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THE GREAT ALASKA EARTHQUAKE

Volume I

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Captain USAF

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AIR FORCE WEAPONS LABORATORY
Research and Technology Division
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New Mexico

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FOREWORD

This report was prepared under Project 5713, Program Element 6.24.05.06.4. Inclusive dates of research were 1 May 1964 to 1 October 1964. The report was submitted on 10 June 1965 by the Project Engineer, Dr. W. E. Fisher, Air Force Weapons Laboratory (WLDC).

This study, sponsored by the Civil Engineering Branch, Development Division, AFWL, resulted from an on-site survey made by the authors in May 1964 throughout the Anchorage area. However, many other persons and organizations gave of their time and talents to provide data included in this report which will complement the growing body of literature documenting the Good Friday Alaska disaster.

Special acknowledgment is due the city officials and residents of Anchorage and the other stricken communities who, despite their own personal concern with the calamity, assisted so generously in providing access and information vital to our study. Similarly, the personnel at several government installations, Elmendorf AFB, Fort Richardson, and other establishments, gave unstinting assistance. Business and industrial concerns, local engineers and technicians, and many private citizens all contributed to the great body of information gathered. The writers, editors, and publications specialists at AFWL and AFSWC extended their most professional efforts to make this report of service to a large and diverse audience. Space precludes any attempt to single out individuals for our thanks. However, our gratitude must be expressed to Colonel Paul W. Stephens, DCS/Civil Engineering, Alaskan Air Command, for providing certain financial support and convenient office space for the authors.

Photographs, maps, and drawings illustrating this report are principally derived from USAF sources. Many of the photographs were taken by the authors or under their supervision. Sources for the basic maps used in this report are the US Department of the Interior, US Coast and Geodetic Survey, US Army Corps of Engineers, and the City Engineers, City of Anchorage, Alaska.

Credit is due the US Army for the following figures:

Figures 9, 10, 11, 15, 16, 17, 18, 19, 20, 21, 22, 26, 27, 28, 29, 30, 31, 32, 34, 38, 39, 44, 45, 54, 55, 56, 58, 59, 60, 61, 62, 63, 64, 65, 67, 70, 74, 77, 78, 81, 83, 89, 95, 96, 99, 100, 103, 104, 115, 117, 137, 138, 139, 140, 157, 218, 227, 243, 281, and 282.

MAC'S FOTO SHOP, Anchorage, Alaska, is the source for figures 94, 114, 134, 135, 136, 187, 216, 219, and 278.

The Anchorage Daily Times is credited with figures 66 and 69.

This technical report has been reviewed and is approved.

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ABSTRACT

The tremendous Alaska earthquake of March 1964 killed many people and caused property damage in the millions. Nevertheless this quake provided scientists and engineers with an almost unique opportunity to study the effects of so huge a natural phenomenon in a relatively urban and built-up environment. The coastal location of the quake's epicenter created a wide variety of temblor effects including crevasses or grabens, pressure ridges produced by landslides, and a broad spectrum of structural damage. The bays, inlets, harbors, and the seacoast for many hundreds of miles were inundated by powerful seismic sea waves (tsunamis). Such diverse effects suggested unlimited areas of study and evaluation. This technical report presents a general summary of all the effects catalogued above, and investigates in some detail the strengths and weaknesses of the many types of structures affected by the temblors. The volume of illustrations which supplement this report shows many details of structural damage, information that could be extremely useful to engineers, architects, contractors, city planners, and others who plan to erect structures on land known to be subject to earthquakes. All maps and illustrations are contained in Volume II of this report.

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CONTENTS

CONTENTS (cont'd)

CONTENTS (cont'd)

TABLES

GLOSSARY

acidic	type of rock which contains large amounts of silica
aftershock	secondary impulse following the principal shock of an earthquake
alluvial	(alluvium) formed by the flow of water; sand, mud, or gravel deposits formed by waterflow, especially those of glacial origin
andesite	rock of volcanic origin, principally feldspar
arcuate	bent or curved, bowshape; said of earthquake fissures or glacial crevasses
argillite	densely compacted sedimentary rock composed of clay minerals
basalt	dark,dense igneous rock, frequently in columnar outflows
batholithic	rock of igneous origin, usually having crystalized deep within the earth
bench	a flat terracelike tract of land on a valley slope, on a coast or along a stream bed, above a river or lake
chert	a very dense rock, chiefly finely crystalline quartz
clastic	rock material composed of fragments of older rock or broken sediments
core	the central portion of the earth, approximately 2,100 miles in diameter
crust	the outer covering of the earth, varying between 3 to 20 miles in thickness
detritus	particles of rock broken away from a mass by erosion
drumlin	a smoothly rounded mound or hill of unstratified glacial detritus
eolian silt	fine sand or surface soil moved by wind action
epeirogenic	forming large geographic features (mountains, oceans, bays, etc.)
fault	a line of slipage or fracture along which movement has taken place
foreshock	the minor or accessory tremor preceding the first major shock of an earthquake
geosyncline	a very extensive warp or downfold in the earth's crust
graben	a fault trough; a downthrown block between two upthrown blocks formed by faulting
graywacke	dark colored sandstone or gritstone
igneous	formed by volcanic fires or heat
kame	a mount or ridge of soil, gravel, rocks left by a retreating ice sheet

GLOSSARY (cont'd)

laccolithic	igneous rock extrusions which extend laterally below the surface and usually between sedimentary layers
lacustrine	geologic strata formed in or alongside a lake
lava	molten or fluid rock issuing from a volcano; the hardened cooled state of same
lens	geologic deposits of one type of material found massed in lens shape in surrounding layers
loess	loamy deposit formed by wind, commonly yellow and calcareous
mantle	generally the segment of the earth below the outer crust and above the core. Roughly 1,800 miles thick
metamorphic	characterized by change of form; change in the structure of rocks under pressure, heat, chemical action, etc.
moraine	mounds of detritus tilled out by the sides (lateral) or snout (terminal) of a glacier. Moraine debris frequently falls back onto the moving ice of the glacier, covering it to a depth of many feet. After the glacier has receded, moraines keep their basic form and structure for many centuries, and are easily identified by geologists.
orogeny (ic)	episode of great deformation; mountain masses or large uplifts produced by massive crustal action of the earth
outwash	detritus of sand and gravel washed out from the bed of a glacier by melting ice
podzol	gray or white ashlike soil deposits caused by leaching of salts or other minerals
pore pressure	pressure built up by moisture in the pores or interstices between grains of sand, etc.
rhyolite	volcanic rock which contains an abundance of silica
rock flour	extremely fine grains of pulverized rock ground out by glacial action and carried down glacial streams, coloring the waters a milky hue
seiche	wave motion in lakes or other landlocked bodies of water, generated usually by changes in atmospheric pressure or more rarely by seismic disturbances
seismic	pertaining to or caused by earthquakes
tectonic	relating to structural geology; the forming of geologic characteristics
temblor	earthquake shock
till	materials or detritus plowed up by glacial action, chiefly clay, rock, and gravel

GLOSSARY (cont'd)

tsunamis	large waves in oceans, seas, or bays caused by earthquakes either submarine or in adjacent land masses; so-called "tidal waves"
varves	paired layers of stratified geologic deposits by annual or semi-annual inundation, etc.
volcanism	condition or effect of active volcano eruption

GEOLOGIC PERIODS

Carboniferous	period of geologic history approximately 250 million years ago when extensive coal deposits were formed
Cretaceous	late middle period of geologic history, approximately 100 million years ago, when small grains and root grasses appeared along with placental mammal life. Reptilian life rapidly declined
Mesozoic	The middle of the span of life forms in geologic history, approximately 100 to 200 million years ago
Ordovician	One of the earliest ages in earth history, approximately 400 million years ago, when fishes, mosses appeared, and some of the oldest rocks and mountains were formed
Pleistocene	the relatively recent periods of glacial activity; ice ages, within the last million years and within man's history on earth
	Nebraskan - first period of glaciation of North America
	Illinoian - third stage of glaciation of North America
	Wisconsin - fourth glacial stage in North America
Pliocene	period just before the glacial age when some of the great European mountain ranges were formed
Proterozoic	extremely ancient period of geologic history, approximately 1 billion years ago, when some of the earliest forms of invertebrate life appeared and when the basic rocks of the earth's crust were being formed.
	Huronian - subperiod of the Proterozoic age
Triassic	period of geologic history, approximately 200 million years ago, when some of the eastern Appalachian mountains attained their greatest mass, when reptiles and amphibians flourished and a few small mammals began to appear

INDEX TO STRUCTURES

INDEX TO STRUCTURES (cont'd)

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SECTION I

INTRODUCTION

At 5:36 p.m. on Good Friday, 27 March 1964, a major earthquake struck south-central Alaska. Many lives were lost, major cities were badly damaged, smaller communities were devastated, untold property was destroyed, and in places whole industries were wiped out. The shocks, which rocked the area for nearly four minutes, registered 8.6 on the Richter Intensity Scale, classifying this quake as one of the most formidable temblors ever recorded on the North American continent. Because the earthquake epicenter was adjacent to the seacoast, huge tsunamis were produced that engulfed many of the coastal communities.

The severest damage in Alaska was apparently limited to the Kenai Peninsula-Prince William Sound area and to Kodiak Island, which altogether comprise less than 10 percent of the Alaska land mass (figure 1). However, approximately one-half the Alaska population is concentrated within this region. The epicenter of the main shock is estimated to have been near Prince William Sound, about eighty miles southeast of Elmendorf Air Force Base and the city of Anchorage. From Prince William Sound to an area in the Gulf of Alaska, south of Kodiak Island, aftershocks occurred along an inferred tectonic hinge zone (figure 1). The Richter magnitude of the main shock has been estimated by several sources (Refs. 1, 2, 3) at about 8.4, on a logarithmic scale for which the magnitude of the largest quakes ever recorded on seismic instruments is 8.9. The energy was estimated at ~200 gigatons (200,000 megatons).

The variety and extent of the damage, the rapid communication of the news of the disaster to the outside world, and the relative ease of placing scientists and engineers on the scene made the 1964 Alaska earthquake one of the most intensely studied in modern seismic history. In fact, research on this quake will continue for many years.

The large amount of data on previous local seismic disturbances and the well-documented surveys of the geological structure of the Alaska area provided an exceptional background for the several types of studies in this report. A glance at the Contents page will indicate the various areas of structural damage investigated in the study. The photographs and other illustrations could prove extremely valuable to scientists, engineers, designers, contractors, and others engaged in construction on areas of the earth with histories of seismic disturbances.

There were 115 people killed and 4,500 rendered homeless in the 1964 temblor, the strongest earthquake to occur in North America since 1899. The resultant damage has been estimated as high as $750 million or more than 100 times the cost to purchase Alaska from Russia in 1867.

As soon as commercial air transportation to Anchorage resumed, engineers, geologists, and geophysicists from the "Lower 48," as Alaskans call the other mainland states, began to pour into Alaska. Along with their Alaskan counterparts, they diligently set about recording aftershock motions, photographing earth slides and damaged structures, taking soil samples and accumulating what will undoubtedly be the greatest volume of information that has ever been gathered after a major earthquake.

Members of the Civil Engineering Branch, Air Force Weapons Laboratory, participated in this scientific research effort. The Civil Engineering Branch has done extensive research in protective construction and has recently assumed the Civil Engineering Research mission for the Air Force. Accordingly, Colonel Paul W. Stephens, Deputy Chief of Staff for Civil Engineering of Alaskan Air Command, requested that experienced personnel from the Branch make a detailed study of earthquake damage on Elmendorf AFB and in nearby Anchorage, and make appropriate recommendations for future Air Force earthquake-resistant construction. The authors arrived at Elmendorf AFB on 5 May 1964 and spent the next three weeks, 5-26 May, photographing and recording the effects of the earthquake on Elmendorf AFB, Fort Richardson, and Anchorage.

The purpose of this report is to document, in detail, the authors' observations and to summarize damage information from other Alaskan communities. The earthquake damage within the Elmendorf AFB-Anchorage area has been divided into two categories--damage produced by landslides and that produced by ground motion. Although the structural damage produced by ground motion has been grouped according to type of construction, there has been no intent to imply that one type is superior to another for earthquake-resistant construction. Examples can be cited of structures of all types which were severely damaged, and of others that received no noticeable damage. It has been the intent of this report to point out apparent weaknesses in design or construction of the structures observed and to recommend means of avoiding the same weaknesses in future construction.

Several years will be required for a complete analysis of the Alaska Good Friday earthquake. Any conclusions reached in this report are necessarily tentative and must await the results of more detailed studies for final confirmation or rejection. It is hoped this report will be of service to other investigators and will, in some way, repay the generous cooperation of the many individuals who made information available to the Air Force Weapons Laboratory.

SECTION I

REFERENCES

1. Grantz, A., Plafker, G., and Kachadoorian, R., "Alaska's Good Friday Earthquake, March 27, 1964, A Preliminary Geologic Evaluation," U.S. Department of the Interior, Geological Survey, Circular 491, 1964.

2. "Preliminary Report, Prince William Sound, Alaskan Earthquakes, March-April 1964," U.S. Department of Commerce, Coast and Geodetic Survey, Seismology Division, 17 April 1964.

3. "Alaska Quake Measurement Is Set At 8.4," Anchorage Daily Times, 23 May 1964, p. 1.

SECTION II

SUMMARY

The 1964 Good Friday Alaska earthquake was a severe test of modern American structural engineering concepts and practices. Many structures, employing various construction materials, were severely damaged. However, the proportion of structures on Elmendorf AFB and in nearby Anchorage that came through the quake in good condition justifies the conclusion that it is both economically and technically feasible to build large structures, on good foundations, which will withstand an earthquake of the same magnitude as the 1964 Good Friday earthquake.

The great majority of lessons to be learned from the Good Friday earthquake are not new; they were available in the large volume of literature dealing with engineering seismology when the quake occurred. Foremost among these lessons is the importance of attention to structural details by experienced professional structural engineers. They must ensure that the connections of a structure transform the individual members, or components, into an integrated system which will respond to stress, strain, shear, etc., as a unit. Many of the damaged structures observed had obviously not responded as a unit because the connections were unable to develop the full strength of individual members.

Structures were damaged both by landslides and ground motion. However, landslide damage was almost wholly confined to small commercial and residential buildings located geographically in the areas subject to landslip. With the possible exception of the case of the Four Seasons Apartments, landslides cannot be blamed for damage to any large multistory building in the Elmendorf-Anchorage area.

Although ground-motion damage to large, multistory buildings was spectacular in several cases, most of these structures performed remarkably well. Many showed an amazing amount of reserve strength, in spite of what appeared to be serious structural damage. In particular the J. C. Penney building, which partially collapsed during the earthquake and afterward leaned noticeably to the north, stubbornly resisted demolition efforts for more than a month before the top four stories were completely razed.

Exterior damage to multistory concrete and steel structures was initially deceiving. Reinforced-concrete buildings, such as the Elmendorf AFB Hospital, showed considerably more exterior distress than did steel buildings, such as the Hill Building in downtown Anchorage. However, detailed inspection indicated the extent of structural damage to both types was probably about the same. Repair of steel buildings had progressed much farther than for buildings of reinforced concrete by the time the authors arrived on the scene, perhaps because major repair of a steel structure is frequently easier to accomplish.

SECTION III

GEOGRAPHICAL ORIENTATION

The city of Anchorage is ensconced at the head of Cook Inlet on the southern coast of Alaska, a bay named after Captain James Cook who explored it in 1778. Surrounded by mountains and inlet waters, the city has only one railroad link with the "Lower 48," and the Glenn and the Seward-Anchorage Highways are the only paved highways in the region. Fortunately, both sea and air transport are available, figure 2.

Situated between the Alaska Peninsula Mountain Range to the west and the Kenai Mountains to the east, Cook Inlet is an ancient mountain valley that is part of the Matanus geosyncline. Just south of Anchorage, the Inlet divides into two branches. The northern branch, Knik Arm, is a shallow arcuate shape, and the city of Anchorage was founded on the lower east bank of this inlet in 1915 as a construction center for the Alaska Railroad. Turnagain Arm, the eastern branch, is situated approximately seven miles south of the city.

The Alaska Range is an arcuate mountain chain that faces the Gulf of Alaska. This range joins the Alaska Peninsula Range approximately 100 to 120 miles west of Anchorage. The eastern end of the Alaska Range joins the inland branch of the St. Elias Range, approximately 240 miles to the northeast of the city. In the Alaska Range, the highest mountain in North America, Mount McKinley, 20,320 feet, is approximately 135 miles north of the city. The Alaska Peninsula Range lies along the Alaska Peninsula that runs in a general southwesterly direction and joins the Aleutian Islands. The three branches of the St. Elias Range from the Gulf of Alaska inland are the Chugach Mountains, the Wrangell Mountains, and the Mentasta-Nutzotin Mountains. The western end of the coastal Chugach Mountains is approximately ten miles east of Anchorage. North of Knik Arm, the Talkectna Mountains run due north to the Alaska Range. Finally, the Kenai Mountains run south from Turnagain Arm down the Kenai Peninsula, figure 3.

The St. Elias Range lies north of the Alexander Archipelago of the southern Alaskan coast and runs through the northwest corner of British Columbia, the southwest corner of the Yukon, and the southeastern Alaskan coast. This range and its two southern branches, the Chugach Mountains and the Wrangell Mountains, support the largest ice fields in North America.

Prince William Sound is an archipelago in appearance and lies to the east and south of Anchorage, just over the mountains. It is a short portage from Turnagain Arm to the Port Wells headwaters of the sound.

Anchorage is located on glacial moraine deposits. Tides in Knik Arm have cut back these deposits to form bluffs all along the eastern side of Knik Arm. The shore line north of the city follows the shallow arcuate shape of the Arm; however, the city is located on a very shallow bay that faces in a general northwesterly direction. The western end of the bay, Point Woronzof, is west of the southern incorporated city limits.

The city is divided by three creeks: Ship, Chester, and Fish Creeks. Eagle River is approximately eight miles north, and Campbell, Furrow, and Rabbit Creeks, south of the city, drain into Turnagain Arm. Eagle River and all the creeks except Fish Creek follow old melt-water channels. "Downtown Anchorage" is located south of the lower end of Ship Creek. Elmendorf AFB and Fort Richardson, west of the Air Base, are on the north side of Ship Creek. A terminal moraine is established in a general east-west direction on the northern sections of both military installations. The terminal moraine "highlands" divide the Anchorage lowlands along Knik Arm into two sections. North of the moraine, the Eagle River section is a pitted surface with many drumlins that parallel Knik Arm. A broad, gently sloping surface of sand and gravel lies parallel to and southwest of the moraine. South of the city to Turnagain Arm, drumlins, kames (ridges and gravel deposits formed by glacial melt), and broad swamps cover the lowlands. The area between the swamp fields and the mountains, southeast of the city, is a low hummocky terrain. The highlands of Point Woronzof and Point Campbell, south of Point Woronzof, extend along the western boundary of the swamp fields. The Point Woronzof-Point Campbell area forms the eastern bank of the Knik Arm-Turnagain Arm intersection.

Figures 3a and 3b show the location of Elmendorf AFB, Fort Richardson, and the city of Anchorage. Outside Anchorage, the larger communities that were damaged by the earthquake are Cordova, Kenai, Kodiak, Seldovia, Seward, Valdez, and Whittier. The epicenter of the main shock is located between Valdez and Whittier; these communities along with Cordova are situated on Prince William Sound. Kenai, Seldovia, and Seward are on the coast of Kenai Peninsula. Except for Kodiak, all the communities are within 150 miles of Anchorage. Kodiak, the largest community on Kodiak Island, is 240 miles southwest of Anchorage, figure 1.

SECTION IV

GEOLOGY OF THE DAMAGED AREA

1. TECTONIC HISTORY

Considering geological time, the southern coastal region of Alaska is a recent formation. The region still contains active volcanoes. Mount Katmai on the Alaskan Peninsula erupted violently on June 6, 1912, and was heard 750 miles away at Juneau and across the Alaska Range at Dawson and Fairbanks (Refs. IV-1). The region is a segment of the tectonic belt that rings the Pacific Ocean. The Aleutian tectonic arc and the North American tectonic arc of the circum-Pacific belt converge in the Kenai Peninsula-Prince William Sound region. These arcs are characterized by orogenic activities associated with the Paleozoic, Mesozoic, and Cenozoic eras, table IV-1.

Excessive volcanism in the Alaskan segment of the circum-Pacific belt occurred in the Carboniferous period. The Pacific coast area was volcanic archipelago in appearance. The internal structure was subjected to extreme compressional forces and contained many batholithic intrusions. Volcanic material and other clastic and carbonate sediments were deposited inward from the archipelago. The archipelago appearance remains along the coastal area from Seattle to Juneau. Associated with this geological activity, epeirogenic movements that persisted into the Triassic period accompanied the volcanic eruptions in the Alaskan segment. Persisting intermittently to the present time, the volcanism in Alaska ranges from stupendous explosions to quiet welling forth of lava. Examples of basic phases of lava analogous to basalt and acidic phases approaching rhyolite have been found in the area, but the majority is of the normal andesites (Ref. IV-3).

The most recent Alaskan orogeny, Pliocene and Pleistocene periods, partially submerged the coastal ranges that consist of Mesozoic strata. At the start of the Pleistocene period, Cook Inlet was narrower. Well-drained lowlands bordered the Inlet. Turnagain Arm was a mountain valley, and Knik Arm contained a stream that was above high tide. The end of the Inlet may have extended as far north as the present Susitna lowlands delta (Ref. IV-4).

Table IV-1

GEOLOGICAL TIME SCALE (Abridged)
(Source: References IV-1 and IV-2)

Era and Duration	Period and Approximate Duration, Millions of Years		Character
Cenozoic: 70 million years	Quaternary:		
	Recent Epoch	0-1	Advent of Man
	Pleistocene Epoch	11-1	Great Ice Age
	Tertiary:		
	Pliocene Epoch	25-11	Formation of coastal ranges
	Miocene Epoch	25-40	Formation of many mountain chains
	Oliogocene Epoch	40-60	
	Eocene Epoch	60-70	Extensive volcanic activity in Western U.S.
Mesozoic: 155 million years	Cretaceous	135-70	Early folding to form Rocky Mountains
	Jurassic	180-135	Beginning of Sierra Nevada Uplift
	Triassic	225-180	Extensive volcanic activity in New England, Pennsylvania, and New Jersey
Paleozoic: 375 million years	Permian	270-225	Folding to form Appalachian Mountains
	Carboniferous:		
	Pennsylvanian Epoch	305-270	Extensive coal-forming swamps
	Mississipian Epoch	350-305	Paleozoic Alps
	Devonian	400-350	Acadian Mountains
	Silurian	440-400	Caledonian Uplift
	Ordovician	500-440	Taconic Mountains
	Cambrian	600-500	Green Mountains disturbance
Proterozoic: 900 million years	Keweenawan		Extensive lava flows
	Huronian		Oldest evidence of glaciation
	Algoman		Folding connected with igneous intrusions
	Timiskamian		
Archeozoic: 550 million years	Laurentian		Rocks much altered and history obscured; primitive life probable
	Keewatin		

The oldest known strata in the Alaskan segment of the circum-Pacific belt is of the Ordovician period, while consolidated metamorphic rocks of pre-Cretaceous (?) age border the Anchorage lowlands. Tertiary age rocks, poorly consolidated, are exposed in a few locations in the lowlands. These rocks are thought to underlie most of the Anchorage area and consist of argillite, graywacke, and chert, as well as altered acidic and basic igneous rocks. The entire area is covered with unconsolidated Quaternary age rocks that were deposited by glaciation during the Pleistocene period. Based on surface outcrops of consolidated metamorphic rocks in the Eagle River area (approximately eight miles northeast of the Anchorage City Hall) and boring records from wells in the Anchorage area, R. C. Gastíl has presumed that a fault has occurred in the bedrock. According to the well records, bedrock is at depths of 230 to 776 feet and the dip is about 2 to 4 percent, with local maxima of 10 to 13 percent (Ref. IV-4).

2. GLACIATION

The oldest evidence of glaciation that is known to man is from the Huronian Period of the Proterozoic Era, over 600 million years ago. In the Anchorage area, however, the unconsolidated rock deposits are recognized as resulting from the Great Ice Age of the Pleistocene Period (table IV-2). Of the five glaciations recognized in the area, only deposits from the three younger glaciations have been found.

During the Nebraskan glaciation period, the 4,396-foot Mount Susitna, 35 miles northwest of Anchorage, was overridden by a glacier. The Mount Susitna glacier rounded summits and spurs at elevations up to 4,400 feet above sea level and scattered boulders on some of the high-level surfaces of the Chugach Mountains to the east of Anchorage. At elevations of 2,200 to 2,800 feet, the spurs and ridges of the Chugach Mountains have been smoothed by glacial action that may be associated with the Caribou Hills glaciation period, Kansan Continental Period. Deposits from the Caribou glacier have been found at elevations of 3,000 feet near Tustumena Lake, 75 miles south, 15° west of Anchorage.

The Anchorage lowlands were covered by the Matanuska lobe of the Eklutna glacier that has been tentatively correlated with the Illinoian ice sheet. Post-depositional weathering has oxidized the drifts to a depth of at least 40 feet, and these deposits represent the oldest glacial deposits that have been found in the Anchorage area. Benchlike remnants resulted from erosion of the Eklutna till and outwash. Undifferentiated deposits along the front of the

Table IV-2

TENTATIVE CORRELATION OF GLACIAL EVENTS IN THE ANCHORAGE AREA WITH NORTH AMERICAN CHRONOLOGY (Source: Reference IV-4)

North American Chronology	Anchorage
Wisconsin	Naptowne
Post-Illinoian Pre-Wisconsin	Knik
Illinoian	Eklutna
Kansan	Caribou Hills (?)
Nebraskan	Mount Susitna (?)

Chugach Mountains east of Anchorage may be related to any of the three glaciers discussed. As the Eklutna glacier advanced down Knik Arm, it is presumed that it coalesced below Anchorage with lobes of the Susitna Valley and Turnagain Arm glaciers.

During the interglacial period between the Illinoian and Wisconsin Continental ice flows, materials were deposited that were to have a profound influence in the Greater Anchorage area during the Good Firday earthquake. Two sublobes, Matanuska and Knik, of the Susitna Valley lobe of the Knik glacier, advanced through the Anchorage lowlands. Another lobe advanced down the valley that now forms Turnagain Arm. The Matanuska-Knik and Turnagain lobes apparently coalesced and then became separated from the larger Susitna Valley lobe as they retreated back up Cook Inlet from their point of farthest advance. The Matanuska-Knik lobe moved to a position north of Anchorage, and the Turnagain lobe moved back up the Turnagain Valley. Whereupon, a glacial lobe from the west or northwest dammed the waters coming from the Matanuska-Knik and Turnagain glaciers. A marginal lake was formed.

The Turnagain lobe apparently retreated faster than the Matanuska-Knik lobe and apparently had a minor influence on the lacustrine deposits of the marginal lake and the present geological features in the Anchorage area. "Rock flour" carried into the lake by rivers from the Matanuska-Knik lobe formed the blue-gray clay that is known locally as Bootlegger Cove clay and underlies much of the Anchorage area.

Environmental requirements of fossils found in peat and oxidation of the upper 6 inches to 2 feet of the Bootlegger Cove clay infer that a warm interglacial period separated the Knik glacial deposits from deposits related to the Naptowne glacial advance of the Wisconsin Age. The till that overlies the Bootlegger Cove clay and the presence of ice-contact features beyond the end moraine suggest that the Naptowne glacial advance fluctuated (Ref. IV-4).

The Naptowne glacier profoundly influenced the appearance of the Anchorage area. Generally speaking, the city of Anchorage was founded on outwash from this glacier. The Elmendorf end moraine of the Naptowne glacier lies along a line just north of the main areas of Elmendorf AFB and Fort Richardson. The outwash deposits of this glacier were eroded by melt-water channels that also cut into both Wisconsin and pre-Wisconsin deposits and exposed the Bootlegger Cove clay along the present creeks in the area. South of Fort Richardson, between the city of Anchorage and the Chugach Mountains, pre-Wisconsin ground moraine has been interspersed with Wisconsin outwash. The area south of Anchorage has been covered with pitted outwash, delta, prodelta, and ground moraine deposits from pre-Wisconsin glacial advances. At the mouth of Campbell Creek, a large deposit of Bootlegger Cove clay has been exposed. Eolian silt, probably derived from the outwash of Wisconsin Age, covers older deposits that underlie the International Airport. Much of this area has been covered by recent swamp deposits (ooze, clays, silts, vegetation).

A section through the earth's crust at Anchorage would reveal that the underlying consolidated rock formation has been folded and faulted and ranges in depth from 200 to 800 feet. Bedrock has been covered with deposits of at least three of the five known glaciers that advanced through the area. These deposits consist of morainial deposits, glacial drift, alluvial fan deposits, kames, delta deposits, glaciofluvial ice-contact deposits, etc. A large blue-gray clay deposit has been sandwiched within the glacial deposits (table IV-3).

Miller and Dobrovalny (Ref. IV-4) report that the following physical properties were obtained in 1949 from an undisturbed sample of Bootlegger Cove clay:

Liquid Limit	39
Plastic Limit	22
Shrinkage Limit	20
Field Moisture Content	35
Cohesion (lbs per sq. ft.)	1,150

> "The Bootlegger Cove clay is a light-gray to dark-greenish-gray silty clay that contains layers or lenses of medium sand...Beds one-fourth inch to 2 inches thick are visible in undisturbed samples, and laminations ranging from 0.25 mm to 1.0 mm thick commonly show within the larger beds. The laminations as well as the beds appear to be cyclic and to consist of alternating light-gray and dark-gray laminae and represent differences in the ratio of silt-size particles to clay-size particles in individual lamina...The upper 12 inches commonly is a yellowish-gray silt that becomes more sandy in the upper 6 to 8 inches. Sand grains are scattered throughout the clay and angular pebbles 1 inch in diameter are common."

Typical sections of the bluffs along Knik Arm are presented in tables IV-4 and IV-5. Note the sharp horizontal contact reported for the Bootlegger Cove clay in the Turnagain Heights section, table IV-4. The contact for this material is suggested as irregular in the Cairn Point Section, table IV-5. North and south of Cairn Point, the Bootlegger Cove clay deposit is only 30 to 50 feet above high tide which is inconsistent with the 126-foot thickness

Table IV-3

STRATIGRAPHIC COLUMN SHOWING QUATERNARY DEPOSITS AROUND ANCHORAGE, ALASKA (Source: Reference IV-4)

Geological Period	Glaciation	Geologic Units
Recent		Loess Alluvium Estuarine silt Dune sand Swamp deposits
Pleistocene or Recent		Alluvial fan deposits Glacial drift (undifferentiated) Morainal deposits (undifferentiated)
Pleistocene	Wisconsin: Naptowne	Silt Abandoned-channel deposits Outwash Pitted outwash Kame field and kame terrace deposits Ground moraine End moraine Advance outwash
	Pre-Wisconsin: Knik	Abandoned-channel deposits Pitted outwash Glaciofluvial ice-contact deposits Bootlegger Cove clay Prodelta deposits Delta deposits Ground moraine Lateral moraine Advance outwash
	Illinoian: Eklutna	Till and outwash

Table IV-4

COMPOSITE SECTION ALONG THE BLUFF OF KNIK ARM IN THE TURNAGAIN HEIGHTS REGION (Source: Reference IV-4)

	Thickness Ft.	In.
Outwash of Naptowne Age:		
Sand, silty with humus; oxidized yellowish-gray	1	6
Sand, fine to medium, contains fine gravel in lenses; gray, some layers oxidized brown; fluvial crossbedding, beds 1 foot thick; contact with Bootlegger Cove clay is sharp and horizontal	18	0
Bootlegger Cove Clay:		
Clay, silty, light-gray dry to dark-greenish-gray moist; upper 12 inches oxidized yellowish-gray, lower limit oxidation even and distinct, no mottling below upper 12 inches; upper 6 to 8 inches more sandy; plastic when wet, compact when dry; breaks with uneven hackly fracture	14	6
Sand, medium, dark-greenish-gray moist	0	8
Clay, light-gray when dry to dark-greenish-gray when moist; compact, breaks with uneven fracture	2	0
Sand, medium, dark-greenish-gray when moist	0	10
Clay, silty, dark-greenish-gray when moist; grades into underlying clay	1	0
Clay, silty, light-gray when dry to dark-greenish-gray when moist; compact when dry, plastic when wet	6	0
Slump and flow debris to beach level	10	0
Total Thickness	54	6

Table IV-5

THICK SECTION OF BOOTLEGGER COVE CLAY MEASURED ALONG RAVINE NEAR CAIRN POINT, WEST OF ELMENDORF AFB IN THE ELMENDORF MORAINE
(Source: Reference IV-4)

	Thickness Feet
Silt, sandy, pale-brown, humic	0 to 7
Glacial Till:	
Silt, sandy to gravelly, yellowish-gray; compact; contains irregular lenses of sand and gravel, somewhat distorted; large erratics locally	110
Bootlegger Cove Clay:	
Clay, silty, light-gray when dry, to dark-greenish-gray when moist; plastic when wet, compact when dry; horizontally banded and laminated in 0.25 mm to 2-inch layers; angular pebbles scattered throughout; upper surface not well exposed, but alinement of seepage and springs suggests irregular contact	126
Tidal Beach:	
Clay, silty to sandy, dark-greenish-gray; sticky, plastic; surface covered by erratic boulders of graywacke and greenstone that range from 1 to 6 feet in the longest dimension--overlaps Bootlegger Cove clay	0 to 10
Total Thickness	236 to 253

reported in table IV-5.

Since the depositional environment of the Bootlegger Cove clay has not been established, the term varved clay has not been applied to the material. The deposition presented has been favored by Miller and Dobrovolny (Ref. IV-4). X-ray analysis of clay samples indicated that the minerals present in the clay include chlorite, mica, kaolinite, quartz, feldspar, montmorillonite, and hornblende; not all minerals, however, were present in each sample. Finally, grain-size curves obtained from five samples of Bootlegger Cove clay are shown in figure 4.

3. POSTGLACIAL HISTORY

The glacial deposits of the Naptowne glacial period were subjected to modification of their original forms by weathering, eolian deposition, plant growth, and erosion. Erosion undercut sea-bluffs, produced landslides or slumps and flows, and downcut consolidated as well as unconsolidated materials along modern stream courses. The deposition of eolian materials is represented by an over-all thin cover of loess and by sand dunes. Moderate podzol soils (white or gray ashlike soil, typically occurring in northern Russia) formed on the slowly accumulating loess as well as on the upper part of the glacial deposits. Podzol results from leaching of the soluble salts and organic matter; however, the podzolization is moderate in the area, so that the ashy-colored layers are not well developed everywhere (Ref. IV-4).

Subsurface drainage in the Anchorage lowlands has been inadequately developed due to the relatively impervious clayey till that underlies much of the area. Downward water movement has been restricted; thus, small swamps are common on hill tops and also cover much of the area south and east of Anchorage. Surface drainage has not fully developed in the swamp areas. In fact, some swamps near Campbell Creek and other streams have cut channels more than 5 feet below swamp levels.

The bluffs that parallel Knik Arm and Turnagain Arm have been slowly undercut by tidal action. At Point Woronzof, the bluff has receded about 95 feet in the period from 1909 to 1947, or about 2 feet per year. Another major factor for the slumps and flows that occur has been seasonal saturation of the Bootlegger Cove clay that underlies much of the area. The clay has been exposed along Knik Arm and along the three creeks in the area--Ship, Chester, and Fish. During cold winter months, the outer 3 to 5 feet of the clay has been frozen. The spring thaw melts the snow cover and much of the melt-water infiltrates the sand and gravel. At the surface of the clay, the melt-water moves laterally towards the bluffs. If the bluffs have a northern exposure, the outer few feet of the clay may still be frozen. The additional ground water saturates the clay, thus reducing its strength and resulting in localized slumps. Further slippage would eventually be prevented by debris accumulating along the toe of the bluff, but unfortunately, much of this debris has been removed by the tides in Knik Arm, so that an unstable condition has been maintained or aggravated. The bluffs have been slowly moving landward in most places, and locally as much as 3 feet a year. An old slide with recurring movement forms a "bench" along Knik Arm between Chester Creek and Ship Creek. Other ancient slumps extend along bluffs that border Chester and Ship Creeks, along the bluff west of Fish Creek, and from just north of Ship Creek to the Elmendorf moraine along Knik Arm (Ref. IV-4).

Numerous slumps and flows have occurred in the Anchorage area, i.e., a retaining wall along Fifteenth Street between K Street and L Street failed. The slope that had been constructed behind the wall was too steep. But another contributing factor may have been oversaturation of the Bootlegger Cove clay along the south bluff of Chester Creek (Ref. IV-4).

Shocks resulting from earthquakes can free water that has been contained within a stratum and can cause the material above the stratum to be displaced. In the case of the Bootlegger Cove clay of Anchorage, the freed water can provide the necessary lubricant to produce a slide or slump surface or to increase the pore-water pressure of the clay layer and thereby decrease its shear strength. In which case the failure "surface" may consist of a layer of material within the clay stratum.

Section V of this report discusses the numerous earthquake tremors and shocks of varying intensity that have been reported in the Anchorage area. The damage from an earthquake in October 1954, reported in the Anchorage Daily Times, was discussed by Miller and Dobrovolny (Ref. IV-4). The Alaska Railroad lost a section of subgrade between Chester Creek and Ship Creek. This is the same area in which a major slide occurred during the Good Friday earthquake. Concrete-block walls were cracked at the International Airport Building. The control tower for the airport collapsed killing one man during the Good Friday quake. Along the steep till bluff of Turnagain Arm, a 140-foot section of the Anchorage Railroad track was left suspended 15 to 20 feet in the air.

SECTION IV

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SECTION V

SEISMOLOGICAL ASPECTS

1. PREVIOUS ALASKA EARTHQUAKES

An estimated 13 million persons have been killed by earthquakes in the last 4,000 years in all parts of the world (over 3,000 persons per year). Earthquakes involve the forces and associated movements that deform the earth crust, i.e., folding, faulting, raising or depressing large sections of continents. To depths of at least 400 miles, tectonic forces within the earth either initiate new faults or movement on existing faults. An earthquake is produced by the redistribution of stresses, tectonic forces within the earth's crust, and it is the shock waves that are transmitted upon and through the earth and the secondary effects produced by them, e.g., tsunamis, or so-called "tidal waves." Earthquakes are always associated with movement along one or more fault lines, and the inertia effects produced by movement of large volumes of materials produce shock waves (Refs. V-1, V-2).

Although there have been many notable exceptions, earthquakes tend to occur in particular areas of the earth. These areas are referred to as belts. The two principal belts are the circum-Pacific belt that encircles the Pacific Ocean and the Alpine-Mediterranean-Trans-Asiatic belt. These two belts nearly coincide with the island arcs and volcanic belts of the earth. In fact, the circum-Pacific belt is referred to as the "ring-of-fire" because of the many large and active volcanoes that are located in the belt. Minor belts exist along submarine ridges in the Artic, Atlantic, and Indian Oceans, and in the rift zones of Eastern Africa and East-Central Siberia. Based on a study of earthquakes occurring between the years 1904 and 1964, Gutenberg and Richter (Ref. V-3) concluded that 90 percent of all earthquakes occur within the circum-Pacific belt.

The annual major earthquakes can be divided into three groups: (1) an average of two great shallow shocks (originating at depths of less than 40 miles), (2) an average of five major intermediate shocks (40 to 190 miles deep), and (3) an average of one large deep shock (originating deeper than 190 miles). Nearly all the deep shocks, which ordinarily produce less surface damage, have occurred in the circum-Pacific belt. But only 80 percent of the shallow shocks, which produce the most damage, have occurred in this belt. The remaining 20 percent of damaging shallow shocks occurring outside the circum-Pacific belt account for the relatively high amount of damage recorded outside the circum-Pacific belt. Based on the earthquakes discussed (Refs. V-1, V-2), at least 50 percent of the recorded major earthquakes that occurred from 1731 were outside the circum-Pacific belt. Of seven earthquakes listed for the period 1450 B.C. up to 1731 A.D., none occurred in the circum-Pacific belt. However, the recorded earthquake history of much of the circum-Pacific belt is not as complete as that of the Mediterranean region, because cultural records and civilization itself were more primitive in the circum-Pacific belt.

Of the ten largest recorded earthquakes (magnitude greater than 8.6) in the period 1918 to 1955, only two occurred in the North American Continent. The epicenter of one of these quakes was in the Aleutian Arc and the other was in the Alaska Peninsula.

Table V-1, from 1918 to 1962, is a brief summary of earthquakes that were recorded in Anchorage, Alaska. Included in the table are earthquakes that registered a magnitude of 6 or greater and that were observed in Anchorage with an intensity of 5 or more (see paragraph 2 for a discussion of magnitude and intensity). With the exception of the October 3, 1954, shock, no "real" quake damage had occurred in Anchorage since World War II. And even the 1954 quake produced only minor damage. As a result, the people of Anchorage were of the general opinion that "earthquakes were nothing to fear." They constructed their homes along bluffs that were slowly slumping away and that were "earmarked" in government pamphlets as dangerous (Ref. V-5). But, perhaps, the "boomtown attitude" of the people is best reflected by a remark made by one man in Anchorage: "Who reads government publications?"

2. MEASUREMENT OF EARTHQUAKES

Neither the absolute intensity of an earthquake nor the exact location and length of the fault, normally, can be determined. Instead, arbitrary procedures have been used that indicate the relative size of earthquakes. The energy released by an earthquake and the intensity of the seismic waves at a given location are estimated by empirical methods. Based on the recorded seismic data at a given seismological station, the distance between the station and the center of the recorded quake is computed. Using the distances computed by three or more stations, the center of the quake is determined from the intersection of arcs of proper radii drawn from each station.

Table V-1

SUMMARY OF ALASKA EARTHQUAKES OF MAGNITUDE 6 AND GREATER AND FELT WITH INTENSITY 5 OR MORE IN THE ANCHORAGE AREA
(Source: References V-4 and V-5)(Data collected by the Coast and Geodetic Survey)

Date and Alaska Time	Locality and Epicenter	Magnitude	Intensity	Remarks
Sep 21, 1911 19:01:4	Prince William Sound and Kenai Peninsula 60.5 N, 149 W	6.9	7-8	Felt 100,000 to 120,000 sq. mi., rock slides, fish killed
Jan 31, 1912 10:11:8	North of Valdez 61 N, 147.5 W	7.25	5	Probably felt 150,000 sq. mi.
Jun 10, 1912 06:06:1	Cook Inlet 59 N, 153 W	7.0	5	Shallow depth
Nov 6, 1912 21:40:4	Entrance to Shelikof Strait 57.5 N, 15 W	7.5	5	Submarine shock reported strong at Seward
Dec 5, 1912 02:27:6	Kodiak Island 57.5 N, 154 W	7.0	5	
Jun 21, 1928 06:27:13	Prince William Sound Region 60 N, 146.5 W	7.0	5	Landslides, rolling wave sensations
Dec 23, 1931 17:47:00	Whale Island (near Kodiak Island) 60 N, 152 W	6.25	5	Moderate
Sep 13, 1932 22:43:00	Prince William Sound and Kenai Peninsula 61 N, 148 W	6.25	5	Clocks stopped
Jan 3, 1933 17:59:28	Seward 61 N, 148 W	6.25	5	Cracks in streets and roads for 20 mi.
Apr 26, 1933 16:36:00	Big Susitna River District and Old Tyonek	7.0	7	50 miles of broken telegraph lines
May 3, 1934 18:36:07	Anchorage 61.25 N, 147.5 W	7.2	6	Broken windows, goods jarred from shelves
Jun 17, 1934 23:13:50	Anchorage 60.5 N, 151 W	6.75	5	Small objects overturned
Aug 1, 1934 21:13:08	Anchorage 61.5 N, 147.5 W	6.0	5	Small objects overturned, dishes broken
Feb 12, 1940 23:17:46	Alaska Peninsula 55 N, 161.5 W	6.75	5	Awakened all in Port Moller
Jul 29, 1941 15:51:21	Kenai Peninsula 60.9 N, 149.2 W	6.25	5	One building thrown from foundation, broken dishes, plaster fell

Table V-1 (cont'd)

Date and Alaska Time	Locality and Epicenter	Magnitude	Intensity	Remarks
Nov 3, 1943 04:32:17	Anchorage 61.75 N, 151 W	7.3	5	Swinging doors and rattling windows
Nov 3, 1945 12:09:03	Kodiak Island 58.5 N, 151 W	6.75	5	
Jan 12, 1946 10:25:37	Gulf of Alaska 59.25 N, 147.25 W	7.2	5	Felt strongly
Sep 27, 1949 05:30:45	Montague Island 59.75 N, 149 W	7.0	5	Broken windows, clocks stopped, objects swayed in rooms
Feb 13, 1951 12:12:58	Alaska Peninsula 56 N, 155.5 W	7.1	5	
Jun 25, 1951 06:12:32	Near Anchorage 61 N, 150 W	6.25	5	Bounced parked cars, shattered lightbulbs and glassware
Nov 29, 1952 13:46:25	Kodiak Island 56 N, 155 W	7.0	5	
Oct 3, 1954 01:18:00	Kenai Peninsula 60.5 N, 151 W	6.75	8	Panic, plaster cracked, landslides, watermain breaks
Jan 20, 1961 07:09:15.7	South of Kodiak Island 56.4 N, 152.3 W	6.75	5	
Sep 5, 1961 01:34:37.3	Seward and Kenai Peninsula 60.0 N, 150.6 W	6.0	6	Slight damage
May 9, 1962 14:03:40.2	Anchorage and Southern Alaska 62.0 N, 150.1 W	6.1	5	No damage
Aug 18, 1962	Moose Pass, Palmer and Nancy Lake 62.3 N, 152.5 W	6.25	5	Widely felt

The focal point for an earthquake has been arbitrarily assumed to be that point at which fracture initiated or, in the case of an existing fault, that point at which first movement along the fault occurred. Thus, an earthquake has been assumed to have a focus which is a specific point within the crust even though movement may have occurred over a fault length of many hundreds of miles. For some earthquakes, the depth from the surface of the earth to the focal point, or depth of focus, has been over 400 miles. The depth of focus of the Good Friday earthquake has been estimated at 12.5 miles which is within the shallow depth range associated with the Aleutian Arc (Ref. V-4).

The point on the surface of the earth vertically above the focal point is called the epicenter for the earthquake. The effects of an earthquake are usually most severe in the epicentral region; this is particularly true for shallow focal points. When earthquakes have deep focal points, the shock is felt over a very broad area; however, there is little damage at any surface point within the area. In general, the largest and most intense areas of surface damage are produced by earthquakes whose focal points fall in the intermediate depth class, 44 miles to 188 miles deep.

The energy released by an earthquake is transmitted upon and through the earth in the form of waves. These waves are recorded on seismographs. All seismographs can be divided into three parts: (1) inertia system, (2) coupling system, and (3) recording system. The inertia system normally consists of a suspended mass whose motion is usually limited to one direction. The relative motion of the mass and its case is transformed by the coupling system into a mode that can be recorded. And finally, the motion of the mass as a function of time is reproduced by the recording system. The inertia system that is best adapted for use in seismological work is a single-degree-of-freedom system. Thus, it is necessary to have three components of motion in order to obtain a complete record of any general displacement. Normally, the motions of two horizontal components, perpendicular to each other, and a third vertical component are recorded. The accuracy with which an instrument can record a wave is determined by the relationship between the natural period of the instrument and the period of the wave that the instrument is recording. Thus, short-period and long-period instruments are generally used. The short-period, high-magnification instrument has a period of 1 to 3 seconds and magnification of 10,000 to 100,000; whereas, the long-period, low-magnification system has a period of 12 seconds and a magnification of 250 to 1,000 (Ref. V-6). In addition to these instruments, some seismological stations also have strong-motion seismographs which are used to obtain complete records of earthquakes at short distances from the epicenter. These seismographs necessarily have small magnifications, regardless of their periods. In general, seismograph stations provide continuous records of the seismic activities of the earth, except for strong-motion records. Strong-motion seismographs are preset to be triggered by a threshold seismic shock. Unfortunately, only marginal strong-motion records were obtained of the Good Friday earthquake. A strong-motion seismograph was triggered in Tacoma, Washington, about 1,450 miles from the epicenter.

Seismic waves produced by movement of large volumes of materials along a fault can be divided into three types: P waves, S waves, and L waves. (Waves that result from reflection and refraction due to changes in density within the earth are ignored.) The first wave to be recorded at a seismograph station is the P or primary wave, sometimes referred to as the longitudinal wave, that is transmitted by changes in volume (dilatation) in the direction of propagation. The P wave travels nearly twice as fast as the S wave or secondary wave which is the second wave type to be recorded. The secondary or transverse wave is transmitted without volume changes and results in changes of shape or shear of the earth (distortion). The last wave type to be recorded (in this simplified example) is the L or long wave which is a complex sinuous wave that travels along the surface of the earth. This complex L wave is composed of two waves, one vibrating vertically in the direction of propagation (the Rayleigh wave), and the other vibrating horizontally (the Love wave). The velocities of the three wave types are (Ref. V-1):

P wave	3.4 to 8.5 miles per second
S wave	2.0 to 4.5 miles per second
L wave	2.5 to 2.7 miles per second

The time of arrival for each wave type is measured by the seismograph records at a seismological station. The time interval between the arrival of the P and S waves is proportional to the travel distance of the waves, and may be used to compute the distance to the wave source or epicenter.

$$D = K\left(T_P - T_S\right)$$

where

D = the distance between the station and the wave source

T_P = P wave arrival time

T_S = S wave arrival time

K = a constant determined from travel-time curves developed for a given station

If an earthquake occurred in an inhabited area, isoseismal (equal intensity) maps of the damaged area can be used to obtain a first approximation of the epicenter. Based upon this location of the epicenter, travel-time curves are developed from the records of a number of different seismological stations that have recorded the earthquake. The epicenter of all subsequent earthquakes that occur in the same generally established area then can be determined from the records of at least three seismological stations. The intersection of arcs, whose radii were determined from travel-time curves for the area, drawn from the stations is the epicenter. Seventy Coast and Geodetic Survey seismological stations were used in the preliminary location of the epicenter for the Good Friday earthquake, table V-2.

The magnitude of an earthquake is a measure of its absolute intensity and relative area. In 1935, a magnitude scale was developed by C. F. Richter that is now universally used. The Richter magnitude scale is based on amplitude-distance curves developed for a specific earthquake region and a group of recording stations. Each member of the amplitude-distance family of curves represents a specific earthquake. Arbitrary numbers are assigned to the amplitude scale, plotted on a logarithmic scale to the base 10. For a given distance and maximum trace amplitude, the Richter magnitude can be determined. On this scale, earthquakes range in magnitude from 0 (barely recorded) to about 8.5 (for the world's greatest recorded shocks). The magnitude of the largest recorded earthquake is 8.9. Thus an earthquake of magnitude 6 is ten times larger than that of magnitude 5.

The magnitude of the Prince William Sound earthquake of 1964 has been set at 8.4, table V-2. The great San Francisco earthquake of 1906 had a magnitude of 8.3, and the Chilean earthquake of 1960 had a magnitude of 8.4. Both of these latter two earthquakes resulted in great loss of life and property damage.

Since amplitudes and periods of vibration vary, the horizontal acceleration that the vibrations tend to produce is a more significant measure of the damage produced by an earthquake. Mercalli in 1901 devised an intensity scale for use in Italy to measure the effects of earthquakes. The intensity scale measures the effects of an earthquake upon man, upon buildings and other structures, and upon the features of the earth's surface. The Mercalli scale was modified by

Table V-2

EPICENTER OF MAIN SHOCK
(Source: Reference V-4)

Origin Time:	05:36:13.0 (local) Standard Error	0.14 seconds
Latitude:	6.05° N	0.022° (1.55 miles)
Longitude:	147.50° W	0.051° (1.61 miles)
Depth:	12.5 miles (restricted)	
Magnitude	8.4 Pasadena	
	8.5 to 8.75 Berkeley	
	8.6 Palisades	
	8.5 C&GS (Wood-Anderson at Albuquerque)	

The location of the epicenter is based on 70 observations. The magnitude of the earthquake has been set at 8.4 (Ref. V-7).

Wood and Newmann in 1931 and abridged by Byerly in 1942 for use in the United States, table V-3. The value of the scale is limited by soil conditions and types of construction in various parts of the world. However, if the scale is applied uniformly over an area to describe the effects of a single earthquake, isoseismal maps (equal intensity contour maps) can be drawn. These maps usually enclose the epicenter and point up areas of poor soil or of poor construction. In view of the long period effects which were not contemplated by Mercalli, it is difficult to assign a modified Mercalli intensity number to the 1964 Alaska earthquake.

The duration of an earthquake is the time interval in which the effects of the shock either produce a measurable seismological record or are observed by many persons in the region of the quake. The duration and magnitude are measures of energy released by an earthquake. It has been estimated that the 1964 Alaska earthquake released at least twice the energy (200 GT) as that of the 1906 earthquake which destroyed San Francisco (Ref. V-8). The Alaska earthquake included a land area of almost half-a-million square miles, figure 1.

Observers in Anchorage have estimated that the duration of the shocking may have lasted as long as 3 to 4 minutes. Where local landslides did not occur, the principal destructive shaking may have continued for one minute. There was an initial short, sharp shake, followed by a strong rolling motion. The long duration of shaking suggests that a break occurred of considerable length or movement along a fault of considerable length (Refs. V-4, V-8).

Breaking of or movement along a fault is not, in general, completed during the main shock. Both foreshocks and aftershocks are part of the general stress relief activities occurring along the fault zone. In fact, it is not always known just which shock is the main one and which are the fore- and aftershocks. Aftershocks are sometimes as large or larger than the main shock. For example, the 1960 Chilean earthquake began with a temblor of magnitude 7.5 on 21 May at 10:03 GCT. This shock was followed by a series of aftershocks; the four major aftershocks had magnitudes of 6.5, 7.5, 7.8, and 7.5, respectively. Twenty-four hours later, at 19:11 GCT on 22 May, a magnitude 8.4 shock occurred which was followed by over fifty aftershocks ranging from 5 to 7 in magnitude (Ref. V-9).

The largest aftershock of the Prince William Sound earthquake registered a magnitude of 6.7, table V-2. As of April 13, 1964, the magnitude of seven aftershocks was greater than 6; ten aftershocks occurred within 24 hours of the main shock. The main and aftershocks occurred in an area that runs from 15

Table V-3

THE MODIFIED MERCALLI SCALE
(Source: Reference V-2)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Vibration like passing of truck.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows disturbed; walls made cracking sound.

V. Felt by nearly everyone; many awakened. Some dishes, windows, and so forth broken; a few instances of cracked plaster; unstable objects overturned.

VI. Felt by all; many frightened and run outdoors. A few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; landslides considerable from river banks and steep slopes.

XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Earth slumps and land slips in soft ground.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

miles north of Valdez to 30 miles south of the Trinity Islands, south of Kodiak Island. All the shocks were northwest of the axis of the Aleutian Trench, and almost all were located southeast of the axis of the Kenai-Chugach Mountains and the mountains of Kodiak Island. The aftershocks were clustered at either end of the area, being relatively sparse in the central part, table V-4. The depth of focus for all aftershocks was established at 12.5 miles for the computation of epicenters; however, the depth did increase slightly towards land.

From the locations of epicenters for the main shock and aftershocks, a 400-mile fault zone can be inferred, figure 1. Physiographic changes indicate that the region east of the fault zone uplifted while that on the west or landward side settled. Land movements reported in table V-5 are based on unconfirmed measurements from tide gages and references to expected tides. Just the reverse change in ground elevations is associated with a typical Pacific island arc-type structure. It would seem that the region can be considered as intermediate between the Pacific island arc-type and the more conventional continental zones of orogeny.

Table V-4

PRELIMINARY EPICENTERS FOR THE MAIN SHOCK AND THE PRINCIPAL AFTERSHOCKS OF MAGNITUDE 6.0 OR MORE AS OF APRIL 13, 1964
(Source: References V-4 and V-8)

Date	Anchorage Time	Latitude Degrees	Longitude Degrees	Magnitude*
March 27	17:36:13.0	61.1 N	147.5 W	8.4
March 27	21:10:21.4	58.8 N	149.6 W	6.2
March 27	22:33:46.1	58.0 N	151.2 W	6.5
March 27	23:01:00.4	56.5 N	152.0 W	6.2
March 27	23:52:54.0	59.7 N	146.6 W	6.2
March 28	00:12:42.0			6.3
March 28	01:08:26.5	60.1 N	148.5 W	6.2
March 28	02:20:48.8	56.5 N	154.1 W	6.5
March 28	04:47:38.7	60.4 N	146.5 W	6.3
March 28	04:49:15.0	60.4 N	147.1 W	6.5
March 28	10:29:05.9	59.8 N	148.9 W	6.6
March 29	16:18:05.9	56.6 N	153.0 W	6.7
March 29	21:09:34.2	59.8 N	145.9 W	6.2
April 4	07:46:07.8	56.3 N	154.5 W	6.3

*Magnitude by Pasadena

Depth of all epicenters restrained at 12.5 miles

Table V-5

LAND MOVEMENT
(Source: Reference V-4)

Area	Movement
Kodiak Town	5.5 feet down
Kodiak Island (Southwestern part)	Normal
Homer (mid-part of spit)	2.5 feet down
Homer (end of spit)	6 feet down
Seldovia	Several feet down
Whittier	5 feet down
Seward	Several feet down
Cordova	6 feet up
Valdez	9 to 14 feet up
Middletown	Perhaps several feet up
Montague	Perhaps several feet up

SECTION V

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SECTION VI

DAMAGE OUTSIDE THE ANCHORAGE AREA

Seismic sea waves or "tsunamis" (Japanese) accounted for the principal property damage and loss of life that occurred outside the Anchorage area as a result of the earthquake. These waves affected coastal communities along south-central Alaska, Canada, and the states of California, Hawaii, Oregon, and Washington. Earthquake-triggered submarine landslides produced local sea waves that hit the waterfront area at Valdez, Seward, and probably Whittier as well as many unrecorded localities in the Prince William Sound region, figure 5. Residual tectonic vertical displacements have allowed normal high tides to inundate resultant low coastal regions. Thus, both the Alaskan highway and railroad systems in addition to inhabited regions were extensively damaged. In general, the damage produced by ground motion was minor outside the Anchorage area; much of the damage debris was washed away by the tsunamis.

Tsunamis have three origins: (1) submarine volcanic eruption, (2) submarine slumping of sediments, and (3) submarine faulting or movement along existing faults. Of the three, the third normally will produce the greatest worldwide effects. Seismic sea waves have moderate height and long wave length. Many records report ship personnel who were unaware that the waves had passed them. However, when the waves encounter land masses, they have great potential destructivity. On the other hand, seaquakes, not to be confused with tsunamis, result from refraction of seismic ground waves from the rocks underneath the sea. Seaquakes are short-period tremors whose effects are merely the shaking of ships, the stunning or killing of fish, and the rippling of the surface of the sea. They rarely, if ever, produce tsunamis.

According to preliminary estimates of vertical land movements, table VI-1, extensive vertical movements occurred in submarine areas. This movement was associated with faulting that extended from Cape St. Elias (along the coast) to Afograk Island (north of Kodiak), figure 5. The maximum seaward extension of the generating area has been estimated at 150 miles south-southwest. Even though the epicenter of the main shock was on land, the extent of the submarine generating area produced the great tsunami effects that inundated the coastal regions along Kenai Peninsula, Prince William Sound, and Kodiak Island, figure 6.

Table VI-1

LAND MOVEMENT
(Source: Reference VI-1)

Area	Movement
Kodiak Town	5.5 feet down
Kodiak Island (southwestern part)	Normal
Homer (mid-part of spit)	2.5 feet down
Homer (end of spit)	6 feet down
Seldovia	Several feet down
Whittier	5 feet down
Seward	Several feet down
Cordova	6 feet up
Valdez	9 to 14 feet up
Middletown	Perhaps several feet up
Montague	Perhaps several feet up

In the coastal communities of south-central Alaska, the fact that the earthquake occurred during low tide minimized the resultant damage. The Alaska communities hardest hit were Anchorage, Seward, Whittier, Valdez, Kodiak, Old Harbor, and Kaguyak, figure 6. Table VI-2 presents representative maximum tsunami wave heights that were estimated from high water marks in many of the Alaskan communities. Major damage occurred along the coastal area of Canada and in Crescent City, California, while minor damage was sustained in the coastal regions of Washington and Oregon and the Hawaiian Islands.

A $1 million contract has been awarded for repair of harbor facilities at Sitka, the second oldest white settlement in Alaska--1799 (Ref. VI-3). Along the Canadian coast, 260 homes were damaged in Alberni, 60 heavily damaged. The forest industries in Port Alberni were heavily damaged. Of the 17 houses in Hot Springs Cove, British Columbia, five were washed away and ten were severely damaged. In Crescent City, California, 300 buildings were destroyed or washed off their foundations within a 27-block area by the fourth and fifth waves to hit the city (Refs. VI-1, VI-2). The city has requested a $50,000 federal grant in order to permit the U.S. Army, Corps of Engineers, to conduct hydraulic model studies of the Crescent City harbor for future protective construction (Ref VI-4).

Four people were drowned at Depoe Bay, Oregon. Both Seaside and Cannon Beach, Oregon, sustained $250,000 in damages. Finally, minor damage in the Hawaiian Islands, nearly 4,000 miles away, included the inundation of three restaurants, a house, and a shopping center (Ref. VI-1).

Minor damage resulted from ground motion in the city of Seward which was 95 miles southwest of the epicenter. The most serious ground motion damage was the rupture of large fuel storage tanks and the ignition of the fuel. About 30 seconds after the start of the tremors, a submarine landslide in an alluvial fan deposit carried over 4,000 feet of the Seward waterfront into Resurrection Bay. The slide removed a dock, a warehouse, and many fuel storage tanks. Before the earthquake, the depth of the bay at the dock was 32 feet; after the quake, the depth was 150 to 200 feet. The submarine slide generated local waves that ran up on Lowell Point south of the city and on the east bank of the bay. Just after the landslides, excess pore-water pressure caused "boils" to occur in the bay, figure 7.

Subsequent to the submarine slide, seismic sea waves battered the town. The entire waterfront area was inundated. Segments of the Alaska Railroad and

Table VI-2

MAXIMUM TSUNAMI WAVE HEIGHTS
(Source: References VI-1 and VI-2)

Communities in south-central Alaska:

Cordova	30 feet
Kodiak	30 to 35 feet
Seward	30 feet
Sitka	16 feet on the third wave
Valdez	30 feet
Whittier	35 feet

Representative maximums in other locations:

Attu Island	2.9 feet
Crescent City	12.0 feet
San Francisco	7.8 feet
Santa Monica	6.6 feet
Los Angeles	3.3 feet

of the Anchorage-Seward Highway were washed away. The railroad yards and fuel storage tanks in the waterfront area were severely damaged. After the quake, ships and houses were suddenly neighbors. Half of one of the Alaska Railroad transit sheds on the waterfront was washed away; another shed was heavily damaged. The Standard Oil docks and warehouses, the U.S. Army docks and warehouses, the San Juan dock, cement plant, and marineways, the small-boat harbor, city dock and scow grid were all washed out to sea, figures 8, 9, 10, and 11. Thirteen drownings resulted from submarine landslides and tsunami (Ref. VI-2).

In addition to emergency repairs to water, sewer, and power lines, debris clearance and demolition of damaged structures commenced the day after the earthquake. The Alaska Railroad yards cleanup project, approximately $760,000 of a $1 million debris cleanup program (Ref. VI-5), included the use of skin divers to aid in underwater salvage. All debris was removed out to a water depth of minus 40 feet, mean-lower-low-water. Only contaminated debris, tank-cars and POL tanks, were removed beyond that depth (Ref. VI-6). Repair of utilities and streets will cost almost $1,400,000 (Ref. VI-7).

The results of an extensive soil investigation program conducted by the U.S. Army, Corps of Engineers, indicated that most of the city is located on ground that can be termed a normal risk category. The risks are no greater than is normally expected in the construction industry. However, the waterfront area that includes the Standard Oil Company dock, Alaska Railroad switch yards, Army dock, the small-boat harbor, and a number of residential blocks just west of the waterfront were classified as a high-risk region. With the exception of grading and light fill, it is recommended that no repair, rehabilitation or new construction with Federal money be undertaken in this risk area, figure 12 (Ref. VI-8).

The soils study has cleared the way for an urban renewal program that will cost in excess of $2 million. In addition, a new industrial development area and a $7.8 million deep-water pier and terminal yard will be located at the headwaters of Resurrection Bay, north of the city (Ref. VI-10).

Much of the damage that occurred in Whittier was caused by seismic sea waves and fire that followed the earthquake. Located at the head of Passage Canal on Prince William Sound, Whittier was only 40 miles southwest of the epicenter. Numerous landslides were triggered in the vicinity of Portage, ten miles west of Whittier. The maximum height of the tsunamis that inundated the city was 35 feet, table VI-2. The force produced by these waves has been indicated by the fact that a 4-cubic-yard, barnacle-covered boulder was carried by the waves 125 feet and deposited at an elevation of 26 feet above normal sea level. The death toll in the town was thirteen (Ref. VI-2). Cleanup of the waterfront area will cost $13,000 (Ref. VI-11).

A remarkable similarity exists between the damage that resulted at Seward and that at Valdez. Located at the head of Valdez Arm of Prince William Sound, 45 miles east of the epicenter, Valdez is founded on alluvial fan deposits of the Lowe River.

The tremors in Valdez, called the Switzerland of Alaska because of its impressive mountain setting, lasted from 3 to 5 minutes. During this time numerous fissures developed throughout the city and many buildings were damaged. The entire pier and harbor facilities were destroyed by a submarine landslide that removed an area of the waterfront 4,000 feet long and 600 feet wide. The water depth at the dock increased from 35 feet to 110 feet. An area near a small-boat harbor formerly exposed at low tide is now covered with 70 feet of water, figure 13. Thirty lives were lost in the dock area. Unlike Seward, no fires broke out during or after the quake in the town, but 0.3 mile southeast of town fuel storage tanks were ignited (Ref. VI-2).

Four seismic sea waves hit the town. The first wave resulted from the submarine landslide. The next three waves were probably tsunami waves generated in the Gulf of Alaska. The first two waves and the last wave to hit the town inflicted great damage. Between 1:00 a.m. and 2:00 a.m., the last wave, 30 feet high, inundated the waterfront area.

It has been estimated that 40 percent of the business district and 10 to 20 percent of the residential district were destroyed. In addition, soil studies have confirmed earlier engineering opinions that large segments of the community were established on incipient landslide blocks.

Under the Federal urban renewal program, the city of Valdez will be relocated at a site in the Mineral Creek area four miles from the present site. It is interesting to note that at the time the city was originally founded, the Mineral Creek area was to be the site for the city; however, the center of commerce developed at the mouth of the Lowe River. The Federal Government advanced $58,000 for planning the new community (Ref. VI-12). No new construction will be permitted in the old town under the urban renewal program; however, a $150,000 project will restore the old town water system (Ref. VI-13).

A new deep-draft dock and warehouse and a six-room grade school will be constructed at the new townsite, and the high school at the old town will be repaired and used until new facilities are constructed at the new site. A tent city will be set up at the new townsite to serve through the winter. The cost of the urban renewal project will be $2,400,000 with a Federal-local matching ratio of 90 to 10 (Refs. VI-14, VI-15). Homes and business property in the old town will be purchased under the urban renewal project at a cost of $1,450,000 (Ref. VI-16). Valdez is not the only city "on the move"; the 15-family, tide-threatened community of Girdwood on Turnagain Arm plans to relocate two miles inland (Ref. VI-17).

Large areas of the eastern coast line of Kodiak Island were inundated by seismic sea waves. The communities of Old Harbor and Kaguyak at the southern end of the island were destroyed. Only 10 battered houses out of 30 homes remain in Old Harbor. In Kaguyak, several men returned to the town after the small second wave. Three of them were drowned when the third wave completely washed away the town (Ref. VI-18). The tsunami warning issued by the Fleet Weather Station on Kodiak Island and prompt evacuation of coastal residents greatly reduced the tsunami death toll on Kodiak.

The earthquake tremor did not damage the town of Kodiak, but four seismic sea waves inundated the waterfront and business areas, figure 14. The fact that the first wave was smooth and fast but without a crest probably accounts for the relatively low Kodiak death toll of 16. The fourth wave, which was ice-laden, between 11:16 p.m. and 11:20 p.m., was 30 to 35 feet high and it inundated large areas of the coast to an elevation of 26.5 feet above normal highest tide. Fishing boats were "lost at sea" or hurled atop homes. Out of 160 crab and salmon boats, 77 were lost or severely damaged. Two of the three seafood processing plants and other waterfront installations were swept away along with 40 percent of the downtown area and 75 percent of the town's food supply. The third cannery was unable to operate for over two months (Ref. VI-18).

Repair of the Kodiak small boat harbor and its parking lots and roads will cost $631,000 (Refs. VI-5, VI-19). Including an emergency timber road, railroad trestle, repair costs for three road sections, a small water system, and power lines in the Kodiak area will be $1.5 million (Refs. VI-20, VI-21, VI-22). An $8 million urban renewal program has been approved for the community. The entire project will cover a 35-acre area and take four years to complete (Ref. VI-23).

Southwest of the epicenter, 160 miles, the small boat harbor at Homer disappeared in a "funnel-shaped" pool that occurred during the violent tremor. The harbor's lighthouse, located on a breakwater, is now 40 to 50 feet below sea level due to complete subsidence of the breakwater. A $960,000 contract has been let for the clearing, basin dredging, and breakwater construction at Homer harbor (Ref. VI-24). Moderate damage occurred in the downtown area of Homer (Ref. VI-2), and from a soil study, the town is in a normal risk area. The Homer Spit, a sand bar that extends 5 miles into Kachemak Bay, is considered a high-risk area by Task Force 9, representing the Alaska Reconstruction Commission (Ref. VI-25).

On the south bank of Kachemak Bay, contracts awarded for the reconstruction of the Seldovia airstrip and small boat harbor amount to $230,000 (Ref. VI-26). About 65 miles north of Homer, the Standard Oil Company of California refineries will require approximately $350,000 for cleanup and restoration of earthquake damage (Ref. VI-27).

Cordova is 70 miles southeast of the epicenter. Tectonic uplift elevated the city 6.5 to 7.5 feet. Submarine landslides that resulted in great damage to Seward and Valdez did not occur at Cordova and Cordova damage was relatively light in comparison to other communities. The first tsunami wave to hit the Cordova waterfront was 20 feet high, but it did not reach the new highest high-tide level which after the tectonic uplift was 21.5 to 22.5 feet above mean-lower-low-water. A seismic wave inundated the waterfront area about 1 a.m. on 28 April when it rose 5 feet above the highest high-tide level. This wave washed away houses and boats and resulted in extensive damage to piers and docks. At Point Whitshed, near Cordova, one man was drowned and 10 cabins were washed away (Ref. VI-2).

While tectonic settlement threatened other coastal areas with flooding, the tectonic uplift in Cordova resulted in the closing of one cannery and required reconstruction of parts of others. New navigational hazards exist in the waterways, and many clam beaches have been destroyed. For some canneries, their docks had to be extended so boats could reach them. Rollers and other means were used to return boats that were in storage to the water (Ref. VI-28). Repair of the small-boat harbor will cost $96,000 (Ref. VI-29), and contracts totaling $108,000 have been awarded for the repair of the town's sewer system (Ref. VI-30).

Chenega, a native village of 76 people on Prince William Sound, was inundated by a large wave that swept away all the homes in the village and drowned 25 of the villagers, 13 of them children. Five persons were killed and much property damage resulted when large waves hit other small Prince William Sound communities of Port Nellie Juan, Port Ashton, and Point Nowell (Ref. VI-2).

As a result of right-of-way subsidence and fracture, landslides, and damage to bridges, numerous sections of the Alaska highway system were rendered impassable. The Anchorage-Seward highway suffered the most severe damage. This highway parallels Turnagain Arm between Anchorage and Portage at the head of Turnagain Arm, then it turns south to Seward, crossing the Kenai Peninsula. Between Potter, 9 miles south of Anchorage, and Portage, 22 bridges were damaged, figures 15 and 16. Soil compaction apparently squeezed some of the bridge abutments together, and the resultant compressive force cambered the bridges, figures 17, 18, and 19. Roadbed subsidence "elevated" some bridges as much as 2 feet above the adjacent roadway, figures 20 and 21.

As determined from the log of a water well, the Portage area is underlain by the following unconsolidated deposits (Ref. VI-2):

0 to 20 feet - sand and gravel

20 to 425 feet - clay

425 to 426 feet - sand

426 to 600 feet - clay

It can be assumed that this clay is part of the Bootlegger Cove clay deposit. Compaction of the clay may account for half of the 7 to 8 feet subsidence that occurred in the Portage area.

The Anchorage-Seward highway is now inundated at normal high tide, and it must be periodically closed to traffic in the Portage area due to impassable road conditions. Spring floods, in addition to tides, have washed out numerous sections of the highway (Refs. VI-31, VI-32, VI-33). The highway is open to nonemergency vehicles only at night; motorists in compact cars have been advised not to attempt the trip (Ref. VI-34). Tides that are over 29 feet have covered the highway with as much as six feet of water in some areas (Ref. VI-35). A $1.1 million contract for emergency repairs to and raising of 17.6 miles of the highway near Portage has been awarded. The emergency road will be 24 feet wide, unpaved (Ref. VI-36). Finally, $13 million has been estimated for the permanent road repairs after the emergency project has been completed (Ref. VI-37).

The Federal Government has approved, in two separate legislative actions, a $22 million relief fund for emergency highway repairs in Alaska (Ref. VI-38). The Alaskan Highway Department has undertaken a $65 million Federal Aid Program for permanent highway repairs in addition to its regular $39 million Federal Aid Program (Ref. VI-39).

The Federally owned and operated Alaska Railroad system sustained extensive damage in the communities of Anchorage, Portage, Seward, and Whittier. In Anchorage, the principal damage was caused by landslides. The railyard building complex suffered ground-motion damage. Contracts totaling $905,000 have been let for repairs to shop buildings (Ref. VI-40).

Near Portage, the major cause of damage was right-of-way fracturing and subsidence. The approaches to the 20-Mile Bridge subsided from 1 to 1.5 feet more than the bridge which rests on 60-foot-deep piles. Similar to the highway bridges, the 20-Mile Bridge failed due to compression. Much of the right-of-way has been inundated by high tides, e.g., the April 13 to 14, 1964, high tide which inundated Portage washed out sections of the right-of-way. Finally, extensive landslides closed the road near Potter (Ref. VI-2).

The western end of the 12.4-mile railroad spur between Portage and Whittier was severely damaged. However, the two tunnels, 18,000 feet total length, were not damaged, nor was the mile-long section of track between the tunnels and Whittier. The port facilities at Whittier were damaged by wave action and fire. Fortunately, the "sea-train" roll-off and roll-on facilities, as well as other port facilities, have been placed back in service, and the ARR line was opened all the way from Fairbanks to Whittier in late April 1964 (Refs VI-41, VI-42).

The earthquake dealt a major blow to the ARR in Seward, figure 22. The lift-off/lift-on loading facilities and warehouses were eliminated by the submarine landslides and seismic waves that hit the Seward waterfront area. Only the dock heating plant survived the quake. Based on the post-quake soil study, the entire terminal yards will be moved north to the mouth of Resurrection River. The U.S. Army, Corps of Engineers, will expend $7.8 million to construct the new facilities. In addition, to restore the rail line into Seward and complete the balance of repairs to other sections of line, will cost $19 million (Ref. VI-41).

Based on observations by airline pilots, there have been no changes in volcanic activities along the Aleutian Islands. In the Anchorage area, no known active volcanoes exist. However, the citizens of Anchorage were alarmed by a "report" of an active volcano in the Chugach Mountains east of the city. The "volcano" turned out to be clouds of dust that resembled smoke and ash and that were caused by landslides and rockslides off precipitous cliffs of Mount Muir, 50 miles due east of the city (Ref. VI-43).

Fluctuations in water wells over most of the conterminous United States and Hawaii were caused by the earthquake, table VI-3. Water in lakes and pools in many locations in North America was agitated by seismic waves. Seiches with waves as high as 6 feet were reported in coastal regions of Louisiana and Texas, and many swimming pools overflowed. Significant stream damming did not occur as a result of the quake (Ref. VI-2). Finally, rumbling, grinding, and crunching sounds along the Kenai Peninsula coast were still being reported three months after the quake (Ref. VI-44).

Table VI-3

FLUCTUATIONS IN WELL-WATER LEVELS, MARCH 28, 1964
(Source: Reference VI-1)

Location (Maximum of two wells per location)	Amplitude of fluctuation in feet
Alabama	6.0 and 7.5
Arizona	1.0
California	1.7 and 2.4
Northern Florida	5.8 and 7.8
Southern Florida	5.3 and 5.8
Western and Southwestern Florida	4.4 and 7.6
Georgia	6.2 and 9.9
Hawaii	1.0 and 1.6
Idaho	1.2 and 4.0
Illinois	7.7
Indiana	3.2 and 8.2
Michigan	4.5 and 4.8
Nevada	1.7
New Jersey	2.9 and 4.4
South Carolina	4.7
Wisconsin	1.2 and 2.5

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SECTION VII

DAMAGE WITHIN THE ANCHORAGE AREA

An old rule of thumb states that the principal damage that is caused by an earthquake will occur within 15 miles of the fault zone. Within the Anchorage area, 9 persons lost their lives, 215 residential buildings and 157 commercial buildings were either destroyed or severely damaged, and 7 destructive landslides were triggered by the quake. The city of Anchorage, however, was approximately 80 miles west of the epicenter of the main shock, figure 23 (Ref. VII-1).

In the epicentral region, short-period motions are invariably observed. Evidence of numerous unbraced, small rigid-masonry buildings not being damaged and instances where china on shelves in houses was practically undisturbed, however, appears to establish the fact that ground motion in Anchorage did not include significant short-period motions. At the same time, every tall building was profoundly damaged. The destructive behavior in Alaska was similar to that caused in Los Angeles and Long Beach by the 1952 Kern County earthquake whose epicenter was 70 to 90 miles from the communities. In Mexico City a number of multistory buildings were damaged, several collapsed, during the 1957 earthquake although the epicenter was approximately 200 miles from the city.

The earthquake damage in the greater Anchorage area, including the nearby military installations, Elmendorf AFB and Fort Richardson, will be separated into two general categories. The first category will include the resultant destruction that was caused by earthquake-triggered landslides. The second category will include all damage not caused by landslides but resulting from seismic ground motion. Accordingly, the damage in the Anchorage area will be presented under several groupings: Rotational Landslides, Slab Landslides, and Effects on Reinforced Concrete Buildings, Structures Employing Prestressed Concrete Members, Steel Buildings, Composite Construction, and Wood Buildings.

There is, however, no intent to imply that one structural system is superior to another for earthquake-resistant construction. Examples of each structural type can be cited that were severely damaged, and others that received no noticeable damage.

SECTION VII

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SECTION VIII

ROTATIONAL LANDSLIDES

In general, a landslide is a mass of soil that is displaced to a lower elevation under the influence of gravity. Along potential slide planes, the tendency for movement is resisted by the strength of the soil. Variations in soil strength result from changes in pore-water pressure or changes in confinement. In Norway, landslides have occurred in sensitive marine clay deposits that were on slopes of less than 3 percent.

Most, if not all, of the landslides in Anchorage were triggered in unconsolidated soil deposits. At the time of the earthquake approximately 8 inches of partially frozen snow covered the slide areas. The frost depth varied from minimal in protected areas to as much as 5 feet in open areas (Ref. VIII-1). The slides were set in motion along bluffs where the soil was not otherwise confined and where the frozen bluff surface acted as a groundwater dam, backing up subsurface water in the bluff.

A rotational landslide is the slump of a relatively thin or shallow section of soil where the movement is idealized as a rotation about an assumed focal point, figure 24. The destructive rotational slides triggered in the Anchorage area are the Turnagain slide, the Bluff Road slide, and the Third Avenue slide; additional rotational slides are the Cherry Hill slide, the Romig slide, and numerous small slides along the bluffs of Ship Creek and Chester Creek, figures 25a and 25b.

1. TURNAGAIN SLIDE

The Turnagain slide emcompassed over 200 acres of the Turnagain Heights residential district established on top of the Knik Arm bluff south of Anchorage, figures 26 and 27. After the earthquake, the slide area was a jumble of individual slide blocks that resulted from both outward movement and lateral spreading, figure 28. Individual blocks moved as much as 400 to 500 feet horizontally and 30 feet vertically. An 8,000-foot-section of the bluff slid away creating the present cliff which extends up to 39 feet in height, figures 29 and 30. The slide area comprised both inhabited, figure 31, and uninhabited, figure 32, regions. The present cliff is a maximum of 1,200 feet inland from the prequake bluff in the uninhabited region, but only a maximum of 500 feet inland in the inhabited region. This difference may be due to the drainage afforded the Bootlegger Cove clay by the sewer system in the inhabited region. Of the 77 residential buildings that were destroyed, 20 were carried beyond the previous shoreline by the slide, figure 33. Typical damage to residential buildings is shown in figures 34 through 42.

In the Turnagain Heights district, the major slide consisted of a series of rotational smaller slides that were triggered at the bluff and progressively worked inland, figure 43. A sand and gravel glacial outwash, up to 24 feet deep, overlays a deposit of clay nearly 200 feet deep that is known locally as Bootlegger Cove clay, table VIII-1. Within this clay deposit the series of rotational slides were initiated in discontinuous layers of saturated clay and silt which liquefied under the repetition of stress induced by the earthquake. The discontinuous layers were between 20 feet above low tide to 10 feet below high tide, and because of high pore pressure were almost on the verge of failure before the earthquake (Ref. VIII-9). After the earthquake, soil samples were obtained from the clay deposit. Generally, the natural moisture content, given in percentages, of these samples were from 1.5 to 9.4 percent lower than their corresponding liquid limits (Ref. VIII-1). These differences compare with those reported by Miller and Dobrovolny as 4 percent (Ref. VIII-6). Only a very small movement was required to increase the pore-water pressure and liquefy the layers within the clay deposit.

Pressure ridges, if they ever existed, along the toe of the Turnagain slide have been eroded by tidal action, figures 44 and 45. The mass of the slide is now acting as a buttress for the present cliff. Natural tidal erosion of this mass has been reducing the stability of the cliff and endangering the badly fractured residential area behind the cliff. The height of the cliff and representative fractures in the residential area are shown in figure 46.

A detailed soil investigation program is being conducted throughout the Anchorage area by the U.S. Army, Corps of Engineers. A report of this study has recommended a method for stabilizing the potential slide area in the Turnagain Heights residential district. Vertical sand drains (sumps) would remove excess ground water from the discontinuous layers of silt and clay. The drains would be located along the present cliff and would drain an area 8,000 feet long by 250 feet wide. The drains would be 12 to 18 inches in diameter and 70 to 80 feet deep. They would be located on 8-foot centers. Thus, approximately

Table VIII-1

LOGS OF REPRESENTATIVE WELLS IN THE TURNAGAIN HEIGHTS RESIDENTIAL DISTRICT
(Source: References VIII-1, VIII-4, and VIII-5)

Material	Thickness (feet)	Depth (feet)
Well No. 50 - Elevation 74 feet (top of bluff)		
Sand	8	8
Sand and gravel	15	23
Coal	1	24
Blue clay	117	141
Sand and gravel	6	147
Blue clay	3	150
Well No. 277 - Elevation 55 feet		
Sand (?)	15	15
Bootlegger Cove clay	204	219
Well No. 278 - Elevation 74 feet		
Sand (?)	24	24
Bootlegger Cove clay	126	150
Well No. 282 - Elevation 68 feet		
Sand, pebbly; brown	12	12
Clay, blue	138	150
Sand, silty, hard; gray	81	231
Clay and rocks, hard	7	238
Very hard layer	12	250
Clay (?), red-blue, oily-looking soft to hard	53	303
Clay and stones, fairly hard; blue	82	385
Gravel, sand, silt, and clay; hard; in alternating layers; water	67	452
Well No. 283 - Elevation 74 feet		
Sand (?)	20	20
Bootlegger Cove clay	148	168
Well No. 284 - Elevation 77 feet		
Sand, brown	15	15
Clay	160	175
Quicksand	25	200
Hardpan	25	225
Sand, mucky	30	255
Clay and gravel	45	300
Clay	40	340
Hardpan	10	350
Clay	10	360
Sand	11	371

33,000 drains would be required in this residential area. Additional drains at one per city block would be located in the remaining residential area behind the cliff. Finally the present cliff face would be protected by a gravel buttress that would replace part of the slide mass (Ref. VIII-7). However, before the final stabilization program is initiated, an $800,000 pilot project is being undertaken to test the performance of the drains and to estimate the total cost of the complete project (Ref. VIII-8)

The Elmendorf AFB power plant, northwest of Bluff Road, overlooks Ship Creek. A steep fill supports the road and at its toe a cooling-water pumping station has been located. The piping system that circulates water between the plant and a cooling pond was ruptured by a rotational landslide that also removed a segment of the road. Within a few hours, auxiliary power sources were in operation, and the damage was easily repaired. However, the rapid loss of cooling water could have significantly damaged the generating equipment. The power plant, pumping station, and piping system after the necessary repairs and regrading of the fill are shown in figures 47 and 48.

2. MINOR SLIDES

In the bluffs just west of the Elmendorf AFB Cherry Hill housing units, a large rotational landslide was initiated by the quake. Fortunately, the resulting movements were less than fifteen inches, figures 49 and 50. Scars from at least two older landslides were also conspicuous along the bluff. A minor slide (the Romig) occurred along the Chester Creek bluff north of West Anchorage High School. The displacements that resulted in the Romig slide were limited to a few feet, figure 51. Numerous minor rotational landslides that were triggered along the north bluff of Ship Creek damaged items of equipment and covered segments of track of the Alaska Railroad. A small slide removed a segment of Third Avenue just east of Post Road. The head of this slide rambled through the Alaska Highway Department equipment yard.

Neither a stabilization program or a soil investigation program have been recommended for the rotational landslides except for the major slide that occurred in Turnagain Heights. If slope erosion is prevented and the toe is stabilized, each of the slide areas, excluding Turnagain Heights, may be stabilized although, in the event of another major earthquake, potentially unstable conditions may still exist. This is particularly true in the case of the steep fill of Bluff Road.

SECTION VIII

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SECTION IX

SLAB LANDSLIDES

A slab landslide is a translation of a block of soil where the slip plane is represented by a composite surface, part of which lies on or within an exceptionally weak stratum. As the slide block moves away from the undisturbed soil, a tension crack is formed. An unstable wedge of material slumps off the head end of the slide block into the void created by the tension crack. The soil formation resulting from this slump is referred to as a tension trough or graben, figure 52. Four slab slides were triggered in the Anchorage area. They were, in order of greatest acreage, the L Street slide, the Fourth Avenue slide, the Government Hill slide, and the First Avenue slide, figure 53.

Additional surcharge load was applied to the Bootlegger Cove clay as a result of earthquake-induced movements of the soil above the clay. Consider a mass located on top of a vertically oriented spring. If the base of the spring is displaced, normal to the orientation of the spring, the spring force will be increased by the resulting dynamic loading. The clay is represented by the spring and the mass is represented by the soil above the clay. Since the clay layer was nearly saturated, a substantial part of the excess load was carried by pore-water. The increase in pore-water pressure reduced the shear strength of the soil, thus permitting large blocks of soil to translate as a unit.

1. FOURTH AVENUE SLIDE

The Fourth Avenue slide affected a 15-block area within the business district of the community, figure 54. Cracking is evident on the surface south and west of the slide for as much as a two-block strip, which is bounded on the east and west by Barrow Street and E Street and on the north and south by West First Street and West Fourth Street, respectively. Approximately four blocks of the slide area were occupied by parking lots. The Coca-Cola Bottling Company building, the Anchorage Cold Storage Company building, and a commodity warehouse in the terminal yard area along First Avenue were destroyed as a result of pressure ridges that developed in the region of this slide, figures 55 and 56.

The average width of the Fourth Avenue slide, or graben, was 110 feet with a maximum vertical displacement of 10 feet, which occurred at Fourth Avenue and C Street, figure 57. The graben paralleled Fourth Avenue for 3 blocks, and destroyed all the commercial buildings in the honky-tonk district on the north side of Fourth Avenue, figures 58 through 64. The shape of the graben was similar to a large arcuate Y whose juncture occurred at Fourth Avenue and C Street. The northern branch of the graben produced a vertical displacement of 1 to 2 feet in the eastern end of the E and E Apartments at Third Avenue and B Street, figure 65 (Ref. IX-3).

The ground between the graben parallel to Fourth Avenue and the pressure ridges along Second Avenue moved as a unit along C Street. The pressure ridges west of C Street destroyed numerous small commercial buildings, figure 66. The resultant displacement of Third Avenue between C and E Streets is shown in figures 67 and 68.

Movements associated with the Fourth Avenue slide continued for three minutes and consisted of a slow continuous outward (northward) movement as manifested by the fact that window glass in many of the displaced buildings was not cracked and signs and marquees were not, in general, damaged, figures 69 and 70. This total northward movement was 18 feet (Ref. IX-3).

The soil investigation program in the Fourth Avenue slide area included 36 test borings up to depths of 150 feet that resulted in 850 soil samples. In addition, visual examinations were conducted in auger holes (Refs. IX-11, IX-12). Results of the program have disclosed that the slide took place in the vicinity of a previous slide which occurred nearly 100 years ago. The more recent slide extends farther east than the previous slide. A 40-foot layer of sand and clay deposits liquefied due to earthquake-induced excess pore-water pressure. An incipient graben developed on D Street just north of Fifth Avenue and within 100 feet of the J. C. Penney building which was destroyed by ground motion, figure 71.

Figure 72 shows the head of the Fourth Avenue slide after most of the demolition work in that area was completed. A plan for the stabilization of the Fourth Avenue slide area has been recommended by the Corps of Engineers based on the current soil investigation program underway in Anchorage. The area would be regraded, drained, and buttressed to protect a one-and-one-half-block strip south of Fourth Avenue (Ref. IX-4) The proposed stabilization program would include grading the area between Fourth Avenue and First Avenue and constructing a buttress along Fourth Avenue and First Avenue. The buttress will be composed of gravel fill upon a concrete mat. In addition, the entire area would have a drainage system constructed on the surface of the slide to preclude surface runoff from entering the underlaying Bootlegger Cove clay, figure 73. Since, in the event of another major earthquake, fissuring would still occur in the stabilized area, only one- and two-story structures would be constructed in the stabilized area, including the strip south of Fourth Avenue (Refs. IX-5, IX-6). However, foundations that require piles or piers will not be sanctioned (Ref. IX-10). The project would cost upwards of $10 million, including acquisition of land, to safeguard a strip of property that has a current value of $20 million and to rehabilitate the slide area valued at $15 million (Refs IX-7, IX-8).

2. THE L STREET SLIDE

The L Street slide is similar to the Turnagain slide in that they both involved land movements along the bluff overlooking Knik Arm. The bluff between Ship and Chester Creeks moved outward in a generally northwestward direction. The slide area included both new and older residential structures as well as some commercial buildings. An approximate 25-block area was affected, figure 74. The slide included the land west of K Street between Seventh and Third Avenues and a line from the intersection of K Street and Seventh Avenue to the intersection of S Street and Eleventh Avenue.

The average width of the L Street graben was about 250 feet and exhibited a maximum vertical displacement of 10 feet that occurred on N Street just north of Ninth Avenue, figure 75. The shape of the graben was arcuate. At Ninth Avenue and M Street the graben passed just north of the Four Seasons Apartments and had a vertical displacement of approximately 2 feet. In fact, the geological mapping, figure 76, that was conducted within a few days of the earthquake, indicates that a fissure may have passed under the apartment structure (Ref. IX-2). The building was within 30 days of occupancy at the time of the quake, and only the fact that construction was not in prcgress prevented a large loss of life, figures 77 and 78. What part subsidence contributed to the collapse of the structure is in doubt; the structural details of the building are discussed in section XI. Various residential buildings near the Four Seasons Apartments have been shown in figures 79 and 80. At 715 L Street the 7-foot vertical displacement that occurred in the graben cut an apartment building in half, figures 81 and 82. It is interesting that the rear of this apartment building was under rehabilitation even before the results of the soil investigation program were known. Along the northern segment of the graben, numerous residential and commercial buildings were destroyed by differential displacements that varied from 3.5 feet to 7 feet, figures 83 through 86. The commercial building shown in figure 87 has been included by reason of its counterpart that was destroyed and has been shown in figure 88. Differential displacements as great as 8 feet were produced along the western end of the graben, figures 89 and 90.

Structures that are located on the L Street slide block were not subjected to differential vertical displacements; the slide block moved laterally as a unit. Included in these structures is a six-story apartment building, Knik Arms, figure 91. The structures on the block are in use today, having sustained only minor damage in spite of the fact that they were moved horizontally 11 feet.

The residential area along P Street between Tenth and Twelfth Avenues has been threatened by ground water that is seeping out from the bluff face. Natural channels for ground water seepage were obliterated by the earth movements triggered by the earthquake (Ref. IX-16).

The soil investigation program in the L Street slide area has disclosed evidence of previous slide activity along the Ship Creek bluff between K and L Streets. A complex double-slip-plane slide was triggered in the newest L Street slide, figure 92. A shallow slip plane affected the central portion of the slide area, and appears as a nearly continuous pressure ridge, extending from Blueberry Park to Stolt Lane, figure 76. The maximum height of the pressure ridge was 7 feet which developed southwest of the Eighth Avenue and O Street intersection. Just east of Seventh Avenue and N Street an 11-foot overthrust occurred (Ref. IX-2). The height of these ridges may have been influenced by the presence of a second slip plane. Many residential buildings were damaged by these pressure ridges. The deeper slip plane moved the Alaska Railroad tracks on both flanks of the slide area and accounted for the wide graben. Land movement of 10 to 12 feet seaward occurred during the quake. Figure 93 indicates movement occurred in the tracks at the west end of the Ship Creek Railroad Bridge just east of the slide area (Ref. IX-13).

To stabilize the L Street slide area would require an extensive grading, draining, and buttressing program. Because of the considerable soil disturbance, the cost of stabilizing the area would be uneconomical. The required buttress would be 200 to 300 feet in width and up to 80 feet deep (Ref. IX-17). The slide occurred in an "old" residential district, the original townsite. Stabilization of the area has been estimated at $30 million (Ref. 13). However, water and sewer lines in the area will be returned to service, and single family residential zoning has been considered (Ref. IX-14).

Landslides were not triggered in the Ship Creek bluff between the Fourth Avenue and L Street slides. There were no differences in soils or geology that would explain why landslides were not produced in this central area. However, a buttressing program has been recommended for the bluff between F and K Streets, figure 73. The cost of this additional buttressing has been estimated at $3 million (Ref. IX-13).

3. GOVERNMENT HILL SLIDE

A photograph of the Government Hill slide area taken before the slide occurred is shown in figure 94. The east-west wing of the Government Hill school and the Alaska Railroad equipment-repair shop at the toe of the bluff had not been constructed. A maximum vertical displacement of 25 feet was produced by the Government Hill slide (Ref. IX-2). A compound graben developed which had a shape similar to a large arcuate Y, figure 95. The juncture of the two branches of the Y occurred at the north-south wing of the Government Hill school, and the north branch of this complex graben destroyed the east-west wing of the school, figure 96. A simple arcuate graben developed at the head of the bluff south of the school, figure 96. The Government Hill school, destroyed by differential settlement caused by the graben, is shown in figures 97 through 102. Evidence of the slow continuous earth movement triggered by the earthquake has been disclosed by the fact that the light fixtures shown in figure 102 were not damaged. The Good Friday holiday averted possible large loss of life or injury. The north branch of the Y graben destroyed two residential buildings and endangered at least three additional buildings, figures 103 through 105. The residential building west of the destroyed buildings in figure 103 has been referred to as the west residential building in figures 106 and 107. The owner of this structure has refused to relocate (Ref IX-15).

Unlike the pressure ridges that developed in the other three slab landslides, the toe movement of the Government Hill slide advanced much farther than would be expected by the 20-foot lateral movement which occurred at the head of the slide. This toe was probably due to excessive moisture in the underlying clay (Ref. IX-2). A Butler-type metal building used by the Alaska Railroad as a warehouse was destroyed by this excessive movement. Compare the damage to the warehouse that is shown in figures 95 and 96 to that shown in figures 108 through 110. The slide also damaged railroad track equipment and covered a section of tracks, figures 111 and 112.

An idealized cross section of the Government Hill slide is shown in figure 113. However, recommendations have not been reported for the stabilization of the Government Hill slide. The Government Hill school and some of the residential structures are being relocated. Thus, it does not appear plausible that an extensive stabilization program can be justified. The present slide mass may stabilize the general slide area.

4. FIRST AVENUE SLIDE

At least two previous landslides have occurred in the region of the newest First Avenue slide. These older slides can be seen in the pre-earthquake photograph of the slide area, figure 114. The simple arcuate shape of the First Avenue graben has been shown in the aerial mosaic projection, figure 115. The maximum vertical displacement produced by the graben was 25 feet, figure 116 (Ref. IX-2). A fuel storage tank at the toe of the slide was displaced and collapsed due to a 10-foot pressure ridge that developed just behind the tank, figure 117. The presence of the tank accounts for the height of this ridge. The pressure ridge as it appeared in May, 1964, has been shown in figure 118.

Recommendation for the stabilization of the First Avenue slide has not been reported. However, it does not appear plausible that an extensive stabilization program can be justified for this slide. The slide area, an uninhabited bluff, may be stabilized by the resultant slide bench. The earthquake did not reactivate the old slide benches that are shown in figure 114.

SECTION IX

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SECTION X

REINFORCED CONCRETE

1. ELMENDORF AFB HOSPITAL, BUILDING NUMBER 24-800

The Elmendorf AFB Hospital is a reinforced-concrete frame structure with exterior masonry-block-filler walls. The building is irregular in plan. The main part is seven stories high with a full basement, rectangular in plan. Two- and three-story wings project from the main structure. A large elevator tower rises three stories above the main structure, figure 119, and is supported on a concrete mat foundation. The remainder of the building rests on individual spread footings. Alternating beam and column sizes are used in the main structure for architectural effect, and it was in this part of the building that diagonal tension cracking of exterior masonry-filler walls was most pronounced. The entire building suffered extensive nonstructural damage to the filler walls, and some interior structural damage due to uneven vertical settlement. However, the exterior part of the reinforced-concrete frame did not appear to have suffered significant damage, figure 120. Diagonal tension cracks in the filler walls were caused by distortion of the reinforced-concrete frame, which was both flexible and strong enough to permit the filler walls to crack without itself failing. The fact that the cracks extended in both directions indicates the building responded about equally in both directions, probably executing several cycles of motion during the quake, which was estimated to have lasted over three minutes (Ref. X-1). The filler walls, being initially stiffer than the frame alone (i.e., having a higher resistance to unit lateral distortion) resisted most of the lateral forces until the masonry cracked, when the lateral forces were then transferred to the frame. In cracking, however, the masonry-filler walls served as energy dissipators, thus relieving part of the peak load on the structural frame. When the stiff filler walls cracked, the natural period of the building increased, which may have further reduced the peak load on the structural frame. A closeup view of the diagonal tension cracks, figure 121, shows a majority of cracks running through the masonry blocks, rather than following the mortar joints. When mortar joints consistently fail before the blocks fail, inferior masonry work is indicated (i.e., either poor mortar, not enough of it, or both). Damage to interior structural members occurred primarily in 5-foot-deep beams which served as framing between the elevator core and nearby columns. Differential settlement between the core mat and adjacent column spread footings had been a problem even before the earthquake. Due to the deeper zone of influence created by the mat in comparison to that developed by the spread footings, at equal contact pressures, the mat settled more than the adjacent footings and caused large distortions in the deep beams used as framing between the core and the columns. Here is a good example of the fact that provision for uniform vertical settlement throughout a structure is of prime importance to ensure structural integrity under static or dynamic forces, either natural or man-made.

2. TWO 750-MAN ELMENDORF AFB BARRACKS, BUILDINGS NUMBER 31-250 AND 31-270

In contrast to the Elmendorf AFB hospital, two identical reinforced-concrete 750-man barracks with exterior masonry-filler walls both failed to develop the potential energy absorption mechanism provided by the walls. Each structure is a three-story reinforced-concrete frame with full basement and with exterior masonry-block-filler walls laid flush with the inside column faces. Thus, the outside column faces project beyond the masonry walls. The main structures are rectangular in plan, 848 feet by 44 feet, figures 122 and 123. Projecting from the central portion of the main structures, but isolated from them by expansion joints, are one-story dining-hall wings, approximately square in plan. Between the central and end portions of the main structures, and isolated from them by expansion joints, are two wings projecting perpendicularly from the main structure, figures 123 and 124. In each building the structural frame cracked, usually within a column at a location where beams frame into it, and the walls were permitted to translate as a unit, figure 125. The frame apparently lacked sufficient strength or ductility to develop the full strength of the masonry walls. Throughout the depth of the beams and at the locations where they frame into the column, the structural plans did not require ties in the exterior columns. At these locations, as a result, the columns failed in shear due to the absence of shear reinforcement afforded by ties. The absence of ties in the failure zone is shown in figure 126. Repair of the structural frame will be an expensive task.

Heavier and more closely spaced column ties throughout the full depth of exterior beam/column connections, as recommended by the Portland Cement Association in their recent earthquake-design manual (Ref. X-2), would probably have prevented much of the damage suffered by these two buildings. Column ties throughout the full depth of a beam/column connection are particularly important for corner columns, which must resist shear loads in two directions. The eccentric manner in which masonry-filler walls transfer their load to the structural frame, noted by Feld (Ref. X-3), undoubtedly also contributed to the damage to these two buildings.

3. ELMENDORF AFB CONTROL TOWER, BUILDING 43-005

The Elmendorf AFB aircraft control tower fits into the southeast corner of a two-story reinforced-concrete bearing-wall communications building, and is separated from the building by expansion joints, figure 127. The tower is square in plan, 19 feet on a side, and extends seven stories above the top of a 16-inch-thick foundation wall, which is about three feet above ground level. A steel balcony extending out beyond the walls at the seventh floor and the eighth floor is a steel observation cupola and another balcony. A concrete elevator shaft in the northwest corner introduces unsymmetrical flexural stiffness. Apparently the tower responded primarily as a vertical cantilever because a regular pattern of horizontal flexural tension cracks between 12 and 24 inches apart developed in the 10-inch-thick reinforced-concrete tower walls up to about the second floor level, figures 128 and 129. The foundation is apparently intact. The horizontal cracks appear to follow cold joints, figure 130, or horizontal reinforcement, figure 131. Figure 131 also shows a vertical reinforcing bar that buckled and fractured in compression. Cracking is particularly severe in the south side opposite the elevator shaft. Above the roof of the communications building the tower itself sustained no visible damage, figure 132, but the observation cupola shook so badly that it was ruined, figure 133. The tower was declared unusable, ordered evacuated, and will be replaced.

4. ANCHORAGE INTERNATIONAL AIRPORT CONTROL TOWER

The Anchorage International Airport control tower was part of the air terminal building, designed in 1951 for the Eighth Regional office of the Civil Aeronautics Administration in Anchorage. The tower was a five-story reinforced-concrete frame with another floor below grade for vehicle access and an observation cab on the roof. The frame stood 56 feet 6 inches above grade, and the below grade vehicle level was 12 feet 6 inches deep, making the total height of the frame 69 feet above the vehicle slab. The north-south outside plan dimension of the tower, parallel to the long axis of the terminal building, was 31 feet 6 inches. The east-west outside plan dimension was 28 feet 8 inches. The first story above grade was 12 feet 6 inches high; the remaining four stories were 11 feet high. Figure 134 shows the west side of the tower, facing the aircraft loading area, before the earthquake. Figure 135 shows about the same view of the collapsed tower after the earthquake. Being outside the Anchorage city limits, the tower was not required by building codes to be designed for earthquake loads. Earthquake structural requirements were first adopted within the city of Anchorage in 1952, at which time Uniform Building Code Zone II requirements were specified. Late in 1954 the requirements were increased to Zone III and have remained at that level ever since.

5. J. C. PENNEY BUILDING

The most heavily damaged large reinforced-concrete structure in Anchorage was the one-year-old J. C. Penney building, located at the southwest corner of Fifth Avenue and D Street, figure 136. It was a five-story flat-plate structure, 149 feet wide and 129 feet deep, with seven rows of columns in both directions. Precast concrete curtain-wall panels enclosed the top four floors on all four sides. Motion of the building caused several of these panels on the north and east sides to fall, killing two persons, figures 137 and 138. Collapse of the northeast corner occurred when several columns and a poured shear panel fractured, dropping the corner portions of the top four floors, figure 139. Apparently the northwest corner was on the verge of a similar collapse when the quake ceased, figure 140. The massive first floor was essentially intact, figure 141. Lateral forces in the top four floors were intended to be resisted by concrete shear panels in the east, south and west walls. In the east wall these panels occupied the two end bays at the second and third floor levels, and the end bays at the fourth and fifth floor levels. In the west wall they occupied the two south bays and the northernmost bay at the second floor level, and all six bays at the third, fourth, and fifth floor levels. The entire south wall was reinforced concrete. There were no shear panels or diagonal bracing of any kind in the north wall above the first story. According to Rice (Ref. X-4), the unsymmetric location of shear walls in the east-west direction, all being located in the south wall, encouraged rotation of the building frame about a point near the south wall, causing excessive distortion at the northeast and northwest corners, where the heaviest damage occurred. This movement caused second-story shear panels in the east and west walls to be unseated, thus reducing the north-south lateral resistance of the building frame, particularly at the second-floor level, figures 141 and 142. Scalloped bottom edges of shear panels in the east wall, which accommodated curtain-wall connection angles, no doubt weakened these particular shear panels, figures 138, 139, and 140. Failures of floor slabs near column connections are evident in figure 143 and several other figures. These slab failures might have been prevented by using drop panels and column capitals to distribute moment and shear loads over a larger cross-sectional area of floor slab; i.e., by using a flat slab system instead of a flat plate system. In fact, the structure's dependence on discrete elements (i.e., the shear panels) for lateral resistance was perhaps its basic weakness, since the shear panels did not perform as intended. If so, this presents a convincing argument in favor of a moment-resisting structural system, having uniform lateral strength, as opposed to one which is laterally weak except for a few elements, which supposedly provide all the lateral resistance.

6. MOUNT McKINLEY BUILDING AND TWELVE-HUNDRED L STREET APARTMENTS

The Mount McKinley Building and the Twelve-Hundred L Street Apartments are discussed together because they were constructed from the same basic plan at about the same time, figures 144 and 145. The Mount McKinley Building faces east at the northwest corner of Fourth Avenue and Denali Street; the Twelve-Hundred L Street Apartments face west at 1200 L Street, as the name indicates. Important structural differences in these two 14-story reinforced-concrete frame and column wall structures are a slightly more open first-floor column pattern in the Mount McKinley Building to accommodate several commercial offices, television station KTVA, and radio station KNIKFM, and the two basement levels of the Twelve-Hundred L Street Apartments while the Mount McKinley Building has only one. The patterns of damage sustained by the two buildings were remarkably similar. Figures 146 and 147 show the north side of the Mount McKinley Building and the south side of the Twelve-Hundred L Street Apartments, respectively. Notice the horizontal column wall fractures in both buildings at the same height above the building foundations. Figures 148 and 149 show closer exterior views of the fractures in both buildings, and figure 150 shows an interior closeup of the Mount McKinley Building fracture.

The most notable exceptions to the similarity of damage patterns in the two buildings are the prominent diagonal tension failures at the second-floor level in the east side of the Mount McKinley Building, which does not appear in the west side of the Twelve-Hundred L Street Apartments, figures 151 through 154. This difference is probably attributable to the difference in basement depths of the two buildings and the more open first-floor column pattern of the Mount McKinley Building, which imposed heavier vertical and shear loads on the exterior walls.

Both buildings have partial mat foundations beneath a central elevator-stairway core. The diagonal tension cracks in vertical spandrels near both ends of the buildings indicate that the cores attempted to rock back and forth on their mats in the north-south direction, but were restrained by vertical shears at the north and south core walls. Figures 144 and 145 show that the diagonal tension cracks began at the second-floor level, where they were most severe, and progressed to the ninth or tenth floor, decreasing in severity with height. Fortunately, the earthquake ended before the crack pattern had progressed to the top of the building.

It is interesting to assume a given number of response cycles required to fail each spandrel, then to estimate from the crack pattern the total number of cycles the buildings experienced. Figures 144 and 145 also show that the heavier central portions of the buildings were less noticeably damaged than the ends, further indicating the central core tended to move as a unit. Had the buildings responded primarily in a horizontal shear mode, the pattern of horizontal shear cracks following construction joints in the central portion of the building would have been more prominent. The damage to these two buildings illustrates the importance of anticipating the dynamic mode of response of a building on the basis of its particular structural configuration.

Columns at the ground-floor level in the south wall of the Mount McKinley Building suffered much more than those in the north wall of the Twelve-Hundred L Street Apartments, because the Mount McKinley Building had smaller exterior columns and fewer interior columns. The result was cracking of at least one column in the Mount McKinley Building and shortening of another near the southeast corner, figure 155. Figure 155 shows that horizontal ties were ineffective in preventing buckling of some of the vertical bars. Rice (Ref. X-4) indicates that shortening of this column was due to "lateral motion," but it seems clear from the alignment of the buckled vertical bars that the primary instrument of shortening was excess axial load.

Rice also states that the patterns of diagonal tension cracks indicate the buildings responded about the same amount in both the north-south and east-west directions. If this were true, a sign cantilevered from the south face of the Mount McKinley Building should have torn loose if not properly guyed. Since the spandrels in the north and south walls are near the center, it seems likely that the buildings responded primarily as shear beams in the east-west direction. If the buildings did respond differently in the two principal directions, it would be difficult to compare the magnitude of the response in each direction by the severity of the corresponding diagonal tension crack pattern.

7. WEST ANCHORAGE HIGH SCHOOL

Heavier and more closely spaced column ties and better column construction joints would have prevented much of the damage suffered by the eleven-year-old West Anchorage High School. Designed in 1952 and built in 1953, the main part of the building faces northeast on Hillcrest Drive, just west of Minnesota Drive, south of the Chester Creek inlet, figure 156. Figure 157 shows an aerial view of the school taken after the earthquake. The taller portion to the right of center is the gynmasium and auditorium; in the center is wing B, and to the left wing A. The domed structure is the library; to the extreme right are shops.

Zone II lateral-force requirements of the Uniform Building Code were in effect within the city of Anchorage at the time wing B and all but the last 80 feet of wing A were designed. Lateral forces to be resisted at each floor and roof level were computed according to the 1949 Uniform Building Code formula

$$F = \left(\frac{0.60}{N + 4.5}\right)W$$

where

F = lateral force to be resisted

W = dead load above the level considered

N = number of stories above the level considered

The roof of both wings is a 9-inch-thick flat slab, supported by exterior columns located at 32-foot centers and interior columns located at 16-foot centers. Spandrel beams 26 inches deep, framing between exterior columns, provide continuous support for the roof slab which extends 2 feet 6 inches beyond the outside face of the spandrel. figure 158. The second-floor slab is also 9 inches thick, hung from 41-inch-deep spandrels and supported by columns located directly beneath those supporting the roof slab. Wing B is approximately 256 feet long and wing A approximately 326 feet long, including an 80-foot addition which appears in figure 157. The top of the roof slab, at the centerline, is 13 feet 4 inches above the top of the second floor slab which is 11 feet 10 inches above the top of the first-floor slab on grade.

The earthquake created hinges at the top and bottom of almost every second-story column in the original wing A and wing B and also fractured the roof slab just beyond the point where the two wings join, figures 159 and 160. There are no columns at the plane dividing wings A and B, where the building suffered the most severe damage, figures 161 and 162. The building also suffered particularly heavy damage at a doorway in the south wall of wing B next to the expansion joint near the auditorium, figures 163 and 164. However, the opposite side of the wing did not show the same extreme distress, figure 165. The auditorium and gymnasium structure sustained no visible damage, figure 166. This portion of the building, along with the wing A addition, was designed to meet Zone III lateral force requirements of the Uniform Building Code. The wing A addition also stood up better than the original two wings. Figures 167 and 168 show that the columns of the wing A addition did not all fail in the manner typical of those in the original two wings. In figure 167 the division between the original wing A and the addition is at the eighth column from the intersection of wings A and B. This is actually a double column, figure 169, and there is noticeably less damage to the newer column. Although the wing A addition did sustain some damage, figure 170, it was primarily in the spandrels and walls and not the columns. The end wall of the addition showed no distress. The library, although built at the same time as the original two wings, suffered less damage in spite of heavy damage to wing A nearby, figures 171 through 173.

Closeups of some of the failed columns in the original two wings are extremely revealing. Particularly obvious in figures 174, 175, and 176 are poor construction joints caused by not removing laitance. Figures 175 and 176 are closeups of two of the columns shown in figure 174 at the second-floor level. A cold joint is obvious in each, although none of the failures is as extreme as those in other parts of the building; horizontal ties were at least partially effective. In other columns, ties were still present but ineffective, figures 177 and 178, and in extreme cases there were no ties to be seen, figures 179, 180, and 181. A column in wing B near the auditorium, only half as long as the rest and therefore about eight times stiffer, fractured in several places in spite of ties and without seriously buckling the vertical bars, figures 182 and 183, indicating a shear rather than compressional failure. Although the second floor of wings A and B was badly damaged, none of the building collapsed and students would probably have been safe in the corridors if not struck by a lampshade or cut by shattering glass, figure 184. No better testimony in favor of the recommendations of the recently published Portland Cement Association earthquake design manual (Ref. X-2), concerning horizontal column ties, can be found than the behavior of columns without extra heavy horizontal ties in the West Anchorage High School.

8. REED BUILDING

An interesting example of damage to an old reinforced-concrete building, built long before Anchorage had adopted an earthquake building code, is the

Reed Building, figure 185. This building had suffered damage in the October 3, 1954, earthquake which shook the Kenai Peninsula (Ref. X-5). Apparently the building front was repaired by moving the first-story wall back several feet and supporting the upper wall by a beam system resting on the three remaining old columns and three new ones. The Good Friday earthquake caused severe vertical cracking at the corners, extending almost the full building height. After the quake, steel channels were used to strap the building together, figures 185 and 186.

SECTION X

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SECTION XI

STRUCTURES EMPLOYING PRESTRESSED CONCRETE MEMBERS

1. FOUR SEASONS APARTMENTS

The failure of the unoccupied six-story, 70-unit Four Seasons Apartments, located at the northwest corner of Ninth Avenue and M Street, resembled the more tragic Saada Hotel collapse during the Agadir, Morocco, earthquake of 29 February 1960 (Ref. XI-1). In both cases all aboveground floors "pancaked." Although not yet occupied, the Four Seasons was structurally complete. Two relatively new construction features were employed: lift-slab erection and prestressed post-tensioned floor slabs. The building stood 52 feet high and was basically rectangular in plan with the north-south axis measuring 135 feet 6 inches and the east-west axis measuring 80 feet 6 inches. Each corner had a 3-foot 3-inch by 25-foot 1-inch indentation, figure 187. The floor slabs were 8 inches thick, supported by steel columns spaced about 25 feet apart in both directions. The L Street slide graben came so close to the Four Seasons, figures 188 and 189, that there was some question as to whether subsidence contributed to the collapse. However, the amount of subsidence within a few feet of the foundation wall appeared to be very slight, if any, and therefore a structural cause seems more likely. The structure's fallen position, figure 190, indicates that the two elevator cores, which both fractured at the first-floor level, fell on top of the roof rather than carrying the top five floors and roof down with them as they fell. The southeast portion of the basement was unexcavated, so the south elevator core was founded just below the first-floor level. The foundation for the north elevator core was below the basement floor. According to the consulting engineer (Ref. XI-2), all lateral force resistance was intended to be provided by the two cores, which were to transmit lateral loads through the first-floor slab to the foundation walls. Architectural considerations precluded cross bracing between the structural steel columns, figure 187. Although the floor slabs were tied to the elevator cores with dowels, the floors exerted no vertical loads on the cores; vertical loads on the cores might have prevented them from overturning. Instead, all vertical loads were carried by the steel columns. In addition to unbonded draped post-tensioned tendons, which supplied the main reinforcing for the floors, supplementary mild-steel reinforcing was located in the top and bottom of the slabs near the column collars, but the bars were not welded to the collars (Ref. XI-2). The chronology of the failure is a matter of conjecture, but the floor slabs appeared to have slid down the columns before the towers overturned, figure 191. Close inspection of the southwest corner column showed that the collars were all intact but had been stripped clean at the collar perimeter, figures 192 and 193. Other columns were in a similar condition. Had slab reinforcing been welded to the column collars, and the slabs transmitted some vertical reaction to the two elevator cores, the Four Seasons building might have survived.

2. FIFTH AVENUE CHRYSLER CENTER

Inadequate lateral strength of masonry-block columns and beam/column connections seems the most likely cause of collapse of the front half of the Fifth Avenue Chrysler Center at 2501 East Fifth Avenue. The building faces south and is basically rectangular in plan, 70 feet wide and 160 feet deep. The roof system consisted of 20 precast, prestressed concrete T-beams, each 8 feet wide and 2 feet 8 inches deep. All but the front four beams were 70 feet long and were supported by a continuous masonry wall. The front four beams were 83 feet long, supported on masonry-block columns, with a 10-foot overhang on the east side and a 3-foot overhang on the west side. The earthquake toppled all four front beams to the north, figure 194. Notice the one standing masonry column. The opposite column on the east side toppled with the beam. At least two T-beams which fell on cars were fractured and some prestressing wire broke at the point of impact, figures 195 and 196. Failure of the end connections occurred both by pulling out from the columns, figure 197, and by failure of welds between the column face plate and the beam web anchor plate. The beam web anchor plates were held by two inclined hooked bars. The next five shorter beams battered the supporting wall and also fell, figure 198. Failure of the roof system was halted at about the middle of the building by an interior masonry wall which runs the width of the building, figure 198. Apparently the steel T-section beam/wall connections, which were not welded to reinforcing in the wall, were inadequate to resist the lateral forces developed by the earthquake, figures 199 and 200. After the earthquake remedial measures were taken to increase the lateral strength of the remaining masonry walls, figure 201. A nearby building of similar construction, but shorter roof span and heavier beam/wall connections which were welded to reinforcing in the wall (according to the owner), survived the quake with no apparent damage, figure 202.

3. GAY AIRWAYS HANGAR AT MERRILL FIELD

The hangar portion of the Gay Airways building at the north edge of Merrill Field, a few blocks east and across from the Fifth Avenue Chrysler Center, suffered total collapse. The northern portion of the building, which did not collapse, did not have a prestressed roof system, figure 203. The hangar T-beams spanned about 60 feet in the east-west direction and were supported at both ends by masonry walls with pilasters beneath each beam web (Ref. XI-3, XI-4). The beam/wall connections, figure 204, were unable to provide lateral strength when the walls toppled to the west, dropping the roofing system almost in one piece. The east wall fractured where the pilaster reinforcing had only an 8-inch rebar overlap which effectively acted as a hinge, figures 205 and 206.

4. WESTERN RADIO AND TELEPHONE BUILDING

The Western Radio and Telephone Building, located on the south side of Merrill Field about due south of the Fifth Avenue Chrysler Center, also had a prestressed single-T roof system supported by masonry-block walls. The south portion of the building collapsed practically in one piece (Ref. XI-3). Six weeks after the quake, the north portion of the roof had also been razed and there was not much left to examine except the east and west masonry walls, held up by props, figure 207. The cause of the collapse was presumably similar to that of the Fifth Avenue Chrysler Center and the Gay Airways hangar, i.e., inadequate lateral strength of supporting masonry walls and beam/wall connections (Ref XI-4).

5. ALASKA SALES AND SERVICE SALES AND SHOP BUILDING

The Alaska Sales and Service sales and shop building, located at the south-east corner of Fifth Avenue and Medfra Street, was the largest structure employing precast, prestressed concrete T-roof beams to sustain severe damage as a result of the earthquake, but it was not yet structurally complete. The basic structure was square, measuring 200 feet on a side. The prestressed roof beams were supported by 36 large T-columns, arranged in 5 bays spaced on 40-foot centers in both directions. The planes of the 20-foot tall, 40-foot wide T-columns were oriented east-west, and the 2-foot 8-inch deep, 10-foot wide T-roof beams spanned between adjacent rows of columns in the north-south direction. The roof beams overhung 14 feet in both front and rear; therefore the roof measured 228 feet by 240 feet. At the time of the quake, the T-columns and roof beams were in place, but post-tensioned bond beams which were to have keyed together the flanges of beams along the east and west walls were not in place to provide lateral support in the north-south direction. Excessive swaying of the structure in the north-south direction felled several roof beams and exterior wall panels, figure 208, in addition to causing web crushing in numerous roof beams, figure 209, and spalling at the base of T-columns along the front (north side), figure 210. A smaller boiler house about 50 feet south of the main building was of similar construction, but had roof girders in place of the T-columns. It was structurally complete and suffered no apparent damage.

According to the designer (Ref. XI-5) the main building will be completed according to the original plan, except that neoprene bearing pads between the roof beams and the T-columns will be replaced by welded, anchored steel plate-bearing connections for all beams.

SECTION XI

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SECTION XII

STEEL STRUCTURES

1. ELMENDORF AFB AIRCRAFT MAINTENANCE HANGAR, BUILDING 11-140

Elmendorf AFB Building 11-140 is a steel aircraft maintenance hangar located near the south end of the north-south runway. It has Pratt roof trusses, well crossbraced by double angles in the plane of the lower chords and by tie rods in the plane of the upper chords, figure 211. The structure suffered minor damage to crossbracing, figure 212, when a connection failed because two of three bolts were missing, figure 213. Failure of the connection in figure 213 appears to have imposed bending loads on the opposite connection, figure 214. The damage was easily repaired, but could also have been easily prevented.

2. HILL BUILDING

The Hill Building, located at the southeast corner of Sixth Avenue and G Street, is an eight-story steel-frame office building with two central reinforced-concrete elevator cores. A penthouse extends one story above the roof, figure 215. Except for a crack in the penthouse wall, the building appeared from the outside to have suffered only minor damage. Figure 216, taken during construction in June 1961, shows how the steel frame surrounds and is tied to the elevator cores. Reinforced-concrete one-way floor slabs span between the two cores at each floor level. Rectangular in plan, the building is 180 feet long and 100 feet wide. It has no basement. According to one newspaper article (Ref. XII-1), the elevator cores settled and also tilted during the earthquake, imposing heavy strains on adjacent steel members and the reinforced-concrete slabs between the cores. The southwest corner of the east core was reported to have sunk [illegible]-1/2 inches, with other corners settling lesser amounts and one corner slightly raised. The cores were raised and leveled using an ingenious system of short needle beams and 75 jacks, devised by the designer, figure 217. Quick-setting concrete was then poured between the raised cores and their foundations. Later the first-story core walls were replaced in sections, but it was not found necessary to replace any of the core walls above the first story. According to the designer, construction joints in the cores were the weak points in the building. They probably contributed to the grinding of the towers at their bases (Ref. XII-1).

3. CORDOVA BUILDING

The Cordova Building, located at the northeast corner of Sixth Avenue and Cordova Street, is a six-story steel frame office building with a single reinforced-concrete elevator core near the north end, figure 218. According to the structural engineer (Ref. XII-2), the building has high-tensile bolted connections and open web floor joists. The frame is designed to be moment-resisting in the east-west direction, corresponding to the orientation of columns with their greatest moment of inertia about axes in the north-south direction. All lateral forces in the north-south direction, however, are to be resisted by the elevator core. The earthquake caused the southeast corner column to buckle in shear, figure 219, perhaps as Rice suggested (Ref. XII-3) because that particular column was stiffer than the other three, being braced at about mid-story height by a stairway stringer, figure 220. Two other first-story columns in the south wall also showed some distress. Note that the most severely spalled column in the Mount McKinley Building, only a few blocks northeast of the Cordova Building, was also near the southeast corner of that building. The Cordova elevator core is reported by Rice (Ref. XII-3) to have fractured on one side, probably in a manner similar to and for the same reason as the Hill Building elevator core fractures. However, vertical reactions from the steel frame prevented the cores in both buildings from overturning. Although the buckled corner column received considerable publicity, it was easily repaired, figure 220, and the building was reoccupied on June 23 by the Bureau of Land Managements (Ref. XII-4), thus disproving one comment by a prestressed concrete products manufacturer that it might be a total loss (Ref. XII-5).

4. ALASKA BREWERY COMPANY STRUCTURE

The Alaska Brewery Company structure, facing south on Whitney Road, is located directly south across the Alaska Railroad yard from the Government Hill slide. The structure is an unfinished steel building, the frame of which appears to be complete, figure 221. Bolted connections are used throughout and the frame appears to have suffered no damage from the earthquake, figure 222. However, the foundation piers did not fare so well, and were almost all badly spalled, figures 223, 224, 225, and 226. Notice that the spalling occurred mostly above the top horizontal tie, except for the pier in figure 226 which apparently had no tie. In the latter case, one anchor bolt tore completely free and rotated 90 degrees.

5. PERMANENTE CEMENT COMPANY CEMENT BIN

During the earthquake, a steel cement bin, located on Ocean Dock Road, figure 227, belonging to the Permanente Cement Company (now called Kaiser Cement and Gypsum Company) (Ref. XII-6), tipped over to the north and tore open, figures 228, 229, and 230. The side of the tank was torn away from the top about halfway around, figure 230, and some of the side seams also tore apart. All seams were bolted, figure 231. The tank plates showed considerable ductility, figure 232.

6. SHELL OIL COMPANY WATERFRONT STORAGE TANKS

In an aerial photo taken shortly after the earthquake, figure 227, only a small puddle of the contents indicated that the internal bracing system in one of the Shell Oil Company storage tanks was severely damaged. However, after a snowfall and one or two strong aftershocks, the top of one tank tore partly away from the side and fell to the bottom, figures 233 and 234. The tank had been drained prior to its collapse. Apparently lateral forces on the tank sides, caused by sloshing of the product, were transmitted to the vertical supporting system, which consisted of an interior ring beam supported by columns which, in turn, supported radial stringers out to the tank perimeter and in to a center column. When the columns collapsed under lateral load, the radial stringers tore away from the ring beam, allowing the top to fall, figures 235, 236, 237, and 238. A second tank adjacent to the collapsed tank also sustained some damage to its vertical supporting system but did not collapse. The top was noticeably buckled and had collected water in the depression.

7. SHELL OIL COMPANY INTERNATIONAL AIRPORT STORAGE TANK

One of the Shell Oil Company International Airport storage tanks also suffered an interesting kind of damage. Although not apparent from a distance, figure 239, closer inspection revealed a well defined buckle running completely around the tank base, figures 240, 241, and 242. Figure 239 shows some damage near the top of the tank; however, the roof did not collapse, and it was strong enough to support the weight of a man with only moderate vibration. Possible causes of the buckle might have been bending stresses near the base set up by sloshing of the contents. More likely the buckle resulted from vertical displacement of the base. The inertial force produced by the acceleration of the liquid increased the fluid pressure acting on the tank. In other words, before the entire fluid mass is set in motion by the displacement, the stationary fluid near the base of the tank is squeezed by the movement of the base. The resultant outward radial movement of this fluid could contribute to the buckling of the tank.

8. ALASKA AGGREGATE CORPORATION DOCK FACILITIES

A cement bin and a crane mounted on a ship which is used as a dock at the Alaska Aggregate Corporation dock facilities about a half mile south of the Permanente Cement bin and Shell Oil storage tanks, were both overturned in an easterly direction, figure 243.

9. ALASKA RAILROAD SHIP CREEK INLET BRIDGE

A steel railroad bridge across Ship Creek Inlet, belonging to the Alaska Railroad, figures 244, 245, and 246, suffered minor dam- e resulting from track movement. Due to pressure ridges that developed along the toe of the L Street slide, the track which parallels the slide area was displaced horizontally. Thus the track was pulled along the bridge which is located just east of the slide area. The total track movement at the bridge was approximately 4 inches. The end floor girders were deformed but continued to function and the bridge remained open to traffic. The bridge abutments are supported on piles and the fill under the abutments may have settled during the quake.

10. STEEL TOWERS

None of the steel towers inspected showed any sign of yielding, foundation damage, or other distress. Included were an Elmendorf AFB water tank, figures 247 and 248; a water tank on Government Hill's Harvard Avenue belonging to the city of Anchorage, figure 249; an unused but old water tank behind the Alaska Native Hospital at Third Avenue and Gambell Street within 100 yards of the First Avenue slide, figures 250 and 251; and a communications tower belonging to the Alaska Communications System on Delaney Street, also atop Government Hill, figure 252.

SECTION XII

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SECTION XIII

COMPOSITE CONSTRUCTION

1. ELMENDORF AFB WAREHOUSE, BUILDING 21-884

The most dramatic structural failure on Elmendorf AFB was the partial collapse of a warehouse built during the early 1950s. Several adjacent warehouses of slightly different construction, however, received only minor damage, figure 253. The 200-foot by 1,000-foot warehouse was divided into five bays by precast reinforced-concrete tilt-up firewall panels. Each bay had a steel frame roof that was supported in its interior by steel columns and at its periphery by either steel columns, column seats cast into the tilt-up panels, figure 254, or girders resting on square tied columns, figure 255. An enclosed railroad loading ramp ran the length of the north side of the building.

Bays 2, 3, and 4 collapsed completely, while bays 1 and 5 suffered only partial collapse, figure 253. Materials stored in bay 3 supported the collapsed roof system.

Horizontal stiffness was provided only at the periphery of each bay, and then only infrequently, figure 256. The sway bracing consisted of either steel crossbracing or horizontal steel channels connected to the columns by steel angles. Negligible rotational resistance was provided by the angles that connected the channels to the webs of adjacent steel columns. The welds that connected the crossbracing to adjacent columns failed without deforming the bracing. The horizontal channel system deformed laterally in the shape of a parallelogram without stressing the horizontal members, figure 257. An interesting side feature of the warehouse failure was the noticeable lack of ductility in reinforcing bars that were fractured at the base of columns along the north side of the train shed, figures 258, 259, and 260. The reinforcing in the concrete columns was tied together with No. 3 bars spaced 16 inches on center, figure 261.

2. ELMENDORF AFB FIELD HOUSE, BUILDING 4-940

The Elmendorf AFB Field House is actually two buildings, a gymnasium and a swimming pool, connected by a passageway, figure 262. Both parts are steel rigid frames enclosed by masonry-block walls, supported by an auxiliary reinforced-concrete frame. The gymnasium portion, in particular, provided an excellent example of two elements of a structure failing to act as a unit. The exterior frame and parts of the masonry walls showed cracks where the steel frame had impacted them from within, figures 263 and 264. A fallen piece of concrete showed few fractures through the aggregate; the cement was almost invariably weaker, figure 265. The steel frame was not damaged, but the plaster board showed stress, figure 266. An identical structure on Fort Richardson received similar damage (Ref. XIII-1). In this type of construction where two elements of different stiffness are expected to act together, the designer has several choices: he can connect the two elements in such a manner that they must undergo the same deformation and proportion them so that each has sufficient strength to undergo the same maximum deformation; he can provide sufficient separation between the two elements so that even under extreme conditions they will not impact (i.e., provide what ICBM shock-isolation designers call "rattle space"); or he can provide sufficient cushioning between the two elements so that the force transmitted from one element to the other is below a certain limit. None of the three conditions was satisfied in the field house.

3. ELMENDORF AFB BUILDINGS 6-920, 6-900, and 2-900

Three identical Elmendorf AFB buildings, built originally as 500-man barracks, two of which had been converted to administrative space, suffered similar non-structural damage. The buildings are rigid steel frames encased in concrete for fire protection with reinforced-concrete floors and exterior walls, figure 267. They have interior nonload-bearing masonry-block walls, several of which cracked or fell, particularly near expansion joints where adjacent sections of the building impacted each other, figures 268 and 269. Greater separation or added cushioning at the expansion joints might have reduced the damage to these buildings although the plans show that the separation at the expansion joints is not carried down through the footings. Almost all pairs of columns along an expansion joint share a common integral footing, a practice also followed in portions of the reinforced-concrete 750-man barracks but not to be recommended. It would be surprising if these footings had not received some structural damage, due to the bending and shear loads imposed on them by their two columns.

4. ANCHORAGE WESTWARD HOTEL TOWER

Although at first glance the 14-story Anchorage Westward Hotel tower, which was still under construction when the quake occurred, appears to be a steel frame, it must be classified as composite construction because it has reinforced-concrete floor slabs, formed and poured over corrugated metal decking (Ref. XIII-2). In addition the building had reinforced-concrete interior shear walls which were being added at the time of the earthquake. The tower faces north on Third Avenue and is near the southwest corner of Third Avenue and E Street between the original Anchorage Hotel on the east and the Westward Hotel on the west.

> "The original Anchorage Hotel is separated from the new building by an entry driveway and is connected to it by an enclosed overpass at the third floor level. The Westward Hotel abutts the new building and is directly connected at the corridors on each of its six floors." (Ref. XIII-3)

The tower is rectangular in plan, measuring 69 feet along and 139 feet perpendicular to Third Avenue. Unlike reinforced-concrete buildings, such as the Mount McKinley Building, Twelve-Hundred L Street Apartments, West Anchorage High School, and Elmendorf AFB Hospital, the Anchorage Westward Hotel showed comparatively little exterior damage, figure 270. An interior inspection of the tower revealed that workmen were still stripping away plaster walls to inspect structural connections, placing steel reinforcing for reinforced-concrete shear walls where doorways had been before, figure 271, and forming extra-heavy door lintels in the plane of the new shear walls, figure 272. Although the building is now claimed to be the tallest structure ever to survive an earthquake of the intensity observed in Anchorage, the damage it sustained delayed its opening by at least two months (Ref. XIII-3). The tower "hammered" against the adjacent 6-story concrete Westward Hotel. Four steel columns were deformed and required replacement. Another preliminary report (Ref. XIII-4) noted damage to light steel erection columns embedded in reinforced-concrete shear walls which fractured, but emphasized that the erection columns were not part of the permanent structural frame. Had the tower stood alone, the designers feel that it would have been undamaged.

5. HILLSIDE APARTMENTS

The Hillside Apartment building, facing north on Sixteenth Avenue opposite H Street, was almost a total loss as a result of the earthquake, figures 273 and 274. The structure stood at the crest of a steep bluff overlooking Chester Creek and showed five stories at the rear but only three at the front. It looked worse immediately after the earthquake than several other structures did after a week's demolition effort. The building has rolled-steel floor beams supported on steel pipe columns. Masonry walls which apparently were to have provided lateral strength failed to do so when they consistently failed along mortar joints, figure 275. Many interior and exterior masonry walls fell apart with hardly a block cracked, and in several instances there appeared to be a lack of mortar, figures 276 and 277. Demolition of the building was originally estimated to take 60 days (Ref. XIII-5); it actually took about half that time (Ref. XIII-6).

6. FIRST FEDERAL SAVINGS AND LOAN ASSOCIATION BUILDING

Before the quake, the year-old First Federal Savings and Loan Association building at the northwest corner of Fifth Avenue and C Street was one of the most modern buildings in Alaska, figure 278. The building is a 3-story steel frame with reinforced-concrete floors poured onto corrugated metal decking, figure 279. The south and east exterior walls were mostly glass with diagonally braced panels covered by brick for lateral rigidity, figure 280. The north and west walls were enclosed by masonry with two shear panels in the west wall. However, the west wall also had two horizontal rows of closely spaced windows which reduced the lateral strength of that wall, figure 281. The effect of the earthquake was to fracture the main shear panel in the west wall and create a pattern of diagonal tension cracks between the lower row of windows, figure 282. Rice (Ref. XIII-7) compares these diagonal tension cracks to those in the Mount McKinley Building and draws a distinction between horizontal and vertical shear mechanisms, although he does not identify the bank building by name. The masonry section of the south (front) wall was also cracked near the foundation. Had there been fewer windows in the west wall, and had the shear panels been stronger, the building would probably have fared well, since glass breakage in the south and east walls was not extreme. Damages to the $500,000 structure were estimated at $175,000, and repairs would have been undertaken immediately except that the bank building was in a high-risk area created by the Fourth Avenue landslide (Ref. XIII-8).

7. WRIGHT WAY AUTO CARRIER BUILDING

The Wright Way Auto Carrier Building at the southwest corner of Fifth Avenue and Denali Street just a block south of the Mount McKinley Building is a steel frame with Pratt roof trusses similar to the Elmendorf AFB aircraft maintenance hangar. However, the Wright Way building had masonry-block exterior wall panels which apparently were not well tied to the steel frame. Motion of the frame battered down most of the masonry and threw out the large factory-glass windows.

Figure 283 shows the frame after most of the rubble had been removed. A portion of the wall remains standing near the southwest corner and shows clean breaks at the mortar joints. An earlier photograph (figure 275) shows many whole blocks or large sections of wall fallen intact indicating masonry work of a quality comparable to that in the Hillside Apartments.

8. DALTON AND COMPANY WHOLESALE SUPPLY STORE

The Dalton and Company wholesale supply store, facing east on D Street between Second and Third Avenues, may have been the victim of compressional features at the toe of the Fourth Avenue slide. However, weak column-base anchorage appears to have been the main cause of near collapse of this light, one-story building, figures 284 and 285. The pile of whole blocks also indicates inferior quality masonry work as does the debris in figure 286. The building had light-gage steel roof beams supported by steel pipe columns, with masonry-block exterior and interior walls and metal window frames. Note the masonry blocks still hanging from the roof in figures 284 and 286 despite the fact that the lower wall portions, including windows, have collapsed.

SECTION XIII

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SECTION XIV

WOOD STRUCTURES

1. ELMENDORF AFB AIRCRAFT MAINTENANCE HANGARS, BUILDINGS 32-060 AND 32-217

The only large wood structures inspected were two identical aircraft maintenance hangars on Elmendorf AFB, called the "birchwood hangars," figure 287. These structures have bowstring roof trusses, figure 288, carried by vertical trusses, crossbraced in the plane of the vertical chords, figure 289. About half the inclined chords of the vertical trusses in both structures were fractured and splintered in compression at the location of a splice below the roof of the office lean-tos, figures 290, 291, and 292. This might have been prevented if the connecting bolts had been staggered, since the splice failure began by splitting the two lines of bolts, figure 290. The crossbracing was split in some locations, figure 293, and in others vertical chord members were fractured, figures 294 and 295. Tie rods in the horizontal plane of the roof-truss lower chords split some of the timbers to which they were connected because of the way in which the timber grain was oriented, figure 296. Both ends of the tie rods should have been connected to the roof-truss lower chords.

SECTION XV

CONCLUSIONS

Based on a fairly thorough engineering investigation of the damage caused in Anchorage by the Alaska earthquake, we can state that if a structure is located where landslides produce large differential displacements, no economical design measures can ensure its safety. Thus, the requirement for judicious subsurface investigation for any major structure before construction is obvious. Old landslide "benches," perhaps the evidence of a previous earthquake, exist along the same bluffs in Anchorage where the Good Friday landslides were triggered and are indications of the unstable geological conditions in the area. In addition the danger of earthquake-triggered landslides in the bluff areas had been predicted and reported in the literature (Ref. XV-1).

The Elmendorf AFB Hospital provides an excellent example of perfunctory foundation design; however, many similar examples can be seen in Anchorage, e.g., the Mount McKinley Building and the Twelve-Hundred L Street Apartments. Uniform vertical settlement throughout a structure is critical to ensure adequate resistance against dynamic forces, whether they be natural or man-made. In general, a mat foundation under an entire structure will provide greater assurance of uniform settlement.

Buildings that require expansion joints, or that have "wings" or appendages, should be designed to ensure independent response of the "wings." At expansion joints and wing junctures, sufficient "rattle space" or cushioning should be provided to prevent adjacent units from "hammering." Elements that unite independent structural systems, e.g., common foundations, must fracture for the systems to truly respond independently.

Where horizontal forces are to be resisted by shear walls, the location of these walls should be symmetrical so that the center of rigidity provided by the walls coincides with the center of mass of the structure. The center of rigidity of the shear walls in the J. C. Penney building did not coincide with its center of mass. The shear walls should also be as near the periphery of the structure as the functional requirements will permit. The Four Seasons Apartments, the Hill Building, and the Cordova Building are examples of resistance to horizontal forces concentrated in central cores. Finally, the walls should not be stiffer or stronger than the structural frame.

Where two structural systems having different stiffnesses are expected to respond simultaneously (e.g., the Elmendorf AFB Field House), the designer has three choices: to connect the systems in such a manner that they can undergo the same deformations synchronously; to provide sufficient "rattle space" between them so that even under extreme conditions they will not impact; or to provide sufficient cushioning between systems so that the force transmitted from one element to the other is below a certain limit.

In reinforced-concrete design, the use of heavier and more closely spaced column ties is to be strongly recommended. Throughout the entire Anchorage area every reinforced-concrete structure that failed had insufficient ties, e.g., columns in the West Anchorage High School and the columns in the train shed of the Elmendorf AFB warehouse. At exterior beam/column connections, the column ties should be spaced throughout the full depth of the beam, as recommended by the Portland Cement Association (Ref. XV-2). A few additional ties placed as recommended by the PCA would have reduced the damage to the Elmendorf AFB 750-man barracks.

Structural details, in general, were responsible for unsatisfactory performance. Many of these details (e.g., arrangement of ties in columns at beam/column connections) are not amenable to precise analytical treatment. Nevertheless, they demand the close attention of a professional structural engineer, and if delegated to a detailer or a subcontractor, the solution should be thoroughly reviewed. Meticulous attention to detail is essential during every phase of design and construction and requires top-caliber designers, construction contractors, and inspectors working together as a team.

In many cases, the dollar difference between structural success and failure was small. For instance, the cost of providing adequate sway bracing and connections in the Elmendorf AFB warehouse, or the cost of using more and heavier column ties in the Elmendorf AFB 750-man barracks and in the West Anchorage High School, would have been a small fraction of the initial construction cost and certainly far less than the cost of replacement or repair.

The fact that there was noticeably less structural damage on Elmendorf AFB than in Anchorage, only a few miles away, is probably due in part to the greater depth of the glacial outwash that overlays the Bootlegger Cove clay beneath the air base. This material may have decreased the ground-shock effects by damping the earth motions. The clay is located approximately 50 feet deeper on Elmendorf

AFB than in the city of Anchorage.

Finally, procedures and criteria for design of earthquake-resistant structures were already available at the time of the Good Friday earthquake; conscientiously applied, these could have provided structures of more resistant design and construction.

SECTION XV

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13. ABSTRACT

The tremendous Alaska earthquake of March 1964 killed many people and caused property damage in the millions. Nevertheless this quake provided scientists and engineers with an almost unique opportunity to study the effects of so huge a natural phenomenon in a relatively urban and built-up environment. The coastal location of the quake's epicenter created a wide variety of temblor effects including crevasses or grabens, pressure ridges produced by landslides, and a broad spectrum of structural damage. The bays, inlets, harbors, and the seacoast for many hundreds of miles were inundated by powerful seismic sea waves (tsunamis). Such diverse effects suggested unlimited areas of study and evaluation. This technical report presents a general summary of all the effects catalogued above, and investigates in some detail the strengths and weaknesses of the many types of structures affected by the temblors. The volume of illustrations which supplement this report shows many details of structural damage, information that could be extremely useful to engineers, architects, contractors, city planners, and others who plan to erect structures on land known to be subject to earthquakes. All maps and illustrations are contained in Volume II of this report.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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