The Alaska Earthquake

March 27, 1964

Regional Effects

Martin-Bering Rivers Area

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-B

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
REGIONAL EFFECTS

Geomorphic Effects of the Earthquake of March 27, 1964 In the Martin-Bering Rivers Area, Alaska

By SAMUEL J. TUTHILL and WILSON M. LAIRD

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-B

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1966

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 30 cents (paper cover)

THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the earthquake in a series of six Professional Papers. Professional Paper 543 describes the regional effects of the earthquake. Other Professional Papers describe the effects of the earthquake on communities; the effects on hydrology; the effects on transportation, communications, and utilities; and the history of the field investigations and reconstruction effort.

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GEOMORPHIC EFFECTS OF THE EARTHQUAKE OF MARCH 27, 1964, IN THE MARTIN-BERING RIVERS AREA, ALASKA

By SAMUEL J. TUTHILL[1] and WILSON M. LAIRD[2]

ABSTRACT

The Alaska earthquake of March 27, 1964, caused widespread geomorphic changes in the Martin-Bering Rivers area—900 square miles of uninhabited mountains, alluvial flatlands, and marshes north of the Gulf of Alaska, and east of the Copper River. This area is at lat 60°30′ N. and long 144°22′ W., 32 miles east of Cordova, and approximately 130 miles east-southeast of the epicenter of the earthquake.

The geomorphic effects observed were: (1) earthquake-induced ground fractures, (2) mudvent deposits, (3) "earthquake-fountain" craters, (4) subsidence, (5) mudcones, (6) avalanches, (7) subaqueous landslides, (8) turbidity changes in ice-basined lakes on the Martin River glacier, (9) filling of ice-walled sinkholes, (10) gravel-coated snow cones, (11) lake ice fractures, and (12) uplift accompanied the earthquake.

In addition to geomorphic effects, the earthquake affected the animal populations of the area. These include migratory fish, terrestrial mollusks, fur-bearing animals, and man.

The Alaska earthquake clearly delineated areas of alluvial fill, snow and rock avalanche corridors, and deltas of the deeper lakes as unsuitable for future construction.

INTRODUCTION

The Martin-Bering Rivers area lies between lat 60°15′ N. and 60°45′ N. and long 144°00′ W. and 144°45′ W. Our discussion is confined to the region shown on the Cordova B-1 (1951), B-2 (1950), C-1 (1959), and C-2 (1959) quadrangles of the U.S. Geological Survey topographic series at a scale of 1:63,360. The western edge of the area is 32 miles east of the town of Cordova. These quadrangles include approximately 900 square miles of uninhabited, marshy, mountainous, and alluvial flatlands, most of which is in the Chugach National Forest. The area is approximately 130 miles east-southeast of the epicenter of the Alaska earthquake.

In the summers of 1962 and 1963, with the financial support of the National Science Foundation, a research team from the University of North Dakota, of which we were a part, studied the limnology, malacology, and glacial geology of the Martin River area. The observations and maps made during these two summers provided the preearthquake data for evaluation of the geomorphic effects after the earthquake.

In 1964, fieldwork was carried on between June 2 and July 10, and was again financed by the National Science Foundation.

The Bering River area has been the subject of intensive geologic study in past years because coal and petroleum exist in the Tertiary rocks of that region. Martin (1904, 1905a, 1906, 1907, 1908, and 1921), C. A. Fisher (1910), C. A. Fisher and Calvert (1914), W. L. Fisher (1912), Miller, Rossman, and Hickcox (1945), Miller (1951), Barnes (1951), Kachadoorian (1955), Payne (1955), and Miller, Payne, and Gryc (1959) have reported on the stratigraphy, economic geology, engineering geology, and structural geology of the area.

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Publications by the University of North Dakota parties include reports by Reid and Clayton (1963), Clayton (1964), Tuthill (1963), Tuthill and Laird (1964), and Reid and Callender (1965).

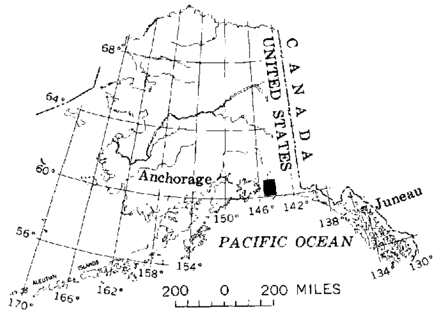
Grantz, Plafker, and Kachadoorian (1964) and Post (1965) have discussed earthquake effects in the Martin-Bering Rivers area and Remnitz and Marshall (1966) have discussed the effects of the Alaskan earthquake on the unlithified sediments of the Copper River delta to the west of the area of this report.

There are several physiographic units and two geologic provinces in the Martin-Bering Rivers area. The region south of the Martin River valley and east of the Ragged Mountains (figs. 1, 16) is underlain by Tertiary rocks. These Tertiary foothills consist of sedimentary and slightly metamorphosed rocks deformed into complex structural features which have east-northeast trending axes. The northeastern one-eighth of the area has been glaciated; valley cross sections are not much different in this area, however, from those beyond the limit of glaciation.

The Ragged Mountains lie between the Copper River delta and the Tertiary foothills east of Martin Lake and consist of a thrust block of Tertiary(?) igneous and metamorphic rocks.

The Copper River delta is a lowland west of the Ragged Mountains underlain by alluvium, and covered by intertidal marsh, alder, and muskeg growths.

The Bering River valley is a low-lying alluvial plain extending from the southwest shore of Kushtaka Lake and the Bering Lake area to the sea.



1.—Index map showing location of the Martin-Bering Rivers area.

The Martin River valley is a flat-lying valley train over which the main channels of the anastamosing Martin River migrate during peak ablation seasons. A terminal moraine of the Martin River glacier extends across the valley from the mountain north of Tokun Lake to the Chugach Mountains in sec. 20, T. 16 S., R. 6 E. (Cordova B-1). About 6 square miles of alluvial plain and dead-ice moraine lie between the terminal moraine and the present ice front of the glacier. This area is designated as the upper Martin River valley. That part of the valley between the terminal moraine and the point where the Martin River makes a sharp turn to the west in the area of the confluence of the Tokun Lake outlet stream and the Martin River (sec. 9, T. 17 S., R. 6 E., Cordova B-2) is designated as the middle Martin River valley. The part of the valley west of this is referred to as the lower Martin River valley.

The Martin River valley is presumably the trace of the Saint Elias-Chugach fault. However, the actual nature and detailed position of this fault is unknown.

The Chugach Mountains are a thrust block of late Mesozoic sedimentary, igneous, and metamorphic rocks. In the area covered by this report, the maximum altitude is 7,713 feet above sea level (1959). Glaciers occupy most of the valleys; all the valleys which penetrate the seaward ridge of the Chugach Mountains are presently glaciated or have contained glaciers. These valleys are steep and U-shaped in cross section.

Heavy precipitation in the area is caused by marine air currents that are forced to drop their moisture as they rise over the Ragged Mountains, the Tertiary foothills, and the Chugach Mountains. Precipitation averages about 145 inches per year (U.S. Dept. of Agriculture, 1941).

Periods of clear weather of a week or more are rare during the summer months, and fieldwork is usually hampered by rapidly fluctuating lake and river levels.

The growth of Pacific Coastal forest in the Prince William Sound area (Heusser, 1960, p. 50) is a direct response to the moist climate. Sitka spruce is found in much of the better-drained area below tree line (approximately 1,000–1,200). Mountain muskeg covers the foothills above and beyond the glacial deposits. Alder growths cover the moraines, the older outwash deposits, and much of the debris-covered terminal surface of the glaciers.

ACKNOWLEDGMENTS

We are deeply indebted to the National Science Foundation for financial support.

We wish to express our gratitude to Mr. Theodore F. Freers of the North Dakota Geological Survey who was a member of the field party during the first two weeks of June 1964. He participated in the collection of data in the Sioux glacier area

and shares responsibility with Tuthill for the map of earthquake-induced ground fractures.

Several residents of Cordova greatly facilitated our field operations. Foremost among these were Mr. Karl Barth, Mr. James Osborne, and Mr. Kenneth Smith.

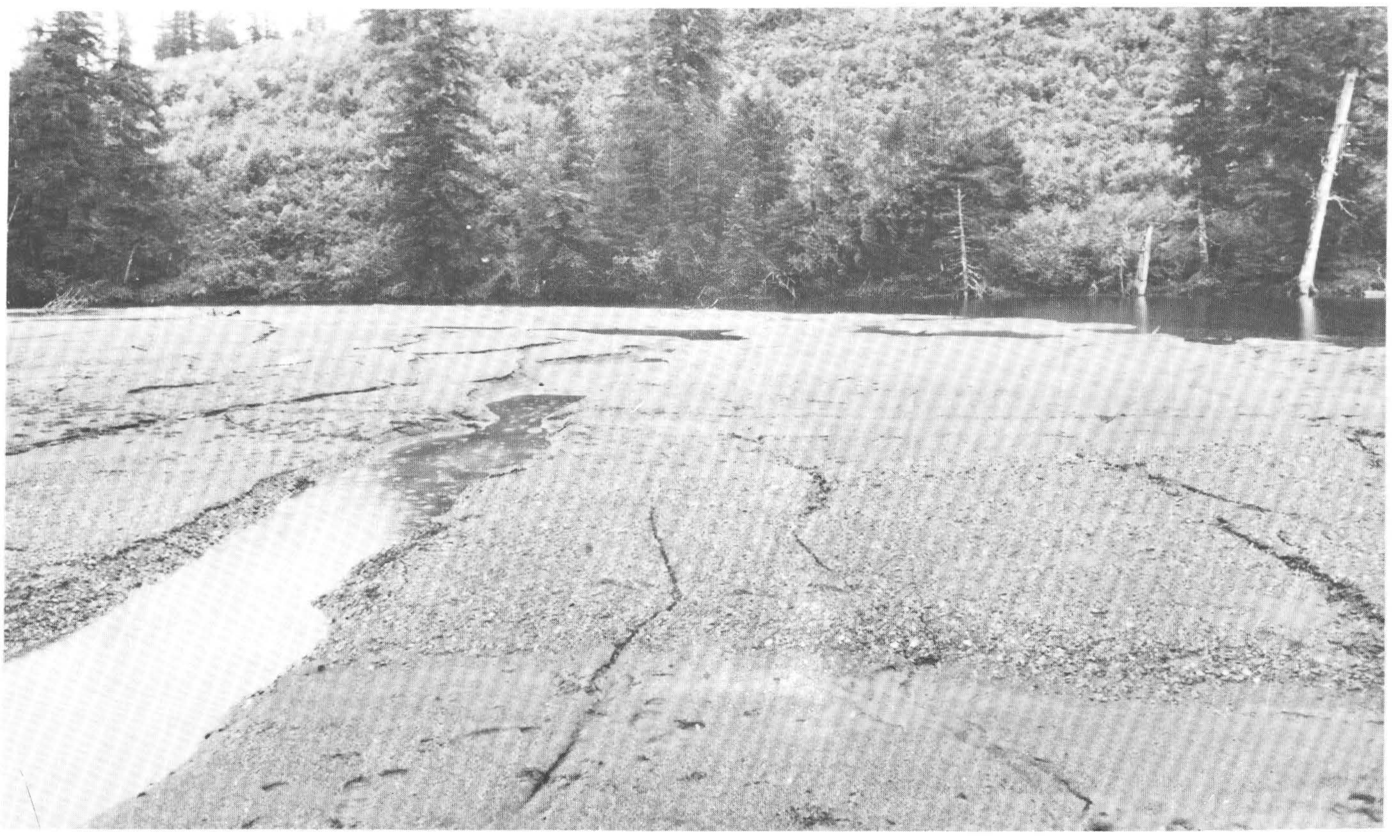
GEOMORPHIC EFFECTS OF THE ALASKA EARTHQUAKE

Twelve geomorphic effects of the Alaska earthquake were observed and (or) studied during the 1964 field season. These were: (1) earthquake-induced ground fractures, (2) mudvent deposits, (3) "earthquake-fountain" craters, (4) subsidence, (5) mudcones, (6) avalanches, (7) subaqueous landslides, (8) turbidity changes in ice-basined lakes, (9) filling of ice-walled sinkholes, (10) gravel-coated snow cones, (11) lake ice fracture, and (12) effects of regional uplift.

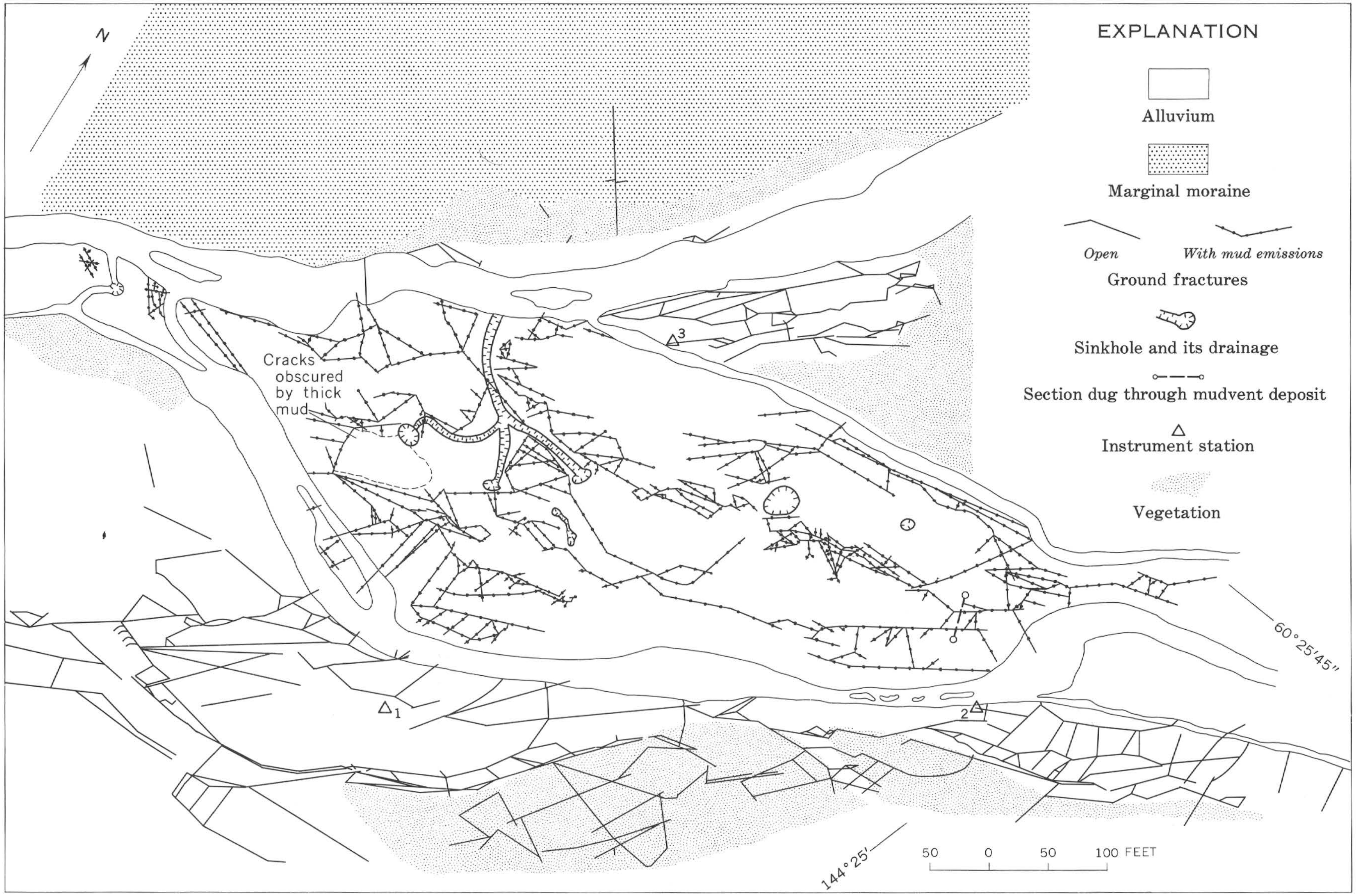
EARTHQUAKE-INDUCED GROUND FRACTURES

The most commonly observed geomorphic effect of the Alaska earthquake in the Martin-Bering Rivers area was earthquake-induced ground fracture (figs. 2, 3). Such features, frequently reported as a result of earthquakes, usually occur in unlithified sediments and are oriented parallel to streambanks. Accounts of ground fractures comparable to those seen in the Martin-Bering Rivers area are given by: Davison (1931), Silgado (1951), Levin (1940), Small (1948), Oakeshott (1954), and Ulrich (1936).

In the Martin River valley, 1,461 fractures were measured



2.—Earthquake-induced ground fractures in the middle Martin River valley. Slump blocks moved toward right. Note vertical displacement, especially beside pool, left.



3.—Earthquake-induced ground fractures in the upper Martin River valley.

for strike and, where possible for horizontal displacement of the adjacent block. Ground fractures were concentrated in the third of the valley nearest the surficial contact with marginal moraines or bedrock and within 50 feet of stream channels. A 600- by 1,200-foot rectangle in the valley was mapped by alidade and planetable to show ground fractures (fig. 3). This map includes 771 fractures 3 feet or more in length. The parallelism between the major fractures and the stream channels is easily observed, and the numerous shorter, interconnecting fractures, which mask the frequency analysis, can also be seen. Only 0.7 percent of the measured fractures were compressional.

The small number of compressional fractures may be due to lack of preservation and difficulty in recognizing them on an aggrading outwash plain where frequent thaw-season floods superimpose confusing minor patterns on preexisting topography.

The fractures are the result of low-gradient slumping in river alluvium. Measurable vertical displacement was only rarely seen (fig. 2). Generally, triangular and rectilinear tracts of alluvium were bounded on all sides by tensional fractures.

The ground was no doubt frozen at the time of the earthquake, and surficial grain adjustments were concentrated in relatively large-dimension fractures rather than at individual grain boundaries.

Ground fractures ranged in length from a few inches to 129 feet and had a maximum open depth of 20 inches. The greatest horizontal displacement measured was 17 inches. Measurements were not made on fractures whose edges appeared to have caved, however; consequently, many of the larger fractures were ignored and the 17 inches of horizontal displacement does not represent a maximum value.

Thirty-two paced traverses, having a total length of 5.9 miles, were made in the Martin River valley, and a total of 687 fractures were noted. The strike of each fracture was plotted and compared with the strike of topography, as taken from the Cordova B-1 and B-2 U.S. Geological Survey 1:63,360 series topographic quadrangles.

Histograms and cumulative curves of percent frequency were prepared for the fractures measured in the upper, middle, and lower sections of the Martin River valley, and from these a cumulative curve for the entire valley was plotted (fig. 4, next page). To supplement these studies, three traverses were made to demonstrate some local relations between topography and crack orientation that were masked in the other diagrams. One more study was made to establish the relation between the measured displacement and the deviation in orientation of the fracture from the strike of the topography.

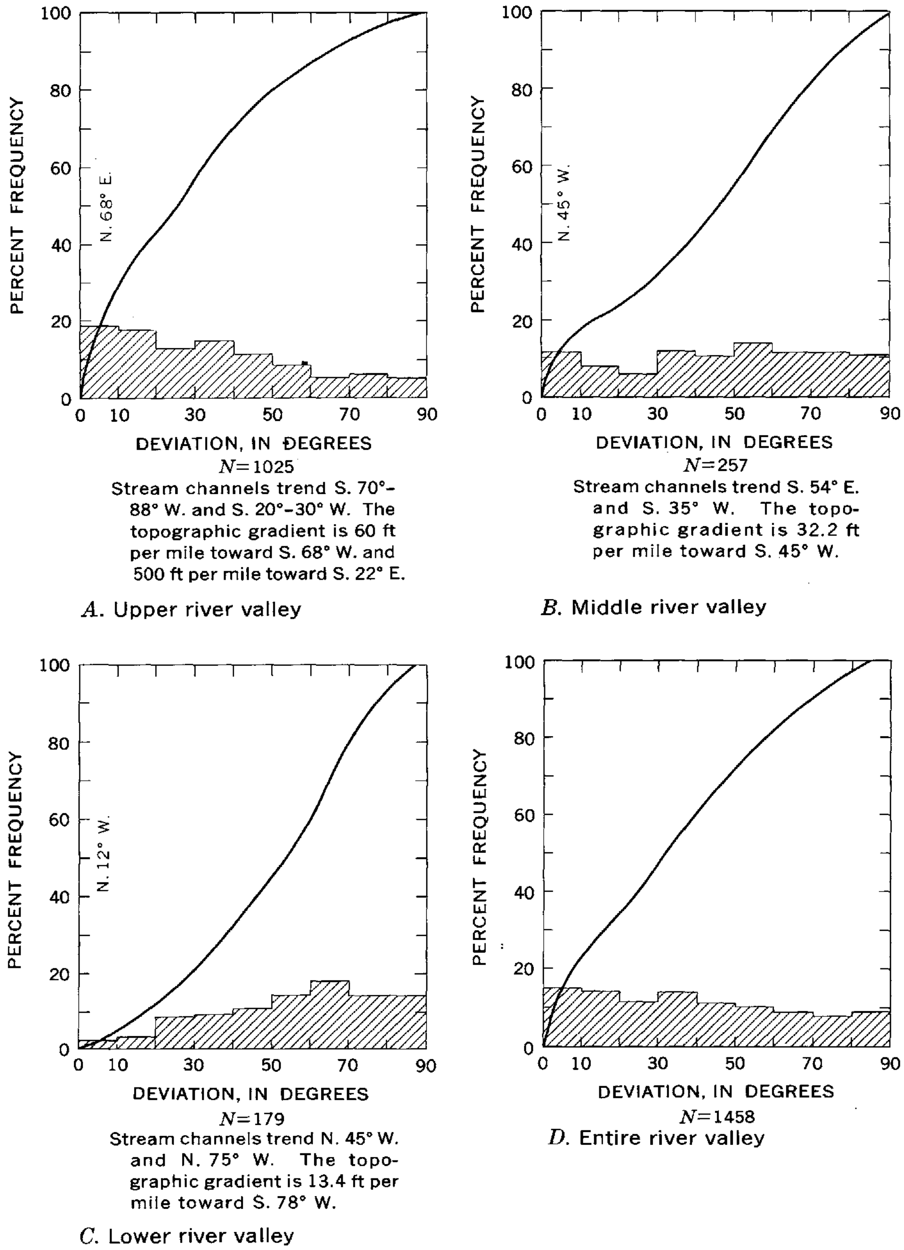
Fracture orientation and topographic strike in the upper Martin River valley (fig. 4*A*) have a regular relation. The cumulative curve rises smoothly and rapidly; on the histogram the median falls in the 20°–30° class and the model class is 0°–10°. The reasons that the central tendency values here are so close to the strike of the topography are that the stream channels approximately follow the strike of the topography, and the topographic gradient is significantly greater than that in the middle and lower parts of the valley.

In the middle Martin River valley (fig. 4*B*), the median is in the 50°–60° class and the modal class is 60°–70°. The range in the histogram is 17.5 percent (0.9–18.4 percent).

The median value in the lower Martin River valley (fig. 4*C*) falls in the 40°–50° class and the modal class is 50°–60°. In this part of the valley, the topographic gradient is approximately the same as in the middle part. The majority of the stream channels trend approximately 55°–25° from the trend of the surface slope. Thus the local relief along the stream channels was the cause of more slumping than was due to the down-valley movement of alluvium due to slumping of the valley fill toward the sea. The orientation of the fractures deviates from the topographic strike more here than in the middle part of the valley where the stream-channel trends deviated from the topographic strike approximately 80° and 90° (fig. 4*C*). This seemingly anomalous condition may be explained by the fact that the middle Martin River valley is adjacent to the terminal moraine of the glacier, and drainage channels are less numerous than in the lower part of the valley where a complex anastamosing of the river has developed.

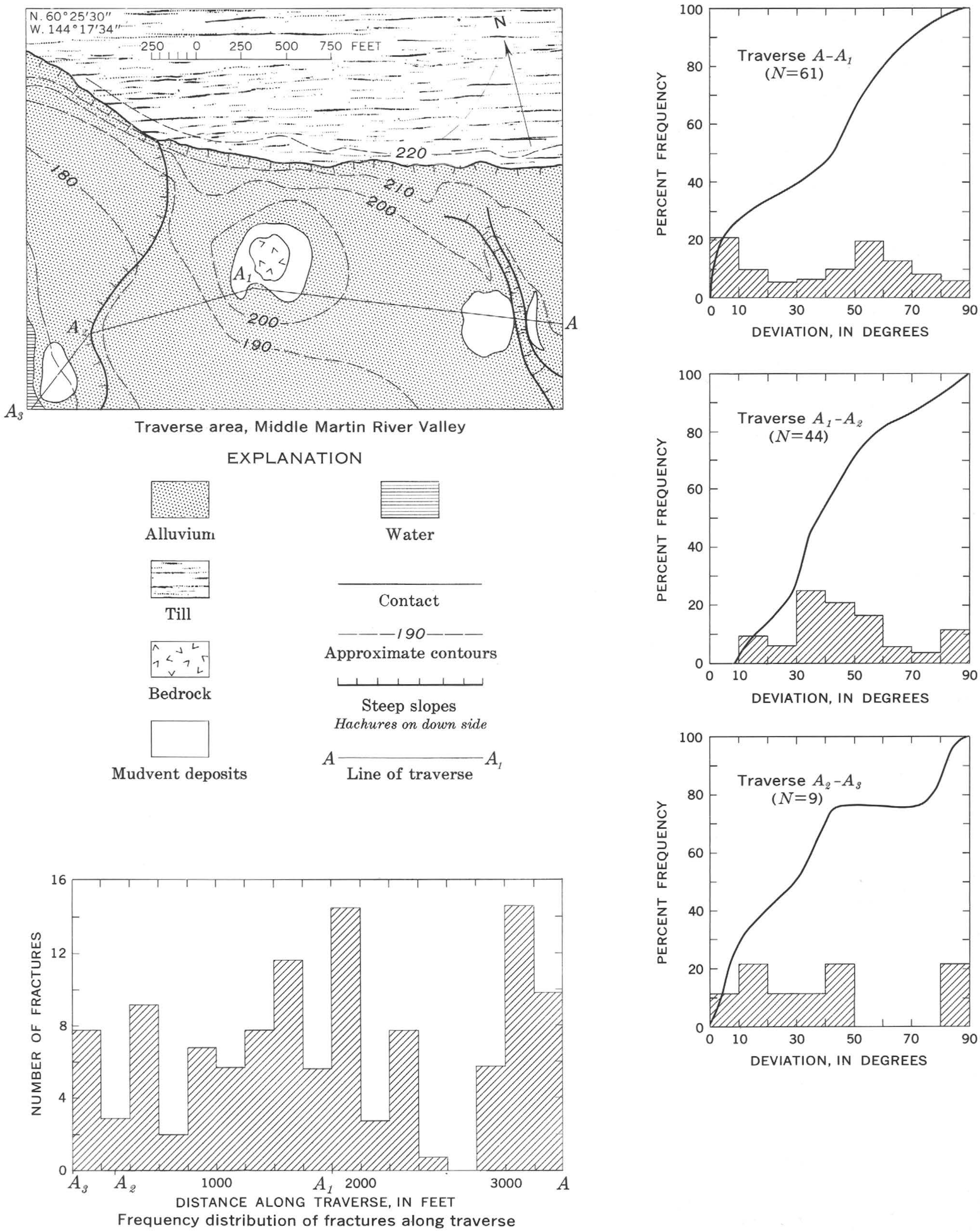
Data from the lower, middle, and upper valleys have been combined in figure 4*D*. A fairly smooth cumulative percent-freequency curve results, having a median value (50 percent) in the 30°–40° class. The modal class is 0°–10°, the range being 7.8 percent (15.1–7.3 percent). The percent-frequency histogram shows that the number of fractures whose orientation diverges from the topographic strike is diminishing. However, this degree of agreement between the strike of the fractures and the strike of the topography does not indicate a rigorous correlation between the two in the alluvium. The limitations may be seen in the diagrams of the data obtained in the middle and especially in the lower Martin River valley. If a few feet (usually not more than 10 ft of free slope along present or abandoned stream channels is oriented in directions not parallel to the topographic strike, the fractures which accomodate the local slumping of these streambanks more or less dominate the frequency-distribution diagrams (fig. 4*B*). It should be noted that the reason the cumulative curve for the valley as a whole (fig. 4*D*) agrees so closely with that for the upper part of the valley (fig. 4*A*) is that 70.3 percent of the data shown for the entire valley comes from the upper part of the valley, and thus masks the data from the middle and lower sections.

Three additional traverses made in the middle part of the valley, which are plotted on a detailed topographic sketch map (fig. 5), clearly demonstrate local relations that are masked in figure 4*D*. The data have been collected in classes of 200 feet of traverse length. The peaks on the graph indicate the increased frequency of fractures near streambanks, especially abandoned ones, and at interfaces between alluvium and bedrock. Areas of mudvent deposits indicate areas of greater frequency of fractures which could not be accurately counted because of the thickness of mud deposits. The histogram and cumulative curve of the traverse A–A_1 is markedly bimodal. The median



4.—Histograms and cumulative curves of percent frequency of earthquake-induced ground fractures in the Martin River valley. N=number of fractures.

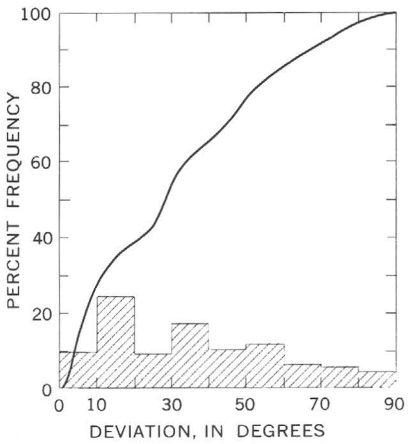
value falls in the 40°–50° class and the modal class is 0°–10°. The second largest class is 50°–60° and is secondary by only 1.6 percent (21.3–19.7 percent). The 50°–60° class is large because of the number of fractures formed by the slumping along the former stream channel at the point 200–250 feet along the traverse, as indicated on the map. The cumulative curve rises slowly until the modal class of 30°–40° is reached. The curve is relatively smooth and convex up to the 80°–90° class, where an upward deflection causes a concavity in the curve. The diagrams showing percent frequency with respect to deviation



5.—Map, fracture-frequency diagram, and series of histograms and cumulative percent-frequency curves for earthquake-induced ground fractures along three traverses in the middle Martin River valley. N=number of fractures.

from topographic strike clearly indicate the relations between regional topographic gradient and local zones of high slope along stream channels as discrete factors controlling slumping.

One other series of measurements was made in order to show the relation between the measured displacement between blocks and the deviation of orientation of the fractures from the topographic strike. The results are shown on figure 6. Displacement was defined as distance between the edges of blocks of alluvium, measured at right angles to the strike of the fracture separating the blocks. No measurements were made on fractures where mud emissions, caving, or washing of the fractures could be observed to have occurred. A total of 320 fractures and 550.7 inches of displacement were measured. The median value falls in the 30°–40° class and the 10°–20° class is the modal class.



6.—Histogram and cumulative curve of total measured displacement in relation to deviation from topographic strike for earthquake-induced ground fractures in the Martin River valley.

The best example of the relation between free slopes along stream channels and earthquake-induced ground fracture was photographed during a flight over the Copper River just west of the Martin-Bering Rivers area (fig. 7). The conditions observed in the Martin River valley were comparable, but not as extensive.

The limitations for construction sites on outwash plains and alluvial areas were clearly demonstrated by the widespread occurrence of ground fractures.

MUDVENT DEPOSITS

As with ground fractures, mudvent deposits are frequently reported as common consequences of earthquakes on unlithified water-saturated sediments. They have been called "sand blows," "silt volcanoes," "sand ridges," and "mud volcanoes" and have been described by many investigators (Bramhall, 1938; Broadhead, 1902; Byerly, 1942; Coombs and

7.—Earthquake-induced ground fractures in Copper River delta several miles west of the Ragged Mountains, showing relation to streams and former drainages.

Banksdale, 1942; Dobrovolny and Lemke, 1961; Housner, 1958; Macelwane, 1947; Morse, 1941; Shepard, 1905; Slemmons, 1957; Steinbrugge and Moran, 1956; Tarr and Martin, 1912; and Tocher , 1956). Housner (1958) discussed the mechanism by which ground water is forced to, and frequently above, the ground surface and by which sediment carried with it is deposited in the immediate area of egress. The process is initiated during an earthquake by grain adjustments which cause pressure gradients in the ground water—a mechanism analagous to piping. The mudvent deposits range in grain size from cobbles to clay (figs. 8, 9). The area studied for ground fractures included a large field in which deposits from mudvents were more than 3 feet thick in places. Because of the great range in grain size observed in the sediments, the term "mud" has been employed rather than one having a specific grain-size connotation.

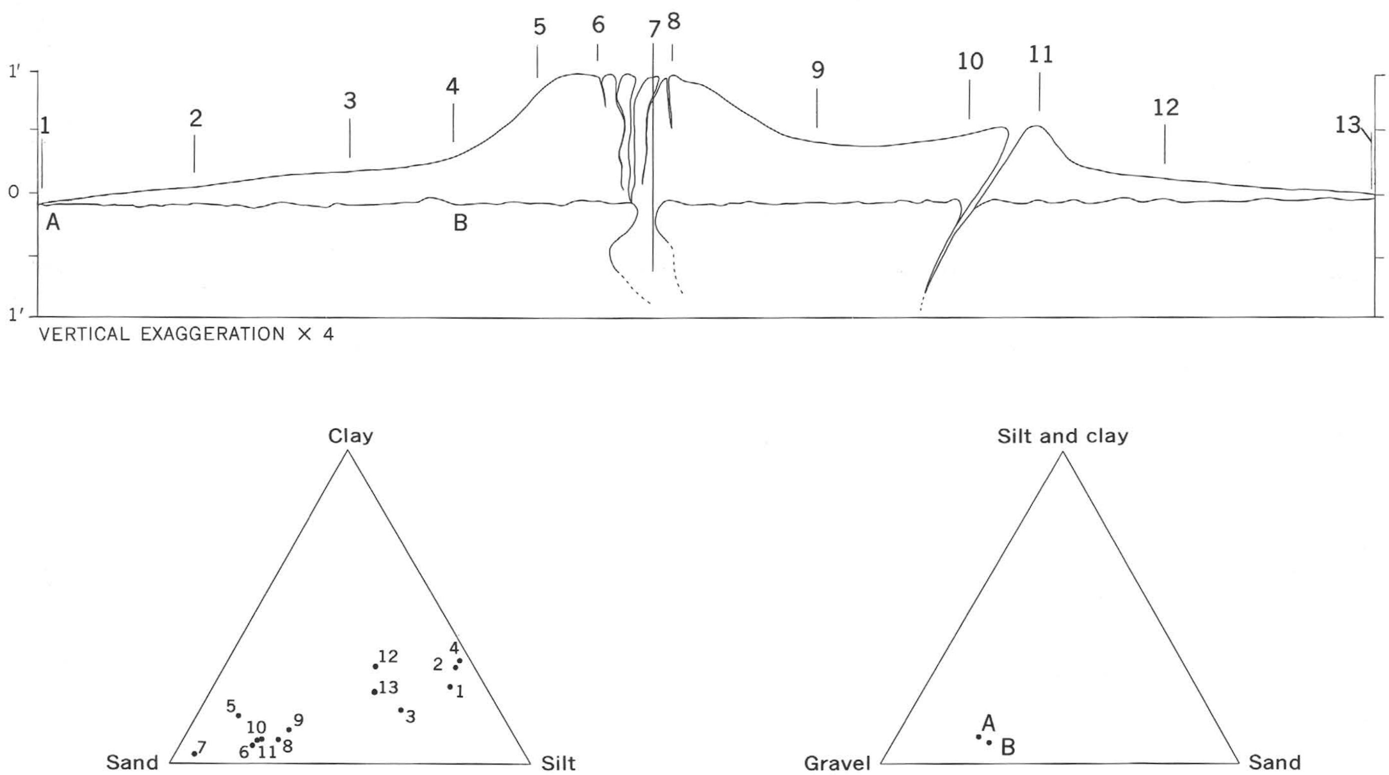
A section was dug through a large mudvent deposit in the area mapped. The grain size of sediments and the central coarse-grained core are shown in figure 10 (next page).

All the mudvent deposits we saw issued from earthquake-induced ground fractures.

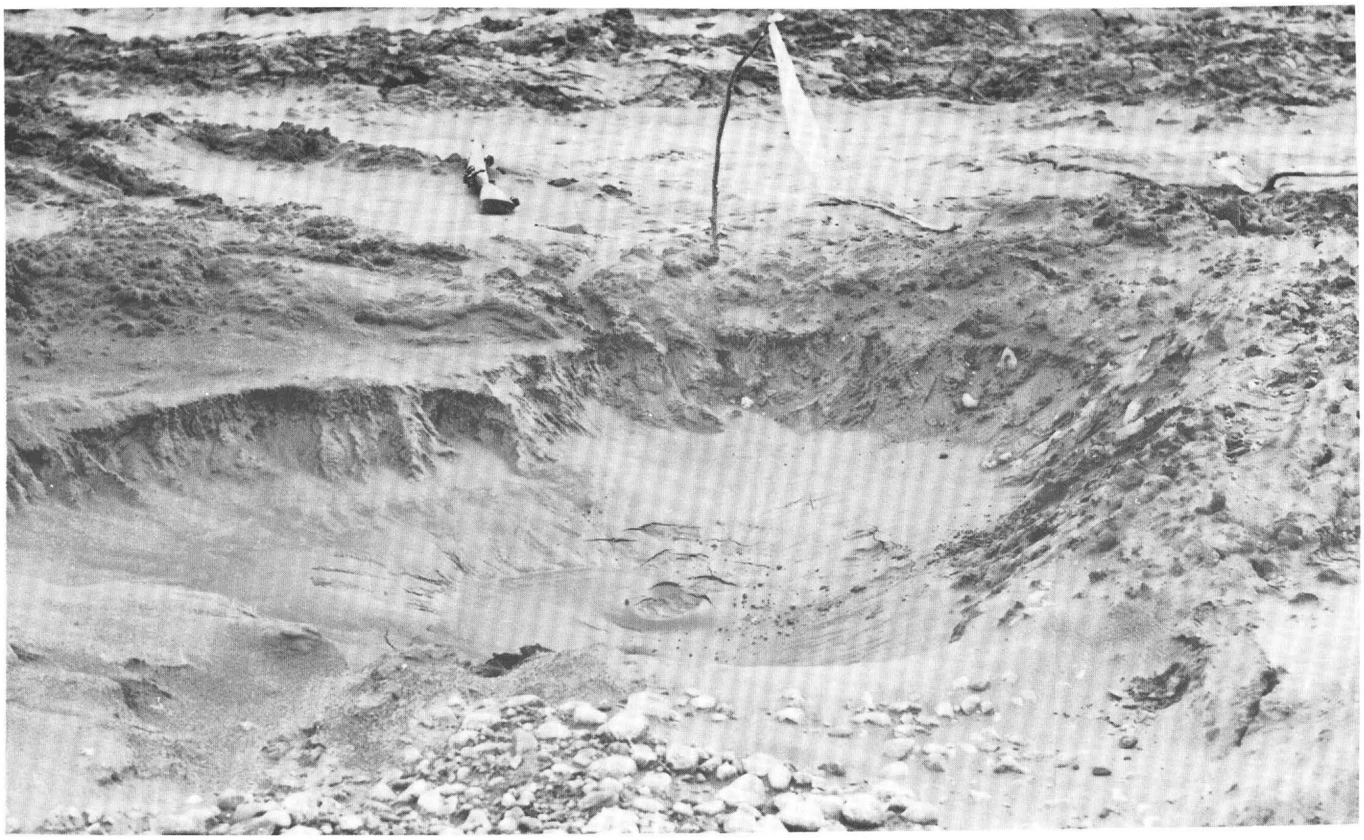
In the Martin-Bering Rivers area, the mudvent deposits were concentrated in the third of the valley adjacent to the valley walls because of the general direction of slumping toward the valley centers. This preferential distribution was not observed on the Copper River delta where mudvents seemed to occur in an unsystematic fashion.

8.—Mudvent deposits in upper Martin River valley. Cracks resulted from differential compaction.

9.—Mudvent deposits in upper Martin River valley. Cracks resulted from differential compaction due to grain-size variation.



10.—Cross section of a mudvent deposit in the upper Martin River valley and diagrams showing grain-size percentages of samples taken from the deposit.



11.—Earthquake-fountain crater in upper Martin River valley. Gravel in foreground is in drainage channel.

Mudvent deposits are fairly resistant to erosion. Several heavy rainstorms which lasted for as long as 4 days had little effect on them. The deposits, therefore, may survive as discrete sedimentary units, if they become covered by other sediments.

EARTHQUAKE-FOUNTAIN CRATERS

Associated with the mudvent deposits were craters from which large amounts of water had issued. The grain size of the sediments in the bowls of these craters usually ranged from coarse sand to medium gravel. The flow of water from earthquake fountains must have been greater than from the mudvents in order to effect such a difference in grain size. The deposits differed both from the underlying alluvial gravel, sand, and silt, and from the mudvent deposits in which they occurred.

Most of the craters were 2–3 feet deep and 4–8 feet across (fig. 11). Drainage channels lead away from these craters. In the area studied (fig. 2), the distributary channels cut through many of the mudvent ridges. In two places, mudvent ridges crossed the drainages, but were not even slightly eroded. Thus, the craters were contemporaneous with the mudvents, and they formed in less time than was required to deposit the mudvent fields.

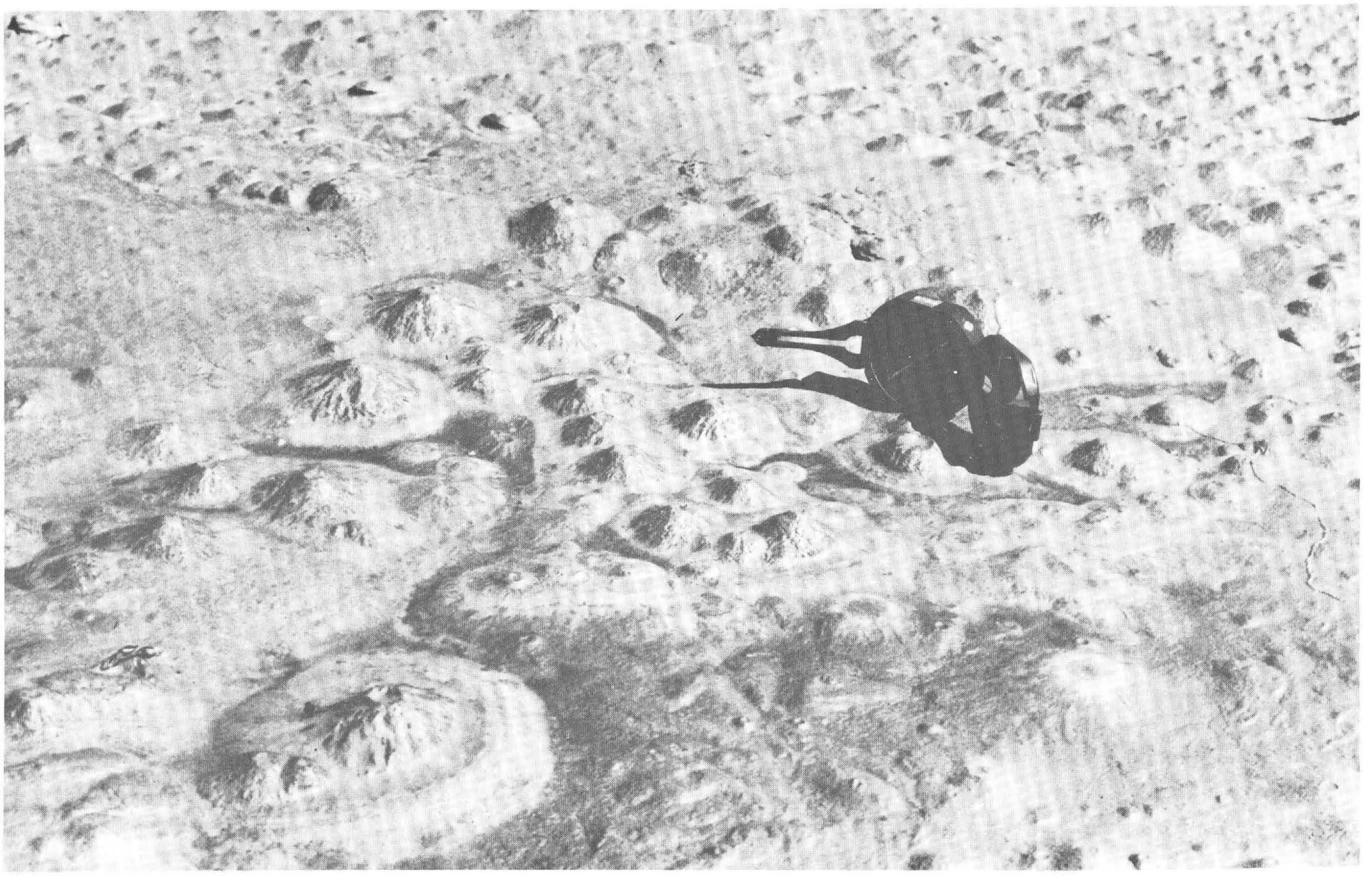
If Housner's theory (1958) about the formation of mudvents is correct, this groundwater activity would have started shortly after the earthquake began and would not have continued long after the earthquake ceased.

SUBSIDENCE CRATERS

Several circular subsidence craters were seen at various places. One, in the upper Martin River valley (fig. 12, next page), about 14 feet in diameter, 5 feet in depth, and conical in shape. It was on a strip of alluvium that was a few feet higher than the surrounding area and was covered by moss and a few alder shrubs, 4–5 years old. The moss remained in a nearly normal growing position in the bottom of the cone. No evidence could be

12.—Subsidence crater in upper Martin River valley.

13.—Subsidence craters in mudvent deposits, western Copper River delta. Arrows indicate en echelon orientation.



14.—Small mudcones on rain-pocked mudvent deposits in upper Martin River valley.

found to indicate that water had flowed from the depression.

In the middle Martin River valley, away from the terminal moraine of the Martin River glacier, three conical depressions were observed in unvegetated alluvium. These depressions were about 20–25 feet in diameter and about 8 feet in depth. Caving of the sides had filled the bottoms of the depressions to form a flat area about 3–4 feet in diameter. No evidence could be found that water had flowed from these depressions either. Unlike the depression in the upper valley which was filled with water, the three in the middle valley were above the ground-water table. The three depressions were alined about N. 20° W. and were approximately 150–200 feet apart. A similar series of four water-filled linear depressions were observed from the air on the west side of the Copper River delta (fig. 13). These Copper River depressions were intimately associated with mudvent deposits.

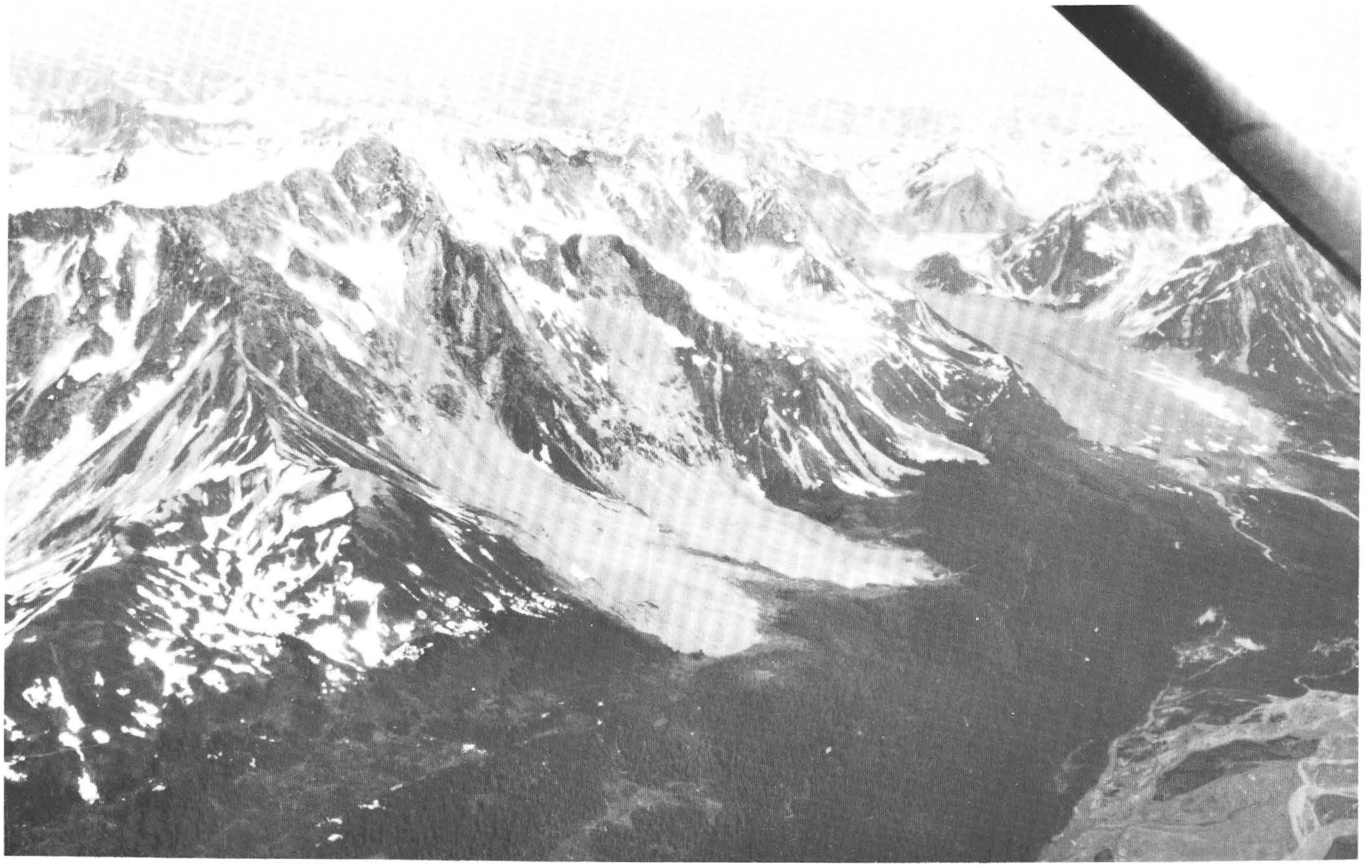
Subsidence craters seem to have formed by the subsurface migration of fine-grained sediments away from the area of the depressions as a result of ground-water flow, or they may have formed by consolidation of loosely compacted alluvium in zones formerly occupied by ice blocks.

MUDCONES

Small mudcones (fig. 14) were very minor and infrequent features. These cones were deposited by slowly flowing springs at the end of mudvent deposition. Slight variation in grain size within the cones indicates that the water flow, responsible for the deposition of the features, fluctuated.

AVALANCHES

The term "snow avalanche" is used here to describe high-speed falls and flows composed primarily of snow. The term "rock avalanche" is used to describe falls, slides, and flows, composed primarily of rock fragments, but observed rock avalanches contained some snow. In two of the rock avalanches studied, snow avalanches clearly preceded the fall of rock material and made up



15.—Camp and Sioux glacier slides. Medial moraine on Sioux glacier darker than fresh rock-avalanche debris.

about 75 percent of the total thickness of the avalanche termini (fig. 15). Most of the rock avalanches started high on the valley walls.

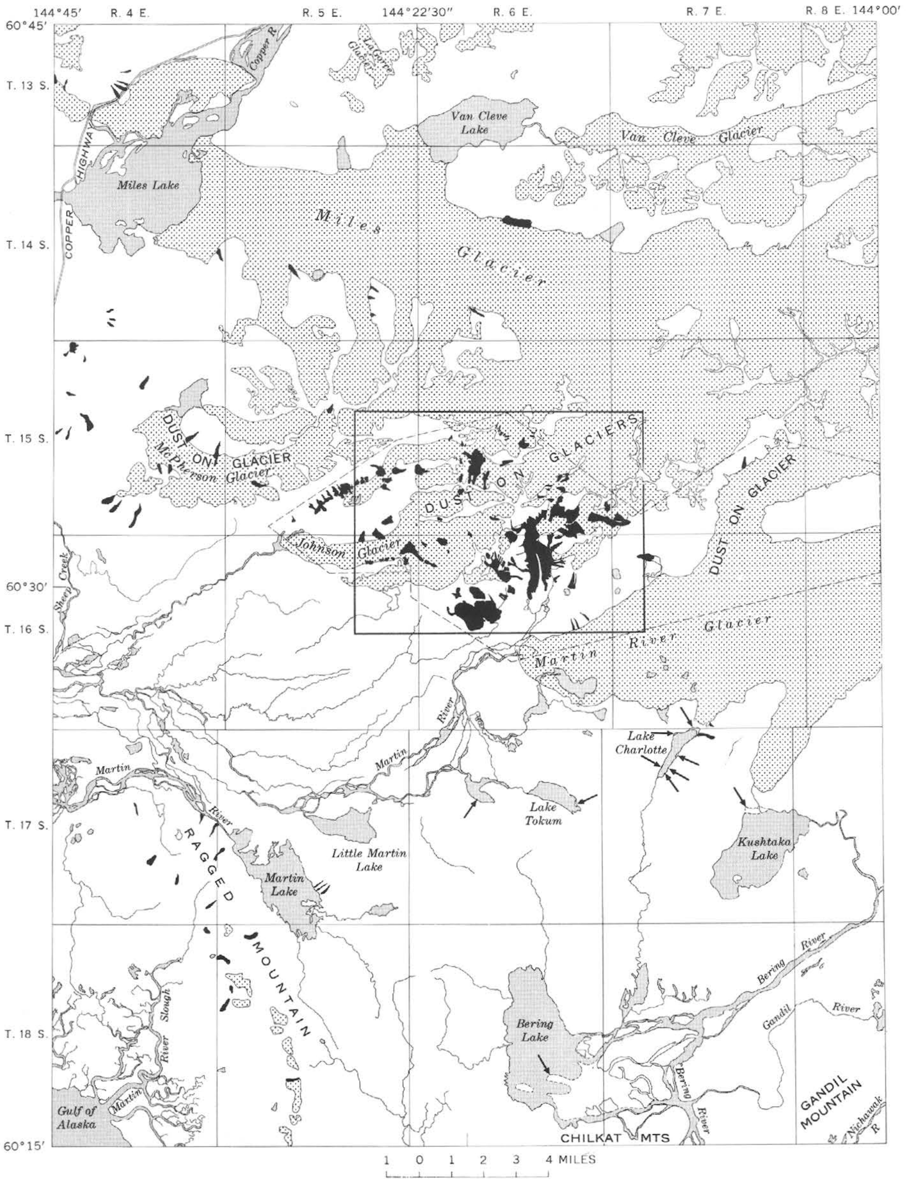
SNOW AVALANCHES

Because the Alaska earthquake occurred at the end of March, nearly optimum conditions for snow avalanching existed. The intensity of the earthquake was so great that it undoubtedly provided one of the most dynamic triggers ever applied to the slopes. The great majority of potential avalanche corridors probably were activated during the Alaskan earthquake.

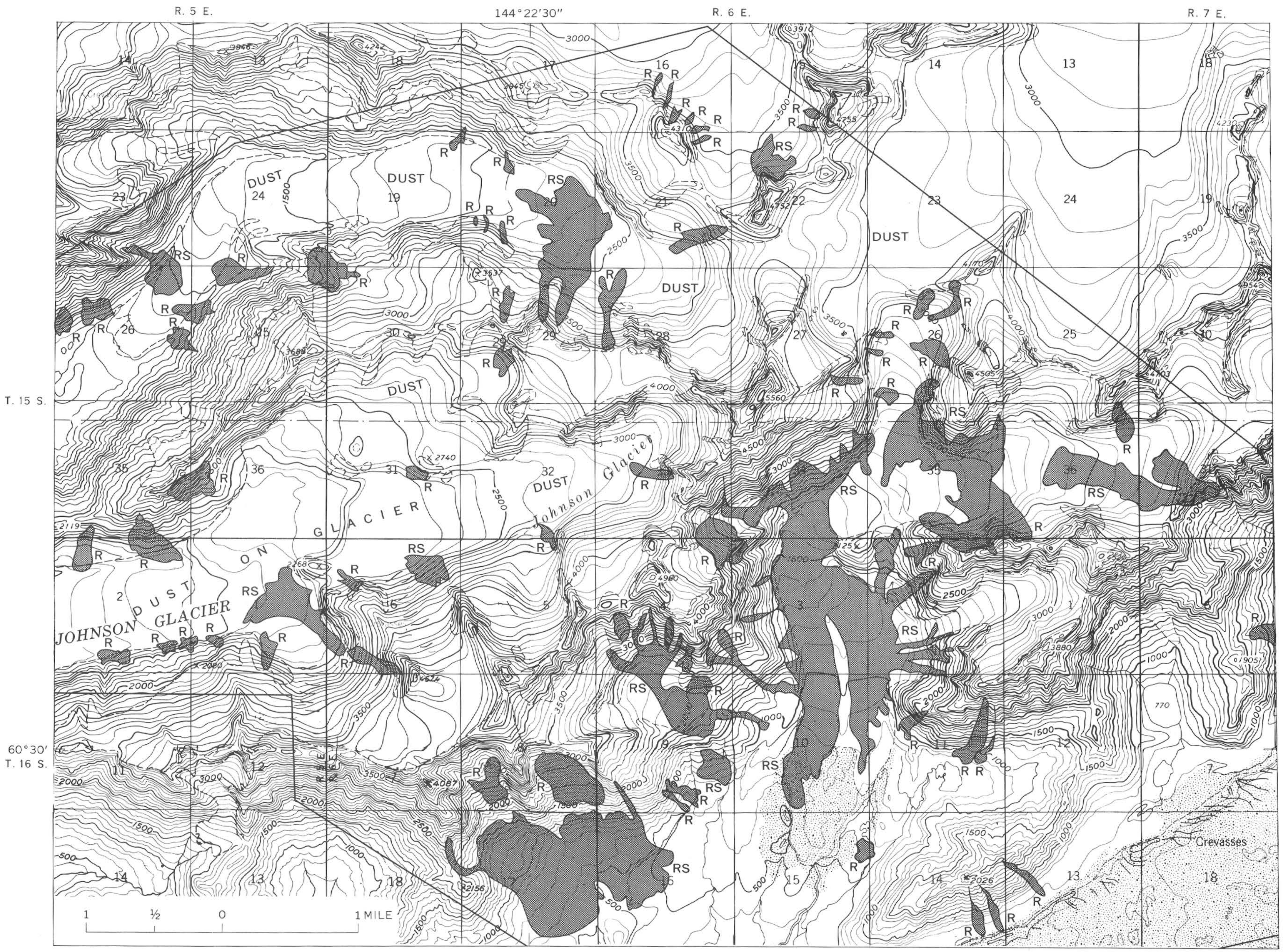
All the snow avalanches observed in the field or identified from aerial photographs taken by the Arctic Institute of North America shortly after the earthquake, are shown in figures 16 and 17. The rock-coated snow avalanches indicate snow-avalanche corridors. A snowfall that occurred in the area the day after the earthquake undoubtedly obscured many smaller avalanches which thus escaped notice. Despite its incompleteness, the compilation shown on figures 16 and 17 should be of service to engineers who may be called upon to choose highway, railroad, or building sites in the area.

Snow avalanches and winds generated by them severely damaged adjacent forests. A stripped area 100–150 feet wide around the terminus of Camp slide (secs. 16 and 17, T. 16 S., R. 6 E., fig. 16) is presumed to have been caused by avalanche-generated winds (fig. 15). One 25-foot-long 24-inch-diameter Sitka spruce tree was impaled in the avalanche snow and rock debris in an inverted position, presumably by the force of these winds.

An almost continuous fall of rock from the upper slopes in the Chugach Mountains during June prevented us from thoroughly examining the upper two-thirds of any of the avalanche bodies. The stratigraphy of the Sioux glacier avalanche showed that the snow avalanches preceded the rock avalanches. Randomly oriented blocks of stratified snow were observed in the pedestal upon which the rock debris



16.—Generalized distribution of avalanches caused by the March 27, 1964, earthquake in the Martin-Bering Rivers area. Avalanches are shown in black. Inset area is shown in detail on the next page.



17.—Avalanches in the Chugach Mountains near the Martin River glacier, 1964. Area within the heavy lines is covered by postearthquake aerial photographs.

rested. Rock debris of the medial moraine beneath the avalanche snow could be distinguished from fresh rock-avalanche debris by its darker color.

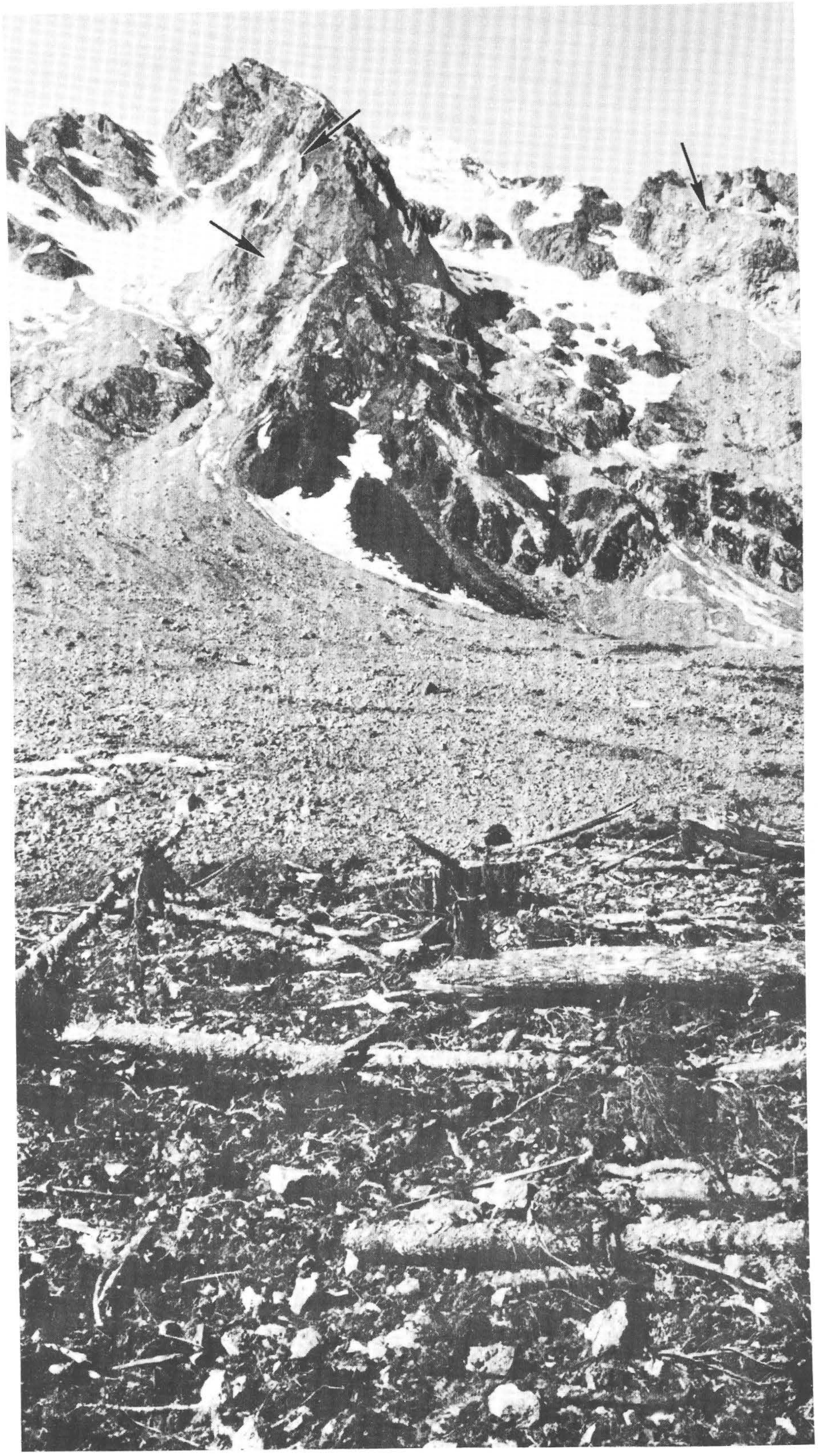
ROCK AVALANCHES

The source areas of the rock avalanches could not be examined because of the previously mentioned fall of rock throughout the month of June. While impressive, these later rockfalls delivered only minor quantities of material to the valley floors when compared with the massive deposits which came down during the earthquake. Observation through binoculars and an examination of the avalanche debris indicated that the source area was intensely jointed granodiorite.

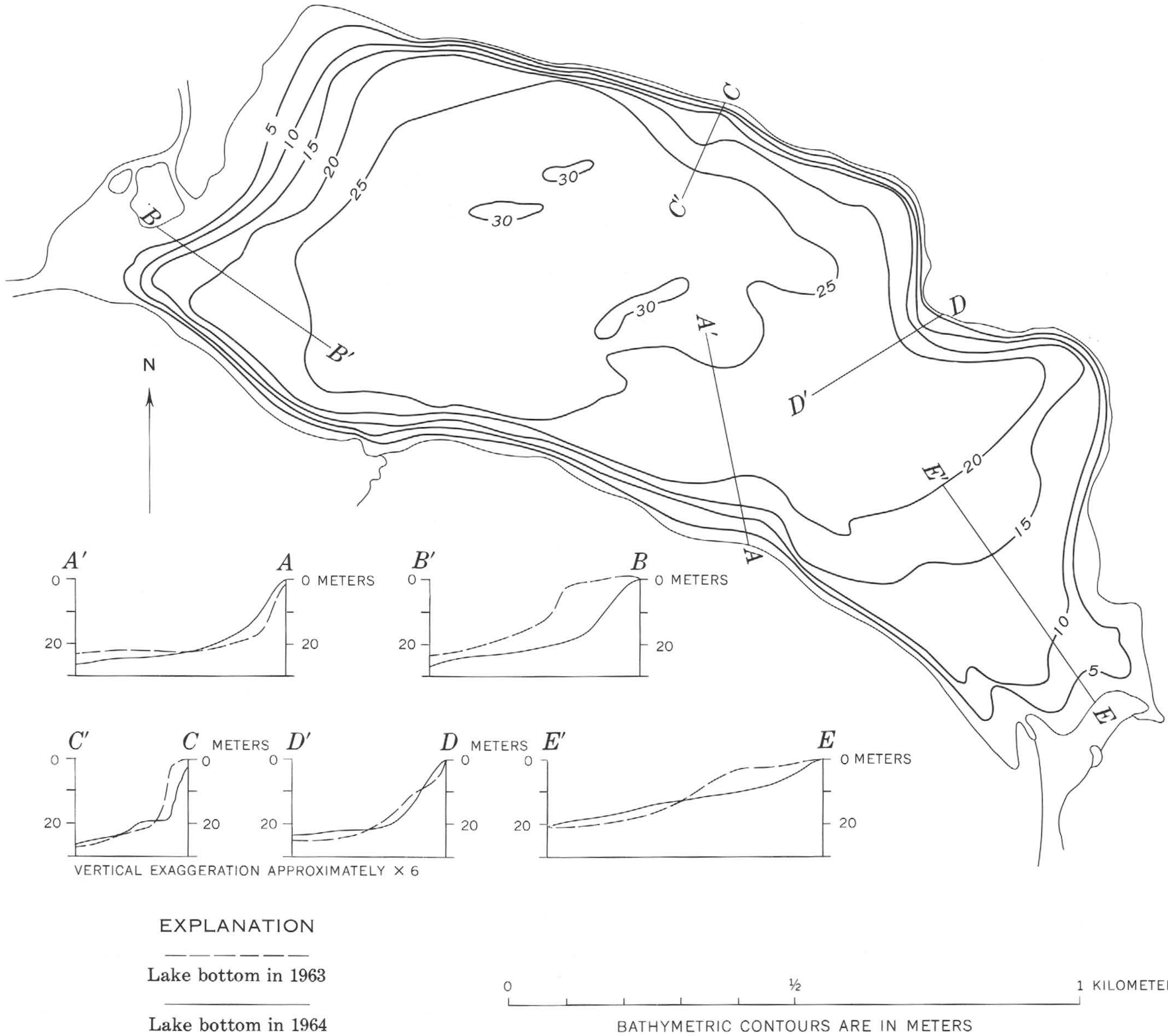
Rock debris on the Sioux glacier made up approximately one-fourth of the terminal thickness of the avalanche body. The area of the slide was approximately 1.2 square miles and the estimated average thickness was 10 feet. Thus approximately 33×10^6 cubic yards of material (9×10^6 cubic yards of rock and the balance snow) was added to the surface of the glacier. The rock debris on the Sioux glacier slide consisted of an assortment of bedrock rubble ranging in grain size from fine sand to blocks having median diameters to 20 feet.

The Camp slide had a stratigraphy similar to that of the Sioux glacier slide, but vegetative debris was included in the avalanche because forested areas were involved (fig. 18). The Sioux glacier and Camp slides were probably air-layer lubricated phenomena of the type described by Shreve (1965, p. 151).

As figure 17 shows, the rock avalanches were concentrated in



18.—Avalanche debris of Camp slide viewed from distal margin. Arrows indicate source areas of rock debris.



19.—Map of Tokun Lake showing bathymetry and profiles of bottom configurations in 1963 and 1964.

the Chugach Mountains near Sioux glacier. Unusually severe snow avalanching, but surprisingly little rock avalanching, occurred in the Tertiary foothills and the Ragged Mountains. Slopes in the Ragged Mountains are as steep as those in the Chugach Mountains, but valley configurations are different. The Chugach Mountains have been extensively glaciated by valley glaciers and all the valleys leading into the Martin River valley are U-shaped. The foothills have been recently glaciated only northeast of Kushtaka, Tokun, and Charlotte Lakes (fig. 17). Slopes are much more gentle in the foothills than in either the Chugach or the Ragged Mountains.

The Martin River valley follows the presumed trace of the Saint Elias-Chugach fault. It is possible that a complexly fractured zone in the trace of the fault acted as a damper to the earthquake shock waves. Thus the smaller number of rock avalanches in the Ragged Mountains and the foothills could perhaps be explained by the absence of as severe a trigger mechanism.

Local faulting in the area of Sioux glacier is also a possibility, but we observed no evidence to support this idea.

DUST

A secondary effect of the rock avalanches throughout the Chugach Mountains was the deposition of a dust coat on the glaciers. The distribution of these dust coats as observed in the field and from the air during June and early July is indicated on figure 16.

SUBAQUEOUS LANDSLIDES

Lakes in the Martin-Bering Rivers area have been divided into two types on the basis of their bathymetric configuration. Lakes of the first type have slopes of about 10° or more around most of their shorelines and have average depths of 70–120 feet. Their bottoms are relatively flat. Tokun Lake, Lake Charlotte, and Kushtaka Lake are examples of this type. The second type of lake is extremely shallow throughout, depths rarely exceeding 6 feet. These lakes have been filled by outwash sediments from either the Martin or the Bering River. Bering Lake and Martin Lake are examples.

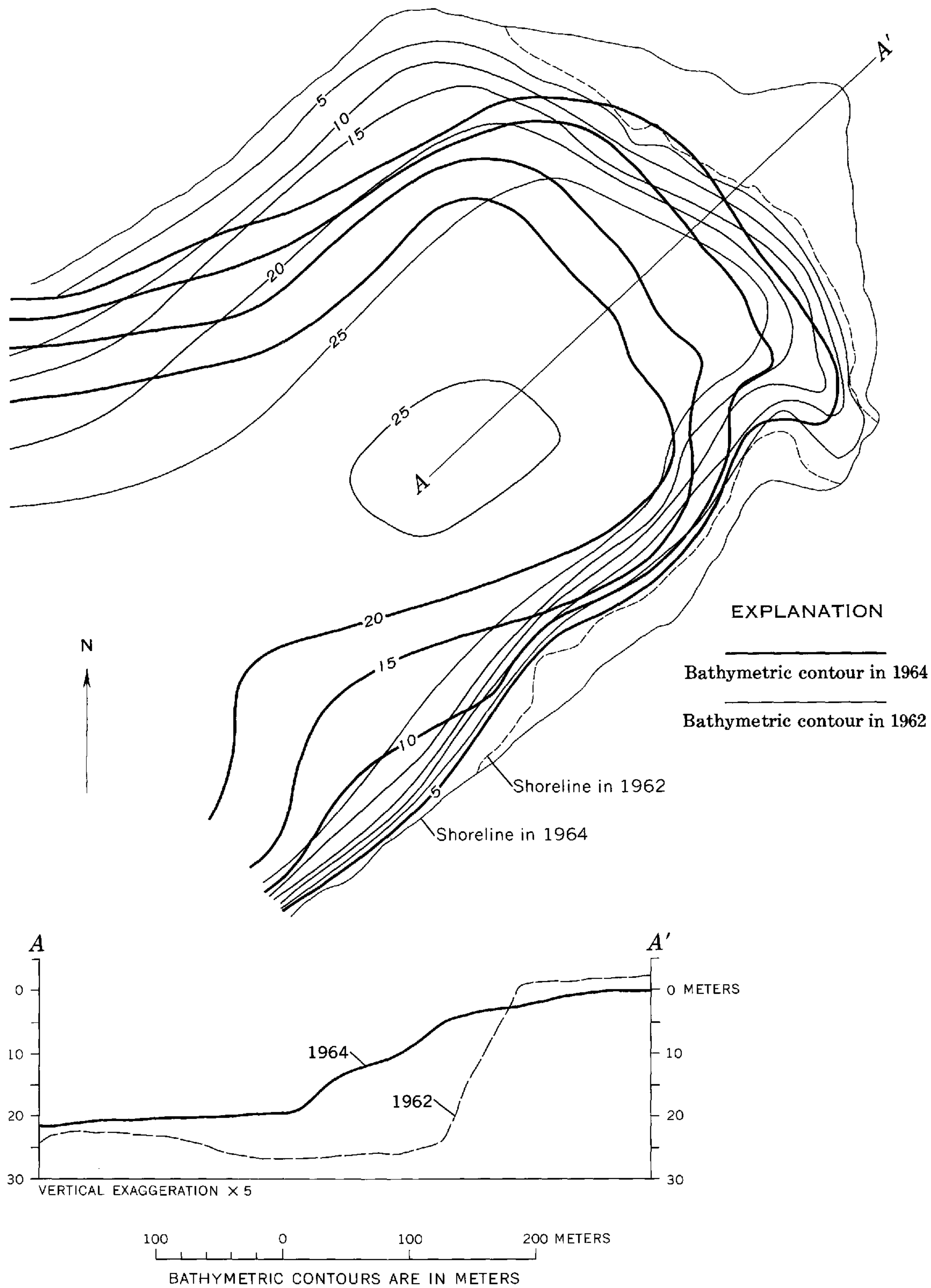
Little Martin Lake is intermediate between the two types. The western half of the lake is filled by outwash sediments from the Martin River to within 6–15 feet of its surface, and the eastern half attains depths of 50 feet. Slopes in the eastern part of the lake are as high as 18°.

Subaqueous landslides occurred in the deltaic sediments of all lakes of the first type. The most detailed study was made of Tokun Lake (fig. 19). The western shore of Tokun Lake consists of outwash sediments and in 1963 had a very low gradient. The north and south shores are steep and are composed of angular boulders and cobbles. Three streams enter Tokun Lake and have formed deltas having steep distal faces. All these deltas slid —presumably triggered by the earthquake. The largest slide in Tokun Lake involved the sediments deposited by Tokun Creek in the eastern quarter of the lake.

The landslides generated waves which fractured lake ice and modified the shores by overturning many flagstones along the southwestern shore. Algae which normally grow on the upper surface of submerged rocks were found on the lower side of these rocks, and dead aquatic insect pupae and larvae were observed on their upper surface. Lake ice and water set in motion by the subaqueous landslides in the opposite (eastern) end of the lake probably overturned the flagstones.

Lake Charlotte has six inlet streams. The largest of these is the melt-water distributary from the Lake Charlotte lobe of the Martin River glacier at the northeastern end of the lake; a large subaqueous slide in its delta lengthened the shoreline 80 feet and increased the area of the lake by approximately 5.1×10^4 square feet (2.1 percent of the 1962 area). In 1962 the shoreline was 29,385 feet in length. The sliding of the delta front of the outwash plain at the northeast end of the lake increased the shoreline by 165 feet. The sliding of other deltas built out into the lake reduced the shoreline by 120 feet so that the 1964 shoreline measured 29,430 feet. The bathymetric changes which occurred in the northeast part of the lake are shown in figure 20 (next page).

At the extreme southeastern end of the shore a delta of angular gravel and sand slid. Mature Sitka spruce trees remained upright and rooted in the proximal part of the subaqueous slide—the upper parts of their trunks remaining above the surface of the lake.



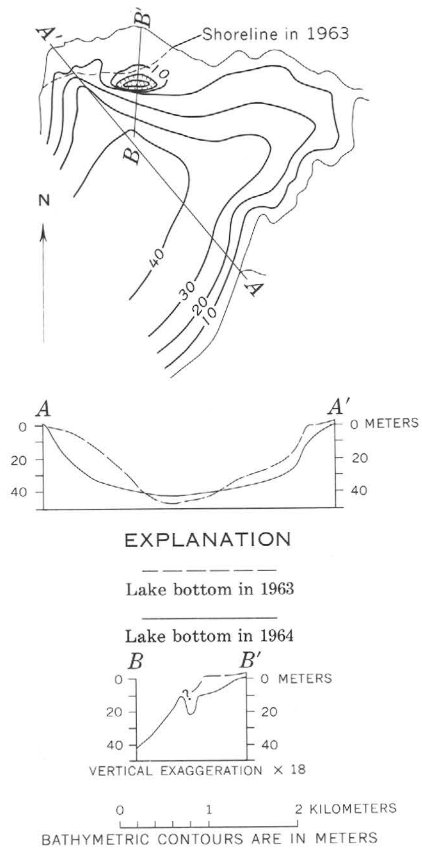
20.—Bathymetric map and profiles showing bottom configurations in northeast part of Lake Charlotte in 1962 and 1964.

A wave generated by this slide caused lake ice to strike the boles of trees and scuff and strip off the bark 3–6 feet above the scarp of the slump, and approximately 11 feet above the July 6 water level.

All the other deltas in Lake Charlotte slid. The one formed by the stream which drains the lake at an altitude of 319 feet, north of Lake Charlotte, modified the bathymetry of the central part of the lake.

Kushtaka Lake, like Lake Charlotte is formed behind a terminal moraine and is fed by melt-water streams from the Kushtaka lobe of the Martin River glacier. In late July 1963 the delta formed by this drainage had slopes (based on depths 100 meters from shore) as high as 11°. The entire front of this delta slid, and slopes were changed to about 40° by this one subaqueous landslide. Figure 21 shows the bathymetric modifications of the northern end of Kushtaka Lake and the front of the delta.

The shallow lakes of the second type exhibited some settling of gravel bars and deltas, but showed no indication of subaqueous slides. The lack of steep free slopes on the distal faces of these bars and deltas no doubt explains their stability even during what must have been rather severe shaking.



21.—Bathymetric map and profiles showing bottom configurations of the northern part of Kushtaka Lake in 1963 and 1964.

TURBIDITY CHANGES IN LAKES ON THE MARTIN RIVER GLACIER

The present ice margin of the Martin River glacier is mantled by superglacial drift over most of its area. The distal half mile or so in secs. 22, 25–27, 35, and 36, T. 16 S., R. 6 E.; secs. 30–34, T. 16 S., R. 7 E.; and parts of the Kushtaka Lake lobe are covered with spruce and alder growths. The forested area is studded with ice-basin lakes that have become insulated by drift, to a greater or lesser degree, from the underlying glacier ice. The water of some of these lakes had become clear and temperate by 1962 and contained aquatic vegetation and animals.

When surface ice melted from these lakes in June 1964, several were observed, from the air, to have become turbid (fig. 22, next page). The insulating drift on the east shore of Black Lake (NE¼, NE¼ sec. 35 and NW¼, NW¼ sec. 36, T. 16 S., R. 7 E.) was only 6 feet thick in 1963. The exposure of the underlying dead glacier ice by slumping of the drift mantle caused turbid melt-water to enter many of the formerly clear lakes along the glacial margin.

The turbidity increase, is estimated at no more than 50–100 ppm (parts per million) of suspended material. Though this increase is well below the turbidity levels of ice-walled sinkhole lakes and proglacial lakes in the area, it will have an unfavorable effect upon both the flora and fauna of the lakes. If drift accumulates and retards melting of the ice, little permanent damage to plants and animals is likely, but several seasons of such turbid conditions would return the lakes to a low state of ecologic complexity—a state equivalent to that at Kushtaka Lake, Lake Charlotte, and the unnamed lake at an altitude of 319 feet north of Lake Charlotte (Tuthill, 1963).

FILLING OF ICE-WALLED SINKHOLES

In 1962 several ice-walled sinkhole lakes on the Lake Charlotte lobe of the Martin River glacier were drained of water (Reid and Clayton, 1963). Four of these lake basins were empty in July of 1963, but in June 1964 two were partially filled with water. No ice had formed on the surface of these two lakes as it had on the adjacent sinkhole lakes which were full of water in July 1963. This lack of winter ice indicates that the filling of the lake basins had occurred in late spring because water would not have been available until ablation had begun; had blockage of the subglacial drainage occurred in the fall, the lake would have been ice covered.

These lake basins probably were sealed during the earth-

22.—Lakes in dead ice and at the margin of active ice of the Martin River glacier. Black Lake in lower right and the two lakes in the extreme lower left were clear water bodies in 1962 and 1963, and contained well-established aquatic flora and fauna. Icebergs in the marginal lake were slightly more numerous than in 1962 and 1963.

quake by readjustment of rock debris in the moulins by which the lakes were drained in 1962.

The lakes drained subglacially on July 7 and caused floods on the narrow outwash plain at the head of Lake Charlotte.

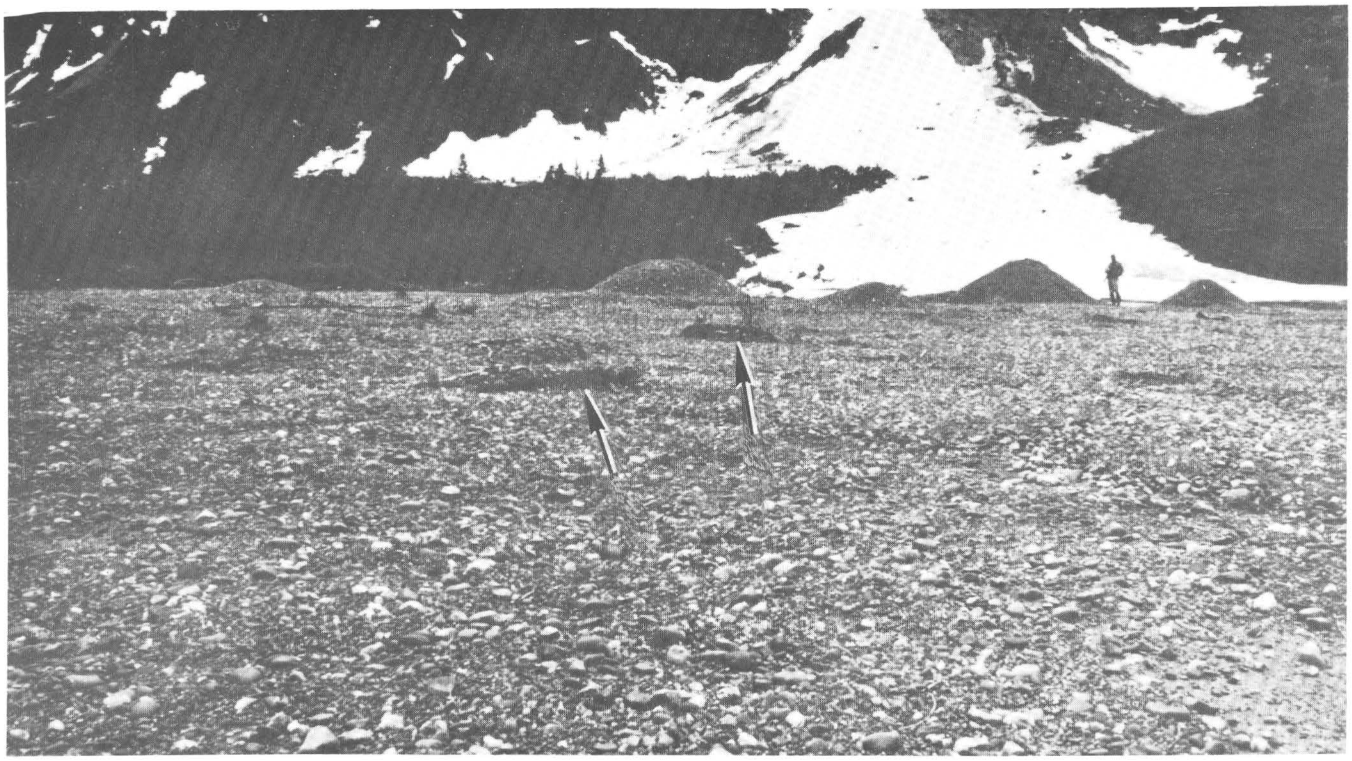
GRAVEL-COATED SNOW CONES

Nine conical mounds of alluvium were observed near the outlet of Martin Lake in the lower Martin River valley where there had been no mounds in July 1963 (fig. 23). The largest cone was 5½ feet high and had a basal diameter of 15 feet. In addition, three 8-inch-thick flat circular bodies of gravel having 3- to 5-inch-wide peripheral rims of well-sorted large pebbles (fig. 24) were observed; apparently they were residues of melted-out snow cones. All the conical mounds had circular aprons rimmed by bands of well-sorted large pebbles.

The conical mounds contained central cores of snow under a layer of unsorted sand and gravel of a type common to this part of the Martin River valley (fig. 25, p. B24).

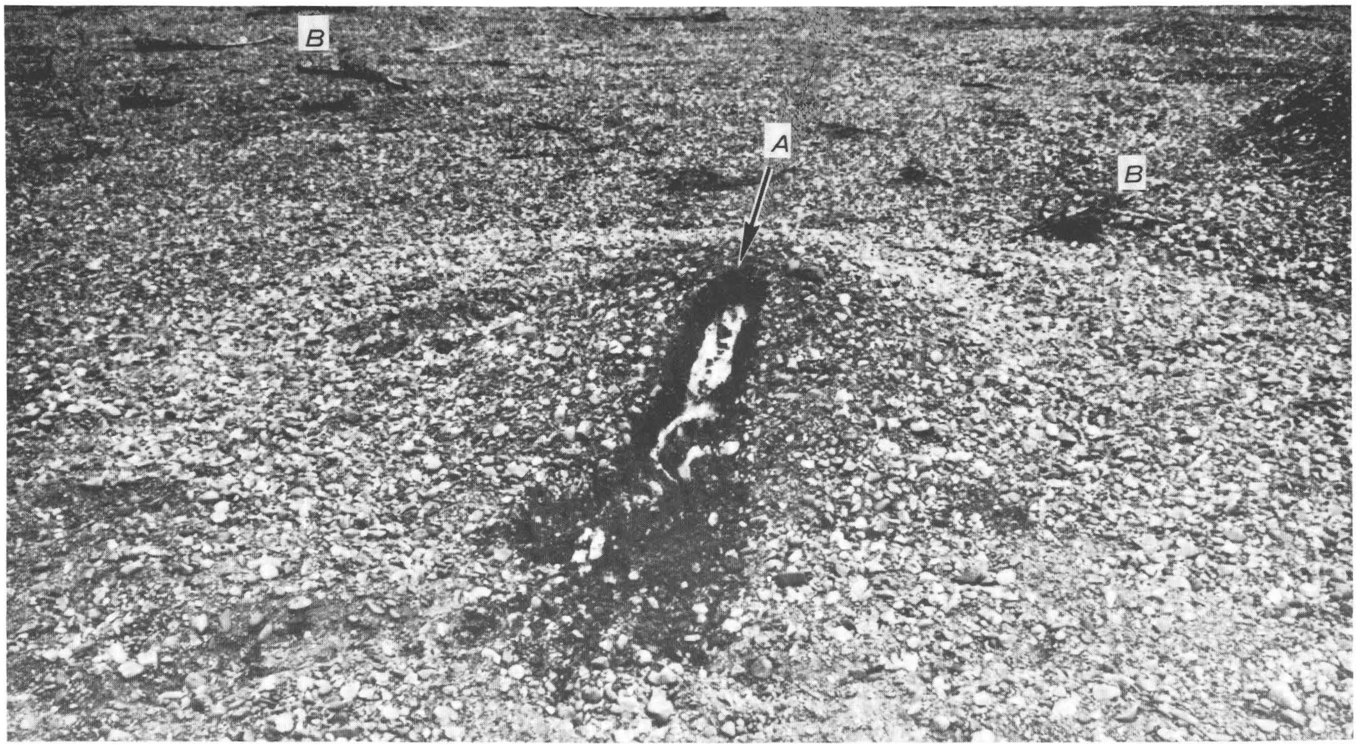
The mounds were on the northeastern bank of the outlet of Martin Lake in NW¼ sec. 13, T. 17 S., R. 4 E. (Cordova B-2 quadrangle). The opposite bank is formed by talus from the Ragged Mountains. Snow of an eroded avalanche stood approximately 15 feet above the southeastern bank, opposite the snow cones. The gravel surrounding the snow cones was littered with avalanche debris such as broken tree trunks and branches, and had vague lineations normal to the drainages of the area (that is, deposited from the southwest).

Earthquake-induced ground fractures and mudvent deposits crossed the apron of one cone and the alluvium between the various cones. This feature and the occurrence of an unusual number of avalanches and rockfalls in the general area indicate that the mechanism which formed these gravel-coated snow cones was the result of the Alaska earthquake.



23.—Gravel-covered snow cones. Arrows indicate flood-plain debris covered by gravel only on the southwest sides. This feature supports the idea that gravel was deposited in a northeast direction. Avalanche snow in background. Geologist is standing on the northeast bank of Martin Lake outlet stream.

24.—Circular bodies of unsorted gravel rimmed with large well-sorted pebbles. Note raised "stone net." Snow cone behind geologist has a circular apron which is also rimmed by large pebbles. Arrows indicate pebble rim.



25.—Partially melted snow cone. Arrow at *A* indicates place where gravel coating has been removed to show snow interior. *B* indicates fresh avalanche debris.

The sequence of events outlined below seems to best explain the conditions observed in the field (fig. 26):

1. The earthquake shock dislodged snow on the northeast flank of the Ragged Mountains and caused an avalanche which flowed toward the north down a couloir.
2. The avalanche struck the Martin Lake outlet stream, which may or may not have been frozen over.
3. Large amounts of water, sand, and gravel were splashed out of the riverbed and onto a preexisting snow drift on the northeast bank of the river.
4. The avalanche-driven water and alluvium eroded the snow drift into several discrete units which were covered by gravel and sand.
5. The sand and gravel retarded ablation of the snow interiors.
6. The largest pebbles rolled down the sides of the cones when the cones were at their maximum size and formed the rim of well-sorted large pebbles.

The pebble rims were easily distinguished in the field at the end of June 1964, but they probably will not be preserved.

LAKE-ICE FRACTURE

All the lakes in the area had fractured surface ice on June 2, 1964. Mr. Lester New of Cordova (see p. 2) stated that the ice of Bering Lake stacked up against the north shore. Geologists who flew over the area shortly after the earthquake reported that fracturing of lake ice was general in the area.

The movement of ice on Bering Lake was evidently the result of uplift of the region. A seiche type of wave must have formed which caused the piling up of ice blocks.

26.—Idealized diagram showing sequence of events suggested as the mechanism of formation for the gravel-covered snow cones in the Martin River valley (not to scale). *A*, Snowcovered Ragged Mountains and snow drift on northeast side of Martin Lake outlet stream. *B*, Earthquake triggers large avalanche which splashed water and alluvium from bed of Martin Lake outlet onto snow drift. *C*, Gravel-covered remnants of the snow drift melted slowly. Because of their higher momentum, large pebbles were dislodged from slopes of cone and collected at the position of greatest basal diameter.

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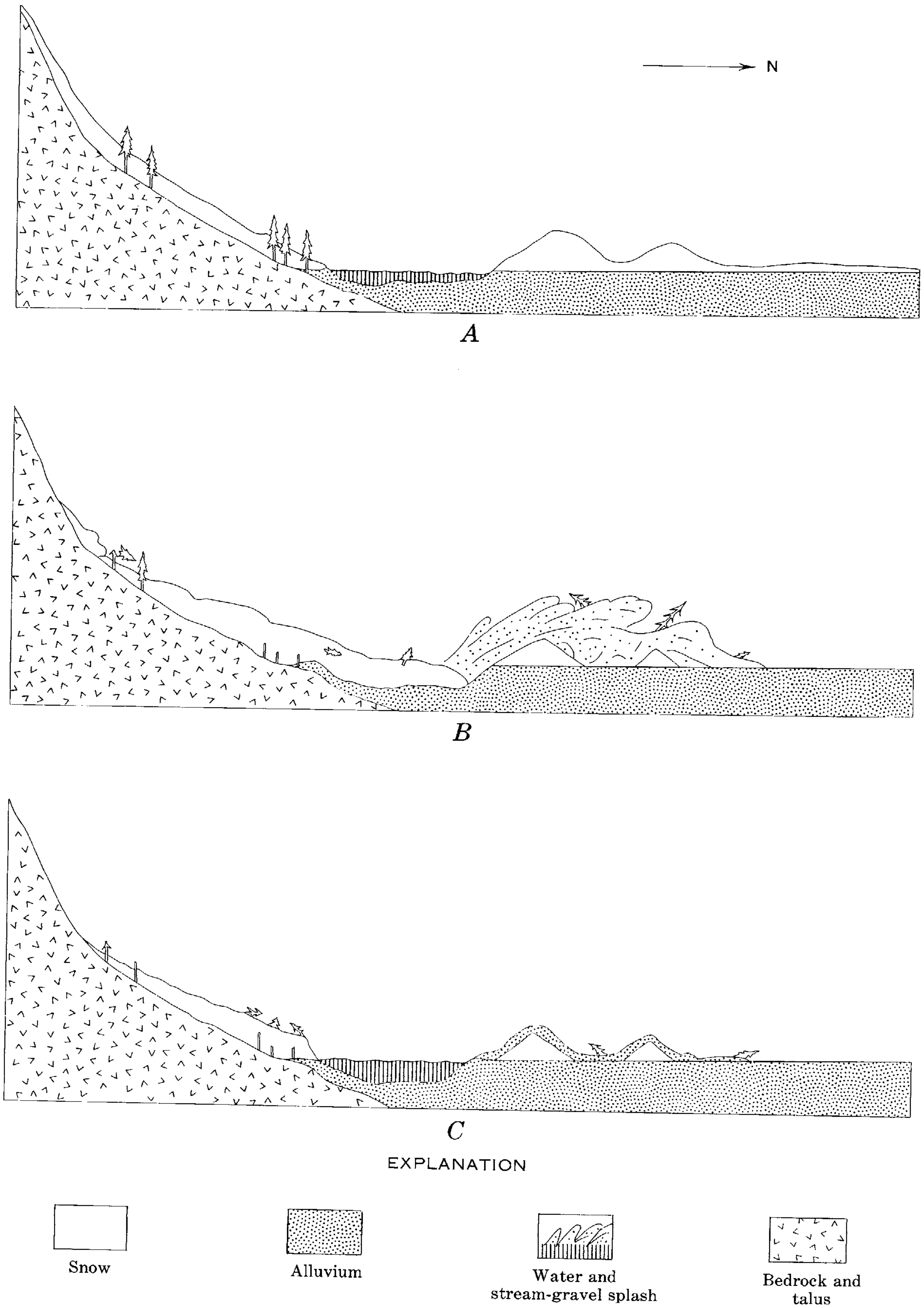
N
A
B
C
EXPLANATION
Snow
Alluvium
Water and
stream-gravel splash
Bedrock and
talus

EVIDENCE OF REGIONAL UPLIFT

Despite search for evidence that the lakes of the area had tilted, none was found. Clearly, the entire Bering Lake area had been raised—a rim of newly exposed land could be seen around the entire lake and the area of the lake was greatly reduced. In 1962 and 1963 Bering Lake was intertidal, in that water-level fluctuations of approximately 18 inches occurred between tides. Large mudflats in the southern and eastern parts of the former lake basin are now above water level (fig. 16).

In the Martin River valley the streams have shifted their channels to a greater or lesser degree. In the middle of the upper Martin River valley the main channel shifted to a former flood channel north of the 1963 channel. In early June, flow of water was divided between the new and the old channels. As the season progressed, the new channel was eroded sufficiently to command most of the flow.

In the upper and middle Martin River valley, only this one diversion could be identified because the variations in river stage during a summer are extremely great. Subglacial drainage of ice-walled sinkhole lakes on the Martin River glacier and variation in amounts of water produced by melting or rain from day to day makes flash flooding a common occurrence. No data exist by which normal river levels or channels can be determined, and it is our opinion that variations are so great that such data would not be useful.

In June 1964 the distributary streams in the lower Martin River valley were cutting new channels in the centers of the 1963 channels. The clear-water streams from Tokun Lake and Martin Lake were not invaded by glacial melt water from the Martin River as they had been in 1963. By July 6, 1964, no meltwater had entered Little Martin Lake, where usually the water became turbid during the melting season because of the mixing of melt water from the Martin River with the clear lake water.

The drainage modifications may not have been wholly due to uplift. The spring season arrived much later in 1964 than in the previous two years. Lake ice and snow in the forests remained fully three weeks longer in 1964 than it had in 1962 or 1963. Thus the ablation of snow and glacier ice probably did not reach its peak until after we had left the field.

FAULTING

No evidence was found that the Chugach-Saint Elias, Ragged Mountain, or any of the previously mapped structures in the Tertiary foothills (Martin, 1908; Miller, 1951) had been reactivated by the earthquake. The concentration of rock avalanches in the area of Sioux glacier may have been associated with local surface faulting, but the bedrock source areas of these avalanches could not be examined closely.

That the area was involved in a large regional uplift is apparent from changes in mean tide levels, but the inland extent of this uplift has not been determined.

EFFECTS OF THE EARTHQUAKE UPON ANIMAL POPULATIONS

Several reactions to the earthquake by the animal population were either observed or reported to us. The absolute assignment of the observed phenomena to earthquake effects is not possible in all places because the patterns of animal behavior in this area are not well known and because our observations were no more than casual.

MIGRATORY FISH

Salmon is an important economic resource in the Martin-Bering Rivers area. In June and July, red or sockeye salmon spawn in great numbers in Lake Charlotte, in the unnamed lake at an altitude of 319 feet north of Lake Charlotte, and in Deadwood Lake. Their seasonal occupancy of Tokun, Little Martin, Martin, Kushtaka, and Bering Lakes has long been known.

In 1963 salmon in the red phase were observed entering Tokun Lake. No "bright" (silvery) fish were seen. In 1964 the fact that all but one of the several thousand fish observed in the lake were "bright" indicates that they had just arrived from salt water and had not taken a long time to migrate to the spawning beds. This shorter migration time gave the fish more time for the spawn and should have insured the optimum chance of a successful spawn.

We suggest that the clearing of the water of the outlet streams farther down valley by the downcutting of the Martin River—probably a result of the uplift of the area—was responsible for the more rapid progress of fish migrating from the sea. Thus the effects of the Alaska earthquake may have helped rather than hurt future salmon crops in this area.

LAND SNAILS

Mr. Rae Baxter of the Alaska Department of Fish and Game at Cordova stated (oral commun., 1964) that large numbers of land snails were trapped in earthquake-induced ground fractures in the area of Mirror and Martin Sloughs on the Copper River delta. The snails evidently fell into the fractures and could not climb out because of the granular nature of the sediments and the unstable sides of the fractures.

In the vegetated delta of Lake Charlotte and Kushtaka Lake the land-snail fauna were destroyed by the subaqueous landslides. The geomorphic adjustments to the earthquake probably had a significant detrimental effect upon land-snail populations throughout the Martin-Bering Rivers area. Because the vegetation of the lake deltas in the area was largely grasses and other low plants, the greatest population density of land snails observed in 1962 and 1963 was in these very areas around the lakes—areas which were most affected by earthquake-triggered subaqueous landslides.

FUR-BEARING ANIMALS

Mr. Lester New of Cordova, who was trapping in the Bering Lake area at the time of the earthquake, states (written commun., Apr. 10, 1965),

> * * * * it [the earthquake] raised the country [the Bering Lake area] so much it pushed the beaver right up out of the water, where there was water left. Hundreds of big five-beaver houses pushed right up out of the water, their entrance ways as much as four feet above the water line. The beaver are gone now. Whether they were killed or left the area I won't know until I go in to town May 15 [1965]. Then I will check with the Fish and Game Dept. to find out what has really happened to the beaver. I think they were killed. I have had a very good season [1965] on other furs such as mink, otter, and wolverine, they apparently were not affected by the quake * * *.

While we were camped in the upper Martin River valley in early June a mature beaver wandered into our camp. It was investigating the many distributary stream channels of the upper Martin River as if looking for a place to build a dam. When it came within a few yards of our camp we noticed its tail was cut through in three places. At the time, we assumed that it had been driven out of a lodge by its elders, and we attached no importance to its appearance in the valley. In light of Mr. New's statement, the migration of this individual may have been associated with the earthquake rather than with the normal pattern of behavior of a beaver-lodge population.

TESTIMONY OF THE ONLY RESIDENT OF THE AREA

As far as we discovered, Mr. New was the only resident of the area at the time of the earthquake. In reply to a request for his recollections, Mr. New sent us the information given below. He states in a covering letter that these recollections were taken from the notebook which he customarily keeps while in "the bush." The following excerpt, slightly edited, is from a note written shortly after the earthquake:

> At 5:32 p.m. the cabin and everything in it all but exploded. It hit very hard. The cabin raunched sideways several feet [to the east (oral commun., July 1 1965)] the first jolt, then the second seemed to raunch it back the other way. Everything was flying that was loose or could be loosened. Utensils, gas lamps, frying pans, everything was in the air. The first thought that came to my mind was, 'This is what I have been dreading, that ominous feeling of doom I had had all day long. Now just what in the world is happening?' Glancing out the window I looked into solid ice, the lake had busted and stacked ice a lot higher than my cabin and it was moving in. I jumped for the door and was thrown down by the gyrations of the cabin. It was much rougher than being on a seine boat in very rough water. When I did get on my feet, I kicked the door open, figuring on the ice coming on into the cabin. Outside there wasn't a breath of air stirring, yet all the trees were gripped in a frenzy, as though they were in a hurricane gale. The ice had come against the shore and now it was piling up off shore like levees or break waters. Looking across the lake over to Hamilton Mt. to the east everything was in movement. Hamilton Mt. to the east, Tokun Ridge to the north, and the Ragged Mt. Range to the west. Looking south at the Chilkat Mt. Range, everything seemed to be moving. All the Sawtooth Range seemed to be hinged and was in one great up and down movement. There were huge rock slides and all the canyons were filled with rock and ice. Then it became deathly quiet, except for the booming of giant boulders moving off the high mountain ranges. For several minutes this continued, then all was quiet.

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