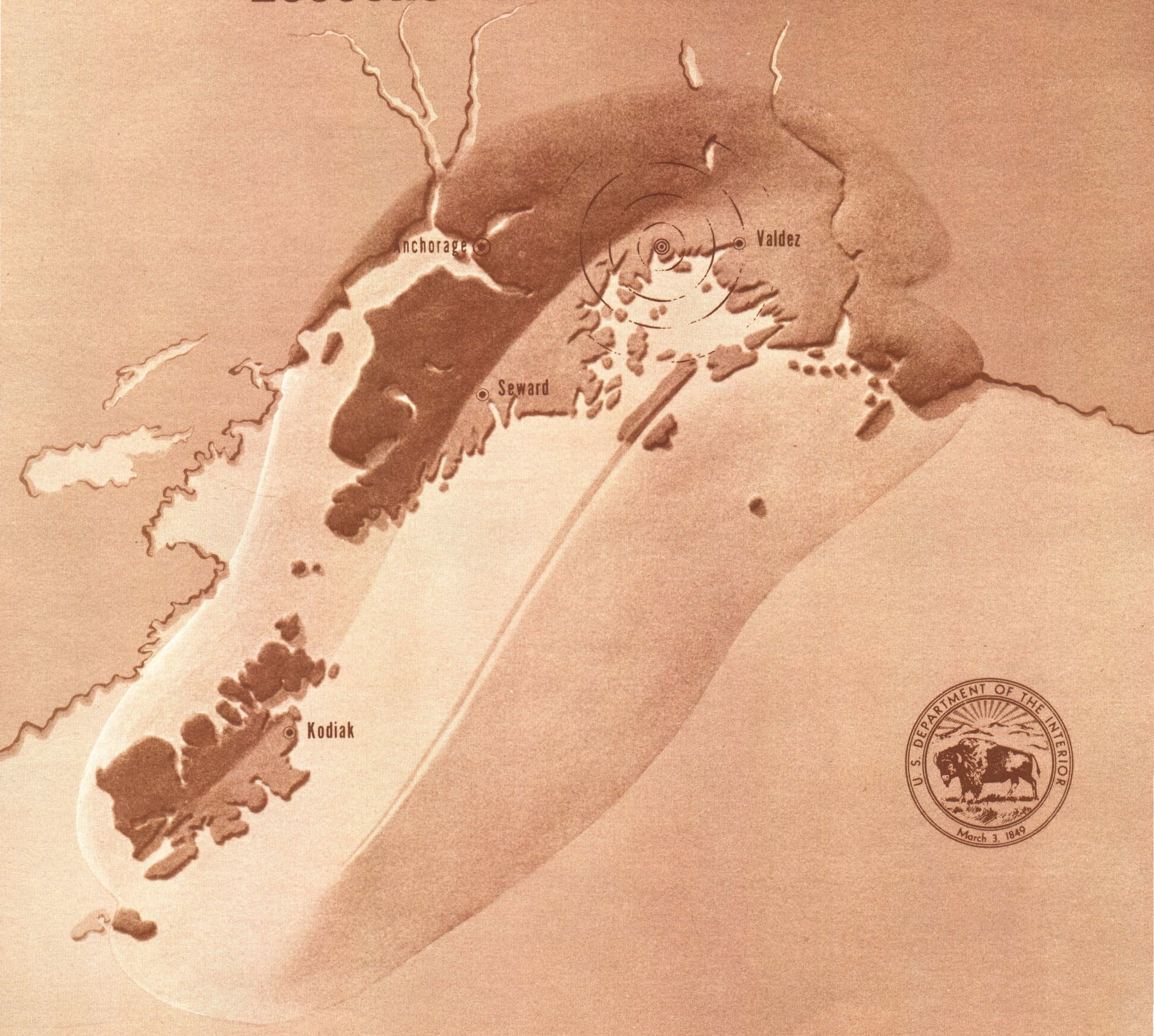
The Alaska Earthquake

March 27, 1964

Lessons and Conclusions



GEOLOGICAL SURVEY PROFESSIONAL PAPER 546

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The Alaska Earthquake March 27, 1964: Lessons and Conclusions

By EDWIN B. ECKEL

A summary of what was learned from a great earthquake about the bearing of geologic and hydrologic conditions on its effects, and about the scientific investigations needed to prepare for future earthquakes

GEOLOGICAL SURVEY PROFESSIONAL PAPER 546

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

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FOREWORD

Few of the effects of the Alaska earthquake of March 27, 1964, on earth processes and on the works of man were new to science, but never had so many effects been accessible for study over so great an area. This earthquake has received more intensive study from all scientific disciplines and specialties than any single previous natural disaster.

In a series of six Professional Papers, the U.S. Geological Survey has published the results of a comprehensive geologic study that began, as a reconnaissance survey, within 24 hours after the event and extended, as detailed investigations, through several field seasons. Professional Paper 541 described early field investigations and reconstruction efforts; 542, in seven parts, the effects of the earthquake on Alaskan communities; 543, in 10 parts, the regional geologic effects; 544, in five parts, the worldwide effects on the earth's hydrologic regimen; 545, in four parts, the effects on Alaska's transportation, communications, and utilities. This volume, Professional Paper 546, "Lessons and Conclusions," is the last of the series; it contains a selected bibliography and an index for the 28 reports.

The findings of the Geological Survey study apply not only to documentation of the Alaska earthquake itself, but, it is hoped, toward better understanding of earthquakes in general; their nature, origin, and effects, and of how man may plan or build to avoid or minimize their consequences.

W. T. PECORA,
Director.

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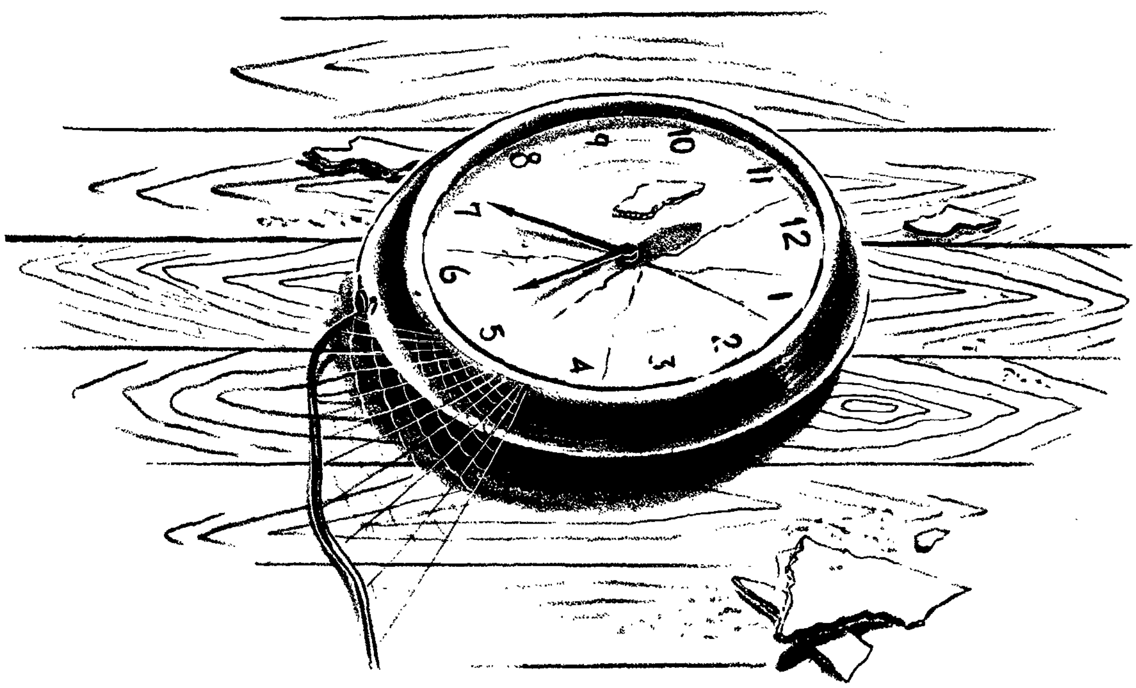


"One of the greatest earthquakes of all time struck in south-central Alaska in the late afternoon of March 27, 1964."

THE ALASKA EARTHQUAKE, MARCH 27, 1964: LESSONS AND CONCLUSIONS

By Edwin B. Eckel

ABSTRACT

One of the greatest earthquakes of all time struck south-central Alaska on March 27, 1964. Strong motion lasted longer than for most recorded earthquakes, and more land surface was dislocated, vertically and horizontally, than by any known previous temblor. Never before were so many effects on earth processes and on the works of man available for study by scientists and engineers over so great an area.

The seismic vibrations, which directly or indirectly caused most of the damage, were but surface manifestations of a great geologic event—the dislocation of a huge segment of the crust along a deeply buried fault whose nature and even exact location are still subjects for speculation. Not only was the land surface tilted by the great tectonic event beneath it, with resultant seismic sea waves that traversed the entire Pacific, but an enormous mass of land and sea floor moved several tens of feet horizontally toward the Gulf of Alaska.

Downslope mass movements of rock, earth, and snow were initiated. Subaqueous slides along lake shores and seacoasts, near-horizontal movements of mobilized soil ("landspreading"), and giant translatory slides in sensitive clay did the most damage and provided the most new knowledge as to the origin, mechanics, and possible means of control or avoidance of such movements. The slopes of most of the deltas that slid in 1964, and that produced destructive local waves, are still as steep or steeper than they were before the earthquake and hence would be unstable or metastable in the event of another great earthquake. Rockslide avalanches provided new evidence that such masses may travel on cushions of compressed air, but a widely held theory that glaciers surge after an earthquake has not been substantiated.

Innumerable ground fissures, many of them marked by copious emissions of water, caused much damage in towns and along transportation routes. Vibration also consolidated loose granular materials. In some coastal areas, local subsidence was superimposed on regional tectonic subsidence to heighten the flooding damage. Ground and surface waters were measurably affected by the earthquake, not only in Alaska but throughout the world.

Expectably, local geologic conditions largely controlled the extent of structural damage, whether caused directly by seismic vibrations or by secondary effects such as those just described. Intensity was greatest in areas underlain by thick saturated unconsolidated deposits, least on indurated bedrock or permanently frozen ground, and intermediate on coarse well-drained gravel, on morainal deposits, or on moderately indurated sedimentary rocks.

Local and even regional geology also controlled the distribution and extent of the earthquake's effects on hydrologic systems. In the conterminous United States, for example, seiches in wells and bodies of surface water were controlled by geologic structures of regional dimension.

Devastating as the earthquake was, it had many long-term beneficial effects. Many of these were socioeconomic or engineering in nature; others were of scientific value. Much new and corroborative basic geologic and hydrologic information was accumulated in the course of the earthquake studies, and many new or improved investigative techniques were developed. Chief among these, perhaps, were the recognition that lakes can be used as giant tiltmeters, the refinement of methods for measuring land-level changes by observing displacements of barnacles and other sessile organisms, and the relating of hydrology to seismology by worldwide study of hydroseisms in surface-water bodies and in wells.

The geologic and hydrologic lessons learned from studies of the Alaska earthquake also lead directly to better definition of the research needed to further our understanding of earthquakes and of how to avoid or lessen the effects of future ones. Research is needed on the origins and mechanisms of earthquakes, on crustal structure, and on the generation of tsunamis and local waves. Better earthquake-hazard maps, based on improved knowledge of regional geology, fault behavior, and earthquake mechanisms, are needed for the entire country. Their preparation will require the close collaboration of engineers, seismologists, and geologists. Geologic maps of all inhabited places in earthquake-prone parts of the country are also needed by city planners and others, because the direct relationship between local geology and potential earthquake damage is now well understood.

Improved and enlarged nets of earthquake-sensing instruments, sited in relation to known geology, are needed, as are many more geodetic and hydrographic measurements.

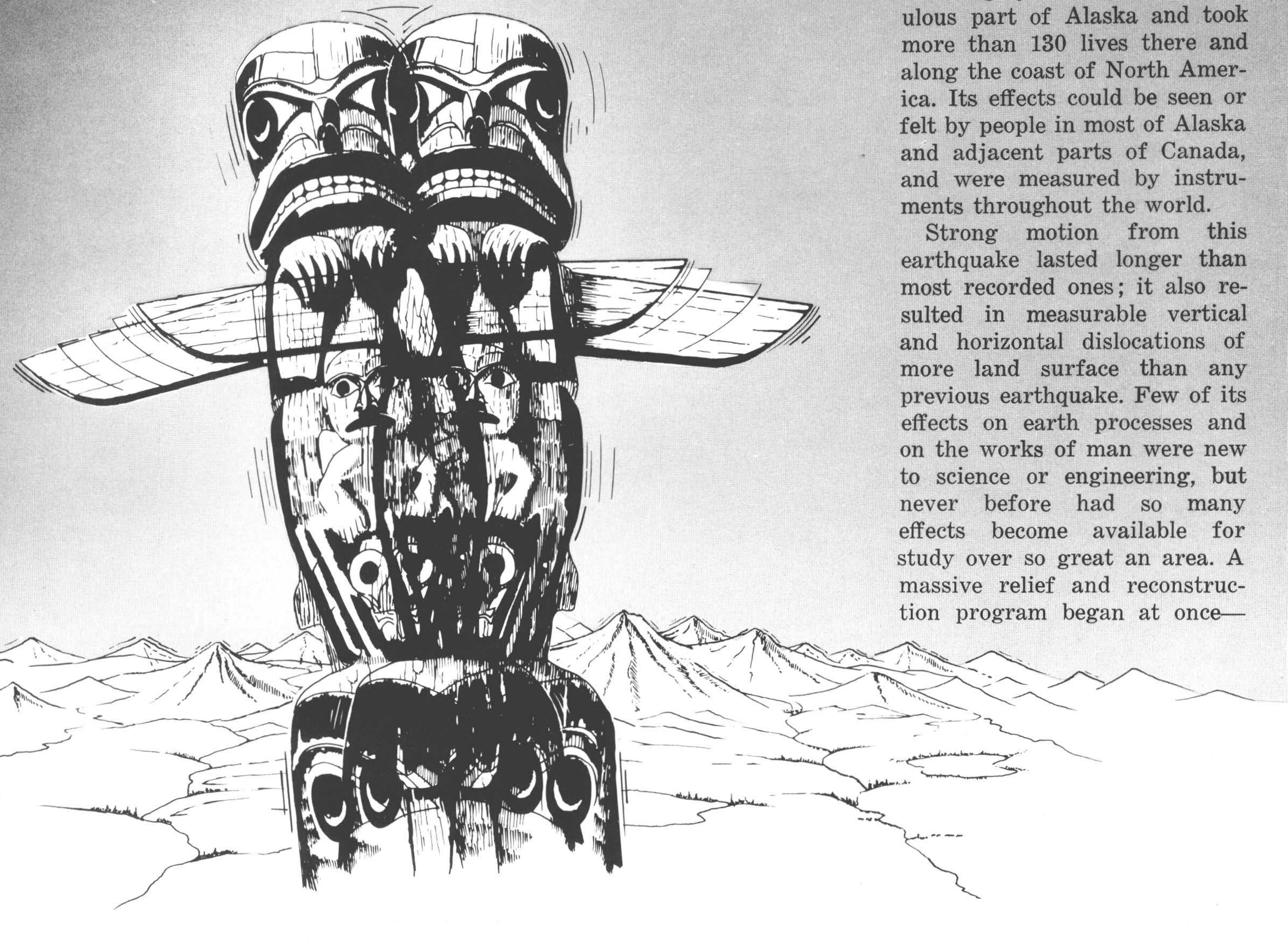
Every large earthquake, wherever located, should be regarded as a full-scale laboratory experiment whose study can give scientific and engineering information unobtainable from any other source. Plans must be made before the event to insure staffing, funding, and coordination of effort for the scientific and engineering study of future earthquakes. Advice of earth scientists and engineers should be used in the decision-making processes involved in reconstruction after any future disastrous earthquake, as was done after the Alaska earthquake.

The volume closes with a selected bibliography and a comprehensive index to the entire series of U.S. Geological Survey Professional Papers 541–546.

"...and lo, there was a great earthquake...

and every mountain and island were moved

out of their places." Revelation VI, 12, 14



INTRODUCTION

One of the greatest earthquakes of all time struck in south-central Alaska in the late afternoon of March 27, 1964 (fig. 1). Variously called the Good Friday earthquake, the Prince William Sound earthquake, and the 1964 Alaska earthquake, it devastated the most highly developed and populous part of Alaska and took more than 130 lives there and along the coast of North America. Its effects could be seen or felt by people in most of Alaska and adjacent parts of Canada, and were measured by instruments throughout the world.

Strong motion from this earthquake lasted longer than most recorded ones; it also resulted in measurable vertical and horizontal dislocations of more land surface than any previous earthquake. Few of its effects on earth processes and on the works of man were new to science or engineering, but never before had so many effects become available for study over so great an area. A massive relief and reconstruction program began at once—

a program in which the Federal Government played a greater part than for any previous physical disaster in the United States.

The Alaska earthquake received more intensive study from scientists and engineers of all disciplines and specialties than any major earthquake in history. Much has been, and is still being, learned from these investigations. The findings apply not only to documentation of the Alaska earthquake itself, but toward better understanding of the nature and origins of earthquakes in general, of their effects, and of how man can plan or build to avoid or ameliorate those effects.

This report is primarily a summary of geologic and hydrologic findings of the U.S. Geological Survey with only incidental excursions into the findings of other organizations and disciplines. For this reason, the enormous amount of new information amassed and published by others is not stressed, though references to it appear in the selected bibliography, and all of it was used by Survey authors as it became available in reaching their conclusions.

The story of the earthquake is told in a general nontechnical way by Hansen and others (1966). More detailed descriptions of many facets of the earthquake and its effects, treated partly by topic and partly by locality, are contained in other reports in this series; the bibliographies in each report, of course, contain references to many other descriptions. No attempt is made here to repeat all these details or even to summarize them. Instead, the intent is to sort out that which was significant or different about the Alaska earthquake as compared with previous ones. Emphasis is given to the lessons learned from it, both technical and philosophic, that can be applied to the studies of future earthquakes and to better understanding of the earthquake process.

GEOLOGICAL SURVEY REPORTS ON THE EARTHQUAKE

The Survey's first report on the earthquake, by Grantz, Plafker, and Kachadoorian (1964), was published only a few weeks after the event. It described in a remarkably accurate and thorough fashion the essential facts about the earthquake and its effects as they were learned during the initial reconnaissance investigations. This preliminary report has been followed by a series of six Professional Papers, under the overall title "The Alaska Earthquake, March 27, 1964," of which this is the concluding volume. Together, these reports constitute a comprehensive description of the earthquake's effects on geologic and hydrologic materials and processes, considerable emphasis being placed on the bearing of those effects on man and his works. They are based primarily on the Geological Survey's own investigations, but several contributions from other authors were sought out and included for more complete coverage.

Each report of the Professional Paper series is liberally illustrated and contains a bibliography. At the end of this volume, the entire series is indexed and complete bibliographic citations are given under the principal authors' names. Parts or all of the series are available for purchase from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20401.

The several Professional Papers and the short titles of their parts are listed here, with a brief statement of contents of each.

Professional Paper 541, "Field investigations and reconstruction efforts," by W. R. Hansen and others (1966): This nontechnical introductory volume describes the time, duration, and extent of the earthquake, its physiographic-geologic setting, and its effects on the communities and transportation facilities of Alaska; it also contains a brief description of the sea-wave damages at coastal communities in British Columbia, Washington, Oregon, and California. Biologic, atmospheric, and possible magnetic effects of the quake are outlined. Separate sections note the governmental and private response to the disaster and the contribution of both sectors to the reconstruction. The following subtitles indicate the contents of the sections:

"A Summary Description of the Alaska Earthquake—Its Setting and Effects," by W. R. Hansen and E. B. Eckel.

"Investigations by the Geological Survey," by W. R. Hansen.

"The Work of the Scientific and Engineering Task Force—Earth Science Applied To Policy Decisions in Early Relief and Reconstruction," by E. B. Eckel and W. E. Schaem.

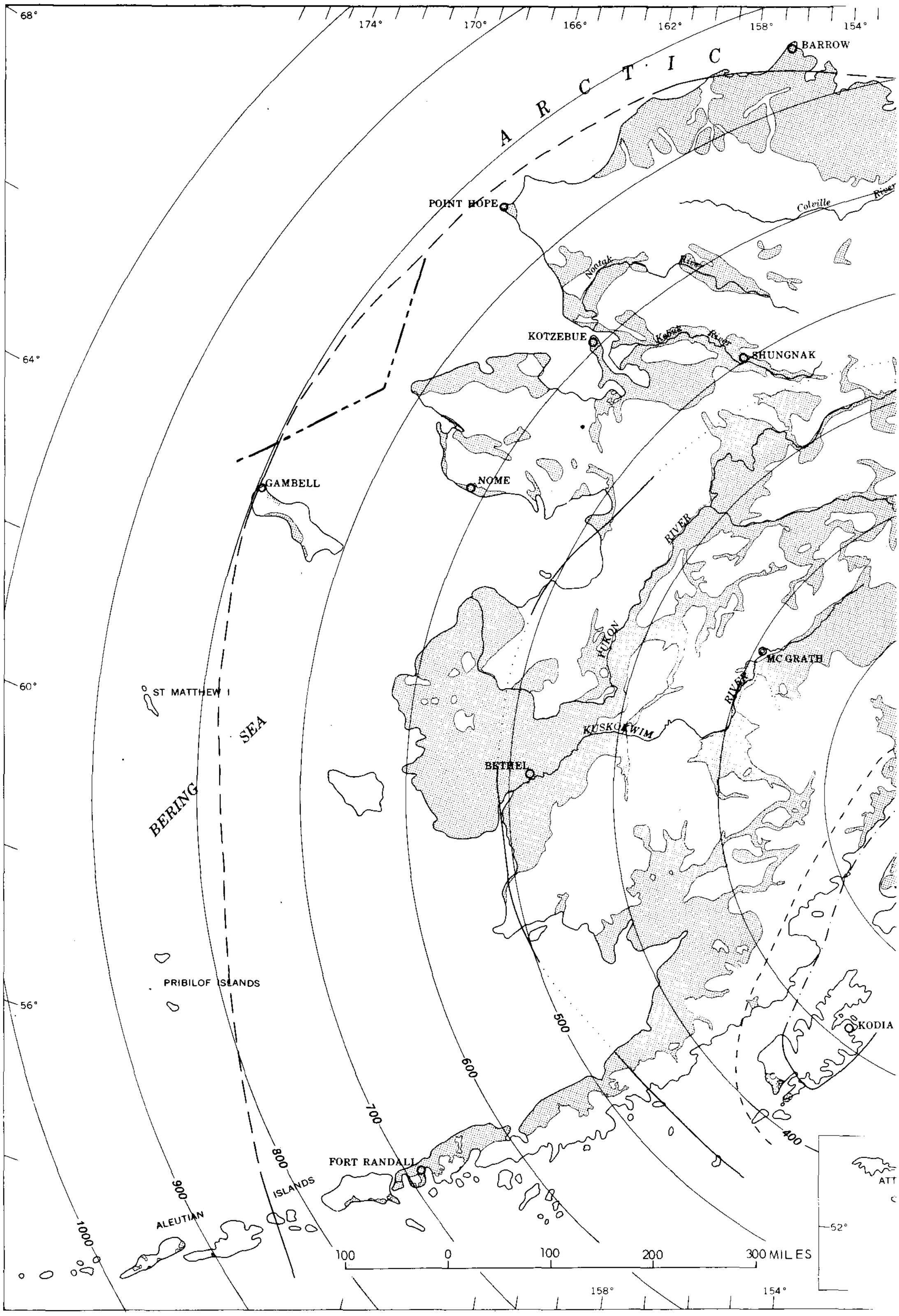
"Activities of the Corps of Engineers—Cleanup and Early Reconstruction," by R. E. Lyle and Warren George.

"Reconstruction by the Corps of Engineers—Methods and Accomplishments," by Warren George and R. E. Lyle.

"The Year of Decision and Action," by Genie Chance.

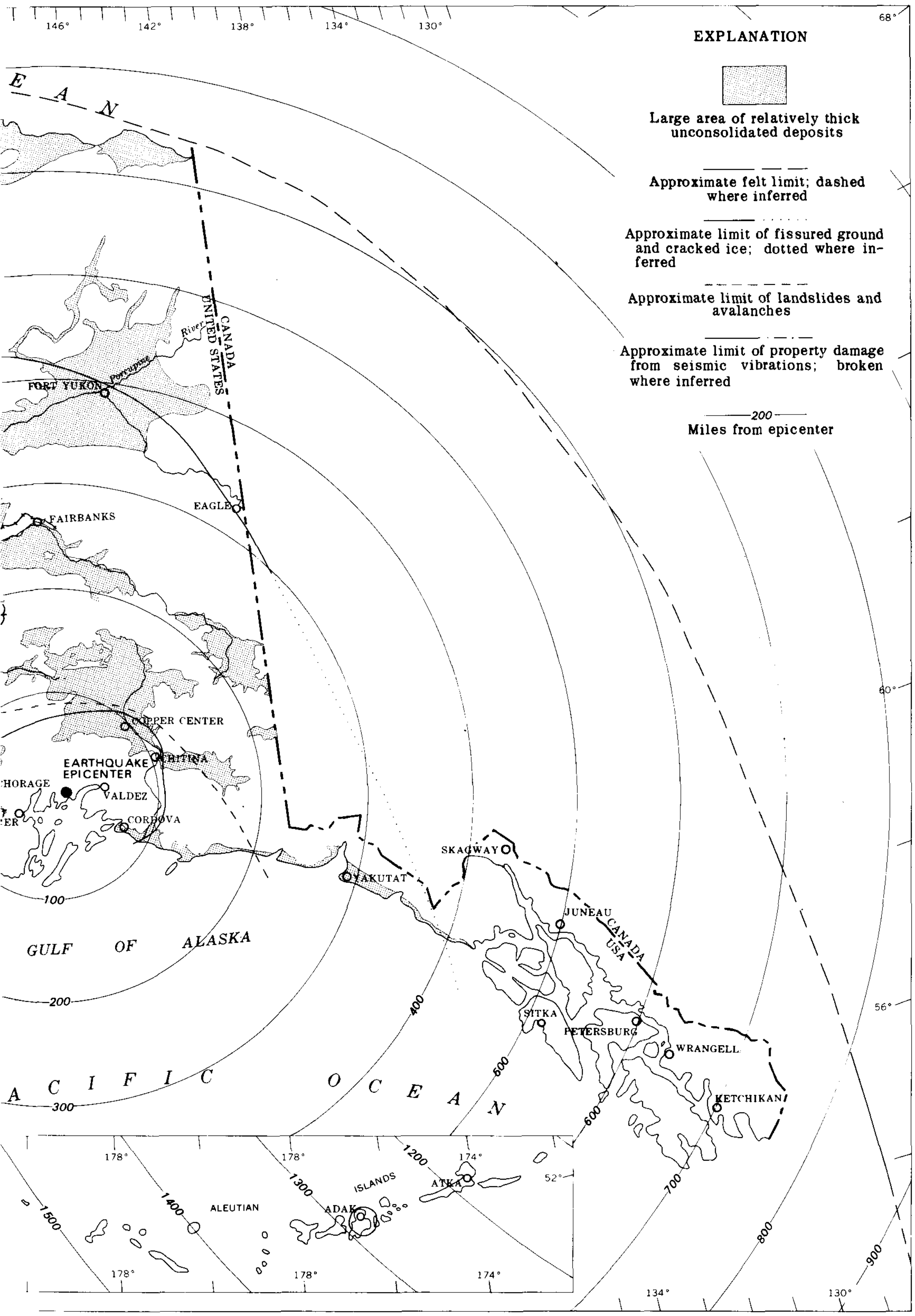
Professional Paper 542: "Effects on Communities," in seven chapters:

A, "Anchorage," by W. R. Hansen (1965). Seismic vibration damaged many multistory



Base from U.S. Geological Survey
1:2,500,000 Alaska Map E

1.—Map showing extent and nature of the c



seismic vibrations related to the earthquake.

buildings, caused extensive ground fissures, and triggered disastrous translatory landslides in some bluff areas underlain by sensitive clays. Because of its size, Anchorage had greater total property damage than all the rest of Alaska.

B, "Whittier," by Reuben Kachadoorian (1965). Land subsidence, waves generated by submarine landslides, fire, and seismic vibration wrecked much of the waterfront area in this small port-rail terminal.

C, "Valdez," by H. W. Coulter and R. R. Migliaccio (1966). Ground fissures, waves, and fire did much damage, and a gigantic submarine slide off the front of the delta town site carried the waterfront away and dictated relocation of the town.

D, "Homer," by R. M. Waller (1966). Submergence caused by tectonic subsidence and by consolidation of sediments exposed much of Homer Spit, economic heart of the community, to the reach of high tides. A separate section by K. W. Stanley describes the beach changes on Homer Spit that resulted from subsidence.

E, "Seward," by R. W. Lemke (1967). Seismic sea waves, submarine slides, and fires destroyed the town's waterfront and necessitated relocation of the Alaska Railroad terminal. Ground fissures damaged numerous buildings, particularly in suburban areas.

F, "Kodiak Area," by Reuben Kachadoorian and George Plafker (1967). Seismic sea waves flooded Kodiak, the nearby Naval Station, and several smaller communities in the Kodiak island group. Regional tectonic subsidence caused further damage in many places.

G, "Various Communities," by George Plafker, Reuben Kachadoorian, E. B. Eckel, and L. B. Mayo (1969). Effects on several scores of miscellaneous communities, where there was loss of life or significant physical damage, are described, as are the extensive wave damage in coastal areas and evidence of vibration throughout Alaska.

Professional Paper 543: "Regional Effects," in 10 chapters:

A, "Slide-Induced Waves, Seiching, and Ground Fracturing at Kenai Lake," by D. S. McCulloch (1966). The earthquake dislodged subaqueous slides from deltas in Kenai Lake that generated destructive waves. The lake basin was tilted and a seiche wave was excited in it.

B, "Martin-Bering Rivers Areas," by S. J. Tuthill and W. M. Laird (1966). Widespread geomorphic changes took place in a large uninhabited area east of the Copper River. Ground fissures—some with associated ejections of mud or water—avalanches, and landslides were among the more important effects.

C, "Gravity Survey and Regional Geology of the Epicentral Region," by J. E. Case, D. F. Barnes, George Plafker, and S. L. Robbins (1966). Gravity stations and reconnaissance geologic mapping in the Prince William Sound area provided background for other investigations of the earthquake. A regional gravity gradient, caused by thickening of the continental crust and local anomalies related to differences in lithology were measured.

D, "Kodiak and Nearby Islands," by George Plafker and Reuben Kachadoorian (1966). Seismic sea waves caused the greatest physical damage throughout the Kodiak Island area. Tectonic subsidence adversely affected much of the shoreline. Vibration, ground fissures, and landslides affected unconsolidated materials but not bedrock.

E, "Copper River Basin Area," by O. J. Ferrians, Jr. (1966). Extensive ground fissures formed in flood plains, deltas, and the toes of alluvial fans. Terrain underlain by permafrost behaved like bedrock and did not crack. Avalanches and rockslides were released in the mountains.

F, "Ground Breakage in the Cook Inlet Area," by H. L. Foster and T. V. N. Karlstrom (1967). Ground fissures, many of which ejected water or sediment, formed on the Kenai Lowland; most of them were on thick bodies of unconsolidated materials. Zonal concentration of ground fissures may have been concentrated along a buried fault.

G, "Surface Faults on Montague Island," by George Plafker (1967). Two reactivated steep reverse faults in Prince William Sound are the only known surface faults caused by the earthquake. They are probably part of a fault system that extends discontinuously for more than 300 miles from Montague Island past the southeast coast of Kodiak Island.

H, "Shoreline Erosion and Deposition on Montague Island," by M. J. Kirkby and A. V. Kirkby (1969). Modification of the shore by subaerial and marine processes began immediately after tectonic uplift. The effect and rate of each process on various materials were measured. Evidence was found of two relative sea-level changes prior to 1964.

I, "Tectonics of the Earthquake," by George Plafker (1969). The earthquake was accompanied by crustal warping, horizontal distortion, and surface faulting over an area of more than 110,000 square miles. Focal mechanism studies, combined with the patterns of deformation and seismicity, suggest that the earthquake probably resulted from movement along a complex thrust fault that dips at a low angle beneath the continental margin. Radiocarbon dating of pre-1964 displaced shorelines provides data on long-term tectonic movements in the earthquake region and on the time interval since the last major earthquake-related movements.

J, "Shore Processes and Beach Morphology," by K. W. Stanley (1968). All coastal features began to readjust to changed conditions immediately after the earthquake. In the subsided areas, beaches flattened and receded; in uplifted areas, they were stranded. Emergence and submergence posed problems of land use and ownership and changed wildlife habitats.

Professional Paper 544, "Effects on the Hydrologic Regimen," in five chapters:

A, "South-Central Alaska," by R. M. Waller (1966). Surface waters were affected by ice breakage, seiching, fissuring of streambeds, and temporary damming. Ground water was also drastically affected, mostly in unconsolidated aquifers. Many temporary and permanent changes occurred in water levels and artesian pressures.

B, "Anchorage Area," by R. M. Waller (1966). Immediate effects on the Anchorage hydrologic system included increased stream discharge, seiches on lakes, and fluctuations in ground-water levels; water supplies were temporarily disrupted by damming of streams.

C, "Outside Alaska," by R. C. Vorhis (1967). The earthquake caused measurable changes of water levels in wells and surface waters throughout nearly all of the United States and in many other countries. A separate section by E. E. Rexin and R. C. Vorhis describes hydroseismograms from a well in Wisconsin and one by R. W. Coble the effects on ground water in Iowa.

D, "Glaciers," by Austin Post (1967). Many rockslide avalanches extended onto the glaciers; some traveled long distances, possibly over layers of compressed air. No large snow and ice avalanches occurred on any of the hundreds of glaciers. Little evidence of earthquake-induced surges of glaciers was found.

E, "Seismic Seiches," by Arthur McGarr and R. C. Vorhis (1968). Hundreds of water-level instruments on streams, lakes, and reservoirs throughout the United States, Canada, and Australia recorded measurable seiches, or hydroseisms. Such recorders can thus serve as useful adjuncts of seismograph networks in earthquake studies.

Professional Paper 545, "Effects on Transportation, Communications, and Utilities," in four chapters:

A, "Eklutna Power Project," by M. H. Logan (1967). Vibration-induced consolidation of sediments damaged the underwater intake structure, and permitted sand, gravel, and cobbles to enter the tunnel. Lesser damage was done by vibration and ground fractures. A separate section by L. R. Burton describes the use of a portable television camera to locate breaks in underground communication systems.

B, "Air and Water Transport, Communications, and Utilities," by E. B. Eckel (1967). All forms of transportation, utilities, and communication systems were wrecked or severely hampered by the earthquake. Numerous airports and all seaports were affected by vibration, subaqueous slides, waves, fire and tectonic uplift or subsidence. Aboveground transmission lines were extensively broken, but buried utility lines were virtually undamaged except where the ground fractured or slid.

C, "The Highway System," by Reuben Kachadoorian (1968). Widespread damage resulted chiefly from destruction of bridges and roadways by seismic vibration and subsidence of foundations. Snowslides, landslides, and shoreline submergence also damaged or drowned some roadways.

D, "The Alaska Railroad," by D. S. McCulloch and M. G. Bonilla (1970). The rail system was extensively damaged; bridges and tracks were destroyed, and port facilities were lost at Seward and Whittier.

"Landspreading" (a term for sediments that were mobilized by vibration and moved toward topographic depressions) was the single most important source of trouble.

ACKNOWLEDGMENTS

Sincere thanks go to all the authors whose work is summarized here and to all my colleagues who played parts in publishing the U.S. Geological Survey's series of reports on the earthquake. Early drafts of this report were reviewed by the authors of each paper in the series and by many other friends, particularly the members of the Committee on the Alaska Earthquake Committee, National Academy of Science. All of these were very helpful in correcting factual and interpretative errors. Special thanks are due Wallace R. Hansen, George Plafker, and David S. McCulloch, who went beyond the call of duty in helping to improve this presentation. Catherine Campbell, who had primary responsibility for processing all the reports in the series; and Elna Bishop and her associates, who did the final editing and saw the reports through the press, deserve the thanks of all authors and readers. Robert A. Reilly used imagination, skill, and patience in preparing the line drawings for these pages.

TECTONICS

THE EARTHQUAKE

The earthquake struck about 5:36 p.m., Friday, March 27, 1964, Alaska standard time, or, as recorded by seismologists, at 03:36:11.9 to 12.4, Saturday, March 28, 1964, Greenwich mean time. Its Richter magnitude, computed by different observatories as from 8.3 to possibly as high as 8.75 (that of the greatest known earthquake is 8.9), has generally come to be described as 8.4–8.6. Its intensity on the Modified Mercalli scale ranged between very wide limits, depending partly on distance from the epicenter but much more on local geologic and hydrologic conditions and distribution of population; hence isointensity lines are difficult or impossible to draw.

The epicenter was instrumentally determined to be close to College Fiord at the head of Prince William Sound, on the south flank of the rugged Chugach Mountains (fig. 2). Calculations of the epicenter vary, but all place it within a 9-mile (15-km) radius of 61.1° N., 147.7° W. The focus, or point of origin, was 12–30 miles (20–50 km) below the surface. References to a single epicenter or depth of focus are misleading in that they imply that the earthquake had a point source. As interpreted by Wyss and Brune (1967), the earthquake rupture propagated in a series of events, with six widely distributed "epicenters" recorded during the first 72 seconds. Thus, energy was released by the earthquake itself over a broad area south and southwest of the epicenter; the thousands of aftershocks were dispersed throughout an area of about 100,000 square miles, mainly along the Continental Shelf between the Aleutian Trench and the mainland.

The long duration of strong ground motion intensified many of the earthquake's effects and added greatly to its scientific significance. At the time, there were no instruments in Alaska capable of recording the duration of motion, but many observers timed or estimated the period of strong shaking as from 1½ to 7 minutes. In most places the time was between 3 and 4 minutes. The majority of observers reported either continuous strong shaking throughout the earthquake or gradually diminishing motion. There is evidence, however, that in Anchorage and possibly elsewhere there were several pulses of strong shaking, separated by periods of diminished vibration.

The earthquake vibrations were felt by people throughout Alaska and parts of British Columbia (fig. 1); they were recorded by seismographs throughout the world. The vibrations themselves, or their immediate effects on bodies of water, were measured on streams and lakes and in wells throughout the United States and in many other countries. Earthquake-caused atmospheric pressure waves and subaudible sound waves were also recorded by instruments at widely separated stations in the conterminous States.

There is general agreement among seismologists and geologists that shallow earthquakes are caused by sudden release of elastic strain energy that has accumulated in the earth's crust and upper mantle. There is no unanimity of opinion, however, as to why the strains are released when and where they are nor as to the details of the earthquake-generation process or mechanism. The Alaska earthquake of 1964 gave some additional insight into these problems but did not solve them all by any means.

Much has been made by both technical and popular writers of the fortunate circumstances that brought the Alaska earthquake on the late afternoon of Good Friday, or Passover, at a time of low tides, and during the off-season for fishing, when there were few people on docks and boats and in nearshore canneries. There is no question that this combination of circumstances resulted in less loss of life than would have occurred at almost any other time.

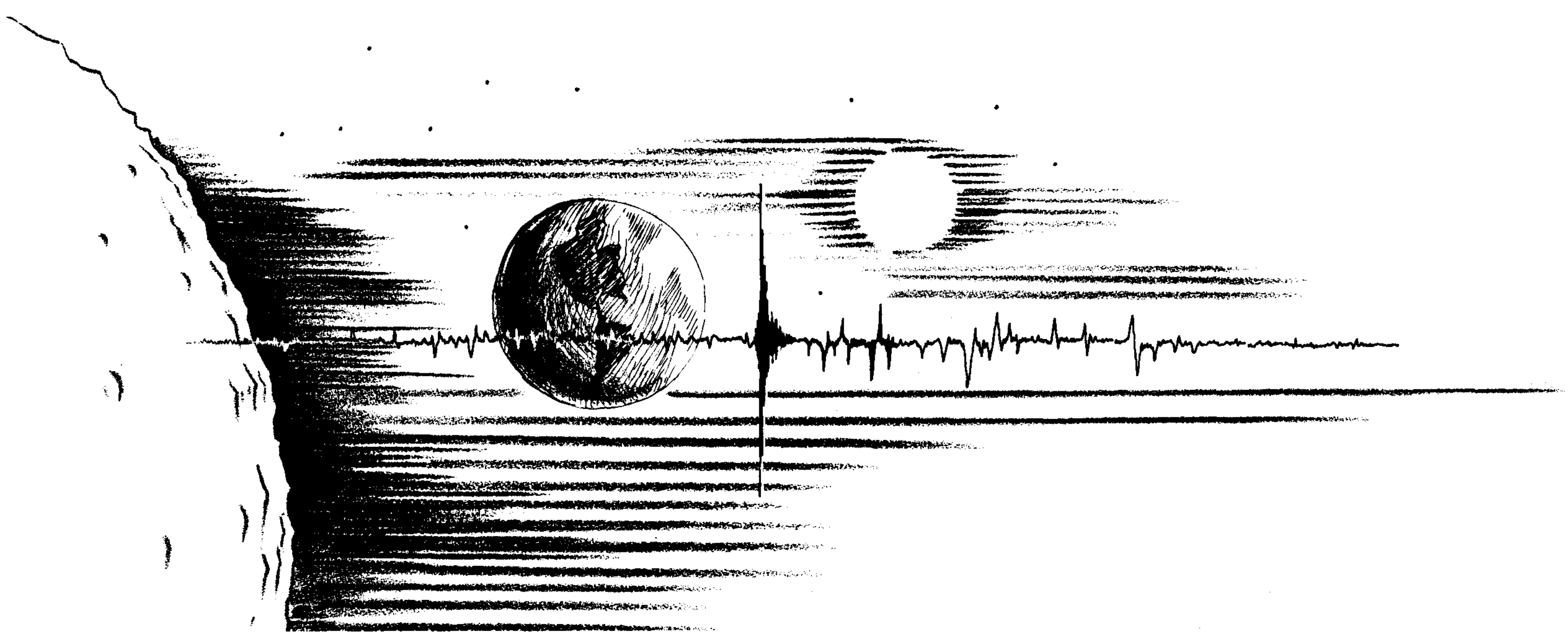
Wilson and Tørum (1968) make the interesting suggestion that the timing of the release of strain was perhaps not fortuitous at all, but was the product of astronomic forces. They base their suggestion on the fact that the earthquake occurred near the time of the vernal equinox—the date on which the religious seasons of Easter and Passover are also based—when the earth, moon, and sun were in opposition at syzygies and ocean tides were at maximum spring range. Wilson and Tørum inferred that six other great earthquakes in recent history occurred at or near the lunar position of syzygy either in opposition or conjunction; they concluded that the maximum earth and ocean tides that result from these conditions are perhaps important triggering devices for releasing built-up strain in the earth's crust. Whether or not their hypothesis is correct, the earthquake could hardly have struck at a time more favorable to minimizing damage and loss of life.

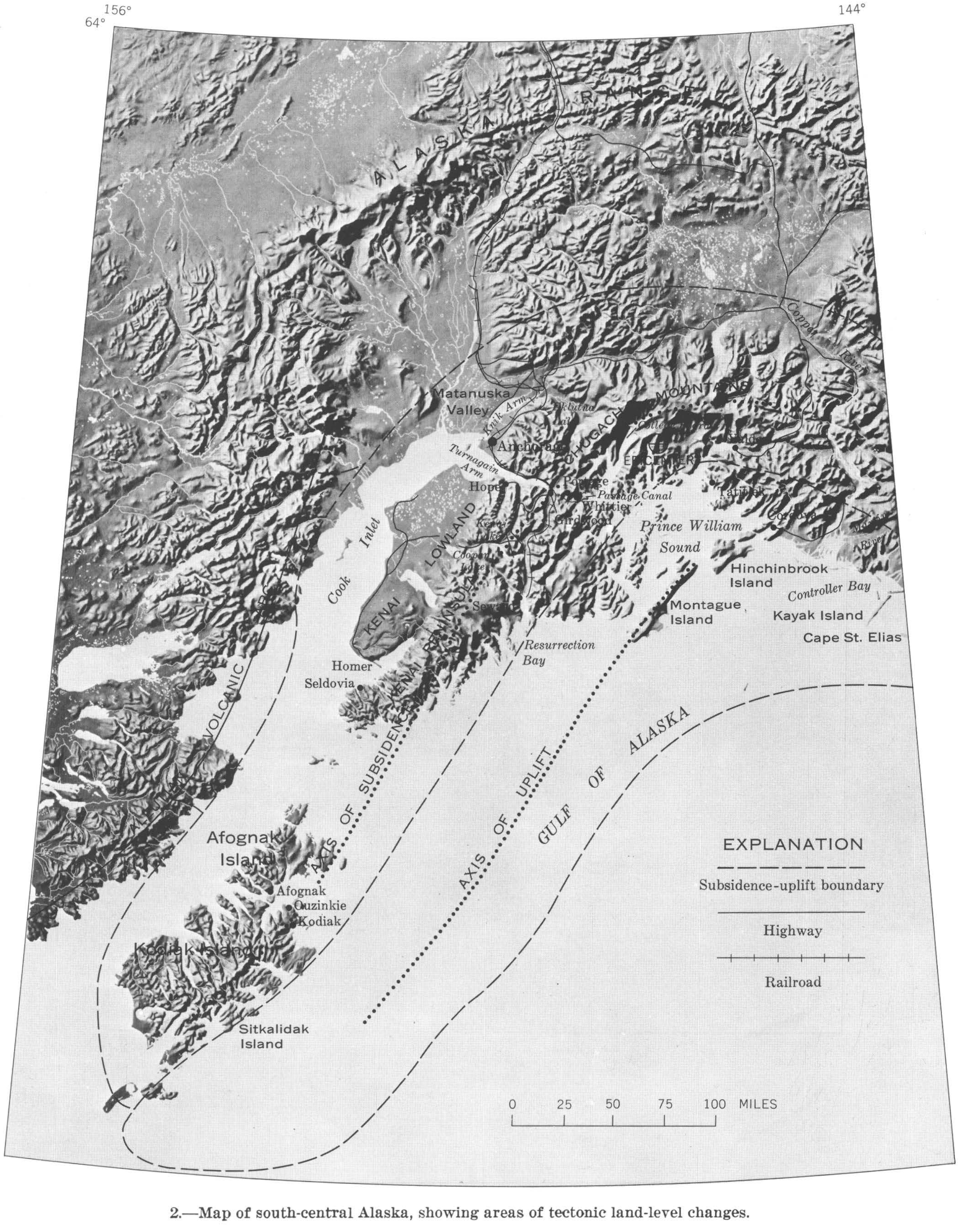
DEFORMATION AND VIBRATION OF THE LAND SURFACE

An earthquake by definition is a shaking of the ground surface and the structures on it, but the shaking is really only symptomatic of the great geotectonic events that are affecting a part of the earth's crust. This truism was well demonstrated by the Alaska earthquake. Vibrations from few, if any, earthquakes in history have been felt by people over a wider area, or have persisted for a longer time. Much of the damage was caused by the vibrations themselves or by their direct results—ground cracks, compaction of sediments, landslides and subaqueous slides, and local waves originated by such slides. But perceptible and disastrous as they were, these effects were insignificant compared to the great geologic event that caused them, even though most other effects of that event were not even recognizable as such until long after shaking had subsided. Indeed, the nature and location of the assumed fault along which the main event occurred are still subjects for inference and speculation, despite intensive studies by many able investigators.

Some other effects were nearly or quite as destructive as were the seismic vibrations. The uplift and subsidence that disrupted ports and navigation routes throughout the affected area had far-reaching, long-term effects (fig. 2). Massive tilting of the ocean bottom undoubtedly initiated the seismic sea waves or tsunamis that wrecked Kodiak and other towns in Alaska and caused many of the deaths there and as far down the coast as Crescent City, Calif. The horizontal seaward movement of the landmass, though not measurable as such without precise geodetic studies and interpretations, may itself have initiated disastrous slides and waves along the shores of

"* * * the timing of the release of strain was perhaps not fortuitous at all, but was the product of astronomic forces."





2.—Map of south-central Alaska, showing areas of tectonic land-level changes.

Prince William Sound and elsewhere.

Perhaps the most significant aspect of the Alaska earthquake was the great expanse of measurable land dislocation. Most of our knowledge of the crustal deformation that marks large earthquakes comes from analysis of the elastic waves that they generate; more direct observations are commonly limited by a lack of critical ground control. In Alaska these deformations were measurable by geodetic and other methods over much of the displacement field (Malloy, 1964, 1965; Plafker, 1965; Parkin, 1966, 1969; Small and Parkin, 1967; and Small and Wharton, 1969). The vast quantity of available facts are interpreted in tectonic terms by Plafker (1969), from whose report most of the following information is taken.

VERTICAL DEFORMATION

Over an area of more than 100,000 square miles, the earth's surface was measurably displaced by the earthquake (fig. 2). Displacements occurred in two arcuate zones parallel to the continental margin, together about 600 miles long and as much as 250 miles wide. West and north of a curving isobase line that extends around the head of Prince William Sound, thence southwestward past the southeast shores of the Kenai Peninsula and the most southeasterly fringes of Kodiak Island, the land and sea-bottom surface subsided an average of 2½ feet and a maximum of 7½ feet. Southeast, or seaward of the isobase line, the surface was uplifted an average of 6 feet and a measured maximum of 38 feet, on Montague Island, where surface faults developed along a zone of severe deformation. There is some evidence that the land west of the subsided zone, involving the Aleutian and Alaska ranges, was uplifted a maximum of 1½ feet, but less is known about this area.

Besides the tsunamis that spread across the entire Pacific Ocean, subsidence and uplift had other consequences, particularly along the seacoasts. Nearly every report in this series describes these effects as observed in some part of the earthquake-affected region. Some effects were immediately apparent to observers; others were not even recognized until hours or days later, when anomalous waves had subsided and new tide levels were affirmed. Only then did people begin to realize the magnitude of the tectonic changes.

Real measurements of the distribution and amount of land-level change required geodetic resurveys of previously established land nets and hundreds of measurements of vertically displaced intertidal sessile organisms. The fact that certain marine plants and animals have definite vertical growth limits relative to tide levels has long been known but, following the early lead of Tarr and Martin (1912), its usefulness in determining relative land-level changes resulting from earthquakes was greatly expanded by Plafker (1969) and his colleagues. The potential accuracy of the method is limited only by the number of observations that can be made with available time, energy, and funds; by the accuracy of our knowledge as to the growth habits of these sessile organisms; and by the accuracy of the observer's estimates of tide stages at the time of observation. In south-central Alaska it provided far more detailed and reliable information on the nature and size of land deformation than could have been determined from the relatively sparse geodetic, hydrographic, and tide-gage control that was available.

HORIZONTAL DEFORMATION

Large-scale horizontal deformation also accompanied the earthquake (Parkin, 1966, 1969; Plafker, 1969). Horizontal movement of the land mass was not noted by observers and could not in any case have been distinguished by human senses from the back-and-forth sensations caused by the seismic waves. Its net results, however, were measured geodetically.

Retriangulation by the U.S. Coast and Geodetic Survey over about 25,000 square miles of uplifted and subsided ground in and around the Prince William Sound region shows definitely that the landmass moved relatively seaward, or southeastward. The amount and distribution of the displacement has been determined relatively but not absolutely. Plafker's interpretation shows systematic horizontal shifts, in a south to southwestward direction, of as much as 64 feet. Parkin, using the same data, found maximum displacements of about 70 feet and in slightly different directions. Whatever the differences in detail and interpretation, there is little doubt that a large mass of land and sea floor moved several tens of feet toward the Gulf of Alaska.

The horizontal land movements produced no known direct effects on man and his structures. Malloy (1965), Wilson and Tørum (1968), Plafker (1969), Plafker and others (1969), all suggest, however, that the sudden seaward land motion may well have caused waves in certain confined and semiconfined bodies of surface water. Too, porosity changes that caused temporary water losses from surface streams and lakes, and lowering of water levels in some wells that tap

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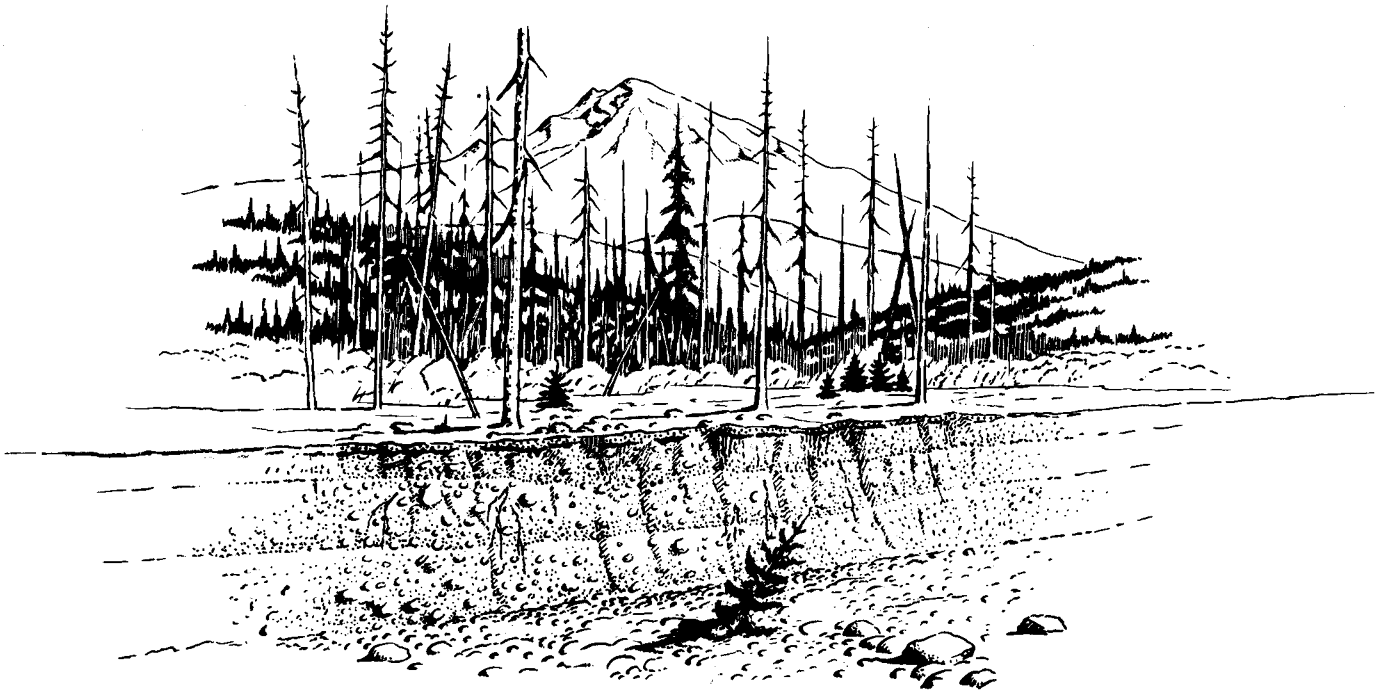


"The Alaska earthquake of 1964 produced only two known surface faults, both on uninhabited Montague Island, in Prince William Sound."

confined aquifers, may have resulted from the horizontal land movements (Waller, 1966a, b).

SURFACE FAULTS

Surface fault displacements accompany many large earthquakes and are much feared because of potential damage to buildings.

The Alaska earthquake of 1964 produced only two surface faults, both on uninhabited Montague Island, in Prince William Sound (Plafker, 1967). They are significant, however, because of their tectonic implications, their large displacements, and their reverse habits. So far as is known, reverse faults rarely accompany earthquakes. The two faults, called the Patton Bay fault and the Hanning Bay fault, were reactivated along preexisting fault traces on the southwestern part of Montague Island. These faults had been mapped by Condon and Cass (1958). New scarps, fissures, flexures, and large landslides appeared in bedrock and in surficial deposits along both traces. Both strike northeast and dip steeply northwest. Vertical displacements are 20 to 23 feet on the Patton Bay fault and 16 feet on the shorter Hanning Bay fault. Both blocks of each fault are uplifted relative to sea level, but the northwestern block of each is relatively higher than the southeastern one. The Patton Bay fault is 22 miles long on land and extends seaward to the southwest at least 17 miles; indirect evidence suggests that the fault system extends southwestward on the sea floor more than 300 miles (Plafker, 1967).

The faults on Montague Island and their postulated extensions southwestward are in the zone of maximum tectonic uplift. Their geologic setting and positions relative to the zone of regional uplift and aftershocks suggest to Plafker (1969) that they are not the primary causative faults of the earthquake but are subsidiary fractures. The hypothetical causative fault is viewed as a low-angle thrust beneath the continental margin.

Inconclusive evidence suggests that ground fissures on the Kenai Peninsula may reflect earthquake-induced movement along an undiscovered buried fault zone (Foster and Karlstrom, 1967). The cracks may, however, have been caused by refraction of seismic vibrations off subsurface bedrock irregularities. Similarly, his bathymetric surveys indicate to G. A. Rusnak of the U.S. Geological Survey (oral commun., 1968) that the earthquake may have formed fault-bounded grabens on the floor of Resurrection Bay, as well as somewhat similar displacements in Passage Canal. Evidence for these suggestions is tenuous, particularly because no direct indications of the postulated earthquake-caused structural features have been found on land, despite diligent search.

MECHANISM OF THE EARTHQUAKE

The widespread vertical and horizontal displacements of the land surface, and the surface faults on Montague Island and southwest thereof, were manifestations of a great geologic event—the sudden release of crustal strains that caused movement along a great fault deep beneath the surface. Nearly all seismologists and geologists agree that such a fault exists, but its exact position, orientation, and sense of displacement are obscure, and will probably remain so.

The elastic rebound theory for the generation of earthquakes states that shallow-focus earthquakes (at depths less than about 40 km.), such as the Alaska one, are generated by sudden fracturing or faulting following slow accumulation of deformation and strain. When the strength of the rocks is exceeded, failure occurs and the elastic strain is suddenly released in the form of heat, crushing, and seismic-wave radiation. Most investigators believe that this sequence of events took place in Alaska. Most believe further that the 1964 earthquake was but one pulse in a long history of regional deformation; this history is summarized by Plafker (1969). Geologic evidence, supported by numerous new radiocarbon datings, indicates that most of the deformed region has been undergoing gradual tectonic submergence for the past 930 to 1,360 years; Plafker tentatively interprets this submergence as direct evidence that regional strain with a downward-directed component had been accumulating in the region for about that length of time.

Intensive studies of the earthquake, and of its foreshocks and aftershocks, have led seismologists to agree that movement was initiated on a new or a reactivated old major fault or fault zone beneath Prince William Sound. Seismologists also agree that the fault is elongate, extending several hundred miles southwestward from near the epicenter to or beyond Kodiak Island and that it is 12 to 30 miles beneath the surface at the epicenter of the main shock. Focal-mechanism studies are inconclusive as to whether the postulated fault dips steeply or at low angles. Either angle fits the available data.

Plafker (1969), who considers the focal-mechanism studies by seismologists in conjunction with the regional geologic history and with regional patterns of tectonic deformation and seismicity, believes that the fault is most probably a low-angle thrust (reverse fault). According to his interpretation, the earthquake originated along a complex thrust fault that dips northwestward beneath the Aleutian Trench. Subsidiary reverse faulting on Montague Island occurred in the upper plate. In his postulated model, the observed and inferred tectonic displacements resulted primarily from (1) relative seaward displacement and uplift of the frontal end of the thrust block along the primary fault and subsidiary reverse faults, such as those on Montague Island, and (2) simultaneous elastic horizontal extension, leading to subsidence, behind the overthrust block.

The concept of a primary low-angle thrust, with the landmass moving relatively toward the Gulf of Alaska, fits most of the known geologic, geodetic, and seismologic facts. Stauder and Bollinger (1966) have shown that focal-mechanism solutions of the main shock and numerous aftershocks based on both *P* and *S* waves favor a low-angle thrust. These same writers, and Savage and Hastie (1966), show that the observed vertical displacements in the major zones of deformation are in reasonably close agreement with the theoretical displacements obtained by applying dislocation theory to a low-angle or horizontal-thrust model.

The low-angle thrust model does not fit all the data, however. For example, Press and Jackson (1965) and Harding and Algermissen (1969) present alternative interpretations of the seismologic data that favor a steeply dipping fault, rather than a thrust. Savage and Hastie (1966) have shown that the theoretical surface displacements from such a model diverge considerably from the observations, and they point out that the surface-wave fault-plane data cited by Press and Jackson in support of a steep fault would apply equally well to a low-angle fault because rupture propagation was along the null axis. However, *P*- and *S*-wave solutions of the main shock suggest to Harding and Algermissen movement on a steep plane. Von Huene and others (1967), too, present oceanographic evidence from the Gulf of Alaska and the Aleutian Trench which they interpret to preclude overthrusting of the continental margin.

There appears to be no unambiguous explanation of the mechanism of the Alaska earthquake. All major arc-related earthquakes, such as this one, are difficult to study because much of the displacement field is invariably submarine; data on earthquakes with offshore epicenters cannot be obtained as readily as for those centered on land. It can be hoped that better seismograph records of long-period motions, together with continuing precise geodetic measurements that would give evidence of the strain accumulations and deformations on land, will permit less ambiguous interpretations of the causes of future Alaska earthquakes. These data would require new techniques for determining subsea displacements and the hypocentral depths and first motions of offshore earthquakes in arc environments.

EFFECTS ON THE PHYSICAL ENVIRONMENT

The shaking and land deformations had profound and lasting effects on the geologic, hydrologic, and oceanographic environments of a large part of south-central Alaska and, to a lesser extent, of an enormously greater area (fig. 1). These effects in turn had immediate and drastic effects on man and manmade structures. The various categories of effects, which were responsible for all the deaths and destruction, are discussed in succeeding paragraphs. Many other effects, such as those on the bird, animal, fish, and shellfish populations and their habitats, are not described here, though they were of outstanding importance to science and to the economy of Alaska.

GEOLOGIC EFFECTS

DOWNSLOPE MASS MOVEMENTS

Of the many downslope mass movements during the earthquake, only four kinds provided much new knowledge about their character and origins. These were (1) the enormous rockslide avalanches on some glaciers, (2) the disastrous subaqueous slides from lakeshores and sea coasts, (3) the near-horizontal movement of vibration-mobilized soil, and (4) the giant translatory slides in sensitive clay at Anchorage.

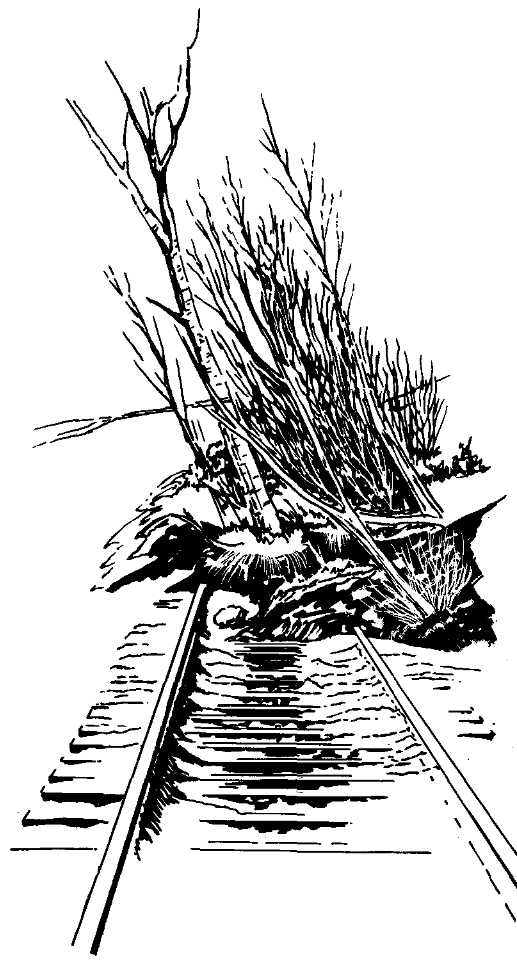
Earthquakes have long been known to cause landslides and rock or snow avalanches, but they are generally subordinate to other more usual causes such as gravity interacting with water or ice (Varnes, 1958). It is not surprising that a great earthquake in a rugged land like south-central Alaska should bring down thousands of landslides and avalanches in the mountains and many subaqueous slides in the deep lakes and fiords.

Property damage from slides in the mountains was generally limited to roads and railroads. Rockslides contributed to only one known death. At Cape Saint Elias, a coastguardsman, seriously injured by a large rockfall, was later drowned by waves (Plafker and others, 1969).

Several writers have attributed the relatively small amount of damage done by avalanches and slides to the sparse population in the mountains. That the rockslides were unprecedented in size and number in recent centuries is demonstrated by the absence of similar deposits of debris on most glaciers before the 1964 event. Large-scale slides triggered by earthquakes doubtless do present a serious hazard in the mountainous regions of Alaska where steep, unstable slopes are present.

With a few outstanding exceptions, most of the slides and avalanches were comparatively simple well-known types and, because they caused little physical damage, they received little attention by investigators.

The landslides along the Patton Bay and Hanning Bay faults on Montague Island (Plafker, 1967) are of interest chiefly because they are related to the only known earthquake-caused surface faults. Although their study added little to general knowledge of landslide processes, Plafker (1967) has noted that, by their very nature,



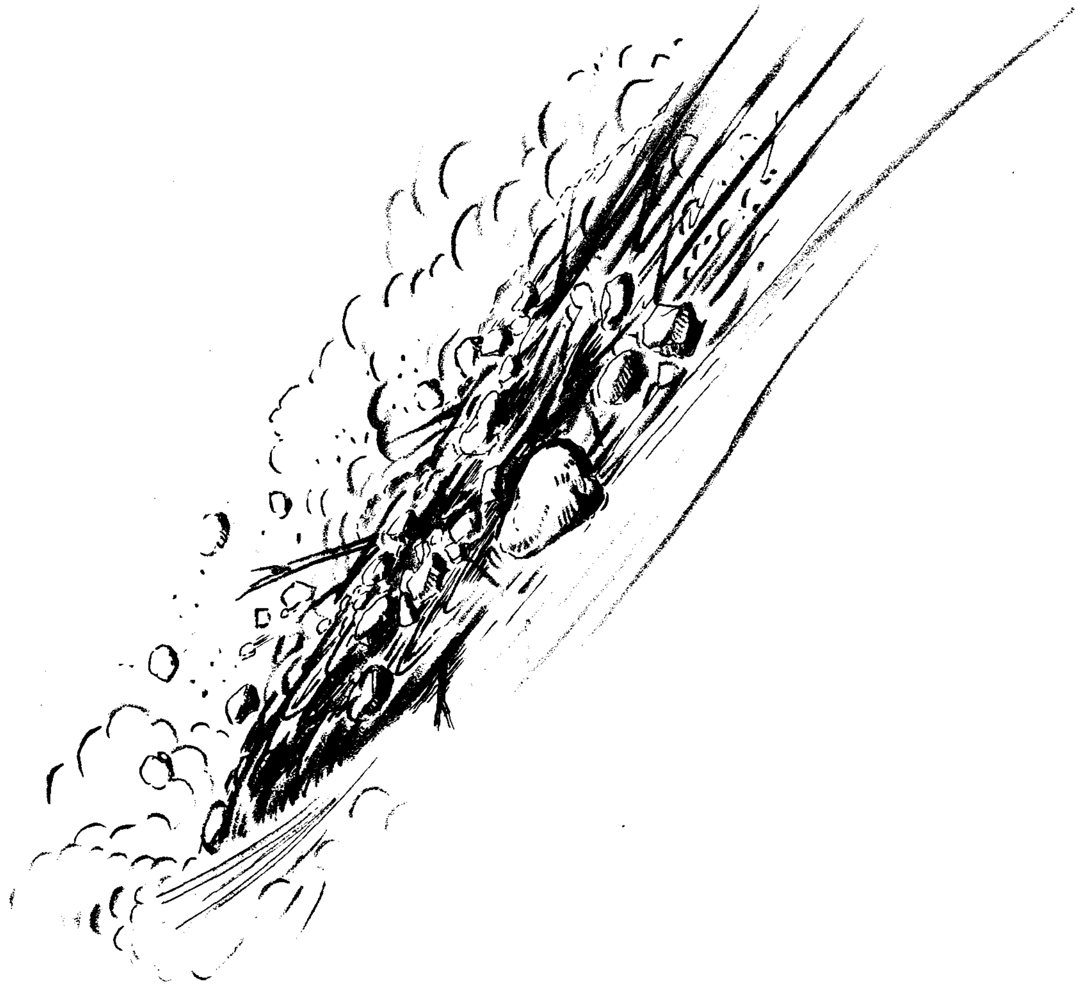
"By far the greatest damage done by slides and avalanches was along the highway and rail net, south and east of Anchorage."

active thrust faults tend to conceal their traces automatically by initiating linear zones of landslides.

Debris slides and rotational slumps developed in many places in and near Anchorage (Hansen, 1965), but they did far less damage and were less important scientifically than the gigantic translatory slides discussed separately below. Slides and slumps on steep slopes near Whittier (Kachadoorian, 1965), Seward (Lemke, 1967), and Homer (Waller, 1966a) also did little damage as compared to submarine slides, waves, and subsidence.

Many landslides occurred on the Kodiak island group in a great variety of geologic settings (Plafker and Kachadoorian, 1966), but aside from temporarily blocking a few roads, they did no significant damage.

By far the greatest damage done by slides and avalanches was along the highway and rail net, south and east of Anchorage. The plotted distribution of these features (Kachadoorian, 1968; McCulloch and Bonilla, 1970) shows how widespread and numerous they were along the roads and railroads. This distribution probably represents fairly well the distribution of downslope mass movements throughout the earthquake-shaken area, with some allowance for the fact that manmade cuts and fills tend to diminish slope stability, hence to increase the number of slides.



"* * * the avalanches initially descended very steep slopes and attained high velocities. * * * These features * * * help substantiate the hypothesis that some large rock avalanches travel on cushions of compressed air."

ROCKSLIDE AVALANCHES

Glaciers and snowfields cover more than 20 percent of the land area that was shaken violently. Almost 2,000 avalanches and snow slides were seen on postearthquake aerial photographs examined by Hackman (1965). Most of these he suspected were caused by the earthquake but as Post (1967) and several others point out, none of these snow and ice avalanches were large enough to materially affect any glacier's regime.

As compared with slides of snow and ice, rockslide avalanches were fewer but much larger. The most thoroughly studied of these is on Sherman Glacier in the Chugach Mountains, 20 miles east of Cordova. There, an enormous mass of rock and some snow and ice fell from two peaks, traveled at high speed, and spread out over half of the glacier's ablation area (Shreve, 1966; Post, 1967; Plafker, 1968). The effects of such deposits on glacier regimes have yet to be fully assessed, but reduction in ice ablation sufficient to favor positive annual mass balances has already been measured. A future modest advance of the Sherman Glacier's terminus can be expected.

Various investigations show that the Sherman and other avalanches tend to have certain common characteristics: (a) the areas were cliffs currently undergoing glacial erosion; (b) the unstable rock available for movement was hundreds of thousands of cubic yards in volume; (c) the avalanches initially descended very steep slopes and attained high velocities; (d) the rock debris spread out over surficial features of the glacier surfaces without greatly modifying them; and (e) the gradients of the avalanches on the glacier surface were very low, yet the material traveled very long distances (Post, 1967). These features together help substantiate the hypothesis that some large rock avalanches travel on cushions of compressed air (Shreve, 1959, 1966b, 1968; Crandell and Fahnestock, 1965).

HORIZONTAL MOVEMENTS OF MOBILIZED SOIL

The movements of mobilized water-saturated soil toward topographic depressions deserve special mention. These movements took place throughout the strongly shaken part of Alaska and were among the major causes of ground fractures along river banks, deltas, and elsewhere. They were best seen and recorded along the highway and railroad systems and were major sources of damage to both (Kachadoorian, 1968; McCulloch and Bonilla, 1970). Elsewhere in thinly populated regions like the Martin and Bering River area (Tuthill and Laird, 1966), lateral spreading did less damage but was nevertheless an important geomorphic process.

In detailed studies of earthquake damage to the Alaska Railroad, McCulloch and Bonilla (1970) observed that ordinary rotational slumps were surprisingly rare and that the elastic response of unconsolidated sediment was a less important source of damage than were *near-horizontal* displacements or "landspreading." This phenomenon has been observed in studies of other great earthquakes. McCulloch and Bonilla describe the distension that occurs within the sediments and note that landspreading takes place on flat or nearly flat ground; thus they differentiate from landsliding, which connotes downslope movement.

Along the railroad, ground fissures, loss of bearing strength, and other effects all took their toll; but in terms of dollars lost, damage caused by landspreading was second only to the loss of terminal facilities at Whittier and Seward caused by submarine slides, waves, and fire (Kachadoorian, 1965; Lemke, 1967). Water-laid saturated sediments responded to the earthquake's vibrations by mobilizing and moving laterally toward free topographic faces that ranged in size from small drainage ditches to wide valleys. The spreading of the mobilized sediments generated stress in their frozen surfaces and caused ground cracking that tore apart railroad tracks and highway pavements. In addition, streamward spreading of the mobilized sediments compressed or skewed numerous bridges by streamward movements of banks. Even deeply driven piles moved toward stream centers, and there was a tendency toward compression and uplift beneath some bridges.

Many of the movements took place in areas where surfaces were nearly flat. Some extended as much as a quarter of a mile back from the topographic depression and offset rail lines or other linear features. McCulloch and Bonilla conclude that the tendency toward mobilization of sediments should be considered in design of structures in earthquake-prone areas. They suggest that it might be minimized by eliminating strong surface irregularities and linear features insofar as possible; skewing of bridges might be reduced by placing crossings at right angles to streambanks.

SUBAQUEOUS SLIDES

Subaqueous slides, and gigantic local waves that were closely related to them in time and origin, caused high loss of life and property. A very few similar slides and their associated waves have been known from other earthquakes, but none had received much study.

Throughout the earthquake-shaken area, steep-fronted deltas collapsed into many of the deeper lakes. The new fronts were generally steeper and less stable than the old ones (Tuthill and Laird, 1966; Ferrians, 1966; Lemke, 1967). Except on Kenai Lake (McCulloch, 1966), none of these slides did much damage, and they were not studied intensively. The several slides along the shores of Kenai Lake yielded more information on the mechanics of sliding and the distribution of resultant debris than was available for the seacoast slides. McCulloch (1966) found that sliding removed the protruding parts of deltas—often the youngest and least consolidated parts—and steepened the delta fronts. He suggests that protruding portions should be the least stable, for they contain the most mass bounded by the shortest possible failure surface. Fathograms show that large slides spread for thousands of feet over the horizontal lake floor and that some of the debris moved so rapidly that it pushed water waves ahead of it and up on the opposite shores.

Because of the presence of coastal communities, submarine slides in the fiords of Prince William Sound and along the south coast of the Kenai Peninsula were far more destructive than those on lakes. The most disastrous ones were at Valdez (Coulter and Migliaccio, 1966), Seward (Lemke, 1967), and Whittier (Kachadoorian, 1965), but there were also slides at Homer on Cook Inlet (Waller, 1966a) and at many other inhabited places. Some of these, and their associated waves, did more damage in proportion to the size of the communities affected than did the better known ones at Seward and Valdez (Plafker and Mayo, 1965; Plafker and others, 1969). In addition to those known to be related to submarine slides, there were numerous destructive waves of unknown origin throughout much of Prince William

Sound. Some of the unexplained waves may have been related to unidentified submarine slides, but some are believed to have been generated by permanent horizontal shifts of the land relative to partly or wholly confined bodies of water (Plafker, 1969; Plafker and others, 1969). How much of the sliding was caused by direct prolonged vibration and how much by the southeasterly shift of the landmass during the earthquake is unknown. It seems probable, however, that vibration was the primary cause of most of it.

All the subaqueous slides that were studied in any detail left new slopes nearly or quite as steep as the preearthquake ones, some even steeper. This is the most significant and ominous finding from the investigations of these features, for it means that the delta fronts are still only marginally stable and hence are subject to renewed sliding, triggered by future earthquakes. The lesson is clear—any steep-faced delta of fine to moderately coarse materials in deep water presents inherent dangers of future offshore slides and destructive waves, whether or not it has slid in the past.

One somewhat unexpected result of the offshore slides, observed on Kenai Lake and at Valdez and Whittier, may well have occurred on other narrow lakes or fiords: the wide and rapid spread of slide debris on the bottom. Some of the debris at Kenai Lake crossed the lake, pushed water ahead of it, and caused wave runups on the far shores (McCulloch, 1966). This feature means that, under some conditions at least, the shore opposite a steep-faced delta may be almost as poor a place for buildings or anchorages as is the delta itself.

In summary, the 1964 earthquake showed that any deep-water delta, such as those in the fiords and many lakes of south-central Alaska, may produce subaqueous slides and associated destructive waves if shaken by a severe earthquake. Such deltas commonly contain much sand or finer grained material, are saturated with water, and have steep fronts; hence they are apt to have very low stability under dynamic conditions.

TRANSLATORY LANDSLIDES IN ANCHORAGE

All the highly destructive landslides in the built-up parts of Anchorage moved chiefly by translation rather than rotation—that is, they moved laterally on nearly horizontal slip surfaces, following drastic loss of strength in an already weak layer of sensitive clay. The translatory slides at Anchorage ranged from block glides, in which the slide mass remained more or less intact, to those that are best classed as failures by lateral spreading (Varnes, 1958).

Translatory slides, caused by earthquakes or other agencies, are uncommon, but they have long been known, and studied to some extent, in Scandinavia, Chile, and the United States (Hansen, 1965). The Anchorage slides of 1964, however, promise to become a classic reference point in the scientific and engineering literature on near-horizontal mass movement of material. They had many novel aspects, and, because facts were needed for far-reaching decisions on the reconstruction of important parts of a thriving city, the Anchorage translatory slides probably received more study by soils engineers and geologists than any comparable group of landslides in history.

Several million dollars was spent by the Corps of Engineers in intensive soils studies of all the Anchorage slides: (1) to determine where reconstruction should be permitted, (2) to build a gigantic stabilizing buttress in the midst of downtown Anchorage, and (3) to experiment

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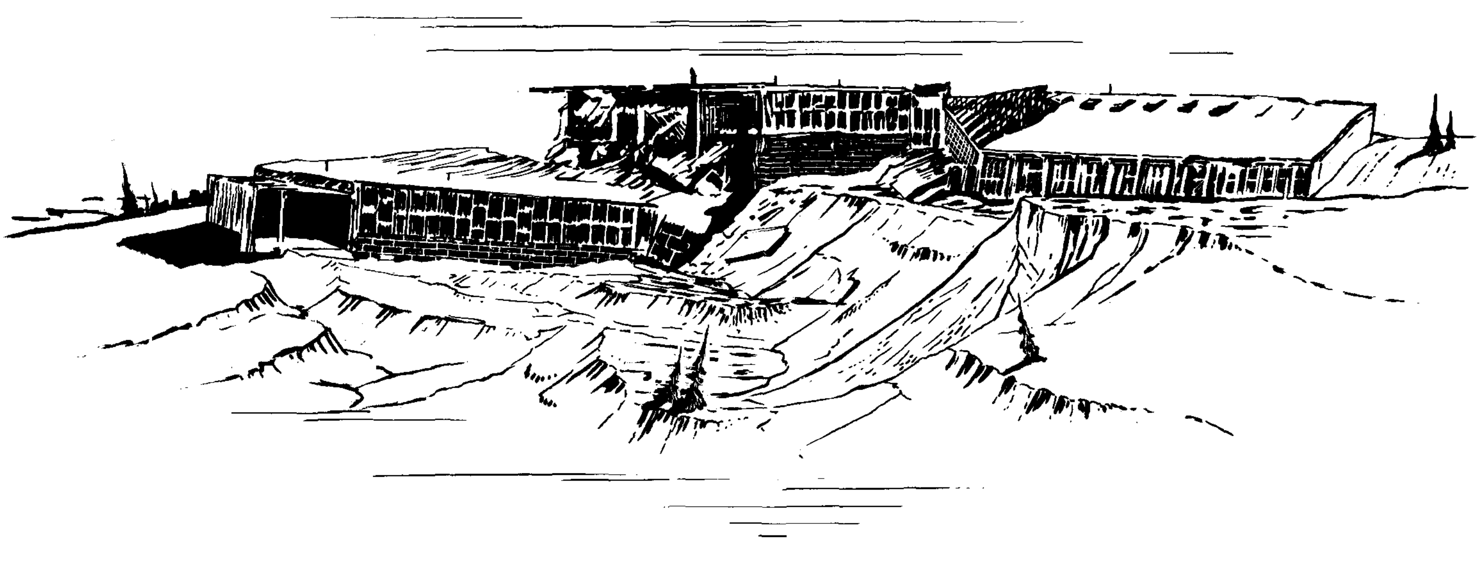

with explosive and electro-osmotic methods of stabilizing the great slide at Turnagain Heights. The slides at Anchorage have also sparked other studies of the stability of slopes in sensitive clays, particularly under dynamic conditions.

All the Anchorage slides involved a hitherto obscure but now famous geologic formation—the Bootlegger Cove Clay of Pleistocene age (Miller and Dobrovolny, 1959). This deposit of glacial estuarine-marine origin underlies much of Anchorage; it is overlain by outwash gravel. All the destructive slides occurred where the Bootlegger Cove Clay crops out along steep bluffs. The formation is comprised largely of clay and silt, with a few thin, discontinuous lenses of sand. The middle part of the formation contains zones characterized by low shear strength, high water content, and high sensitivity; these failed under the earthquake's vibrations.

The most thorough report on the geology of the Anchorage slides, as distinct from the soils engineering aspects, is that by Hansen in which he reconstructed the highly complex Turnagain slide by maps and cross sections (Hansen, 1965, pls. 1, 2). Many other reports on the mechanics of the Anchorage slides or on theoretical and experimental work engendered by the Anchorage experience have already appeared in the civil engineering literature (Shannon and Wilson, Inc., 1964; Long and George, 1967a, b; Seed and Wilson, 1967), and more will appear in the future.

As described by Hansen (1965) earthquake vibrations reduced the shear strength of saturated sensitive zones in the clay. A prismatic block of earth moved laterally on a nearly horizontal surface toward a free face, or bluff. Tension fractures formed at the head of the slide and allowed collapse of a wedge-shaped mass, or graben. Pressure ridges were formed at the toe of the slide block. In complex slides, and with continued shaking, the process was repeated so that slice after slice moved forward toward or beyond the former bluff face.

Seed and Wilson (1967) agree in most respects with Hansen's view of the mechanics of the Anchorage slides. They are much more inclined, however, to ascribe the initial translatory motion to liquefaction of layers or lenses of sand in the clay than to weakening of the clay itself. Seed has found by experiment with modified triaxial shear devices that laboratory-reconstructed sand, similar to that in the Bootlegger Cove Clay, liquefies and loses all its shear strength with far fewer vibratory pulses than are required to liquefy the clay. He is doubtlessly correct as to the initiating mechanism, but there is no question that drastic weakening of the clay contributed to the lateral movements once they had begun. Even under static conditions prior to the earthquake, the bluffline at Turnagain Heights was being undermined at its foot in a continuous zone of clay slumps and liquefied-clay mudflows.

Large-scale field tests were made at Turnagain Heights to determine if remodeling by blasting or treatment by electro-osmosis might add to the strength of the jumbled mass of clay that slid seaward during the 1964 earthquake. Neither method produced very promising results, but when the tests were abandoned the Corps of Engineers and its consultants had determined that the landslide material along Knik Arm had naturally regained all its preearthquake strength. The Corps concluded therefore that the new slopes in the Turnagain area now form a natural buttress to the undisturbed bluff behind the slide that should withstand a future earthquake similar to that of 1964, provided the buttress toe is protected against erosion. In 1969 there were no plans for such erosion protection.

The greatest unanswered question about the Anchorage translatory slides is whether they will recur in the event of another great earthquake, and if so, what can be done to prevent them. There is abundant evidence that repeated similar slides, some in the same places, have been triggered by earlier earthquakes or by other causes (Miller and Dobrovolny, 1959: Hansen, 1965; McCulloch and Bonilla, 1970). There is also every reason to suppose that new slides will develop if and when another severe earthquake occurs. With present knowledge, the most practical means of avoiding or ameliorating future translatory slides would seem to be to reduce the slopes on bluffs, to avoid loading the upper parts of slopes or bluffs, or to construct gigantic earth buttresses like that at the Fourth Avenue slide. Other means of slide prevention may be developed in the future. Meanwhile, the U.S. Geological Survey, in cooperation with Anchorage Borough authorities, is preparing detailed maps that will show, among other things, the outcrops of the Bootlegger Cove Clay and the distribution of steep slopes (Dobrovolny and Schmoll, 1968). Such maps should be useful to borough and city officials in determining the general areas where slides are most likely to occur. Very detailed investigations will, of course, be necessary at any specific site in order to determine the soil conditions and to design corrective or preventive measures.

GROUND FISSURES

Ground fissures, also called cracks or fractures by various authors, are formed by nearly all severe earthquakes and by some smaller ones. Possibly more resulted from the 1964 earthquake than from any previously recorded earthquake. Certainly they were more noticeable and more intensely studied, especially by means of aerial photographs. The ground surface was frozen in nearly all of the earthquake-affected area; this condition not only resulted in more fissures but favored their preservation long enough to permit observation, photographing, and mapping.

General distribution of fissured ground throughout the earthquake-affected area is shown by Plafker and others (1969). Only a very few of the fissures that developed have been mapped, but good examples of their patterns, character, and geologic settings are shown in maps of the Kenai Lake area (McCulloch, 1966); along the railroad and highway nets (Kachadoorian, 1968; McCulloch and Bonilla, 1970); at Valdez (Coulter and Migliaccio, 1966); at Anchorage (Hansen, 1965; Engineering Geology Evaluation Group, 1964); at Seward (Lemke, 1967); and elsewhere. In addition, Ferrians (1966) and Tuthill and Laird (1966) made detailed studies of the fissures and associated landforms in the Copper River Basin and Martin-Bearing Rivers areas. The very extensive ground breakage on the Kenai Lowland was mapped by Foster and Karlstrom (1967).

Ground fissures, many marked by copious emissions of muddy or sandy water or by minor local collapse features, were widespread within about 100 miles of the epicenter, but they were noted as far as 450 miles away (fig. 1).

Flood plains, the tops and fronts of deltas, toes of alluvial fans, low terraces with steep fronts, and lake margins were among the geomorphic features most affected. Fissures varied greatly in length but some individual ones could be traced for thousands of feet. Some open fissures were several feet wide; many fissures opened and closed with the passage of seismic waves.

Most ground fissures were necessarily studied only at the surface. Some fissures on the Kenai Lowland, however, and on Kodiak Island and elsewhere are known to have extended at least 20 to 25 feet beneath the surface, because coal, gravel, pumice, and other materials that exist at those depths were brought to the surface by spouting water (Foster and Karlstrom, 1967; Plafker and Kachadoorian, 1967).

Great quantities of water, mixed with varying amounts of sand and silt, were ejected as fountains or sheets of water from ground fissures in many places (Waller, 1966b). Most ejections came from linear fractures, but in flat-lying homogeneous sediments some came from point sources. Among the chief consequences of the ejections were local subsidence of the land surface and further cracking by removal of water and material from below.

Geologically, most ground fissures were ephemeral features and, of themselves, left little permanent evidence of their presence. Cracked mats of peat, however, were still preserved in 1967, and clastic dikes formed by sand or mud injections may last for many years. Evidence of local subsidence caused by ejection of water and mud from fissures is somewhat more permanent also, as are a few other minor landforms that resulted from them. Several unusual geologic-geomorphic features, such as mud-vent deposits, fountain craters, subsidence craters, and snow cones, are described by Tuthill and Laird (1966) in the Martin-Bering Rivers area. Most of these are related to the pumping of water and sediments from ground fissures. Similar deposits were left by mud spouts or by melting of snow avalanches in many parts of the earthquake-affected area (Waller, 1966a, b; Lemke, 1967; McCulloch and Bonilla, 1970). All these features are of some scientific interest, but they are ephemeral and are not likely to be preserved in the geologic record unless they are soon buried by other deposits.

Widespread damage resulted from fissures, though on the whole it was minor as compared to that from other sources. Ground fissures disrupted buried utility lines and did other damage in Anchorage (Hansen, 1965; Burton, in Logan, 1967; McCulloch and Bonilla, 1970). At Seward, remaining parts of the fan-delta whose front slid into Resurrection Bay were severely cracked and left unstable. Fissures also damaged many homes and roads in Forest Acres outside of Seward (Lemke, 1967). At Valdez, 40 percent of the homes and most commercial buildings that were not wrecked by the giant submarine slide were seriously damaged by earth fissures that destroyed their structural integrity, broke pipes, and pumped immense quantities of sand and silt into their lower parts (Coulter and Migliaccio, 1966). At the Eklutna Lake powerplant, numerous cracks, some of them damaging, developed in both natural and artificially compacted sediments (Logan, 1967). At the Cordova airport, the foundation of the

FAA office building was split by a ground fissure, and underground utility lines were broken in so many places that most had to be replaced (Eckel, 1967).

All fissures were directly related to local geologic conditions. Many of them formed in thick coarse-grained unconsolidated deposits, where the water table was close to the surface and where the topmost layers were frozen, hence brittle. Many others, as on the mudflats of the Copper River Delta, Controller Bay, and near Portage, developed in fine-grained deposits. Artificial fills were very susceptible. Many cracks followed backfilled utility trenches. Many highway fills compacted and cracked marginally. Few fissures formed in well-drained surficial deposits, and hardly any in bedrock or in permafrost.

Only on the Kenai Lowland was there any suggestion of tectonic control of the fracture patterns (other, of course, than the regional tectonic factors that controlled the general distribution of all the earthquake's effects). On the lowland, and to some extent in the Chugach Mountains north of it, Foster and Karlstrom (1967) noted an alinement of ground fractures that suggested to them that the fractures might reflect earthquake - caused movement along hypothetical faults in the underlying bedrock.

Seismic vibration was the ultimate cause of virtually all the fissures. Some were formed directly by the shaking, others by differential horizontal or vertical compaction, others by local subsidence. Many formed near slopes or surface irregularities when underlying materials liquefied or, mobilized by vibration, moved toward topographic depressions. The best known examples perhaps are the ground fractures back of the translatory slides at Anchorage (Hansen, 1965), the extensive fissures on the Resurrection River Delta near Seward (Lemke, 1967), and the thousands of fissures along the rail and road systems (Kachadoorian, 1968; McCulloch and Bonilla, 1970). Unconfined slopes were not essential to the formation of fissures, however; many formed on flat unbroken surfaces such as that of the Copper River Delta.

As a possible explanation for the origin of a certain type of ground fissure that formed in the Copper River Basin in flat-lying areas where there were no free faces toward which the materials could move, Ferrians (1966) suggests that surface waves flexing the layer of frozen surficial materials, which was in a state of tension, caused the initial cracking of the surface. The passing surface waves subjected the saturated sediments beneath the seasonal frost to repeated compression and dilation in the horizontal direction; consequently, large quantities of water and silt- and sand-sized material were ejected from the cracks, and sediment particles were rearranged. The net result of these forces was horizontal compaction, which caused the formation of numerous ground cracks that extended for great distances and formed a systematic reticulate pattern in the flood plains of some of the larger rivers.

Permanently frozen ground, because it behaves dynamically like bedrock, had few if any fissures; in some places, however, where water-bearing layers were perched between the permafrost and the seasonal frost layer at the ground surface, there was extensive cracking (Ferrians, 1966).

Except in a general way, the occurrence and distribution of ground fissures would be difficult to predict for any given earthquake. The conditions under which they develop are now well known, and it is possible to identify bodies of sediments that are susceptible to fissuring during a large earthquake of long duration (McCulloch and Bonilla, 1970). Formation of individual fissures or fissure systems is so dependent

"All fissures were directly related to local geologic conditions. Many of them formed in thick coarse-grained unconsolidated deposits, where the water table was close to the surface and where the topmost layers were frozen, hence brittle."

on local geologic and ground-water conditions, however, that highly detailed knowledge of local surface, subsurface, and subaerial conditions would be required for precise predictions.

CONSOLIDATION SUBSIDENCE

Seismic vibration caused consolidation of loose granular materials in many places. Rearrangement of constituent particles, aided by ejection of interstitial water through waterspouts or mud spouts, caused compaction and local differential subsidence of the surface. Lateral spreading, too, caused lowering of surface levels in places. In coastal areas where local subsidence was superimposed on regional tectonic subsidence, as on Homer Spit (Grantz and others, 1964; Waller, 1966a), Kodiak Island (Plafker and Kachadoorian, 1966), and near the head of Turnagain Arm (Plafker and others, 1969), for example, the likelihood of destructive flooding was heightened.

The intake and spillway at Eklutna Lake, which feeds the Bureau of Reclamation's Eklutna hydroelectric plant, provided special instances of damage by consolidation subsidence. The concrete intake structure was cracked when the lake sediments beneath it compacted and subsided. As a direct result, about 2,000 cubic yards of sand and rock passed through the broken intake and into the main tunnel. The concrete spillway gate at Eklutna Dam was also severely cracked, but not until long after the earthquake. As described by Logan (1967), saturated alluvium below the frozen surface layer subsided as it was consolidated by the earthquake and left a void below the frozen layer. Later as thawing progressed, the frozen material collapsed into the void, breaking the gate structure.

SHORE PROCESSES

Thousands of miles of coastlines were modified by the earthquake, partly by transitory but highly destructive water waves and, more generally and much more permanently, by uplift or subsidence. All but a few reports in this series describe such damage, particularly at inhabited places along the coast. There were, however, comparatively few studies of the coastal processes themselves. The changes in beach-forming processes at Homer Spit, because of their economic importance, were investigated in detail by Stanley (in Waller, 1966a) and by Gronewald and Duncan (1966). Similarly, but for scientific reasons only, stream mouths and beach changes caused by sudden uplift on Montague Island were studied by Kirkby and Kirkby (1969), and the shallow deltaic sediments off the mouth of the Copper River were investigated by Reimnitz and Marshall (1965). The Geological Survey itself made few detailed studies of shore processes (McCulloch, 1966; Waller, 1966a, b) but, with support from the Committee on the Alaska Earthquake, National Academy of Sciences, the Survey persuaded K. W. Stanley (1968) to prepare a general report on this subject based on his own observations and on summaries of the sparse published work of others. Periodic detailed observations over many years would be needed to provide a more complete understanding of the many geologic and biologic adjustments still in progress along the coasts.

All along the coasts, the shoreline began immediately to conform to new relative sea levels. Subsided beaches moved shoreward, building new berms and slopes. Relatively higher tides attacked receding blufflines. Faster erosion locally scoured source areas for beach nourishment, and thus provided more material to replenish losses caused by subsidence. Streams whose mouths were drowned began to aggrade their beds.

In the uplifted areas, on the other hand, beaches were stranded above tidewater and some surf-cut platforms became terraces or benches. Wave erosion of bluffs was stopped, and bluff recession was slowed to the rate set by subaerial processes. Uplift speeded streamflow, with consequent entrenchment and increased sediment load. New beaches began to form below the abandoned ones.

Within the span of a few minutes, the earthquake caused changes in coastal conditions and processes that normally require centuries. In the subsided areas it also wrought changes that are usually associated only with rare severe storms.

HYDROLOGIC EFFECTS

The hydrologic regimen other than glaciers was studied by fewer investigators than were most other phenomena. Nevertheless, these studies produced much new knowledge. Hydrologic effects possibly were more extensive than any previously observed on the North American continent; quite certainly they were the greatest ever recorded, for fluctuations of surface and ground-water level were measured not only throughout most of North America but in many other parts of the world.

GLACIERS

Glaciers cover about 20 percent of the land area that was violently shaken by the earthquake. Numerous glaciologists and geomorphologists, particularly those who had continuing interests in the life histories of specific glaciers, were eager to study the effects of the earthquake. But aside from the great rock avalanches, surprisingly few effects were observed within the first several years.

Studies added weight to the theory that some rock avalanches descend on a cushion of compressed air (Shreve, 1959, 1966b, 1968). It is also quite clear that the avalanche debris will drastically alter the regimens of the glaciers by insulating the ice surfaces on which they came to rest. Aside from these facts, most of the glacial studies had indecisive results. There were several enormous rockslide avalanches, but no large snow or ice avalanches, and relatively few small ones occurred on glaciers, despite the fact that avalanche hazard was already high at the time of the earthquake (Post, 1967). There were no significant changes in the calving of icebergs from tidewater glaciers, although some glacier fronts were shattered and glacial ice was thrown out onto ice-covered lakes that fronted them (Waller, 1966b). Few changes occurred in glacial streams or ice-dammed lakes. There was no evidence of dynamic response to earthquake shaking or to avalanche loading. The glaciers' response to tectonic uplift, subsidence, or lateral movement was too small to detect, at least during the few years that have been available for study.

By far the most significant conclusion reached by the glaciologists was a refutation of Tarr and Martin's theory (1912) that earthquakes are likely to initiate rapid advances or surges in glaciers by triggering extraordinary numbers of avalanches in the glaciers' alimentation area. Post (1967), on the basis of long-continued studies, thinks that the surges actually bear no relation to earthquakes. Many such surges involve sudden advances of ice from the upper to the lower parts of glaciers, with little or no advances of the termini. Knowledge that surges did not immediately result from this earthquake does not remove the danger that sudden advances of glaciers from other causes may increase flood hazards to places like Valdez (Coulter and Migliaccio, 1966).

ICE BREAKAGE

In Alaska and nearby Canada, ice was broken on lakes, streams, and bays over an area of more than 100,000 square miles (fig. 1). The cracked ice afforded an easily observed measure of the geographic spread of the earthquake's effects, but otherwise it had minimal significance (Waller, 1966a, b; Plafker and others, 1969). Breakage did little physical damage except to a few beaver houses; in fact, the ice cover on many bodies of water probably diminished the intensity of destructive wave action.

Some of the cracking was caused directly by seismic vibrations, but much more resulted from long-continued seiches, as on Portage Lake (Waller, 1966b) and on Kenai Lake (McCulloch, 1966). Horizontal tectonic movements of the landmass may have been a factor in causing ice breakage in some places. Cracking of ice in lakes and fiords was doubtlessly initiated by subaqueous slides off delta fronts and by the local waves engendered by the slides. Still lacking is a firm explanation as to why the ice on a few lakes and stream segments, even near the earthquake epicenter, was unbroken. Possibly the earthquake vibrations did not coincide with the natural periods of these water bodies, so that there was no buildup of resonance.

GROUND WATER

The surging of water in wells and the temporary or long-lasting changes in water levels as a result of earthquakes have possibly been known ever since man has had wells. Within Alaska these effects from the 1964 earthquake were not much different from those observed in the past, though their magnitudes and durations may have been greater. Over most of the violently shaken area in south-central Alaska, ejection of vast quantities of sediment-laden water through ground fractures lead in places to subsidence of the water-bearing sediments. As described by Waller (1966a, b), the water in many shallow wells surged, with or without permanent changes in level, pump systems failed, and water became turbid. In some of the subsided areas, coastal salt water encroached into some wells. Most of these effects were temporary, but some were permanent or semipermanent.

Many artesian wells were also greatly affected. In several of these wells, at Anchorage for example, artesian-pressure levels dropped as much as 15 feet, either permanently or for several months. Perhaps this change was caused by porosity-increasing grain rearrangements in the aquifers, or by material displacements that permitted freer discharge of water at submarine exposures of the aquifers. Significantly, all such wells were in areas of known or inferred regional horizontal extension and vertical subsidence where porosity-increasing changes must have occurred in the aquifers (Plafker, 1969).

The observations of the earthquake's effects on ground water outside Alaska were of tremendous scientific significance. Other earthquakes have caused fluctuations or disturbances in the ground-water regime at far-distant points, but never before have such effects been noted at as many recording stations and over the entire world (Vorhis, 1967; McGarr and Vorhis, 1968). "Hydroseisms" (a word coined by Vorhis to include all seismically induced water-level fluctuations other than tsunamis) were recorded in more than 700 water wells in Europe, Asia, Africa and Australia, and in all but four of the 50 States. Most records showed only brief fluctuation of the water level, but the fact that about a fourth of them showed either a lasting rise or decline in water level suggests that the earthquake caused a redistribution of strain throughout North America. Especially sensitive well stations recorded both the surface seismic waves that traveled the long way and those that traveled the short way around the globe. Some wells as far away as Georgia were muddied.

SURFACE WATER

Research into the earthquake's effects on surface waters yielded even more significant information than studies related to ground water. Within Alaska the effects were widespread, though they taught little that was new (Waller, 1966 a, b). Seiches dewatered some lakes, fissures in streambeds and lakeshores caused water losses, regional tilting may have reduced the flow of some rivers, and landslides or avalanches blocked or diverted some streams. Recording gages on streams measured seiches like those on lakes. Perhaps the most interesting side effect of local surface-water reaction to the earthquake was the realization that some large Alaskan lakes may be useful as giant tiltmeters for future vertical strain measurements (McCulloch, 1966; Hansen and others, 1966).

The observations of the effects on surface waters outside Alaska also were scientifically illuminating. The worldwide distribution of these effects was first reported by Vorhis (1967); later the findings were elaborated by McGarr and Vorhis (1968) to answer some of the theoretical questions that arose earlier.

Seismic seiches caused by the Alaska earthquake were recorded at more than 850 gaging stations on lakes, ponds, and streams throughout North America and at four stations in Australia. The seiches are believed to be related to the amplitude distribution of short-period seismic surface waves, particularly those having periods that coincide with similar-length oscillation periods of certain bodies of water. They were concentrated in areas underlain by thick soft sediments or where sediment thickness increases abruptly. Major tectonic features exerted a strong control; the Rocky Mountains, for example, provided a wave guide along which seiches were more numerous than to either side.

Preliminary as they are, the findings of McGarr and Vorhis have far-reaching significance in the understanding of the worldwide amplitude distribution of short-period seismic surface waves. Most importantly, McGarr and Vorhis (1968) have shown that records of seiches on surface-water bodies, as measured by the network of water-level recorders that is necessarily much denser than any seismograph network can be, are powerful potential tools in future studies of seismic waves and of earthquake intensities.

Another lesson learned from the earthquake's effects on hydrology was that long-continued records from properly equipped observation wells and gaging stations are essential to proper interpretation of postearthquake observations.

OCEANOGRAPHIC EFFECTS

Violent waves of diverse kinds and origins wrought havoc along the shores of south-central and southeast Alaska and on the northern Pacific shores from British Columbia to California; they also took most of the lives that were lost. Had the coast been more heavily populated or had the earthquake struck at high tide, damage would have been even more extensive than it was.

The terminology applied to earthquake-generated water waves differs among various authorities, but in this series a general distinction is made between seismic sea waves, or tsunamis, and local waves. Local waves were generated along the coast or in lakes and affected areas of limited extent; they characteristically struck during or immediately after the earthquake. Seismic sea waves, or tsunamis, on the other hand, comprised a train of long-period waves that spread rapidly over the entire Pacific Ocean and struck the Alaskan coast, after shaking had subsided. Locally, seiches, caused by the to-and-fro sloshing of water in partly or wholly confined basins, complicated the overall wave picture.

Within Alaska, there were few instrumentally determined records of the waves, because all nearby tide gages were destroyed or incapacitated. The nature of both seismic sea waves and local waves, therefore, was deduced from the accounts of eyewitnesses, from direct observations of wave effects on shores, and from indirect underwater investigations.

The wave histories at specific communities, and descriptions of their effects, are discussed in reports on Whittier (Kachadoorian, 1965); Valdez (Coulter and Migliaccio, 1966); Homer (Waller, 1966a); Kodiak (Kachadoorian and Plafker, 1967); and Seward (Lemke, 1967).

Wave effects were also studied along most of the shores of Prince William Sound, along the south end of the Kenai Peninsula, and on the Kodiak island group (Plafker and Kachadoorian, 1966; and Plafker and others, 1969). Concurrently oceanographic studies of the effects of slides and waves were being studied in much of Prince William Sound, Resurrection Bay, and Ailiak Bay (G. A. Rusnak, unpublished data).

The history and significance of the seismic sea waves, both near the origin and throughout the Pacific, were investigated by Van Dorn (1964), among others. Though necessarily based in large part on a synthesis of facts collected by others shortly after the earthquake, the exhaustive treatment of all the kinds of waves and of their effects on coastal engineering structures by Wilson and Tørum (1968) is the most comprehensive that has appeared.

LOCAL WAVES

Knowledge of the origin and importance of earthquake-induced local waves, hitherto very sparse, was greatly augmented by studies of the Alaska earthquake. One of the most striking characteristics of the waves was their localized and seemingly erratic distribution, though actually it was the distribution of the causative slides that was erratic, rather than the waves. Furthermore, the local waves struck during the earthquake, or immediately after it, and had generally subsided long before the arrival of the train of seismic sea waves, or tsunamis.

There is much evidence of the genetic relationship of the local waves to subaqueous slides. In general, this evidence consists of (1) wave-damage patterns that radiate from the vicinity of deltaic or morainal deposits, (2) presence of subaerial scarps or oversteepened near-shore slopes, and (3) bathymetric measurements that indicate removal of material from upper parts of slopes and deposition of slide debris in deeper water.

Many of the destructive local waves, however, cannot be attributed with any assurance to subaqueous slides. Some formed in shallow embayments or semienclosed basins, where slides are unlikely to have occurred. It seems possible that the horizontal displacement of the landmass may have been either a primary or a contributing cause (Malloy, 1965; Plafker, 1969, and Plafker and others, 1969). Other factors that may have played a part are regional tilt, submarine faulting, and seismic vibrations, but none of these should have caused waves as large as some of those observed. Plafker (1969) has suggested that the long-period high-amplitude seiche waves recorded at Kenai Lake may have been caused primarily by horizontal shift of the lake basin rather than by regional tilt as originally suggested by McCulloch (1966).

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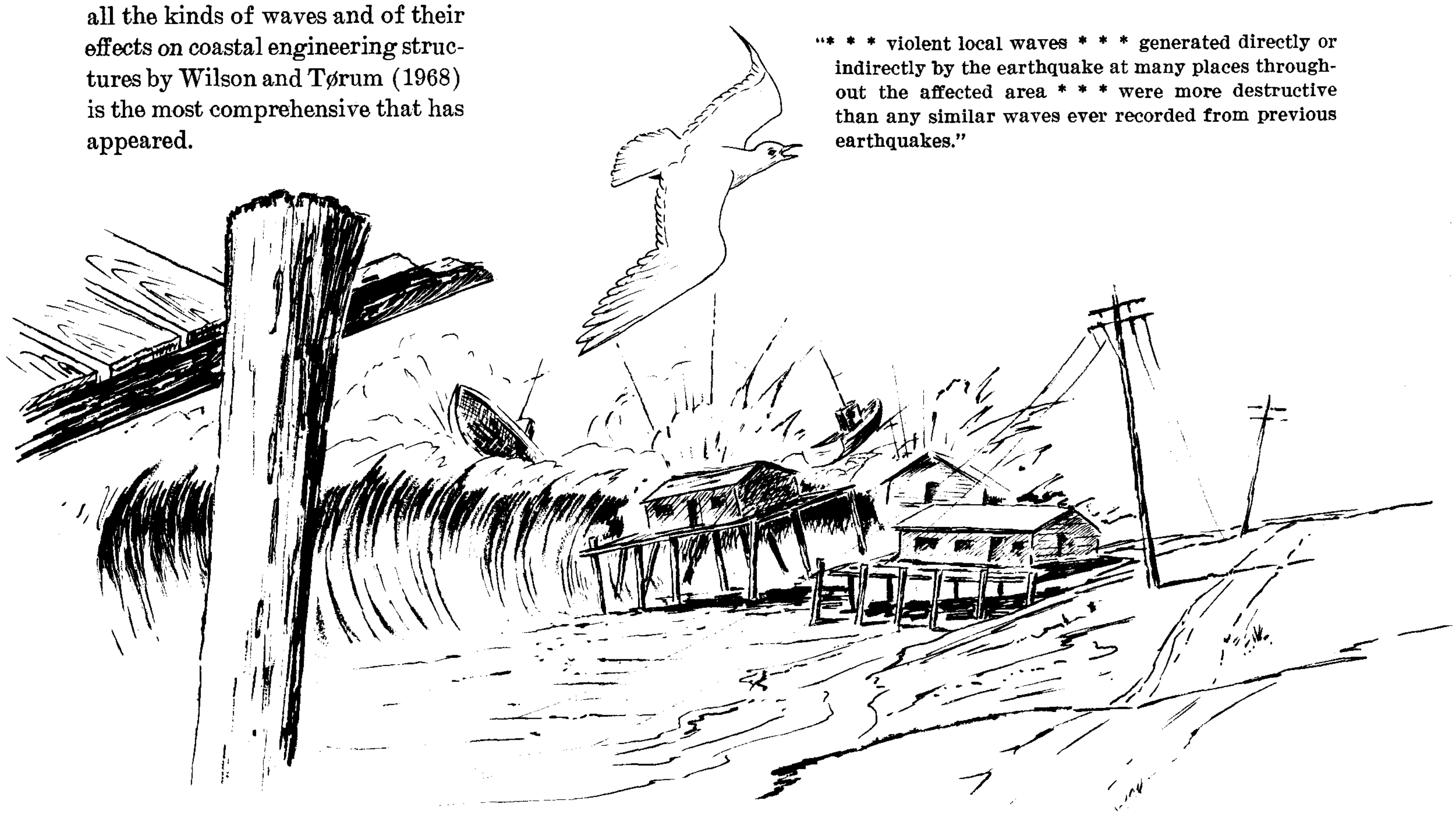

The origin of many of the local waves must remain in doubt, but it is known, (1) that violent local waves were generated directly or indirectly by the earthquake at many places throughout the affected area, (2) that, except for the giant waves of Lituya Bay (Miller, 1960), they were more destructive than any similar waves ever recorded from previous earthquakes, and (3) that a basis for predicting the recurrence of some of them exists.

SEISMIC SEA WAVES

The first of a train of seismic sea waves (tsunamis) struck the shores of Kodiak Island, the Kenai Peninsula, and Prince William Sound from 20 to 30 minutes after the earthquake. Succeeding waves, with periods ranging roughly from 1 to 1½ hours, followed during the night—the highest waves of the series commonly striking around midnight near the time of high tide. These waves were generally much lower in amplitude than the locally generated waves, and in some places resembled high fast-moving tides more than they did breaking waves. They flooded large areas and wrecked many vessels and shore installations, particularly where the land had already subsided because of tectonic downdrop or compaction of sediments.

Outside Alaska, the seismic sea waves were measured instrumentally at many stations around the Pacific, even as far away as Antarctica (Donn, 1964; Donn and Posmentier, 1964). The second measurement ever recorded of the passage of a seismic sea wave in the open ocean was made near Wake Island (Van Dorn, 1964). The first such measurement, also made on the gage near Wake Island, recorded the tsunami from the March 9, 1957, earthquake in the Aleutian Trench (Van Dorn, 1959).

The seismic sea waves were generated on the Continental Shelf within the Gulf of Alaska. This was shown clearly by the arrival times of initial waves, the distribution of wave damage, and the orientation of damaged shorelines. Other evidence, such as tide-gage records outside the area affected by the earthquake, demonstrates conclusively that the violent upward tilt of an enormous segment of the sea floor provided the force that initiated the seismic sea waves and oriented the wave train. The waves thus began along the linear belt of maximum tectonic uplift that extends from Montague Island to near Sitkalidak Island, southwest of Kodiak Island (Van Dorn, 1964; Spaeth and Berkman, 1965; Pararas-Carayannis, 1967; Plafker, 1969; Wilson and Tørum, 1968). Most of the shallow Continental Shelf off the coast of south-central Alaska was involved in the upward tilting of the sea floor, which forced a great quantity of water to drain rapidly from the shelf and into deeper water. Reconstruction of the source volume from available data on the area and amount of uplift suggests that the potential energy of the seismic sea waves was of the order of 2×10^{22} ergs, or roughly 0.1 to 0.5 percent of the seismic energy released by the earthquake (Plafker, 1969).

The source area of a train of seismic sea waves and their originating mechanisms were better defined for the Alaska earthquake of 1964 than for most other earthquakes that have been studied. As Van Dorn says (1964), "Never before has sufficient detailed knowledge been obtained on sea-floor motion, type of motion, and the deep-water spectrum offshore, to permit a convincing reconstruction of the generating mechanism." Furthermore, the seismic sea waves generated by the Alaska earthquake largely confirmed empirical-statistical data used by oceanographers to relate the size of the source area and tsunami heights and periods to the energy released by the initiating earthquake (Wilson and Tørum, 1968).

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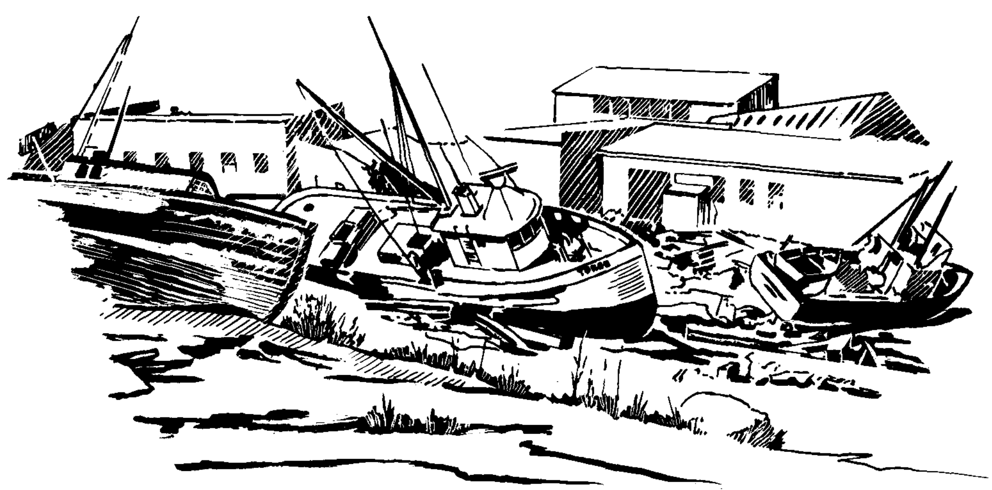


MISCELLANEOUS EFFECTS

The earthquake had many other effects of great economic, sociologic, and biologic importance. These are summarized briefly by Hansen and others (1966) and are treated at length by many writers. There remain a few effects, at least partly related to geology, that are worth noting here.

AUDIBLE AND SUBAUDIBLE EARTHQUAKE SOUNDS

Audible sounds that accompany or even precede the onset of an earthquake have been reported many times in history, but such sounds have never been instrumentally recorded and seldom have they been scientifically authenticated. The Alaska earthquake of 1964 followed the pattern—numerous observers reported hearing sounds, but, so far as is known, no instrumental records were made of these sounds.

On Kodiak Island, several witnesses heard a low-pitched rumbling noise about 5 seconds before the initial tremors were felt. Many Kodiak people also heard deep rumbles just before some of the aftershocks were felt (Plafker and Kachadoorian, 1966). At Homer, too, and at Portage Lake near Turnagain Arm, some people heard rumbling sounds a few seconds before feeling the initial shock. They also heard sounds variously described as rumbling, cracking, and popping during the period of violent earth motion (Waller, 1966 a, b), as well as the windlike noise of rapidly swaying tree branches. Crackling sounds in the ground were heard at South Naknek, 350 miles southwest of the epicenter (Plafker and others, 1969). Observers at Valdez (Coulter and Migliaccio, 1965), in the Copper River Basin (Ferrians, 1966), on the Kenai Peninsula, in Prince William Sound, and at many other places also heard sounds during the quake (Chance, 1966a).

That the Alaska earthquake produced sounds audible to alert observers over a wide area seems a well established fact, though the cause of the sounds has not been determined. In all probability there were many causes, operating at different places and at slightly different times. Cracking or bending of trees, breaking of ice on water bodies or in glaciers, and ground fractures in frozen near-surface soils all probably made audible sounds. How much, if any, of the sound effects can be ascribed to deeper sources, such as breaking of rock along faults in depth or to crunching of sands and gravels as they were consolidated by vibration or as they formed slides on land or under water, is unknown. It seems possible, however, that some of the sounds, particularly those that preceded recognizable ground vibrations, were caused by processes such as these. It also seems possible that the earthquake tremors, coupled to the overlying air envelope, caused audible vibrations. This explanation would apply particularly to the fast-moving, lower amplitude *P* waves that can often be heard but not felt.

Although audible sound waves are not known to have been recorded, subaudible sound waves were recorded. Waves of very low, subaudible frequencies were recorded by the National Bureau of Standards at stations in Washington, D.C., Boulder, Colo., and Boston, Mass. These sound waves, generated by the earthquake itself and by seismic waves as they passed through the earth, excited the atmosphere. In addition, Rayleigh waves (surface seismic waves) that displaced the ground created subaudible sound waves that traveled upward, with amplification, to the ionosphere. The resultant oscillation of the ionosphere was detected by means of reflected radio waves (Bolt, 1964; Davies and Baker, 1965; Leonard and Barnes, 1965; Smith, 1966; and Row, 1967).

MAGNETIC EFFECTS

A recording magnetometer in the city of Kodiak recorded several magnetic disturbances a little more than 1 hour before the earthquake struck. Moore (1964) thinks that the magnetic events so recorded may have resulted from piezo-magnetic effects of rocks undergoing a change in stress. He also suggests that magnetic monitoring may provide a means of predicting major earthquakes in time to save lives and property.

VISIBLE SURFACE WAVES

As with audible sound waves, the passage of visible waves over the surface of the ground during strong earthquakes has been reported by many observers. The Alaska earthquake of 1964 was no exception to the general rule; many observers reported seeing ground waves, but their observations were not substantiated instrumentally.

On the Kodiak island group, surface waves reportedly were seen at Ouzinkie and Afognak. These waves, perhaps propagated in ground that had become semifluid with vibration, were estimated at about 30 feet in length and about 3 feet in height (Plafker and Kachadoorian, 1966).

Many people reported seeing surface waves in various parts of the Copper River Basin. At a point 100 miles from the epicenter, the waves were said to be about 10 feet apart and 3 feet high. At

165 miles from the epicenter, they were reported as longer and lower, with lengths of 50 to 60 feet and heights of 18 to 20 inches (Ferrians, 1966).

Perhaps the most reliable observation of surface-wave amplitudes was made by an experienced geologist at Valdez. As quoted by Coulter and Migliaccio (1966), the geologist noticed a 6-foot youth standing 410 feet away from him. As crests passed the youth, he appeared in full sight, with one trough between him and the observer. Passage of troughs caused him to sink partly out of sight. The observations indicate wave heights of 3 to 4 feet and lengths of several hundred feet.

There is no question that many people saw, or thought they saw, waves on the ground surface in many places. Whether all the waves were real or imaginary, and if real, what caused them, must remain subjects for speculation.

PERMAFROST

Because it was one of the few well-studied earthquakes that has affected perenially frozen ground, the 1964 Alaska earthquake added much to our knowledge of the reaction of frozen ground to seismic shock. Permafrost, or perennially frozen ground, has long been a perplexing and exasperating engineering problem in arctic and subarctic regions. The perennially frozen unconsolidated deposits affected by the 1964 quake behaved like solid rock and were far less susceptible to seismic vibration than were similar but unfrozen deposits.

The seismic response of permafrost was studied in detail in the Copper River Basin (Ferrians, 1966). In the basin, most fine-grained sediments are perennially frozen from depths as great as 200 feet to within 1 to 5 feet of the surface, except beneath cleared areas where the top of the permafrost is 10 to 20 feet deep. Coarse-grained deposits along the major streams and deposits close to large deep lakes generally are free of permafrost.

There were no ground cracks and little or no vibration damage of any kind where permafrost approaches the surface. Thus ice-rich perennially frozen ground apparently behaved much like bedrock in transmitting and reacting to earthquake shocks. However, perched ground water between permafrost and the seasonally frozen layer at the surface caused some fissuring and other evidences of vibration.

CABLE BREAKS

Several underwater cables were broken by the earthquake vibrations or by subaqueous slides. The only one broken in the heavily devastated area was the Federal Aviation Agency cable under Beluga Lake at Homer (Waller, 1966a). This break was probably caused by vibration, for the lake is shallow and there is no evidence of offshore-slides.

The Southeastern Alaska coaxial submarine cable was broken at a point 19½ miles south of Skagway, in Lynn Canal, near the mouth of the Katzehin River; a similar break occurred in this area as a result of the 1958 earthquake. The 1964 break occurred early on the morning of March 28 and was apparently caused by a submarine slide in silt that was triggered by the seismic sea wave (Lt. Col. Alexander Alvarado, USAF, written commun. to George Plafker, May 1, 1964).

Near Port Alberni, British Columbia, the Commonwealth Pacific Communication Service cable from Port Alberni to Hawaii was ruptured. This break occurred only 2 minutes after the onset of the earthquake and was evidently caused by seismic vibrations. The cables between Port Angeles, Washington, and Ketchikan and between Ketchikan and Sitka were unaffected (Comdr. H. G. Conerly, U.S. Coast and Geodetic Survey, oral commun. to George Plafker, May 1964).

TUNNELS, MINES, AND DEEP WELLS

One aspect of the earthquake's effects on manmade structures that deserves further study is the fact that no significant damage has been reported to underground openings in bedrock such as tunnels, mines, and deep wells, although some rocks and earth were shaken loose in places. The Alaska Railroad tunnel near Whittier (McCulloch and Bonilla, 1970) and the coal mines in the Matanuska Valley (Plafker and others, 1969) were undamaged. The tunnel and penstocks at the Eklutna hydroelectric project were damaged only by cobbles and boulders that were washed through the intake structures (Logan, 1967). A small longitudinal crack in the concrete floor of the Chugach Electric Association tunnel between Cooper Lake and Kenai Lake is believed to have been caused by the earthquake (Fred O. Jones, oral commun., 1967).

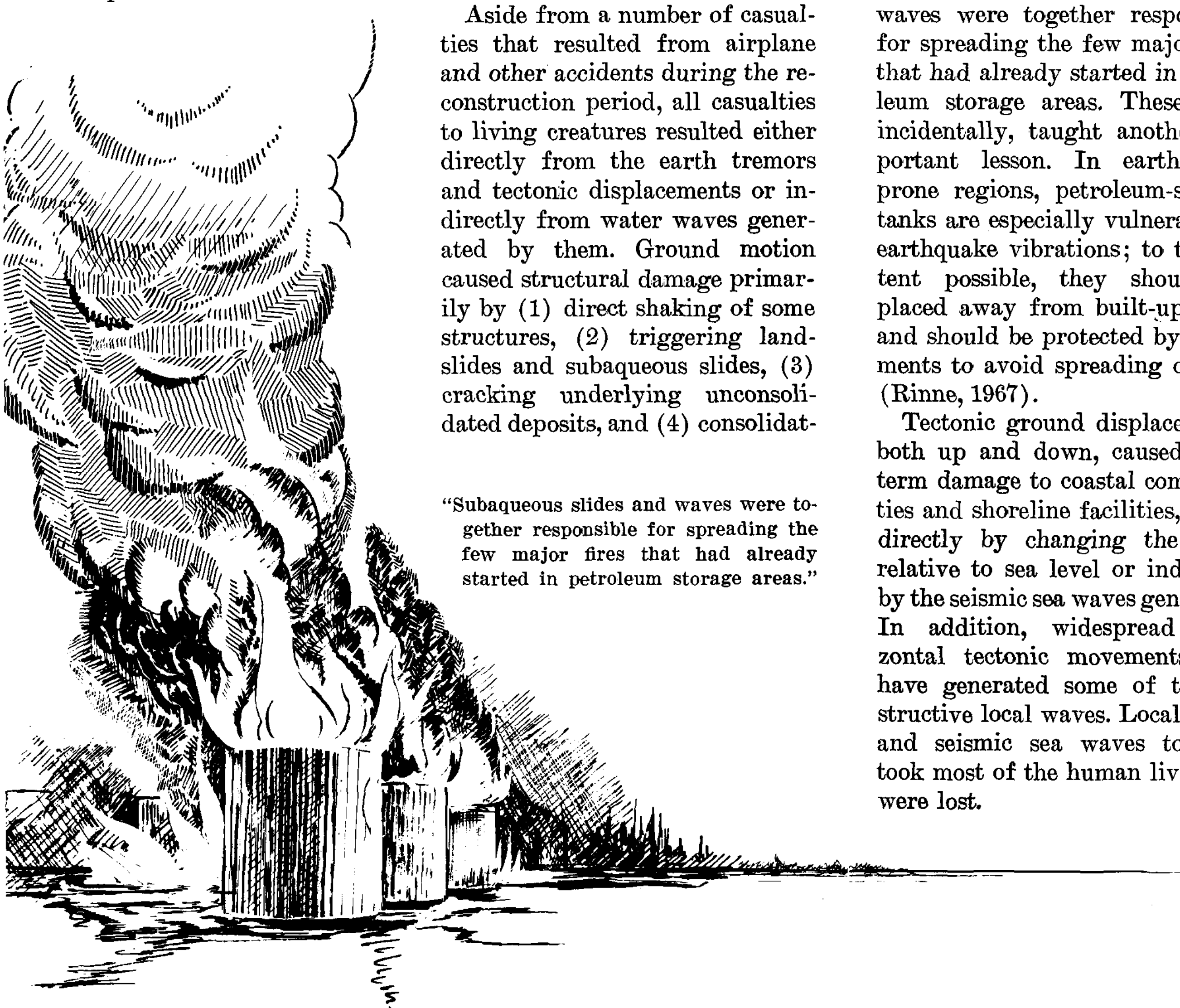
The collars of some drilled wells were displaced by vibration or by consolidation of adjacent soils, and a few water wells and one abandoned exploratory oil well near Yakataga were sheared off. There are, however, no reports of damage to any wells that were more than a few hundred feet deep, such as the many oil and gas wells in and along Cook Inlet. In and near the landslide areas in Anchorage, most sewers and other underground utility lines were extensively fractured or displaced (Burton, in Logan, 1967; Hansen, 1965; Eckel, 1967; McCulloch and Bonilla, 1970). Ground fissures also broke many buried pipelines in Seward (Lemke, 1967) and elsewhere. In Valdez, Coulter and Migliaccio (1966) were able to use the horizontal separation of water lines to measure the amount of lateral displacement back of the main submarine slide. Elsewhere, pipelines that traversed unfissured ground received little or no damage.

ARCHEOLOGIC REMAINS

Regional and local subsidence of Kodiak Island, as elsewhere, resulted in increased erosion of some sediments along the shore. In a few places near Ouzinkie, erosion exposed rich accumulations of stone and bone artifacts mixed with bones of sea animals. The archeologic remains occur at two horizons, separated by dark soil. Apparently they belong to the Aleut or Koniag cultures, but some may be older (Chaffin, 1966). Elsewhere in the Kodiak group of islands, many coastal archeological sites in subsided areas were made inaccessible or were subjected to accelerated erosion (Plafker and Kachadoorian, 1966).

EARTHQUAKE EFFECTS, GEOLOGY AND DAMAGE

The earthquake took 130 lives and caused more than $300 million in damage to manmade structures. Details are not recounted here, but an attempt is made to relate the loss of life and the structural damage to the earthquake and its effects, especially as these effects were modified by local geology and terrain.



Aside from a number of casualties that resulted from airplane and other accidents during the reconstruction period, all casualties to living creatures resulted either directly from the earth tremors and tectonic displacements or indirectly from water waves generated by them. Ground motion caused structural damage primarily by (1) direct shaking of some structures, (2) triggering landslides and subaqueous slides, (3) cracking underlying unconsolidated deposits, and (4) consolidating and subsiding loose sediments. The violent local waves that accompanied or followed most subaqueous slides were major indirect effects. Subaqueous slides and waves were together responsible for spreading the few major fires that had already started in petroleum storage areas. These fires, incidentally, taught another important lesson. In earthquake-prone regions, petroleum-storage tanks are especially vulnerable to earthquake vibrations; to the extent possible, they should be placed away from built-up areas and should be protected by revetments to avoid spreading of fires (Rinne, 1967).

"Subaqueous slides and waves were together responsible for spreading the few major fires that had already started in petroleum storage areas."

Tectonic ground displacements, both up and down, caused longterm damage to coastal communities and shoreline facilities, either directly by changing the shore relative to sea level or indirectly by the seismic sea waves generated. In addition, widespread horizontal tectonic movements may have generated some of the destructive local waves. Local waves and seismic sea waves together took most of the human lives that were lost.

GEOLOGIC CONTROL OF VIBRATION DAMAGE

The long-known fact that the intensity and duration of earthquake vibrations are enhanced in unconsolidated water-saturated ground was evident in the distribution of vibration damage in Alaska. The varied intensity and effect of shaking were much more closely related to the local geology than to distance from the epicenter. In general, intensity was greatest in areas underlain by thick saturated unconsolidated deposits, least on indurated bedrock, and intermediate on coarse gravel with low water table, on morainal deposits, or on moderately indurated sedimentary rocks of late Tertiary age.

Nowhere was there significant vibration damage to structures founded on indurated bedrock or on bedrock that was only thinly veneered by unconsolidated deposits. Where direct comparisons could be made, as at Whittier (Kachadoorian, 1965) and Cordova (Plafker and others, 1969), the difference in the behavior of buildings on bedrock and of those on loose material was striking.

Distance from the epicenter, too, had far less influence on the intensity of vibration damage than did the local geology. Buildings on bedrock that were only 12 to 25 miles from the instrumental epicenter were undamaged except for jostled contents (Plafker and others, 1969), and the ice on some small rock-enclosed lakes in this vicinity was not even cracked (Waller, 1966b). Buildings at Anchorage, however, more than 75 miles away from the epicenter but founded on unconsolidated materials, were demolished by earthquake vibrations (Hansen, 1965). Some structural damage resulted from shaking at even greater distances.

The lack of coincidence between structural damage and distance from the epicenter is partly explained by the fact that the generally accepted instrumental epicenter marks only one of several widely scattered points directly beneath which strong motion was centered at various moments during the history of the earthquake (Wyss and Brune, 1967). Moreover, selective damage to larger and taller buildings at Anchorage is attributed by Steinbrugge (1964) to the fact that longer period large-amplitude ground motions are dominant at some distance from earthquake epicentral regions, in contrast to the short-period motions that characterize close-in localities.

Locally, seismic vibrations caused minor structural damage to communities situated on late Tertiary sediments or on unconsolidated materials with low water table on the Kenai Peninsula, the west shore of Cook Inlet, in the Matanuska Valley, and elsewhere (Waller, 1966b; Plafker and others, 1969).

By far the most severe vibratory damage to buildings or to highway and railroad roadbeds and bridges occurred in areas of relatively thick, noncohesive unconsolidated deposits, generally where the materials were fine grained and where the water table was close to the surface. Anchorage, the Alaska transportation systems (Kachadoorian, 1968; McCulloch and Bonilla, 1970), the FAA station on the Copper River Delta, and Girdwood and Portage on Turnagain Arm (Plafker and others, 1969) are examples of sites of such vibratory damage. At most of these places, and many others, more damage resulted from foundation failure than from direct vibration of buildings. Ground cracks, differential compaction, and liquefaction of saturated materials accompanied by landspreading toward topographic depressions all were contributory factors.

"Buildings at Anchorage, however, more than 75 miles away from the epicenter but founded on unconsolidated materials, were demolished by earthquake vibrations."

SURFACE FAULTS

From the standpoint of public safety, perhaps the most important bit of knowledge that was reemphasized by the Alaska earthquake is that faults, with breakage and displacement of surface materials, are relatively minor causes of widespread earthquake damage. In Alaska, of course, there were no fault displacements in populated places. The only displacements on land were on uninhabited Montague Island in Prince William Sound, though there is good reason to believe that rocks on the sea floor were broken and displaced for a long distance southwestward of the island (Malloy, 1964; Plafker, 1967). Aside from the destruction and death dealt by sea waves, all of the damage was done by seismic vibration or its direct consequences.

The lesson is clear for all communities in earthquake-prone regions that the presence of an active fault, such as the San Andreas in California, constitutes only one of the dangers from future earthquakes. Delineations of such faults and predictions as to where, how, and when they may move are essential, for they may very well localize areas of great destruction when an earthquake strikes. The lesson of the Alaska earthquake, however, is that no one can take comfort simply because he, his home, or his town is some distance removed from an active fault or from the possible epicenter of a future earthquake. The foundation on which he builds is far more significant.

LANDSLIDES

Translatory slides at Anchorage (Hansen, 1966) and subaqueous slides at Whittier (Kachadoorian, 1965), Valdez (Coulter and Migliaccio, 1966), Seward (Lemke, 1967), and elsewhere were all caused indirectly by seismic vibrations, though horizontal tectonic displacement of the land may have been a factor in starting some of them. All of these slides were in soft, saturated unconsolidated materials in which the vibration caused sufficient loss of strength to make preearthquake slopes unstable. Such materials were consolidated to some extent by vibration, but it is doubtful that consolidation was sufficient to make any of the materials significantly less prone to failure in the event of future earthquakes.

Many of the violent local waves were generated by known subaqueous slides, either as backfills of the space left by the downslid material or on opposite shores where the spreading slide material pushed water ahead of it (McCulloch, 1966). Subaqueous slides that occurred as a series of small slumps apparently did not generate waves. Many of the other local waves that developed around the shores of Prince William Sound are suspected to have been caused by subaqueous slides, though some that struck the shores of fiords and semienclosed embayments must have had other causes.

VERTICAL TECTONIC DISPLACEMENTS AND SEISMIC SEA WAVES

Tectonic uplift and subsidence of the land relative to sea level wrought much long-term damage, either by inundating shore installations or by raising them above all but the highest tides. These effects were independent of local geologic conditions, except where the net amount of submergence or emergence was affected by vibration-caused surficial subsidence of unconsolidated sediments. Homer Spit (Waller, 1966a) and several communities on the Kodiak group of islands (Kachadoorian and Plafker, 1966) provided good examples of submergence resulting from both tectonic and surficial subsidence. Seldovia (Eckel, 1967), Hope, Girdwood, Portage, and several other towns (Plafker and others, 1969) all underwent tectonic subsidence; remedial raising or relocation of buildings, roadways, and wharves was necessary.

In Prince William Sound, where the land was tectonically raised, dredging of harbors and lengthening of piers were necessary to compensate for the lower

"Translatory slides at Anchorage and subaqueous slides * * * elsewhere were all caused indirectly by seismic vibrations, though horizontal tectonic displacement of the land may have been a factor in starting some."

relative water levels. Cordova, Hinchinbrook Island, and Tatitlek were the places most affected (Eckel, 1967; Plafker and others, 1969).

Of far greater importance than the tectonic uplift and subsidence, so far as damage was concerned, was an indirect effect—the generation of seismic sea waves (tsunamis) by the sudden uplift of a large expanse of the ocean floor. Besides the damage they did to Alaska, the tsunamis struck southward as far as California. They took 12 lives and wrecked the waterfront at Crescent City, Calif., and did appreciable damage to shore facilities as far away as Hawaii.

Local geologic conditions had little effect on the amount of damage caused by seismic sea waves, though local topography, both above and below water, was of great importance in guiding and refracting the waves and controlling their runups. One local geologic complication of sea-wave damage was in the Kodiak harbor; here strong currents generated by the tsunami scoured all unconsolidated material from the bedrock floor, making pile driving difficult or impossible (Kachadoorian and Plafker, 1966).

GROUND AND SURFACE WATER HYDROLOGY

Local geology helped control the earthquake's effects on water. In areas underlain by unconsolidated deposits where ground fissures occurred, there was temporary loss of water in the floors of some lakes and streams, or ground water was emitted from beneath the surface through mudspouts and waterspouts. In some places, ejected ground water flooded valley floors (McCulloch and Bonilla, 1970). Vibration caused rearrangement of particles in aquifers, with resultant surges in wells and temporary or permanent changes in water levels. Regional or local subsidence led to intrusion of sea water in some coastal aquifers.

Regional geology, too, to a large extent controlled the earthquake's effects on hydrologic systems, as shown in the conterminous United States, where McGarr and Vorhis (1968) found that seiches in wells and bodies of surface water were controlled by geologic structures of regional or continental dimensions.

BENEFICIAL EFFECTS OF THE EARTHQUAKE

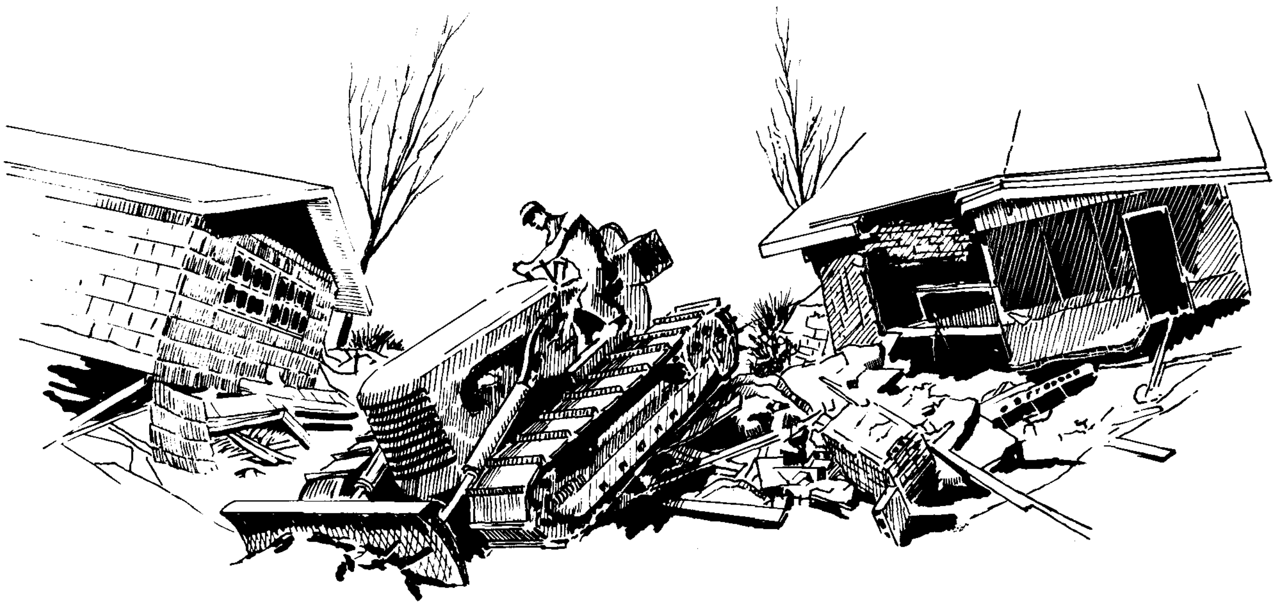
SOCIOECONOMIC BENEFITS

Devastating as was the Alaska earthquake of March 27, 1964, it had many long-term beneficial effects. Most of these benefits were in the fields of socioeconomics and engineering and are only mentioned briefly here.

Economically, the Federal monies and other funds spent for reconstruction exceeded the total damage cost of the earthquake, largely because of decisions to upgrade or enlarge facilities beyond their preearthquake condition.

Many improvements resulted from the aid poured into reconstruction. One whole town, Valdez, was razed and rebuilt on a more stable site; the area of one of the most disastrous landslides in the business heart of Anchorage was permanently stabilized by a gigantic earth buttress; new and better port facilities were provided in all the affected seacoast towns; the fishing fleet acquired, under very favorable financial terms, new boats and modern floating or land-based canneries. The pattern of rail-sea transport was drastically changed, partly because of the discovery that the port of Anchorage could actually be used year-round, despite the ice in Knik Arm that had hitherto closed it in winter. (This change of pattern, of course, was hardly a benefit to Seward and Valdez.) Forced by pressures of reconstruction, builders learned that plastic tents over their buildings permitted construction work to continue during the sub-Arctic winter. These and many other direct benefits from the earthquake are summarized by George and Lyle and by Chance (in Hansen and others, 1966).

One of the more important social-political-economic developments was use by the Federal Government of a new device to channel and control reconstruction and rehabilitation aid: The Federal Reconstruction and Development Commission for Alaska represented both the legislative and the executive arms of Government and included the heads of all Federal agencies that had a part to play in the reconstruction effort. One of the Commission's offspring, the Scientific and Engineering Task Force, brought soils and structural engineers, geologists and seismologists together in an effort to apply



"Many improvements resulted from the aid poured into reconstruction. One whole town, Valdez, was razed and rebuilt on a more stable site."

their combined skills to guide decisions as to land use (Eckel and Schaem, in Hansen and others, 1966). The many opportunities that were provided by the reconstruction effort for team work and mutual understanding between engineers and earth scientists were themselves among the more valuable byproduct benefits of the earthquake. In addition, scientists learned much that helps toward a better understanding of earthquake mechanisms and effects and how to investigate them. They also learned many new basic facts about the structural and historical geology and the hydrology of a large part of south-central Alaska. Some of these scientific benefits from the earthquake and its investigation are worthy of brief mention.

DIRECT GEOLOGIC BENEFITS

Truly beneficial direct geologic effects of the earthquake were few. Navigation conditions and harbor facilities were improved in a few places by tectonic uplift or subsidence, and tidewater and beach lands were improved or extended. For example, the subsidence that led to tidal flooding of Homer Spit also exposed new deposits of material to erosion, with the result that the spit began at once to heal itself and to build new storm berms (Stanley, in Waller, 1966; Stanley, 1968). Landslide hazards were averted, at least for some years to come, by uplift of Hinchinbrook Island; elsewhere imminent landslides and avalanches that might well have harmed people or property later were harmlessly triggered by the earthquake. Though the direct physical benefits of the earthquake were few, the earth sciences benefitted greatly from the intensive investigations of it. The knowledge thus gained added not only to the general fund of human knowledge; more importantly, it created an awareness of many potential hazards, previously unrecognized or ignored, both in Alaska and in other earthquake-prone areas, and of how to apply earth-science knowledge to reduce such hazards.

SCIENTIFIC BENEFITS

NEW AND CORROBORATIVE GEOLOGIC AND HYDROLOGIC INFORMATION

One of the richest rewards of the earthquake study lay in the additions to geological and hydrologic knowledge and in corroborations of existing theory. The myriad observations essential to understanding the effects of the Alaska earthquake threw much new light on earthquake processes and earthquake effects in general. In addition, the investigations added greatly to our scientific knowledge of a large part of Alaska. Some of the knowledge so produced might never have come to light under ordinary circumstances. Other discoveries were advanced by many years under the earthquake-generated acceleration of basic investigations.

The earthquake investigations led to better understanding of the regional tectonics of south-central Alaska. The regional gravity field was better defined than it had been before, and it was reevaluated in terms of its relation to the underlying geology and to changes caused by the earthquake. Data, hitherto unavailable, were provided on the seismicity of the region. Knowledge of the structure and age of the rocks was greatly expanded. Thanks to the need to understand the vertical tectonic displacements caused by the earthquake, new knowledge was obtained on the history of submergence and emergence throughout Holocene time. Field evidence was augmented by many new radiocarbon datings. Reconnaissance marine geological and geophysical studies were undertaken over much of the Continental Shelf, slope, and contiguous deep-sea floor. These studies have materially increased our understanding of the submarine areas.

Detailed geologic maps became available for most of the affected cities and towns. Strip geologic maps along the ramifying rail and highway net provided a skeleton control of geologic knowledge of a wide area, particularly as to the distribution and nature of the unconsolidated deposits on which man does most of his building.

Accurate and abundant geodetic control, on stable ground, is essential for evaluating tectonic movements in the mobile belts of the world; the earthquake of 1964 gave impetus to establishment of such control. For a significant part of Alaska itself, better geodetic control resulted from the earthquake-caused need for accurate triangulation and leveling and for establishment of tidal bench marks and tide gages. These data will be invaluable in any studies of future tectonic dislocations of the land surface.

Support for the hypothesis that some great landslides and avalanches travel on cushions of compressed air came from the earthquake studies. Conversely, evidence was brought to light that tends to discount a widely held theory of glacial advance as a result of earthquakes (Tarr and Martin, 1912).

One kind of landslide that has received little attention in the past from geologists and engineers—the translatory slide that was so disastrous in Anchorage—is now well understood, although extrapolation of the knowledge gained to future earthquakes will still be extremely difficult. Extensive studies led to the beginning of an explosion of new knowledge on the behavior of sensitive clays and sands under dynamic conditions. A minor byproduct of the Anchorage landslide studies was the discovery of microfossils that shed new light on the environmental conditions under which the Bootlegger Cove Clay was laid down, hitherto a puzzling point for geologists. Other byproducts of these studies were (1) production of detailed topographic maps of highly complex landslide areas and (2) development of the "graben rule" (Hansen, 1965) by which the depth to the sliding plane of a translatory slide can be easily and rather accurately estimated.

Too little study was made of the response of shore processes to sudden changes in relative sea levels, but many bits of useful information were discovered nevertheless.

The shape, character, and stability of fiord deltas built to deep water is now better known than before as a result of intensive geologic, soils, hydrographic, and hydrologic studies both on land and under water. Such studies were essential to an understanding of

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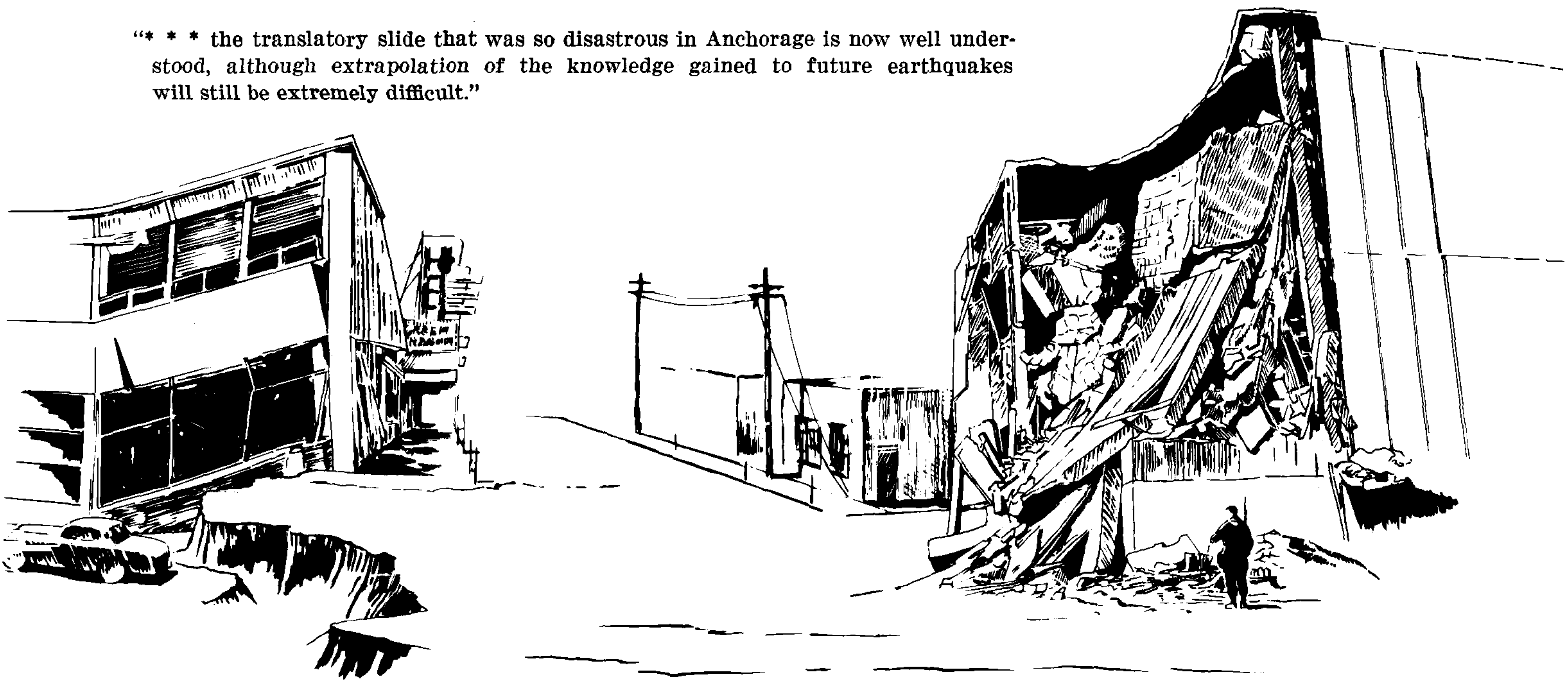


the destructive subaqueous slides that had been almost unknown as important effects of great earthquakes.

Knowledge of the water resources of south-central Alaska was increased by earthquake-prompted studies of ground and surface waters; much new information also came to light as to the relations between earthquake-caused ground fissures and local water tables. The study of hydroseisms, or seiches and surges in surface-water bodies and wells, throughout the world produced greater understanding of the relation of hydrology to seismology.

Seismic sea waves, or tsunamis, have been studied intensively for many years because of the dangers they hold for coastal communities. The Alaska earthquake of 1964, however, presented an unparalleled opportunity to relate the source, generation, and propagation of a sea-wave train to measurable tectonic dislocations of the crust.

NEW AND IMPROVED INVESTIGATIVE TECHNIQUES

Virtually all investigative techniques known to earth scientists were applied in studies of the Alaska earthquake. Some, such as scuba diving, bathymetric surveys, and use of helicopters and fixed-wing aircraft were, of course, not new, but their widespread application to specific earthquake-connected problems was either new or little-used in the past. Many unorthodox photogrammetric, engineering, biological, and geodetic techniques and data were applied in the attempts to appraise preearthquake conditions in areas of poor horizontal and vertical control.

Some of these techniques, discussed briefly below, were new to Alaska or to individual investigators assigned there. A secondary result of the earthquake investigations of no mean significance, therefore, was the development of a large cadre of experienced and technologically well-equipped scientists who will be available for knowledgeable investigations of future great earthquakes.

Of utmost importance for the future is the fact that the knowledge gained from the Alaskan experience can be adapted by the scientific community to underline possible hazards in other earthquake-prone areas. Thus, it should be possible to relate ground conditions to urban planning, zoning regulations, and building codes in such a manner to forestall or minimize future earthquake disasters.

USES OF RECORDING GAGES

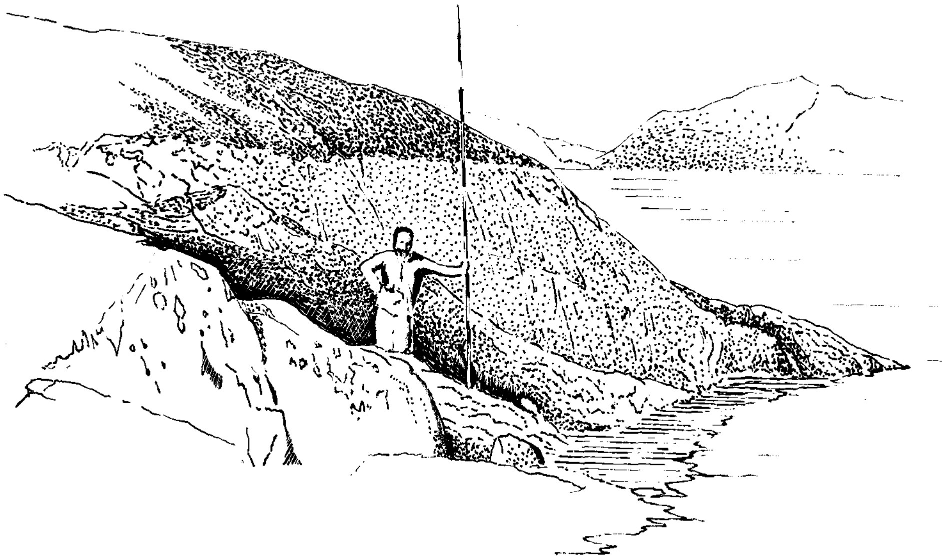
The records from continuously recording gages served purposes not originally intended. A water-level gage at the power station on Kenai Lake, for example, enabled McCulloch (1966) to make a precise study of seiche action in a closed basin and to draw conclusions of far-reaching importance. Again, fluctuations in the recording of an automatic outside-air temperature recorder at Whittier gave a rough measure of the duration of earthquake vibrations there (Kachadoorian, 1965). Stream gages on Kodiak Island, designed to measure the levels of flowing streams, suddenly became excellent recorders of wave runup and even served as tide gages when the mouths of streams on which they were installed were brought within the reach of tides by local and regional subsidence (Plafker and Kachadoorian, 1966; Waller, 1966b). By far the most significant extension of knowledge of the usefulness of recording gages came from the study of hydroseisms in wells and on surface waters on continent-wide or even larger bases. Investigations showed that, among other results, a network of recording water-level gages can act as a valuable adjunct to the worldwide seismograph network. It was also shown that any earthquake near a coast that is capable of causing as great fluctuations as that recorded by the Nunn-Bush well in Minnesota is also capable of generating a seismic sea wave (Vorhis, 1967; McGarr and Vorhis, 1968).

TELEVISION FOR UNDERGROUND OBSERVATIONS

A novel application of television to the mapping of cracks in buried utilities—and incidentally of fractures or fault displacements in the surrounding soil—is described by Burton (in Logan, 1967). To avoid costly excavation of buried utility systems, a small-diameter borehole television camera was drawn through the ducts. Cracks were clearly visible and easily measured; their location and the amount and direction of offset of the ducts added materially to the general knowledge gained from other sources as to the character of ground movements in the Anchorage landslide areas.

LAKES AS TILTMETERS

Kenai Lake was the only long lake that happened to have bench marks at both ends; hence McCulloch (1966) was able to use it as a unique giant tiltmeter. It gave a permanent record of landwarping caused by the earthquake. McCulloch's method of comparing the preearthquake height of the lake surface with preearthquake bench marks at the two ends of the lake necessarily left some ambiguity in the measurements because of difficulty in locating the preearthquake bench marks accurately, but it left no doubt whatever



"Measurement of the displacement of intertidal sessile marine organisms emerged as one of the most useful techniques for determining vertical tectonic movements along coasts."

that the Kenai Lake basin was tilted westward about 3 feet. As a direct outgrowth of the earthquake investigations, and in order to monitor future crustal changes in south-central Alaska, a network of permanent bench marks has now been established on the shores of 17 large lakes within a 500-mile radius of Anchorage. These bench marks were referenced to the water levels of the lakes so that the direction and amount of any tilting can be obtained from periodic monitoring (Hansen and Eckel, 1966). A systematic study of these lake levels was started by D. S. McCulloch and Arthur Grantz in the summer of 1966 (written commun., 1968).

MEASUREMENT OF LAND-LEVEL CHANGES

Measurement of the displacement of intertidal sessile marine organisms emerged as one of the most useful techniques for determining vertical tectonic movements along coasts. The technique had been used elsewhere, by Tarr and Martin (1912), for example, who studied the effects of the Yakutat Bay earthquake of 1899. With the aid of Dr. G Dallas Hanna, a marine biologist of the California Academy of Sciences, however, the method was greatly refined and was applied by Plafker and his associates after the Alaska earthquake of March 27, 1964, to a far larger area than ever before (Plafker, 1969).

The deeply indented rocky coast of the area affected by the 1964 earthquake was ideal for application of the method. The common acorn barnacle (*Balanus balanoides* (Linnaeus)), which is widely distributed and forms a prominent band with a sharply defined upper limit relative to tide level, was used in hundreds of "barnacle-line" measurements; in its absence the common olive-green rockweed (*Fucus distichus*) was almost equally useful. The normal preearthquake upper growth limit of barnacles and rockweed relative to mean lower low water was determined empirically for the range of tidal conditions in the area at 17 localities where the amount of vertical displacement was known from pre- and post-earthquake tide-gage readings. Departures of the post-earthquake barnacle line from its normal altitude above mean lower low water was taken as the amount of vertical displacement at any given place along the shore. By this method, absolute land-level changes could generally be measured to an accuracy within 1 foot; even under unfavorable circumstances, the error is probably less than 2 feet.

Other methods of determining land-level changes along the coasts and elsewhere were also employed. Changes in gravity, as determined before and after the earthquake with the same instrument, were used by Barnes (1966) in computing elevation changes. In subsided areas, it was noted that wells became brackish, vegetation was killed by invasion of salt water, beach berms and stream deltas were shifted landward and built up to higher levels, and roads or other installations along the shores were inundated by the tides. In tectonically uplifted areas, indications of uplift include new reefs and islands, raised sea cliffs, and surf-cut platforms. Wherever feasibl., the method used was the most accurate known—comparison of pre- and postearthquake tide-gage readings at accurately placed tidal bench marks of the U.S. Coast and Geodetic Survey. Even where gages were destroyed, some bench marks were recoverable and new series of readings could be made to determine land-level changes. Unfortunately, there were only a few permanent automatic recording gages in south-central Alaska, and also many tidal bench marks were on unconsolidated deposits where ties to bedrock were difficult or impossible to reestablish.

DISTINCTION BETWEEN LOCAL AND REGIONAL SUBSIDENCE

Clear distinctions between local subsidence caused by compaction of sediments and more widespread subsidence caused by tectonic downdrop of the region are not always easy to make. One technique used by Plafker and Kachadoorian (1966) on Kodiak and the nearby islands was to note the difference in amount of inundation of unconsolidated shoreline features as compared with nearby rock outcrops. The lowering of the rock cliffs, as measured by barnacle lines or other means, represents tectonic subsidence, whereas the lowering of beaches and delta surfaces represents a combination of tectonic subsidence and local compaction. By using a similar technique—measuring differences in the heights of piles whose tops were originally level—Plafker and Kachadoorian were able to distinguish between local compaction-subsidence of beach deposits and tectonic downdrop.

Casings of deep wells may also be helpful in distinguishing local and regional subsidence. Near the end of Homer Spit, for example, the top of a well casing that had previously been a known height above the ground stood several feet higher after the earthquake. Such protrusion could only have been caused by compaction and subsidence of the unconsolidated materials around the casing, for regional subsidence would have carried the casing down along with the land surface (Grantz and others, 1964, fig. 6).

EVIDENCE OF WAVE ACTION AND RUNUP

As part of their studies of wave-damaged shorelines, various investigators made extensive use of natural materials that indicated the relative intensity and movement direction of waves (McCulloch, 1966; Plafker and others, 1969; Plafker and Kachadoorian, 1966). Runup heights were determined from strandlines of wave-deposited debris, abraded bark or broken branches in vegetation along the shore, and water stains on snow or structures. Movement directions of the waves could be inferred from the gross distribution of damage along shores, the directions in which limbs and trunks of trees and brush were scarred, bent, and broken off, and the directions in which objects such as buoys, structures, and shoreline deposits were displaced. To aid in comparative studies of wave-damaged shorelines along the coast, Plafker and Mayo devised a scale of relative magnitude of wave damage (Plafker and others, 1969)—a scale which was also used by McCulloch and Mayo (McCulloch, 1966) in modified form for plotting wave damage along the shore of Kenai Lake. The magnitude scale evolved is summarized below in order of increasing damage.

Wave-magnitude scale

[After Plafker and others, 1969, pl. 2]

1. Brush combed and scoured in direction of wave travel. Small limbs broken and minor scarring of trees. Runup heights only a few feet above extreme high-water level. Some wooden structures floated from foundations.
2. Trees and limbs less than 2 inches in diameter broken. Small trees uprooted. Driftwood and finer beach deposits thrown up above extreme high-water level. Piling swept from beneath some structures and wooden structures

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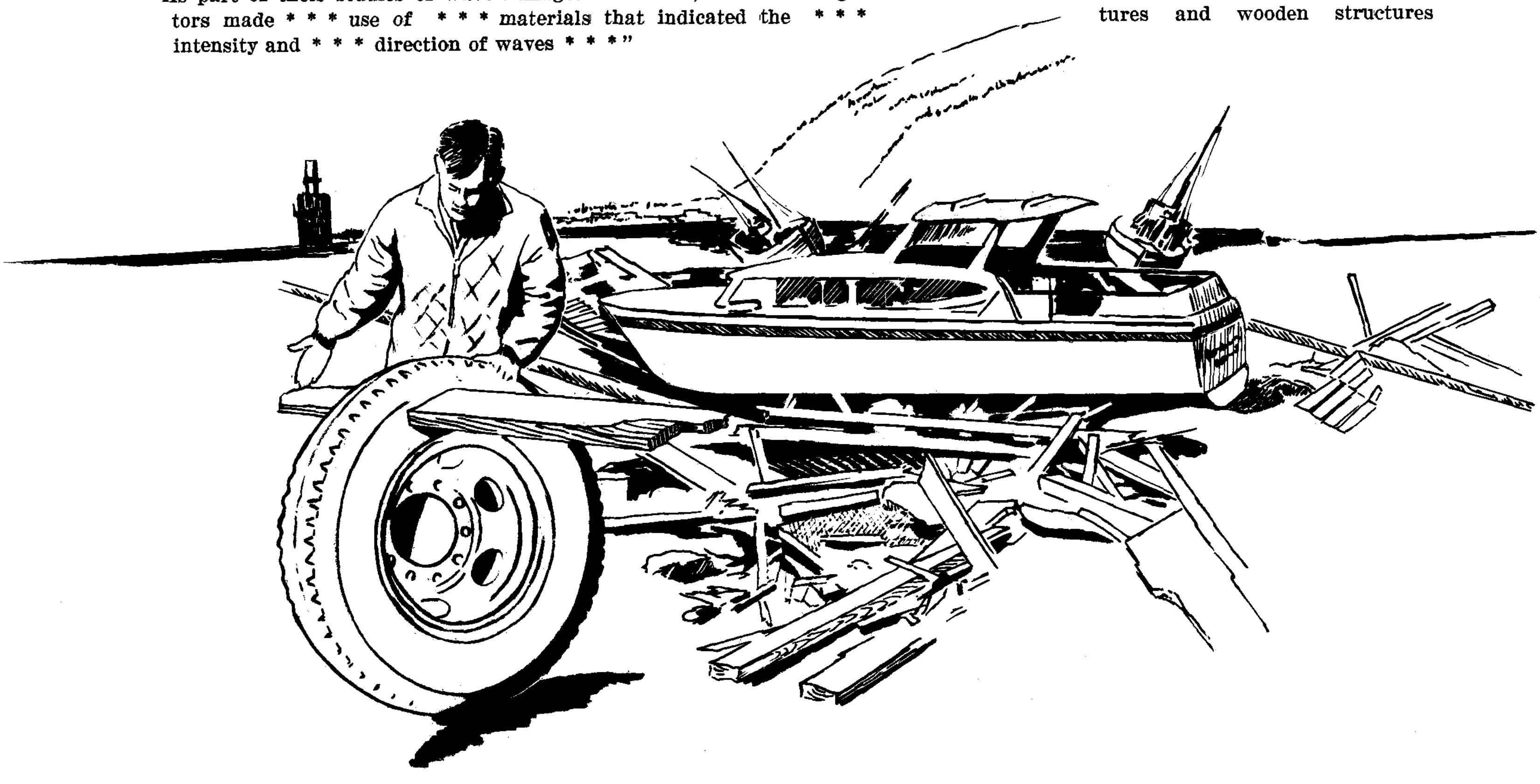

floated off their foundations. Runup reached about 25 feet on steep shores.
3. Trees and limbs as much as 8 inches in diameter broken; some large trees overturned. Rocks to cobble size eroded from intertidal zones and deposited above extreme high-water level. Soil stripped from bedrock areas. All inundated structures except those of reinforced concrete destroyed or floated away. Heavy machinery moved about. Maximum runup height 55 feet.
4. Trees larger than 8 inches in diameter broken, uprooted, and overturned. Boulders thrown above extreme high-water line. Loose rocks on cliffs moved. All strucrocks and equipment damaged or destroyed in inundated areas. Maximum runup height 70 feet.
5. Extensive areas of total destruction of vegetation. Boulders deposited 50 feet or more above normal extreme high-water level. Maximum runup height 170 feet.

Using a wave-magnitude numbering system modified from an early version of Plafker and Mayo, to allow for the additional damage caused by ice, McCulloch (1966) mapped the distribution of intensity and maximum runup of waves on the shores of Kenai Lake. The highest runup measured there was 72 feet, where a wave struck a steep bank. By measuring the upper limit of wave damage to trees in the direction of wave travel, McCulloch also was able to show the history of the wave crests that overran several deltas.

CONCLUSIONS

SCIENTIFIC PREPARATION FOR FUTURE EARTHQUAKES

FUNDAMENTAL RESEARCH

Much more research is needed on the origins and mechanisms of earthquakes, on crustal structure and makeup, and on generation and prediction of tsunamis, local waves, and seiches. Better theoretical and experimental means of determining focal mechanisms are particularly needed, not only for scientific reasons but to aid earth scientists and structural engineers in relating focal mechanisms to ground motion and in relating the response of buildings to seismic shock. Study is needed too on all phases of rock and soil mechanics, with emphasis on the causes and nature of rock fracture in the earth's interior, on the response of different rocks to strong seismic motion, and on the behavior of soils under dynamic loading.

Well-conceived research in any of these fields is certain to show results that apply to the overall earthquake problem. Existing research projects should be supported, and new ones, designed to fill the gaps in existing knowledge, should be sought out and encouraged. In-depth studies by such groups as the Federal Council for Science and Technology (1968) have clearly defined the needs. The rate of accomplishment of research, however, is far less than it should be. It cannot be too strongly recommended that funds be provided as soon as possible to support these necessary research programs.

EARTHQUAKE FORECASTING AND EVALUATION OF EARTHQUAKE HAZARDS

An ability to predict precisely the time, place, and magnitude of future earthquakes would represent an accomplishment of the greatest importance and significance to the scientific community. Because of the sociologic, political, and economic consequences that would result from erroneous predictions, and because useful results seem to be more easily attainable, it is believed that more attention should be directed, initially, toward forecasting in terms of the probability of earthquakes of certain magnitude ranges within seismic regions, rather than as to the exact time when the next earthquake may be expected at a specific place. Every forward step will be directly applicable to the development of better and more detailed earthquake-hazard maps based on improved knowledge of regional geology, fault behavior, and earthquake mechanisms. Hopefully, each step will also lead to better guides for land-use planning, hence to closer control of new construction in areas of potential earthquake hazards.

One step toward useful forecasting of future earthquakes that should be taken at once is the preparation of earthquake-hazard maps. Such maps should be based in part on detailed knowledge of active faults and their behavior during historic and geologic times, as well as on recent instrumental observations of earthquakes and fault movements. Although an earlier version was adopted by the International Conference of Building Officials, by military construction agencies, and by some State and local governments, the official seismic risk map of the United States (U.S. Coast and Geodetic Survey, 1969) is too lacking in detail to be of value for other than very broad planning.

"* * * the hazards are enormously compounded if [port, dock, and cannery] facilities are built on steep-faced deltas * * * that are marginally stable under seismic conditions. * * * If [such sites] must be utilized, knowledge that they are vulnerable to future earthquakes may stimulate planning to minimize the hazards."

Preparation of useful earthquake-hazard maps, on whatever scale, will require close collaboration of earthquake engineers, seismologists, and geologists. These maps are essential to local and regional planning officials and to all others who are involved in formulation of plans for coping with earthquakes; their preparation should begin at once. They are, perhaps, especially needed by building-code officials and by designers of earthquake-resistant structures, for the response of foundation materials to seismic loads and the interactions between foundation and structure are just as important as antiseismic design of the structure. Such maps should be revised periodically as more geologic and seismic data become available.

GEOLOGIC MAPPING OF COMMUNITIES

Within the area that was tectonically elevated or depressed by the Alaska earthquake, virtually all inhabited places were damaged or devastated, though the kind, amount, and causes of damage varied widely. Unfortunately, the very features that make a site desirable for building are often the ones that make it subject to earthquake damage.

Ports, docks, and canneries obviously have to be built close to the shore. But the Alaskan experience indicates that the hazards are enormously compounded if such facilities are built on steep-faced deltas or other deposits of unconsolidated materials that are marginally stable under seismic conditions. At many places, such deposits offer the only level surfaces near tidewater for easy or economical construction. If they must be utilized, advance knowledge that they are vulnerable to future earthquakes may stimulate planning to minimize the hazards.

The same reasoning applies to earthquake hazards inland. If all towns, railroads, and highways could be built on bedrock, they would be in comparatively little danger from any earthquake effects except surface faults, floods, or avalanches. There would be vibration damage, of course, but much less of it than on materials other than solid rock. Unfortunately, building sites on bedrock are scarce and tend to be economically infeasible, particularly in rugged terrain like Alaska's. Man must therefore often build on less stable terrain, including water-saturated unconsolidated sediments, on potentially unstable slopes, and on or near active faults. Even though it is necessary to build in earthquake-vulnerable areas, builders and planners should recognize the potential hazard in advance and build accordingly.

A vigorous program of geologic mapping should therefore be carried out in all inhabited earthquake-prone parts of the country. As a direct result of the lessons learned from the earthquake of 1964, the U.S. Geological Survey began engineering-geologic studies of all of Alaska's coastal communities, whether or not they received earthquake damage. Similarly, the geology of some western cities and metropolitan complexes in the conterminous States is already known or is under study. However, many other towns and cities that may well be struck by earthquakes in the future are without adequate geologic maps. All such communities, as well as places where communities are likely to spread or develop in the future, should be geologically mapped by trained personnel as rapidly as is feasible with available funds. The need is increasing at a far faster rate than is the required geologic information.

The minimum geologic map for each community would delineate all active faults and landslides and would discriminate between areas underlain by bedrock and those underlain by unconsolidated materials. The next most needed refinement would be to distinguish areas of fine- and coarse-grained soils and to note whether the near-surface layers are normally dry or saturated. The topographic base of the geologic map would of course also show unconfined slopes bordering topographic depressions, even minor ones, where earth fissures or lateral spreading of loose materials are to be anticipated. Such maps could be prepared quickly and at relatively low cost. They would be extremely valuable in guiding authorities to wise decisions on land use, in the location of seismic instruments that would develop a maximum of useful information, and in the preparation or refinement of earthquake-hazard maps.

Much more elaborate—and more costly—geologic maps can be prepared, of course. Such maps are needed for all larger communities and for smaller ones where the geologic and soils problems are complex. Ideally, these maps should contain all the geologic, topographic, and hydrologic detail that could have any bearing on the relative reaction of parts of the community's foundations to earthquake stresses. They should depict not only the makeup of the land, but the character of contiguous water bodies and their bottom materials. Knowledge of the character, shape, and stability of off-shore deposits derived from surface observations, borings, bathymetric surveys, and bottom sampling would go far toward warning coastal residents of their danger in the event of an earthquake. Cooperative effort by soils engineers, geologists, and oceanographers is needed for this work.

Provision of good geologic maps alone is not enough, of course, to insure that the facts they show will be used effectively in reducing earthquake hazards. This lesson was forcefully taught by the Alaska experience of 1964. Modern geologic maps of Anchorage were available, and geologists had warned in print that one of the map units, the Bootlegger Cove Clay, would be unstable in the event of future earthquakes. The warnings went unheeded, however, because civic authorities, builders, and others either were unaware of the existence of the geologic information or ignored its implications.

Disastrous translatory landslides initiated by the earthquake of 1964 amply proved the correctness of the warnings.

Obviously, means must be sought to acquaint city planners, engineers, builders and the populace with the existence of useful geologic information and with its implications in terms of earthquake hazards and land use.

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INSTRUMENTATION AND MEASUREMENTS

Suitable networks of recording seismographs should be installed in all areas where earthquakes are considered likely to occur. Where feasible, signals from the seismometers should be telemetered by telephone lines or by radio to a central recording and data-processing facility. The seismograph networks should be supplemented by other earthquake-sensing instruments, such as strain meters, tiltmeters, magnetometers, and gravimeters. In some areas, existing networks maintained by university and Federal agencies can be used as bases for improved modern telemetry networks. In other areas, entirely new networks must be installed.

In selecting the sites for such instruments, it is essential that the local and regional geology be known in some detail and that the instruments be placed so as to obtain the maximum amount of information on the behavior of active faults and the effects of the various kinds of rock and soils on seismic response. It is particularly important that the seismograph networks be of such geometric form that earthquakes can be located accurately and immediately by means of digital computers and related to known or suspected active faults.

In addition to the networks of standard seismographs and other earthquake-sensing instruments, the existing networks of strong-motion seismographs should be strengthened and extended to all earthquake zones. Strong-motion seismograph recordings are particularly useful in testing the interactions between buildings and different materials on which they rest when subjected to seismic shock, and it is, therefore, important that strong-motion seismographs be sited on the basis of detailed knowledge of the local geology.

The instruments discussed above are now available and can be installed immediately. A new generation of instruments is also needed—laser strain meters, absolute-stress measuring devices, and devices for monitoring minute variations with changing stress of acoustic velocities in rock. These instruments can be developed, and should be developed without delay.

The arrays of standard and strong-motion seismographs in all earthquake-prone areas might well be supplemented by a nationwide system of test wells in confined aquifers, equipped to record long-period seismic waves and to damp out subsequent water fluctuations. Studies of well records after the Alaska earthquake demonstrated that hydroseisms can be used effectively to predict and explain certain hydrologic phenomena and can also serve as supplemental seismic recorders. In addition to a system of water-level recorders in wells, improved stream gages are needed, built to withstand earthquake shocks and to remain operational in winter. Such gages provide needed information on the reaction of streams and surface-water supplies to earthquake-induced land movements, and there is also abundant evidence that the measurements of seiches in streams and lakes can contribute greatly to the study of sites of high seismic activity.

Many more bench marks, triangulation stations, tide gages, and tidal bench marks are needed in earthquake-prone regions to permit accurate measurements of lateral or vertical crustal strains between, as well as during, major earthquakes. To the extent possible, all such stations should be established on bedrock and should be so built as to withstand earthquake vibration, inundation by giant waves, and local land movements. Bench marks should also be established at the ends of long lakes throughout earthquake-prone regions, and their altitudes should be resurveyed periodically. With a suitable net of tidal bench marks and level lines and a suitable number of lake tiltmeters, both long-term and sudden warping of the earth's surface can be determined accurately and cheaply. Such data are required to test the hypothesis that premonitory vertical displacements sometimes precede major earthquakes; if they do, these displacements could be an important prediction tool.

More information on the normal height of barnacles and other sessile organisms relative to tide levels along all the shores of the Pacific would permit students of future earthquakes to make quick and reasonably accurate measurements of tectonic changes. Effective use of this information would also require improved tide tables based on tide-gage measurements at many localities.

Detailed geomorphic studies supplemented by many more radiocarbon dates along emergent and submergent shores are needed to clarify the Holocene history of vertical land movements. These studies would provide an understanding of the distribution and recurrence interval of earthquake-induced changes in land levels within the time range of radiocarbon-dating methods. Such studies might lead to the development of useful earthquake-forecasting techniques in some seismically active coastal regions because they they can roughly define broad areas of susceptibility to future major earthquake-related tectonic displacements at specific localities.

INVESTIGATIONS OF ACTUAL EARTHQUAKES

Every large earthquake should be regarded as a full-scale laboratory experiment whose study can give scientific and engineering information unobtainable from any other source. For this reason it is essential that every earthquake strong enough to damage manmade structures or to have measurable effects on the natural environment should be studied thoroughly by scientists and engineers.

NEED FOR ADVANCE PLANNING

In total, the scientific and engineering investigations of the Alaska earthquake were remarkably successful. They resulted in accumulation and interpretation of far more knowledge, in more disciplines, than has ever been amassed before for any single earthquake. These results were obtained through the efforts of many individuals, sponsored by many governmental and private groups. There was no overall organizational plan for the investigations, and except for the work of the Committee on the Alaska Earthquake, National Academy of Sciences, and for voluntary personal interactions of individuals and groups, no determined attempt was made to coordinate and integrate all the studies. This approach, even though ultimately successful, left some gaps in the record and produced some waste and duplication of effort when time and available skills were critical. Such shortcomings in future disaster investigations could be avoided by advance planning and at least a skeletal permanent organization.

Presumably the Federal Government will be deeply involved not only in relief and reconstruction after, but also in technical investigation of, any future earthquake disaster that is at all comparable to the Alaska earthquake of 1964. For this reason, it seems imperative that the Federal Government should take the lead in contingency planning for future disastrous earthquakes. This is not to say that the Federal Government should act alone in planning for disaster or in activating the plans made. State and local governments, universities, and other groups all have major responsibilities and skills that must be brought to bear on the problems. Largely as a result of the Alaskan experience, numerous well-integrated local and State groups in several earthquake-prone regions are already (1969) active in making plans for the investigation of future earthquakes. A great earthquake, however, brings with it an immediate need for massive application of resources, both human and material, from outside the stricken locality or region. Moreover, and as the Alaskan experience made so plain, strong and immediate logistic and other support from the military is absolutely essential in dealing with a great earthquake disaster, either for technical investigations or for relief and reconstruction.

The chief objectives of a planning effort in preparation for future great earthquakes would be (1) to define the kind and scope of investigations needed for scientific purposes and for protection of life and property; (2) to provide guidelines to assume that the primary responsibilities of various organizations or individuals, governmental or private, are brought to bear on all necessary investigations; (3) to provide for coordination between investigative groups; and (4) to provide means for immediate funding and fielding of investigators when disaster strikes, including military logistic and photographic support.

It is emphasized that this proposal applies only to preplanning for disaster. Once disaster has struck, actual investigations must be left to individual groups with the requisite skills, responsibilities and funds. But the better the overall preplanning effort, the better integrated and funded will be the actual investigations and the better their chances of complete coverage.

GEOLOGIC, GEOPHYSICAL, AND HYDROLOGIC INVESTIGATIONS

Once a decision has been made to investigate a reported earthquake, a small reconnaissance party should be dispatched at once, as was done successfully by the U.S. Geological Survey for the Alaska earthquake. Preferably it should be composed of one or more mature geologists and geophysicists who have a thorough knowledge of the local and regional geology of the disaster area and who have had experience with earthquakes or other similar natural disasters. The sounder the decisions at this stage the better will be the results. The duties of the reconnaissance party would be partly to observe and record as many ephemeral features as possible but would be primarily to assess the situation and to formulate advice as to the size and character of the problem and of the task force needed to attack it. Many investigations would end with the reconnaissance phase; a few would be found worth full-scale study.

If further studies are recommended, a field team of investigators should be formed and a leader appointed. Team size and makeup depend on the character of the problem and on the skills and aptitudes required, but every effort should be made to provide coverage of all earth-science aspects of the disaster. Some team members, especially in the early phases of the investigations, should know the local and regional geology. However, both local knowledge and experience in disaster studies help in making fast, accurate observations of ephemeral geologic processes and effects.

Once the field team is formed, its members should continue to be responsible only to the team leader until all field work and reports are completed. Decisions should be made early as to the general scope and character of preliminary and final reports on the earthquake. These determinations, however, should be flexible enough as to permit pursuit of significant research problems as they unfold.

Every effort must be made to coordinate the geologists' and geophysicists' work with that of all other investigative groups in order to assure free interchange of information, to avoid confusion and duplication of effort, and to identify gaps in the investigative effort.

The work required of the field team will vary between wide limits, depending, among other things, on the size and geologic character of the affected region, on the nature and effects of the earthquake itself, and on the kind, amount, and distribution of damage done. In general, however, all work done should be aimed at two principal objectives: (1) collection of all geologic and geophysical information that has any bearing on reconstruction efforts or that can be used in preventing or alleviating the damaging effects of future earthquakes, and (2) collection of all information that can lead to better scientific understanding of earthquake processes and effects.

More specifically, the following steps should be taken in the geologic investigation, with initial emphasis on ephemeral effects that may disappear or be modified within a few hours or days:

1. Initiate immediate aerial surveys to provide complete stereo-photo coverage, at scales of 1:20,000 or larger, of all areas in which any earthquake effects are photographically recordable. The minimum coverage required might be specified by the reconnaissance party, to be expanded later as followup investigations progress. All of the studies listed below can be made or expedited with suitable airphoto coverage.
2. Study relations between the earthquake effects and the local and regional geology.
3. In cooperation with soils engineers, investigate any new faults or reactivations of preexisting faults.
4. Map ground fissures, sand spouts, and pressure ridges, especially where they affect the works of man.
5. Measure subsidence or uplift of the ground surface and distinguish between tectonic displacement and that caused by consolidation of sediments.
6. Investigate mass movements of materials, such as avalanches, landslides, and underwater slides.
7. Observe changes in stream courses and regimens.
8. Map local geology and soils, paying special attention to ground-water conditions, wherever damaging movements have occurred.
9. Ascertain the effects of tsunamis and local waves and the changes in shorelines initiated by waves or tectonic movements.
10. Study any earthquake-caused changes in volcanic activity.
11. Initiate studies, by means of portable seismographs, of aftershocks especially for the purpose of locating them and relating them to active faults.
12. Initiate geodetic and aerial surveys, both for use in studying earthquake effects and in determining horizontal and vertical tectonic displacements.
13. In close cooperation with soils and structural engineers, examine the effects of shaking and of ground movements on structures, paying particular attention to the relationship between underlying geology and structural damage.
14. Produce good map and photographic coverage of the earthquake's effects for the permanent record.

AVAILABILITY OF MAPS AND OTHER BASIC DATA

One of the most important lessons learned from the Alaskan earthquake was the value of pre-earthquake information in studying the effects of the quake. Topographic base maps, geologic, soils, and glaciologic maps, aerial photographs, tidal and other bench marks, triangulation stations, records of building foundations—all these were invaluable to investigators.

Current base maps—topographic maps and hydrographic charts—are essential tools for scientific and engineering investigators; so are pertinent reports and maps on local geology and soils. Detailed city plans, preferably those that show utility systems as well as streets and buildings, are needed not only by technical investigators but by relief and rehabilitation workers and by the general public. All such basic materials will be needed in quantity immediately after an earthquake. The availability of such materials should, of course, be made known to city officials and other potential users.

QUESTIONNAIRES

Questionnaires, widely distributed by mail to postmasters and others or published in local newspapers, are an effective means for determining the extent, distribution, and character of an earthquake's effects, as well as for identifying alert and interested eyewitnesses who should be interviewed by investigators for more detailed facts than can be recorded on the returned questionnaire. The questionnaire method, supplemented by innumerable interviews, was widely and effectively used in studies of the Alaska earthquake by the U.S. Coast and Geodetic Survey, which routinely gathers such data on all earthquakes, by the U.S. Geological Survey, and by several other groups. The questionnaire used by the Geological Survey in Alaska is reproduced in the report by Plafker and others (1969).

SCIENTIFIC AND ENGINEERING TASK FORCE

Immediately after the Alaska earthquake, the Scientific and Engineering Task Force of the Federal Reconstruction and Development Planning Commission for Alaska (Eckel and Schaem, in Hansen and others, 1966) was set up to advise the Commission, and through it, the Federal fund-supplying agencies, as to where it was safe to permit new construction or rebuilding of earthquake-damaged structures. The Task Force's advice, based on technical studies of the earthquake's effects on geology and soils, was translated into Commission decisions as to availability of Federal funds for specific areas and purposes.

The approach of the Scientific and Engineering Task Force was highly successful during the reconstruction period after the Alaska earthquake. Its potential longer term benefits to the general public were somewhat lessened, however, because there were no provisions for continuing observance of its recommendations after the Federal Commission was dissolved and because there was no control over actions of local governments or use of non-Federal funds.

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