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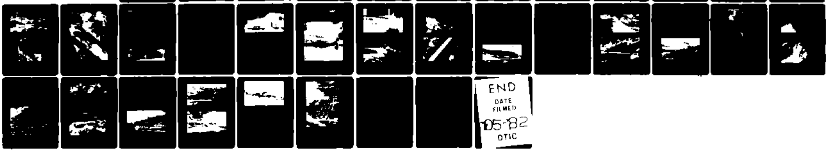

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REPORT 82-1

US Army Corps
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Cold Regions Research &
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The Alaska Good Friday Earthquake of 1964

Cover: The Turnagain Slide. The earthquake triggered a large, nearly horizontal motion toward the sea (northerly direction) of a part of this Anchorage suburban settlement. The locus of that slide was the sensitive Bootlegger Cove clay stratum. The steep mounds in the picture are extrusions of that clay left when the slide came to rest. (Photograph by the author.)

CRREL Report 82-1

February 1982

The Alaska Good Friday Earthquake of 1964

George K. Swinzow

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On 27 March 1964 a major earthquake struck Southern Alaska. The city of Anchorage, which contained a large part of Alaska's population, suffered loss of life and destruction of property. The time of the day, the season, and ground conditions were such that loss of life and property was minimized. The frozen ground and the ice on fresh water bodies responded to the earthquake shocks in a seldom-observable pattern, which was noted and recorded. Changes of sea level and slides into the sea were responsible for waterfront destruction. It is concluded that the main factor that limited structural damage was the frozen state of the ground.

PREFACE

This report was prepared by Dr. George K. Swinzow, Geologist, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

Technical review of the report was performed by John M. Stubstad and Thaddeus C. Johnson of CRREL.

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THE ALASKA GOOD FRIDAY EARTHQUAKE OF 1964

George K. Swinzow

ABSTRACT OF EVENTS

On 27 March 1964, at 5:37:20 pm, the clock on the Post Office in Anchorage, Alaska, was stopped by a violent earth tremor. This precise time is considered the official start of the Good Friday Earthquake. Destructive earth tremors lasted for about 4 minutes, during which time many towns and cities in southern Alaska were ruined. Highways, bridges and railroads were destroyed, and people were maimed and killed. Avalanches and landslides rushed down into the valleys, and the ice on rivers and lakes broke up. The coastline was invaded by *tsunamis* (tidal waves), which devastated many populated areas.

According to University of Alaska seismologists, the quake measured between 8.6 and 8.7 on the Richter (1958) scale. Its epicenter was believed to be 75-80 miles east of Anchorage in Prince William Sound. During the following week there were many aftershocks. The last one had a magnitude of 7.5, and its epicenter was located in the Aleutian Trench, 970 miles from the original epicenter. Although it was clearly felt in the area affected by the Good Friday quake, little destruction was noted. This was partially because of the remoteness of the epicenter, but also because all potential avalanches and landslides had already occurred, and all weak structures had been destroyed on 27 March.

It is believed that the earthquake affected roughly one million square miles of dry land, about the same area that was affected by the Lisbon Earthquake in 1755. Unlike the latter, however, the Alaska quake was a very thoroughly studied event. Aerial photography, modern surveying techniques, seismological data, and geodesy contributed greatly to the understanding of what actually happened. The data indicate a somewhat complex crustal movement during the quake. 22,000 square miles of land and sea floor sank some 5.4 ft, and 12,000 square miles rose 7.5 ft (Grants et al. 1964).

As news of the earthquake spread around the world, there was almost universal concern that the number of victims might reach the thousands, in line with previous experiences with earthquakes of similar magnitude. A major earthquake is a disaster that affects humans in many different ways: buildings collapse, fires break out, floods and rock and earth slides occur, and coastlines are battered by destructive tidal waves *(tsunamis)*. All these things did in fact happen during and after the Good Friday Earthquake; it was unquestionably a major disaster. But the cost in human life was, fortunately, less than anticipated. There were some 200 victims, including deaths caused indirectly and people missing.

There were several reasons for the relatively low loss of human life. The area affected by the earthquake was sparsely populated. The quake occurred at 5:37 pm on a Friday toward the end of the winter; for most people the working day had ended; the weather was good. At any other time on almost any other day there would have been more people indoors and, therefore, more serious injuries. Witnesses say that the earthquake began with tremors which were relatively weak at first and then gradually grew stronger.

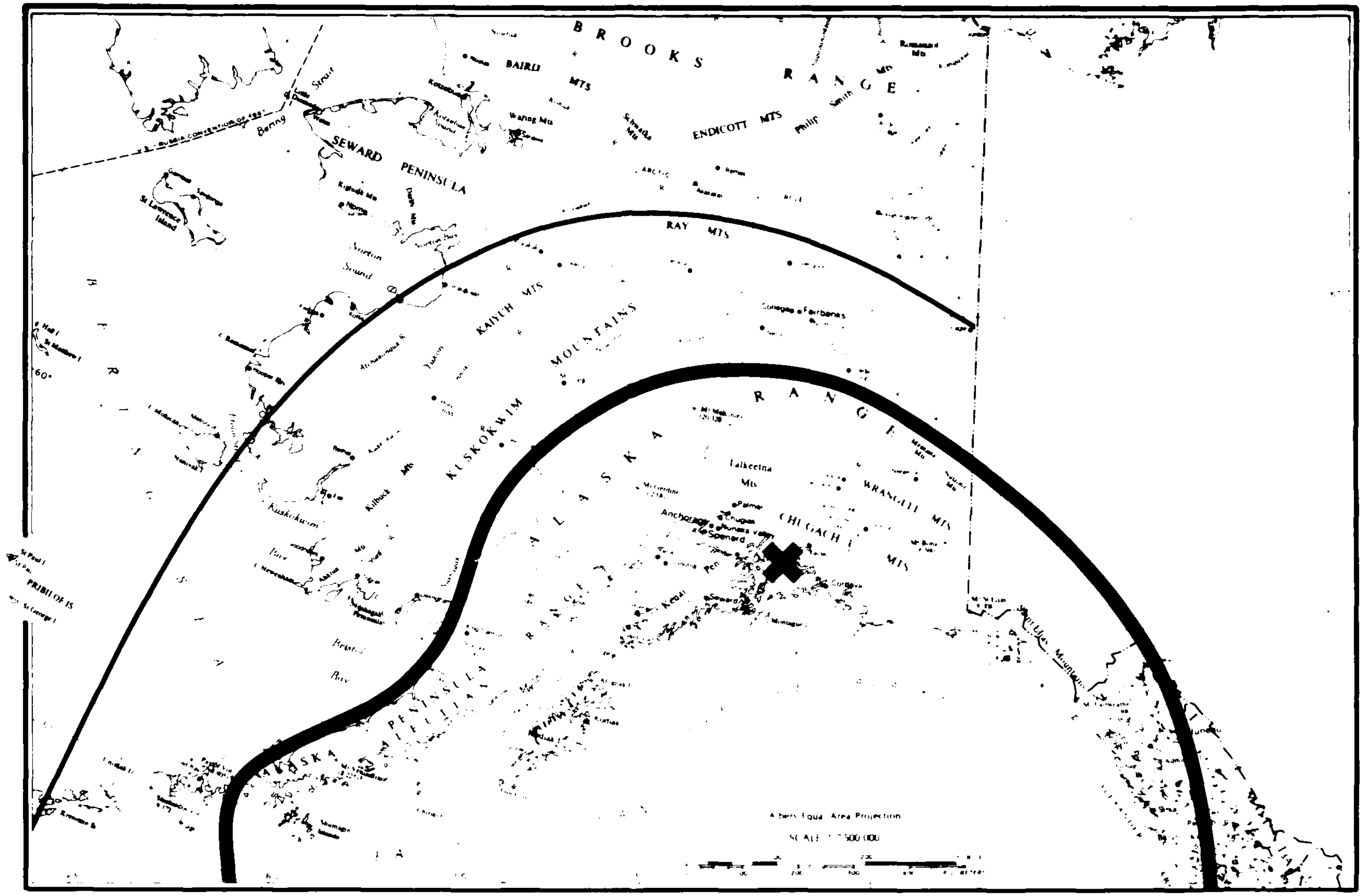


Figure 1. Map of Alaska. The epicenter of the Alaska Good Friday Earthquake was located in the northern part of Prince William Sound (X). The extent of significant damage is approximately indicated by the heavy line surrounding the epicenter. The second line farther north shows the extent of minor disturbance, such as the cracking of river ice. The earthquake was perceptible all over Alaska, but beyond the second line there was almost no damage.

This alerted many people, who proceeded outdoors. The people in many coastal villages were warned of the *tsunamis* by radio. Telephone service was disrupted, but in this area there had never been much reliance on the telephone anyway. Finally, frost penetration is deepest toward the end of winter. The unconsolidated but frozen ground had concrete-like properties, and it encased structures and protected them from complete destruction. Many houses survived violent shocks, settlement and landslides. The great strength of seasonally frozen sub-bases, abutments, and the ground surrounding structures in general prevented the destruction from being as violent as might have been expected. Next to solid rock, frozen ground or permafrost is the best base for a structure during an earthquake.

More destruction and loss of human life can be attributed to the accompanying *tsunamis* than to the earthquake itself. Statements collected from survivors indicate that there were two or more distinct phases of sea reaction. A relatively small wave arrived shortly after the earthquake but was observed in only a few towns along the Gulf of Alaska. It was probably triggered by massive landslides into the sea. The actual *tsunami* came later, as did many other waves that washed inland along the shoreline.

EARTHQUAKES AND FROZEN GROUND

Alaska is the largest state in the United States, but it is sparsely populated. The city of Anchorage contains a large part of Alaska's population. Since the southern coast of Alaska is part of the circumpacific tectonic belt, earth tremors in Anchorage are rather frequent. Realizing this, the builders of the town—architects, contractors, and others—often took measures to increase the stability of their structures.

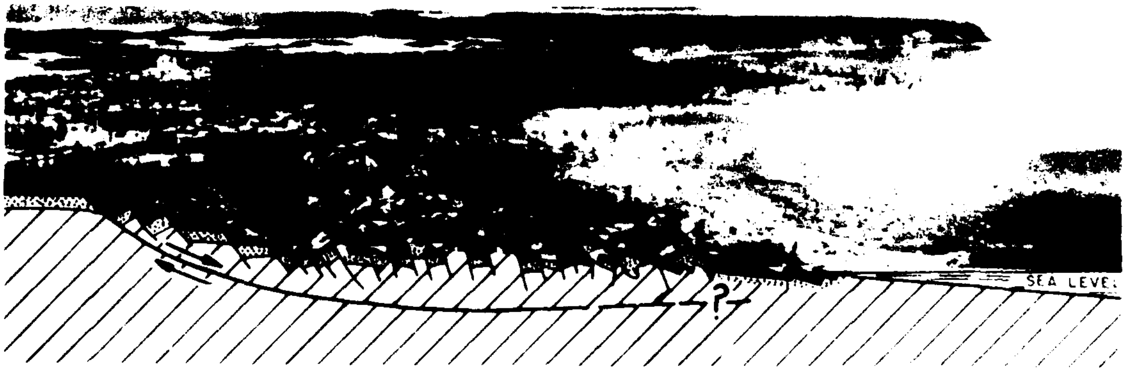
However, an unfortunate settlement habit is observable almost universally; with the exception of Manhattan and a few other places, people settle and build cities and towns at river junctions, on deltas and inlets, or on other areas of flat ground underlain by unstable alluvium. One of the main attractions seems to be the ease of cellar hole excavation. So strong is this habit that direct warnings about ground instability and landslide danger are often ignored. Miller and Dobrovolny (1959), describing the geology of the Anchorage area in a monograph, pointed out the dangers of landslides in the Turnagain Heights area, a densely populated suburb of Anchorage. The geology profile there, typical of the greater Anchorage area, consists primarily of alluvial, fluvio-glacial, unstable deposits. Despite this, many buildings were erected there even after the monograph appeared. Many were lost in the 1964 earthquake.

The site of Anchorage, the "Anchorage Bowl," is a gently sloping deposit area consisting of recently accumulated sediments. On the bedrock there is a fill mantle overlain by stratified blue clay with streaks and lenses of water-permeable sand. This formation, which slopes gently toward the sea and increases in thickness, is covered by a blanket of unconsolidated, coarse, water-permeable material. The bottom of the clay formation, the Bootlegger Cove clay, is below sea level. The streaks of sand allow the passage of water and make the material sensitive to earthquake shocks.

The devastating slides in Anchorage had their locus of motion in the clay. The nearly horizontal movement in the biggest slide, in Turnagain Heights (Fig. 2-8), affected the stratum to a considerable depth, possibly below sea level. The slide moved essentially north and traveled a long distance (up to 1800 ft) into the sea. The top 7 to 9 ft of the otherwise unconsolidated deposit was frozen, and the ground broke up into large blocks, or "rafts" as the people called them. For this reason many residential structures survived the landslide movement. They tilted badly, and became completely unusable, but they did not collapse and crush their occupants.

Unconsolidated deposits such as sand, gravel, etc. are capable of supporting building foundations indefinitely if properly compacted. During an earthquake or a landslide, unconsolidated subsoil supporting a foundation can collapse, leading to total catastrophic destruction of structures. Freezing of pore water causes a dramatic increase in the stability of a subsoil. Depending upon pore saturation, a frozen mixture of sand and gravel may have a mechanical strength close to that of concrete. A frozen material with many small pores is stronger than one with large pores, such as uniform coarse gravel. Pure clay—a material with sub-microscopic pores—is rather weak in the frozen state, because a large part of the pore water in clay does not freeze except at extremely low temperatures. Mixing sand and gravel in a proportion of approximately two to five by volume and flooding it results, after freezing, in the strongest material.

a An aerial photograph taken from an altitude of about 500 feet a mile from the center of the slide



b A cross sectional interpretation along a line through the center of Figure 2a

Figure 2 The Turnagain Heights slide was a large essentially horizontal slide Turnagain a populated suburb of Anchorage suffered great damage The frozen ground broke up into large 7 ft thick blocks

Figure 3. Blocks of frozen ground or "rafts" as they were called by the local people temporarily preserved many structures. A maximum of 1200 ft of shore bluff retreat was measured in the Turnagain area

Figure 4. Clay extrusion in the Turnagain area. The plastic, water-saturated clay was squeezed and in some cases extruded up to 12 ft. The Bootlegger cove clay was the actual locus of the slide. The slide debris traveled 1800 ft

Figure 5. Paved surfaces. The several fragments of pavement failed in tension between large blocks. In the lower left are portions of a cinder block garage. Cinder block structures were most sensitive to earthquake shocks. Where the ground was dry, it collapsed.

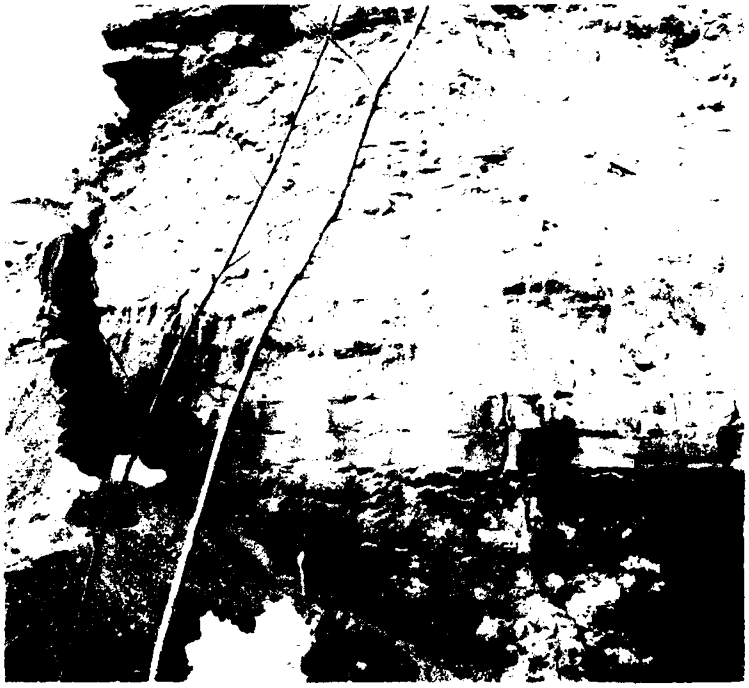


Figure 6. An outcrop along the slide escarpment. The normally unconsolidated sandy gravel stratum in the top portion of the outcrop is frozen. Below is a layer of ancient peat ashes. The clay outcropping in the lower portion is unfrozen and in a plastic state.

Figure [illegible]. The slide escarpment. The following summer this scarp retreated to the south (left). Boulders above the escarpment were temporarily preserved.

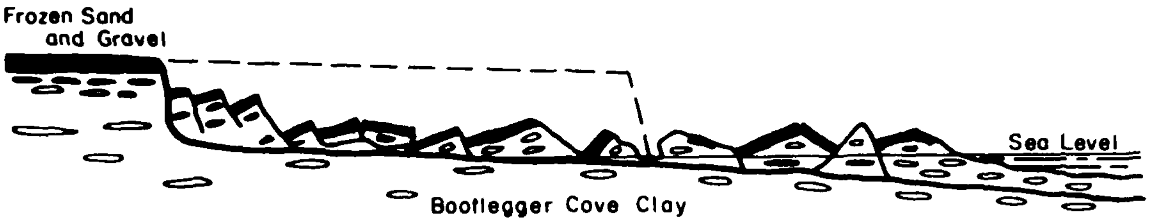


Figure 8. A schematic drawing of the Turnagain slide emphasizing the predominantly horizontal motion with the individual slices tilting away from the direction of motion. The shoreline retreated some 800 ft to the north (right). The almost horizontal slide surface was approximately 50 to 70 ft deep. The width of the slide-affected area was approximately 1 mile.

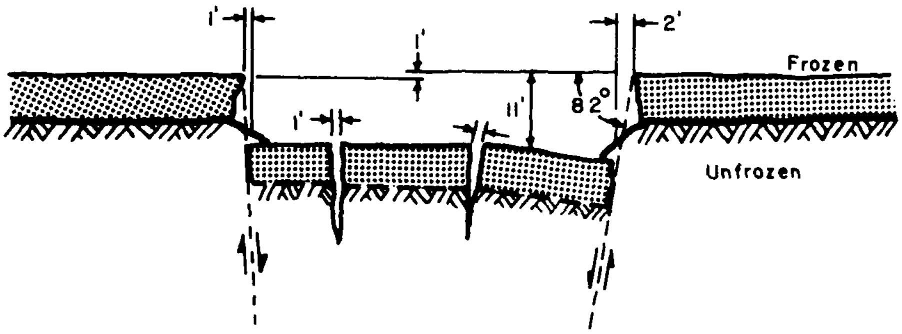


Figure 9. A graben-like surface disturbance in Anchorage. The frost preserved surface permitted many detailed measurements. If the material of the surface had been unfrozen, many of the features would have been obliterated.

Figure 10. A destroyed school building in the Government Hill area in Anchorage. The vertical separation was 12 ft. The right fault ran through the middle of the building. The school was empty at the time of the quake and there were no victims.

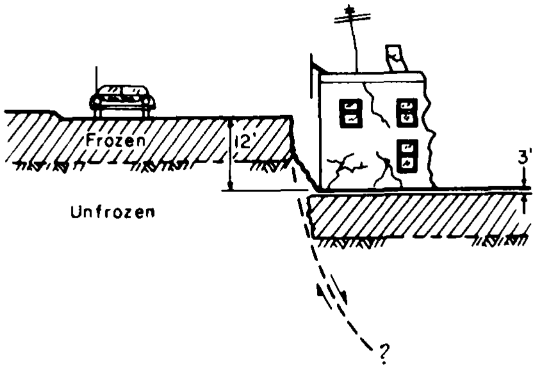


Figure 11. A 12-ft fault-like vertical drop on Fourth Avenue in downtown Anchorage. Most impressive was the relatively small amount of structural damage and the large vertical drop.

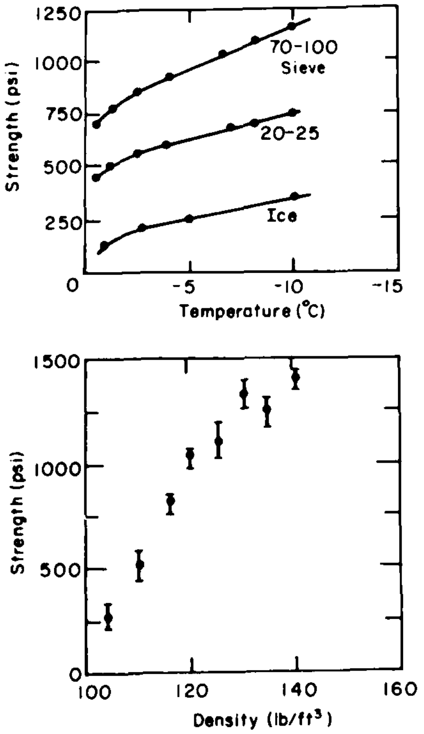


Figure 12. Some properties of frozen ground. Water-saturated soil freezes into a competent solid. The lower the temperature, the higher the mechanical strength of the material. Finer pores mean higher strength since there are fewer flaws in the ice cement. Mixtures of coarse, medium and fine particles are usually denser than material of uniform size. The higher the density the stronger the frozen ground. 20-25 and 70-100 are sieve size numbers of sand.

In many places in the greater Anchorage area the upper, frozen layer had such properties. That is why in all cases of land disturbance—slides, *grabens*, etc.—the upper, frozen surface broke up into large slabs, and the landslide edges were steep to vertical. During thaw later in the spring the extent of the ground disturbance increased. Soil collapse, settling and slump proceeded as a series of frost-delayed earthquake aftereffects.

Except at Turnagain Heights landslides in Anchorage did not result in a very large horizontal motion. Some of the motion resulted in *graben*-like surface disturbances. The use of the term *graben* may be inappropriate for the case of unconsolidated deposits. But the material was consolidated, in the sense normally construed by geologists, by frost. Figures 9 and 10 explain and show such motion in a series of earthquake disturbances in Anchorage. The damage was relatively low in some cases, as shown schematically in Figure 11. It is a type of "fault" motion with vertical displacement up to 12 ft. Anchorage's 4th Avenue was an example of such motion. A portion of its northern side sank, so that the second floors of the buildings were at street level.

Most of the numerous landslides, *graben* formations and fault movements (Fig. 6-10 and others) were either close to the Knik Arm coastal bluff or around the edges of Ship Creek Valley. The frozen ground elsewhere in the Anchorage area was subject to crevassing and cracking, but there were no spectacular ground disturbances. Cracking of the frozen ground resulted in a dramatic decrease of water flow in many streams, the water suddenly disappearing into the ground. This phenomenon was a temporary one, however. The crevasses soon closed or were filled in.

Structural damage outside the areas of landslide motion, faulting, etc. was relatively minor. Apparently the most vulnerable buildings were concrete block structures and the most stable were the very popular log houses. It appears that earthquake survival is possible in a log house under all circumstances unless it is tipped on its side.

The overall view of damage to man-made structures (Fig. 13-17) leads to the impression that besides the soundness of the construction, the soundness of the subsoil—the ground on which they were built—determined whether or not they survived the Good Friday Earthquake. Log houses surrounded by frozen ground reaching bedrock ended up with nothing but cracked chimneys. Incompetent, sensitive clay resulted

Figure 13. This structure in Anchorage was located over a subsidence and was violently damaged. Modern light construction prevented its total collapse. Old-fashioned masonry houses found in other earthquake regions such as around the Mediterranean Sea inevitably collapse into piles of rubble, resulting in large loss of property and life.

in catastrophic landslides and demolished structures. But, as mentioned, the 7-ft-thick "crust" of solidly frozen ground considerably decreased loss of property and life.

How is earthquake damage estimated? A collapsed building is a total loss. The cost of repairing damage is the loss when a structure is partially destroyed. In this aspect Anchorage, with mostly vertical displacements, such as the L Street *graben* and other places in the city (Fig. 10, 11, 15-17), had less damage than the total losses in Turnagain. Again, it is apparent that the frozen state prevented extensive soil collapse, which would have resulted in much greater damage.

The amount of ground disturbance caused by the earthquake, exemplified by fissures, crevasses and cracks, decreased to the east. The impression is that the decreasing total thickness of unconsolidated material, and perhaps of the sensitive Bootlegger Cove clay stratum, was the reason.

Highways in the Anchorage area were severely damaged in many places. But considering their length, the overall damage was relatively less than that to vertical structures in landslides. One recurring pattern of highway destruction was a set of longitudinal crevasses, such as those seen in Figure 18 and interpreted in Figure 19. Fill on relatively steep bedrock slopes was apparently differentially compacted and showed evidence of some downslope motion. Again, the deep frost penetration into the highways apparently prevented much more extensive damage. In places with little or no unfrozen fill, longitudinal damage crevasses were absent. Disturbance like that shown in Figure 18 was progressively more frequent away from Anchorage in a general easterly direction. It may be that closer to the epicenter the rising compressional waves of the earthquake were steeper and more intensive. Especially bad was the situation on the highway leading from Anchorage to Portage along the Turnagain Arm of Cook Inlet. Together with the

Figure 11. Frozen gravel exposed at Anchorage. The very top is constituted of completely ice-saturated material, while the gravel at the bottom does not contain as much ice. Some [illegible]

Figure 15. Fault scarp in Anchorage. The ice-saturated ground was frozen 7 ft deep at this location, temporarily preserving the two buildings and the utility line.

Figure 16. Government Hill in Anchorage. The 12 ft displacement appears to have caused only minimal damage to the building. Frost penetration was irregular but still sufficient to temporarily preserve the house.

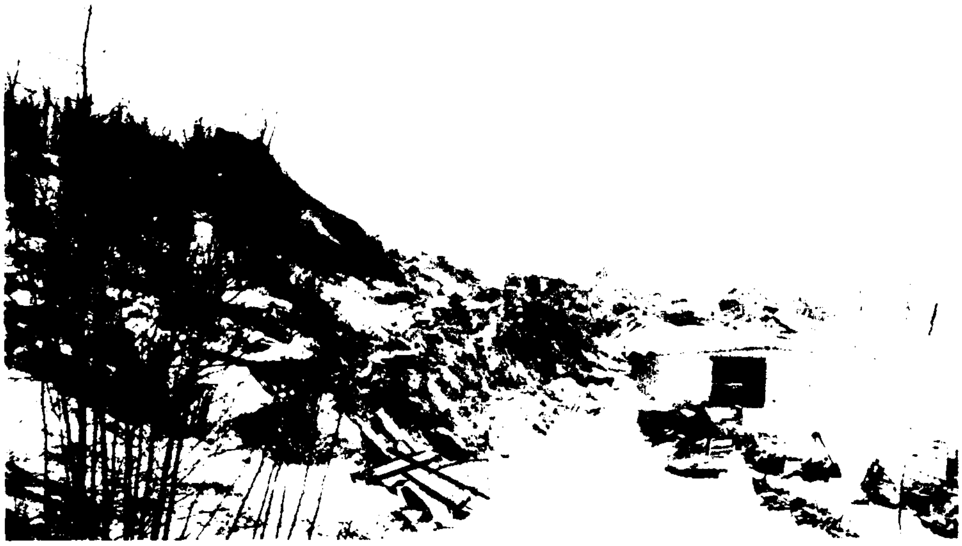


Figure 17. The eastern end of the graben shown in Figure 10 became a single slide farther down the hill, damaging parts of the railroad yard.

Figure 18. Aerial view of damaged highway near Portage. The longitudinal crevasses were formed by till displacement down the slope toward Turnagain Arm on Cook Inlet. Besides a series of avalanches which came to rest on this highway, there were several places with such longitudinal crevasses.

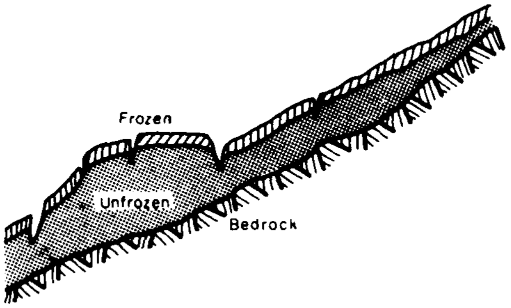


Figure 19. Deformation of the lower slope of the valley occupied by Turnagain Arm. The alluvium settled with some downslope motion. The cracks and crevasses were essentially parallel to the valley train. Frost penetration was deep under the highway. Crevassing, such as that shown in Figure 18, was relatively rare.

numerous longitudinal crevasses, avalanches and rock and ice slides cut the highway in many places and made it impassable.

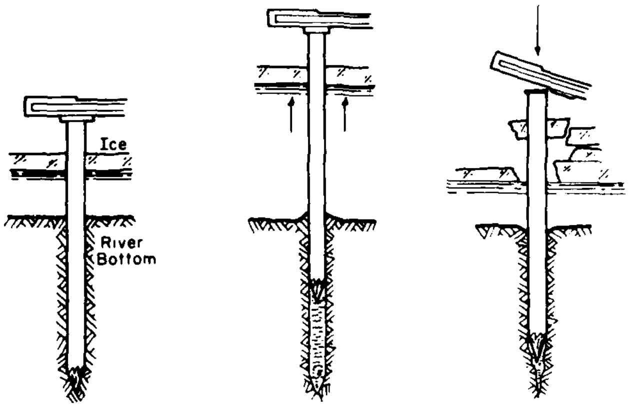
Other highways also became impassable in many places. Slides, avalanches and mud flows disrupted them, and frozen roadbeds were fissured and crevassed (see Fig. 18). When the highways were needed most, they could not be used, because of crevasses, landslides, and avalanches. But to repair them required only a fraction of the effort needed to build them in the first place, because frozen till had limited the destruction.

THE RESPONSE OF FRESHWATER *ICE SHEETS TO EARTHQUAKE SHOCK*

Except for a few waterfalls and the runoff from hot springs all fresh water bodies in Alaska develop ice sheets. In the area affected by the earthquake the ice cover on lakes grows to a considerable thickness. Depending on altitude, latitude, etc. it may be 3 to 7 ft thick toward the end of the winter.

The ice cover on fresh water bodies seems to be most sensitive to earthquake disturbances, and is the first feature to react to earthquake shock energy. It was reported that ice cracked on rivers and lakes as far from the epicenter of the Good Friday Earthquake as the foothills of the Brooks Range, some 350 miles away. In Fairbanks, where there was little or no earthquake damage, the river ice developed crevasses, breaking open "with a rumbling noise." Farther south the lakes and ponds developed fissures, ice mounds and icings. Cracks opened and water flowed out onto the surface. South of Anchorage, on the Kenai Flats, the ice on shallow circular lakes developed circular fissures, indicating deformation by a seiche (Fig. 20). The ice on elongated or irregularly shaped lakes broke up

Figure 20. A lake on the Kenai Flats. On many small lakes the ice responded in a manner suggesting a seiche, or standing wave, response to the earthquake shock. Lakes with irregular shorelines broke up without showing any regular pattern.



a. Before. *b. During.* *c. After.*

Figure 21. Small bridge deformation apparently caused by wave action. Small rigid bridges on pile foundations were in many cases uplifted in the manner shown. In cases where such uplift, suggesting a traveling wave in the water, was irregular, the damage to the bridge was substantial.

completely. The circular pattern of disturbance could be easily imitated in a qualitative way in the laboratory. A round, shallow container with the bottom covered with water and a thin layer of fine-grained ice broke up upon disturbance in a circular pattern similar to that seen in Figure 20.

Rivers and streams broke up into predominantly transverse blocks of ice. Close to the sea, part of the ice floated out, leaving the water open. The impression was that the earthquake shock resulted in a quick rise of the water under the ice, breaking it up. Part of the ice was found grounded on the river banks. Since in most cases there were no sources of high water, such as broken dams, etc., the earthquake must have released a sort of traveling wave in the river channels which moved through the ice and water, lifting it up. At the time of the earthquake, bridge piles were frozen into the ice covers of rivers and streams. When the ice was lifted up by the wave the piles went up also, resulting in a distinctive form of destruction. Figure 21 is an interpretation of that process: *a* represents the original position of a bridge support; *b* is the point of high water level when the ice lifted up the pile. At that time the bond strength of the adhering ice was high enough to overcome the friction resistance of the buried part of the pile and the weight of the bridge structure. The situation after the water receded is shown in *c*. The pile could not return to its original position, its hole in the weak ground had closed up. The weight of the structure was insufficient to force the pile back down. The absence of uniformity of such an uplift often contributed to the extent of the damage. Examples of this type of destruction are shown in Figures 22 and 23. Such damage was widely observed on the Seward-Anchorage highway in the Girdwood area, on the Twentymile River, and on many other streams. Other damage to bridges consisted of settlement, longitudinal compression, and displacement.

It is generally recognized that water level changes under the ice cover around pile-supported structures can result in damage, but effective countermeasures still need to be developed. Actually, there might be several mechanisms involved in this process. The heave of foundation piling beneath shoreline and offshore structures may proceed in a gradual way due to changes of water level.

Ice bonded to piles in winter exerts an uplift force whenever the water level rises. The effect of such repeated uplifting is greatest in early spring when the ice is thickest. Since tidal water level fluctuations are repeated regularly and are predictable, countermeasures can in principle be devised. Most important appear to be measures to weaken the bond between the pile and the surrounding ice.

However, tidal fluctuation of ice levels

Figure 22. A pile foundation bridge in the Portage area. The ice encasing the pile clusters adhered firmly. The rapid rise and fall of the water in the stream resulted in a regular uplift. Some fill and lumber were used to make it passable.

Figure 23. Differential heave. Parts of this bridge were differentially uplifted by the mechanism indicated in Figure 21. Due to the different composition of the materials in which the pile clusters were embedded, the bridge settled differentially.

around embedded piles of shore installations may be significantly *different from the cases il*lustrated in Figures 22 and 23. Figure 22 shows a rigid reinforced concrete structure resting on eight piles embedded into unfrozen, unconsolidated water-saturated river deposits. The total weight of the 24 × 60-ft reinforced concrete structure was probably in the vicinity of 200,000 lb. The bond strength between the piles and the surrounding ice was 100 to 150 psi (instantaneous resistance; long term application would produce less). The skin friction of the bearing parts of the piles embedded in the river bottom was between 1 and 5 psi.

The eight 14-in.-diameter piles *had a total of* about 422,000 in.² of skin contact with the unconsolidated riverbed deposits. This made a pull-out resistance of approximately (422,000 × 2) 844,000 lb. Adding to this the weight of the bridge gives over 500 tons of pull-out resistance. The ice to which the force of the passing wave was applied had a total surface area in contact with the piles of about 12,600 in.². At 150 psi of *bond strength between the ice and the piles*, a lifting force of approximately 950 tons could have been applied to the bridge. Therefore, the bridge damage mechanism suggested in Figure 21 is plausible.

There were many different combinations of *mechanisms* by which highways and bridges were destroyed or damaged (e.g., Figure 23).

THE EARTHQUAKE DISTURBANCE IN GLACIATED MOUNTAINS

The Kenai Peninsula and the Chugach Mountains surrounding Prince William Sound have several types of glaciers, for example Alpine glaciers (including valley glaciers and hanging glaciers with icefalls) and Turkestan-type glaciers fed by regular avalanches (accumulation and outflow separated). There are also icefields and Piedmont glaciers.

The earthquake came at *the end of the sea*sonal snow accumulation period. The slopes were loaded with snow, and the shocks released avalanches simultaneously at many locations. All slopes where avalanches recur seasonally, as well as those where they are only intermittently discharged, avalanches. In valleys they were most frequently the reason for highway and railroad disruption.

In many places rockfalls and landslides came down on the glaciers, and many fresh crevasses formed in glacier basins. Surging was evident in

Figure 24. Aftermath of flash flood on the Knik River. The flood was released when proglacial Lake George was emptied by the earthquake. The highway was obstructed by a slide and the floodplain, frozen several feet deep, was cracked by the earthquake and flooded when the water from Lake George passed through.

Figure 25. Rock avalanche. A large rock flow on the Yalik Glacier came to rest at the bottom in a way suggesting fluid flow.

places where glaciers reached the sea, icebergs broke off.

The biggest rock mass discharged on the Schwann Glacier in the Copper River Valley covered 10 square miles of ice with debris.

A unique disturbance took place on the Columbia Glacier. Part of the glacier lay on top of a small water body—an ice-dammed lake. The earthquake drained the lake, leaving an unusual depression. Another proglacial lake in the area, Lake George, also drained abruptly due to the earthquake (see Fig. 24). The Copper River Valley contains a very large amount of massive ground ice, and streams "disappear," as local people say, underground. The earthquake resulted in the collapse of numerous thermokarst cavities and fresh exposures of unusually massive ground ice. As Figures 25–31 show, the effect of the earthquake on the mountains, snowfields and glaciers was dramatic and significant.

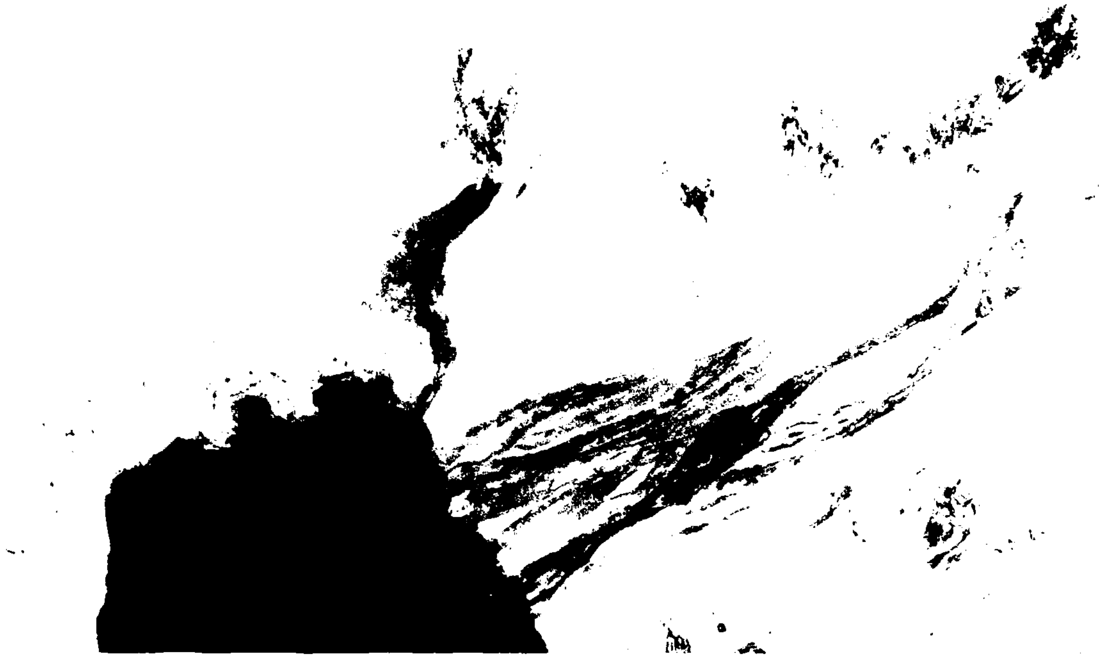


Figure 26. Holgate Glacier. This glacier lost a large amount of ice from its snout. The rockfall to the right went to the bottom of the fiord.

Figure 27. Dingelstadt Glacier. The large rock slide landed in the fiord, apparently shattering a part of the glacier snout. A strong sub-glacial stream emerges at the lower left.

Figure 28. The western embayment of the Columbia Glacier. The drawing, representing [illegible] caused by the earthquake, is a composite made from oblique aerial photographs.

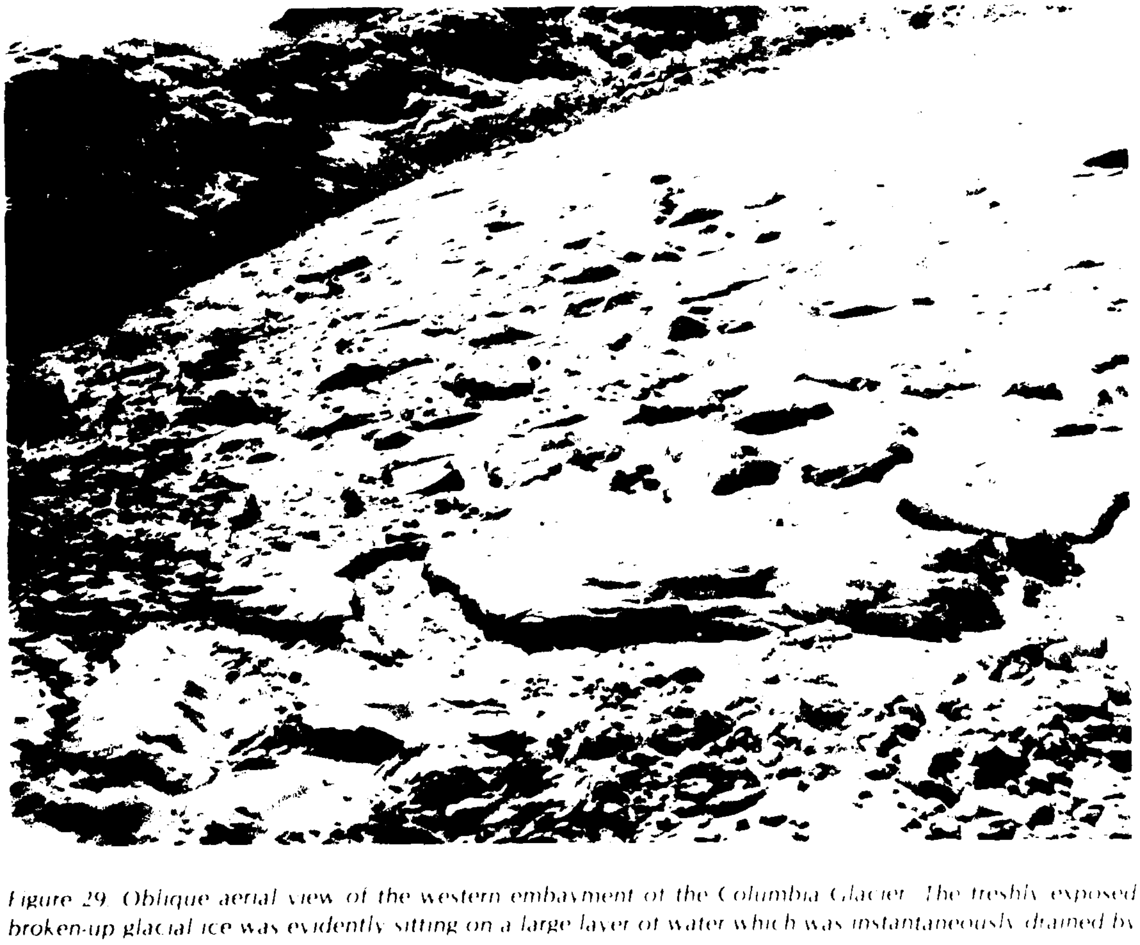


Figure 29. Oblique aerial view of the western embayment of the Columbia Glacier. The freshly exposed broken-up glacial ice was evidently sitting on a large layer of water which was instantaneously drained by the earthquake.

Figure 30. Columbia Glacier. The crushed glacial ice escarpment [illegible] earthquake. The [illegible] of the embayment dropped [illegible] the earthquake's epicenter.

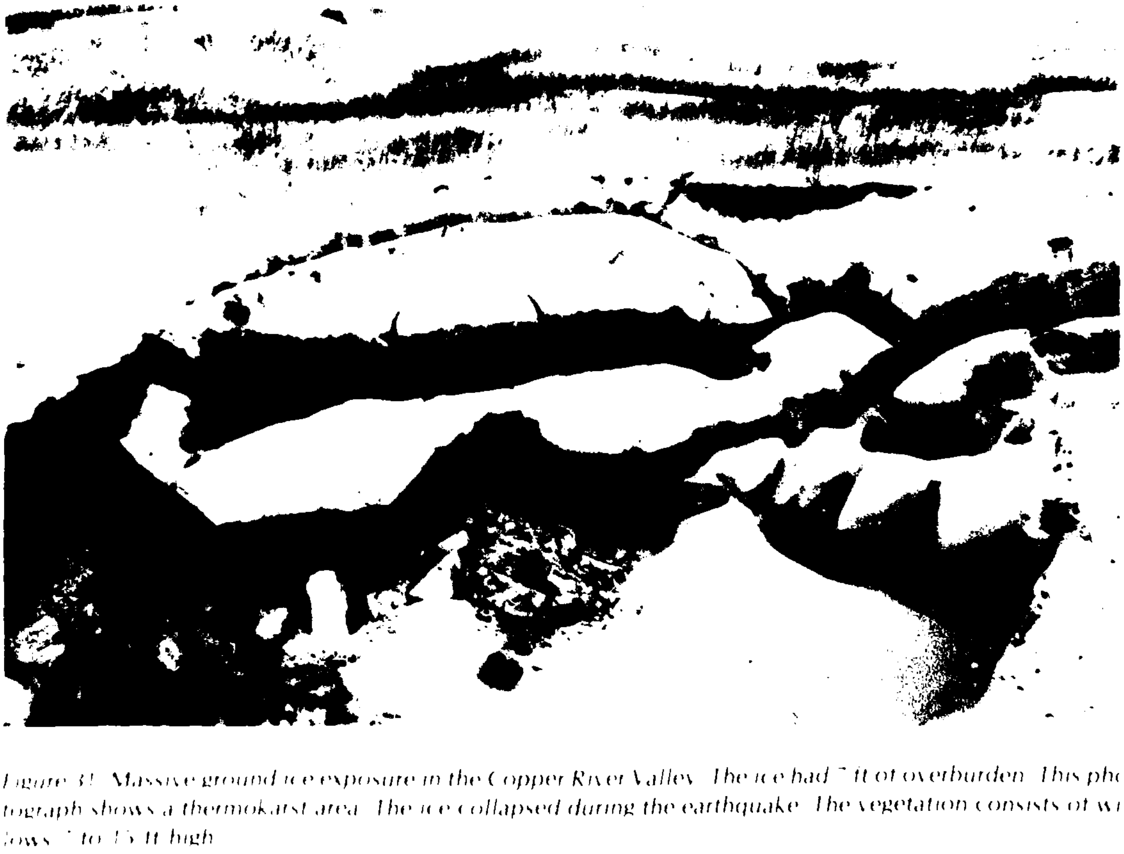


Figure 31. Massive ground ice exposure in the Copper River Valley. The ice had 7 ft of overburden. This photograph shows a thermokarst area. The ice collapsed during the earthquake. The vegetation consists of willows 7 to 15 ft high.

DISTURBED WILDLIFE

Few observations of wildlife reaction to the tremors and shocks of the earthquake were made. Too many events of more immediate concern were taking place so it is unknown whether or not moose, wolf or mountain goat panicked or became confused. However, it has been established that porcupine and bear left their dens and wandered around following the quake. Bear tracks in the snow were clearly visible from the air as well as on the ground. Hungry bears in search of food came uncomfortably close to human habitat in several cases.

TIDAL WAVES

When the sea bottom is subjected to an earthquake, its surface reacts by forming a tidal wave or *tsunami*. Such a disturbance spreads circularly in all directions, but is otherwise dissimilar to the ring waves that form when a small object is dropped on a quiet water surface. For one thing, *tsunami* waves travel at up to 400 mph, can have a very high amplitude, and seldom, if ever, have a point source. Furthermore, such waves are subject to additive or subtractive interference and can be canalized through straits and increased to very large amplitudes.

Apparently the sea floor and dry land dropped as much as 5 ft to the west of Shelikof Strait and rose some 7 ft in the area of Prince William Sound during the earthquake (Fig. 32, [illegible]). In addition, there were massive submarine landslides, each accompanied by its own large wave.

For these reasons the appearance of sea waves in the aftermath of the earthquake was extremely complex. Dissipation, focusing, local generation by landslides, and generation by aftershocks and tremors caused a dozen destructive waves to be recorded on gauges and many others to be noted by observers. Most of the tidal gauges in the area were destroyed or gave false readings.

The height of the tidal waves was reported as anywhere from insignificant to 30 ft. A local wave in Valdez reached a height of 170 ft (Fig. 36). The town has now been relocated at a safer place.

Figure 32. Waterfront in Seward. The earthquake triggered several large tidal waves. [illegible] The first came immediately after the earthquake, apparently due to massive coastal slides. [illegible] photograph shows the damage in the southern part of the town.

Figure 33. Large portions of the Seward waterfront slid into the sea, setting off destructive waves that reached a considerable distance inland. Large destructive tidal waves pounded the south-central shore of Alaska several times in the hours after the earthquake.

Figure 34. Effects of sea waves. The toppled storage tanks caught fire and burned. The waterfront was destroyed by several waves. It was difficult to distinguish between tsunamis and the many waves formed by submarine local landslides, but the toll in life and property loss due to both types of waves invading the land was high. Abnormally large waves continued to invade Prince William Sound until the day after the earthquake.

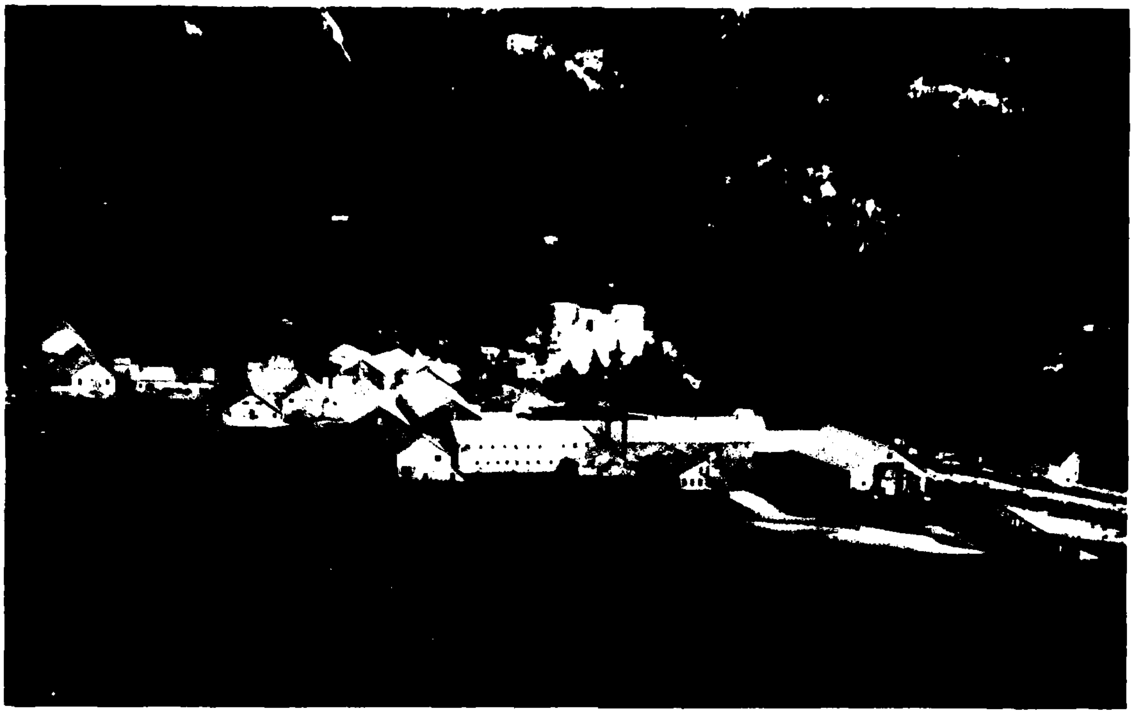


Figure 35. Rising of the sea bottom. The land east of Prince William Sound was uplifted. This cannery in Cordova was left about 6 ft higher above sea level than before. Homer and Kodiak suffered the opposite fate; Homer sank 5 ft and Kodiak 5.5 ft.

The greatest loss of life and property in the seacoast settlements of Alaska was mainly due to devastating sea waves rather than to earthquake shocks. But while "walls of water" were observed by survivors in many places, others reported only insignificant rises in water level. It seems that along an irregular coastline like Alaska's, the extent, violence and destructiveness of *tsunami* waves is unpredictable. That they will occur, however, is highly predictable. *Tsunami* waves were also observed and recorded in California, Japan and Hawaii.

Finally, the only real measure of the violence of a tidal wave is the extent of the loss of life and property. In the Good Friday Earthquake, at least the loss of life was relatively low.

SUMMARY

Some say that earthquakes can be predicted, but it seems that most have not been. There are regions with very few earthquakes while others have them frequently. Why certain regions have them more often is understood only vaguely, but based on past experience southern Alaska is one of these regions.

An earthquake may strike at any season, day or night. A major earthquake affects man in two main ways: by disrupting his transportation routes and by destroying his structures. Man's habit of settling on rather incompetent ground aggravates the situation.

Earthquakes can be minor, major or disastrous. There are several scales for evaluating their magnitude. The effect on man of a major earthquake can be minimized or maximized by certain factors. If it strikes in the night, in bad weather, or at the beginning of a cold winter (little or no frozen ground), and in darkness, the loss of life and suffering will be maximized. The Alaska Good Friday Earthquake struck after a long winter, at the end of the work week and the work day, and during good weather (at least in Anchorage, where most of the affected people lived). For these reasons there were more people awake and outdoors than at other times.

At the time of the earthquake, frost penetra-

Figure 36. Valdez. The earthquake shocks resulted in large crevasses in the alluvium on which the town was built. Approximately 650 ft of the waterfront was lost to a massive slide. All port installations were destroyed. The remainder of the town settled down because of alluvium compaction. Fire broke out in spilled petroleum. Large sea waves repeatedly penetrated inland, destroying life and property. The town was later relocated to a safer place.

tion into the ground was at the maximum. The ground surrounding buildings did not collapse as it would have otherwise, but broke up into large, strong slabs. The integrity of many structures was temporarily preserved, especially in the Turnagain Heights slide.

Due to its remoteness and the sparsity of the population, Alaska relies on radio communications more than on ground lines. Most telephone lines were down after the quake but radio messages brought warnings and allowed coordination of rescue work. For these reasons the regrettable loss of life and the suffering were less than was initially anticipated.

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