.

The landslide must be younger than the material incorporated in it, so the radiometric date is interpreted as indicating the landslide occurred at or slightly more recently than ca. 5200 radiocarbon years ago. Radiocarbon ages differ systematically from calendar ages because the production and uptake of the natural radioactive 14C isotope in the atmosphere has not been linear through time. Calibrating the radiocarbon date to calendar age suggests this avalanche occurred ca. 5800-6300 years ago.

This landslide may record the oldest prehistoric earthquake known from the Valdez area. The date on the landslide debris is older than any of the other dates obtained during this study on paleoseismic events and ancient tsunamis (see below).

My currently preferred interpretation is that this landslide does not record collapse from a rockface or hillslope, but instead originated when debris collapsed from glacial moraines that mantle the surface just above the slide area. In this area, our field reconnaissance and mapping from the aerial photographs indicates that glaciers in the Solomon River valley extended downvalley to near the modern damsite. The lake that was present in this valley prior to the arrival of modern settlers was naturally dammed by terminal moraines, and coeval lateral moraines can be traced in the aerial photographs up to the bench on the south side of the valley where they cross the ridge above the landslide deposits. I believe this landslide deposit consist of morainal material that slid down from the area of glacial deposits on the ridge above, possibly in response to a large earthquake. This is consistent with the presence of deformed alluvial and lacustrine sediments intercalated with the landslide deposits, as a landslide originating in glacial deposits would have incorporated a wide variety of a glacial sedimentary facies from the area of glacial sediments at the top of the ridge.

Submarine Landslides in Port Valdez

As part of this study I examined bathymetric data from the floor of Port Valdez to look for submarine landslide deposits that might record paleoseismic activity. The 1964 Good Friday earthquake generated submarine landslides that produced destructive tsunamis, but the volume and extent of these features has been unknown. I have previously been involved in mapping submarine landslides in Seward, Valdez, the Aleutians, the Canary Islands and other areas as part of a NOAA study, and have experience in interpreting digital elevation models (DEM) showing submarine topography.

The most prominent feature in the submarine DEM images are a set of Large hummocks in Port Valdez near the Shoup Bay Moraine. These hummocks are partially buried in sediment, so their original height and extent cannot be accurately determined. However, they form discrete blocks as much as 50 m high, and appear to be grouped in two clusters, one lying seaward and southeast of the Shoup Bay Moraine, and one lying southwest of the Shoup Bay Moraine. Lee and others (2006) interpreted these deposits to be submarine landslide deposits, and I agree with their interpretation. The large hummocks are interpreted as discrete and coherent masses of landslide debris that did not totally disintegrate during the slide, while the matrix of the landslide presumably formed a fluidized mass that surrounds the lower parts of the large blocks and today is mostly buried by more recent sedimentation.

While my interpretation of the origin of these deposits is similar to that of Lee and others (2006), I differ from their interpretation in one critical element. Their published report suggests these huge landslide blocks are a product of the 1964 earthquake and caused the 1964 tsunami. However, I believe their interpretation of the age of these deposits is partly wrong. The large landslide hummocks cannot all be the products of submarine landslides in 1964, because there is no slide scarp or source areas for these large slides anywhere along the slope of the Shoup Bay Moraine. Any slide large enough to produce these blocks would have left a “hole” in the source regions where the slides originated. This “hole” would of necessity be as large as the composite slide mass on the floor of Port Valdez. There is no such hole or slide scarp anywhere on the Shoup Bay Moraine (Figs. 11, 12). The seaward slope of the moraine is everywhere straight and flat, precluding the possibility that it was the source of the large landslide blocks on the floor of Port Valdez. The landslide blocks and the mostly buried submarine landslide deposits therefore record an older set of submarine

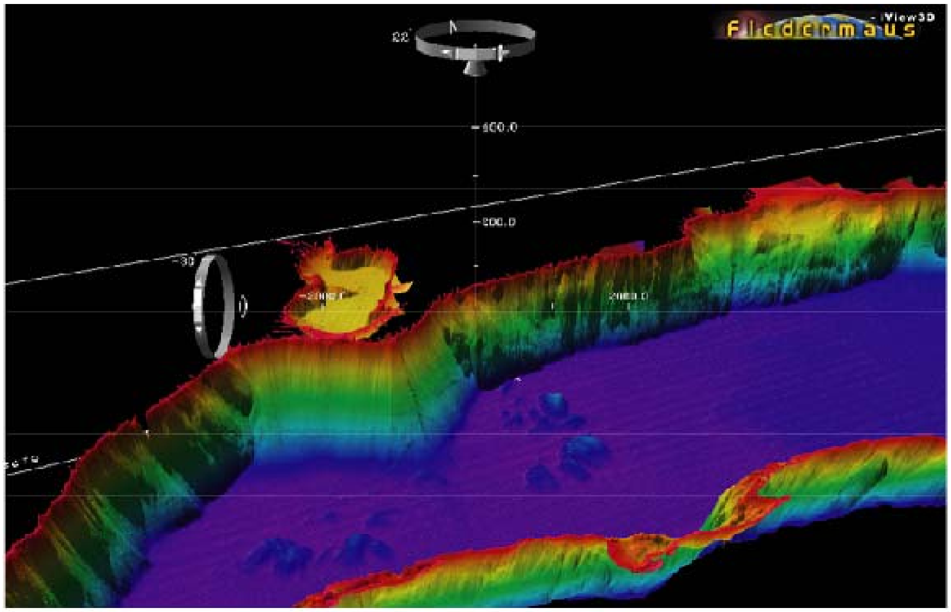

Figure 11. Shoup Bay Delta Moraine and submarine hummocks surrounding it on the floor of Port Valdez interpreted here as landslide deposits. Note that Shoup Bay is a hanging glacial valley perched high above the floor of Port Valdez. Glaciers that advanced down Shoup Bay in the recent past dumped sediment into Valdez Arm. The 1964 earthquake produced skin failures on the moraine front. No landslide scarps large enough to account for the huge mass of sediment in the landslide hummocks on the floor of Valdez Arm are visible on the moraine front, indicating these features predate the Little Ice Age moraine and 1964 earthquake.

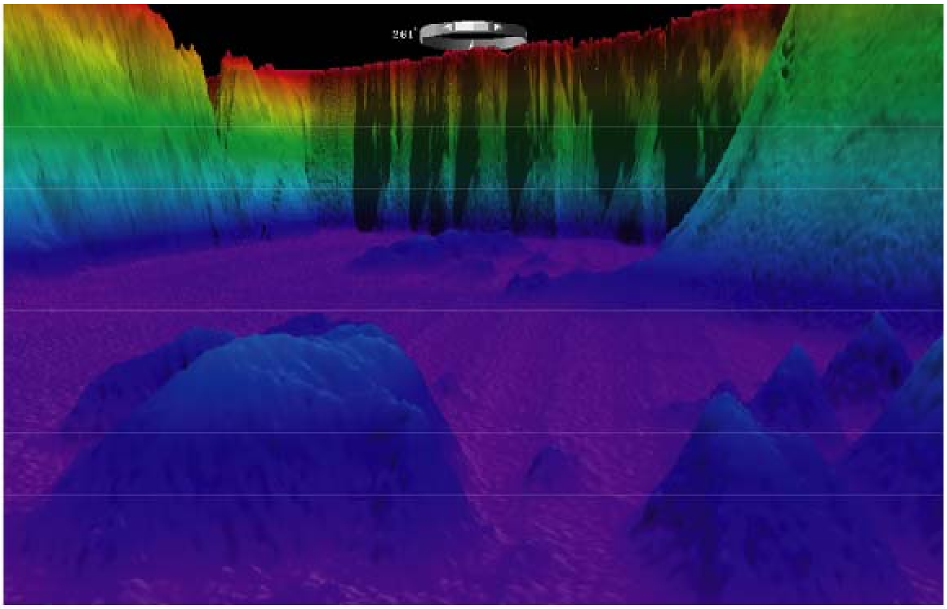

Figure 12. Shoup Bay Delta Moraine and huge submarine hummocks interpreted as prehistoric landslide deposits. Scarps on the moraine front are interpreted as the sources of submarine landslides in 1964 that produced tsunamis.

landslides that predate the Shoup Bay Moraine (which probably formed during the Little Ice Age 400-100 years ago) as well as being older than the 1964 earthquake. The 1964 submarine tsunamigenic landslide is apparently recorded by a scarp exposed along the surface of the Shoup Bay Moraine, and the area of hummocky topography adjacent to the slide front. The 1964 landslides along the front of the moraine apparently did not create large scarps, basins or scarps along the front of the moraine that can be identified in the bathymetric data.

Two sets of landslide deposits may also be present along the fan delta at the mouth of the Valdez Glacier Stream. In 1964 a massive slope failure affected the seaward parts of the Valdez Glacier Stream and Lowe River fan deltas at the old Valdez Town site. The dimensions of the 1964 slides in this area can be estimated with some accuracy from the historic accounts. The area affected by the slide in 1964 along the Valdez waterfront was 1,300 m long and 180 m wide. The slide occurred near the front of the Lowe River delta when a scarp, estimated to be 6 to 9 m high formed during the earthquake as the slide mass moved into the waters of Port Valdez. Eyewitnesses report that a "boil" of muddy water appeared several hundred meters offshore followed by a tsunami 10 to 13 m high that rushed back to inundate the waterfront area and lower portion of Valdez. The slide and wave resulted in the tragic loss of 30 lives before the violent shaking had subsided.

The total volume of the 1964 slide in this area was about 50 x 10^6 m^3 based on the eyewitness accounts and later surveys. The tsunami wave reached a maximum height of ca. 9-10 m at the original Valdez town site, but had minimal effects along nearby parts of the Lowe River delta. As at Shoup Bay, very large hummocks and blocks appear to be present on the floor of Port Valdez, even though no slide scarps of similar size are present anywhere on the modern fan of the Valdez Glacier Stream (Figs. 13, 14). These blocks appear to record slides from the southern part of the Lowe River fan delta rather than the area of the Valdez town site. Again, there is no slide scarp or “hole” in the slope or the Lowe River fan delta that could be the source of these large blocks. This suggests that the largest submarine slide blocks record a prehistoric landslide from the Lowe River fan delta that predates the 1964 landslide and predates the 1964 landslide.

Field Mapping at the Shoup Bay Moraine

In August Beget and Addison used an Avon inflatable boat to access the Shoup Bay Moraine. The sediments that comprise the moraine form an arc typical of “delta-moraines” left by tidewater glaciers. The moraine occurs just where Shoup Bay enters Port Valdez. A steep gravelly beach occurs on the seaward side of the moraine, with low, marshy terrain occurring behind it. The moraine is the source of submarine landslides in 1964 that generated tsunamis. We examined the 1964 tsunami deposits on the moraine and in adjacent areas to determine the sedimentological characteristics of the 1964 proximal tsunami deposits (Table 2).

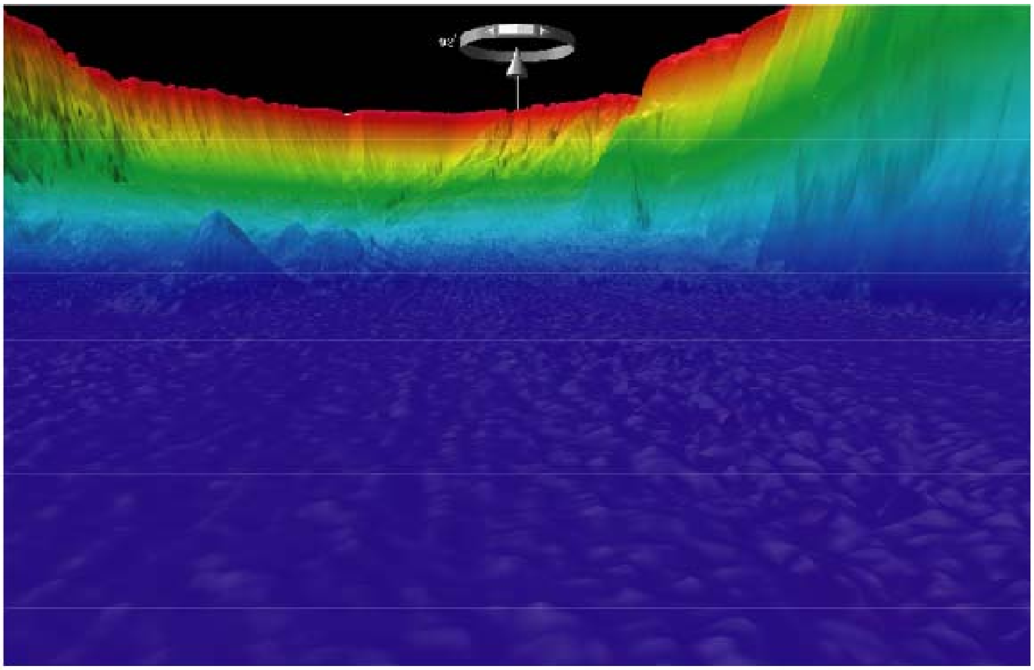

Figure 13. East-looking view of the Lowe River fan delta and huge submarine hummocks (?) interpreted as prehistoric landslide deposits. Scarps on the moraine front are interpreted as the sources of submarine landslides in 1964 that produced local tsunamis.

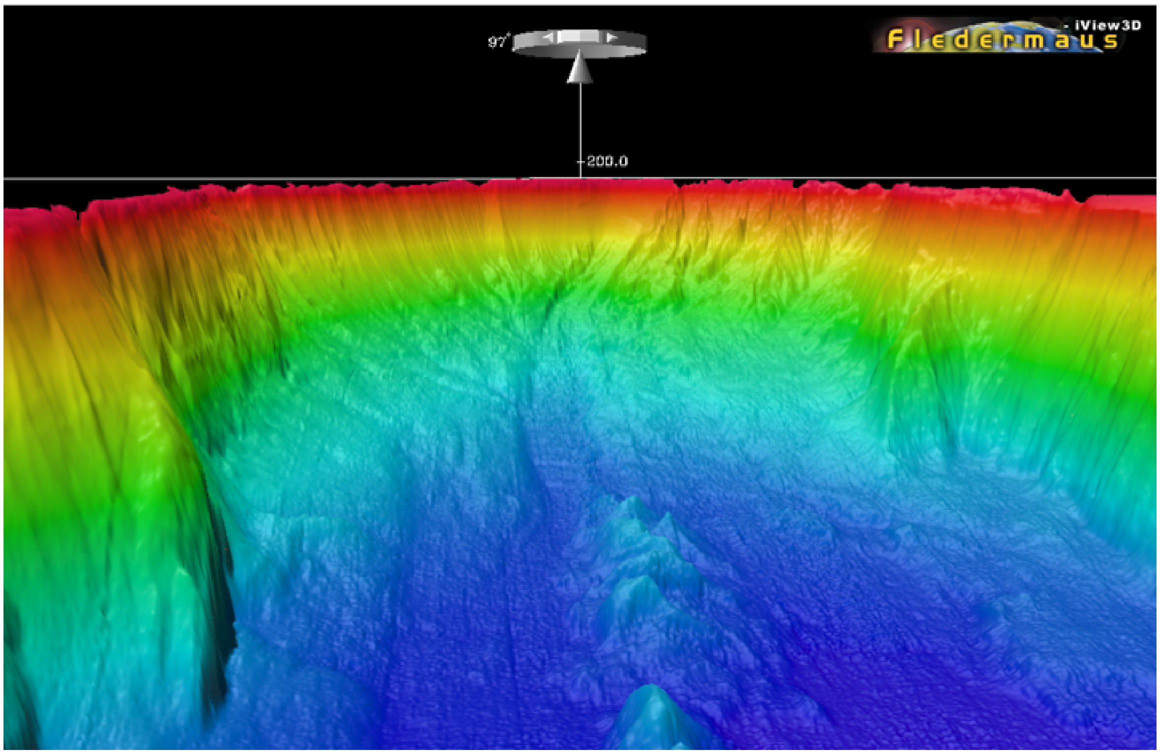

Figure ___: E-facing view of Lowe River delta. Note the presence of channel/excavated scarp?. Also hummocky topography is evident immediately seaward of channel – '64 deposit?

Figure 14. East-looking view of the central portion of the Lowe River fan delta and huge submarine hummocks (?) interpreted as prehistoric landslide deposits. Subdued and partially buried hummocky material on the floor of Port Valdez near the shoreline are probably additional prehistoric landslide deposits of various ages.

We identified and mapped fault scarps, grabens and other the tectonic geomorphologic features on the eastern part of the moraine (Figs. 15, 16). The surface of the moraine was truncated by widespread erosion caused by the passage of tsunamis in 1964. The highest tsunamis produced anywhere in Alaska by the 1964 earthquake occurred at the moraine, where waves were locally more than 50-65 m high. As a result the normal irregular topography that characterizes moraines is missing. Deposits of coarse sand and gravel containing occasional boulders were preserved locally on the moraine where it had been swept by the tsunami, and resemble very coarse-grained tsunami produced by large waves (Scichitano et al., 2007)

The discovery that the sediments exposed at the surface of the Shoup Bay Moraine are cut by linear troughs and scarps that trend NS-SE has significant implications for understanding the cause of the 1964 tsunamis, and for evaluating future hazards. The surface relief on these scarps is only ca. 1-2 m, but they almost certainly reflect faults that cut entirely through the moraine and developed during the 1964 earthquake. The troughs are interpreted as grabens, and reflect subsidence that occurred during the four minutes of shaking during the 1964 earthquake. The subsidence was clearly occurring along faults that extended downward into the moraine, and had the 1964 earthquake lasted longer or had the shaking been more intense, we speculate that these faults might have contributed to a massive collapse of parts of the central zone of Shoup Bay moraine. This would have resulted in much bigger landslides, and much larger tsunamis.

Newly Discovered Records of Prehistoric Tsunamis and Earthquakes in the Port Valdez area

Earthquakes are transient geologic events, lasting no more than a few seconds to a few minutes. Traditionally, geology focused on the study of sediments produced by slow long-lived processes lasting millions of years rather than sediments produced by brief, catastrophic events like earthquakes or tsunamis. However, geologists have recently developed new approaches to identify, characterize and age date the unique deposits produced by earthquakes. Following the catastrophic Indonesian earthquake of December 26, 2004, when more than 250,000 people were killed by a tsunami in the Indian Ocean, scientific attention has been focused on ways to better understand the links between earthquakes and tsunamis. I participated in the international conference on “Earthquakes and Tsunami Deposits” sponsored by the U.S. National Science Foundation in 2005, where scientists from around the world gathered to share ideas and new approaches that might aid in the evaluation of seismic hazards, and helped author the final report to the federal government. These recent scientific breakthroughs in the study of tsunami deposits have been successfully applied in New Zealand, Japan and other areas and demonstrate that by recognizing and studying the history of tsunami deposits, it is possible to unravel the history of earthquakes which produced the tsunamis.

Figure 15. Linear fault scarp on the surface of the Shoup Bay Moraine produced by shaking during the 1964 earthquake. The linear fault scarp runs diagonally across the image. The lake in the center is a down-dropped block (graben) that had begun to settle during the earthquake. Continued shaking might have resulted in complete failure of this portion of the moraine.

Figure 16. Close-up of vertical scarp produced by slumping and landslide during the 1964 earthquake at the Shoup Bay Moraine. The scarp is 1.5 m high, and is capped by deposits of the 1964 tsunami, proving the fault displacement occurred prior to the generation of tsunamis at this site.

This report presents the initial application of the use of paleotsunami deposits as a record of earthquakes in the Valdez area. The existence of a relationship between earthquakes and tsunamis in the Valdez Area is clearly demonstrated by the events in 1964, when the Good Friday earthquake generated large local tsunamis due to submarine landslides as well as a regionally extensive tectonic tsunami.

During fieldwork in July 2006 I discovered record of prehistoric tsunamis and earthquakes in a new roadcut created by construction along the VMT road on the southside of Port Valdez near the Solomon Gulch fish hatchery. The roadcut exposed a section of peat more than 3 m thick and 25 m long. Stratigraphic studies within the peat identified a series of silt, sand and gravel beds within the peat. The sand and gravels are poorly sorted (Table 2), and consist mainly of angular to rounded clasts of meta-sediments of the Valdez Group, with a minor component derived from crystalline and metamorphic rocks (Fig. 17).

During fieldwork in August 2006 a second site was found where and gravel horizons intercalated within a thinner peat deposit on Saw Island, a small island within the VMT at the west end of the tanker berthing areas.

The presence of sand and gravel layers within peat deposits is unusual and anomalous as peats are typically deposited in bogs or still-water environments. Peats typically form in areas where relatively little inorganic sedimentation occurs. The sand layers preserved in the peat therefore record unusual sedimentation events that only rarely and intermittently brought clastic sediments into the peat bog area. This is characteristic of tsunami deposits preserved in terrestrial areas (Dawson and Shi, 2000; Paris et al., 2007).

At the Solomon Gulch site, the uppermost sand and gravel layer could be traced for more than 25 m across the peat and up the slope behind it, and clearly records a major sedimentation event that affected both the area of the peat bog and the slopes behind it. The peat deposit itself lies east of a large rock knob which separates it from Solomon Creek, indicating that the sand layers cannot be alluvial sediment and were not deposited during a flood. Similarly, the presence of a small number of crystalline clasts derived from igneous and metamorphic rocks indicates that the sediment could not be derived locally from the rock slopes uphill from the peat, because these areas do not contain crystalline rocks.

On Saw Island, the lithologies of clasts in the layers within the peat also show a dominance of locally derived rocks, but with the presence of a small component of sediments that are non-local. Many of the clasts are rounded and apparently were derived from the nearby beach and transported into the peat.

The sand and gravel layers within the peat deposits at Port Valdez are

Figure 17. Paleotsunami deposit at the Solomon Gulch site. The 1964 tsunami was too small to reach this site, but the thick peat deposit is interrupted by a continuous layer of sand and gravel recording an episode of wave inundation and deposition by a prehistoric large tsunami. Radiocarbon dates indicate this tsunami occurred about 950-1000 yr BP.

interpreted as paleotsunami deposits, with the sand layers recording deposition from waves which entrained sediments along the beaches and coastal areas and transported them inland. This interpretation explains the presence of the sand and gravel layers in the peat, as well as the presence of heterolithic clasts with non-local provenance and the poorly sorted character of the sediments themselves. Similar sand layers have been found in other peat sites where tsunamis have been reported (Dawson and Shi, 2000; Beget and Kowalik, 2006).

The discovery of paleotsunami deposits provides a way to evaluate tsunami and seismic hazards in the Port Valdez area. The number and distribution of the paleotsunami deposits provides direct evidence of the timing, frequency, and magnitude of past tsunamis in the Valdez area. The paleotsunami deposits can also be interpreted as indirect, proxy records of prehistoric earthquakes.

The age of the paleotsunami deposits was determined using accelerator mass spectrometry (AMS) radiocarbon dating and conventional radiocarbon dating on the peat horizons intercalated with the sand and gravel layers. Peat is an almost ideal material for radiocarbon dating, as it consists of organic plant remains that accumulate in situ over thousands of years. For this dating study, thin slices of peat and samples of individual macrofossils were collected from just below and within the paleotsunami sands (Table 1).

The radiocarbon dates indicate that the uppermost sand and gravel horizon in the peat at the Solomon Gulch site was deposited ca. 950-1000 years ago. Altogether five radiocarbon dates were obtained a multiple sites along the 25 m long sand horizon. All of the dates were concordant and provide strong evidence that the sand deposit preserved across 25 m of exposure records a single event that affected the entire peat bog consistent with the paleotsunami interpretation.

At Saw Island, a thinner peat deposit was found, but it also contained thin layers of sand and rounded gravel derived from nearby beaches. Two radiocarbon dates indicate the upper sand and gravel at Saw Island was also deposited about 1000 years ago. The agreement in the radiocarbon age of these two deposits occurring in quite different areas and separated by four kilometers is highly significant, as it provides further evidence in support of the tsunami hypothesis. Its very unlikely that any processes other than a tsunami could simultaneously deposit sand horizons in two peats in completely separated sites.

The upper sand and gravel layer at the Solomon Gulch site can easily be traced to the most inland part of the peat deposit, more than 25 m inland from the modern shoreline and 7 m higher than the current high tide line, indicating the 1000 yr BP tsunami affected areas 7 m above high tide, in an area where the 1964 tsunami had no effect. In an attempt to determine the maximum height of the 1000 yr BP tsunami, we dug multiple soil pits on the hillslopes above the

Figure 18. Older paleotsunami deposit at the Solomon Gulch site. The 1964 tsunamis did not reach this site, but the thick peat deposit is interrupted by three layers of silt, sand and gravel recording multiple episodes of wave inundation by prehistoric large tsunamis. Radiocarbon dates indicate this paleotsunami deposit formed about 3800 yr BP.

Figure 19. Paleotsunami deposit at the Saw Island site. The 1964 tsunami reached this site, and left a thin layer of sand and gravel. Excavations revealed a deeper thin peat deposit interrupted by a layer of sand and gravel (at tool tip) recording an older episode of wave inundation by a large tsunami. Radiocarbon dates indicate this prehistoric tsunami occurred about 950-1000 yr BP., identical to the age paleotsunami deposits at Solomon Gulch.

peat. We were able to find sand horizons in the soils pits up to 17m above the high tide line. We cannot be certain these sands are correlative with the 1000 yr BP tsunami, as we couldn't find material suitable for radiocarbon dating in the soil pits. The results indicate a tsunami much larger than that produced in 1964 affected this area about 950-1000 years ago, and deposited sediments at least 7 m and possibly to 17 m above the modern high tide line.

Two lower sand and silt horizons were found in the Solomon Gulch peat deposit (Fig. 18). Both of these are much finer grained, thinner, and less extensive than the deposit of the 950-1000 year BP tsunami (Fig. 21). The uppermost sand was radiocarbon dated at ca. 2800 yr B.P., while the lowermost silty sand was radiocarbon dated to ca. 3400 yr B.P. (Table 1).

At the Saw Island site, the peat horizon is much thinner (Fig. 19). No other prominent sand and gravel horizons were found below the. However, a horizon above the 950-1000 yr B.P. tsunami deposits was found in one soil pit. Two radiocarbon dates were collected on peat associated with this paleotsunami deposit. Both of these dates were modern, i.e. the radiocarbon dating method indicated the sand horizon had been deposited less than 100 years ago (Table 1).   I interpret this upper sand horizon as a tsunami deposit produced by the 1964 tsunami. Contemporary accounts of the 1964 tsunami suggest that it did impact the Saw Island area (Pflaker and others, 1969), so the discovery of a 1964 tsunami deposit in this area demonstrates that paleotsunami deposits were produced in peats by the 1964 earthquake and tsunamis. This finding supports the validity of this research approach.

Additional Paleoseismic data from marine cores in Port Valdez

Marine sediment cores were recovered from Port Valdez in June 2004 during a PWSRCAC-sponsored science cruise onboard the M/V Auklet (Savoie et al., 2006). Using analytical and descriptive data generated by this previous study, and applying a series of interpretative proxies that describe changes in the lithogenic and biogenic sediment flux, it is possible to generate a localized marine history of paleoseismicity for this region (fig. 20, 21). Resuspension of marine sediment along Alaskan continental margins is often accomplished through seismically generated gravity flows and turbidity currents. These deposits are identified through their sedimentologic properties; given the scope of the Savoie et al. data considered in this analysis, it is not possible to confirm the presence of these deposits. Nevertheless, it is possible to speculate using the geophysical and geochemical parameters considered herein.

Though the study of Savoie et al. (2006) was intended primarily as a hydrocarbon survey, several datasets were generated that readily lend themselves to paleoseismic work. Savoie et al. utilized a discrete core sampling protocol where, amongst other measurements, dry bulk densities, total aluminum concentrations, and total organic carbon concentrations were analyzed.

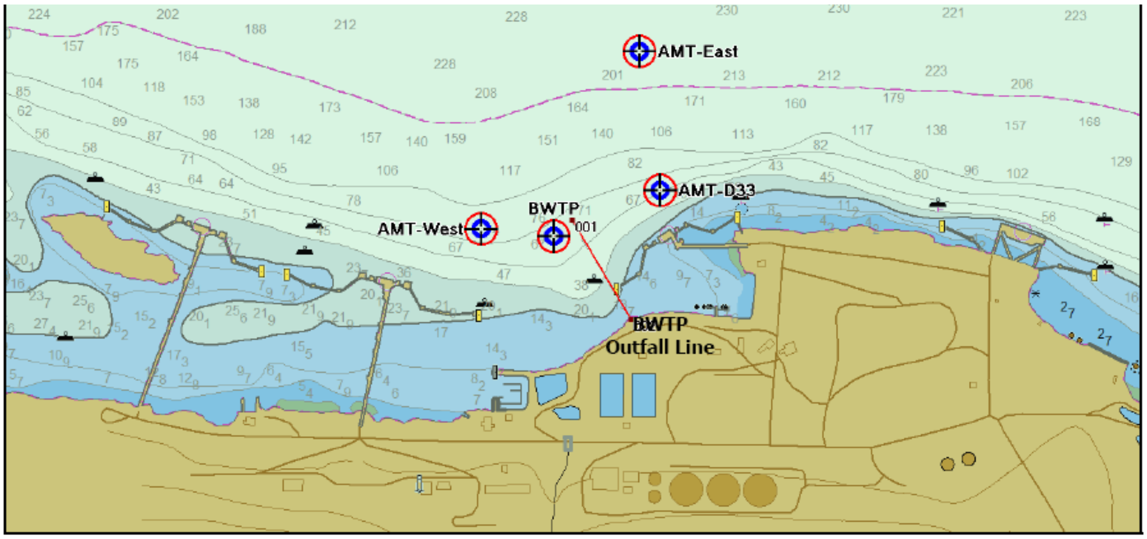

Figure 20: Location of Valdez Bay marine core sites at the Alyeska Marine Terminal (modified from Savoie et al., 2004).

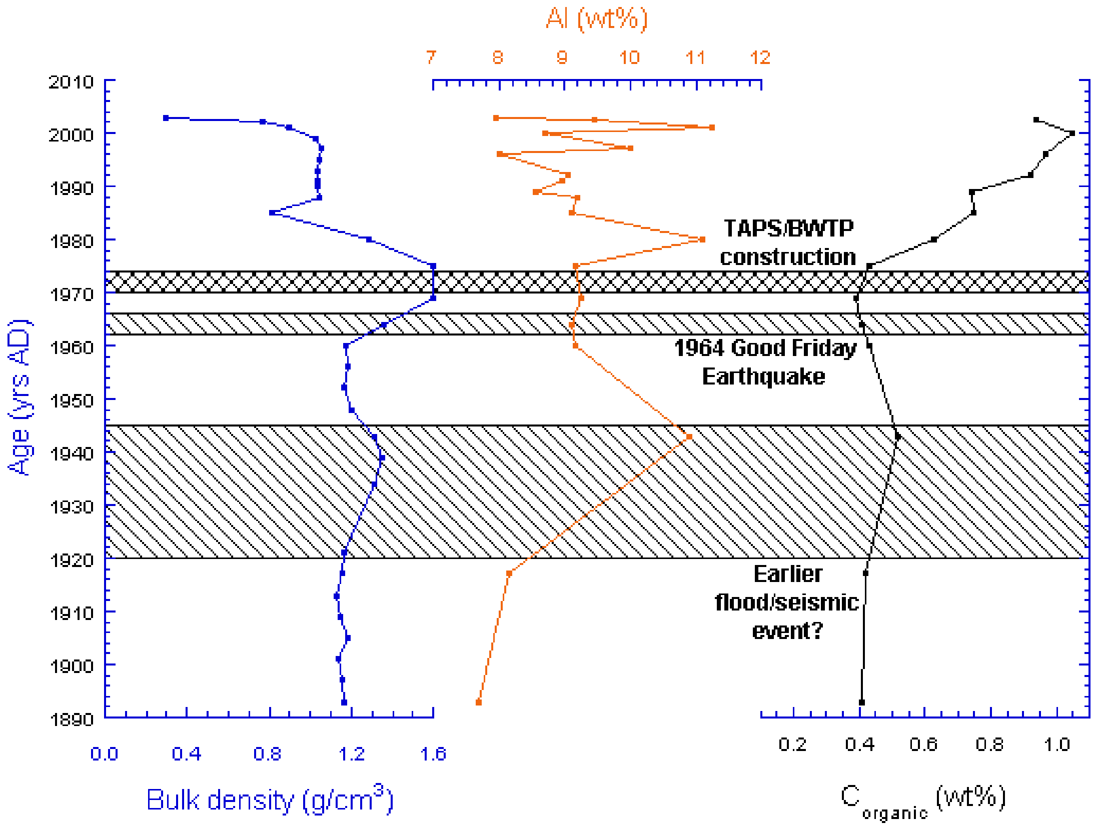

Figure 21: Dry bulk density, total aluminum, and total organic carbon analyses for the BWTP core in marine sediments of Valdez Arm reinterpreted to show sediment response to the 1964 earthquake.

Additionally, the core chronologies developed using coupled ^{137}Cs & excess ^{210}Pb age models will be utilized in the following analysis. This approach builds on much prior work done on sediment gravity flows in Port Valdez (Sharma and Burbank, 1973; Sharma, 1979; Naidu and Klein, 1988).

Dry bulk density is used to qualitatively evaluate the proportions of lithogenic and biogenic sedimentary components. Total organic carbon (C_{org}) concentrations were measured using a Shimadzu TOC-5050A carbon analyzer according to the methods described in Savoie et al. (2006). This biogenic proxy is a measure of total carbon exported to the sedimentary record from the overlying water column. This includes both marine-derived carbon (primarily plankton) and terrestrially-derived carbon (surface run-off and fluvial influx). A noted problem with the application of this proxy is preservation; under oxic bottom water conditions, preservation can range from .1 – 60% due to oxidation or microbial respiration (Hartnett et al., 1998; Hedges et al., 1999). The sediment-water interface in Port Valdez is most likely oxic to dysoxic, suggesting that C_{org} preservation may be questionable. Aluminum concentrations were measured using flame atomic absorption spectrometry according to the method of Trefrey and Metz (1984), such that total aluminum present was measured. This parameter is considered to primarily represent terrestrial influx since the dominant source of aluminum to the coastal environment is the fluvial & eolian input of aluminosilicate minerals, and dissolved Al is extremely particle reactive (Dymond, 1981). In the Valdez area, the Lowe River is the primary source of fluvial input, with secondary influx from several small creeks. However, changes in total Al may represent two different processes: a change in fluvial input or remobilization of previously deposited marine sediment, primarily through slumping or turbidity currents. Finally, because Al is relatively immobile within the aqueous environment, this proxy does not suffer from dissolution within the sedimentary record, such that total Al potentially represents a well-preserved record of terrestrial influx to the marine environment (Murray and Leinen, 1996).

The recognition of three end member situations is possible given the above parameters. The first is increased terrestrial influx as an episodic flood event; this situation would most likely be marked with increases in both the Al and C_{org} due to increased surface run-off and increased fluvial discharge, whereas bulk density changes would reflect the relative contribution of terrestrial lithogenic versus biogenic components in this run-off. Conversely, a highly productive marine euphotic zone would contribute only high concentrations of C_{org}, and thus contemporaneous decreases in bulk density and aluminum would be expected. The third likely scenario is one in which dense, low C_{org}, and Al-rich sediment is deposited; this situation would likely represent remobilization of previously deposited marine sediment. Because microbial utilization of carbon would lead to both decreased C_{org} and increased bulk density, deposits with these characteristics represent an episodic record of sedimentary seafloor change.

A 55-cm-long gravity core recovered from 76-m-water-depth offshore of the Valdez Marine Terminal's Ballast Water Treatment Plant (BWTP) has a basal date of AD 1893 as determined from the coupled ^{137}Cs & excess ^{210}Pb age model (Savoie et al., 2006). Bulk density, aluminum concentration, and total organic carbon analyses show contemporaneous trends (Fig. 22). Discounting the construction of the Valdez Marine Terminal and the associated BWTP in the early 1970s, two periods of possible seismically-derived sedimentological change are apparent. The more recent of these two events is clearly associated with the 1964 Good Friday earthquake. This event is marked with an increase in bulk density, and decreases in both Al and C_{org}, all of which suggest an increase in lithological flux to the seafloor. This flux does not represent a flood event since C_{org} remains low; rather this material represents previously-deposited, Al-poor sediment that has been remobilized as a result of seismicity, either as a slump or turbidity current.

A second older event is visible as a deposit of slightly denser, Al- and C_{org}-rich sediment that was deposited sometime between the mid-1920s and early 1940s. However, the proxy trends suggest this records a flood event rather than a submarine landslide or tsunami event. This deposit probably correlates with a major flood at Fort Liscum that occurred during this time period, and would've carried large amounts of sediment into the central portion of Port Valdez. At the present time there is no core data currently available going back 1000-6000 years that can be examined to match the terrestrial paleotsunami and paleoearthquake record obtained during this consulting project.

Paleoseismic and Paleotsunami History of the Port Valdez Area

The famous Good Friday Earthquake in 1964 is the largest known earthquake to have occurred in North America, and is either the second or third largest earthquake ever measured on our planet. In Port Valdez and several other areas around Prince William Sound local tsunamis were generated by submarine landslides. The highest local tsunami anywhere in 1964 occurred in the Valdez area where waves as much as 52 m high swept across hillslopes near the Shoup Bay moraine. Deadly local tsunamis were also produced by a submarine landslide originating at the old Valdez townsite. These events provide a model for understanding and interpreting the paleoseismic and paleotsunami history of the Port Valdez area from the deposits described earlier in this report.

The peats at the Solomon Gulch site contain three layers of silt, sand and gravel interpreted as paleotsunami deposits (Fig. 22). No deposits of 1964 sand and gravel were found at this site. This is consistent with contemporary accounts of the 1964 tsunami that show that the 1964 wave did not overtop the shoreline in this area (Pflaker and others, 1969). All of the paleotsunami deposits at the Solomon Gulch site therefore record tsunamis that were larger than the 1964 tsunami in this area.

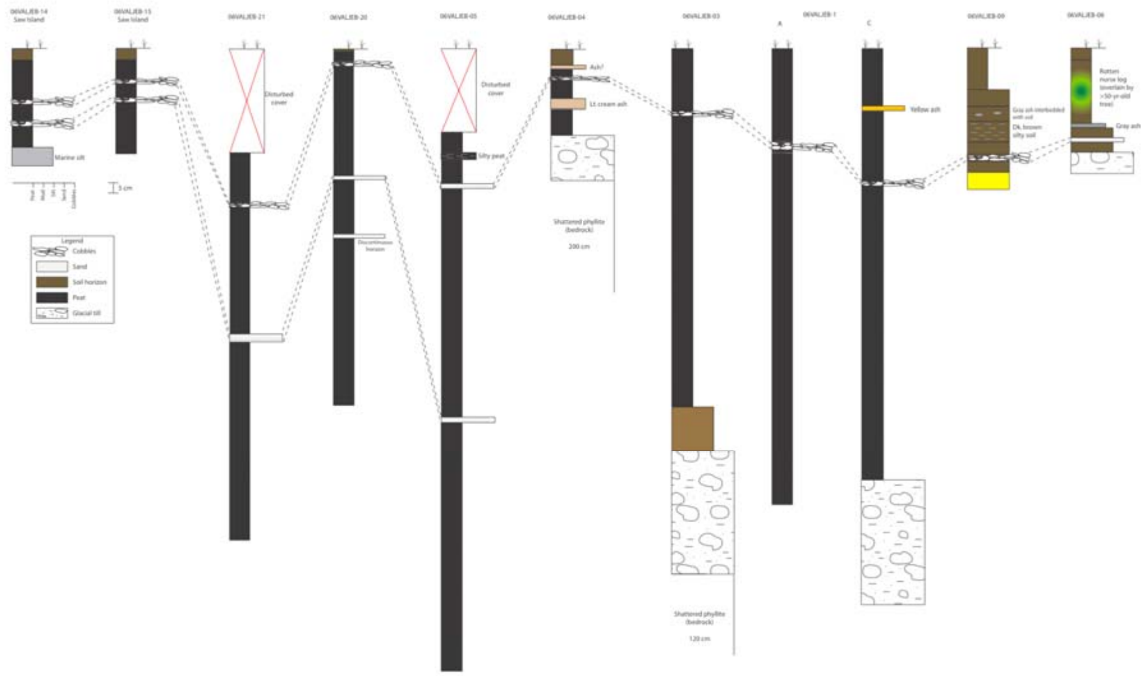

Figure 22. Geologic fence diagram showing the stratigraphy of multiple paleotsunami deposits, and correlations between paleotsunami deposits of the same age at the Solomon Gulch site and the Saw Island site.

The character and distribution of the paleotsunami deposits show that the 950-1000 year old tsunami was the largest and highest tsunami to hit the Solomon Gulch area in the last 8000 years. As discussed above, the 950-1000 yr BP tsunami deposited sediment at considerable distances inland from the modern coast, and at elevations from 12 to 17 m above the modern high tide line at a site where the 1964 tsunami had no effect at all.

The record at Saw Island is consistent with this interpretation (Fig. 22). There are 1964 tsunami deposits in the Saw Island peat, but the 950-1000 yr B.P. sand and gravel layer is coarser and thicker, and contains rounded beach cobbles as much as 5-10 cm in diameter. This data suggests the tsunami wave 950-1000 yr B.P. may have been somewhat higher in the Saw Island and adjacent VMT area than the 1964 tsunami.

What reason might be there be for a tsunami that occurred 950-1000 years ago to be significantly larger than the enormous 1964 tsunami? The most obvious explanation would be that it was generated by even larger submarine landslides than occurred in 1964. This interpretation is consistent with my mapping of submarine landslides discussed in an earlier chapter in this report. Portions of the deposits of large submarine landslides at Shoup Bay and fronting the Lowe River fan delta that cannot have been generated in 1964, because there are no scarps or landslide hollows that are large enough to have been the source of these huge deposits. I suggest here that these large landslide deposits are correlative with the thick and high 950 yr B.P. paleotsunami deposits.

The next older paleotsunami deposit at the Solomon Gulch peat has been radiocarbon dated to ca. 3800 yr B.P. This deposit is much thinner and less extensive in the peat than the 950-1000 yr BP deposit, and apparently records a smaller tsunami wave, although one that was still larger than the 1964 tsunami in the Solomon Gulch area. One still older tsunami deposit is radiocarbon dated to ca. 4300 yr B.P., and apparently records another prehistoric earthquake and coeval tsunami larger than 1964 tsunami, but smaller than the 950 yr BP tsunami. Radiocarbon dating of the large landslide at the VMT-TAPS site provides suggestive evidence of another earthquake ca. 5400 yr BP.

What is the recurrence interval of subduction zone earthquakes in south-central Alaska?

Taken together, the paleoseismic record compiled during this study allows the reconstruction of the history of recent earthquakes in the Port Valdez area. The ages of the last four earthquakes are now known: 1964, and ca. 950-1000 yr BP, 3800 yr BP, 4300 yr BP, and possibly at 5400 yr BP. It is apparent from this sequence that the recurrence interval between earthquakes is irregular. Based on the past history of earthquakes, it is impossible to precisely predict when the next earthquake will occur. The shortest period of time between earthquakes over the last several thousand years was ca. 500 years, while the longest interval between major quakes may have lasted 2800 years.

It is possible to make general inferences about the pattern of behavior and recurrence intervals of giant earthquakes on the portion of the Pacific Plate sliding into the subduction zone beneath south-central Alaska. There have been four major earthquakes in 4300 years, and possibly five in the last 5800 years, indicating such earthquakes occur on average every 1000-1200 years. This recurrence is significantly shorter than the 2-3000 year recurrence interval assumed during construction of the VMT. Even so, the data suggests that another great earthquake on the subduction won't occur for many hundreds of years.

Was the 950-1000 yr BP earthquake larger than the 1964 Alaska earthquake?

One interesting implication of this earthquake record developed in this study comes form the fact that ca. 950 years passed prior to the 1964 event, but 2800 years passed between earthquakes prior to the 950 yr BP event. The size of an earthquake is proportional to the amount of stress that has accumulated prior to the seismic release. In a subduction zone, where plate motion velocity is essentially constant over time scales of thousands of years, the amount of accumulated stress should be directly proportional to the amount of time that has passed since the last earthquake. This suggests a possible explanation for the fact that the 950 yr BP submarine landslides and tsunami appear to have been larger than the 1964 event. The amount of accumulated stress was apparently significantly larger prior to the 950 year BP earthquake than it was prior to the 1964 earthquake.

I suggest here that the 950 yr BP earthquake was larger than the 1964 earthquake because it released 2800 years of accumulated stress, while the 1964 quake released about 1000 years of stress. The 1964 earthquake, as discussed above, had a magnitude of 9.2, and was one of the largest known earthquakes. However, the 1960 Chile earthquake was 3-4 times larger. If the 950-1000 yr BP earthquake was several times larger than the 1964 quake, it may have approached the size of the 1960 Chile quake.

Summary and Discussion of future seismic hazards and tsunami hazards in the Port Valdez area

This study has shown that the 1964 Good Friday earthquake and tsunami was evidently preceded by similar events ca. 950-1000 yr BP, 3800 yr BP, and 4300 yr BP. A large landslide dated to 5800 yr BP may have been triggered by an even older earthquake.

The history of prehistoric earthquakes and the distribution of paleotsunami deposits and submarine landslides described above can be used to evaluate the nature of seismic and tsunamis hazards in the Port Valdez area from future great earthquakes. The development of a well-defined chronology for the last 4-5 great earthquakes to affect the Port Valdez area provide a real, physical basis for evaluating the likelihood of great earthquakes and tsunamis in the future.

This report shows that the Port Valdez area can be affected by tsunamis even larger than those that were produced in 1964. While paleotsunami records have been developed at only two localities, both of these sites record a tsunami ca. 950 yr B.P. that was bigger than the 1964 tsunami at the same site. The earthquake that generated the 950 yr BP tsunami may also have been larger than the 1964 earthquake.

These findings suggest that some caution is needed in using the 1964 earthquake as a baseline for evaluating seismic hazards, as the 1964 event may not be representative of the maximum possible future seismic event. In particular, the data in this report shows that the intensity and duration of shaking and the size of coeval tsunamis may be larger than was observed during the 1964 earthquake. For instance, at the Solomon Gulch site about 4 km east of the VMT, the 950 yr B.P. tsunami was more than 7 m (22 feet) higher than the 1964 tsunami.

This report also showed that great subduction zone earthquakes similar to the 1964 event have occurred infrequently, with quiet periods lasting between 500-2800 years separating large earthquakes. The long duration of quiet periods between earthquakes and tsunamis found for the Port Valdez area by this study confirm the theoretical suggestion that such great earthquakes occur only rarely, and require stress to build up again in the subduction zone after each earthquake.

The 1964 earthquake occurred only 43 years ago. If this event released all the accumulated stress at the subduction zone, then many hundreds of years must pass for enough stress to accumulate at the subduction zone for another great earthquake to occur on the portion of the Pacific Plate that generated the 1964 earthquake.

If the 1964 earthquake did not release all the accumulated stress, then it is theoretically possible for another large earthquake to occur in the same area affected in 1964. Even without another earthquake at the subduction zone, a tsunami hazard in the Port Valdez area exists from earthquakes on small local faults in the Valdez area, or from very large earthquakes on other parts of the subduction zone fault that did not rupture in 1964.

The sites of future submarine landslides and tsunamis are likely to be the same as those identified in 1964. Earthquakes have the potential to trigger submarine landslides and tsunamis from the active composite Valdez Glacier Stream fan delta and Lowe River Fan Delta, other smaller alluvial fan deltas, or even large landslides from the steep slopes on the northwest side of the Valdez

Narrows.

Probably the most significant hazard to the Port Valdez area is the stability of the Shoup Bay Moraine. Field mapping during this study found that the Shoup Bay Moraine was fractured and cut by faults during the 1964 earthquake. The existence of the faults created in 1964 may make the moraine more susceptible to failure and the generation of submarine landslides during future earthquakes.

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REFERENCES

Barker, Fred, Farmer, G.L., Ayuso, R.A., Plafker, George, and Lull, J.S., 1992, The 50 Ma granodiorite of the eastern Gulf of Alaska: melting in an accretionary prism in the forearc: Journal of Geophysical Research, v. 97, p. 6757-6778.

Bradley, Dwight C., Haeussler, Peter J., and Kusky, Timothy M., 1993, Timing of early Tertiary ridge subduction in southern Alaska: in Till, A., and Dusel-Bacon, C., eds., Geologic studies in Alaska by the U.S. Geological Survey, 1992, U.S. Geological Survey Bulletin 2068, p. 163-177.

Bol, A.J. and Gibbons, Helen, 1992, Tectonic implications of out-of-sequence faults in an accretionary prism, Prince William Sound, Alaska: Tectonics, v.1, p. 1288-1300.

Bouma, A.H., 1962, Sedimentology of some flysch deposits: Elsevier, Amsterdam, 166 p.

Connelly, William, 1978, Uyak complex, Kodiak Islands, Alaska: a Cretaceous subduction complex: Geological Society of America Bulletin, v. 89, p. 755-769.

Crowe, D.E., Nelson, S.W., Brown, P.E., Shanks III, W.C., and Valley, J.W., 1992, Geology and geochemistry of volcanogenic massive sulfide deposits and related igneous rocks, Prince William Sound, south-central Alaska: Economic Geology, v. 87, p. 1722-1746.

Dawson, A. G. and Shaozhong Shi (2000). Tsunami Deposits. Pure and Applied Geophysics v. 157, p. 875-897.

Dumoulin, J.A., 1987, Sandstone composition of the Valdez and Orca Groups, Prince William Sound, Alaska: U.S. Geological Survey Bulletin 1774, 37 p.

Dymond, J., 1981, Geochemistry of Nazca plate surface sediments: An evaluation of hydrothermal, biogenic, detrital, and hydrogenous sources, in Kulm, L.D., Dymond, J., Dasch, E.J., Hussong, D.M., and Roderick, R., eds., Nazca Plate: crustal formation and Andean convergence: Memoir - Geological Society of America: Boulder, CO, Geological Society of America, p. 133-173.

Farmer, C.L., Ayuso, Robert, Plafker, George, 1993, A Coast Mountains provenance for the Valdez and Orca Groups, southern Alaska, based on Nd, Sr, and Pb isotopic evidence: Earth and Planetary Science Letters, v. 116, p. 9-21.

Grantz, Arthur, 1966, Strike-slip faults in Alaska: U.S. Geological Survey Open-File Report 267, 82 p.

Hartnett, H.E., Keil, R.G., Hedges, J.I., and Devol, A.H., 1998, Influence of oxygen exposure time on organic carbon preservation in continental margin sediments: Nature, v. 391, p. 572-574.

Hedges, J.I., Hu, F.S., Devol, A.H., Hartnett, H.E., Tsamakis, E., and Keil, R.G., 1999, Sedimentary organic matter preservation: A test for selective degradation under oxic conditions: American Journal of Science, v. 299, p. 529-555.

Hood, D. W., W. E. Shiels and E. J. Kelley (eds.), 1973. Environmental Studies of Port Valdez. Inst. Marine Science, University of Alaska, Fairbanks, Ak 99701. 495 pages.

Jones, D.L., Siberling, N.J., Coney, P.J., and Monger, J.W.H., 1987, Lithotectonic terrane map of Alaska (west of the 141st meridian): U.S. Geological Survey Miscellaneous Field Studies Map MF 1847-A.

Haeussler, Peter J., Bradley, Dwight C., Goldfarb, Richard J., Snee, Lawrence W., and Taylor, Cliff, 1995, Link between ridge subduction and gold mineralization in southern Alaska: Geology, v. 23, no. 11, p. 995-998.

Haeussler, P.J., and Nelson, S.W., 1993, Structural evolution of the Chugach-Prince William terrane at the hinge of the orocline in Prince William Sound and implications for ore deposits, in Dusel-Bacon, Cynthia, and Till, A.B., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1992: U.S. Geological Survey Bulletin 2068, p. 130-142.

Hudson, Travis, Plafker, George and Peterman, Z., 1979, Paleogene anatexis along the Gulf of Alaska margin: Geology, v. 7, p. 573-577.

Lanphere, M.A., 1966, Potassium-argon ages of Tertiary plutons in the Prince William Sound region, Alaska in Geological Survey Research 1966: U.S. Geological Survey Professional Paper 550-D, p. 195-198.

Lee, H., Ryan, H. Kayen, R. E., Haeussler, P, Dartnell, P., and Hampton, M. A., 2006. Varieties of submarine failure morphologies of seismically-induced landslides in Alaskan fjords. Norwegian Journal of Geology 86, 221-130.

McDougall, Ian, and Harrison, T. Mark, 1988, Geochronology and thermochronology by the 40Ar/39Ar method, Oxford Monographs on Geology and Geophysics, 9, 212 p.

Moffit, F.H., 1954, Geology of the Prince Sound region, Alaska: U.S. Geological Survey Bulletin 989-E, p. 225-310.

Murray, R.W., and Leinen, M., 1996, Scavenged excess aluminum and its relationship to bulk titanium in biogenic sediment from the central equatorial Pacific Ocean: Geochimica Et Cosmochimica Acta, v. 60, p. 3869-3878.

Naidu, A. S. and L. H. Klein. 1988. Sedimentation Processes. Chapter 4. In: Shaw, D. G. and J. Hameedi (eds.). 1988. Environmental Studies in Port Valdez, Alaska. Springer-Verlag, New York, p. 69-91.

Nelson, S.W., Dumoulin, J. and Miller, M.L., 1985, Geologic map of the Chugach National Forest, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1645-B, 16 p., 1 pl., scale 1:250,000.

Nelson, S. W., Miller, M. L., and Dumoulin, J. A., 1989, Resurrection Peninsula ophiolite in Guide to the geology of Resurrection Bay, eastern Kenai Fjords area, Alaska, Guidebook, edited by S. W. Nelson, and T. W. Hamilton, Geological Society of Alaska, Anchorage, p. 10-20.

Nelson, S.W., Miller, M.L., Goldfarb, R.J., Snee, L.W., Sherman, G.E., Roe, C.H., and Balen, M.D., 1994, Mineral resource assessment of the Chugach National Forest Special Study Area in northern Prince William Sound, Alaska: U.S. Geological Survey Open-File Report 94-272, 20 p.

Nelson, S.W., and Nelson, M.S., 1993, Geochemistry of ophiolitic rocks of Knight Island, Prince William Sound, Alaska: in Dusel-Bacon, Cynthia, and Till, A.B., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1992: U.S. Geological Survey Bulletin 2068, p. 130-142.

Paris, R., F. Lavigne, P. Wassmer and J. Sartohadi. 2007. Coastal sedimentation associated with the December 26, 2004 tsunami in Lhok Nga, west Banda Aeh (Sumatra, Indonesia). Marine Geology, v. 238, p. 93-106.

Phillips, Patti J., 1996, Sandstone composition and provenance of the Orca Group, Chugach National Forest study area, south-central Alaska: in Moore, Thomas E. and, Dumoulin, Julie A. eds., Geologic studies in Alaska by the U.S. Geological Survey, 1994, U. S. Geological Survey Bulletin, B 2152, p. 157-167.

Plafker, George, 1969, Tectonics of the March 27, 1964, Alaska Earthquake: U.S. Geological Survey Professional Paper 543-I, p. 1-74.

Plafker, G., Kachadoorian, R., Eckel, E. B., and May, L. R., 1969. Effects of the earthquake of March 27, 1964 on various communities. United States Geological Survey Professional Paper 542-G, 50 p.

----1971, Possible future petroleum resources of Pacific-margin Tertiary basin, Alaska in Future petroleum provinces of North America: American Association of Petroleum Geologists, Memoir 15 p. 120-135.

Plafker, George, and Campbell R.B., 1979, The Border Ranges fault in the Saint Elias Mountainsin Johnson, K.M., and Williams, J.L., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1978: U.S. Geological Survey Circular 804-B, p. 102-104.

Plafker, George, Jones, D.L., and Pessagno, E.A., Jr., 1977, A Cretaceous accretionary flysch and melange terrane along the Gulf of Alaska marginin Blean, K.M., ed., The United States Geological Survey in Alaska: Accomplishments During 1976: U.S. Geological Survey Circular 751-B, p. B41-B43.

Plafker, George, and Lanphere, M.A., 1974, Radiometrically dated plutons cutting the Orca Groupin Carter, Claire, ed., United States Geological Survey Alaska Progream, 1974: U.S. Geological Survey Circular 700, p. 53.

Roe, C.H. and Balen, M.D., 1994, U.S. Bureau of Mines mineral investigations in the Unakwik Inlet area, Chugach National Forest, Alaska: U.S. Bureau of Mines Open-File Report 50-94.

Savoie, M.A., Savoie, J.M., Trefry, J.H., Semmler, C.M., Woodall, D.W., Trocine, R.P., Brooks, J.M., and McDonald, T. 2006. Port Valdez sediment coring program: final 2004 monitoring report: Prince William Sound Regional Citizens' Advisory Council Contract No. 961.04.1, 76 pgs.

Scicchitano, G., C. Monaco and L. Tortorici. 2007. Large boulder deposits by tsunami waves along the Ionian coast of south-eastern Sicily (Italy). Marine Geology, v. 238, p. 75-91.

Schrader, F.C., 1900, A reconnaissance of a part of Prince William Sound and the Copper River district, Alaska, in 1898: U.S. Geological 20th Anniversary Report, pt. 7, p. 341-423.

Sharma, G. D. 1979. The Alaskan Shelf: Hydrographic, Sedimentary, and geochemical Environment. Springer-Verlag, New York, 498 pages.

Sharma, G. D. and D. C. Burbank. 1973. Geological Oceanography. Chapter 1. In: Environmental Studies of Port Valdez. Inst. Marine Science, University of Alaska, Fairbanks, Ak., p. 15-100.

Shaw, D. G. and J. Hameedi (eds.). 1988. Environmental Studies in Port Valdez, Alaska. Springer-Verlag, New York, 423 pages.

Trefry, J.H, and Metz, S. 1984. Selective leaching of trace metals from sediments as a function of pH: Analytical Chemistry, v. 56, pp. 745-749.

Tysdal, R.G., and Case, J.E., 1979, Geologic Map of the Seward and Blying Sound quadrangles, southern Alaska: U.S. Geological Survey Miscellaneous Investigation Series Map I-1150, scale 1:250,000.

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska, U.S. Geological Survey Professional Paper 482, 52 p.

Winkler, G.R., 1973, Geologic map of the Cordova A-7, A-8, B-6, B-7, and B-8 quadrangles, Hinchinbrook Island, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-531, 1 sheet, scale 1:63,360.

-----1992, Geologic and summary geochronology of the Anchorage 1° x 3°

quadrangle, southern Alaska: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1984.

Winkler, G.R., and Plafker, George, 1981, Geologic map and cross sections of the Cordova and Middleton Island quadrangles, southern Alaska: U.S. Geological Survey Open-File Report 81-1164, 24 p.

-----1993, Geologic map of the Cordova and Middleton Island quadrangles, southern Alaska: U.S. Geological Survey, Miscellaneous Investigation Series, Map I-1984.

Winkler, G.R., and Tysdal, R.G., 1977, Conglomerate in flysch of the Orca Group, Prince William Sound, southern Alaskain Blean, K.M., ed., U.S. Geological Survey in Alaska: Accomplishments During 1976: U.S. Geological Survey Circular 751-B, p. B43-B44.

Winkler, G.R. Goldfarb, R.J. Pickthorn, W.J. and Campbell, D.L. .1999. Potential for metallic mineral resources in the Valdez 1° x 3° Quadrangle, Alaska. U. S. Geological Survey Map (2 sheets).

Table 1. Radiocarbon dates from Valdez

Sample Data Measured 13C/12C Conventional
Radiocarbon Age Ratio Radiocarbon Age(*)
Beta - 219683 1000 +/- 60 BP -27.1 o/oo 970 +/- 60 BP
SAMPLE : 06-VAL-1-2
ANALYSIS : Radiometric-Standard delivery (with extended counting)
MATERIAL/PRETREATMENT : (peat): acid/alkali/acid
2 SIGMA CALIBRATION : Cal AD 980 to 1200 (Cal BP 970 to 750)

Beta - 219684 4300 +/- 40 BP -27.7 o/oo 4260 +/- 40 BP
SAMPLE : 06-VAL-3-1
ANALYSIS : AMS-Standard delivery
MATERIAL/PRETREATMENT : (peat): acid/alkali/acid
2 SIGMA CALIBRATION : Cal BC 2920 to 2870 (Cal BP 4860 to 4820) AND Cal BC 2800 to 2770 (Cal BP 4750 to 4720)

Beta - 219685 1000 +/- 70 BP -26.9 o/oo 970 +/- 70 BP
SAMPLE : 06-VAL-5-1
ANALYSIS : Radiometric-Standard delivery (with extended counting)
MATERIAL/PRETREATMENT : (peat): acid/alkali/acid
2 SIGMA CALIBRATION : Cal AD 960 to 1220 (Cal BP 990 to 730)

Beta - 219686 3830 +/- 50 BP -26.7 o/oo 3800 +/- 50 BP
SAMPLE : 06-VAL-5-2
ANALYSIS : Radiometric-Standard delivery
MATERIAL/PRETREATMENT : (peat): acid/alkali/acid
2 SIGMA CALIBRATION : Cal BC 2430 to 2120 (Cal BP 4380 to 4070) AND Cal BC 2090 to 2050 (Cal BP 4040 to 4000)

Beta - 219687 8120 +/- 50 BP -26.8 o/oo 8090 +/- 50 BP
SAMPLE : 06-VAL-5-3
ANALYSIS : Radiometric-Standard delivery
MATERIAL/PRETREATMENT : (peat): acid/alkali/acid
2 SIGMA CALIBRATION : Cal BC 7170 to 7030 (Cal BP 9120 to 8980)

Dr. James Beget Report Date: 9/20/2006
Sample Data Measured 13C/12C Conventional
Radiocarbon Age Ratio Radiocarbon Age(*)
Beta - 219689 1200 +/- 80 BP -27.1 o/oo 1160 +/- 80 BP
SAMPLE : 06-VAL05

ANALYSIS : Radiometric-Standard delivery
MATERIAL/PRETREATMENT : (peat): acid/alkali/acid
2 SIGMA CALIBRATION : Cal AD 680 to 1020 (Cal BP 1270 to 930)

Table 2. Grain size analyses of sediment samples from Valdez, Alaska" Size fractions (mm)

Sample Name	Significance*	>12.5	4.00	2.00	1.00	0.50	0.25	0.13	0.06	<.063
06VALJEB-08C	16 m above MHHW;	0.28	0.38	0.45	0.56	0.74	0.83	0.92	0.96	1.00
06VALJEB-20C	3800 yrs BP tsunami	0.00	0.08	0.28	0.50	0.78	0.91	0.99	1.00	1.00
06VALJEB-21C	3800 yrs BP tsunami	0.00	0.02	0.41	0.61	0.81	0.91	0.98	1.00	1.00
06VALJEB-21C2	3800 yrs BP tsunami	0.00	0.02	0.23	0.43	0.71	0.85	0.94	0.98	1.00
06VALJEB-01-1	970 yrs BP tsunami	0.00	0.10	0.33	0.56	0.79	0.90	0.95	0.97	1.00
06VALJEB-01-2	970 yrs BP tsunami	0.31	0.54	0.70	0.81	0.90	0.95	0.98	0.99	1.00
06VALJEB-05-1	970 yrs BP tsunami	0.30	0.60	0.75	0.86	0.94	0.97	0.98	0.99	1.00
06VALJEB-20A	970 yrs BP tsunami	0.00	0.06	0.12	0.41	0.67	0.83	0.95	1.00	1.00
06VALJEB-20B	970 yrs BP tsunami	0.24	0.52	0.67	0.80	0.92	0.97	0.99	1.00	1.00
06VALJEB-21D	970 yrs BP tsunami	0.00	0.03	0.18	0.38	0.62	0.79	0.88	0.95	1.00
06VALJEB-20D	Lowest tsunami	0.00	0.28	0.33	0.63	0.87	0.95	0.98	1.00	1.00
06VALJEB-14E	Saw Island;	0.00	0.07	0.36	0.57	0.75	0.87	0.97	1.00	1.00

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06VALJEB-14B   Saw Island;         0.25 0.73 0.83 0.89 0.93
     0.96 0.99 1.00 1.00

06VALJEB-14C   Saw Island;         0.00 0.17 0.41 0.60 0.77
     0.87 0.97 1.00 1.00

06VALJEB-15A   Saw Island;         0.57 0.77 0.85 0.90 0.94
     0.97 0.99 1.00 1.00

06VALJEB-15B   Saw Island;         0.11 0.49 0.69 0.78 0.87
     0.93 0.97 0.99 1.00

06VALJEB-17A   Shoup Bay moraine;  0.19 0.39 0.59 0.80 0.94
     0.98 0.99 1.00 1.00

06VALJEB-17B   Shoup Bay moraine   0.15 0.40 0.64 0.83 0.97
     0.99 1.00 1.00 1.00

06VALJEB-18A   Shoup Bay moraine;  0.48 0.66 0.73 0.79 0.85
     0.91 0.95 0.97 1.00
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