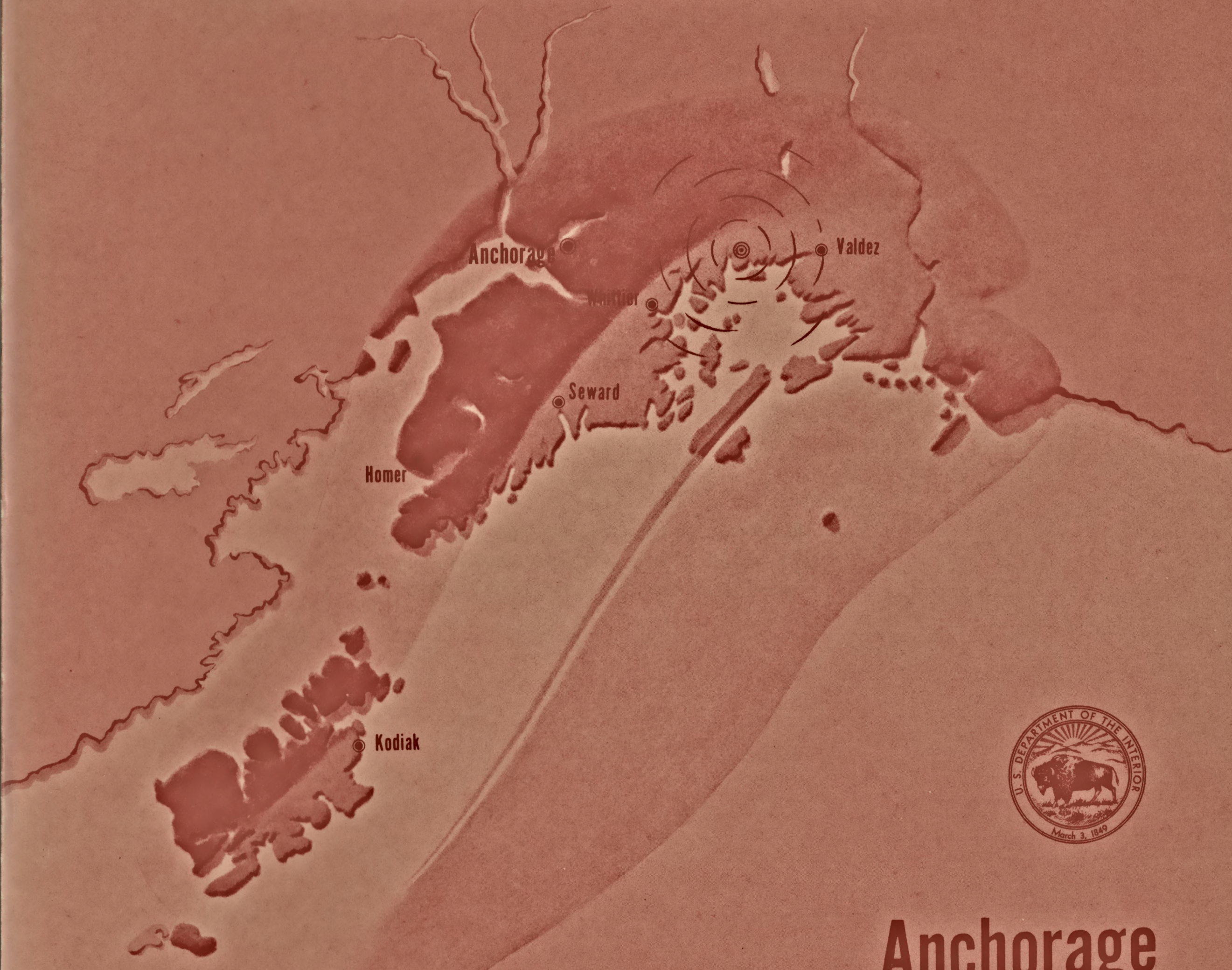
# The Alaska Earthquake
## March 27, 1964

# Effects on Communities




# Anchorage

GEOLOGICAL SURVEY PROFESSIONAL PAPER 542-A

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

# Effects of the Earthquake Of March 27, 1964 At Anchorage, Alaska

BY WALLACE R. HANSEN

*A description and analysis of the damage resulting from seismic vibration, ground cracks, and especially landslides in Alaska's largest city*

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[Plates are in pocket]



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By Wallace R. Hansen


## *ABSTRACT*

Anchorage, Alaska's largest city, is about 80 miles west-northwest of the epicenter of the March 27 earthquake. Because of its size, Anchorage bore the brunt of property damage from the quake; it sustained greater losses than all the rest of Alaska combined. Damage was caused by direct seismic vibration, by ground cracks, and by landslides. Direct seismic vibration affected chiefly multistory buildings and buildings having large floor areas, probably because of the long period and large amplitude of the seismic waves reaching Anchorage. Most small buildings were spared. Ground cracks caused capricious damage throughout the Anchorage Lowland. Cracking was most prevalent near the heads or within landslides but was also widespread elsewhere. Landslides themselves caused the most devastating damage.

Triggering of landslides by the earthquake was related to the physical-engineering properties of the Bootlegger Cove Clay, a glacial estuarine-marine deposit that underlies much of the Anchorage area. The Bootlegger Cove Clay contains zones of low shear strength, high water content, and high sensitivity that failed under the vibratory stress of the earthquake. Shear strength in sensitive zones ranged from less than 0.2 tsf to about 0.5 tsf; sensitivity ranged from about 10 to more than 40. Sensitive zones generally are centered about 10 to 20 feet above sea level, between zones of stiff insensitive clay. Many physical tests by the U.S. Army Corps of Engineers were directed toward analyzing the causes of failure in the Bootlegger Cove Clay and finding possible remedies. Strengths and sensitivities were measured directly in the field by means of vane shear apparatus. Atterberg limits, natural water contents, triaxial shear, sensitivity, dynamic modulus, consolidation strength, and other properties were measured in the laboratory. Pulsating-load tests simulated earthquake loading.

Most of the destructive landslides in the Anchorage area moved primarily by translation rather than by rotation. Thus, all the highly damaging slides were of a single structural dynamic family despite wide variations in size, appearance, and complexity. They slid on nearly horizontal slip surfaces after loss of strength in the Bootlegger Cove Clay. Some failures are attributed to spontaneous liquefaction of sand layers. All translatory slides surmounted flat-topped bluffs bounded marginally by steep slopes facing lower ground. Destructive translatory slides occurred in the downtown area (Fourth Avenue slide and L Street slide), at Government Hill, and at Turnagain Heights. Less destructive slides occurred in many other places—mostly uninhabited or undeveloped areas.

In most translatory slides, damage was greatest in graben areas at the head and in pressure-ridge areas at the toe. Many buildings inside the perimeters of slide blocks were little damaged despite horizontal translations of several feet. The large Turnagain Heights slide, however, was characterized by a complete disintegration and drastic lowering of the prequake land surface. Extensive damage back from the slide, moreover, was caused by countless tension cracks.

An approximation of the depth of failure in the Bootlegger Cove Clay in the various slides may be obtained by using a geometric relationship herein called the "graben rule." Because the cross-sectional area of the graben at the head of the slide approximated the cross-sectional area of the space voided behind the slide block as the block moved outward, the depth of failure was equal to the area of the graben divided by the lateral displacement. This approximation supplements and accords with test data obtained from borings. The graben rule should apply to any translatory slide in which flowage of material from the zone of failure has not been excessive.

Geologic evidence indicates that landslides similar to those triggered by the March 27 earthquake have occurred in the Anchorage area at various times in the past.

# INTRODUCTION

Anchorage, "metropolis of the north" and Alaska's largest city, is the rapidly expanding commercial center of the 49th State. Anchorage is about 80 miles west-northwest of the epicenter of the March 27 earthquake (fig. 1).

The Anchorage Lowland, a broad, undulatory glacial plain on which the greater Anchorage area is situated, is roughly triangular. It is bounded on the northwest by Knik Arm of Cook Inlet, on the southwest by Turnagain Arm, and on the east by the abrupt west front of the Chugach Mountains. Anchorage itself is crowded close to Knik Arm, but its perimeter is moving east and south because of suburban growth and soon, no doubt, will reach Turnagain Arm. Expansion north and northeast toward the Eagle River, along the narrow corridor between the mountains and Knik Arm, is largely checked by the military reservations of Fort Richardson and Elmendorf Air Force Base.

## ACKNOWLEDGMENTS

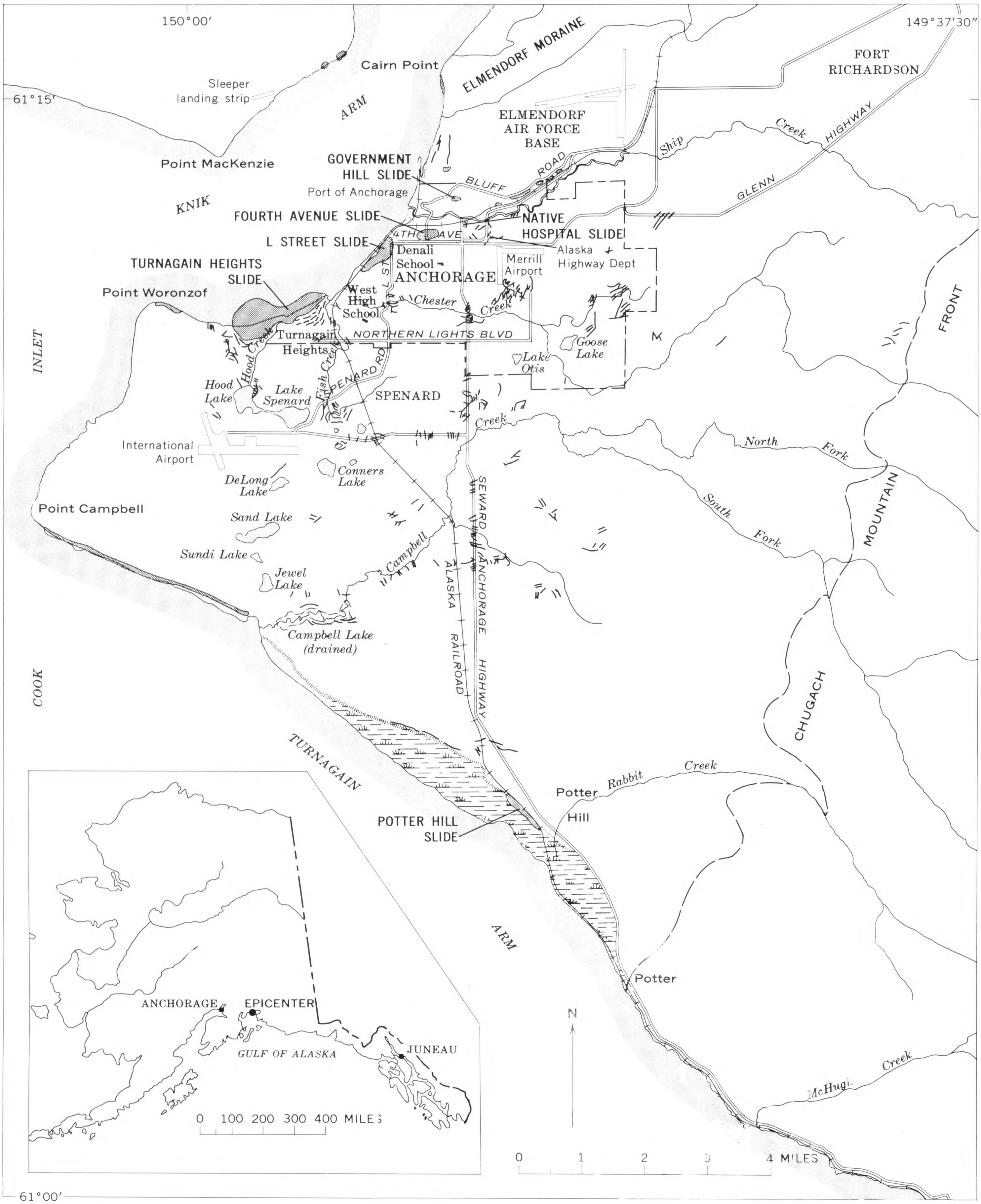
Many ideas and conclusions presented in this report were reached in concert with R. D. Miller and C. A. Kaye, both of whom shortly after the March 27 earthquake joined the author in field investigations at Anchorage. Most of the credit for devising the "graben rule" (see p. A41) must go to Kaye. Discussions with M. G. Bonilla, Ernest Dobrovolny, E. B. Eckel, Reuben Kachadoorian, D. S. McCulloch, and Roger M. Waller consciously or unconsciously led to thoughts incorporated into this report. J. R. Helm, A. B. Dodd, and Arthur Gervais of the Topographic Division, U.S. Geological Survey, ran control for profiles of the various landslides. Helm also prepared the topographic maps of the Native Hospital, Government Hill, and Turnagain Heights slides, using a Wild B–8 plotter. Special thanks are due the U.S. Army Corps of Engineers for the materials and information that they supplied. A report prepared for the Corps by Shannon and Wilson, Inc. (1964) has been freely utilized, and several of its illustrations are reproduced herein. The Engineering Geology Evaluation Group (see p. A10), an ad hoc organization that carried out early investigations at Anchorage at a critical time immediately after the earthquake, is also thanked for its free release of otherwise unobtainable information.

## THE EARTHQUAKE AND ITS IMMEDIATE AFTERMATH

At 5:36 p.m. on Good Friday, March 27, 1964, Anchorage and all southern Alaska within a radius of about 400 miles of Prince William Sound were struck by perhaps the strongest earthquake to have hit North America within historic time. The magnitude of this great quake has been computed by the U.S. Coast and Geodetic Survey at 8.5 on the revised Richter scale. Its epicenter was about 80 miles east-southeast of Anchorage near the head of Prince William Sound. Reportedly, the quake was felt throughout most of Alaska, including such remote points as Cape Lisburne, Point Hope, Barrow, and Umiat, 600 to 800 miles north of the epicenter on the Arctic Slope of Alaska, and at Fort Randell, 800 miles southwest at the tip of the Alaska peninsula.

Eyewitness accounts of happenings at Anchorage during and immediately after the earthquake have been reported in many publications, both technical and popular. Much valuable information has thus been gained from the objective observations of individuals who were equal to the task. Calm detachment under such trying circumstances plainly is a rare and admired virtue. Some confusion and contradiction did appear in early accounts, not surprisingly, in view of the distressing conditions under which the observations were made.

The duration of the earthquake at Anchorage can only be surmised owing to the lack of strong-motion seismograph records. Although seismographs have since been installed, none was present in Southern Alaska at the time of the quake. Intense seismic motions seem to have lasted 3 to 4 minutes, possibly longer. Where localized ground displacements occurred, as in or near landslides, strong motions may have lasted appreciably longer, after strong seismic shaking had ceased. According to Shannon and Wilson Inc. (1964, p. 11), the durations at Anchorage, timed on wrist or pocket watches, by several eyewitnesses whom they consider reliable, ranged from 4 minutes 25 seconds to 7 minutes. Even longer durations were reported outside the Anchorage area. Steinbrugge (1964, p. 62) noted that persons at Anchorage were able to accomplish several time-consuming tasks during the shaking, including such things as leaving and reentering buildings more than once, or helping other individuals to escape, despite much difficulty in standing and walking. In some areas, however, people reportedly were thrown to the ground by the force




1.—Map of Anchorage, Alaska, and vicinity showing locations of major landslides and ground cracks, much generalized.

of the acceleration and were unable to regain their footing.

There seems to be general agreement that the first waves to arrive at Anchorage had strong east-west components of movement. Objects reportedly were thrown from shelves and cupboards on east and west sides of rooms, and some individuals were said to have been propelled bodily across rooms in those directions. Figure 2 shows the trace on an asphalt tile floor made by a dresser leg. Because the epicenter was east of Anchorage, an east-west ground motion was expectable. As the shaking continued, however, the motion is said to have shifted to north-south, and tall buildings that had first rocked to-and-fro east and west began to rock north and south as well, in a complex combination of movements. Strain-fracture patterns in the walls of multistory buildings at Anchorage seem to bear out such observations. North-south components of motion, moreover, are theoretically plausible, especially in view of the severe tectonic readjustments southeast and south of Anchorage in the Prince William Sound and Kodiak Island areas. The earthquake seems to have resulted from the rupture of rock at depth beneath a very broad area, extending from some point near the epicenter southwest to the south tip of Kodiak Island (U.S. Coast and Geodetic Survey, 1964, p. 31; Grantz and others, 1964, p. 2); the arrival of seismic waves at Anchorage from such a broad source must have caused a very complex ground motion (fig. 2).

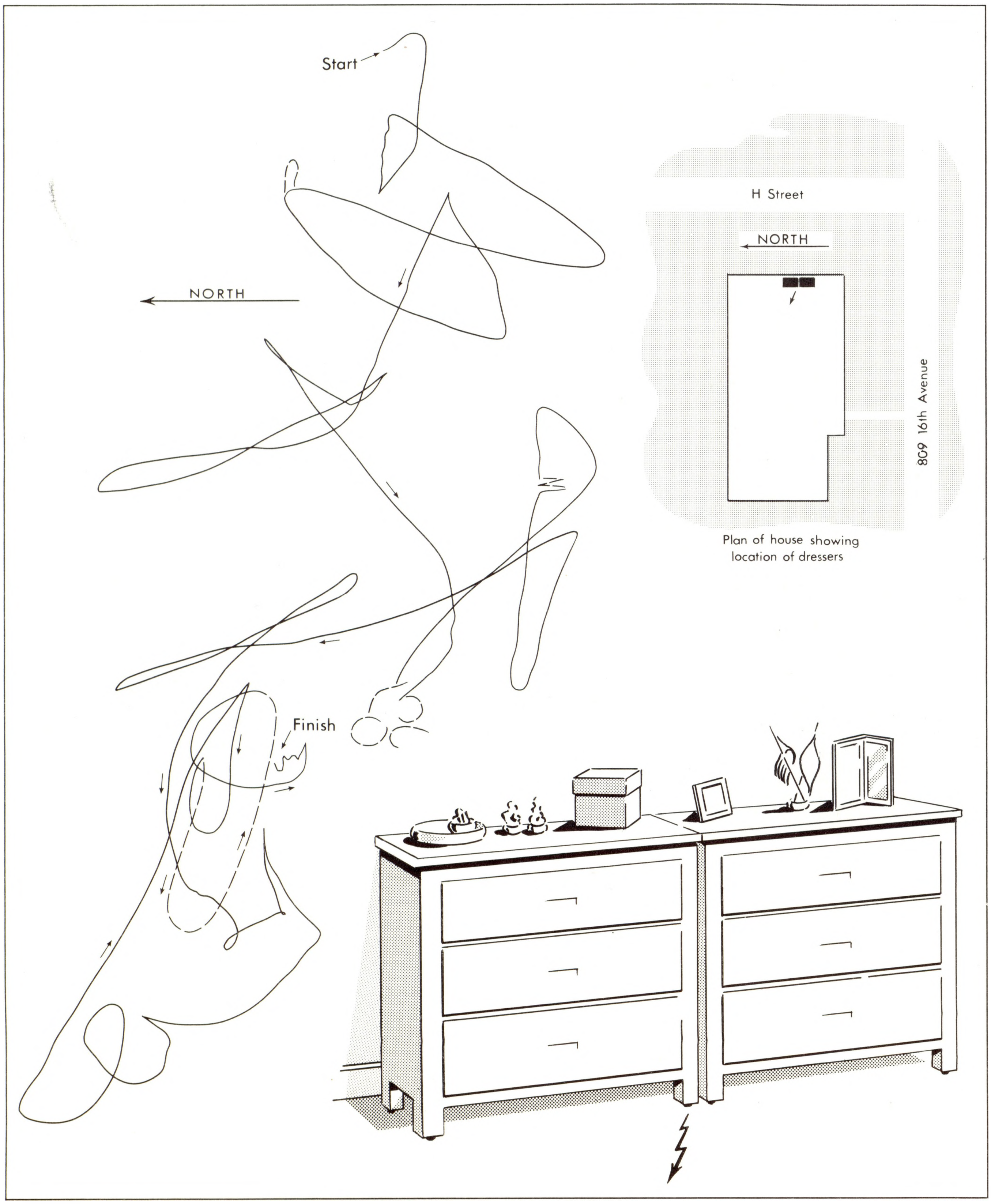
Total earthquake damage to property in the Anchorage area has not been fully evaluated and perhaps will never be fully known. Nine lives are reported to have been lost—five in the downtown area, three at Turnagain Heights, and one at the International Airport. In less than 5 minutes, more than 2,000 people, including apartment dwellers, were made homeless, according to press estimates. The loss of life was less in Anchorage than in some of the small coastal towns, where many people were killed by sea waves. But Anchorage, because of its much greater size, bore the brunt of the property damage and property losses reportedly were greater there than in all the rest of Alaska combined.

Early estimates by the Office of Emergency Planning indicated that about 75 percent of the City's total developed worth was measurably damaged. Early estimates of total damage, however, tended to be larger than later ones. According to the Anchorage Daily Times of April 9, 1964, 215 homes were destroyed in Anchorage and 157 commercial buildings were destroyed or damaged beyond repair (Grantz, Plafker, and Kachadoorian, 1964, p. 14). At Turnagain Heights alone, 75 or more dwellings were destroyed. Estimates by the Daily Times placed the damage at about $200 million. Later, the Office of Emergency Planning estimated the total damage to Alaska at about $537,600,000, of which about 60 percent was sustained by the Anchorage area (National Board of Fire Underwriters and Pacific Fire Rating Bureau, 1964, p. 5). The final total damage estimate for Alaska, exclusive of personal property and loss of income, was about $311 million (Federal Reconstruction and Development Planning Commission for Alaska, 1964, p. 11). Scores of buildings throughout Anchorage sustained damage requiring repairs costing many thousands of dollars.

The school system was hard hit. Early estimates of damage came to about $3.86 million. Classes were not in session, fortunately, so the buildings were empty. Twenty of the 26 schools in Anchorage were soon back in operation. West Anchorage High School, however, was severely damaged by seismic vibration. Government Hill Grade School, astride a landslide (fig. 3), was nearly a total loss, although plans have been made to salvage an intact part of the building outside the slide for use other than as a school. Denali Grade School was damaged by ground cracks and was closed indefinitely, pending damage evaluation and repair.

In downtown Anchorage (the L Street and Fourth Avenue landslide areas), about 30 blocks of dwellings and commercial buildings were destroyed or severely damaged (fig. 4). A new six-story apartment building, the Four Seasons, was razed. A new five-story department store (J. C. Penney Co.) was damaged beyond repair by seismic shaking and had to be torn down (fig. 5). Many automobiles in the downtown area were struck by falling debris. Twin 14-story apartment buildings, though a mile apart, sustained massive, nearly identical vibratory damage, much of it in response to vertical shearing forces caused by oscillation. Many other multistory or large-area buildings were severely damaged.

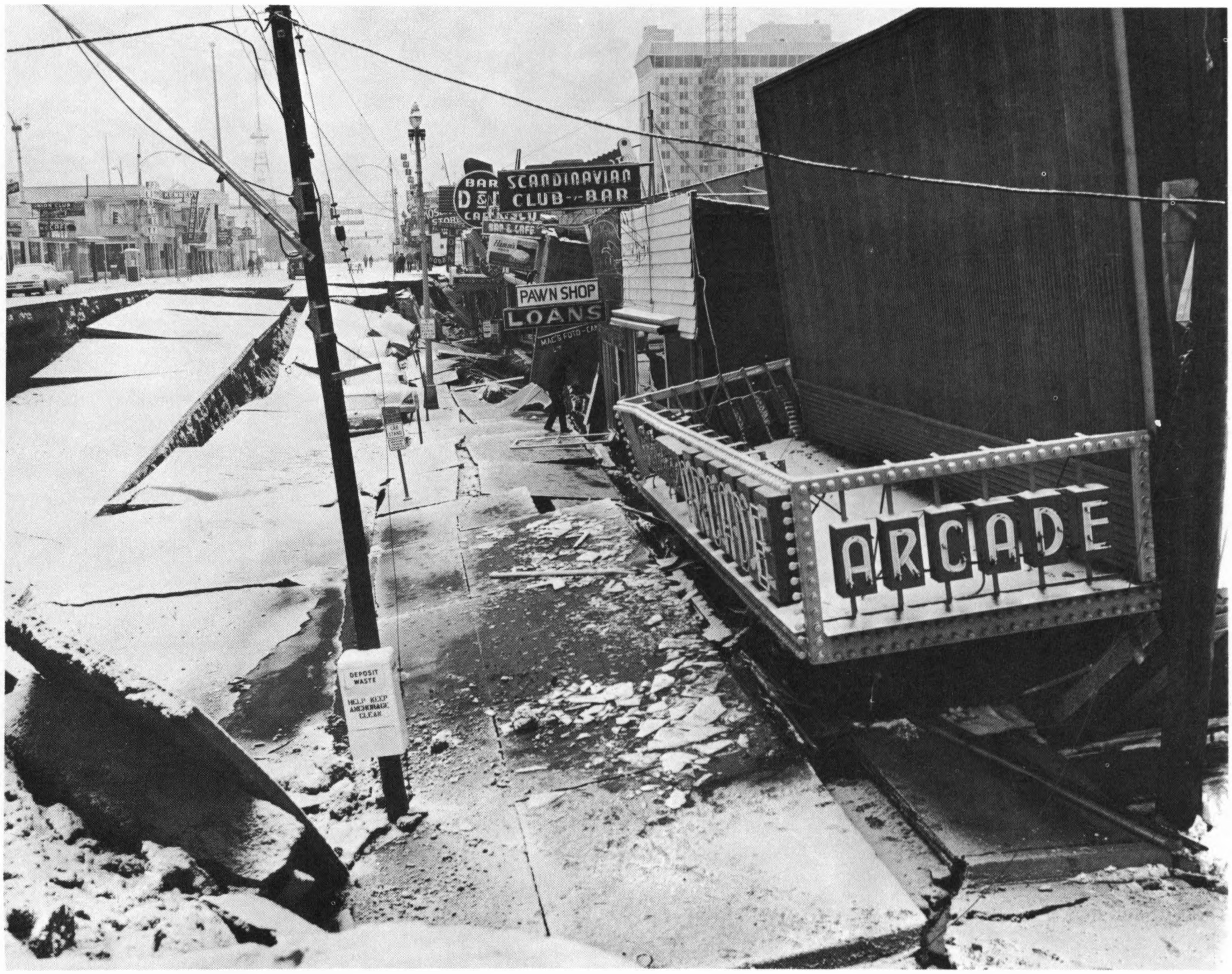
Water mains and gas, sewer, telephone, and electric systems were disrupted (Waller, Thomas, and Vorhis, 1965, p. 126). Total damage to utilities has been estimated at about $15 million (Alaskan Construction Consultants Committee, 1964, p. 11). Providentially, electric power failed at the very onset of the quake. Although the loss of power might seem to be an added hardship to the stricken city, untold numbers of fires were




2.—Horizontal trace on asphalt tile flooring left by dresser leg during earthquake. Net movement of dresser was about N. 75° W. Other legs left nearly identical traces. Sundry items on dresser tops were little disturbed. Trace reproduced by Oliver V. Kola, published by permission of Dr. M. A. Sozen. Scale of trace, ×½.

3.—Wreckage of Government Hill School. The south wing of the building, shown here, collapsed into a graben at the

head of the slide. Net slip of the graben block is shown by the displacement of the roofline. Photograph by M. G. Bonilla.




4.—View west along Fourth Avenue at head of landslide. North (right) side of street has collapsed into a graben. Vertical displacement is about 10 feet. Photograph by Mac's Foto, Anchorage, Alaska.

probably avoided because of the lack of electric current in all the severed wires—and at a time, too, when water was unavailable for fighting fire. The destruction of San Francisco by fire on the heels of the earthquake of 1906 is forcefully recalled. Fukui, Japan, was similarly destroyed in 1948. Anchorage spent the night of March 27 in total darkness, but the city had no fires and was prepared to deal with the many disrupted electric circuits when service was restored.

Roads and railroad facilities were badly damaged. In the downtown area, many streets were blocked by debris, and in landslide areas, streets and roads were completely disrupted. Differential settlement caused marginal cracking along scores of highway fills throughout the Anchorage Lowland. In The Alaska Railroad yards where landslide debris spread across trackage and damaged or destroyed maintenance sheds (fig. 6), an estimated $2,370,700 damage was sustained (Alaskan Construction Consultants Committee, 1964, p. 74). Cars and equipment were overturned, and car shops were damaged by vibration. Along the main line of the railroad, bridges failed, fills settled, and tracks were bent or buckled; at Potter, near the south margin of the Anchorage Lowland, several hundred feet of track was carried away in an area that has had a long history of repeated sliding.

At the Anchorage International Airport, the control tower failed under seismic vibration and collapsed to the ground (fig. 7), killing one occupant and injuring another. The airport terminal building, although tied structurally to the tower, was only slightly


5.—Wreckage of Penney's department store, Fifth Avenue and D Street, Anchorage. Building failed after sustained seismic shaking. Most of rubble has been cleared from streets. Photograph by George Plafker.

damaged except where it adjoined the tower. A nearby Post Office building was damaged a moderate amount (Berg and Stratta, 1964, p. 14). Almost 20,000 barrels of aviation fuel was lost from a ruptured storage tank. Runways and taxiways were slightly damaged but not put out of commission; air traffic was temporarily controlled first from a parked aircraft and then from a tower at the nearby Hood Lake landing strip (Federal Reconstruction and Development Planning Commission for Alaska, 1964, p. 25).

Facilities at the Port of Anchorage were damaged by seismic vibration and ground cracks. Four cranes jumped their tracks and in so doing, damaged their undercarriages and counterweight arms (Berg and Stratta, 1964, p. 44 and 47). Two steel storage tanks were toppled and destroyed. Nearby oil-storage tanks were damaged superficially, but large quantities of fuel oil were lost. An expected seismic sea wave fortunately did not materialize.

Landslides caused the greatest devastation in the Anchorage area. Great slides occurred in the downtown business section (Fourth Avenue slide), in the lower downtown business and residential area (L Street slide), at Government Hill, and at Turnagain Heights. Less devastating slides occurred in undeveloped or unpopulated areas near the Alaskan Native Service Hospital, at Romig Hill, at the Alaska Highway Department garage, at Bluff Road near the U.S. Army Corps of Engineers Headquarters Building, on the west bluff of Government Hill, at Point Woronzof, Point Campbell, Cairn Point, and on the west side of Knik Arm near Sleeper landing strip in an uninhabited area recently opened to homesteading. The slide at Potter has already been mentioned.

Capricious damage was caused by ground cracks. Such damage was mostly localized, and many areas were spared. Cracking was most common behind the heads of landslides, but it was also prevalent throughout the lowland in areas underlain by clay or silt or artificial fills on muskeg. Differential compaction was a common cause. Cracking was minimal in areas of thick ground moraine.

The flow of streams, such as Ship Creek and Chester Creek, was greatly reduced, temporarily, by percolation of water into cracks. Gages in water wells recorded

6.—Damage to yards of The Alaska Railroad, looking northwest, caused by earthflow at toe of Government Hill slide. Note undamaged water tank in background.

marked fluctuations, not just in Anchorage and southeast Alaska, but at places as distant as Georgia, Florida, and Puerto Rico (Waller and others, 1965, p. 126, 131).

For a city of its size, Anchorage has in residence a large contingent of geologists and other earth scientists. Within hours after the quake, many of these individuals had begun independent investigations of the location, severity, nature, and causes of earthquake damage. On March 29, 2 days after the earthquake, a small group of geologists under the leadership of Dr. Lidia Selkregg of the Alaska State Housing Authority was commissioned by the housing authority and the city of Anchorage to outline "necessary and immediate courses of action" to be taken by the city. This group became known as the Engineer-

7.—Wreckage of control tower at Anchorage International Airport. Six-story tower failed under sustained seismic shaking. Photograph by George Plafker.

ing Geology Evaluation Group (Schmidt, 1964, p. 13). Its membership rose to 40 after a call was made for technical help.

The group immediately began a program of mapping and data gathering. They contracted for aerial photography, started a drilling program in the major slide areas in cooperation with the Alaska Department of Highways, and ran standard laboratory tests on the various soil zones involved in the land failures. Drilling and soil testing were subsequently taken over and greatly expanded by the office of the U.S. Army District Engineer at the request of the city of Anchorage, under a contract dated 25 April 1964 between the District Engineer and Shannon and Wilson, Inc., soil mechanics and foundation engineers, Seattle, Wash. The Corps of Engineers meanwhile had immediately begun disaster relief.

The work of the Engineering Geology Evaluation Group deserves high praise. Its preliminary findings and recommendations were completed on April 12, 1964, 2 weeks after the earthquake, and a final report was completed on May 8, 1964. The findings and conclusions of the group provided the basis for many subsequent investigations by other agencies. Much of the information presented by this paper has been derived from the work of this group.

## GEOLOGIC SETTING

Anchorage is near the east border of a deep structural trough filled with moderately consolidated Tertiary rocks that underlie Cook Inlet and extend northeastward toward Mount McKinley at the head of the Susitna Lowland (Capps, 1916, 1940). At Anchorage, Tertiary rocks are covered by Pleistocene deposits, but they have been penetrated by drill holes.

The Chugach Mountains just east of Anchorage consist chiefly of Mesozoic argillite and graywacke, variably deformed and metamorphosed, and intruded by small bodies of igneous rock (Capps, 1916, p. 153). The nature of the contact between the soft Tertiary rocks of the lowland and the harder Mesozoic rocks of the mountains has not been ascertained, owing partly to a lack of exposures and partly to a lack of study, but the very straight trace of the mountain front and the seeming truncation of structural trends by the mountain front suggest that the contact is a fault. On similar evidence, Karlstrom (1964, p. 21) inferred that the Kenai Mountains—a southward structural and topographic extension of the Chugach Mountains—are also bounded by a fault on the west. If these inferences are correct, a major structural displacement separates the Cook Inlet

Lowland from the bordering mountains.

Cook Inlet and the Anchorage Lowland were occupied repeatedly by large piedmont glaciers in Pleistocene time (Karlstrom, 1957, 1964; Miller and Dobrovolny, 1959). Karlstrom has distinguished five major Pleistocene glacial advances in Cook Inlet, although not all reached the Anchorage area. At the site of Anchorage, Pleistocene deposits accumulated to a thickness of 600 feet or more. In general, these deposits seem to thicken westward from the mountain front toward Cook Inlet. They exerted a vital influence on the location and the extent of earthquake damage in the Anchorage area.

Because the Pleistocene deposits of the Anchorage area have been described previously in considerable detail (Miller and Dobrovolny, 1959; Karlstrom, 1964; Cederstrom, Trainer, and Waller, 1964), they will be described but briefly here. They consist chiefly of three categories of material: glacial till, deposited as ground moraine; proglacial silty clays (including the Bootlegger Cove Clay) deposited in estuarine-marine or lacustrine-estuarine environments; and fluvioglacial deposits of several types, but chiefly outwash sand and gravel.

Most of Anchorage lies on late glacial (Naptowne-Wisconsin) outwash deposited in front of the youngest Pleistocene glacier that entered the area. This glacier constructed a large end moraine north of the city at Elmendorf Air Force Base (Miller and Dobrovolny, 1959, p. 59). Remnants of the moraine are also preserved west of Knik Arm about 2½ to 3 miles northeast of Point MacKenzie. Outwash sand and gravel from this glacier spread southward across the Anchorage Lowland and buried ground moraine and Bootlegger Cove Clay alike to depths as great as 60 feet. In general, the outwash thins toward the west and south away from its source. It wedges out completely between Turnagain Heights and Point Woronzof.

East of Anchorage along the foot of the Chugach Mountains, a massive lateral moraine was deposited by one or more of the pre-Wisconsin glaciers that occupied the area (Miller and Dobrovolny, 1959, p. 21). This moraine stands generally 1,000 to 1,200 feet above sea level and has a maximum altitude of about 1,400 feet. Because the area commands impressive views across Cook Inlet toward the snow-swept Alaska Range and Mount McKinley, it has experienced a mild real estate boom, and the next few years should see extensive urbanization of its heights. The moraine fared well in the March 27 earthquake; structures built on it were little, if at all, disturbed.

## BOOTLEGGER COVE CLAY

The Bootlegger Cove Clay has become renowned, since the March 27 earthquake, for its part in the devastation. Most of the severe damage in the Anchorage area is traceable to failure within this formation, and an understanding of the mechanisms of landsliding in the Anchorage area requires some knowledge of its character and physical properties. Because of its critical relationship to the landsliding, it has been studied intensively since the earthquake, by the Corps of Engineers and by consultants to the corps.

The Bootlegger Cove Clay was named and first described by Miller and Dobrovolny (1959, p. 35–48). In general the formation consists of three physically distinct but gradational zones—an upper and a lower stiff competent zone and a central weak sensitive zone. Failures occurred chiefly in the central zone. Waves generated by the earthquake led to a drastic loss of strength, a consequent failure of dynamically sensitive saturated sand, silt, and silty clay, and a resultant disruption of the ground surface by landsliding (Shannon and Wilson, Inc., 1964, p. 1–3).

The Bootlegger Cove Clay underlies most of Anchorage and much of the adjacent area (Miller and Dobrovolny, 1959, pls. 3 and 6; Trainer and Waller, 1965). Along Knik Arm, it is exposed almost continuously from a point about three-quarters of a mile east of Point Woronzof northward at least to the Eagle River. Just north of Anchorage, it passes beneath the Elmendorf Moraine. Toward the east and southeast, it laps across older glacial deposits and thins out against higher ground in the morainal belt at the base of the Chugach Mountains. South of Anchorage, it is continuous beneath a cover of sand and muskeg west from the Seward-Anchorage Highway to the east base of the Point Woronzof-Point Campbell highland area and south to Turnagain Arm. It laps up and thins out against the deltal sand and gravel of the Point

Woronzof-Point Campbell highland area.

As described by Miller and Dobrovolny (1959, p. 39), the Bootlegger Cove Clay consists chiefly of silty clay, light gray (N7)[1] when dry and dark greenish gray (5GY 4/1) when wet. Very commonly the upper several inches to several feet immediately beneath the overlying outwash is oxidized to yellowish gray. The clay generally is delicately laminated in layers a fraction of a millimeter to several centimeters thick, although some intervals several feet thick are free of visible bedding. Throughout the clay are scattered layers of sand, some mere partings but others 25 feet or more thick. Such layers are lenticular and can only be traced short distances. In at least one landslide (Fourth Avenue), liquefaction of a sand layer is believed to have been the chief immediate cause of failure (Shannon and Wilson, Inc., 1964, p. 41).

Scattered pebbles are present throughout the Bootlegger Cove Clay. Cobbles and boulders are present also but are rare. These stones contributed nothing to the failure of the clay and had no part in the landsliding, but they do indicate the periglacial environment in which the clay was deposited. Only ice rafting could have emplaced the larger boulders. Pebbles are most numerous in the lower part of the formation. On the west side of Knik Arm opposite Cairn Point, where the base of the formation is above tide water, the clay grades downward into stony till, seemingly without a clear-cut contact.

[1] Numerical designations refer to the Rock-Color Chart number (Goddard and others, 1948).

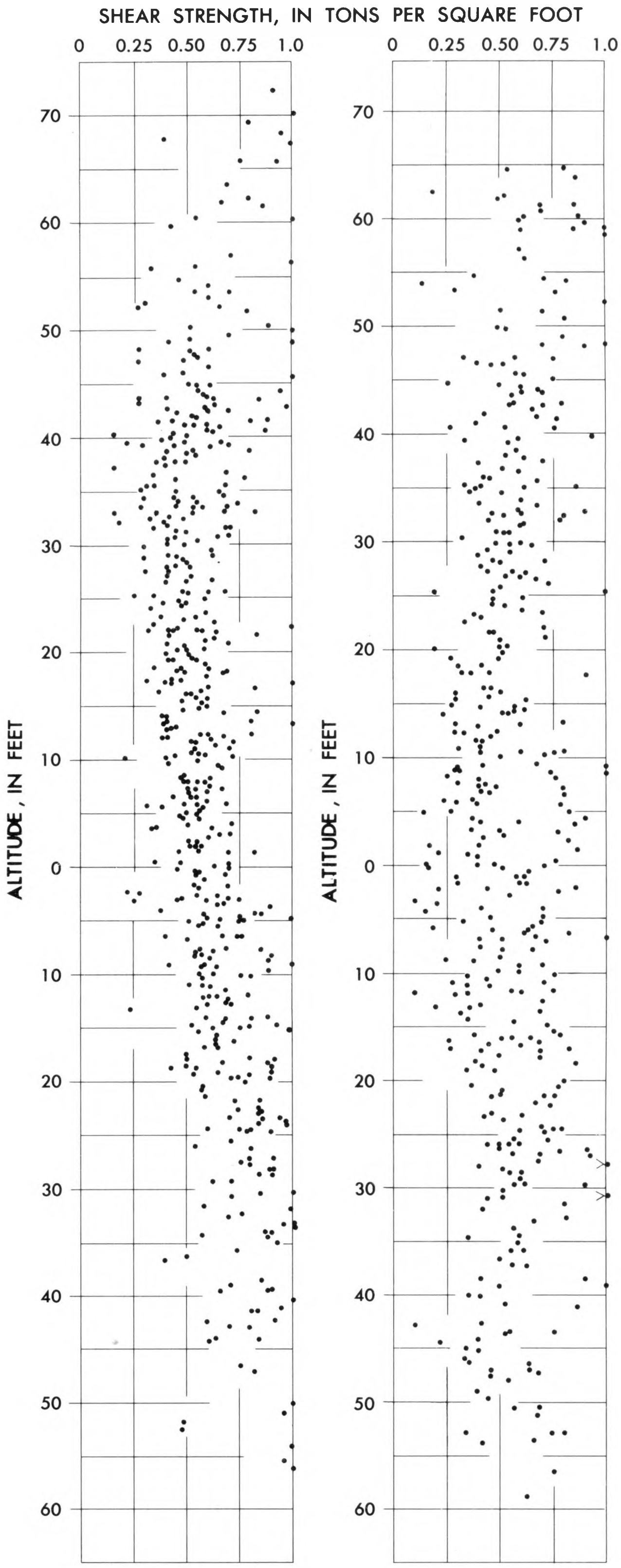
## PHYSICAL PROPERTIES

Soon after the earthquake, work started by the Engineering Geology Evaluation Group (1964) and later taken over by the U.S. Army Corps of Engineers (Shannon and Wilson, Inc., 1964) showed that the physical properties of the Bootlegger Cove Clay are far from uniform. Rather, a medial zone of low static shear strength and high sensitivity grades upward and downward into stiffer nonsensitive zones. Sensitivity is defined as the ratio of undisturbed shear strength of a soil sample to remolded (kneaded or squeezed) shear strength of the same sample, regardless of the cause (Terzaghi and Peck, 1948, p. 33).

Numerous physical tests by the Corps of Engineers—both in the field and in the laboratory—were made to analyze the causes of failure in the Bootlegger Cove Clay and find possible remedies. These tests are described in detail by Shannon and Wilson, Inc. (1964, p. 13–30); most of the information in the following paragraphs was abstracted from their report. About 150 borings were drilled within and adjacent to the several landslide areas, either into or through the sensitive zone of the Bootlegger Cove Clay. Most borings were sampled at 5-foot intervals, and continuous samples were obtained at selected locations. Undisturbed samples were collected in 3- by 36- or 3- by 37-inch steel Shelby tubes. Five large-diameter "bucket auger" holes were drilled by the Corps for visual inspection of critical zones in the clay, for in-place shear-strength tests, and for carving out undisturbed samples by hand. Vane-shear tests in standard 3-inch holes were made at 12 locations in the Fourth Avenue, L Street, and Turnagain Heights slide areas to measure in-place strengths and sensitivities of the clay. Similar tests were made on undisturbed samples both in the field and in the laboratory. In the laboratory, samples were also analyzed for Atterberg limits (see p. A14), natural-water content, triaxial shear, sensitivity, dynamic modulus, and consolidation strength.

### SHEAR STRENGTH

Shear strength was measured in torsional-vane-shear tests, undrained triaxial tests, consolidated-undrained triaxial tests, and consolidated-drained triaxial tests; strain, stress, volume change, and pore-water pressure were recorded throughout the tests (Shannon and Wilson, Inc., 1964, p. 28). The results of vane-shear tests for the Fourth Avenue and Turnagain Heights slide areas are shown in figure 8. Triaxial tests performed on the clay generally correlated well with the vane-shear tests within the ranges of strengths at which failure was prevalent. Tests correlated well in the range 0.4 to 0.5 tsf (tons per square foot), but for clays of higher strength, the triaxial tests generally yielded somewhat higher values than the vane tests. Most of the samples of clay from critical depths in the landslides had initial shear strengths between 0.2 and 0.7 tsf, and in this range the ratio of torsional-vane-shear-test results to triaxial-compression-test results is generally between 0.7 and 1.5 (Shannon and Wilson, Inc., 1964, p. B8). This ratio indicates a fairly good correlation between test methods. In any event, the vane-shear-test results shown by the graphs of figure 8 clearly demonstrate the generally lower shear strength of the clay at intermediate depths as compared with shallower and deeper layers.




8.—Summary of torsional-vane-shear strengths of selected borings, Bootlegger Cove Clay, from Fourth Avenue slide area (left) and Turnagain Heights slide area (right). Simplified from Shannon and Wilson, Inc. (1964, pl. B15).

Torsional-vane-shear apparatus was also used to measure the strength of the Bootlegger Cove Clay under sustained stress, because it was recognized that the duration of stress influences the resulting shear strength shown by the tested specimen (Shannon and Wilson, Inc., 1964, p. B7). At a given level (0.1 tsf), shear stress was applied for varying lengths of time. These tests showed that the Bootlegger Cove Clay loses shear strength as stress application is prolonged. In other words, the longer the stress is sustained, the lower the shear strengths.

## SENSITIVITY

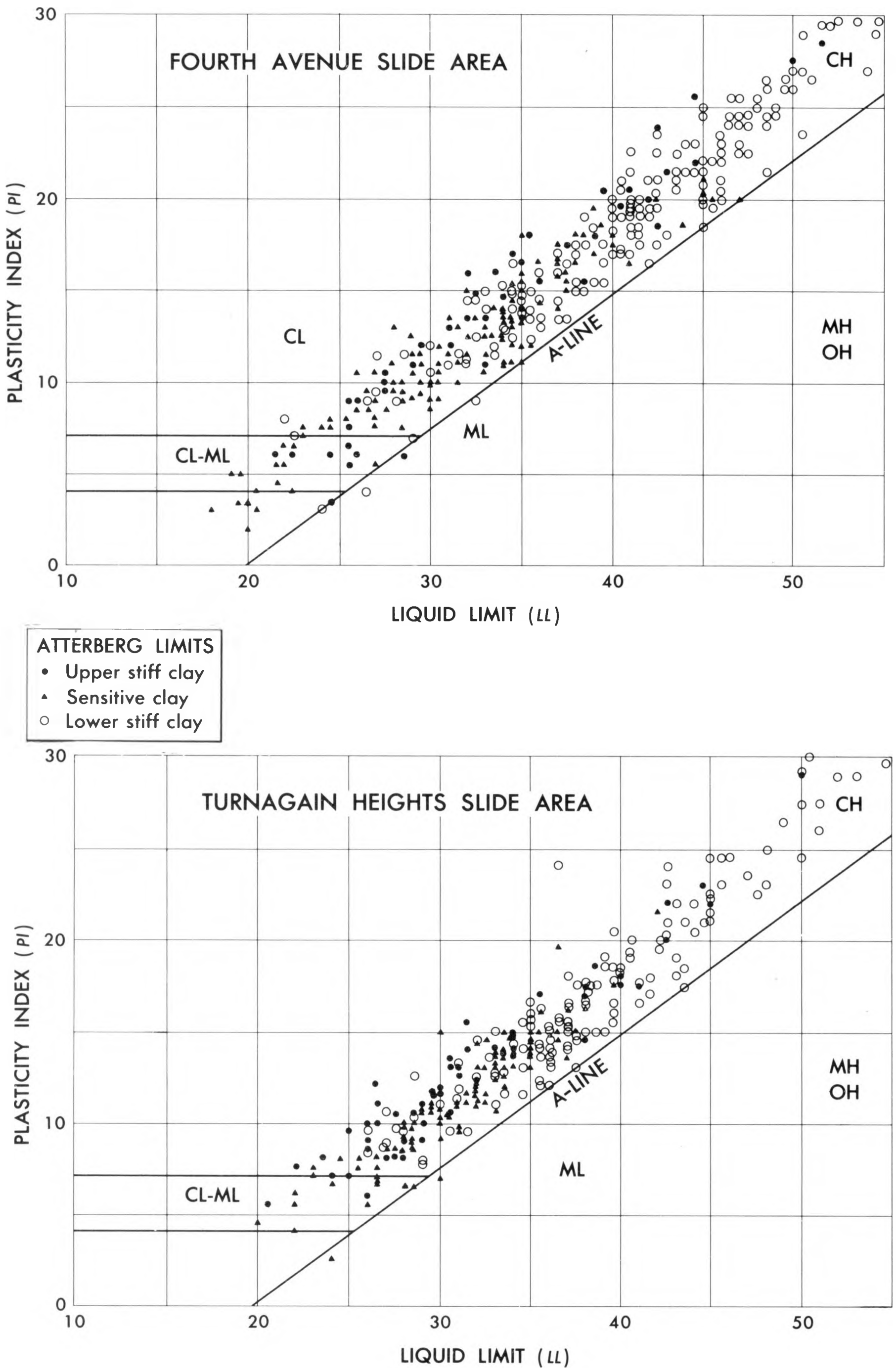
Sensitivity has previously been defined as the ratio of undisturbed shear strength to remolded shear strength. For example, a clay having an undisturbed shear strength of 0.4 tsf and a remolded shear strength of 0.02 tsf has a sensitivity of 20. Sensitivies were measured by the Corps of Engineers on about 2,100 selected samples of the Bootlegger Cove Clay by means of field and laboratory vane-shear devices (Shannon and Wilson, Inc., 1964, p. 27), and a record of sensitivities was plotted on the boring logs. Of the 2,100 samples tested, 302, or 14 percent, had sensitivities greater than 10; 125, or 6 percent, had sensitivities greater than 20; 40, or 1.9 percent, had sensitivities greater than 30; and 11, or 0.5 percent, had sensitivities greater than 40. The highest sensitivity measured was 60.

The sensitive zone generally ranges in thickness from about 20 to 30 feet, but it is as much as 40 feet thick in some places and is nonexistent in others. In most places the center of the sensitive zone is above sea level, generally 10 to 20 feet above, but in parts of the Turnagain Heights area it is below sea level. At no place has sensitive clay been observed higher than about 50 feet above sea level or lower than about 30 feet below sea level. Laboratory tests by the Corps indicate that the shear strength of the sensitive clay ranges from less than 0.15 to about 0.40 tsf, and the sensitivity ranges from about 25 to as high as 60. The maximum shear strengths of the stiffer clays exceed 1 tsf.

### ATTERBERG LIMITS

In a laboratory analysis of fine-grained cohesive soils, it is customary to perform tests that yield information on the plasticity of the soils. These tests include measurements of natural water content (*Wn*) liquid limit (*LL*) and plastic limit (*PL*). The liquid limit is the water content in percentage of dry weight at which the soil passes from the liquid state into the plastic state. Similarly, the plastic limit is the water content of the soil at the boundary between the plastic state and the solid state. These limits of consistency are defined by standardized test procedures and are known as the Atterberg limits (Terzaghi and Peck, 1948, p. 32–36). The numerical difference between the liquid limit and the plastic limit is called the plasticity index (*PI*). The plasticity index represents the range of moisture content within which the soil is plastic. Clayey soils thus have higher plasticity indices than nonclayey or silty soils because they remain plastic through a wider range of moisture content (Stokes and Varnes, 1955, p. 85, 110; U.S. Bureau of Reclamation, 1960, p. 8, 28).

The plasticity charts (fig. 9) show the statistical relationship of liquid limit to plasticity index of the Bootlegger Cove Clay in the Fourth Avenue and Turnagain Heights slide areas, as measured for the Corps of Engineers by

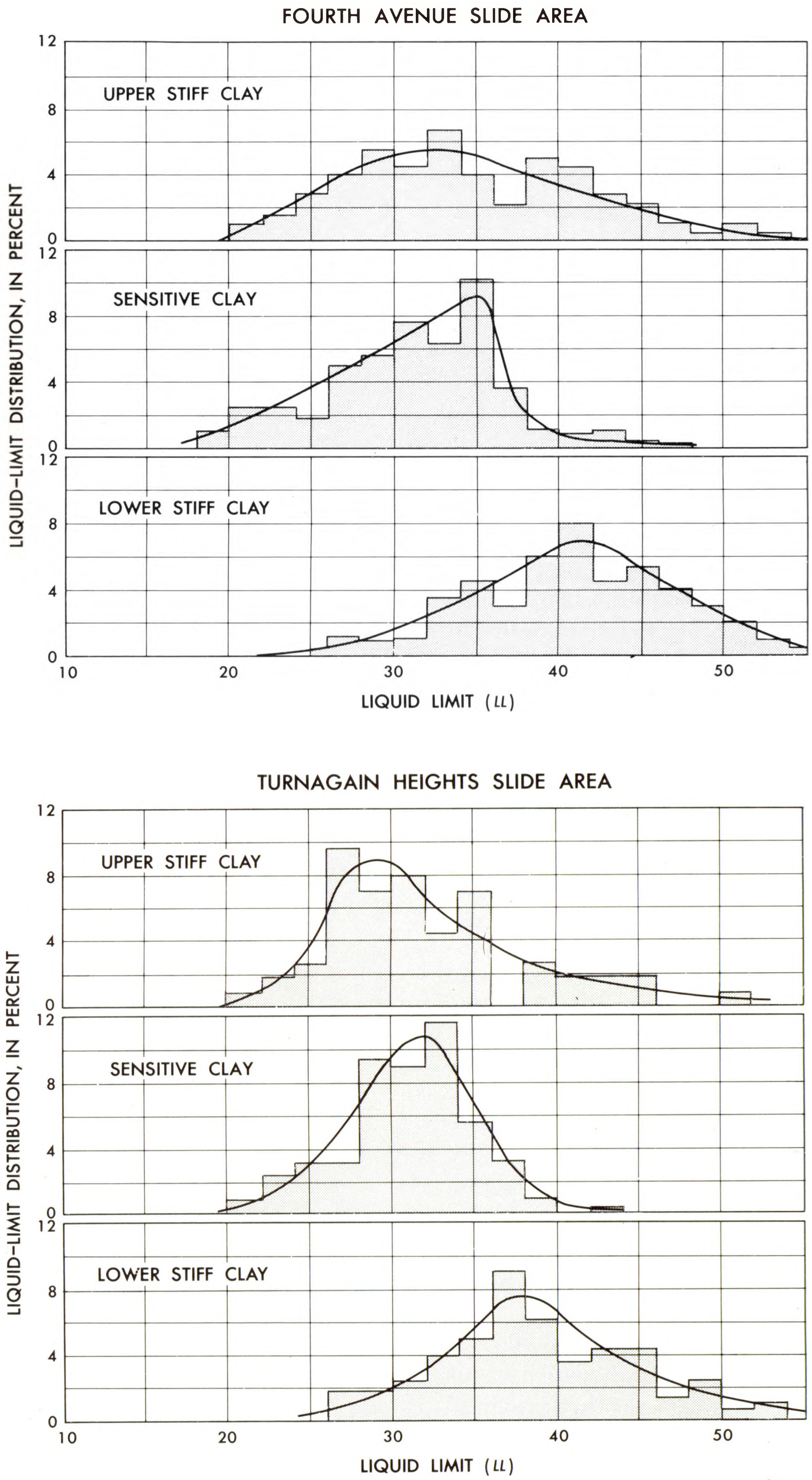



9.—Plasticity charts from selected borings, Bootlegger Cove Clay, Fourth Avenue and Turnagain Heights slide area. Reprinted from Shannon and Wilson, Inc. (1964, pl. B16). CL, inorganic clay of low to medium plasticity; ML, inorganic silts and very fine sand; CH, inorganic clay of high plasticity; MH, inorganic silt; OH, organic clay.

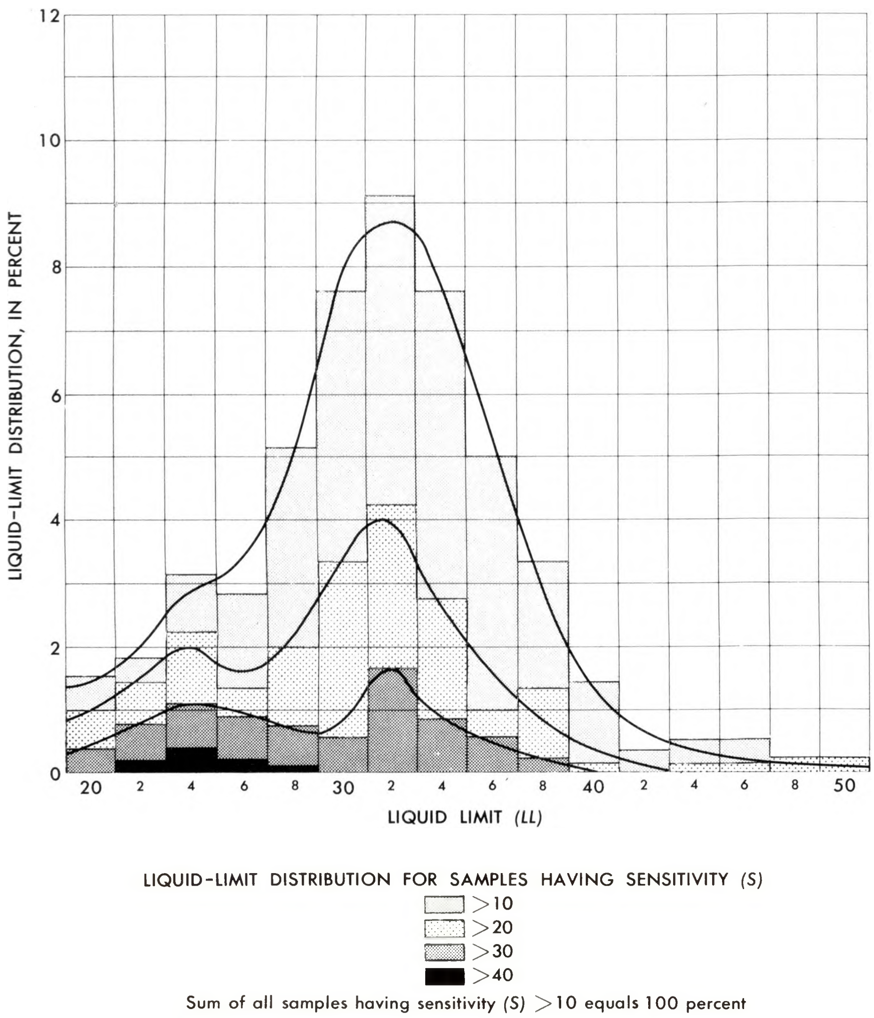
Shannon and Wilson, Inc. (1964). These charts show generally higher plasticity indices and liquid limits for the lower stiff clay than for the upper stiff clay or the sensitive clay. Differences between the upper stiff clay and the sensitive clay are not obvious on these charts, but they are quite apparent on statistical liquid-limit distribution curves (fig. 10). Nearly all points plotted on the plasticity charts lie above the "A" line—the line which separates soils of high cohesion and low permeability above from soils of low cohesion and high permeability below (Casagrande, 1947, p. 801).

The statistical liquid-limit distribution curves (fig. 10) show the distinctions between the three zones of the Bootlegger Cove Clay in the Fourth Avenue and Turnagain Heights areas. These curves bring out the differences between the upper stiff zone and the sensitive zone, and also the higher liquid limit of the lower stiff zone. The statistical relationship of sensitivity to liquid limit is shown by figure 11. In general, about 80 percent of the soil samples tested had liquid limits within the range of 22 to 48 percent, regardless of their vertical position in the formation. About 80 percent of the liquid limits of the sensitive clay range from 22 to 38 percent, and about 80 percent from the lower stiff clay range from 32 to 50 percent. As sensitivity increases, the upper limit of the liquid limit decreases. Most clay samples of sensitivities greater than 10 had liquid limits in the range of 20 to 40 percent, and no sensitive-clay sample had a liquid limit above 45 percent. For sensitivities greater than 40, the range of liquid limits was only 22 to 28 percent (Shannon and Wilson, Inc., 1964, p. B11). Several samples analyzed had a natural-water content greater than their liquid limits.

To relate the limit values of a soil to its natural-water content, the water-plasticity ratio, or liquidity index, is sometimes used (Casagrande and Fadum, 1944, p. 341). This ratio is equal to the natural-water content of the soil minus the plastic limit divided by




10.—Statistical liquid-limit distribution curves from selected borings, Bootlegger Cove Clay. Reprinted from Shannon and Wilson, Inc. (1964, pl. B16).




11.—Liquid-limit sensitivity distribution curves, Bootlegger Cove Clay. Reprinted from Shannon and Wilson, Inc. (1965, pl. B17).

the liquid limit minus the plastic limit; that is $(Wn-PL)/(LL-PL)$. For the Bootlegger Cove Clay, it was found that in most soils having a water-plasticity ratio greater than 1.0 the liquid limit ranged from 20 to 40 percent, and in soils having a water-plasticity ratio greater than 2.0 the liquid limit lay in the range 19 to 27 percent. A direct correlation also was found between sensitivity and the water-plasticity ratio (Shannon and Wilson, Inc., 1964, p. B11, pl. B17; see fig. 12, next page). Thus in the Bootlegger Cove Clay a high water-plasticity ratio is related to low shear strength, high sensitivity, and high susceptibility to failure.

### VIBRATION TESTS

Representative samples of sand and clay from the various slides were subjected to vibration tests from which the dynamic Young's modulus and the dynamic shear modulus of elasticity could be computed. These tests were designed to simulate in part the vibratory effects of the earthquake on the sand and clay. The vibration apparatus, developed by Shannon and Wilson, Inc. (1964, p. E3), subjected a cylindrical specimen to a sinusoidal vibration in a longitudinal or torsional mode in such a way that the frequency corresponded to a state of resonance. Both longitudinal and torsional resonance frequencies increased as straight-line functions of increased confining pressure.

The shear modulus of the sands was found to be dependent on the confining pressure. The shear modulus of the stiff clay was about 5,000 psi (pounds per square inch), and that of the soft sensitive clay was about 1,500 psi (Shannon and Wilson, Inc., 1964, p. 28). In nearly all tests, the value of the shear modulus and of Young's modulus increased as straight-line functions of increased confining pressure.

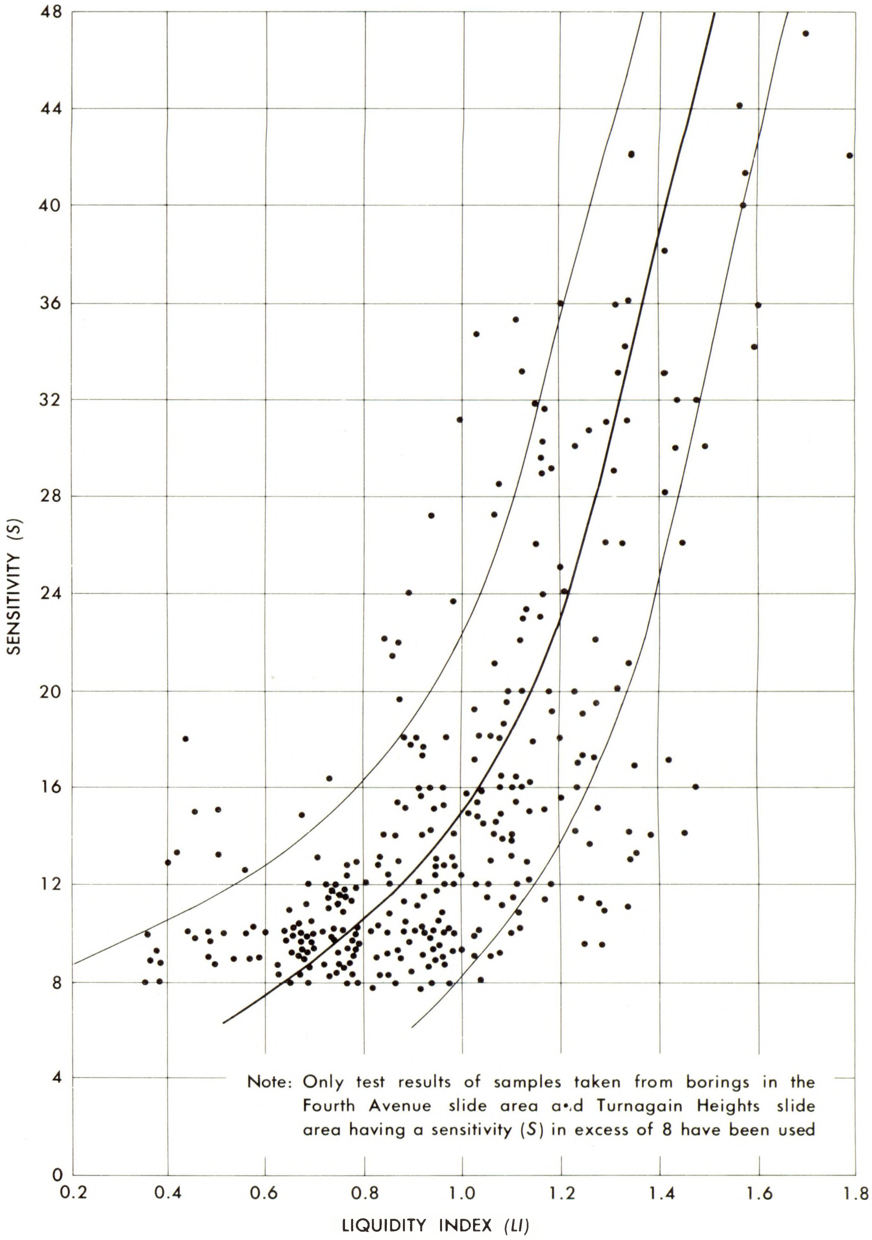
### PULSATING-LOAD TESTS

Pulsating-load tests on saturated fine silty sand and on undisturbed samples of silty clay and clayey silt were run for the Corps of Engineers by H. B. Seed and K. L. Lee of the University of California at Berkeley (*in* Shannon and Wilson, Inc., 1964). These tests demonstrated the susceptibility of the Bootlegger Cove Clay and associated sands to loss of strength under pulsating-load conditions such as would be induced by an earthquake. In other words, the shear strength of the samples was markedly less under pulsating-load conditions (simulating an earthquake), than under static load.

Seed's apparatus was so designed that applied deviator (axial) stress could be increased and decreased in one direction or could be changed from vertical to horizontal during each stress cycle, and thus the direction of shear stress in the specimen could be reversed. The latter test is called a "stress-reversing test."

Because it is not feasible to collect undisturbed sand samples, sand specimens were artificially deposited in water in the laboratory under conditions that simulated natural sedimentation. The sand was then subjected to pressures comparable to the in-place overburden pressures of the natural environment, about 1.8 kg per cm². Under stress-reversing conditions, sand specimens showed negligible strains, but they did show progressive increases in pore-water pressures with increasing numbers of stress cycles. Failure abruptly followed a sudden increase in pore-water pressure equal in magnitude to the applied confining pressure, accompanied by large strains and complete liquefaction. Liquefaction followed 50 cycles of pulsating deviator stress of about 0.5 kg per cm² applied at a frequency of about 2 cycles per second. This stress level is only about 10 percent of the strength of an identical specimen tested under static-loading conditions.

Clay samples were found to fail at levels of pulsating deviator stress substantially lower than the undrained compressive strength. Undrained compressive strengths of the specimens tested ranged from about 0.4 to 1.8 kg per cm², and sensitivities ranged from about 15 to 60. Moreover, under stress-reversing conditions, the level of failure was substantially lower than under non-stress-reversing conditions. Thus, under a non-stress-reversing pulsating load at a frequency of 2 cycles per second, failure generally followed 50 cycles of maximum stress of 80 to 100 percent of the static undrained strength, after a gradual buildup of strain, whereas under stress-reversing conditions, failure occurred abruptly without prior significant strain after a maximum stress of only about 55 percent of the static undrained strength. The natural vibration of an earthquake, according to Seed, probably has a pulse form somewhere between the two types used in these laboratory tests. It is concluded, therefore, that under earthquake conditions, failure would occur at a stress level below the static undrained strength of the clay, that is, somewhere between the limits indicated by the two types of pulsating stress applied in the laboratory.




12.—Relation between sensitivity and liquidity index (water-plasticity ratio), Bootlegger Cove Clay. Reprinted from Shannon and Wilson, Inc. (1964, pl. B17).

### SPECIFIC GRAVITY

Specific gravity was measured by Shannon and Wilson, Inc. (1964, p. B11–B12) on 26 test specimens from various depths at seven different slide areas. Of the specimens tested, 1 had a specific gravity of 2.67, but the other 25 ranged from 2.71 to 2.82, the average being 2.78. No correlation between specific gravity and shear strength or sensitivity was apparent.

## PHYSICO-CHEMICAL TESTS

Physico-chemical analyses of six samples were made for the Corps of Engineers by J. K. Mitchell (*in* Shannon and Wilson, Inc., 1964, p. I3). Four of the samples—two from Turnagain Heights and two from the Fourth Avenue area—were cuts from core intervals that also were analyzed mineralogically. The other two samples came from the L Street slide. Each sample was tested for pH, salt content, conductivity, and base-exchange capacity. Values of pH ranged from 8.2 to 10.3. These relatively high base values, according to Mitchell, are "consistent with high sensitivity because of the tendency of a high pH to promote dispersion of remolded samples" (*in* Shannon and Wilson, Inc., 1964, p. I3).

The salt content of the samples, expressed in terms of equivalent NaCl, ranged from 1.03 grams per liter to somewhat less than 6 grams per liter. "By way of comparison," Mitchell points out, "the salt content of sea water is about 34 grams per liter. Thus if the Anchorage clays are of marine origin then the results of these tests would suggest that they have been leached of salt since their original deposition. Such leaching could be important in generating a high sensitivity and stable suspensions after remolding." In support of this view, a marine depositional environment of near normal salinity, at sample depths spanning the zone of landslide failure, is indicated by the microfaunal assemblages in the clay (Patsy J. Smith, written commun., 1964). The paleontology of the clay is discussed on page A20.

In measuring electrical conductivity, Mitchell (*in* Shannon and Wilson, Inc., 1964, p. I4) found that remolded clay had consistently greater conductivity at all frequencies than undisturbed clay. Remolded clay generally also had a greater variation in conductivity as frequency was varied. Mitchell attributed these differences to greater dispersion (parallelism of clay particles) and smaller average effective particle size in the remolded samples.

Base-exchange capacities of the six samples studied by Mitchell ranged from 4.6 to 10.9 milliequivalents per 100 g of dry clay. Of the three cations determined—sodium, calcium, and magnesium—Mitchell found that calcium was the most abundant in solution in all but one sample. Sodium was next and magnesium was least abundant. This ratio also suggests that authigenic brine was leached from the clay by the action of ground water; hence that leaching may have been a cause of the sensitivity.

## MINERALOGY

Not much mineralogic work has been done on the Bootlegger Cove Clay. Seven samples collected by Miller and Dobrovolny (1959, p. 42–43) from four localities and from seven different parts of the section were analyzed by X-ray diffraction in two fractions each—clay ($<2\mu$) and silt (2 to $74\mu$). Both fractions of each sample contained quartz, feldspar, mica, and chlorite as the chief constituents. Some contained montmorillonite, mixed layered chlorite-montmorillonite, or mixed layered chlorite-montmorillonite-hornblende (Miller and Dobrovolny, 1959, p. 42). Quartz predominated in most silt fractions, followed by feldspar, but it was subordinate in the clay fractions, in which chlorite predominated. These seven samples resembled, in composition and general proportions of minerals, samples of other silty clay collected from lake, estuarine, and till deposits of the same general vicinity but of different ages. Their compositions, therefore, probably reflect parent material more than diagenesis.

A single clay sample collected at Turnagain Heights after the earthquake was found to contain chlorite, illite, quartz, and feldspar in its clay fraction (Grantz, Plafker, and Kachadoorian, 1964, p. 26). Its composition by size was 25 percent clay, 61 percent silt, and 14 percent fine sand.

Samples of Bootlegger Cove Clay from four drill holes, two from the Fourth Avenue area and two from Turnagain Heights, were analyzed by X-ray, differential thermal, thermogravimetric, and petrographic means by T. S. Shevlin for the Corps of Engineers (Shannon and Wilson, Inc., 1964, p. H3). Two of the samples were sensitive; two were stiff. Shevlin found that quartz predominated in all samples; its peak intensities (X-ray) were greater than any other mineral in all size fractions analyzed. Feldspar was present in finely divided form in all samples, and kaolinite, illite, and chlorite were also present. One of the stiff samples was gritty and much siltier than the others, but there was no consistent variation either in size or mineral content between the sensitive and the stiff samples. Shevlin's table 1 is reproduced in part at top of page 20 to show the distribution of particle sizes.

| Sample [1] | Depth (feet) | Classification | Percent finer than particle size (microns) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 38 | 10 | 8 | 4 | 2 | 1 |
| A117AX | 77.6–78.3 | Sensitive | 99.6 | 81.5 | 78.9 | 64.7 | 49.0 | 36.0 |
| A117AX | 124.5–125.2 | Stiff | 96.9 | 96.7 | 92.2 | 73.4 | 52.7 | 38.5 |
| C108B | 73.2–73.9 | Sensitive | 96.8 | 64.0 | 60.3 | 46.6 | 33.3 | 24.4 |
| C117 | 116.7–117.4 | Stiff | 81.8 | 26.7 | 22.3 | 12.9 | 8.1 | 5.5 |

[1] Samples prefixed with A are from Fourth Avenue area; samples prefixed with C are from Turnagain Heights

## DEPOSITIONAL ENVIRONMENT

Recent paleontologic studies by Patsy J. Smith (written commun., 1964) indicate that the Bootlegger Cove Clay is of marine origin throughout but that it was deposited in environments of variable salinity. The depositional environment bears on the origin and distribution of sensitivity in the clay. Clay deposited in saline waters tends to flocculate. Flocculation occurs when negative particle surfaces are attracted to positive particle edges by electrostatic forces (Lambe, 1958, p. 8; Rosenqvist, 1962, pl. 5; Meade, 1964, p. B4–B5); flocculated clay in turn acquires sensitivity when the interparticle bond is destroyed, as when ground water leaches the cation and thereby diminishes the electrolyte concentration (Mitchell, 1956, p. 693). Such leaching is promoted when marine clay beds are elevated above sea level. According to Bjerrum (1954, p. 49; 1955, p. 108), the reduced electrolyte concentration, by decreasing the activity of the clay minerals, leads to a lowering of the Atterberg limits, which in turn reduces the shear strength of the clay by as much as 30 percent.

Until recently the depositional environment of the Bootlegger Cove Clay was in serious doubt, if not dispute (Miller and Dobrovolny, 1959, p. 44; Schmidt, 1963, p. 350; Karlstrom, 1964, p. 35; Cederstrom, Trainer, and Waller, 1964, p. 30). A brief review of past thinking, therefore, seems warranted. The environment has been considered to have been lacustrine, estuarine, or marine, or some combination thereof. Marine organisms had been noted in the Bootlegger Cove Clay by several investigators, although some doubt had existed as to whether the specimens noted were in place or had been cast ashore by storm waves (Miller and Dobrovolny, 1959, p. 45). Trainer (*in* Miller and Dobrovolny, 1959, p. 45) found estuarine mollusks that he was convinced were in place. Schmidt (1963, p. 350) verified Trainer's find and added an abundant microfauna in confirmation. Miller and Dobrovolny (1959, p. 46) reasoned that varvelike beds and laminations high in the clay near Cairn Point indicated probable fresh-water deposition, a view subsequently shared by Cederstrom, Trainer, and Waller (1964, p. 32) but on slightly different evidence—the presence of well-sorted interbedded sands. Karlstrom (1964, p. 38) expressed the opinion that "the Bootlegger Cove Clay records proglacial-lake sedimentation * * * with an intervening interval of marine deposition"—in other words, fresh-water deposits separated by salt-water deposits.

Smith's conclusions (written commun., 1964) are based on studies of microfossils from drill samples collected by the Corps of Engineers. These continuously cored samples afforded a chance not provided by surface exposures to examine the depositional environment of the clay from the top of the formation down through and below the sensitive zone. Smith concluded that the formation was marine throughout the interval studied but that the upper part was deposited in a deltaic environment of low variable salinity such as now exists in the Yukon and Kiskokwim deltas. Fossils from the lower part of the formation, including the sensitive zone, indicated a shallow (25± meters) marine environment probably of near-normal salinity. Vertical variations in the depositional environment, as indicated by fossils, thus may provide an explanation for the zonal character of the sensitivity: the stiffer clays accumulated in water of low salinity and the more sensitive clays accumulated in waters of near-normal salinity. Since deposition, reduction of the brine concentration by leaching probably has altered the plasticity of the clay and increased the sensitivity.

Fossils identified by Smith, and their relative abundance, are shown in tables 1 and 2.

TABLE 1.—*Foraminifera from Bootlegger Cove Clay, Anchorage, Alaska, Shannon and Wilson, Inc. (1964) boring A120 A*

[Abundances estimated: A, abundant; C, common; F, few; R, rare]

| Species | Sample interval (feet) | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 29.9–32.0 | 34.9–37.0 | 39.7–42.0 | 44.7–46.0 | 54.7–56.5 | 64.0–66.5 | 69.0–71.5 | 71.5–74.0 | 79.0–81.5 | 80.0–86.5 | 89.9–90.5 | 92.3–93.9 | 96.4–98.9 | 101.6–103.8 | 106.3–108.8 | 115.9–118.4 | 120.9–122.5 | 125.0–127.5 | 130.0–132.5 | 136.8–137.9 | 137.5–142.0 | 142.2–144.3 |
| *Protelphidium* cf. *orbiculare* (Brady) | F | F | | F | R | F | R | R | A | | F | F | R | C | A | A | F | F | F | | C | F |
| *Elphidium clavatum* Cushman | | | | | | F | | | | | | | R | | F | | | | | | | |
| *frigidum* Cushman | | | | R | | | | | | | | | | | | | | | | | | |
| *bartletti* Cushman | | | | | | | | | | | | | | F | | F | | | | | | |
| *Pateoris hauerinoides* Loeblich and Tappan | | | | | | | | | | | | | | F | F | R | | | | | | |
| *Polymorphina* sp | | | | | | | | | R | | | | | | F | | | R | | | | |
| *Fissurina* sp | R | | | | | | | | | | | | | R | R | | | | | | | |
| *Buliminella curta* Cushman | | | | | | | | | | | | | | | | | | | R | | | |
| Ostracodes | | | | | | | | R | R | | | F | | | A | R | | | | | | |

TABLE 2.—*Foraminifera from Bootlegger Cove Clay, Anchorage, Alaska, Shannon and Wilson, Inc. (1964) borings A 110 A and B*

[Abundances estimated: AA, very abundant; A, abundant; C, common; F, few; R, rare]

| Species | Sample interval (feet) and boring letter | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 27–38 (B) | 28–28.7 (B) | 28.7–29.5 (B) | 29.1–30 (B) | 30–30.9 (B) | 30.9–31.8 (B) | 32–32.8 (B) | 32.8–33.6 (B) | 33.6–34.4 (B) | 38.3–39 (A) | 44.6–45.5 (A) | 45.5–46.5 (A) | 48.5–49.5 (A) | 49.5–50.5 (A) | 50.5–51.5 (A) | 51.5–52.5 (A) | 53.3–54.5 (A) | 54.3–55.5 (B) | 54.9–56 (A) |
| *Protelphidium* cf. *orbiculare* (Brady) | R | | | R | F | R | AA | C | C | AA | B | AA | A | A | A | A | A | A | A |
| *orbiculare* (Brady) | | | | | | | | | | | | | | F | C | | | | |
| *Elphidium clavatum* Cushman | | | F | F | | R | | | | | | | | | | | | | |
| *subarcticum* Cushman | | | | | | | | | | C | | | | | | | | | |
| *bartletti* Cushman | | | | | | | | | | | | | F | | F | C | C | C | C |
| *incertum* (Williamson) | | | | | | | | | | | | | | | | R | | | |
| *Elphidiella groenlandica* (Cushman) | | | | | | | | R | | C | | F | F | C | | | | | |
| *Quinqueloculina* cf. *seminula* (Linné) | | | | | | R | | | | | | | C | C | C | | | | |
| *Pateoris hauerinoides* Loeblich and Tappan | | | | | | | | | | C | | | | C | C | C | C | F | C |
| *Polymorphina* sp | | | | | | | | | | F | | | C | C | | F | R | R | F |
| *Fissurina* sp | | | | R | | | R | | | | R | R | R | F | F | A | C | F | F |
| *Dentalina* sp | | | | | | | | | | | | | | R | F | F | | R | R |
| *Cassidulina islandica* Nørvang | | | R | | | | | | | R | | | | | | | | | |
| *Buliminella curta* Cushman | | | | | | | | | | R | | R | | | | | | | |
| *Bolivina pseudopunctata* Höglund | | | | | | | | | | | | R | | | | R | | | |
| *Buccella frigida* (Cushman) | | | | R | | | | | | | | R | | | | | | | |
| *inusitata* Anderson | | | | | | | | R | | | | | | | | C | | R | |
| *Rosalina* sp | | | | | | | | | | | | | | | | R | | | |
| *Globigerina bulloides* d'Orbigny | | | | R | | | | | | | | R | | | | | | | |
| *pachyderma* (Ehrenberg) | | | | | | | | | R | | | F | | | | R | R | | |
| Ostracodes | R | R | R | | R | R | C | F | | F | | | C | C | C | C | C | C | C |
| Mollusk fragments | | | | | | | | | | | | | R | | | | | | |

# EARTHQUAKE EFFECTS

## DIRECT SEISMIC EFFECTS

Most of the more spectacular structural damage in the Anchorage area resulted from secondary causes such as landslides and ground cracks, themselves triggered by seismic vibration. Structural damage due directly to seismic vibration was subordinate in terms of total property damage and financial loss and, for the most part, was relatively unspectacular. Nevertheless, the extent of such effects must not be underestimated. The cumulative damage was impressive, and had there been no landslides at Anchorage, vibratory effects of the earthquake undoubtedly would have received more attention by investigators and by the press.

Vibratory damage to buildings and other structures is not strictly a geologic effect, but the extent and amplitude of vibration is dependent partly on geologic factors such as foundation and subfoundation conditions. Other things being equal, vibration is more intense and damage is greater in areas of thick unconsolidated deposits than in areas of bedrock. Examples of this rule are too numerous and too widely recognized to need documentation. All the severe vibratory damage in the Anchorage Lowland was in areas underlain at some depth by Bootlegger Cove Clay. Design and construction practices, on the other hand, are critical nongeologic factors that influence building performance and vibratory damage. As pointed out by Berg and Stratta (1964, p. 58), structural weaknesses are quickly ferreted out by earthquakes.

Inasmuch as this report emphasizes primarily the geologic effects of the March 27 earthquake in the Anchorage area, only the highlights of the vibratory effects are summarized here. Detailed analyses of structural response to vibratory stress have been presented by several authors (Berg and Stratta, 1964; McMinn, 1964; National Board of Fire Underwriters and Pacific Fire Rating Bureau, 1964; Steinbrugge, 1964), and the following summary is based largely on their findings.

The distribution and character of direct seismic damage were unusual to say the least. Probably few buildings in the Anchorage area were totally undamaged, but many blocks of homes and small commercial buildings received cursory damage at most and sustained virtually no damage to structural members, frameworks, or foundations. Many chimneys toppled, and quite a few fireplaces separated from adjoining exterior walls. Indoors, plaster cracked and objects were thrown to the floors of many homes. On many buildings however, fragile decorative facings, pillars, and cornices were unscathed. Church steeples remained standing. Headstones in cemeteries—long used as indicators of earthquake intensity—stood untoppled throughout the area. Large elevated well-guyed water tanks were undamaged (fig. 6), although trees whiplashing back and forth touched the ground on either side according to eyewitnesses. On the other hand, multistory buildings and buildings having large floor areas commonly sustained significant structural damage; several such buildings were total losses (figs. 5 and 13), and many required major repairs.

Thus, direct seismic damage was highly selective. Aside from variations in design, construction practice, and workmanship, large buildings were more severely damaged than small ones. Inertia was a factor, of course; other things being equal, heavy structures are more susceptible to vibratory damage than light ones.

Steinbrugge (1964, p. 58–72) has described vibratory damage effects in the Anchorage area in terms of engineering seismology. He ascribed (p. 59) the selectivity of the effects to the great magnitude of the quake and the distance of Anchorage from the epicenter: "The ground motion at Anchorage did not appear to contain significant short period motion which has been commonly observed in epicentral regions of destructive shocks." He added (p. 71): "The earthquake damage in Anchorage was selective * * *. This damage pattern appears to be attributable to the distance that Anchorage was from the epicenter, with the longer period ground motion having a dominant effect at this distance." According to White (1965, p. 91), attenuation of sinusoidal seismic waves at low frequencies should vary as the square of the frequency. Where seismic vibrations have long periods and large amplitudes, distortion and strain are far more severe in large structures than in small ones. The reason for the selectivity of the March 27 earthquake at Anchorage is thus apparent. The prolonged duration of the shaking must also have heightened all other effects; as mentioned before, strong motion lasted 3 to 4 minutes, possibly longer.

In general, most buildings outside of landslide areas withstood well the effects of the earthquake. The low loss of life is, in some measure, a tribute to the structural soundness of most of the larger buildings but in part also is the result of the low susceptibility of smaller structures to the long-period vibrations that racked the area. All the high-rise structures in Anchorage (10 stories or more) sustained moderate to heavy damage without collapse or loss of life. Four structures of medium height—four to nine stories—collapsed or were damaged beyond repair. Several low buildings of less than four stories were totally destroyed, but most such structures were damaged little or not at all.

In the general downtown area, outside the Fourth Avenue and L Street slides, a 5-story department store (J. C. Penney Co.) was a total loss, 4 buildings 1 or 2 stories high were heavily damaged, 9 buildings 1 to 14 stories high sustained moderate damage, and about 22 buildings received light damage (National Board of Fire

Underwriters and Pacific Fire Rating Bureau, 1964, p. 26). In the same area, however, many single family dwellings, stores, and small commercial buildings were damaged little if at all. Steinbrugge (1964, p. 71) found no evidence to indicate that one construction material was superior to another, given comparable attention to design and construction.

A few buildings seem to have been designed without regard to earthquake stresses. The Hillside Apartments and various warehouses that collapsed were examples. In other buildings, inadequate connections between structural parts were the most common causes of failure; improperly welded joints, inadequate ties in reinforced-concrete members, and improperly spliced reinforcing rods all were loci of failure. Welded precast- and prestressed-concrete structural members seemed to be particularly susceptible to joint failure, although some buildings so framed were undamaged. In some buildings, construction joints were inadequately keyed. Poured nonmonolithic concrete joints were sites of shear failures, and some concrete appeared to be substandard. Most poured-in-place concrete structures, however, fared well. In some multistory buildings, provisions for vertical shear were inadequate to withstand a stress of the intensity generated by the March 27 earthquake (Berg and Stratta, 1964, p. 58).

Small wood-frame buildings outside areas of ground displacement were generally little damaged (Steinbrugge, 1964, p. 63–64). Unreinforced masonry walls and chimneys were usually intact, and most interior wooden stud walls sustained nothing more than minor nonstructural cracking. Foundations of poured concrete or hollow concrete block (some apparently unreinforced) generally were intact. Usually windows were unbroken, and objects remained on shelves indoors.

Of the many buildings damaged or destroyed by direct seismic vibration in Anchorage, several structures described briefly below are most significant for the damage or lack of damage they sustained, relative to design and construction practice. These structures, therefore, have received the most attention from investigators. The following synopsis is based mostly on the reports of Berg and Stratta, Steinbrugge, and the National Board of Fire Underwriters and Pacific Fire Rating Bureau.

#### ALASKA PSYCHIATRIC INSTITUTE

The three-story steel-framed Alaska Psychiatric Institute, southeast of the main part of Anchorage, is notable because it sustained so little damage. There were minor cracks in stair wells and broken pipe hangers and machinery mounts in the penthouse. The nearby new Providence Hospital and the Alaska Methodist University also were little damaged. Significantly, perhaps, these three buildings are outside the area underlain by Bootlegger Cove Clay.

#### THE ALASKA RAILROAD MARSHALLING YARDS

Several buildings in the Alaska Railroad marshalling yards were damaged. Warehouses collapsed and shops were slightly damaged. The steel-framed wheel-shop building partly collapsed and has since been torn down. Some buildings were in or near the toe area of the Fourth Avenue landslide and, hence, may have been subjected to ground displacements as well as to seismic vibration.

#### ALASKA SALES AND SERVICE BUILDING

The one-story Alaska Sales and Service Building on East Fifth Avenue at Medfra Street was under construction but was structurally almost complete at the time of the earthquake; it was a total loss. Collapse is attributed chiefly to failure of welded connections between T-shaped precast-concrete columns and roof beams, caused either by the breaking of welds or tearing out of bar inserts. The exterior precast-concrete walls of the building partly collapsed when the roof gave way.

#### ANCHORAGE INTERNATIONAL AIRPORT

The Anchorage International Airport control tower, a reinforced-concrete structure, collapsed to the ground (fig. 7), killing one occupant and injuring another and damaging the connecting walls of the adjacent terminal building. The terminal building was otherwise little damaged. At the airport post office building, a rear wall pulled away from the roof trusses and leaned outward; moderate nonstructural damage was sustained indoors.

#### ANCHORAGE WESTWARD HOTEL

The steel-framed Anchorage Westward Hotel complex is just west of the Fourth Avenue landslide area facing Third Avenue between E and F Streets and is within the area of peripheral cracking. Several cracks passed through the building foundations and first floors. Some cracks had vertical offsets. There was little visible damage to the flexible exterior metal skin of the 14-story tower, but there was significant structural damage (since repaired) to the more rigid interior structural elements. Reinforced-concrete columns were buckled, and reinforced-concrete shear walls were damaged. An interior east-west shear wall had failures above all door openings in every story. At the eight-story level there was shear-wall damage along a horizontal join between older and newer sections of the building. Considerable damage was caused by pounding between the 14-story tower and the adjacent 3- and 6-story wings.

### CORDOVA BUILDING

The Cordova Building is a six-story structure at the northeast corner of Sixth Avenue and Cordova Street. The damage was mostly light and was caused chiefly by an east-west movement of the building. This direction is parallel to the shorter dimension of the floor plan and also is the direction of greatest strength in the steel support columns (Berg and Stratta, 1964, p. 37). Damage was mainly in the first story. The southeast-corner support column failed below the second-floor beam, and the exterior reinforced-concrete curtain walls sheared at the top of the basement; the corner broke away at the first and second stories. The center column in the south wall buckled. The reinforced-concrete stair and elevator shaft sheared at the base of the first story. The penthouse collapsed. Repairs have since been completed.

### ELMENDORF AIR FORCE BASE

At Elmendorf Air Force Base the reinforced-concrete control tower was damaged by cracks extending from its base to a height of about 15 feet. A warehouse (No. 21–884) partly collapsed when roof-beam anchor bolts pulled away from poured-in-place concrete piers. The Elmendorf Field House was slightly damaged at the roof corners and at the junctions of the side walls with the steel frame. Elmendorf Hospital was damaged by X-shaped shear fractures in block-panel walls at the second- through the fifth-story levels, by interior failures at a few reinforced-concrete columns and at the elevator shaft, and by some movement between different sections of the building. Damage has since been repaired, reportedly at a cost of more than $1 million (R. M. Waller, written commun., 1965).

### FIFTH AVENUE CHRYSLER CENTER

The one-story Fifth Avenue Chrysler Center just north of Merrill Field was a total loss. It had a precast- and prestressed-concrete T-beam roof supported by concrete-block walls. The front of the building collapsed and the T-beam roof fell in on the showroom. The hollow-core concrete-block side walls failed at the rear corners of the building.

### FIRST FEDERAL SAVINGS AND LOAN BUILDING

The three-story First Federal Savings and Loan Building is located at the northwest corner of Fifth Avenue and C Street. Ground cracks opened parallel to its east and south walls evidently in back fill. Even though the east and south faces of the building are mainly glass, there was little glass breakage. The west and north walls and the brick panels in the east wall sheared horizontally through the second story. The building has been repaired.

### FOUR SEASONS APARTMENT BUILDING

The Four Seasons Apartment Building at West Ninth Avenue and M Street was a spectacular total loss (fig. 13). It was designed for year-round luxury living, but didn't survive its first season. The building was nearing completion at the time of the earthquake, but fortunately it was not yet occupied—it collapsed in a pile of rubble. It was a six-story lift-slab reinforced-concrete building with two central poured-in-place cores, one for a stairwell and one for an elevator. The floor slabs were torn loose from shear heads on the structural-steel columns and pulled away from keyways in the stairwell and elevator cores. Some dowels connecting the slabs to the cores broke; others were pulled free.

The collapse of the Four Seasons Apartment Building was witnessed from 1000 Tenth Avenue by Glen L. Faulkner, a consulting geologist, who reported (oral commun., 1964) that the building collapsed just before the end of the quake, after shaking violently for perhaps 2 to 3 minutes. Just before it fell, it seemed to start crumbling near the second-floor level in the area of its northeast corner. Then with a slight tilt northward it collapsed vertically in a great cloud of dust. The two central cores were left leaning sharply northward. The steel support columns fell to the north also, and the slab floors were stacked one on another like pancakes.

The effects of seismic vibration in areas of cracked ground cannot always be separated from the effects of ground displacement. The collapse of the Four Seasons Apartment Building (fig. 13), a case in point, has been attributed to seismic vibration. Perhaps vibration was the dominant factor in the building's failure. The building, however, was close to the L Street graben at West Ninth Avenue and M Street, and a large subsidiary fracture, trending about west-northwest, passed directly under the building. In the chaotic pile of rubble left after the

13.—Wreckage of six-story Four Seasons Apartment Building, Anchorage, Alaska. Canted elevator shaft at center. Large crack in foreground, filled in on M Street to restore traffic, passed beneath building.

quake, the fracture may have been overlooked by early investigators. Furthermore, part of the fracture was quickly bulldozed over to restore traffic along M Street. In any event, the fracture was mapped by the Engineering Geology Evaluation Group, and its extensions east and west were still well preserved 2 months or more after the quake. Near the building the fracture had a vertical displacement of about 2 feet; the north side dropped down—a displacement that few manmade structures could be expected to withstand. The actual displacement beneath the building, however, is uncertain. The fact that the elevator shaft and stair well of the building fell northward suggests that they tilted in that direction in response to the northward displacement along the fracture. Support pillars collapsed in the same direction.

The building reportedly withstood most of the earthquake, although it shook violently, but it collapsed suddenly shortly before the end of the quake. Eyewitness accounts of the L Street slide (Shannon and Wilson, Inc., 1964, p. 53) indicate that sliding there occurred in the latter part of the quake. The timing seems more than coincidental; the crack beneath the Four Seasons Apartment Building must have attained offset at about the same time. It could not have had offset until the slide itself had begun.

### HILL BUILDING

The Hill Building, an eight-story office building at the southeast corner of Sixth Avenue and G Street, was slightly damaged. There apparently was no damage to the steel frame, and there was little exterior damage. A reinforced-concrete column failed at its junction with the canopy roof of the service entrance. The center cores, which were intended to resist horizontal forces, dropped as much as 5 inches at one point and 3 inches at another where they were partly shattered at their connections with the footings. The core walls were cracked also, and the beams between the cores were sheared by vertical stresses.

### HILLSIDE APARTMENTS

The Hillside Apartments were on the south side of Sixteenth Avenue between G and H Streets on a bluff overlooking Chester Creek. They were damaged beyond repair and have since been dismantled. This was a split-level building, five stories high on the south side and three stories high on the street side. It had a post-and-lintel frame with steel-pipe columns, rolled-steel beams and concrete floor slabs on steel joists.

Walls were unreinforced hollow concrete block. The building was sheared in an east-west direction at the third-story level on the south side and in the lower two stories on the north side—the upper stories lurched west relative to the lower stories. Seemingly, no provision had been made for resistance to strong lateral seismic stress.

### KNIK ARMS APARTMENT BUILDING

The six-story Knik Arms Apartment Building, of poured-in-place reinforced-concrete framing, is on the west side of L Street between Sixth and Seventh Avenues, on the L Street landslide block between the headward graben and the bluff overlooking Knik Arm. It is especially noteworthy for its apparent lack of damage, despite a lateral displacement of about 10 feet west-northwest as it was carried along with the underlying slide block. Many smaller residential buildings on the slide block were also undamaged or little damaged.

### MOUNT McKINLEY BUILDING AND 1200 L STREET APARTMENT BUILDING

The Mount McKinley Building and the 1200 L Street Apartment Building are twin 14-story reinforced-concrete apartment buildings about a mile apart and facing in opposite directions. They sustained similar damage, almost matching crack for crack, although damage in general was somewhat more severe in the Mount McKinley Building. The Mount McKinley Building is on Denali Street between Third and Fourth Avenues; the 1200 L Street Apartment Building is across town near Inlet View School.

The most obvious damage to both buildings was X-shaped shear cracks in spandrel beams, caused by vertical shear between exterior support piers as a result of lateral swaying. Spandrels in general were most heavily damaged in the middle third of the floor levels. Interior walls were less damaged than exterior ones.

In the Mount McKinley Building, vertical piers sheared horizontally at the third-story level on the north side of the building (at a construction joint) and at the second story on the south side. An exterior column fractured diagonally at the first-story level. A television-antenna tower on top of the building was undamaged.

Failures similar to those in the Mount McKinley Building occurred in the 1200 L Street Apartment Building in piers at the south face of the building at the second- and third-story levels. Corner spandrels were more heavily damaged than those in the Mount McKinley Building.

An account of the earthquake as related by an occupant of the 12th story of the 1200 L Street Apartment Building was provided by William G. Binkley (written commun., 1964). Mr. Binkley, a geologist, noted wryly that he was living in a sort of oversized seismograph. The quake was first felt in the building as a light tremor that intensified rapidly until objects began to fall to the floor. About 30 seconds of trembling motion was followed by perhaps 2 minutes of violent jarring, in which the building seemed to sway 8 to 10 feet horizontally and 1 to 2 feet vertically. Bookcases were overturned, and fallen books and furniture were thrown back and forth across the room. Violent shaking was accompanied by a deep rumble and by higher pitched sounds of shattering plaster and falling dishes and furniture. In the kitchen, everything from the cabinets and refrigerator crashed to the floor, where it was "churned into a melange of broken dishes and glass, catsup and syrup, flour, beans, pots and pans, eggs, lettuce, and pickles." Mr. Binkley was able to crawl from the living room to a hall where he braced his feet against one wall and his back against another. Then the building stopped "jumping," the noise stopped abruptly, and the motion of the building diminished gradually with a subsiding, weaving tremble.

Most people at ground level experienced far less violent shaking than those in tall buildings. Many individuals were unaware of the catastrophic proportions of the quake until much later when the reports began to come in. In the heights of the 1200 L Street Apartments, however, the accelerations undoubtedly were greatly magnified.

### PENNEY'S DEPARTMENT STORE BUILDING

The Penney's Department Store Building (fig. 5) was a total loss and has since been dismantled. Photographs of its wreckage have been widely distributed in magazines and newspapers. Penney's was a five-story reinforced-concrete structure having shear walls on three sides and a curtain wall of precast panels on the north. Failure is attributed to torsion caused by rotational displacements, in turn caused by an eccentric position of the center of rigidity of the structure. This rotational motion sheared off the west support wall at the second-story level, causing the wall and all overlying floors to collapse. The floor slabs also sheared at their connections to the next adjacent column wall to the east. The northeast corner of the building collapsed (fig. 4), and most of the precast panels on the north face fell to the street. Berg and Stratta (1964, p. 35) reconstructed the sequence of events as follows: The northeast corner of the building collapsed following failure of the east shear wall at that point; the west shear wall then failed at the second-story level at the north end of the building. The east shear wall failed at the south end of the building, and the precast curtain-wall panels collapsed at the north face of the building.

The north-facing curtain wall must have fallen rather late in the quake. Some motorists reportedly were able to start their parked cars and move them away from below the wall before it fell. One motorist who ran to her car in an attempt to move it, however, was trapped and killed (R. M. Waller, written commun., 1965).

#### PORT OF ANCHORAGE AREA

Much of the damage in the Port of Anchorage area was caused by ground displacements along fractures, but some damage is attributable to direct seismic shaking. The main pier lurched laterally 5 to 19 inches. Large longitudinal cracks and several transverse ones opened up, and the walls of several buildings were cracked. All four gantry cranes were damaged. Steel piles penetrated the deck of a subordinate pier. Approach roads and railroads settled as much as 18 inches. Two cement-storage tanks were toppled, one at the property of the Permanente Cement Co. at the entrance to the U.S. Army Dock and one at the Alaska Aggregate Corp. facility just north of Ship Creek. Oil-storage tanks in the dock area were mostly superficially damaged, but some tanks were bulged outward at the bottom, probably by rocking and pounding back and forth as the contents sloshed to and fro.

#### WEST ANCHORAGE HIGH SCHOOL

West Anchorage High School is on the south side of Hillcrest Drive a few blocks west of Spenard Road and just south of a bluff overlooking Chester Creek. Structurally separate parts of the school building reacted differently to the vibrations. The two-story classroom section of the building was heavily damaged, especially the second story. Exterior columns failed at connections with the roof and with the second-floor spandrels. Extensive damage was caused by pounding between the gymnasium section and the classroom section. There was extensive ground cracking along the bluff above Chester Creek and a small rotational slump formed due north of the school.

## GROUND DISPLACEMENTS OTHER THAN LANDSLIDES

### GROUND CRACKS AND COMPACTION

The distribution of ground cracks in the Anchorage area (generalized in fig. 1) was mapped by the Engineering Geology Evaluation Group (1964, pl. 1) shortly after the earthquake. Most of the observations on which this map is based were made on traverses adjacent to streets and highways but some were obtained from a scrutiny of aerial photographs. Many unobserved cracks probably formed in the less-accessible snow-covered undeveloped areas. Frozen muskeg in and bordering swamps, for example, was very susceptible to cracking. The map, nevertheless, shows clearly the widespread distribution of cracking, and it emphasizes the high susceptibility to cracking of lowland areas underlain by silty clay and outwash, as opposed to highland areas underlain by ground moraine. Made land in former muskeg areas, reclaimed either by draining or by filling directly over muskeg, was also very susceptible to cracking.

Reportedly, many ground cracks opened and closed with the rhythm of the earthquake. Such action may help explain the extensive damage some cracks caused. A pulsating fracture would cause more damage to a superencumbent structure than a fracture that merely opened.

The most severely cracked ground was adjacent to landslides (fig. 40) where cracks were caused by tension directly related to sliding. The cracks in turn caused much structural damage in built-up areas. Some cracked ground undoubtedly would have developed into landslides had the earthquake lasted longer, as for example at Turnagain Heights, back of the landslide (pl. 1). Here, the pattern of fracturing was concentric to the head of the slide, and many crescentic tension cracks extended as far as 2,200 feet from the slide proper, to the vicinity of Northern Lights Boulevard. In the downtown area, many streets and buildings were damaged by cracks behind the periphery of the Fourth Avenue slide. Major cracking and ground adjustments extended a city block or more back from the slide. In contrast, the L Street and Government Hill slides broke away clean; they were much cracked themselves, but few cracks extended behind them.

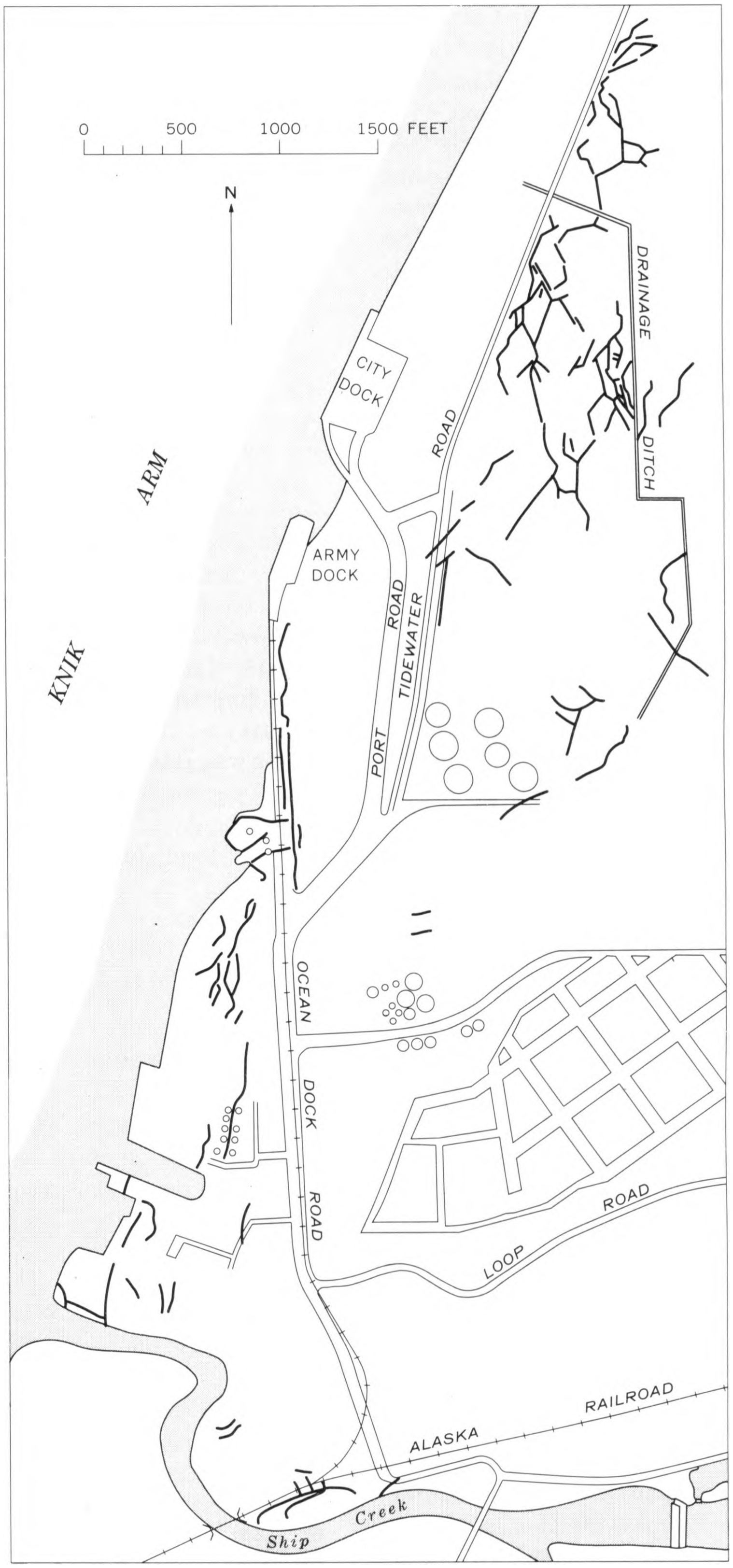
Preexisting zones of weakness in the ground were particularly susceptible to cracking. Some cracks followed backfilled utility trenches, for example, or backfills around building foundations. Old frost cracks in pavement—caused by contraction at low temperatures—were reopened by the earthquake; at Turnagain Heights, the pattern of cracking was very striking—ground cracks veered along concrete curbings, crossed streets at right angles along old contraction cracks, and then resumed direction on the other side. In filled areas, cracks commonly formed near the contact between filled and preexisting ground. Some buildings unfortunately constructed partly on fill were sundered by cracking between the fill and the adjacent ground.

Trees were split by cracks that passed through their root systems (fig. 40), their roots being held fast by the frozen ground.

On sloping ground, cracks generally formed parallel to the slope, owing to differential compaction, lateral shifting (lurching) under the influence of gravity, tension, and rupture.

Alternate cuts and fills along streets, highways, and railroads demonstrated a predictable pattern of fractures. Fills that compacted under the vibratory stress of the quake were cracked adjacent to the fill-cut contact. Many cracks of this sort crossed the Seward-Anchorage Highway, some fills dropping several inches. One in particular formed a very sharp pavement break on the north approach to the Rabbit Creek crossing near the south margin of the Anchorage Lowland. Similarly, an Alaska Railroad embankment across Fish Creek east of Turnagain Heights cracked to pieces and collapsed.

Extensive ground cracks formed in the Port of Anchorage area on the flats extending north from the mouth of Ship Creek to and beyond City Dock between the bluff on the east and the shore of Knik




14.—Ground cracks, Port of Anchorage and vicinity. Anchorage, Alaska. Many of these cracks spouted mud, particularly those east of City Dock. Base by city of Anchorage, Office of City Engineer.

Arm on the west (fig. 14). This area is underlain by estuarine silt, peat, muskeg, and artificial fill (Engineering Geology Evaluation Group, 1964, p. 22), all highly susceptible to cracking under the stresses of prolonged vibration and compaction. Great quantities of mud were extruded from large polygonal fractures in the flats northeast of City Dock. To the south, longitudinal cracks 300 feet or more long extended the full length of the Army Dock embankment. At the south end of the embankment, in an area of transverse cracks, a steel cement-storage tank was overturned. Collapse of the tank, however, may have been caused by inadequate anchoring of base plates to support columns (Berg and Stratta, 1964, p. 46).

Facilities south of the Army Dock to the west of Ocean Dock Road were also damaged by ground cracks. Cracks extended through the tank farm of the Union Oil Co. of California and damaged the adjacent Alaska Fish and Farm Products lease and the Cook Inlet Tug and Barge lease. There was ground cracking in the dock area at the mouth of Ship Creek, where another cement storage tank toppled and where the right abutment of the adjacent Alaska Railroad bridge across Ship Creek was damaged by subsidence and cracking.

Incipient and minor slumping along the bluff east of the dock area also produced many cracks, some of them large. All these, however, were in undeveloped woodland areas, mostly on military land.

### SAND BOILS AND MUD FOUNTAINS

Sand boils and mud fountains are transient or short-lived features commonly produced by strong earthquakes where ground breakage occurs. They were wide spread in the damage zone of the March 27 Alaskan earthquake (Grantz, Plafker, and Kachadoorian, 1964, p. 6). At Anchorage they have been reported at several localities and probably occurred in many others.

Mud fountains were produced where the water table was shallow and frozen ground overlying saturated, unconsolidated sand or silt was cracked by the earthquake. Intense shaking possibly accompanied by settlement and compaction forced muddy water out through the cracks.

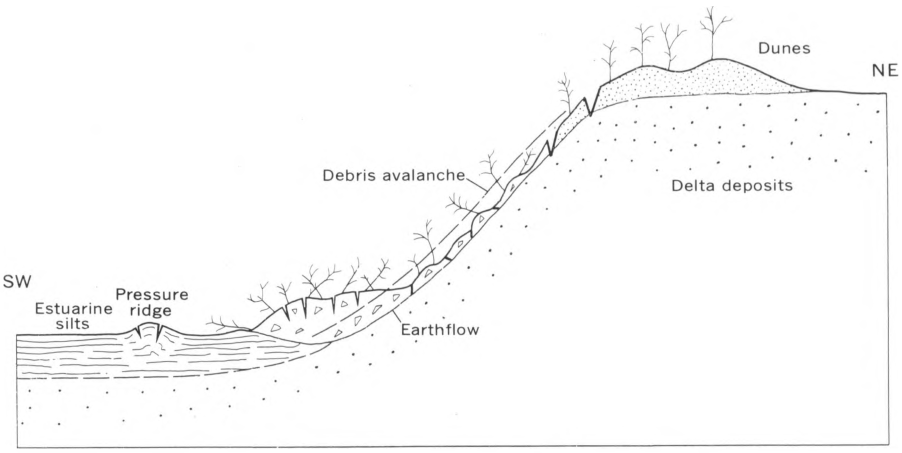
At the Port of Anchorage, mud was ejected from many cracks east and northeast of the City Dock and from a few cracks between the Army Dock and Ship Creek. The ground was snow covered at the time, and consequently the ejected mud shows plainly on aerial photographs taken shortly after the earthquake.

A mile above the mouth of Chester Creek, where Spenard Road crosses it, large mud fountains were reported by a motorist whose passage was blocked by cracks in the road. The fountains reached higher than his car (R. D. Miller, oral commun., 1964).

At Turnagain Heights, large sand boils, unlike any others in the area, resulted from agitation and settlement of slump blocks within the landslide (fig. 15). These boils built ridges of sand 2 to 3 feet high, 3 to 6 feet wide, and about 100 feet long. Some ridges had hollow cores. The sand generally was finer grained than the subjacent outwash, from which it must have come, and it may, therefore, have been sorted by natural elutriation in a pulsating water column.

15.—Part of a sand boil, Turnagain Heights slide area. Ridges 2 to 3 feet high and 100 feet long or more were formed as fountains of water were ejected through frozen outwash.

A large kidney-shaped boil near Turnagain Heights, but outside the landslide area, spread over an area of about 3,200 square feet. This boil was just west of a collapsed Alaska Railroad embankment across Fish Creek one-fourth mile north of Northern Lights Boulevard (Engineering Geology




16.—**Diagrammatic section near Point Campbell, showing mode of failure along bluff line overlooking Turnagain Arm.**

Evaluation Group, 1964, pl. 8). Two other large boils poured out of the opposite side of the same embankment. They may have been caused by spontaneous liquefaction of subjacent silty sand, that was pumped to the surface when the embankment fill collapsed. Several similar but smaller boils formed in the downtown area in the toe of the Fourth Avenue slide, east and just below the intersection of E Street and West Second Avenue (Engineering Geology Evaluation Group, 1964, pl. 5).

Most of the lakes in the Anchorage area—solidly frozen over at the time of the quake—developed distinctive patterns of peripheral ice cracks extending generally 50 to 100 feet out from shore but in places much farther. The fracture zones in the larger lakes were wider than those in the smaller ones, and some small lakes had no cracks at all. Most of the cracks ejected fountains of water during the quake, and where the bottom was shallow enough they ejected mud, particularly in toward shore. Large mud fountains formed at Lake Otis (on the northeast shore), Lake Spenard, Hood Lake, and Connors Lake, to name a few.

The earth dam impounding Campbell Lake, near Turnagain Arm, broke during the earthquake. As the water level fell, ice on the lake broke into blocks, and fountains of muddy water squirted up through the cracks. Reportedly, these fountains reached heights of 20 feet or more.

## LANDSLIDES

### DEBRIS SLIDES, AVALANCHES, AND ROTATIONAL SLIDES

Landslides precipitated along the bluffs of Knik and Turnagain Arms and along the benches above Ship Creek were the most spectacular and awesome manifestations of earthquake damage in the area. The slides took several forms and occurred in several types of earth material. The most destructive slides, in terms of property damage, resulted from failures in the Bootlegger Cove Clay. Serious failures, however, also occurred in glacial till, delta deposits, and dune sands—the only criteria being unconsolidated surficial deposits having insufficient shear strength to resist the accelerations of the quake in potentially unstable topographic settings. A landslide occurs where the ratio of shearing resistance of the ground to the shearing stress on the potential slide surface decreases from a value greater than one to unity. An earthquake can cause an almost instantaneous decrease in this ratio (Terzaghi, 1950, p. 110).

### SLIDES ALONG TURNAGAIN ARM

Structurally, the simplest slides were in the bluffs facing Turnagain Arm southeast of Point Campbell (fig. 16). There, a thin cover of wind-blown sand and slope wash had been loosely anchored to the steep face of the bluff by an overgrowth of trees, shrubs, and grasses. The entire superficial mat, probably frozen at the time, slumped downward a few inches to several feet along the full length of the bluff from Point Campbell to Campbell Creek, a distance of about 4 miles. Locally the slumping was more intense, and the face of the bluff was laid bare from top to bottom. Southeast of Campbell Creek, minor or incipient slumping and cracking extended along the bluff to the tracks of The Alaska Railroad near Potter, where slides destroyed trackage and embankments.

Between Point Campbell and Campbell Creek, the earth slid either in a mass, as a shallow nonrotational glide, or it disintegrated into blocks and fragments, as a debris slide or avalanche (Varnes, 1958, pl. 1). All intermediate steps are represented. The velocity of motion has not been ascertained, but it probably was rapid because of the height and steepness of the slope and the granular incoherent character of the material.

Trees carried along in the slides were tilted at all angles of disarray, many were rotated outward, some inward, and some were overridden by surging at the base of the slope. In some places the debris surged out into lobate forms on the estuarine muds and swamps at the foot of the bluff, and in many places one, two, or three pressure ridges were formed at the foot of the slope or out on the flats. Some ridges were more than a thousand feet from the bluff. The flats below the bluff were snow covered at the time and probably frozen. Pressure probably was transmitted directly from the slide through the frozen layer to the points of failure on the flats.

The high, steep part of the bluff nearest Point Campbell consists chiefly of loose deltaic sand and gravel veneered with dune sand. The bluff supported little or no vegetation prior to the earthquake because of more or less continuous buffeting by storm waves. It had, therefore, practically no cohesion with the slope and failed chiefly by avalanching.

Many gaping cracks remained along the edge of the bluff between Point Campbell and Campbell Creek after the temblor ceased. The sliding, however, was entirely superficial and did little to alter the firmness of the land surface back from the bluff. Nevertheless, by partial removal of the stabilizing vegetative mantle, the vulnerability of the slope to continued sapping has been heightened, and intermittent sluffing will probably take place for a long time to come. Slow, gradual backwasting, in fact, should be regarded as normal.

What effect tectonic subsidence—about 2 feet in the Anchorage area—will have on the stability of the bluff line is still undetermined. Certainly the part of the bluff near Point Campbell will be even more exposed to the attacks of tide and wave than it was before the quake. Other points along the bluff farther southeast probably will be attacked by occasional storm waves also, especially when strong winds coincide with highest tides. It seems likely that, wherever the foot of the bluff is accessible to storm waves, new slope profiles will have to be established before equilibrium can be fully regained.

#### POTTER HILL SLIDES

Destructive slides carried away several hundred feet of track and right-of-way along The Alaska Railroad between mile posts 103 and 104 about 2½ miles northeast of Potter (fig. 17). These slides, known as the Potter Hill slides, were mapped and examined in detail after the earthquake, on April 20, 1964, by D. S. McCulloch and M. G. Bonilla of the U.S. Geological Survey on behalf of The Alaska Railroad. The following summary is based on their findings.

The Potter Hill area has a history of landsliding that extends back at least 35 years. Bert Wennerstrom, chief accountant of The Alaska Railroad recalled that "in the late twenties and early thirties, heavy rains caused sliding along this section (mile 103–104). The largest slide took out about 1,000 feet of track." Wennerstrom remembered that the failures involved cuts in the natural bank material (McCulloch and Bonilla, written commun., 1964).

On October 3, 1954, landslides caused by an earthquake again destroyed trackage in the same area. One slump left 140 feet of track suspended 15 to 20 feet in the air (Miller and Dobrovolny, 1959, p. 105). Although it is not clear just what materials were involved, failure probably occurred in natural bank material as well as in fill.

The slides of March 27, 1964, affected cuts in both natural bank material and fill. The ground was frozen at the time of the earthquake and, presumably, there was little surface runoff. Sand boils, however, indicate that the material in the slides had a high water content.

Several kinds of material were involved. Glacial till forms the top of the bluff back of the slides and most of the exposed face of the bluff in the northern part of the slide area. The till rests on outwash with a contact that dips gently north. The outwash in turn lies on a sequence of blue clay, silt, and fine sand, which perhaps is equivalent to the Bootlegger Cove Clay. This sequence forms the lower part of the slope. At the south end of the slide area, a coarse gravel overlies the till. The materials in the bluff abut against and probably pass beneath intertidal silts in the flats at the base of the bluff.

The bluff is saturated at its base, and, at several levels above its base, ground water escapes laterally through permeable beds in the outwash. In wells east of the slide area, ground-water levels reportedly are 30 to 240 feet above sea level. During the earthquake, sand spouts issued from cracks 400 feet east of the edge of the bluff.

All the slides along Potter Hill had a similar form. They con-

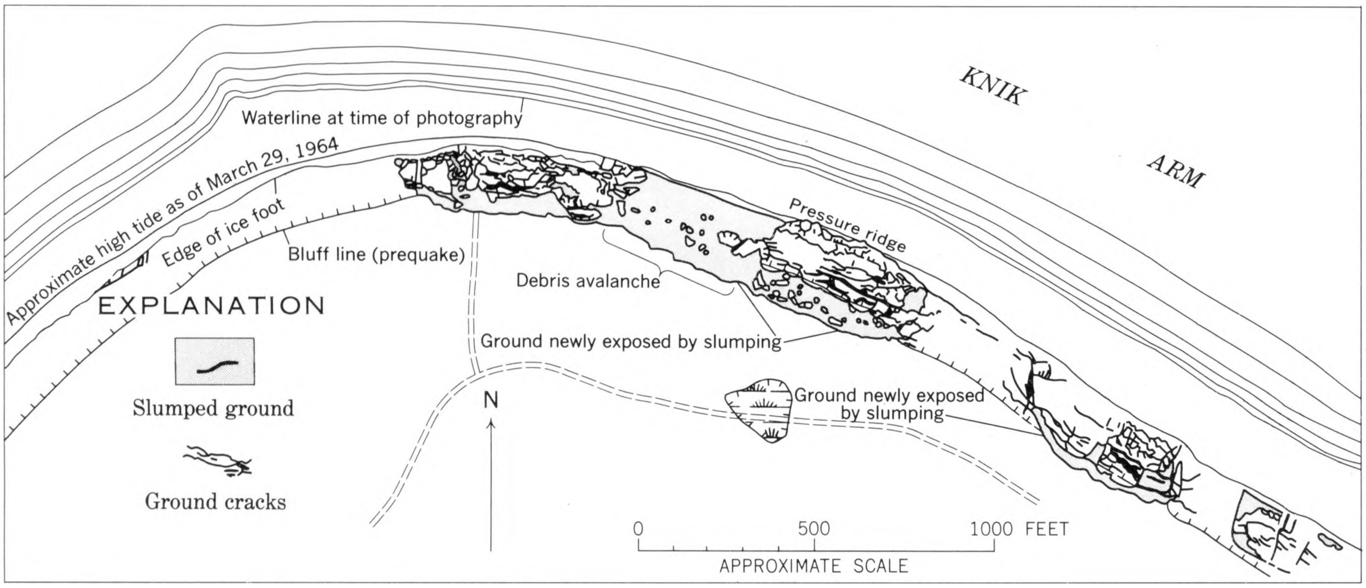

**17.—Map and profile of Potter Hill landslide area near Anchorage, Alaska.**

sisted of elongate fragmented slump blocks rotated backward and broken into many pieces toward the base of the slope. In places at the toe, they turned into earth and mudflows derived partly from the intertidal silt of Turnagain Arm and partly, perhaps, from the clay-silt-sand sequence in the lower part of the bluff.

Many pressure ridges formed on the flats below the slides; some smaller ones were as far as a third of a mile beyond the toe, but most of the larger ones were within 400 feet. They were formed by compressive stresses probably transmitted horizontally from the toe of the slides through the frozen upper layers of the estuarine silt.

Marginal fractures bounded the slides roughly parallel to the face of the bluff. They cut across natural bank material and fill alike as high as the level of the tracks, in the roadbed itself, and in the drainage ditch beside the tracks. Near Rabbit Creek, where the tracks turn southward across the flats, cracks reached nearly to the top of the bluff. At one point they extended as far back as 400 feet from the edge of the bluff. Sand that was ejected from these cracks during the quake spread out onto the surface of the snow. But in general, cracking was confined to the face of the bluff itself.

The mechanics of sliding has been investigated by D. S. McCulloch and M. G. Bonilla (written commun., 1964). They concluded that sliding was initiated by failure and flowage of material from the base of the slope. Higher parts of the slope slumped and distintegrated as a consequence. Flowage may have occurred in the modern estuarine silt at the base




18.—Photogeologic sketch map of Point Woronzof landslide area, Alaska.

of the slope, which carried part of the weight of the roadbed, or in the fine silt and sand in the lower part of the bluff. Perhaps it occurred in both.

Measurements by McCulloch and Bonilla indicate that the volume of the slide material that accumulated at the base of the slope and on the adjacent flats was less than that of the material removed from the slope by sliding. They concluded, therefore, that this difference in volume was compensated partly by flowage in the estuarine silt and partly by lateral translation through the silt to pressure ridges on the flats.

#### SLIDES AT POINT WORONZOF

Point Woronzof is underlain by loose unconsolidated sand and gravel. Because it projects north into Knik Arm, the point is exposed continuously to the ebb and flow of the strong tidal currents and to the pounding of storm waves propelled across the arm by northerly winds sweeping down across the Susitna Lowland. The maximum tidal range at Anchorage is about 38 feet. Point Woronzof, therefore, has been subjected to more or less continuous and vigorous shoreline erosion, and, since 1909 at least, has retreated southward at a mean rate of about 2 feet per year (Miller and Dobrovolny, 1959, p. 89).

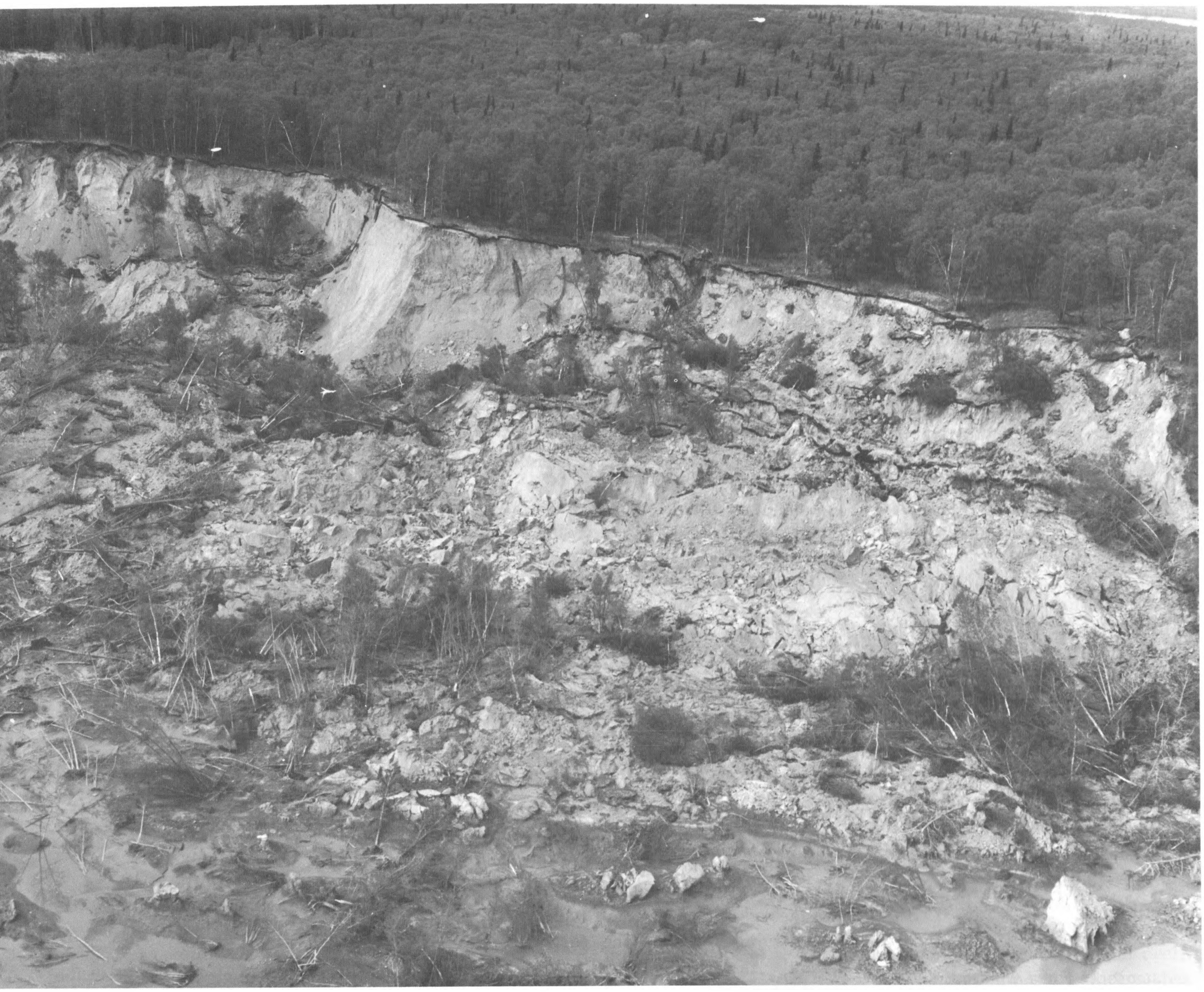
Waves and tides, by periodically removing sluffed increments of sand and gravel from the foot of the point, have kept the slopes above in a state of precarious repose. It is not surprising, therefore, that on March 27 large volumes of material slumped down the face of Point Woronzof under the driving force of the earthquake. As shown by figure 18, the bluff caved away in three separate parts, mostly by modified rotational slumping. The largest mass, directly beneath Point Woronzof, extended about 1,500 feet along the bluff and about 50 to 100 feet back behind the old bluff line. Part of the slumped mass disintegrated into a debris avalanche, but most of it slid down as an intact though much fractured block. It probably moved very rapidly.

The next smaller slide was 300 feet east. It extended about 500 feet along the bluff and caved back about 30 to 40 feet behind the old bluff line. It, too, was a much fractured but basically intact slump. The smallest slide, 150 feet farther east, was about 200 feet wide. It broke away from the slope entirely below the old bluff line.

#### SLIDES NEAR CAIRN POINT

Several small landslides were generated by the earthquake along Knik Arm just south of Cairn Point at the west end of Elmendorf Air Force Base. Cairn Point, like Point Woronzof, projects out into Knik Arm and is subject to vigorous erosion by waves and tidal currents. It, too, therefore, has a past history of instability and slumping.

At Cairn Point an exceptionally thick sequence of Bootlegger Cove Clay is overlain by silty till of the Elmendorf Moraine. The clay is at least 126 feet thick, and the till is at least 110 feet thick (Miller and Dobrovolny, 1959, p. 39). The quake-induced landslides probably



19.—Rotational slump near Sleeper landing strip, on the west side of Knik Arm opposite Cairn Point. At its foot, the slump passed into an earthflow. Tidewater in foreground. Scarp to left of upper center is about 80 feet high.

involved both materials, but they broke away mostly from the lower half of the slope and, hence, were mostly in the Bootlegger Cove Clay. Morphologically, the slides were rotational slumps, modified by disruption and flowage.

The largest slide was about 450 feet wide at beach line, and it surged out at least 200 feet onto the tidal mudflat. From its appearance after the quake, it must have disintegrated into many blocks as it moved downslope, the parts that moved farthest disintegrating most completely. At its toe, it passed into an earthflow. The several other slides, although smaller, were identical to the largest in form.

#### SLIDES ON WEST SIDE OF KNIK ARM

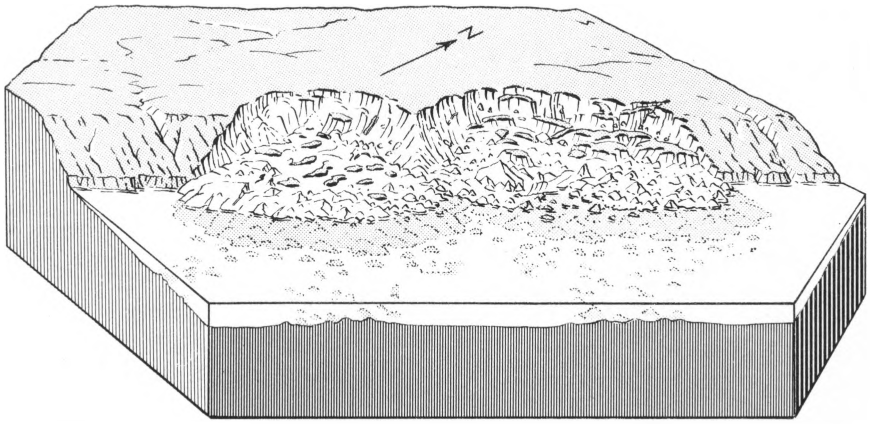
Two large rotational slumps were generated by the earthquake on the west side of Knik Arm about a mile northeast of Sleeper landing strip. The larger of the two (fig. 19) was just below hill

204 in sec. 35, T. 14 N., R. 4 W. (This hill is shown on the U.S. Geological Survey 1962 map of Anchorage and vicinity.) The smaller slide was about a quarter of a mile southwest. The Bootlegger Cove Clay rests on glacial till at about the level of mean high tide, with a contact that appears to be gradational. The clay contains scattered pebbles throughout, especially near the base; some are as large as 4 inches across.

Bootlegger Cove Clay extends nearly the full height of the bluff, to an altitude of about 190 to 195 feet, where it is topped by a veneer of sand, silt, and peat. Sliding, therefore, was largely in the clay. Till may have been involved near the foot of the slides, but if so, it was pushed out into Knik Arm below tidewater. Both slides surged out onto the tidal mudflat in broad earthflow lobes that reached an undetermined distance into the water below low tide.

Before the earthquake, the top and slope of the bluff supported a forest of birch and cottonwood in the slide areas. These trees were rotated backward in an arc of about 30° to 60°, the angle of tilt being progressively greater farther downslope. In the earthflow lobes, many of the trees lay flat, their crowns pointed toward the bluff and their roots toward Knik Arm.

Detailed land measurements have not been made of either slide. Estimates based on air and ground reconnaissance and on photographs indicate that the larger slide was about 700 feet wide along the bluff line. It worked headward about 200 feet into the bluff, and it surged out perhaps 500 feet onto the mudflat for a total length of at least 700 feet from crown to toe. It was a compound slide in that it extended back into the bluff in two large joined arcuate alcoves (fig. 20). The slide was complex in that the slumped mass broke into several slices below the crown and into countless jumbled blocks toward the foot, where it passed into an earthflow. Its main scarp had a pronounced concave-outward profile and a maximum height of about 80 feet from the crown to the jumbled blocks below.




20.—Block diagram of compound slump near Sleeper landing strip. Two lobes of slide surged out onto mudflat below high tide.

The smaller slide was similar to the larger one in morphology and habit, but its main scarp formed a simple arcuate alcove about 90 feet high. Gouging and slickensides on the face of the scarp indicate that the slumped mass slid diagonally downward from upper left to lower right (as viewed from the crown) rather than directly down the fall line; the reason for the diagonal slipping is unclear, unless the mass slumped almost instantaneously and at the same time lurched laterally in response to the ground motion of the quake. The slumped mass itself was rotated backward toward the bluff, but it was broken into helter-skelter blocks in various attitudes of disarray, particularly out toward the toe.

Near the foot of the smaller slide there were sand boils 3 to 4 feet high. Because the bluff had only a thin veneer of sand at the top, the boils presumably were derived from the subjacent beach.

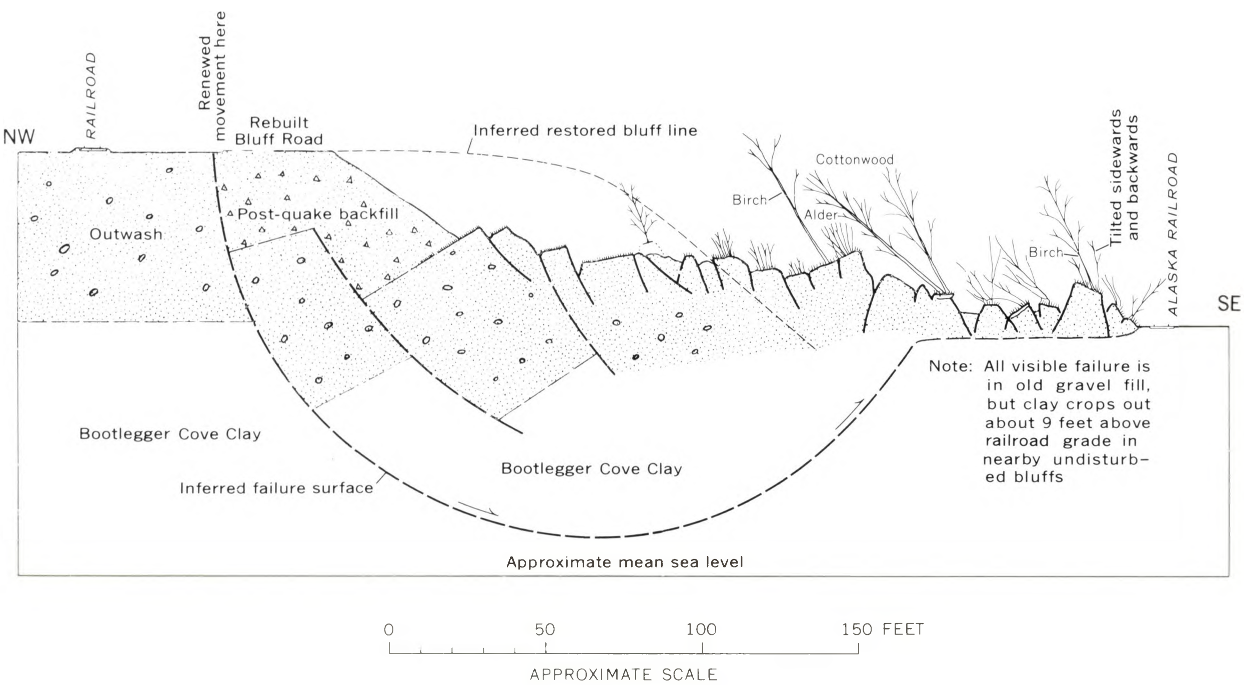
The slip plane of an older slide was exposed in section on the south side of the main scarp of the smaller slide. The older slide—no longer preserved as a topographic form—was truncated by the slip plane of the younger one.

Further slumping at a gradually diminished rate is forecast for both slides. The toes of both slides project far out into Knik Arm where they are under relentless attack by tidal currents and waves and where removal of material will reduce whatever buttressing effect may have existed immediately after the quake. Loss of buttress support, in turn, will encourage further rotation of the main slide masses; this rotation will remove support from the main scarps. These scarps already are precarious, and will remain so until headward slumping has reduced their height and pitch to a more stable configuration. In brief, therefore, erosion at the toes and slumping at the heads will continue indefinitely at a gradually diminishing rate until something approaching the prequake profile of the bluff has been restored.

21.—Chaotic pressure ridge at toe of rotational slide, Bluff Road.. In part, toe surged forward as an earthflow. Compare with figure 22.

#### ROTATIONAL SLIDES ALONG BLUFF ROAD

Several rotational slides gave way along the south-facing bluff line of Ship Creek, between Bluff Road and the tracks of The Alaska Railroad (fig. 1). The most widespread failure in that area extended east along the bluff between the district offices of the Corps of Engineers and the steam generating plant of Elmendorf Air Force Base. About 1,300 feet of bluff gave way in a compound displacement consisting of four separate but connected slumps. Collapse at the heads of the slumps extended back horizontally into the bluff as much as 120 feet. An additional 400 feet of bluff line east and west of the main slide mass cracked and began to slump. Altogether, about 650 feet of Bluff Road was destroyed, dropping as much as 40 feet below the prequake gradeline and rotating backward 15° to 30°.




22.—Sketch section through rotational slide at Bluff Road.

All four slumps were modified by multiple cracking, internal breakup, and flowage. None moved as a simple block. Within each slump, slices rotated on individual slip surfaces, their motions modified by interference or shoving of one slice against another. There was evidence, moreover, of flowage beneath each slump, as well as of extrusion of material at the toe.

At the toe, each of the four slumps bulged out into a chaotic lobe of jumbled blocks (fig. 21). These lobes were transitional in form between pressure ridges and earthflows. Three of them stopped short of The Alaska Railroad tracks; the most easterly lobe, however, advanced across two sets of tracks, but without damaging the tracks or the roadbed. Each slump had a length of about 300 feet from crown to toe.

In general, the rotation of blocks within the slides diminished downslope from the head of each slide toward a position about halfway down, below which rotation either increased again or the attitude of the blocks became chaotic (fig. 22). In other words, the old ground surface was tilted most near the head and least about halfway to the toe. This differential tilting (in addition to rotation) seems to have been in response to a withdrawal of material from beneath the headward parts of the slumps, either by flowage and extrusion, by lateral spreading, or by a combination of the two. If by a combination, these slides represent a transitional form between the simple slumps of the Point Woronzof and Cairn Point areas and the block-glide displacements in the downtown Anchorage area.

Most of the visible landslide material was coarse outwash gravel. Some of it had been disturbed prior to the quake, and some plainly had been backfilled artificially. Bootlegger Cove Clay, however, was exposed along a line of springs 9 feet above the base of the slope of the bluff just west of the slides, and it must have extended into the slide area. Its loss of strength under the vibratory motion of the quake very likely contributed to the failure of the slope and to the flowage at the toes and beneath the heads of the slumps.

East from the steam generating plant, cracks and smaller separate slumps extended along the bluff a total distance of about 3,000 feet. The bluff beyond was appreciably lower and presumably more stable. Some of these slumps showed clear evidence of movement prior to the March 27 earthquake, particularly the slump just east of the steam plant and the one in the next bend of Bluff Road farther east. Old settlement cracks in the road at these places had been filled and patched before the quake.

Emergency repairs along Bluff Road did little to stabilize the sliding triggered by the quake. These repairs consisted simply of backfilling collapsed areas with gravel to reestablish the grade profile, without regard for the unbalancing effect that the backfilling might have on the slide itself. At several points along the bluff, fill material dumped onto the slides probably caused continued movement by overweighting the head and altering whatever balance had been achieved naturally. By mid-May of 1964, new cracks with small vertical displacements had already formed in the repaired fills. Unless remedial procedures are altered, therefore, continued slow movements at the heads of the slumps seem inevitable. A comprehensive stabilization program for these slides, on the other hand, may be less feasible economically than intermittent road repair and maintenance.

### TRANSLATORY SLIDES

All the highly destructive landslides in the built-up parts of Anchorage were of a single structural-dynamic family, despite wide variations from slide to slide in size, appearance, and complexity. All moved chiefly by translation rather than rotation. They slid laterally on nearly horizontal slip surfaces following drastic loss of strength in previously weak sensitive zones of the Bootlegger Cove Clay. Slides in which the slid mass was practically intact are classed as block glides; those in which the slid mass underwent appreciable disruption are probably best classed as failures by lateral spreading (Varnes, 1958, pl. 1). Between these limits, all gradations of form were represented—not only from place to place but also in time. Structurally, the Fourth Avenue slide was the simplest and the Turnagain Heights slide was the most complex. The Turnagain Heights slide, however, must have begun as a simple though highly transient block glide, or perhaps as several such block glides, arising independently along the bluff line. As sliding progressed, the Turnagain Heights slide deteriorated rapidly into a complex failure involving simultaneous motions in several directions. Its predominant motion, however, remained translatory. Destruction to property in the several slides was caused by tilting, wrenching, warping, and disruption of structures over the cracked, collapsed, and compressed zones of the slides. Structures in undistorted parts of some slides were little damaged despite horizontal ground translations of several feet.

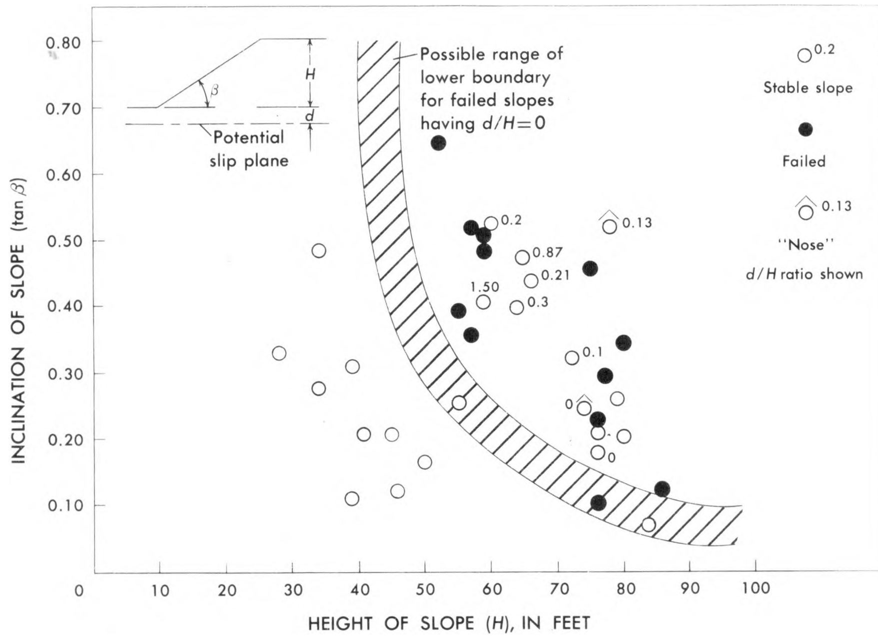
Translatory slides are less common than rotational slides. They have, therefore, received less attention in the literature. Examples similar in many respects to those at Anchorage, however, have been reported and described from Scandinavia where the Pleistocene history has been comparable in some ways to that at Anchorage. Notable translatory slides occurred at Skottorp, Sweden, in 1946 (Odenstad, 1951) and at Bekkelaget, Norway, in 1953 (Eide and Bjerrum, 1955, p. 88–100; Rosenqvist, 1960, p. 10). The Skottorp slide, particularly, resembled the Turnagain Heights slide, except that it was smaller; the Bekkelaget slide was similar to the Fourth Avenue slide. Translatory slides in the conterminous United States somewhat like those in Anchorage have been described by Crandell (1952, p. 552; 1958, p. 73) and by Varnes (1958, p. 26–32). All these slides—in Scandinavia and in the United States—moved in response to gravitational stress, without the intervention of earthquakes.

Earthquake-triggered landslides accompanying the great New Madrid, Mo., earthquakes of 1811 seem to have been very similar to the slides at Anchorage. The physical setting of the slides was analogous to that at Anchorage. Fissures, sand blows, and various other features related to sliding are described by Fuller (1912, p. 48, 59–61) on the basis of early accounts and on observations made nearly 100 years after the quakes. Fuller's descriptions might well apply to the Turnagain Heights slide. Grabens and tension cracks, for example, were formed where clayey alluvium, afloat on quicksand, glided laterally.

The Chilean earthquake of May 22, 1960, triggered three large landslides at Lago Riñihue, 65 kilometers east of Valdivia in central Chile. The descriptions of Davis and Karzulovíc (1963, p. 1407) indicate that these slides resembled the Turnagain Heights slide in form, size, and mode of failure. Translatory movement predominated; rotational movement was subordinate. Significantly, these slides occurred in an area of previous landsliding and were partly superimposed on preexisting landslides.

#### GEOLOGIC SETTING

All areas of translatory sliding in Anchorage had the same general geologic environment. All were underlain at various depths by Bootlegger Cove Clay that had zones of low shear strength, high water content, and high sensitivity. All surmounted flat-topped bluffs bounded on one side by steep slopes. In all areas, except the westernmost part of the Turnagain Heights slide, the Bootlegger Cove Clay was overlain by outwash sand and gravel. These deposits thinned markedly over a distance of a few miles from north to south and from east to west; grain size diminished concomitantly from gravel to sand. Near the Alaska Native Service Hospital the outwash is about 55 feet thick, near Government Hill




23.—Slope stability chart. Reprinted from Shannon and Wilson, Inc. (1964, pl. 7.1).

School about 40 feet, in the downtown area about 30 to 40 feet, and at Turnagain Heights from about 25 feet to zero.

Outwash deposits had no critical part in the sliding. Failure was confined to thin zones of sensitive clay, silt, and sand within the Bootlegger Cove Clay.

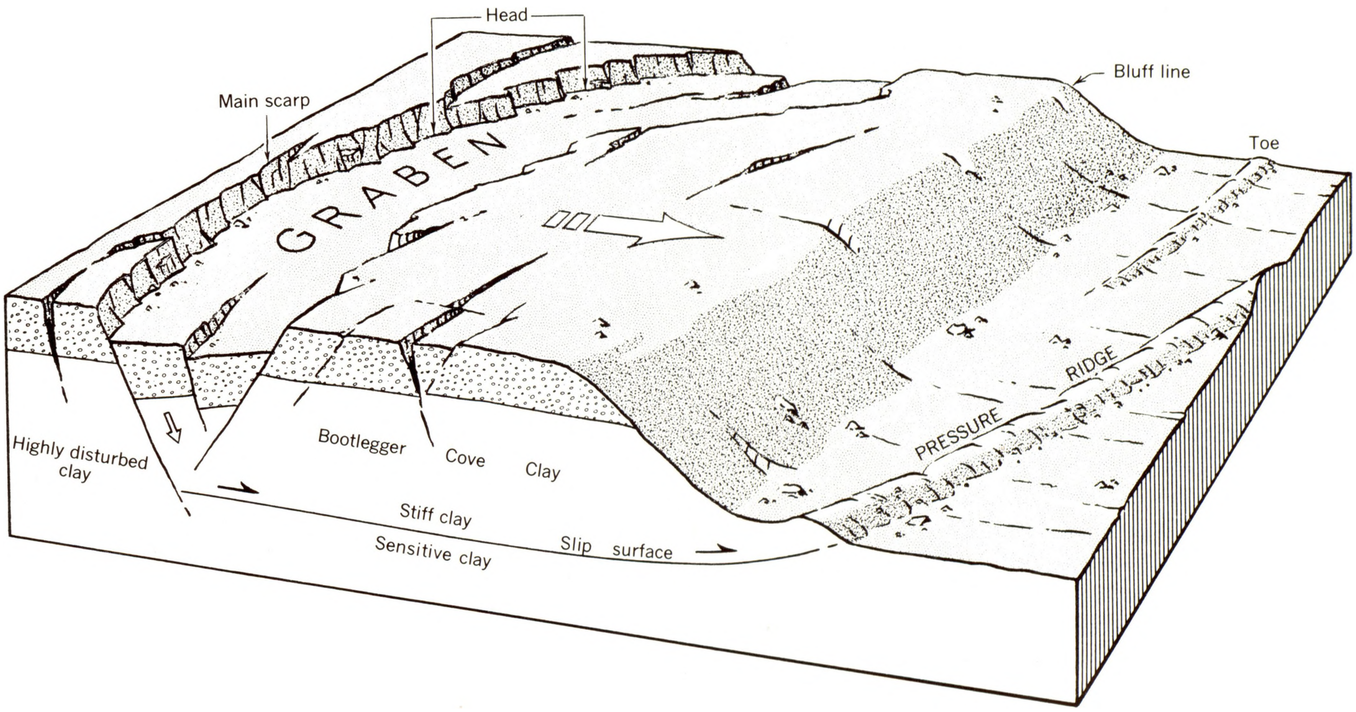
Several geologic factors acting in concert with earthquake shaking probably caused failure in the several slide areas. All these factors are themselves variables at each site. They include: (1) the topographic elements of bluff configuration—the height of the bluff above its base, the slope angle or declivity of its face, and perhaps the ground-plan configuration, (2) the soil-strength profile, including consistency, dynamic shear strength, and sensitivity, and (3) water content and liquid limit of the soil at the critical depth below the ground surface. Some of these factors seem to be interdependent—the height, slope, and ground-plan configuration, for example, may have influenced the water content of the soil, which in turn influenced the consistency.

The influence of topography, particularly the bluff profile, on failure susceptibility seems obvious. The ultimate driving force of landsliding was gravity, operating on a nearly horizontal shear surface in the direction of least shear resistance (the free face of the bluff) and acting on a dynamically sensitive soil that had undergone a severe loss of strength by earthquake shaking. Other factors being equal, the higher and steeper the bluff profile, the greater is the shearing stress, the less effective is the shear resistance of the clay, and the greater is the susceptibility of the bluff to failure.

The full significance of ground-plan configuration is uncertain and may involve several variables difficult to evaluate. Most failures took place along fairly straight or recessed bluff lines, for reasons not entirely clear, although possibly because such places are apt to be well watered (Shannon and Wilson, Inc., 1964, p. 33). Salients or cuspate areas ("noses") generally were spared failure, again possibly because they are apt to be well drained, although the slide at the Native Hospital failed precisely at just such a salient.

Using factors of height and slope, only, Shannon and Wilson, Inc. (1964, pl. 7.1), constructed a slope stability chart that grouped failed and stable slopes and showed lower limits of slope-to-height ratios below which failure is improbable (fig. 23). The higher the slope, the flatter the angle at which the slope is susceptible to failure, other variable factors such as soil strength and water content being equal. The fact that several stable slopes, including salients or "noses," have slope-to-height ratios within the same area of the chart as slopes that failed seems to point up the modifying influences of other factors such as soil-strength profile and water content. A low slope underlain by soil having a high water-plasticity ratio, for example, may be more susceptible to failure—may have a lower safety factor—than a high slope underlain by soil having a low water-plasticity ratio. In a unit of time, other factors being equal, a salient should drain and desiccate more rapidly than a recess; hence it should be more stable.

The length of time a bluff has been stationary and unmodified by erosion may perhaps influence its dynamic stability by affecting the water content of the underlying Bootlegger Cove Clay. Far more information on the water content of the clay at critical localities than is now available would be needed to test this hypothesis, but presumably a long-stationary bluff line would have a better chance of desiccation, and hence of




24.—Block diagram of a translatory slide.

dynamic stability, than an actively retreating one. Permeability is extremely low in most of the Bootlegger Cove Clay, and a long period of immobility would be required to promote even a low degree of drainage and desiccation. At Turnagain Heights, for example, the bluff line facing Knik Arm, which failed so dramatically during the earthquake, was in a state of relatively rapid regression owing to active shoreline processes prior to the quake, whereas the bluff line facing Fish Creek was relatively stationary before the quake and did not fail during the quake.

#### GEOMETRY AND MODE OF FAILURE

Translatory slides of the Anchorage area varied widely in size, shape, and internal complexity, but they all conformed to a single basic geometric format. Figure 24 is a simplified block diagram showing the essential structural elements, including the head, toe, bluff line, slip surface, graben, and pressure ridge. Sections through both the Fourth Avenue and the L Street slides closely approximate the idealized section at the front of the block diagram. The so-called slip surface probably is not generally a surface at all, at least at the onset of sliding, but rather is a narrow planar zone of failure.

Geometric development of the translatory slide is reconstructed in the following sequence: Earthquake shaking drastically reduces the shear strength of saturated sensitive zones in the Bootlegger Cove Clay. The strength of the clay falls below the level of shear stress caused by the weight of material in the bluff and the accelerations of the quake. Under the influence of gravity, therefore, a prismatic block of earth begins to move laterally on a nearly horizontal slide surface toward the free face of the bluff. In effect, the block is afloat on a zone of disturbed clay whose strength properties are those of a confined viscous liquid. As the block starts to move, tension fractures form at the head of the slide and widen as movement progresses. These tension fractures dip toward the slide block at commonly observed angles of about 60° to 70°. As the fractures widen, their hanging wall (on the moving block) loses support and collapses along one or more antithetical fractures to form a graben.

The term "graben," since the earthquake, has become a household word to the populace of Anchorage. The downward piston-like movement of the graben is synchronous with the lateral slippage of the slide block. Continued slippage places more ground under tension behind the slide, and additional fractures form as the slide retrogresses headward. In the more complex slides such as the Government Hill slide, and, especially, the Turnagain Heights slide, this process occurred repeatedly, and a series of alternate horsts and grabens developed regressively, parallel to the direction of slippage. (See figs. 37, 44, and pl. 2).

As the block moves outward, tension at the head of the slide is partly countered by compression at the toe, and pressure ridges form in the flats below. This step may be transient, because continued compression leads to rupture and overthrusting. Both steps occurred in each of the translatory slides and caused extensive local damage. The Turnagain Heights slide not only sheared off at the toe, but it slid under gravity down the mudflat into Knik Arm—at one point it slid more than half a mile. But if resistance in the toe builds up to a level equal to the thrust of the moving block plus the shear resistance of the clay at the slip surface, motion will stop. A modification of this principle was utilized by the Corps of Engineers in designing remedial buttresses. The Corps, however, visualized the driving mechanism of the slide as the "active earth pressure" of the earth mass behind the head of the slide (Shannon and Wilson, Inc., 1964, p. 32) plus the acceleration of earthquake ground motion. But inasmuch as the head of the slide block is plainly under tension during sliding, there obviously can be no "active earth pressure" from the mass behind it. Furthermore, inasmuch as regression and sliding continued after earthquake ground motion had ceased (p. A64), the accelerations of the quake cannot be the driving mechanism either. Rather, sliding was precipitated by gravity as soon as the accelerations of the quake had reduced the shear resistance of the soil to the point of failure. The earthquake was the "trigger"; gravity was the "propellant." Sliding continued as long as the gravitational component on the sliding surface exceeded the shear resistance of the soil. At Turnagain Heights, sliding probably continued a full minute or more after earth shaking had stopped (see page A64).

In plan, each slide was bounded laterally by a series of crescentic tension fractures, which also marked the outer wall of the outermost graben. Subordinate crescentic tension fractures—bounding potential slide blocks—commonly extended headward, outside the slide proper, scores or hundreds of feet beyond the bounding fractures. At Turnagain Heights, numerous crescentic tension fractures extended back through the subdivision as much as 2,200 feet beyond the head of the slide (pl. 1); had the earthquake lasted longer, sliding undoubtedly would have retrogressed back into that area. "Retrogression," as applied to landslides, means a headward expansion of the slide. (See Varnes, 1958, p. 31.)

Extensive internal fracturing also characterized all slides, although internal fracturing was minimal in the L Street slide. The Native Hospital slide contained abundant radial fractures; as noted before, this slide occupied a salient or "nose" on the bluff line, and the radial fractures undoubtedly were tensional responses to lateral spreading.

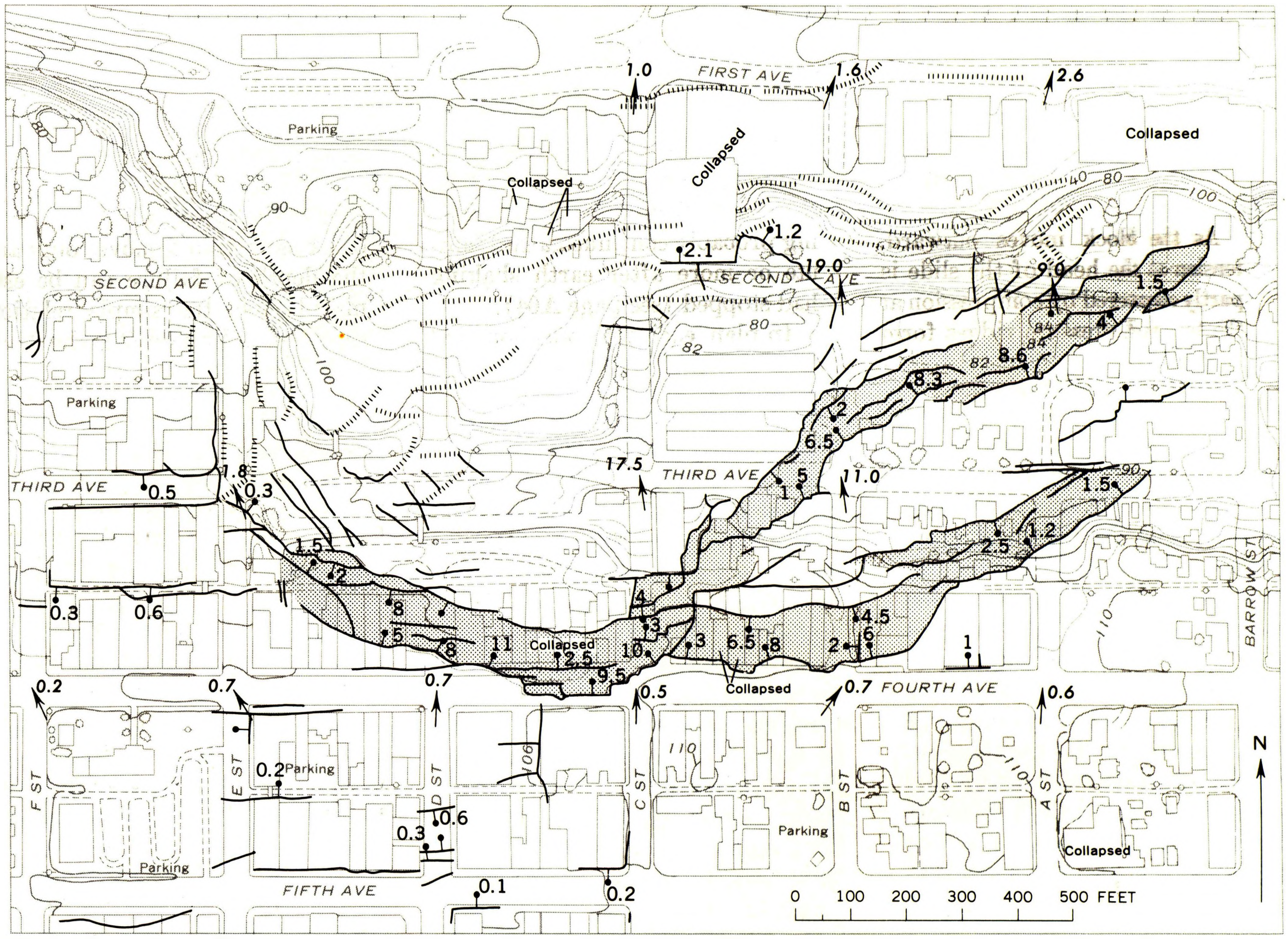
#### THE GRABEN RULE

A close approximation of the depth of failure is prerequisite to planning remedial or stabilization procedures. A significant geometric relationship, here called the "graben rule," affords a rapid, yet reliable, estimate. The graben rule should apply to any translatory slide in which flowage of material from the zone of failure has not been excessive. Because the cross-sectional area of the graben trough approximates the cross-sectional area of the space voided behind the block as the block moves outward, the depth of failure can be estimated from the simple relationship $D=A/l$ where $D$ is the depth of failure, $A$ is the cross-sectional area of the graben, and $l$ is the lateral displacement of the block. For example, the Fourth Avenue graben, on the average, was about 11 feet deep, 100 feet across, and had an area ($A$) of about 1,100 square feet. Its maximum lateral displacement ($l$) was about 17½ feet, as determined by postquake resurveys. The calculated depth of failure ($D$) was about 63 feet, or about 43 feet above mean sea level. Subsurface exploration, though somewhat indecisive in its results, yielded a nearly identical figure.

#### INDIVIDUAL TRANSLATORY LANDSLIDES

##### Fourth Avenue Slide

The Fourth Avenue slide involved all or parts of 14 city blocks in a roughly oval area of about 36 acres, containing perhaps 2 million cubic yards of earth, centered at the north side of downtown Anchorage (fig. 25). It was bounded headward on the south by Fourth Avenue, on the west by E Street, on the north approximately by First Avenue, and on the east somewhat indefinitely by Barrow Street. Its length north to south in the direction of slippage was about 1,050 feet; east to west it was about 1,800 feet across. Strong fracturing and related ground displacements extended 1½ blocks (about 450 feet) or so south of the slide proper, where considerable damage was inflicted on buildings,




Base by U.S. Army Corps of Engineers

Compiled from aerial photographs and data taken from reports of Engineering Geology Evaluation Group (1964) and Shannon and Wilson, Inc, (1964)

EXPLANATION

1.5

Fracture, showing downthrown side and displacement in feet

Pressure ridge

Graben

9.0

Lateral displacement of bench mark, in feet. New position at point of arrow. No appreciable movement since earthquake

25.—Fourth Avenue landslide area, Anchorage, Alaska.

streets, and sidewalks. Minor displacements extended as far south as 600 feet. Eyewitnesses reported that sliding began about 2 minutes after the earthquake started and stopped about the same time as the earthquake (Grantz, Plafker, and Kachadoorian, 1964, p. 15).

Most of the damaging tensional fractures within the slide mass were between Second and Fourth Avenues in the east part of the slide and between Third and Fourth Avenues in the west part. North from those areas, downslope, compressional movements in the foot of the slide caused numerous pressure ridges.

Ground dislocations were most severe in the graben areas at the head of the slide along the north side of Fourth Avenue (fig. 4). Ironically, these areas also had the highest property evaluations. Many small business and commercial buildings, apartment houses, and residences were destroyed or badly damaged. Vacant lots and parking spaces within the slide block to the north were little disturbed. Just east of C Street the main graben bifurcated, and two long belts of severe damage extended northeast toward Barrow Street.

Between B and D Streets, where the destruction was total, the main graben had a width of 100 to 150 feet and a depth of as much as 11 feet. Lateral displacements near the center of the slide just north of the graben were as much as 17½ feet toward the north, according to surveys by the City Engineer's office. Near the foot of the bluff on Second Avenue a block east of B Street, a complex of pressure ridges was pushed up by 19 feet of lateral displacement—apparently the greatest local slippage in the slide. Although several days elapsed after the quake before resurveys were started, there appears to have been no movement since the main quake. None of the strong aftershocks caused measurable movement.

Subsurface exploration of the Fourth Avenue slide was started by the Engineering Geology Evaluation Group soon after the earthquake, and was expanded and concluded by the Corps of Engineers. The findings of these groups indicate that failure occurred at the top of the sensitive zone of the Bootlegger Cove Clay at a depth of about 60 feet (48 feet above mean sea level). Additional failures may have occurred at greater depths, inasmuch as many pressure ridges formed at the surface in the toe of the slide at altitudes below 48 feet, unless, as suggested by their sharply peaked crests and steep sides (fig. 26), the ridges were caused by simple surface translations of the rigid frozen surface layer of the soil.

Shear-strength profiles measured near the head of the slide by Shannon and Wilson, Inc. (1964, p. 41) show that the clay decreases in strength from about 1.0 tsf at altitude 70 (top of clay) to as low as 0.25 tsf between altitudes 45 and 20, then increases in strength to about 0.75 tsf at 15 feet below sea level. The zone of maximum sensitivity coincides with the zone of minimum strength, and failure appears to have followed spontaneous liquefaction of sand layers as well as loss of strength in silty clay.

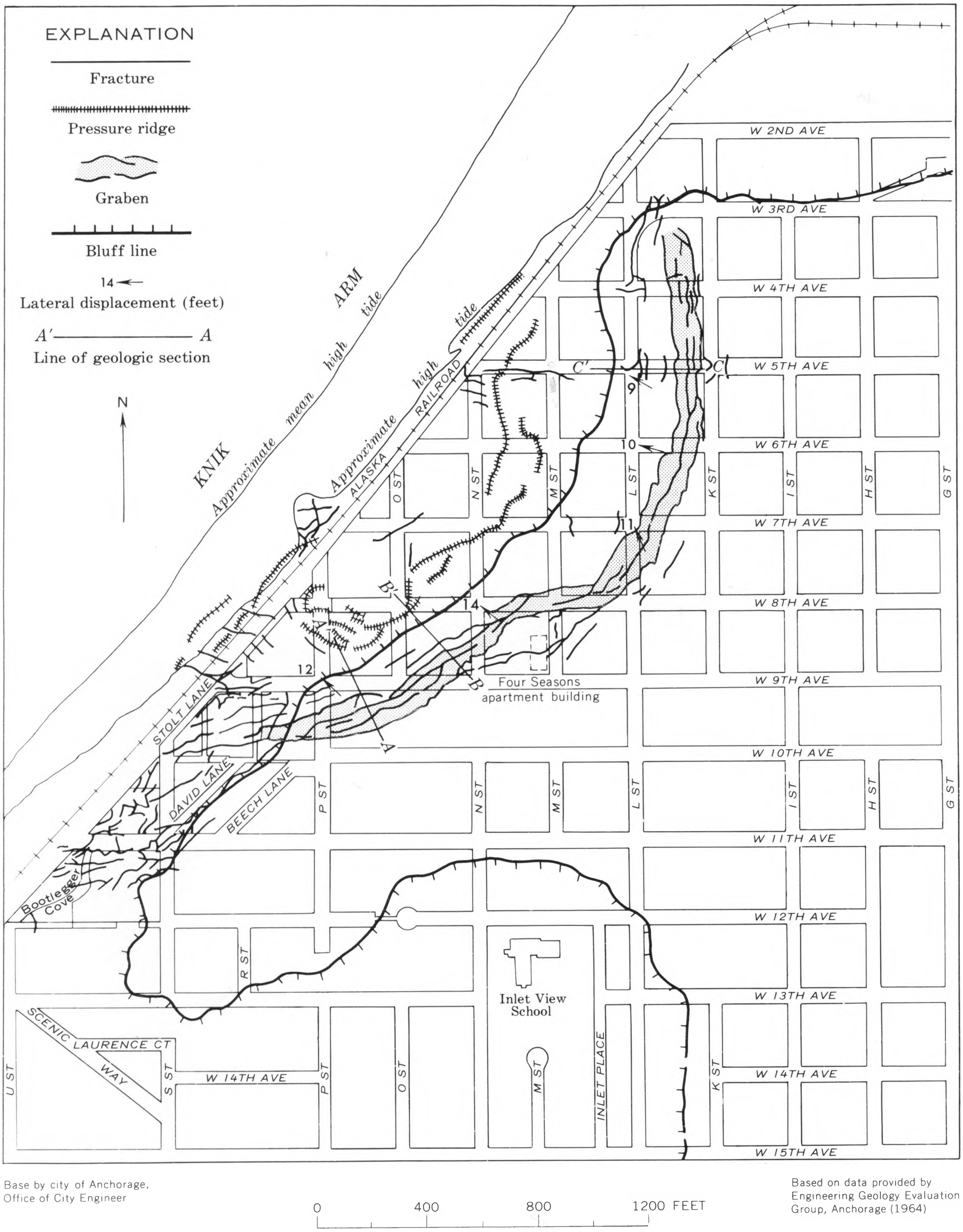
#### L Street Slide

The L Street slide involved all or parts of about 30 city blocks in the northwest part of Anchorage adjacent to Knik Arm (fig. 27). It extended northeast about 4,800 feet along the bluff and had a maximum breadth northwest across the bluff of about 1,200 feet, parallel to the direction of slippage. It reached about a block and a half back from the bluff line into thickly settled residential and commercial neighborhoods of Anchorage. In all, about 72 acres were included between the graben at the head of the slide and the outermost pressure ridges at the toe. The total volume probably approached 6 million cubic yards though an accurate estimate is difficult. Much of the 72-acre area, however, was little if at all damaged, despite lateral shifting of as much as 14 feet. Most of the damage was concentrated along the graben, which with marginal fractures covered about 14 acres, and along the pressure ridges, which were mainly linear features but which involved properties of a total area of perhaps 7 to 8 acres. There was very little fracturing much beyond the bounding fractures of the graben, and there was not much fracturing within the slide mass itself except for the graben area. Eyewitness reports indicate that slippage began during the latter part of the earthquake (Shannon and Wilson, Inc., 1964, p. 53).

The whimsical pattern of destruction in Anchorage was perhaps best exemplified by the L Street slide; here wrecked buildings inside or astride the graben faced almost undamaged adjacent properties on either side (fig. 28). The irregular trends of the bounding fractures further compounded the fateful selectivity of the slide. Damage was equally capricious, moreover, in the compressed areas at the toe of the slide; here individual dwellings were buckled or shoved by pressure ridges that as often as not left adjoining buildings undisturbed (fig. 29).

The graben itself formed a broad arc in plan, concave toward the slide block. It extended south from West Third Avenue between K and L Streets and curved westward to R Street between Ninth and Tenth Avenues. It was about 3,600 feet long and had a maximum width of about 250 feet; generally, its width was between 150 and 200 feet (fig. 30). Its depth—that is, the displacement of the down-dropped block—reached a maximum of about 10 feet; the displacement was greater south of Sixth Avenue than north. Overall, the graben looked like a dry canal or a streambed, and, when contrasted with the lack of damage on either side, it stirred considerable speculation in the minds of early viewers. One popular magazine account stated that it resulted from collapse of an old

26.—Sharp-crested pressure ridge at Second Avenue and C Street, Anchorage. Probably caused by shallow translation of frozen surface layer. Note smaller pressure ridge in street part way up block and toppled chimney of building behind car. Photograph by Mac's Foto, Anchorage.




Base by city of Anchorage, Office of City Engineer

Based on data provided by Engineering Geology Evaluation Group, Anchorage (1964)

27.—L Street slide area, Anchorage, Alaska. Geologic cross sections are shown in figure 30.

28.—Wrecked dwelling astride boundling fracture, L Street graben at Eighth Avenue and N Street. Damage caused entirely by ground displacement along fracture.

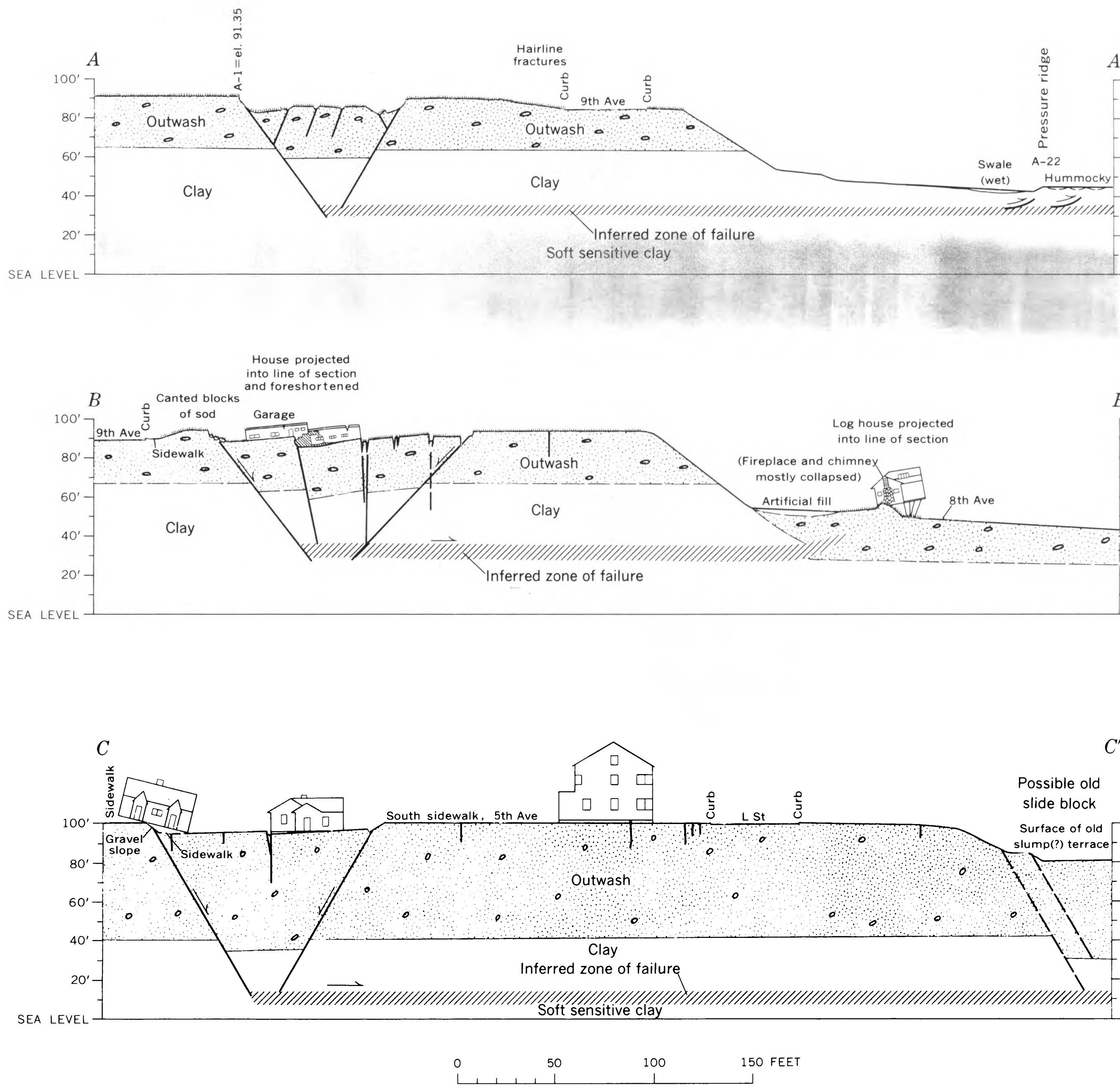
29.—House pushed off foundation by pressure ridge at toe of L Street slide. Well-framed house not otherwise visibly damaged. Push must have been shallow and nearly horizontal.

buried but melted-out ice-filled channel!

Many buildings on the slide block, including a six-story apartment building carried 10 feet laterally, sustained little or no damage, but utility service to the slide block was curtailed. Overhead wires and buried water, gas, and sewer lines all were disrupted where they crossed the graben. In most places, entirely new emergency connections had to be made before service could be restored. Many buildings, therefore, which were not themselves damaged were nevertheless evacuated.

Pressure ridges below the slide block were concentrated mostly in a zone about 200 feet wide close to the foot of the bluff at 40 to 55 feet above sea level (figs. 27, 30). A few extended beyond The Alaska Railroad tracks, which were damaged by lateral shove, and even onto the tidal flat of Knik Arm about 500 feet from the foot of the bluff and only about 15 feet above mean sea level. Individual ridges ranged in length from a few tens of feet to more than 600 feet. They ranged in width from sharply peaked ridges 10 to 15 feet across to broad gentle budges several tens of feet across. Most were less than 3 feet high, but a few were as high as 7 feet. Many were ruptured and overthrust toward Knik Arm.

The available evidence, both surface and subsurface, favors the view that the pressure ridges were caused chiefly by shallow compressional translations of the frozen superficial soil mantle, which in turn was shoved laterally by the sliding block behind. This mantle was only a few feet thick, but it was highly competent in its frozen state. Some indication of its strength was provided at one point where a small chunk of partly buried concrete caught in a surface fracture was so firmly held in place that it parted in half instead of breaking free from the frozen soil. In further support of the shallow depth concept, the altitude of the




**30.**—Geologic section through the L Street slide. In section $C$–$C'$ the toe of the slide is to the right of $C'$.

pressure ridges above sea level was very close to the inferred altitude of failure beneath the main slide block.

Damage caused by pressure ridges was extensive in the L Street slide although it was generally less devastating and less spectacular than that caused by tensional cracking and displacement in the graben area. Even so, losses to many small dwellings totaled thousands of dollars; more expensive losses were sustained by larger structures. Some buildings that showed little evidence of damage on the outside sustained severe structural damage within. Utilities were badly damaged also.

Subsurface exploration of the L Street slide, as of the Fourth Avenue slide, was started by the Engineering Geology Evaluation Group soon after the earthquake, to learn the causes of sliding, to predict future behavior of the slide, and to recommend courses of action to be taken by the city. Subsequently, this work was transferred to the Corps of Engineers.

Extensive drilling and sampling by the Corps, augmented by surface studies, indicated a complex and varied stratigraphy, modified by erosion downslope from the bluff line and by prior landsliding of undetermined age. Shannon and Wilson, Inc., (1964, p. 54) reported the following general sequence of stratigraphy:

1. At the top, outwash sand and gravel, generally 40 to 60 feet thick.
2. Stiff, silty clay, about 30 to 50 feet thick, and interbedded layers of sand and silt. This clay had a static shear strength generally greater than 0.5 tsf.
3. Silty clay, sensitive, 20 to 30 feet thick, having very sensitive layers of clayey silt, silt, and fine sand. Static shear strengths ranged from about 0.2 tsf to more than 0.5 tsf, and sensitivity ranged from about 5 to 30.
4. Stiff silty clay containing scattered sand grains, pebbles, and lenses of sand; thickness undetermined but greater than 50 feet. Static shear strength in this unit generally exceeded 0.5 tsf and increased with depth.

Despite numerous borings, the position of the zone of failure in the L Street slide was not definitely established, although zones of very low strength and high sensitivity were clearly indicated. Presumably, slippage occurred at the top of the sensitive zone, where the strength was lowest and the shearing stress was highest (Shannon and Wilson, Inc., 1964, p. 55). This position varied appreciably—from about 55 to 85 feet below ground surface (45 to 15 feet above sea level)—in different drilling locations. Estimates based on the graben rule place the zone of failure within that range also. Pressure ridges at the foot of the slide lie within the same range of altitudes. Therefore, if failure beneath the block was within that range, the pressure ridges—as noted above—must have been caused by shallow translations of the relatively thin frozen surface layer—a sort of shove effect—rather than by deeper surfaceward shear. If so, some of the remedial buttresses proposed by the Corps of Engineers (Shannon and Wilson, Inc., 1964, pl. 9.6) would require design changes to be effective in the event of future movement.

Failure by liquefaction may also have occurred in saturated sand layers within the clay because several such layers were penetrated during the drilling program. Remolding would not necessarily lead to strengthening of these sand layers, unless repacking led to consolidation accompanied by escape of excess pore water. Unless these strengthening conditions have been met, the sand could fail again under similar circumstances as before.

#### Native Hospital Slide

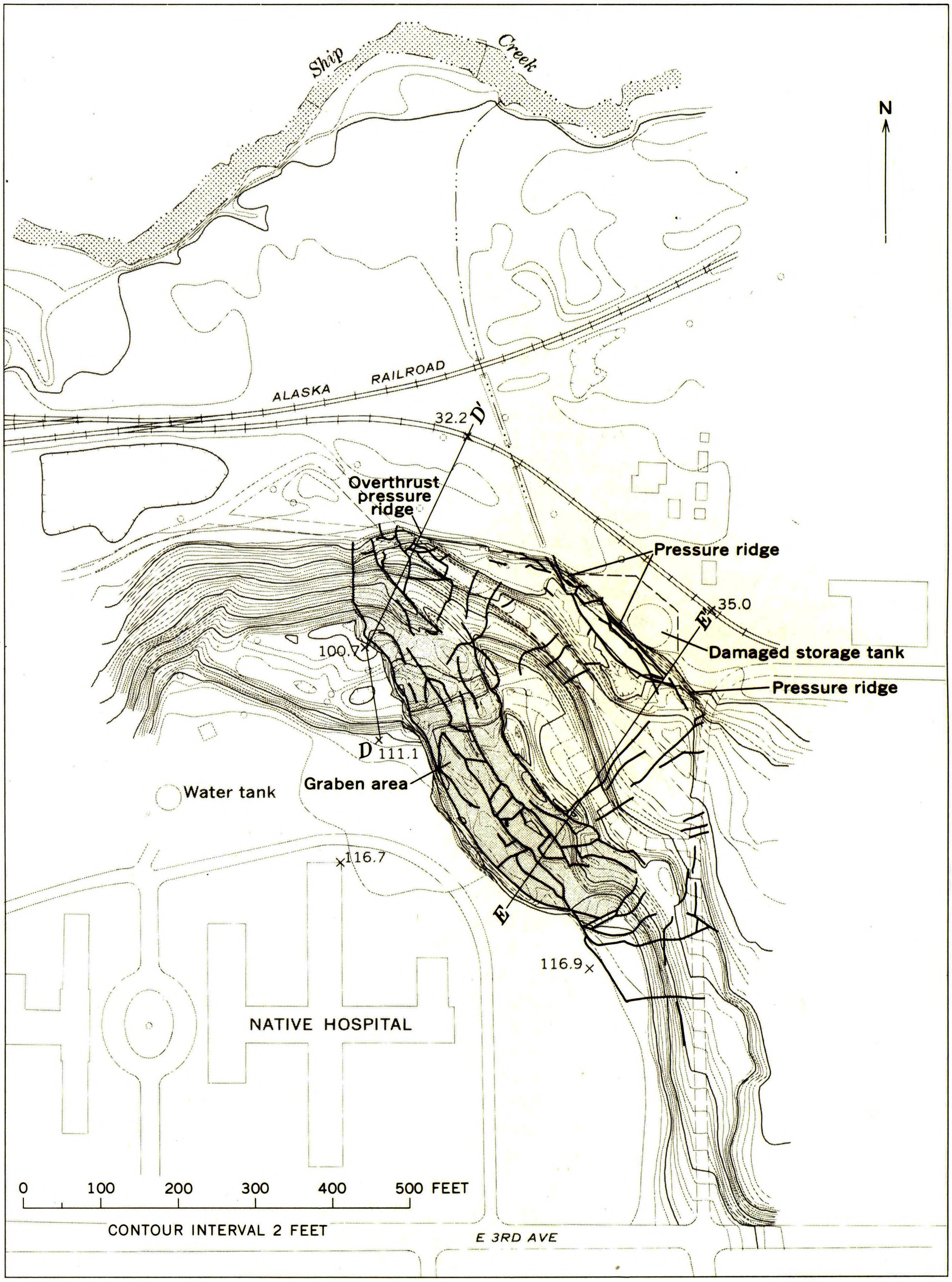
The Native Hospital slide, or First Avenue slide [2] as it has occasionally been called, disrupted part of the grounds of the Alaska Native Service Hospital and wrecked a fuel-storage tank at the foot of the bluff (figs. 31, 32). Although it was a small slide and not a very destructive one, it was of unusual scientific interest because of its clear portrayal of repeated translatory landsliding in the same area. The slide of March 27, 1964, transected an earlier slide of identical habit and exposed the older graben in full cross section (fig. 32) in the headward scarp of the present graben. This site of failure, therefore, seems to answer the question as to whether natural remolding and consolidation of the clay after sliding is sufficient in itself to forestall further sliding—it obviously was not, in the Native Hospital slide. Most other slide areas at Anchorage and vicinity also presented evidence of multiple sliding, but none did it as clearly as the Native Hospital slide. Multiple sliding is discussed further on pages A66–A67.

The Native Hospital slide involved only slightly more than 4 acres of ground and perhaps 360,000 cubic yards of earth. From flank to flank—northwest to southeast—it was about 650 feet across; from head to toe it was about 350 feet. Most of the disruption was in the slopes of a cuspate salient on the bluff line behind the hospital, but about three-fourths of an acre of upland behind the hospital collapsed into the graben as the main headward fracture opened up 120 feet or so back from the rim. Part of the parking lot of the hospital and an area of lawn-covered grounds were destroyed. Fractures that extended back from the slide damaged the hospital building itself.

The graben was exceptionally large for the size of the slide. Its disproportionate size is attributed to the large apparent lateral slippage of the slide. Arcuate in plan, it was about 600 feet long; it had a mean width of about 120 feet and a downthrow (depth) of as much as 25 feet which averaged about 20 feet. Its depth diminished rapidly toward the south, where horizontal slippage died out also.

Near the center of the slide, the downdropped graben wedge broke off precisely at the bluff line and tilted headward as it collapsed, so that the displacement at the headwall of the graben was greater than at the front wall and gave

[2] Inasmuch as First Avenue does not extend into this part of Anchorage, the name "First Avenue slide" is misleading.

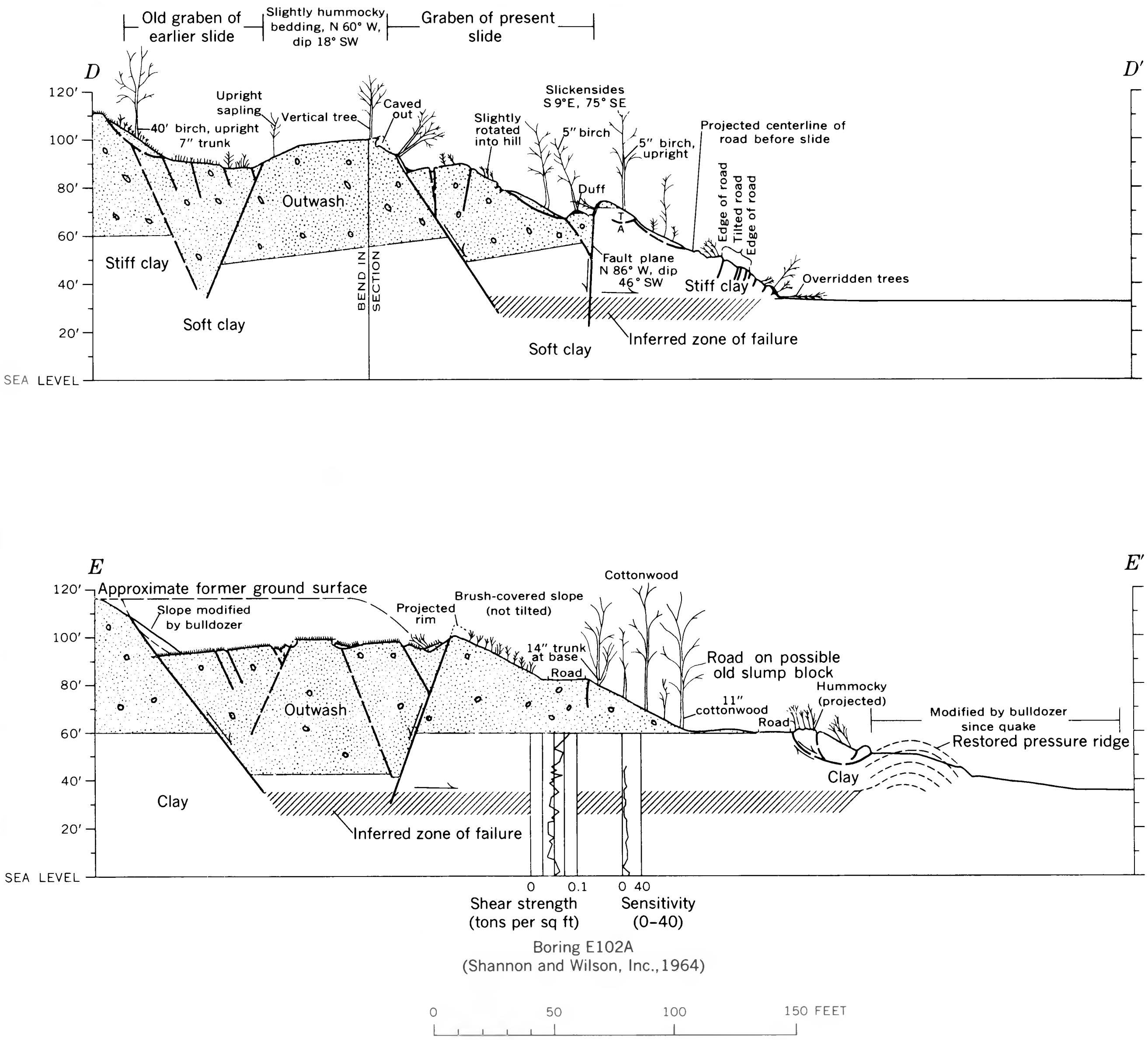



Topography sterocompiled by J. R. Helm, U.S. Geological Survey

Graben indicated by shading

31.—Native Hospital slide area, Anchorage, Alaska. Graben indicated by shading.

32.—Air view (looking south) of Native Hospital slide showing graben and pressure ridge. The scar of an older landslide is transected by the slide of March 27, 1964. Photograph by U.S. Army.




33.—Geologic sections through the Native Hospital slide, Anchorage, Alaska. Section *D–D′* transects the graben of an earlier landslide (upper left). Boring data from Shannon and Wilson, Inc. (1964).

the slide a pseudorotational appearance; however, the causative failure and dominant movements were horizontal, as verified by the perfectly upright attitude of trees in the main slide block. Longitudinally, the graben wedge was rent by great gaping tension cracks. The total relations are well illustrated by the aerial view (fig. 32) and by the cross sections (fig. 33).

Inasmuch as the slide moved outward from a salient, it was unconfined laterally. Accordingly, it spread as it moved outward, and tension cracks opened in a fanlike arrangement at the periphery. Some of these tension cracks are visible in figure 32. They have been plotted in figure 31.

A large shallow-rooted pressure ridge about 500 feet long at the toe of the slide absorbed much of the thrust of the slide. At its greatest development the ridge was about 15 feet high and 40 to 50 feet wide. It wrecked the fuel-storage tank at the foot of the bluff (fig. 32) and overrode overturned trees where it thrust forward as much as 12 feet (fig. 34).

Exactly how much the Native Hospital slide block was displaced laterally has not been determined, owing to a lack of good prequake horizontal control. Lateral offsets in roads and trails that crossed the block, however, afford a basis for reasonable estimates. These estimates range from 17 feet of slippage near the north flank of

34.—Overthrust toe of Native Hospital slide. Road is bulged up and displaced about 12 feet laterally. Note overridden trees at left.

the slide to 25 feet near the center. Furthermore, at least 15 feet of slippage can be accounted for in the pressure ridge at the toe of the slide. Projections to the theoretical slip surface of the slide, based on these figures and using the graben rule, place the slip surface at a depth of 85 to 95 feet or 25 to 35 feet above sea level. This altitude is very close to the height of the flat on which the pressure ridge formed at the foot of the slide and to the top of the sensitive zone of the Bootlegger Cove Clay beneath the bluff. It is a probable altitude, therefore, for the zone of failure. Thus lateral slippage of 17 to 25 feet within the slide block is geometrically reasonable. Any appreciably smaller slippage would require an inordinately deep slip surface to compensate for the relatively large sectional area of the graben.

Figure 33 shows cross-sectional reconstructions of the Native Hospital slide based on both surface and subsurface data. Although subsurface exploration by the Corps of Engineers did not disclose the surface of rupture, it did clearly define zones of stiff clay above and below a zone of weaker clay. Most of the clay sampled had sensitivities below 10, but the sensitivity of some of it exceeded 30. Several thin sand layers may have contributed to failure by liquefaction.

#### Government Hill Slide

The Government Hill slide caused severe dislocations in the south-facing bluff on the north side of Ship Creek (fig. 35). Altogether, about 11 acres of land was involved, including about 2¼ acres of bottomland below the bluff where the slide passed into an earthflow and spread out in the yards of The Alaska Railroad. The volume of earth involved was about 900,000 cubic yards.

From flank to flank the slide

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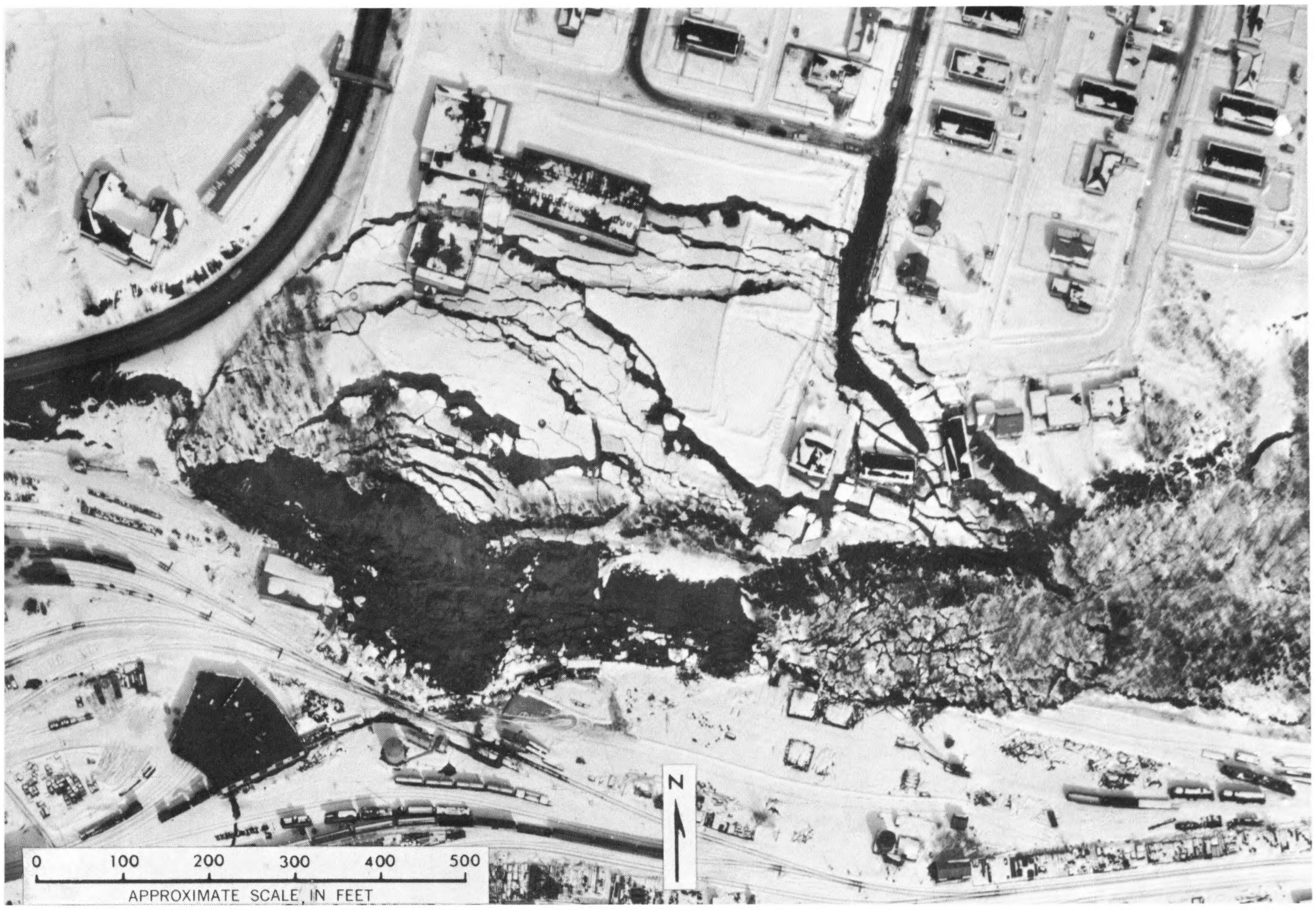



35.—Air view of Government Hill slide, Anchorage, Alaska. Graben plainly discernible. Compare with figure 38. Photograph by Air Photo Tech, Anchorage, Alaska.

had a width of 1,180 feet. From head to toe its greatest length, in the direction of slippage, was about 600 feet. The head of the slide regressed back about 400 feet behind the prequake bluff line, where it intersected the Government Hill Grade School. The slide devastated all but one wing of the school, destroyed two houses, damaged a third, left a fourth (since removed) perched precariously above a cliff, wrecked a shed in the railroad yards at the foot of the bluff, and did extensive damage to railroad equipment and trackage.

If any good fortune accompanied the March 27 earthquake, it was its timing; had school been in session, the diaster would have been unthinkable. The south wing of the school dropped as much as 20 feet vertically into a graben after being sheared cleanly in half (fig. 3). Electric wall clocks stopped at 5:36 p.m. The east wing, also astride a graben, collapsed after being split longitudinally. The playground was a mass of chaotic blocks and open fissures (fig. 36).

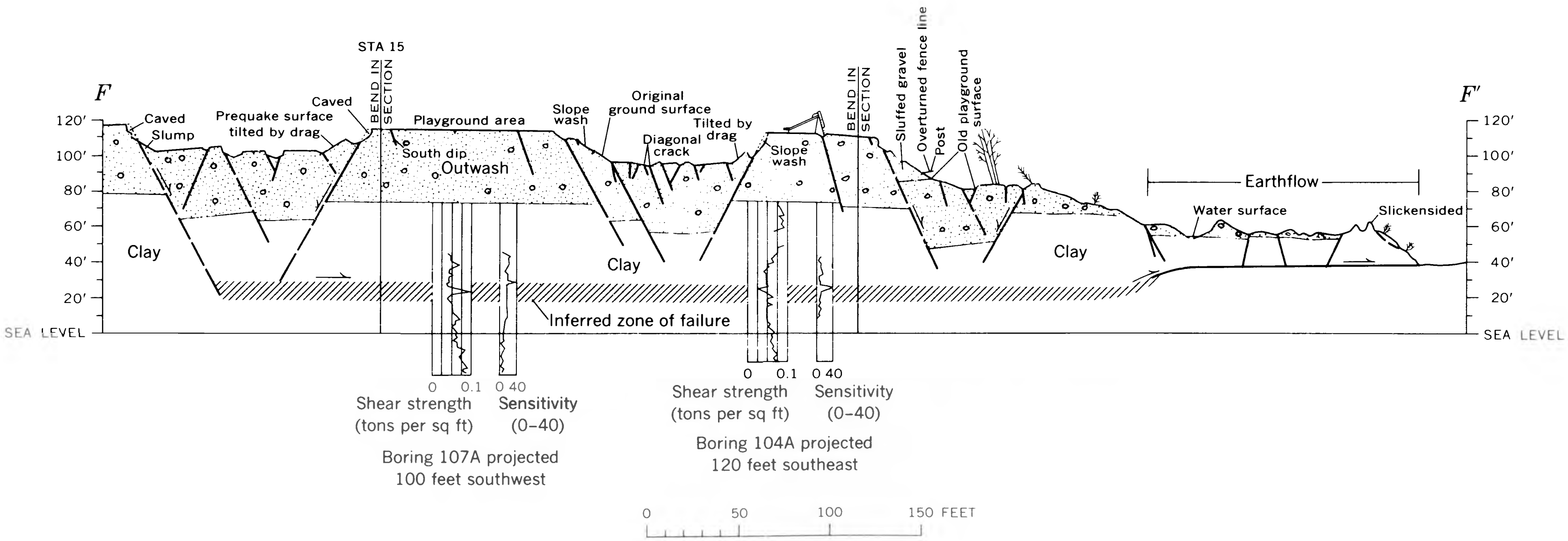
The slide was more complex than the Fourth Avenue, L Street, or Native Hospital slides. Its complexity was a step further toward the total disruption shown by the Turnagain Heights slide (fig. 37). As shown by the map (fig. 38), a complex of arcuate horsts and grabens, more or less concentrically disposed, retrogressed headward as the slide pulled away from the bluff. Two or three partly integrated grabens formed side by side along the crown of the bluff; these were complicated by internal collapses, cracking, and slumping along the face of the bluff. Two additional grabens formed behind the crown on the upland surface. The head of the slide broke away clean; back from the head there was very little cracking and virtually no damage to property.

Each graben was about 100 feet across. The two upland grabens, however, merged laterally, and at their junction the downdropped block was 200 feet across. The outer grabens were deepest—they exceeded 20 feet in depth; the

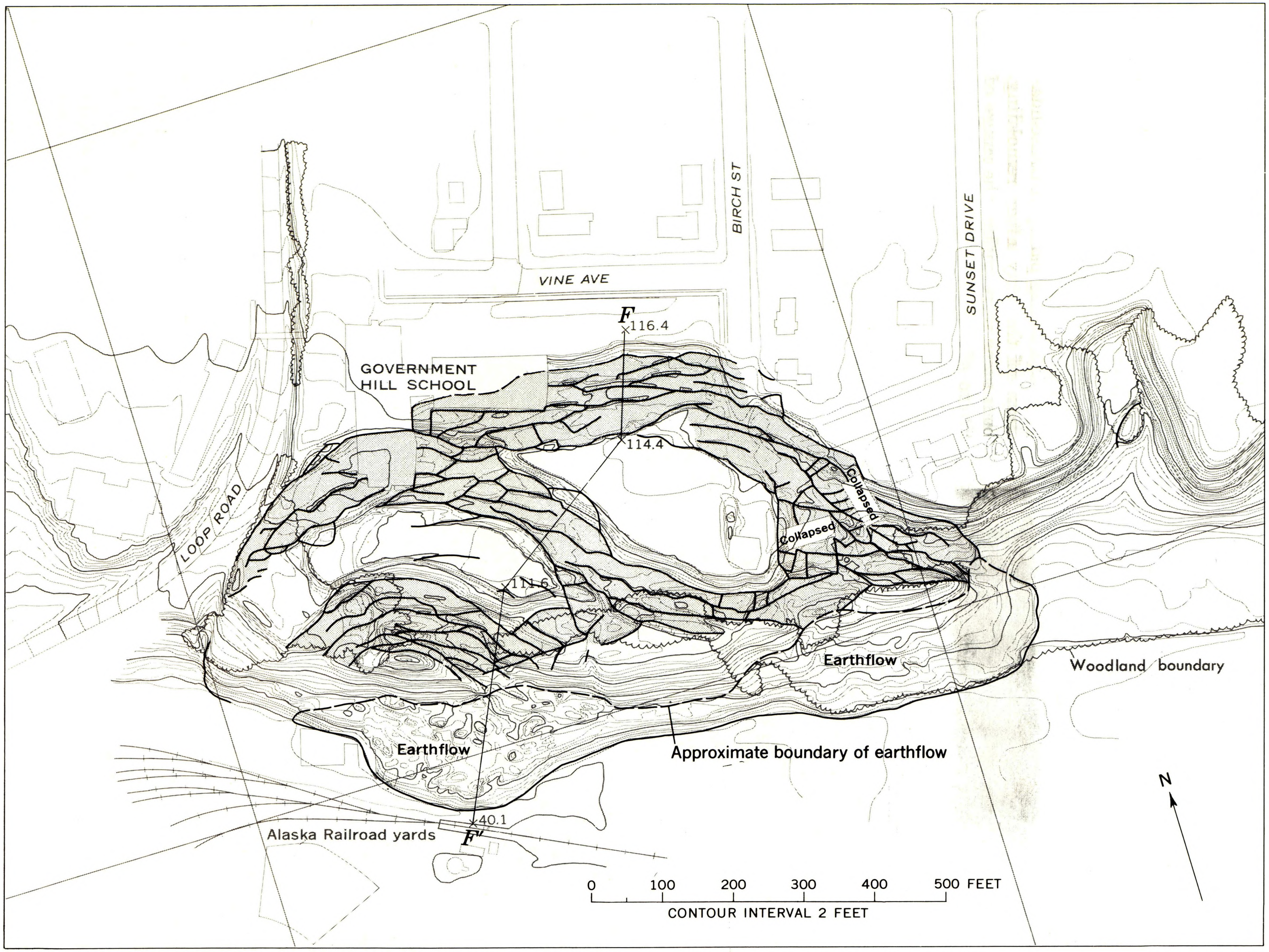
36.—Wreckage of Government Hill School as viewed from the playground, looking west. Graben in foreground is about 12 feet deep. Note undamaged water tower.

medial graben was 14 to 16 feet deep, and the inner graben averaged 12 to 14 feet deep. The intervening horsts glided laterally with slight vertical displacement.

Lateral displacements on the slide varied greatly from place to place inasmuch as the movement of the outermost horst block must have equalled the sum of movements of all blocks behind it plus its own differential movement. Although precise figures for displacement are unavailable, careful comparisons of prequake and postquake aerial photographs give reasonable approximations. The south wing of the elementary school shifted laterally 6 to 7 feet to the southwest. A house at the end of Birch Street, on a horst detached from the main bluff, but otherwise little disturbed, moved about 35 feet southwestward. On the playground south of the school building and across a graben from the building, a children's slide and whirligig moved about 35 feet southwestward. South of the whirligig across another graben, an old concrete blockhouse moved about 65 feet. The outermost points on the toe of the slide moved as much as 150 feet; these points, however, moved partly by flowage.




37.—Geologic section through Government Hill slide. Boring data from Shannon and Wilson, Inc. (1964).




Topography sterocompiled by J. R. Helm and Gaylord Johansen, U.S. Geological Survey

Graben indicated by shading

38.—Map of Government Hill slide, Anchorage, Alaska. Many small fractures have been omitted. Graben areas indicated by shading. Compare with aerial photograph, figure 35.

39.—Homes devastated by Turnagain Heights slide; deep within slide area, upper; at main scarp, lower. About 75 homes were destroyed.

Surface inspection of the bluff line and subsurface studies by the Corps of Engineers indicate that the top of the Bootlegger Cove Clay is somewhat uneven in the Government Hill slide area but averages about 70 feet above sea level (40 to 55 feet below the original ground surface of the bluff). Overlying the clay is outwash sand and pebble gravel.

Shear strength profiles of the Bootlegger Cove Clay measured by Shannon and Wilson, Inc. (1964, p. 94) show the characteristic weak zone, in which static strength ranges from about 0.35 to 0.5 tsf, separated by stiffer clay zones above and below. Scattered throughout the section are lenses of sand and silt. In general, the strength profiles show a gradual decrease in strength to a depth of 85 to 90 feet (altitude 25 to 30 feet) followed by a gradual increase in strength down to the lowest depth tested. The top of the weak zone (shear strength less than 0.5 tsf) generally lay at an altitude of about 40 feet. Most sensitivities were relatively low, perhaps owing partly to consolidation of the clay after remolding, but some were within the range of 20 to 40.

Most of the clay contained a percentage of water less than the liquid limit, but some clay—particularly at critical depths near the indicated depth of failure—had natural water contents equal to or greater than the liquid limit. Thus, the zone of lowest strength and highest sensitivity in the clay coincided with a zone of critically high water-plasticity ratios.

Failure appears to have occurred somewhere between altitudes of about 20 to 40 feet—depths somewhere between 70 and 90 feet below the prequake bluff line. This depth is very close to the top of the weak zone of the clay, and is near the altitude (40 feet) of the flat at the base of the bluff in The Alaska Railroad yards. It also coincides closely with the minimum depth of failure estimated according to the graben rule by using a horizontal translation of 35 feet divided into a graben sectional area of 2,500 square feet.

Several independent factors operating in concert helped precipitate failure. These factors included low shear strength, high sensitivity, and water contents exceeding liquid limits, combined at a depth where static shear stress was critically high, and where added stress conditions were introduced by the accelerations of the earthquake. An additional factor—artificial modification of the toe of the bluff by excavations at the base of the slope—may have contributed to failure by increasing the static shear stress on the slope. Aerial photographs taken in 1962 show plainly that the slope had been modified artificially prior to the earthquake. Shannon and Wilson, Inc. (1964, pl. 13.3), also presented clear evidence that the face of the slope had been modified by removal of material from the toe.

40.—Tree trunk split by tension fracture, Turnagain Heights slide. Many trees were similarly damaged because their roots were firmly embedded in the frozen ground.

**Turnagain Heights Slide**

The Turnagain Heights slide was the largest, most complex, and physiographically most devastating landslide in the Anchorage area (figs. 39, 40; pl. 1). It extended west to east along the bluff line about 8,600 feet. Its maximum headward retrogression from the bluff was about 1,200 feet; its average retrogression into the heavily populated residential section of Turnagain Heights, where 75 homes reportedly were destroyed (fig. 39), was about 500 feet. A total area of about 130 acres was completely devastated by displacements that broke the ground into countless deranged blocks, collapsed and tilted at all odd angles. The ground surface within the slide area behind the prequake bluff line was lowered an average of about 35 feet below the old prequake level. The volume of earth within the slide was about 12½ million cubic yards.

Lateral spreading extended the slide seaward, as the leading edge glided down the mudflat into Knik Arm beyond the low tide line. The leading edge of the slide extended farther out beyond the old bluff line than the head of the slide regressed behind; in most places it reached much farther, even twice as far, before passing below tidewater. Maximum lateral slippage exceeded 2,000 feet. Thus, the landslide, on coming to rest, occupied an area considerably more than twice as large as the original undisturbed area.

As seen in plan, the Turnagain Heights slide was composite. It consisted of two main lobes: a West Turnagain lobe and an East Turnagain lobe, each in front of a separate headwall. Each lobe probably started as a separate landslide, but the two lobes merged laterally at a northward-projecting salient that was spared of sliding on the new bluff line. This salient centered on the mouth of

41.—Furrowed, slickensided clay ridge, Turnagain Heights slide. Ridge is about 20 feet high. Tilted collapsed block at left. Compare with figure 42.

Hood Creek and extended southward along the Hood Creek ravine. For a distance of 150 to 300 feet from the creek this shallow ravine formed an immobile, apparently stable, crack-free buttress that projected into the heart of the slide and divided the slide into east and west counterparts (pl. 1).

Each lobe removed about 4,300 feet of bluff line. The West Turnagain lobe, however, retrogressed headward much farther and extended farther seaward than the East Turnagain lobe, but the fractured area behind the East Turnagain lobe was much broader and more intensely broken than the area behind the West Turnagain lobe. If the East Turnagain lobe had retrogressed to the limit of intensive fracturing, it would have become a nearly exact counterpart of the West Turnagain lobe. Apparently the West Turnagain lobe had approached a state of dynamic stability by the time shaking stopped. In other words, the lobe probably had retrogressed to a point of near equilibrium under the dynamic conditions of the time; it probably would not have reached much farther back if shaking had continued. The ground behind the East Turnagain lobe, on the other hand, was left in a state of precarious equilibrium when shaking ceased; it undoubtedly would have retrogressed much farther—possibly as far as Northern Lights Boulevard—if shaking had continued.

In addition to the slide proper, hundreds of tension fractures (fig. 40; pl. 1) opened behind the head of the slide—as far away as 2,200 feet from the main scarp of the East Turnagain lobe (Engineering Geology Evaluation Group, 1964, pl. 8b). These fractures were disposed concentrically about the two main centers of regression—one south of the East Turnagain lobe between Fish Creek and Hood Creek, and one south of the West Turnagain lobe west of Hood Creek. Besides causing great structural damage to housing in the Turnagain Heights subdivision, these fractures totally disrupted all underground utilities and seriously damaged streets and curbings. Even more ominous, they outlined a potential headward expansion of the landslide that was forestalled only by the cessation of ground shaking. Continued shaking undoubtedly would have involved much more property in the landslide.

The ground behind the East Turnagain lobe had in fact begun to move, and the displacement increased toward the new bluff line. Preliminary studies reported by the Engineering Geology Evaluation Group (1964, p. 17) indicated that the area along Turnagain Parkway between the head of the slide and Northern Lights Boulevard was lengthened by more than 3 feet. Differential movement in this distance was taken up by the opening of tension cracks. There also was subsidence of 6 inches or more within a city block of the new bluff line. Detailed measurements by Dickinson Oswald and Associates, Anchorage, for the Engineering Department, City of Anchorage (summarized by Shannon and Wilson, Inc., 1964, p. 64) indicate that movement occurred chiefly before resurveying began—probably during the strong-motion period of the quake—and that no appreciable movement occurred during a 3-month period following the quake when detailed measurements were still being made.

It thus appears that the weak zone in the Bootlegger Cove Clay under the intensely fractured area between the slide proper and Northern Lights Boulevard did indeed fail, but sufficient shear resistance remained in the block after shaking stopped to prevent further sliding. The area at that time was buttressed, of course, by the passive pressure of the slide debris in front of it.

At the east margin of the slide, the bluff line facing Fish Creek held firm despite a sharp local re-

42.—Sharp-crested clay ridge, Turnagain Heights slide. Collapsed blocks tilted toward ridge on both flanks. Note horizontal stratification in ridge. Compare with figure 41.

lief of 40 feet or more. The slide, in fact, moved northwest almost diametrically away from Fish Creek, leaving behind a somewhat cracked but otherwise little-damaged salient or riblike buttress 70 to 400 feet wide projecting north along Loussac Drive. Conditions at Fish Creek, thus, were comparable to those at Hood Creek at the far side of the East Turnagain lobe.

One can but conclude that the shallow valleys of Fish Creek and Hood Creek were instrumental in limiting ground failure in the Turnagain Heights slide. Their function is unclear, but they may have acted as natural sumps that partly dewatered, and hence stabilized, the adjacent ground in the slopes of the ravines and in the bordering uplands some distance back from the ravines. This supposition gains support from subsurface data at Fish Creek where a boring by the Corps of Engineers penetrated clay of high strength, low sensitivity, and low water-plasticity ratios at the critical depths where failure had occurred nearby. The boring nearest Hood Creek (200 feet southeast of the creek) showed high sensitivity and low shear strength at the critical depth, but it showed high strength and low sensitivity immediately above. Fish Creek (altitude near mean sea level) had eroded its channel to the depth of the sensitive zone, but Hood Creek—a smaller stream—had not. But by cutting through the overlying clays, Hood Creek must have effectively lowered the water table in the adjacent ground, and in so doing further stiffened the upper clays. A drill hole closer to Hood Creek might have provided more conclusive data.

Hundreds of sharp-crested clay ridges alternating with collapsed troughs, and oriented normal to the direction of slippage, distinguished the disruption pattern of the Turnagain Heights slide from all other slides at Anchorage. The ridges, however, were exact homologs of the horsts of the Government Hill slide; the troughs were exact homologs of the grabens. The chief distinction of the Turnagain Heights slide, therefore, other than its size, was the utter totality of its disruption. Its pattern is well portrayed by the topographic map (pl. 1) and by the strip map and section (pl. 2).

Most of the clay ridges ranged in height from about 10 to 15 feet, but a few were more than 20 feet high. They were as much as 300 feet long and were spaced 50 to 150 feet apart. Their steep sides, which sloped 60° to 70°, were furrowed and grooved by slippage of one surface against another (figs. 41, 42). On the average, the ridges were sharper crested and more closely spaced in the West Turnagain lobe than in the East Turnagain lobe.

Stratification was greatly disturbed in the collapsed areas between ridges, but it was little disturbed in the ridges themselves; the ridges were displaced virtually without rotation. There was, moreover, little vertical displacement as the ridges glided toward Knik Arm. Detailed studies along the disrupted seaward projection of Turnagain Parkway (pl. 2) indicated that clay ridges which were displaced as much as 300 feet laterally were reduced only about 12 feet vertically. Some of this reduction may have been due to attrition at the slip surface or to flowage in the sensitized clay below, but most of it probably was due to a seaward slope on the slip surface itself. This slope, then, must have had an inclination of about 4 percent.

The complete disruption of the ground surface within the Turnagain Heights slide may have been due to several factors in combination—including the shallow depth to the zone of failure—but the unhindered movement of the slide down the wet mudflat toward Knik Arm certainly was paramount. In every other translatory slide at Anchorage, slippage was resisted by dry or frozen ground at the toe and by an abrupt flattening of the ground slope at the foot of the slide below the bluff line. At Turnagain Heights, however, the slide broke away from the bluff within the intertidal zone and slid out directly onto the sloping tidal muds, which themselves were wet and sensitive. At the flanks of the slide, the tidal flat slopes about 3°, or 5 to 6 percent; before failure it probably had a comparable slope in front of the slide also.

Shear resistance of dry or frozen ground in front of a given slide must have had a natural buttressing effect that in turn must have been a factor in the resistance of the slide to slippage. All the translatory slides at Anchorage possessed such natural buttresses except the Turnagain Heights slide. The ground at the top of the intertidal zone, where the Turnagain Heights slide sheared to the surface, had previously had little opportunity to desiccate, and the thickness of the frozen layer must have been minimal—if indeed, the ground there was frozen at all. Reconnaissance along the foot of the bluff several years prior to the earthquake, moreover, disclosed a prevalence of saturation, slumpage, and flowage in the clay at the foot of the bluff. More or less continuous slumpage, abetted by wave and tidal action which constantly removed the accumulated debris, prevented drying of the naturally wet clay and kept the bluff line in a precarious state of repose.

Part of the slip surface of the slide was left as a window near the west end of the slide, where the overlying debris slid free out to tidewater (fig. 43). Sliding, however, was not confined to this one surface. On the contrary, there is every indication that blocks slid out one on another at higher levels in the same vicinity. In other places, failure may have occurred mainly at some other level. But this surface was plainly an important locus of shearing in this particular part of the landslide.

Altogether, about a quarter of an acre of the slip surface was uncovered. The surface was mantled here and there by small pyramidal mounds and blobs of clay. Long furrows and welts, oriented in the direction of slippage (N. 3° W.) and extending the length of the exposure, were well preserved 6 weeks after the earthquake, despite desiccation and cracking.

The surface itself passed below highest tide at its seaward margin. It sloped about 15 feet per 100 feet, on the average, but it was convex; the outer edge was steeper than the inner edge. The exposed surface was precisely on the projection of the old prequake shoreline, so there is no doubt as to where the slide sheared off with reference to the prequake topography; it must have sheared to the ground surface at tidewater at the very foot of the bluff.

Mounds of clay left on the slip surface, showing evidence of having been overridden themselves, were grooved and slickensided on their tops and flanks. Their sides sloped steeply down to the slip surface on which they rested, angles of 40° to 60°.

In places the slip surface was overlain by blocks of peat and forest duff. Frozen at the time of the quake, these blocks must have been lowered onto the slip surface as the intervening incompetent clay slid and flowed out from under them. The conclusion seems inescapable that the clay overlying the slip surface glided seaward primarily under the influence of gravity; a window to the slip surface could have been exposed in no other way.

At the extreme east end of the slide the slip surface did not break through to the ground surface. Instead, it died out laterally, as the thrust of the sliding mass was taken up by a large pressure ridge in the tidal silts just below the foot of the bluff (fig. 44). This ridge cut dramatically at an oblique angle across an old riprap embankment placed along the beach at the foot of the bluff—years before the earthquake—to retard marine erosion. The embankment was arched up into an anticline where the pressure ridge passed beneath it. The ridge was about 700 feet long, as much as 50 feet wide, and 10 to 15 feet high on the landward side. On the seaward side it was higher and was modified by subsidiary slumping on its oversteepened flank. Just west of the pressure ridge the translatory movement of the landslide was greater, and the slide itself was correspondingly more complex. The tidal silts failed, and the overriding slide blocks glided far out into the Knik Arm.

Subsurface explorations of the Turnagain Heights slide were made by the Corps of Engineers after an initial investigation was started by the Engineering Geology Evaluation Group. Undisturbed samples for field and labo-

43.—Slip surface of Turnagain Heights slide exposed near west margin of slide. Furrows and welts still well preserved despite desiccation and weathering. Point Woronzof and Knik Arm in distance.

ratory tests were collected from borings at 42 localities within the slide and adjacent to it. In some places the low strength of the clay made it difficult to collect undisturbed samples; some of this clay may have lost strength by remolding.

Surface and subsurface observations showed that the Bootlegger Cove Clay is mantled by outwash sand of somewhat varied thickness; the sand is about 20 feet thick at the east end of the slide and tapers nearly to zero at the west end. The clay is as much as 100 feet thick. Shear-strength profiles showed that the clay diminished gradually in strength from about 1 tsf at the top of the clay to about 0.25 tsf at an altitude of 15 to 20 feet above sea level; it then increased gradually in strength to about 0.6 tsf at some depth (generally about 30 feet) below sea level. Values of minimum strength in some borings were much less than 0.25 tsf, again perhaps because of partial remolding of disturbed sensitive clay.

The depth of lowest strength commonly coincided with the depth of highest sensitivity and highest water-plasticity ratios. Throughout much of the Turnagain Heights area the clay at lowest shear strength contained water in excess of its liquid limit and had sensitivities greater than 40. Remolded, this clay had a shear strength of about 0.02 tsf (Shannon and Wilson, Inc., 1964, p. 65).

Thus, the depth of failure probably was 15 to 20 feet above sea level, at or near the top of the zone of lowest shear strength. This altitude also was the height of the knick point or slope break at the base of the bluff before the earthquake—the position at which the slide evidently broke to the surface and glided seaward down the mudflat.

The mode of failure of the Turnagain Heights slide differs in degree rather than in kind from the other translatory slides of the Anchorage area. Some idea of the sequence of failure can be had by examining different parts of the slide where movements had gone to different stages of completion by the time the earthquake stopped. At the extreme east end of the slide near the mouth of Fish Creek, for example, the failure compared morphologically with failure at the Native Hospital slide and near the east flank of the Fourth Avenue slide. A little farther west where the deterioration was somewhat greater, the failure was comparable to that in the Government Hill slide.

As stated previously, the slide was composite in that it was formed by the lateral merger of two main lobes. Within each of the main lobes there were subsidiary lobes that apparently formed independently at the bluff line, then merged laterally as they retrogressed, and finally slid in unison toward Knik Arm. They moved different distances, and the leading edge of their combined mass at tidewater therefore had a scalloped outline after motion ceased. (See map, pl. 1.) In the East Turnagain lobe, they also retrogressed unevenly into the bluff, making the new bluff line very irregular.

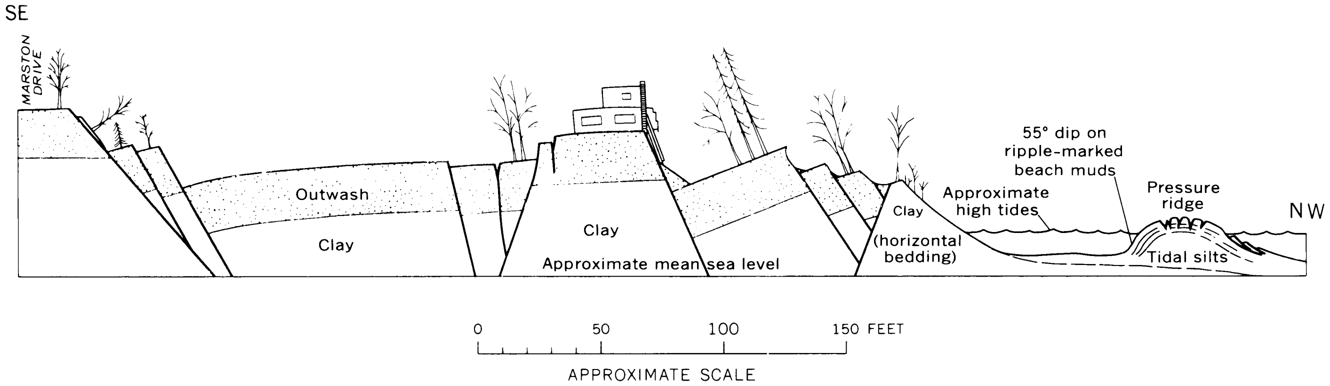
Interference or crowding between subsidiary lobes was accompanied by complex shifting and wrenching of blocks. Such movements may have caused lateral components of displacement of as much as 150 feet in a direction parallel to the old bluff line—as indicated by the postquake positions of objects such as houses transported on the slide toward Knik Arm (Engineering Geology Evaluation Group, 1964, pl. 1). As the blocks pushed and shoved in response to the overall motion of the landslide, they also were lurched sharply from side to side by the vibratory motion of the earthquake. This lurching was mirrored by abrupt deflections in furrows and slickensides preserved on the sides of clay ridges.

Some time after the onset of the earthquake, the bluff line is visualized as having begun to fail along a broad front, but mainly from one or more centers in each main lobe of the slide. Blocks then began to break off headward and to the flanks of each center. Eyewitness accounts indicated that 2 minutes or more elapsed from the start of the quake before the bluff began to give way (Shannon and Wilson, Inc., 1964, p. 64) and that movement continued for some time after the earthquake had subsided. A particularly lucid and informative report was given by Mr. Brooke Marston to Mr. E. R. Bush (Grantz, Plafker, and Kachadoorian, 1964, p. 14):

> I was driving my automobile westward on McCollie Avenue when the earthquake occurred. I immediately stopped my automobile and waited until the quake subsided. It appeared to me that the car was rocking from north to south. It rocked so violently that I nearly became seasick. From my car I could observe an earth crack alined north-south and opening and closing from east to west. As soon as the quake subsided I proceeded to drive westward to the corner of McCollie Avenue and Turnagain Parkway. After turning right on Turnagain Parkway and driving approximately 180 feet north, I realized the bluff was gone north of my driveway, which paralleled the bluff in an east-west direction. I got out of the car, ran northward toward my driveway, and then saw that the bluff had broken back approximately 300 feet southward from its original edge. Additional slumping of the bluff caused me to return to my car and back southward approximately 180 feet to the corner of McCollie and Turnagain Parkway. After I stopped at this point, the bluff continued to slowly slide northward as I continued to back my auto southward on Turnagain Parkway. The bluff slowly broke away until the corner of Turnagain Parkway and McCollie had slumped northward.
>
> It is my impression that the Turnagain Bluff area slumped northward in segments and that much of the southward receding of the bluff occurred after the major earthquake had subsided.

From Mr. Marston's account, it is clear that large-scale ground displacements were still in progress after the earthquake had stopped. After the quake, during the time that Mr. Marston drove down McCollie Avenue, turned north down Turnagain Parkway, got out of his car and returned, then backed south along Turnagain Parkway, stopped, and resumed backing—all this after the shaking had stopped—the bluff continued to regress southward. It regressed at least 200 feet, and the elapsed time must have been a full minute or more. If Mr. Marston had been driving 5 miles per hour, for example, including backing but not counting stops, he would have needed about 55 seconds to go 400 feet. He probably drove appreciably farther than 400 feet, however, and his stops must have taken several seconds each.

Small-scale slumping continued for several days after the quake as oversteepened slopes along the new bluff line continued to sluff away and frozen blocks of sand and forest duff began to thaw. One house, left precariously balanced, but not severely damaged on the rim of the bluff at Chilligan Drive, toppled and collapsed several days later. So far as is




44.—Sketch section through eastern part of Turnagain Heights slide. Note pressure ridge, upright blocks at center and to left of pressure ridge, and tilted collapsed blocks between.

known, aftershocks did not cause any additional sliding.

Failure at Turnagain Heights probably occurred near the top of the lowest-strength zone of the Bootlegger Cove Clay, at an altitude of 15 to 20 feet above sea level. Inasmuch as the top of this zone was a subhorizontal surface, the failure itself must have been along a subhorizontal surface also, and the initial movements of the slide must have been translatory. Because the clay contained water in excess of its liquid limit, because the strength of the clay under pulsating or vibratory stress was appreciably less than under static stress, and because the zone of lowest strength coincided with the zone of highest sensitivity, the face and crown of the bluff were—in effect—afloat on a liquefied layer of viscous clay. The bluff then began to glide slowly seaward under the influence of gravity, leaving a gaping crack in its wake. The presence of open cracks—denoting release of tension—is significant; nearly all eyewitness reports allude to them.

Earth materials strained under horizontally directed tension commonly have two sets of tension fractures: one set antithetical to the other such that alternate fractures dip toward and away from one another and both sets are oriented normal to the direction of maximum tension. As the slide began to spread, countless tension fractures disrupted its surface and the surface of the ground behind the slide; after movement stopped, incipient grabens were preserved in the subdivision behind the slide.

Along antithetical fractures dipping south, the unsupported hanging wall generally collapsed toward the north; along fractures dipping north, the hanging wall collapsed toward the south. At a given clay ridge bounded by opposed fractures dipping away from the ridge, adjacent collapsed blocks commonly were tilted toward the ridge on both flanks (figs. 41, 42). Farther from the ridge in the bottom of the adjoining trough or graben, collapsed blocks were tilted into helter-skelter attitudes.

As each new block pulled away from the bluff, the new bluff line was left unsupported on the seaward side. Tension fractures reduced support on the landward side. Blocks were pulled away successively by gravity as long as the shear resistance at the slip surface was exceeded by the force of gravity plus the accelerations of the earthquake. When the earthquake stopped, the force of gravity alone was sufficient to cause large-scale failure for some time afterward. And in the hanging wall of each tension fracture, subordinate blocks collapsed and toppled under their own weight—the entire mass at the same time gliding slowly toward Knik Arm.

After the earthquake, the outermost slide block of the original bluff line was preserved to view only at the extreme east end of the slide (fig. 44) where the thrust of the toe was countered by a pressure ridge. Elsewhere along the front of the slide, where movement was much greater, the toe of the slide and the old bluff line passed beneath the waves of Knik Arm. Only at the east end of the slide, therefore, where the movement did not go to completion, is it possible to visualize what happened at the outset when the bluff first began to fail. Rotational movement at the east end of the slide is ruled out; stratification in the Bootlegger Cove Clay was undisturbed despite lateral shifting of several feet, and trees on the slide block remained perfectly upright. Rotational effects came into play behind the block, however, where the overhanging trailing edge of the block, lacking support, tilted backward and collapsed.

Some idea of the complexity of the disruption is presented in plates 1 and 2 and in a restored section through the slide prepared for the Corps of Engineers by Seed (*in* Shannon and Wilson, Inc., 1964, pl. 10.8). Seed's restoration is in general agreement with figure 43 and with the steps previously outlined, although it emphasizes the part played by rotation in the process and minimizes the effects of translatory motion. Seed's restoration also contains minor geometric inconsistencies. Contrary to Seed's view, translatory motion under gravity is here envisaged as the primary operative mechanism of landsliding, not only at Turnagain Heights but at the other major slides in Anchorage as well. Rotation, as well as flowage, must have occurred in some degree in all the slides, but rotation is viewed as a subordinate process not germane to the failure of the ground, even though it certainly was significant in the disruption of the ground surface.

## LANDSLIDING PRIOR TO THE MARCH 27 EARTHQUAKE

Geologic evidence indicates that landslides similar to those set off by the March 27 earthquake have occurred previously in the Anchorage area. Most of these slides predated the settlement of Anchorage, and it is not known, therefore, whether or not most of them were triggered by earthquakes; the morphology of some, by analogy with the March 27 slides, suggests that earthquakes have had a part. Some inferences as to timing suggest the same. The earthquake of October 3, 1954, clearly triggered slides along The Alaska Railroad near Potter Hill.

Evidence of old landslides in certain areas of Anchorage has been cited elsewhere in this report (p. A31, A49). The evidence is here reiterated, together with evidence of sliding elsewhere. Miller and Dobrovolny (1959) recognized many areas of past landsliding, showing them on their map (pl. 1) as "areas covered by landslides, slumps, or flows," with the prognosis that "shocks, such as those associated with earthquakes, will start moving material that under most conditions is stable" (p. 104).

Old landslides, like recent ones, were concentrated along bluff lines where topographic relief caused high static-shearing stress on the underlying soil. Most old slides have the form of recessed alcoves with uneven terracelike floors. Small slides may have the form of steplike breaks on the sides of the bluffs. Some slumps have left lobate accumulations of earth at the foot of the bluffs. The fact that an area has slid previously apparently is no basis for predicting that it will or will not slide again. Many former landslides were stable during the March 27 earthquake, but in some places new slides were superimposed directly on old ones.

Compelling evidence of previous translatory sliding was found at the site of the Native Hospital slide, where a well-preserved graben was truncated by the slide of March 27. The old slide block and its graben are shown well in figure 32. Birch trees growing on the scarp of the old graben average about 7 inches in trunk diameter at breast height. Trees of that size on well-drained ground in the Anchorage area average about 60 years in age (Reed and Harms, 1956, p. 241). Five years or more may have been required after sliding to establish forest growth on the raw gravel. About 65 years, therefore, is the probable minimum age of the slide, an age which dates to about the turn of the century. Many earthquakes, some of them severe, occurred at about that time in southern Alaska (Davis and Echols, 1962), and one of them might have triggered landslides at Anchorage. The great Yakutat earthquake of 1899 was felt in much of southern Alaska, including points more distant that Anchorage (Tarr and Martin, 1912, p. 68 and pl. 33), but whether the quake's intensity was sufficient to trigger landslides as far away as Anchorage is uncertain.

Remnants of old slides are abundant elsewhere along the bluffs of Ship Creek. Between the Native Hospital slide area and the Fourth Avenue slide area, the Alaska State Highway Department facilities are located in an old slide area that was partly reactivated on March 27. The alcovelike area centered at the city parking lot north of Fourth Avenue, between C and E Streets, probably also is the scar of an old landslide (Shannon and Wilson, Inc., 1964, p. 39; R. M. Waller, written commun., 1965). The area coincides almost exactly with the Fourth Avenue slide of March 27, except that the Fourth Avenue slide retrogressed farther into the bluff. The salient west of this slide partly bounded by Christensen Drive and Second Avenue appears to be a lowered slump block.

On the north side of Ship Creek, the recess just west of the destroyed Government Hill School may be an old slide scar. Points farther west along the bluff and north around the bend above the Port of Anchorage have many of the topographic markings of landslides, including alcoves, step terraces, and grabenlike depressions. The bluff at Cairn Point below the Elmendorf Moraine has a long history of minor slumping. Evidence of prior slumping along Bluff Road east of Government Hill School has been noted previously.

Along the bluff above Knik Arm between L Street and O Street, scallop-shaped recesses and terracelike benches below the crown of the bluff probably are old slide blocks. A remarkable channellike trench that trends diagonally southwest from the vicinity of R Street and Tenth Avenue toward S Street and Eleventh Avenue probably is a remnant of an old graben. Trees in this trench are comparable in size to those in the old graben near the Alaska Native Hospital.

Farther southwest near the mouth of Chester Creek, the bench along Bootlegger Cove Drive probably is an old slide block, and due east from there the broad recess centered near Inlet View School probably is an old slide area also (fig. 27). This feature is very subdued and probably is very old.

The bluff line along the south side of Chester Creek from the mouth of the creek discontinuously as far east as Rogers Park shows evidence of past slumping. Terracelike features lacking continuity along the valley margin, especially those deeply recessed into alcovelike niches, or those having irregular floors—particularly back-sloping floors, probably are slump blocks. On March 27 a small slump occurred in the bluff just north of West High School. Forest Park Golf Course between the mouths of Chester and Fish Creeks appears to be situated in an area of old landslides.

West from Fish Creek to Point Woronzof the bluff line has had a long history of slumping. There is no indication of previous sliding comparable to the disastrous Turnagain Heights slide, but small-scale sluffing away and localized slumping were continuing problems; the long-range effect was a slow but relentless sapping away of the bluff line.

The long bluff line south of Anchorage facing Turnagain Arm showed little evidence of landsliding prior to the March 27 earthquake except at Potter Hill and Point Campbell. Slumping at Potter Hill has been a recurrent problem, only in part caused by earthquakes. At Point Campbell, intermittent debris slides and sand runs have been caused by ordinary wave and current erosion at the foot of the bluff—processes unrelated to earthquakes.

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PLATE 2


Topography by J. R. Helm and A. B. Dodd

Geology by W. R. Hansen and R. D. Miller, May 1964

## EXPLANATION

- Sod — Turf, sod, forest duff
- Ow — Outwash
- Rd — Road and drive surfacing
- Cl — Bootlegger Cove Clay
- Water
- Tree, showing direction and tilt of tree
- Slickensides or grooves on clay, showing direction and plunge

# GEOLOGIC MAP AND SECTION THROUGH PART OF TURNAGAIN HEIGHTS LANDSLIDE, ANCHORAGE, ALASKA

SCALE 1:480
50 0 50 100 150 200 FEET
CONTOUR INTERVAL 2 FEET
DATUM IS MEAN SEA LEVEL PRIOR TO EARTHQUAKE

783-132 O - 65 (In pocket)