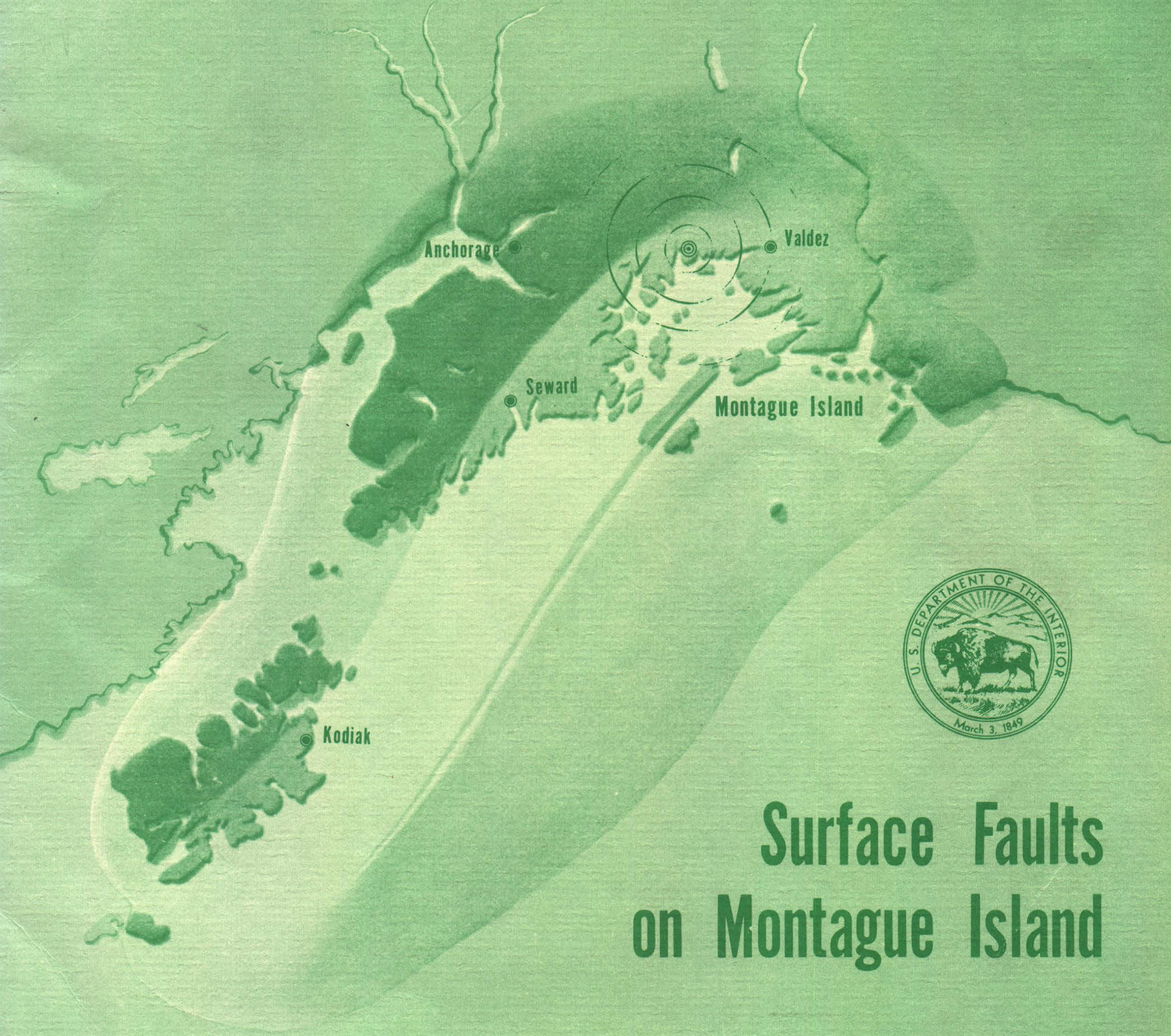
The Alaska Earthquake
March 27, 1964

Regional Effects



Surface Faults on Montague Island

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-G

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
REGIONAL EFFECTS

Surface Faults On Montague Island Associated with the 1964 Alaska Earthquake

By GEORGE PLAFKER

A description and tectonic analysis of ground breakage and surface warping along two reactivated reverse faults

GEOLOGICAL SURVEY PROFESSIONAL PAPER 543-G

Former sea floor at Cape Cleare, Montague Island, Prince William Sound, exposed by 26 feet of tectonic uplift. The surf-cut surface, which slopes gently from the base of the sea cliffs to the water, is about a quarter of a mile wide. The white coating on the rocky surface consists mainly of the desiccated remains of calcareous algae and bryozoans. Photograph taken at about zero tide stage, May 30, 1964.

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the Alaska earthquake of March 27, 1964, in a series of six professional papers. Professional Paper 543 describes the regional effects of the earthquake. Other professional papers describe the history of the field investigations and reconstruction effort; the effects of the earthquake on communities; the effects on the hydrologic regime; and the effects on transportation, communications, and utilities.

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SURFACE FAULTS ON MONTAGUE ISLAND ASSOCIATED WITH THE 1964 ALASKA EARTHQUAKE

By George Plafker

ABSTRACT

Two reverse faults on southwestern Montague Island in Prince William Sound were reactivated during the earthquake of March 27, 1964. New fault scarps, fissures, cracks, and flexures appeared in bedrock and unconsolidated surficial deposits along or near the fault traces. Average strike of the faults is between N. 37° E. and N. 47° E.; they dip northwest at angles ranging from 50° to 85°. The dominant motion was dip slip; the blocks northwest of the reactivated faults were relatively upthrown, and both blocks were upthrown relative to sea level. No other earthquake faults have been found on land.

The Patton Bay fault on land is a complex system of en echelon strands marked by a series of spectacular landslides along the scarp and (or) by a zone of fissures and flexures on the upthrown block that locally is as much as 3,000 feet wide. The fault can be traced on land for 22 miles, and it has been mapped on the sea floor to the southwest of Montague Island an additional 17 miles. The maximum measured vertical component of slip is 20 to 23 feet and the maximum indicated dip slip is about 26 feet. A left-lateral strike-slip component of less than 2 feet occurs near the southern end of the fault on land where its strike changes from northeast to north. Indirect evidence from the seismic sea waves and aftershocks associated with the earthquake, and from the distribution of submarine scarps, suggests that the faulting on and near Montague Island occurred at the northeastern end of a reactivated submarine fault system that may extend discontinuously for more than 300 miles from Montague Island to the area offshore of the southeast coast of Kodiak Island.

The Hanning Bay fault is a minor rupture only 4 miles long that is marked by an exceptionally well defined almost continuous scarp. The maximum measured vertical component of slip is 16⅓ feet near the midpoint, and the indicated dip slip is about 20 feet. There is a maximum left-lateral strike-slip component of one-half foot near the southern end of the scarp. Warping and extension cracking occurred in bedrock near the midpoint on the upthrown block within about 1,000 feet of the fault scarp.

The reverse faults on Montague Island and their postulated submarine extensions lie within a tectonically important narrow zone of crustal attenuation and maximum uplift associated with the earthquake. However, there are no significant lithologic differences in the rock sequences across these faults to suggest that they form major tectonic boundaries. Their spatial distribution relative to the regional uplift associated with the earthquake, the earthquake focal region, and the epicenter of the main shock suggest that they are probably subsidiary features rather than the causative faults along which the earthquake originated.

Approximately 70 percent of the new breakage along the Patton Bay and the Hanning Bay faults on Montague Island was along obvious preexisting active fault traces. The estimated ages of undisturbed trees on and near the fault trace indicate that no major displacement had occurred on these faults for at least 150 to 300 years before the 1964 earthquake.

INTRODUCTION

The great earthquake of March 27, 1964, in south-central Alaska was accompanied by regional tectonic warping that caused both extensive subsidence and uplift relative to sea level. During the months after the earthquake geologists made a concerted search for evidence of surface faulting. A U.S. Geological Survey field party headed by the writer found two reverse faults on southwestern Montague Island in Prince William Sound through combined air reconnaissance and studies of shoreline displacements. Although it is assumed that the fault displacements occurred during the main shock, or possibly during some of the subsequent large aftershocks, there were no eyewitnesses to fix the precise time of rupture. The faulting definitely occurred prior to March 31 (4 days after the earthquake), when a part of one scarp was photographed during a reconnaissance flight over the island. The faults could not be examined on the ground until 2 months later, at the end of May.

As far as could be determined, no movement occurred along any other surface faults on land during the earthquake. A diligent search was made for indications of renewed movement on known preexisting faults, particularly in the vicinity of the zero isobase between the major zones of regional tectonic uplift and subsidence, but no measurable surface faulting was found. There were no anomalous abrupt changes in amounts of uplift or subsidence along the coast or along level lines inland from the coast suggestive of displacement along concealed faults. All reported suspected surface faulting that was checked in the field turned out to be linear zones of landslides or surficial cracks in unconsolidated deposits. Although some of these lines of landsliding or cracking could possibly reflect fault movements at depth, no direct evidence for such movements is available.

This report substantially enlarges upon preliminary summaries of the nature and tectonic significance of the surface faulting that were based on data acquired during the 1964 field season (Plafker, 1965; Plafker and Mayo, 1965). It presents details of the varied and unusually well exposed surface manifestations of the faults on Montague Island which have an important bearing on tectonic analyses of the earthquake. The methods used in determining the location, displacement, and surface dip of the faults are fully described because detailed descriptions of overthrusts involving predominantly reverse or thrust movements are scarce compared to the literature on strike-slip or normal faulting. Such data are of increasing practical importance to geologists and others who are concerned with identifying potentially *active* faults and evaluating the possible effects of renewed activity on engineering works.

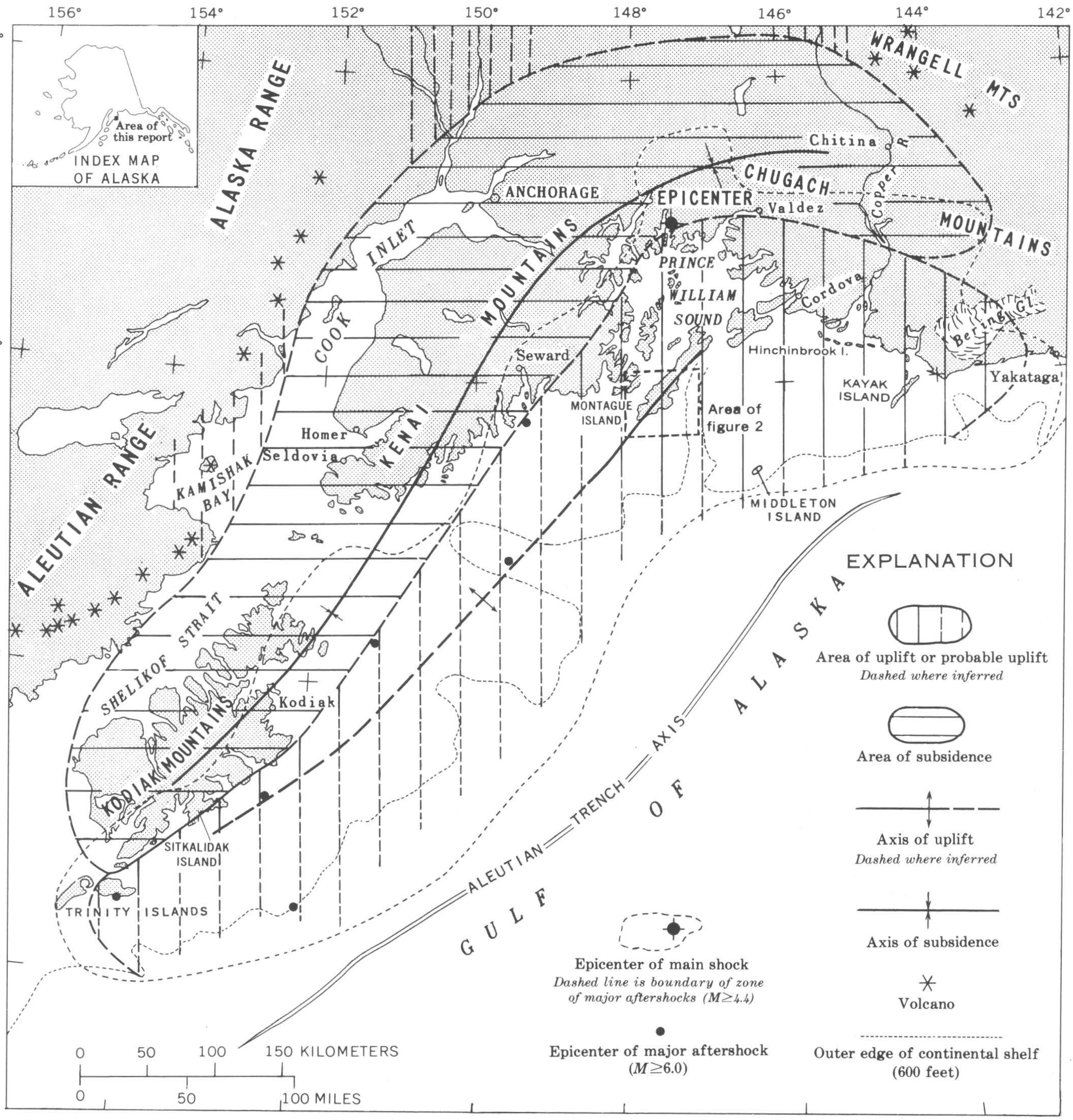
Previous descriptions of the surface manifestations of overthrust faults are limited to studies of the great earthquake of 1931 centered on Hawke Bay, New Zealand (Henderson, 1933), the 1945 Mikawa earthquake in southeastern Honshu, Japan (Tsuya, 1950), the 1952 Kern County, Calif., earthquakes (Buwalda and St. Amand, 1955), and the great 1957 Gobi-Altai earthquake in Mongolia (Florensov and Solonenko, 1963). With the possible exception of some Gobi-Altai faults, the relative displacements on the faults on Montague Island are considerably larger than any overthrusts previously described. They are also unique in that absolute, as well as relative, displacements could be determined across these faults at four points where they intersect the shoreline.

I am grateful to colleagues in the U.S. Geological Survey for assistance in the field and for much stimulating and helpful discussion. Field mapping of the faults was carried out by a boat-based and helicopter-supported U.S. Geological Survey party from May 30 to June 3, 1964, and by a helicopter-supported party from July 31 to August 7, 1965. L. R. Mayo and J. B. Case assisted in the 1964 fieldwork, and L. R. Mayo and M. G. Bonilla collected much of the data during the 1965 season. Additional critical observations on the northeastern segment of the Patton Bay fault were made by L. C. Cluff, of the firm Woodward-Clyde-Sherard and Associates, who visited the area briefly during the summer of 1966. The faults and related features were mapped on postearthquake vertical and oblique aerial photographs taken by the U.S. Army at scales of 1:15,000 and 1:20,000 and on vertical photographs taken by the U.S. Coast and Geodetic Survey at scales ranging from 1:4,000 to 1:20,000. Preearthquake vertical photographic coverage available for the entire island at a scale of 1:20,000 proved to be invaluable for determining the relationship of the fault movements to older geologic structures.

REGIONAL TECTONIC SETTING

The surface breaks on Montague Island lie within the focal region of the earthquake, as defined by aftershock distribution, and within a region of tectonic deformation associated with the earthquake (fig. 1). The regional deformation has been described briefly in preliminary reports (Grantz and others, 1964; Plafker and Mayo, 1965; Plafker, 1965). Only the broad aspects of the regional tectonic movements will be outlined here to provide a proper perspective for the tectonic significance of these surface faults. A detailed description and analysis of the overall tectonic displacements will be given in a separate chapter on regional earthquake effects in this series.

Tectonic movements, both vertical and horizontal, occurred over an area of at least 70,000 square miles, and possibly more than 110,000 square miles, of south-central Alaska. The deformed region, which is more than 500 miles long and as much as 200 miles wide, is roughly parallel to the Gulf of



1.—Setting of Montague Island with respect to regional tectonic deformation and seismicity that accompanied the **March 27, 1964**, earthquake.

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Alaska coast from the Kodiak group of islands northeastward to Prince William Sound and thence eastward to about long 143° W. It consists of a major seaward zone of uplift bordered on the northwest and north by a major zone of subsidence. These two zones are separated by a line of zero land-level change that trends northeastward to intersect the mainland between Seward and Prince William Sound. It then curves eastward through the western part of Prince William Sound to the vicinity of Valdez and crosses the Copper River valley about 50 miles above the mouth of the river.

The zone of subsidence includes most of the Kodiak group of islands, Cook Inlet, the Kenai Mountains, and the Chugach Mountains. The axis of maximum subsidence within this zone trends roughly northeastward along the crest of the Kodiak and Kenai Mountains and then bends eastward in the Chugach Mountains. Maximum recorded downwarping is about 7½ feet on the south coast of the Kenai Peninsula.

In the northern part of the deformed area, uplift that averages about 6 feet occurred over a wide zone including most of the Prince William Sound region, the mainland east of the sound, and offshore islands as far southwest as Middleton Island at the edge of the Continental Shelf. Large-scale uplift of the Continental Shelf and slope southwest of Montague Island is inferred from the trend of isobase contours in the northeastern part of the deformed zone and from the presence of a fringe of uplifted capes and points along the outer coast of the Kodiak Island area. The minimum extent of this inferred offshore zone of uplift is thought to be roughly outlined by the earthquake focal region, or belt of major aftershocks, shown in figure 1.

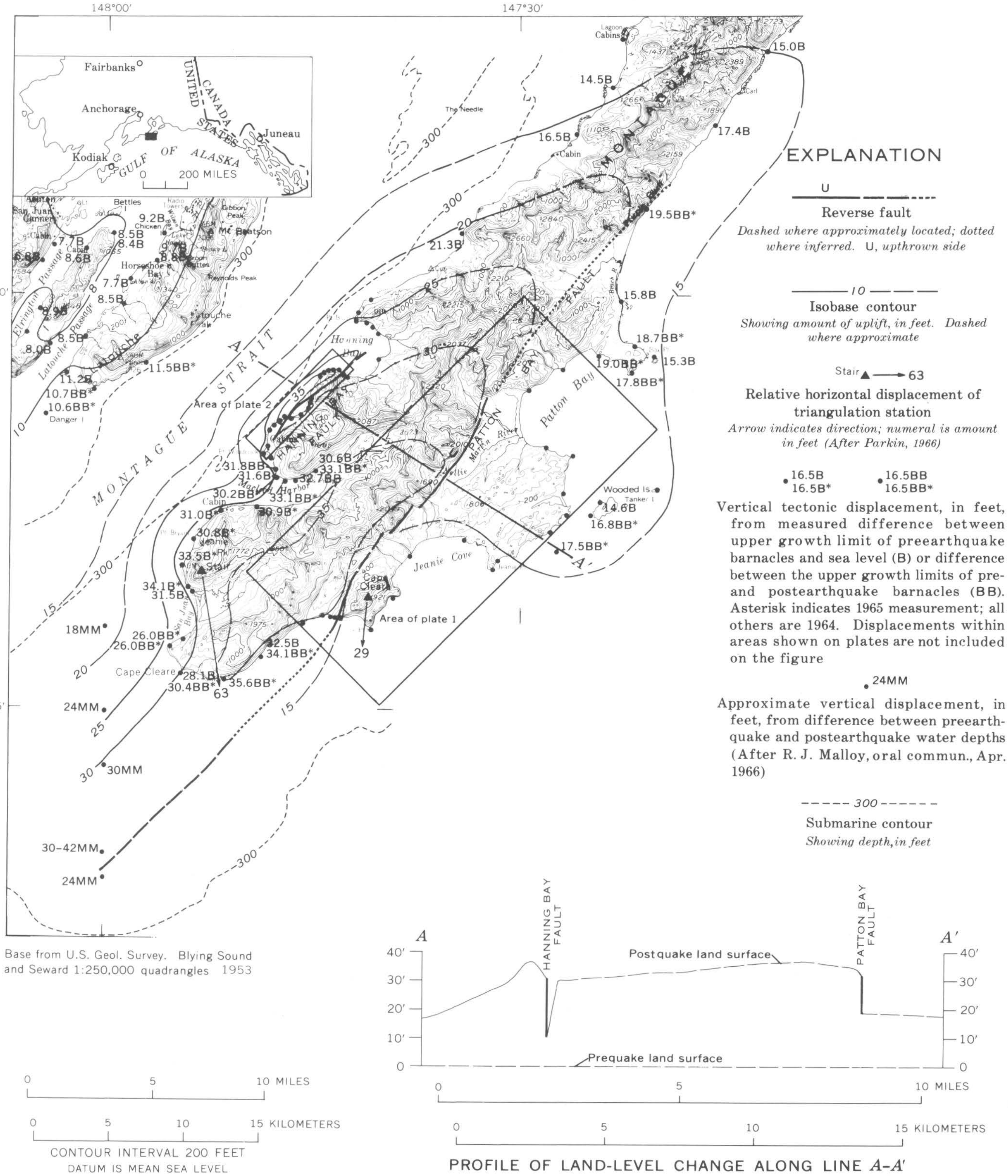
Montague Island lies within the earthquake focal region along the axis of maximum tectonic uplift. Combined surface faulting and regional warping have elevated the southwestern end of the island relative to sea level by as much as 38 feet (fig. 2). Southwest of Montague Island the sea bottom may have been uplifted more than 50 feet where pre- and postearthquake bottom soundings show residual vertical displacements at least as large as those on the adjacent land. As discussed later (p. 26), there is indirect evidence which suggests that the axis of maximum uplift and faulting may extend southwestward more than 300 miles to the area off the southeast coast of Kodiak Island.

GEOGRAPHIC AND GEOLOGIC SETTING

Montague Island is the most southerly of three long narrow islands that trend northeast across the south side of Prince William Sound (fig. 2). The island, which is 51 miles long by 4 to 12 miles wide, consists of a topographically rugged mountainous backbone ridge with average summit altitudes of 2,400 feet and a maximum altitude of 2,841 feet. A dense growth of timber and brush mantles much of the valley floors, raised beaches, and lower mountain slopes below an altitude of 1,000 feet. Access through the vegetated areas is difficult, and is mainly along streams, beaches, and bear trails. Open areas of muskeg—a mat of sphagnum moss several feet thick—sedge, and open-growth scrub occur wherever drainage is impeded by low and gently sloping topography or by impermeable soils. There are no permanent roads or inhabitants on the island although a few loggers and hunters usually live there intermittently during the summer months. No one was on Montague Island during the earthquake.

The geology of Montague Island is known only in a general way from regional reconnaissance studies (Grant and Higgins, 1910; Moffitt, 1954; Case and others, 1966; Plafker and MacNeil, 1966). The bedrock is part of the Orca Group, which consists of a thick sequence of well-indurated interbedded sandstone and siltstone, minor amounts of limestone as thin beds or lenses, and tabular to lenticular masses of basaltic lava. The Orca is at least in part of early Tertiary (probably middle to late Eocene) age.

The rocks were complexly folded and faulted in early Tertiary time. They generally strike northeast parallel to the trend of the island, but there are numerous local deviations from this trend. Folds on the island are characteristically overturned towards the northwest with near-horizontal axes; folds in most of the remainder of Prince William Sound are overturned mainly toward the southeast. Faults associated with the folding are mainly southeast-dipping overthrusts. Well-developed sets of steeply dipping conjugate shear joints trend at high angles to the strike of fold axes and faults in



2.—Map and profile showing faults and horizontal and vertical tectonic displacements on southwestern Montague Island.

the southwestern part of the island. Surface faults associated with the 1964 earthquake parallel or cut obliquely across the strike of the older bedrock folds and faults at a small angle and are clearly discordant with the dip of these structures.

Unconsolidated Quaternary glacial till of variable thickness veneers bedrock on low-lying parts of the island, and thick deposits of coarse alluvium occur along the lower reaches of the larger streams. Talus, landslide deposits, and frost rubble commonly conceal bedrock on and at the base of the steeper slopes.

DESCRIPTION OF THE FAULTS

The locations of mapped fault traces on Montague Island and the distribution of vertical uplift relative to sea level are summarized in figure 2, and details of the features associated with the Patton Bay and Hanning Bay faults are shown on plates 1 and 2, respectively. The following general features are common to both the Patton Bay and Hanning Bay faults: (1) Both strike northeast almost parallel to the long axis of Montague Island; (2) both blocks are uplifted relative to sea level, with the northwest blocks upthrown relative to the southeast blocks; (3) the faults are northwest-dipping reverse faults; (4) both faults may have small components of left-lateral strike-slip displacement near their southern limits of exposure amounting to less than one tenth the dip-slip component; and (5) the new breakage occurred along or near the traces of preexisting faults which appear to have undergone earlier Holocene displacements.

Measurement of the inclination of the fault plane and the dip-slip component of displacement is hampered by the general tendency (1) for the slip plane to be concealed by slumping or landsliding across the steep to overhanging fault scarps or (2) for bedrock displacements to be reflected at the surface by flexing and fissuring of overlying unconsolidated deposits and surface vegetation. Approximate surface dips could be determined from the inclination of sheared rock at several places along the fault scarps (pls. 1, 2); the dip of the Patton Bay fault is also visible in the sea cliff where the fault intersects the coast.

Absolute, as well as relative, vertical displacements could be determined at shoreline intersections of the faults by measurement of shoreline changes relative to sea level. The isobase contours of figure 2 show the amount and direction of vertical displacement that accompanied the earthquake. Directions and relative amounts of change were determined at about 75 localities on southwestern Montague Island from measurements of the displacement of the upper growth limit of sessile intertidal organisms along the seashore and from changes in the altitudes of storm beach berms. Measurements were made at 14 of these localities both in 1964 and 1965. Data-point locations and measured vertical displacements are shown in figure 2 and on plates 1 and 2.

The technique used for measuring vertical displacements from the height of the upper growth limit of barnacles above tidal planes has been outlined elsewhere (Plafker, 1965, p. 1675–1679) and, consequently, will not be elaborated upon here. Those measurements based on differences in pre- and postearthquake altitudes of the upper growth limits of barnacles are thought to be generally accurate to about 1 foot. Many of the 1964 measurements, however, are based only on the postearthquake altitude of these organisms above sea level; they contain inherent errors due to deviation of sea level from predicted heights and to variations in the growth limits of these organisms resulting from local factors of exposure, rock type, and water characteristics. The measurements made on the eastern side of the islands are estimated to be accurate to within 1½ feet in sheltered bays and to within 2½ feet on segments of the coast exposed to heavy surf and swells along the ocean side. At two localities on sandy stretches of beach where barnacles were not present, the vertical movements were determined from differences in altitude of the pre- and postearthquake storm beach berms. The accuracy of these measurements is unknown, although they give results consistent with those obtained from barnacle-line measurements at nearby rocky shores.

Submarine control for the isobase contours southwest of Montague Island is provided by comparisons of pre- and postearthquake bathymetric charts. Because of navigational and other technical problems in carrying out such surveys, the inferred submarine displacements could locally be in error by 10 feet or more.

Measurements of vertical displacement away from the shore are based mainly on the heights of slope breaks in surficial deposits which may or may not accurately reflect the vertical displacement within the underlying bedrock. In those rare instances where the displacement is apparently localized along a scarp in bedrock, the scarp height is taken as the net vertical displacement. Only the vertical component of surface displacement is shown on plates 1 and 2; dip-slip displacements may be as much as 25 percent greater, depending on the indicated dip of the fault at any given locality.

PATTON BAY FAULT

After the earthquake, the Patton Bay fault was traceable by a succession of exceptionally interesting and complex features, such as fresh fault scarps, surface flexures, and gigantic landslides. From the place where the fault strikes out to sea 1½ miles west of Neck Point, the rupture extends 11 miles northeastward to the valley of the Patton River (pl. 1). Northeast of Patton River, displacement is distributed across a broad zone of subparallel fissures as much as half a mile wide that can be traced an additional 11 miles as far as Purple Bluff on the southeast coast of the island.

In the following account, the fault on land is described from southwest to northeast. Places referred to, including the locations photographed and diagramed, are shown on the map of the surface ruptures (pl. 1). The northeastern segment of the fault is not shown on the detailed map, but is shown at a smaller scale in figure 2. Figure 2 also shows the measured and inferred vertical displacements relative to sea level at and near the two faults and along a section across them.

BEACH AND SEA CLIFF NEAR NECK POINT

The Patton Bay fault is best exposed at its southwestern end at the beach and sea cliff 1½ miles west of Neck Point. It is marked by a pronounced scarp 6 to 8½ feet high which trends north-south across the beach and the newly uplifted surf-cut platform seaward from the beach (figs. 3, 4, following pages). Beach gravel draped across the scarp conceals the actual fault plane everywhere except at the one small outcrop at the toe of the beach prism where a 4-foot-wide zone of sheared siltstone dips westward at an angle that averages about 85° (fig. 5).

The near-vertical fissure exposed in the sea cliff is along the most probable continuation of the fault. Its steep dip, which is consistent with the fault attitude indicated by the sheared siltstone along the scarp, may represent only a near-surface steepening of the fault plane where it breaks to the surface along the most direct path. Previous movement could have occurred along the dipping faults exposed in the sea cliff (fig. 3), which are undoubtedly associated with this same line of faulting but which apparently were not reactivated during the earthquake.

The position of the barnacle line along the shore in the vicinity of the fault provides an excellent means of determining the absolute vertical displacement of the blocks at and near the fault as well as the relative vertical displacement. The measurements indicate that both blocks are uplifted relative to sea level and that the western block is upthrown 20 to 23 feet in relation to the eastern (pl. 1, section *A–A′*). Uplift of the western block decreases progressively from 35 to 38 feet at a distance of 800 feet from the fault scarp to 21 to 23½ feet at the scarp; uplift of the eastern block is about 15 feet at the scarp. Only 6 to 8½ feet of the displacement occurred along the fault scarp that cuts the beach gravel and the reef at the shore (fig. 3); the remainder of the offset takes the form of a pronounced downwarping of the upthrown block within 800 feet of the fault.

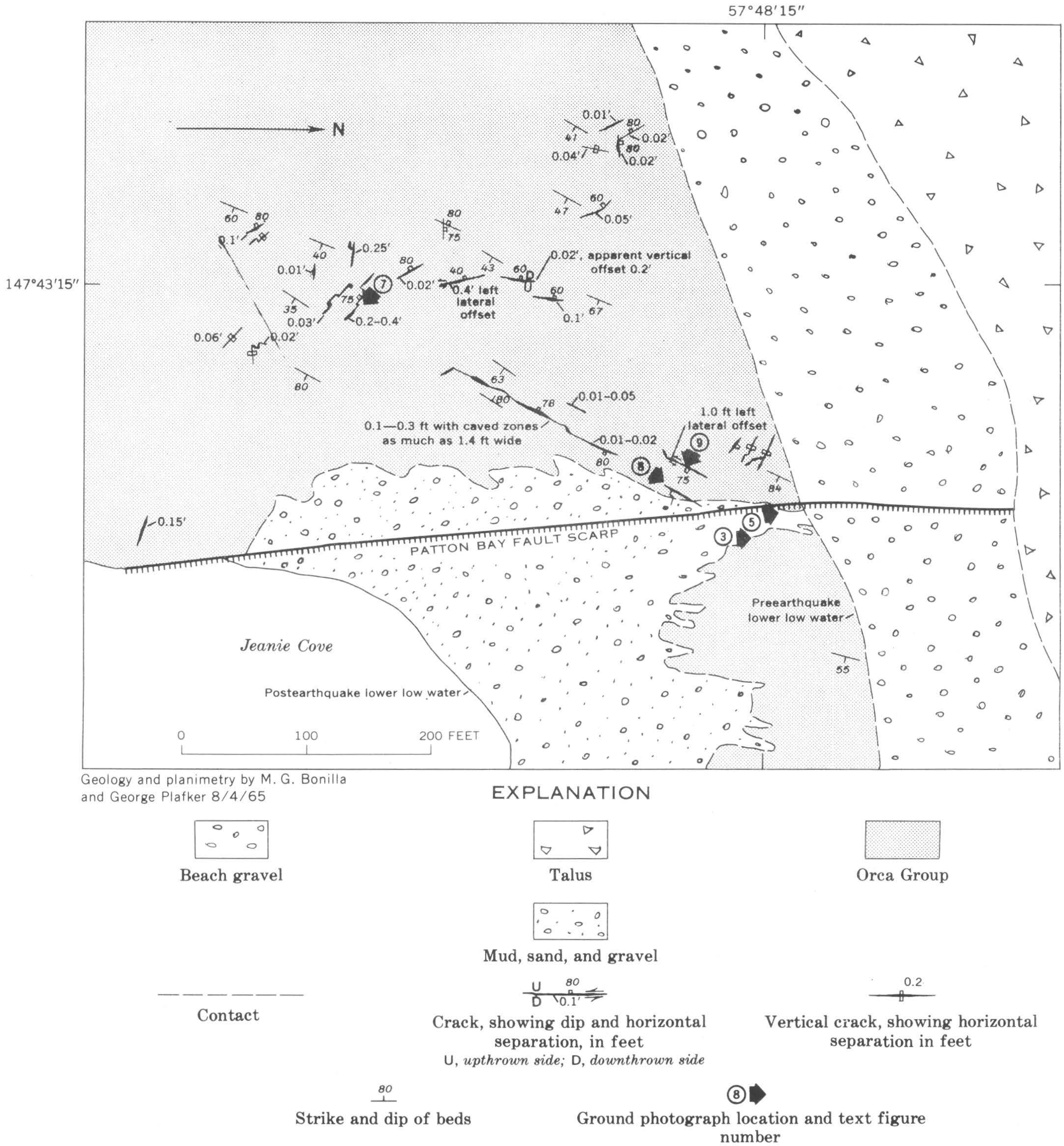
Numerous surface cracks as much as 170 feet long formed in bedrock on the reef part of the upthrown block within 400 feet of the scarp. These newly opened cracks can be readily differentiated from preearthquake cracks because they expose fresh surfaces that do not have a white coating of calcareous algae. Locations, orientations, and displacements of the largest and most conspicuous of these cracks, which were mapped by a pace-and-compass survey, are shown in figure 6. Three typical cracks are illustrated in figures 7–9; the photographs were taken at the locations indicated in figure 6. No newly opened cracks were found near the fault in the downthrown block; close to the fault, however, this block is largely covered by beach deposits.

The cracks all dip steeply or are vertical, and they appear to occur exclusively along bedding planes and preexisting joints. Displacement in the overwhelming majority of cracks is an extension perpendicular to the crack face ranging from less than 0.01 to 0.4 foot. Locally, the cracks are substantially widened where loose narrow wedge-shaped rock slivers as much as 1.4 feet wide have dropped down along them. Left-lateral displacements occurred along two of the cracks. One of the two trends northeast at an oblique angle to the fault scarp and was displaced 1.0 foot (fig. 9). The other crack, which is almost parallel to the scarp, had 0.4 foot of lateral offset.

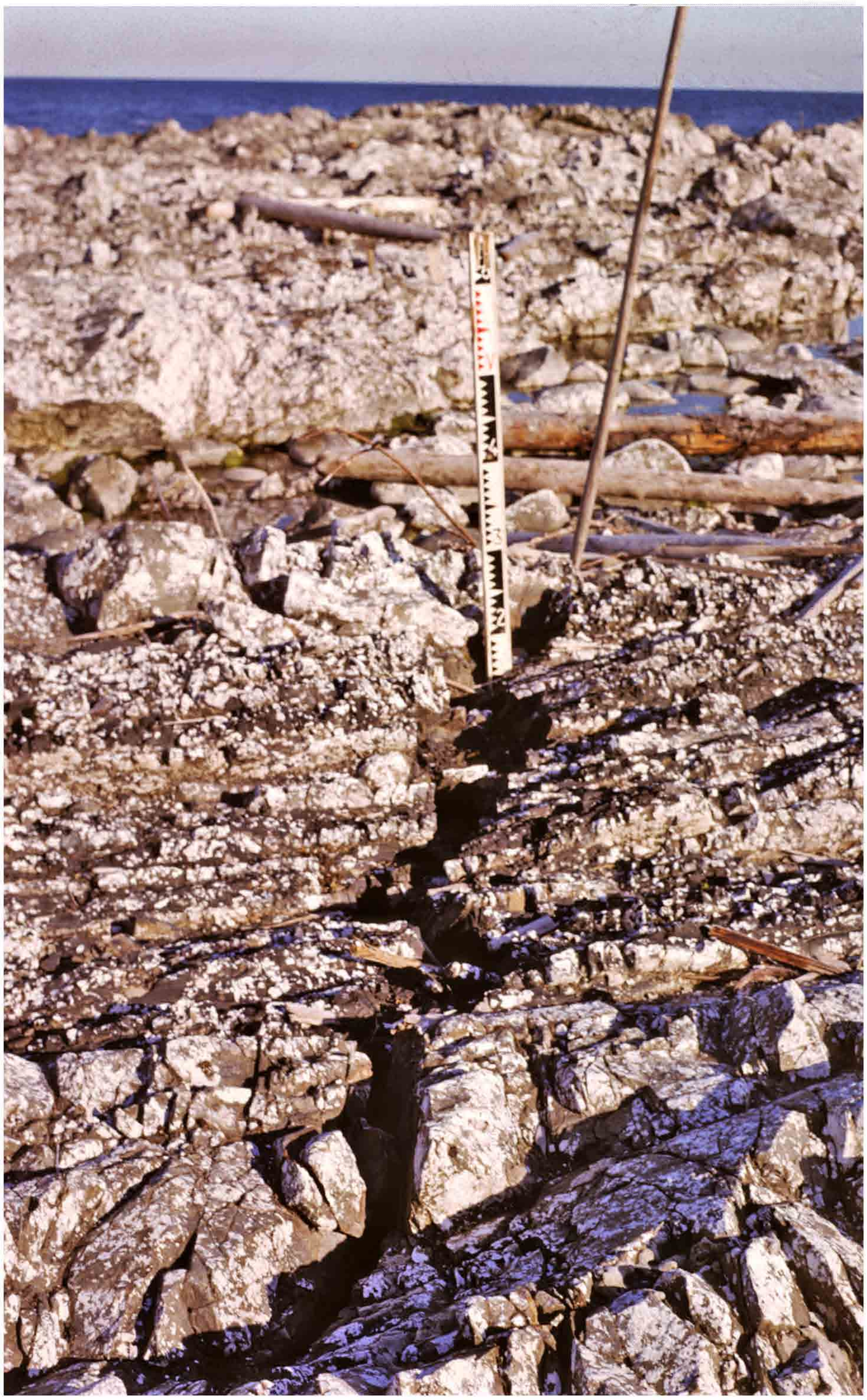
3.—Patton Bay fault (heavy solid and dotted line) at the beach and sea cliff near Jeanie Point. Note the vertical offset of contact between beach deposits (Qb) and talus (Qt). The man (circled) is standing at the base of a scarp 8½ feet high. Light dotted lines are bedding traces in the Orca Group (To); heavy dashed lines are probable fault traces on which there apparently was no movement during the earthquake. Location shown in figure 6.

4.—View south from top of the sea cliff in figure 3. Arrows indicate fault trace which displaces the elevated beach prism and cuts obliquely across bedrock structures in the surf-cut platform on the upthrown block. The lower part of the scarp was partially obliterated with newly deposited marine sand and gravel by the time this photograph was taken in August 1965.

5.—Near-vertical zone of sheared quartz-veined argillite and graywacke along the Patton Bay fault trace at the shore. Location shown in figure 6.



6.—Sketch map of the scarp and open cracks in the upthrown block of the Patton Bay fault at the shore near Jeanie Point.



7.—Crack 0.2 to 0.4 foot wide and at least 2 feet deep in the warped relatively upthrown block of the Patton Bay fault. Crack follows preexisting bedding and joint planes. Location shown in figure 6.

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8.—Looking down on vertical crack 0.01 to 0.015 foot wide along preexisting joints in a hard graywacke bed. Location shown in figure 6.

9.—Crack along bedding plane in massive indurated sandstone; 1 foot of left-lateral separation. Location shown in figure 6.

10.—One of the larger fissures along the trace of the Patton Bay fault. The fissure, which is 3 feet wide and 7 feet deep, is in unconsolidated glacial till.

One crack was found on the uplifted wave-cut bedrock surface of the relatively upthrown block approximately 1,000 feet southwest of the fault. It is as much as 0.2 foot wide and had possible right-lateral movement of less than 0.1 foot and dip-slip displacement of less than 0.2 foot.

The open cracks that occur in the reef on the upthrown block are probably tension cracks associated with the downwarping near the fault. Left-lateral displacements observed on two of these cracks suggest a possible small strike-slip component of movement of less than 1½ feet on the Patton Bay fault at this locality. No conclusive evidence for horizontal offset of the preearthquake beach strand lines that cross the fault scarp was found on the ground, although an apparent slight tendency for left-lateral bending of these lines was noted on the large-scale vertical aerial photographs.

FROM THE SEA CLIFF TO TORTUOUS CREEK

From the sea cliff to Tortuous Creek the Patton Bay fault trace is poorly defined by a discontinuous zone of fissures, warped surfaces, small landslides, and poorly exposed shear zones in rock (figs. 10–13). The fault in this segment angles obliquely across the structural and topographical grain of heavily timbered low rolling terrain with less than 700 feet of relief. It gradually changes strike from due north at the shore to N. 37° E. at its northern end. In this segment the fault trace is anomalous in that it does not coincide with a major topographic or structural lineament. Features such as alined swampy muskegs subtly suggest that some prior small vertical displacement occurred in Holocene time. The prominent northwest-trending lineaments and imposing scarps along Deception Creek and upper Slide Creek immediately to the west of the 1964 rupture apparently define a major fault trace along which large vertical up-to-the-northwest movements occurred previously but which shows no evidence of reactivation during this earthquake (pl. 1).

The fault trace cannot be located precisely within a few hundred feet inland from the top of the sea cliff, because it is obscured by the headwall scarps of enormous incipient landslide blocks that occur all along the upper part of the cliff. It reappears some 500 feet inland from the cliff where it coincides with the linear edge of a muskeg swamp. The fault trace here consists of a north-south trending zone of parallel surface fissures and flexures in glacial till and sphagnum peat. Individual fissures that parallel the trace are open as much as 3 feet (fig. 10) and have vertical offsets of as

much as 5 feet with the west (downhill) sides upthrown relative to the east sides. Net vertical displacement across the fissures is about 7 feet; the amount of vertical movement resulting from warping is not known. A possible left-lateral component of horizontal displacement is indicated by a 17-inch offset of segments of a log that had been frozen into the ground in a position almost normal to the trend of one of the larger surface breaks. A few gaping cracks that trend N. 15° W. at an oblique angle to the fault trace are also suggestive of some left-lateral strike-slip movement. No evidence for lateral offsets was found anywhere else along the fault trace.

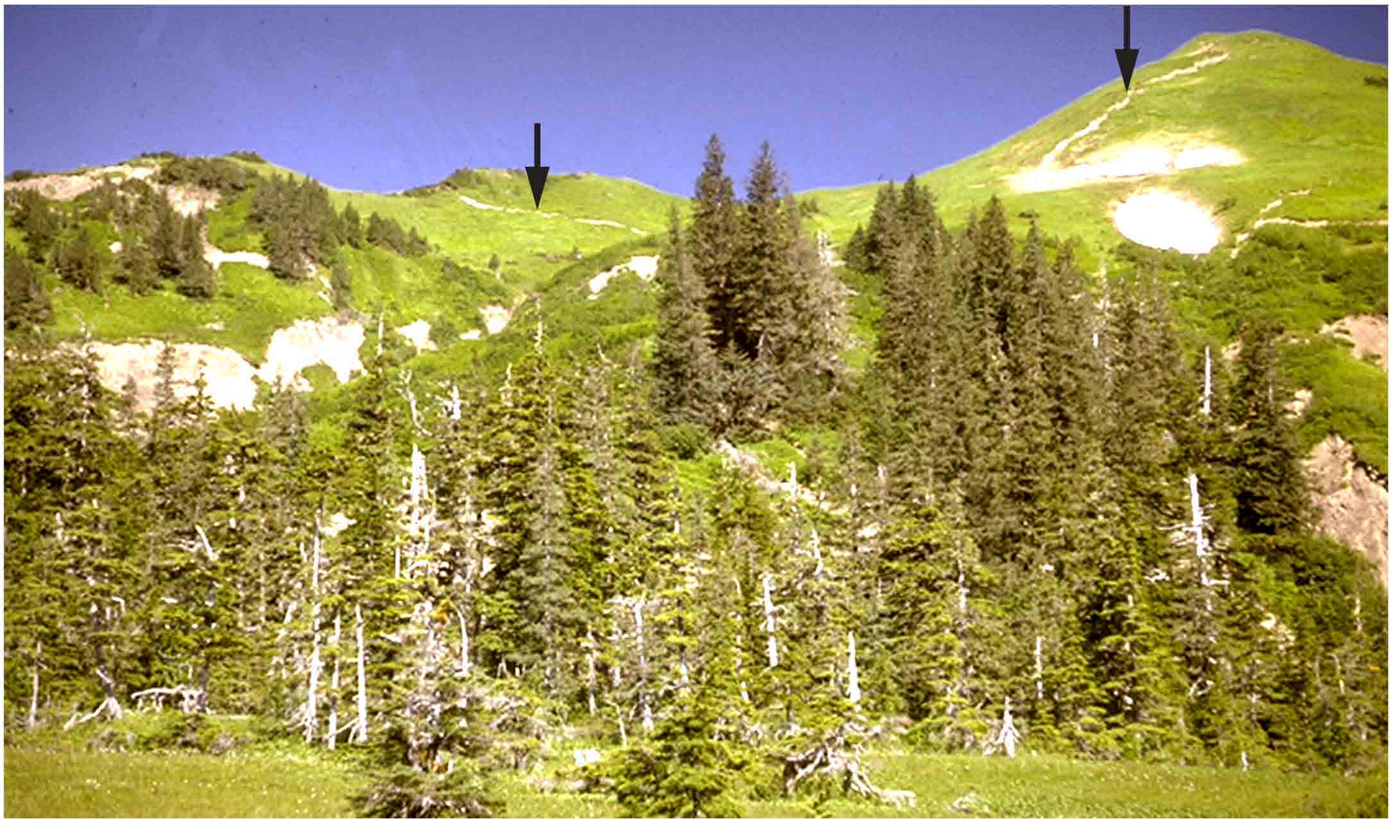
The fault continues for a mile as a line of poorly defined fissures and flexures through densely timbered terrain to the point where it intersects a muskeg bog about 500 feet long by 100 feet wide that was formerly flat and was crossed by a small meandering stream. Faulting has resulted in a pronounced eastward tilt of the eastern half of the muskeg and a slight anticlinal flexing of the central part. The tilted segment is now partly inundated by a lake that is more than 8 feet deep where it is dammed against an erosional scarp that borders the meadow on the east; the lake shallows toward the center of the muskeg (fig. 11). The anticlinal flexure forms a low north-south trending ridge immediately west of the lake.

On the flood plain of Strike Creek, the fault trace is vaguely defined by partially diverted drainage and tilted trees. Immediately to the west of Strike Creek, where it cuts through a muskeg bog in a N. 35° E. direction, the fault trace is clearly visible as a broad flexure through the formerly horizontal bog surface and

11 (above).—Formerly flat muskeg that was warped and tilted eastward along the Patton Bay fault trace. The newly formed lake is more than 8 feet deep at the eastern (left) margin of the muskeg. Photograph by L. R. Mayo.

12 (above right).—Warped and fissured muskeg surface along the Patton Bay fault trace. West (left) side of this formerly flat meadow is uplifted 16½ feet relative to the east side. Tilted trees in the background are along the flexure zone that marks the fault trace. Note the characteristic tilt of tree crowns toward the downthrown block. Arrows indicate fissures.

13 (bottom right).—Part of the zone of tectonic fissures north of Tortuous Creek. Two of the larger laterally persistent fissures (arrows) that trend obliquely across the slopes are visible above the brush line. The cracks and scars below the brush line result from earthquake-induced landslides and soil flows. Photograph by M. G. Bonilla.



the adjacent wooded area. A continuous sharp flexure about 60 feet wide in the muskeg is broken by a series of open fissures parallel to the trend of the fault that displace the muskeg-covered surface and underlying stream gravel (fig. 12). Relative vertical displacement across the part of the flexure in the bog is roughly 16½ feet. This estimate of the vertical movement is minimal, because it includes only part of the zone of surface warping associated with the fault. The total width of the zone, as indicated by the distribution of spruce trees which are tilted towards the downthrown block owing to warping of the surface, is roughly 125 feet at this locality.

From Strike Creek to Tortuous Creek the fault trends across heavily timbered terrain in which the trace is indicated by a vaguely defined discontinuous broad zone of tilted trees, ground fissures, and small landslides. These features were mapped from vertical and oblique photographs and from aerial observation. An outcrop consisting of highly sheared siltstone was observed in the bank of Slide Creek at about the point where the fault trace would cross the creek, but no indications of new surface displacement were found in the densely vegetated valley bottom.

Immediately to the north of Tortuous Creek, displacement is indicated by a zone of fissuring about half a mile wide that lies between the southern and central segments of the fault (pl. 1; fig. 13). The fissures range from a few hundred to more than 1,000 feet in length, and most have east-facing scarps. The more continuous of these fissures are clearly tectonic features inasmuch as they ignore topography and trend obliquely across mountain slopes and even over ridges as high as 1,800 feet. However, apparent tectonic fissures that nearly parallel the contours of steep slopes are difficult to distinguish from scarps at the heads of incipient landslides. Scarps parallel to the slopes that show evidence of downhill movement of the downhill side are arbitrarily mapped as landslide scarps; undoubtedly some represent fissures along which sliding has subsequently developed.

TORTUOUS CREEK TO THE VALLEY OF PATTON RIVER

The 5¾-mile-long segment of the Patton Bay fault between Tortuous Creek and the valley of Patton River trends N. 35° E. and is the most continuous and impressive of all the segments. It lies at the base of a line of imposing ridge spurs which are part of the modified scarp formed on the upthrown block of the Patton Bay fault. Along the ridge spurs the fault is marked by a spectacular series of gigantic landslides with headwall scarps as high as 300 feet, soil flows, and surface cracks associated with incipient slides on the slopes (figs. 14–16). The line of landslides along these spurs is broken only at the valleys of deeply incised streams that dissect the upthrown block intersecting the fault approximately at right angles. In some of these incised-stream valleys the actual fault trace could be seen, but in the interfluves the trace was concealed by the chaotic mass of crushed and pulverized landslide debris and a virtually impenetrable tangle of fallen brush and timber. The process by which landslide debris tends to bury the fault trace where it follows along the base of a prominent scarp is illustrated diagrammatically in figure 17. This process of automatic self-concealment undoubtedly occurs on most active overthrust faults and is probably one of the major reasons why faults of this type are commonly difficult to recognize and map by surface geologic methods.

These ridge spurs were especially susceptible to mass gravitational movements through a combination of (1) steep slopes composed in part of unstable debris resulting from prior faulting; (2) bedding dips that tend to parallel the slopes; and (3) local zones of sheared and shattered bedrock along the fault plane and near it within the upthrown block. In view of this inherent instability, it is not surprising that oversteepening resulting from renewed uplift along a steep or overhanging fault scarp at the base of the slopes, coupled with transient accelerations due to the elastic ground vibrations and tectonic displacements during the earthquake, should have caused the massive slope failures. The transient movements alone seem to have been sufficient to trigger landslides under comparable circumstances elsewhere in the area, such as along upper Slide Creek, even where renewed faulting did not occur.

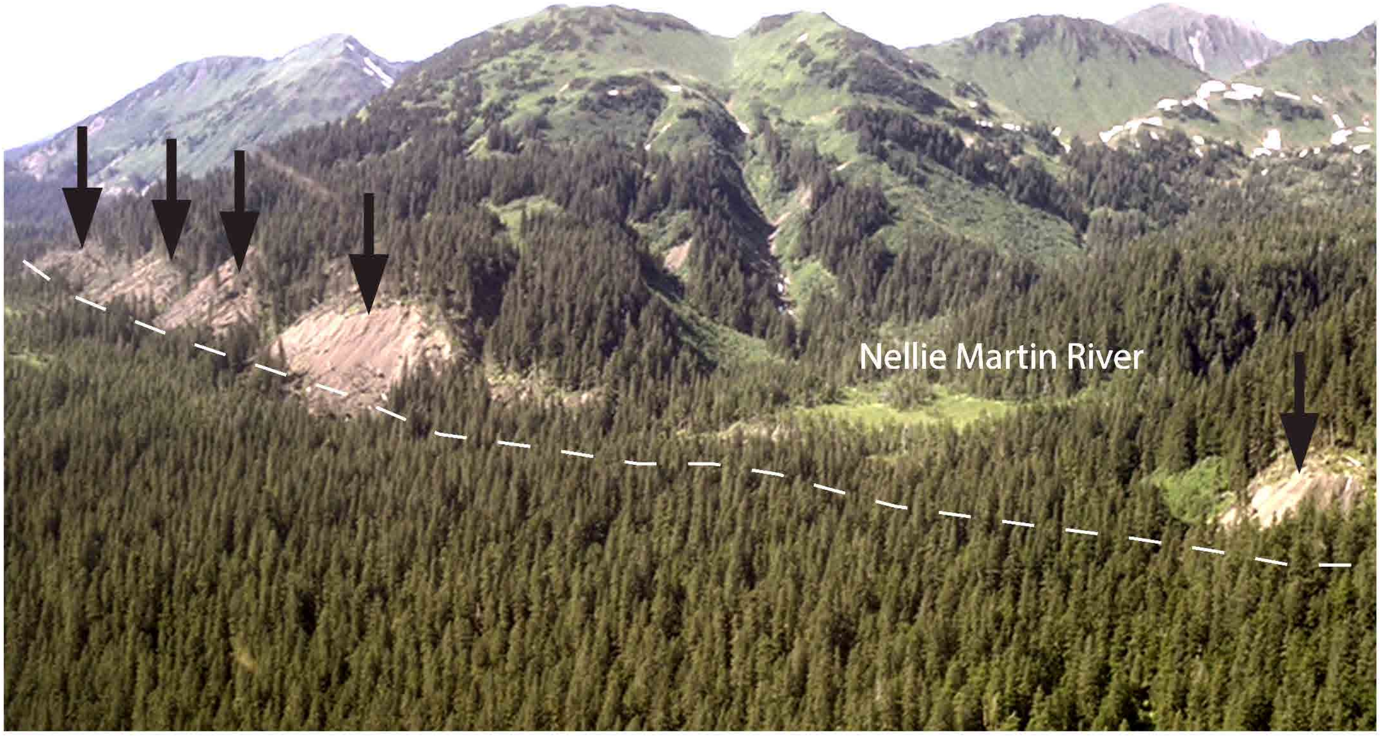
From Tortuous Creek to Jeanie Creek the fault trace is marked by a line of landslides at the base of an imposing eastward-facing slope that rises 1,500 feet at an average

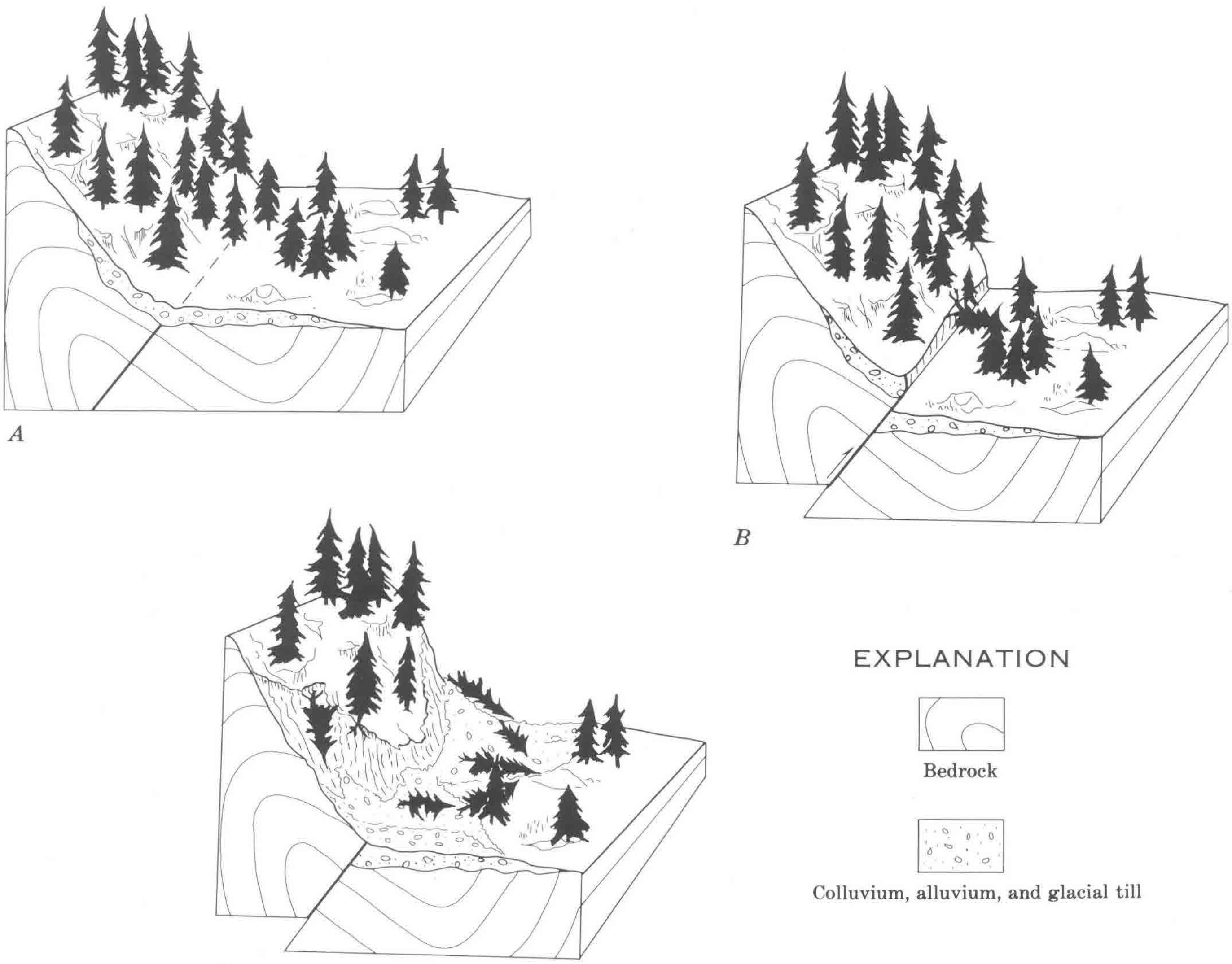
14.—Looking southwest along the Patton Bay fault in the vicinity of Jeanie Creek. Fault trace (dashed) is marked by the line of landslides at the base of the prominent scarp that is formed on the relatively upthrown block. →

15.—Patton Bay fault (dashed) looking northeast toward Jeanie Creek. The segment of the fault north of Jeanie Creek is offset about 0.4 mile to the east relative to the segment south of the creek. →


Jeanie Creek


Jeanie Creek


Nellie Martin River


A
B
C
EXPLANATION
Bedrock
Colluvium, alluvium, and glacial till

18.—Shattered lenticular boudins of light-gray indurated sandstone in a matrix of sheared black argillite dipping 75° to 85° northwest along the Patton Bay fault at Jeanie Creek. Alaska Earthquake 112

16 (above left).—Landslide scars as high as 200 feet (arrows) on the relatively upthrown block of the Patton Bay fault (dashed) near Nellie Martin River. The fault is exposed in the river channel where it dips about 50° northwest (right) and has at least 16 feet of vertical displacement. Alaska Earthquake 111

angle in excess of 30°. Sheared rock is exposed along the fault trace in an isolated bedrock outcrop 2 feet wide along the south bank of a small stream 0.8 mile north of Tortuous Creek. The outcrop consists of intensely fractured argillite and graywacke that contain lenticular veinlets of quartz and thin seams of dark-gray clay gouge less than 1 inch wide dipping 65° to 75° NW. Except for this one outcrop, the stream valley was so choked with slide debris that no information could be obtained on the displacement.

Between the south and north forks of Jeanie Creek the fault is offset about 0.4 mile to the east (fig. 15). The base of the slope in this area is entirely concealed by landslide debris, so whether the two segments of the fault here are connected by an abrupt bend or whether they are offset en echelon in a right-handed sense is not known.

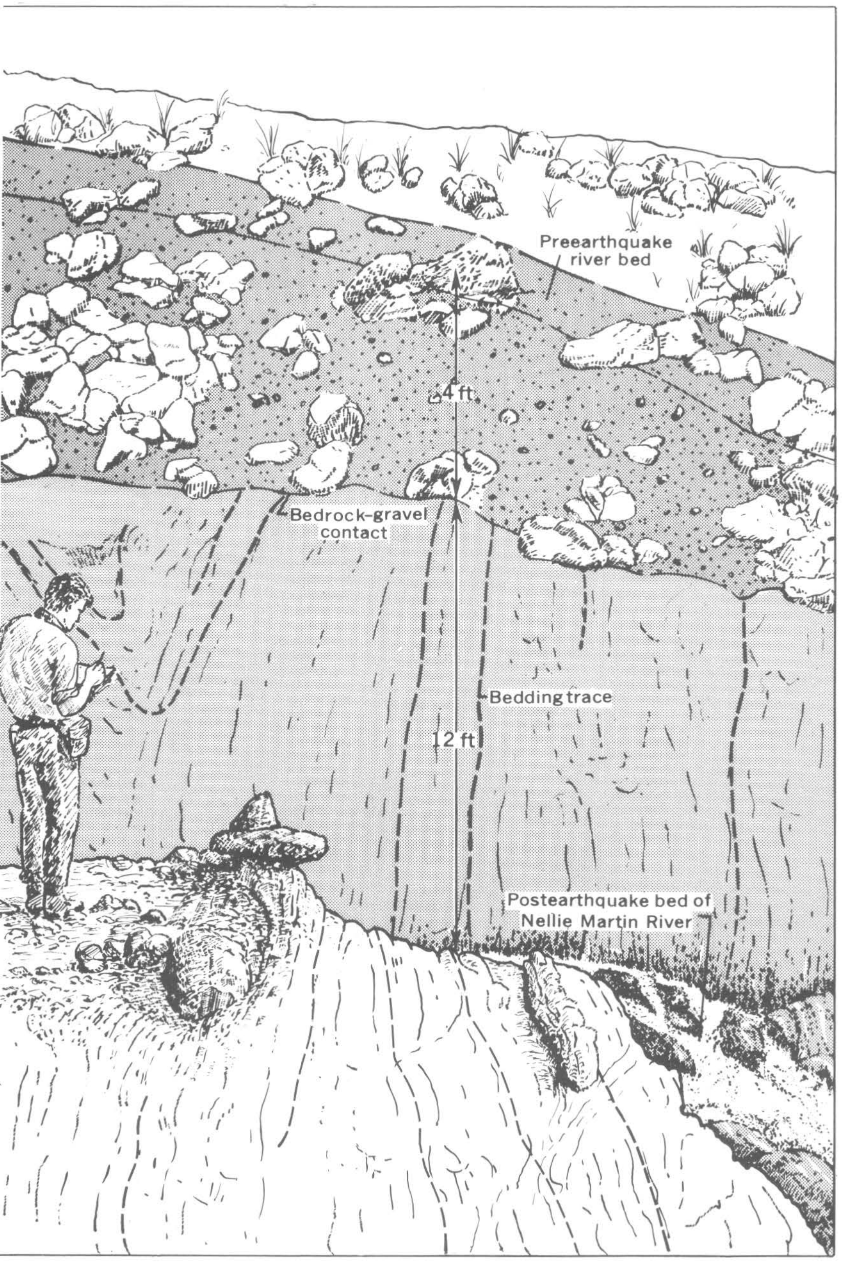
Part of the fault zone is exposed in a 3-foot-wide outcrop in the bank of Jeanie Creek. The outcrop consists of shattered lenticular boudins of light-gray fine- to medium-grained arkosic sandstone in a matrix of sheared black argillite (fig. 18) that strikes N. 65° E. and dips 75° to 85° northwest. On the north side of the creek the fault passes through a terrace deposit of stream gravel which has been displaced into four gently sloping steps 10 to 20 feet wide separated by three fissured rises of comparable width that are strongly tilted toward the downthrown (east) block. Minimum cumulative vertical displacement of 10 to 12 feet is represented by the rises that displace the terrace.

17 (below left).—Sequential diagram illustrating stages in growth of landslides along the base of a fault scarp of the reverse type upon renewed dip-slip displacement. *A*, preearthquake condition; *B*, overhanging scarp formed near base of slope by renewed fault movement; *C*, collapse of unstable slope above the fault scarp.

One mile farther north the fault plane is again exposed in the banks of Nellie Martin River; its trace is clearly defined where it crosses the broad alluvial flood plain of the river. The fault zone in the upthrown block along the river consists of 75 feet of intensely sheared siltstone containing veins and lenticular masses of quartz less than half an inch wide; bedrock is concealed by stream deposits in the downthrown block. The siltstone in this zone is so fractured throughout that it can be readily broken into chips by hand. The sheared rock trends N. 35° E. and dips northwest at angles ranging from 50° to near vertical. By August of 1965 the Nellie Martin River, which flows directly across the strike of the bedding and the fault, had incised its channel below the preearthquake level, through 4 feet of stream gravel and 12 feet of bedrock immediately upstream from the fault trace. The amount of incision suggests a minimum of 16 feet of relative vertical displacement across the fault at this locality (fig. 19).

Both north and south of the river channel, the fault trace is marked by a well-defined flexure of the alluvial deposits and the usual associated ground fissures and tilted trees. A profile perpendicular to the strike of the flexure zone about 300 feet north of Nellie Martin River is shown as B–B' on plate 1. Open extension cracks as much as 1 foot wide parallel the upper part of the flexure; steeply tilted and downed trees, with crowns pointing downslope, were found along its base. It may be assumed that, if there was no previous break in slope along the new flexure, the vertical displacement is the offset of the sloping alluvial fan surface across the flexure zone.

19.—Incised channel of the Nellie Martin River immediately upstream from the gravel and 12 feet of bedrock at this locality between March 27, 1964, and August



atton Bay fault scarp. The rejuvenated river has eroded about 4 feet of boulder
1965. Photograph by L. R. Mayo.

As shown in the profile, the indicated maximum vertical displacement at this locality is about 20 feet.

To the north, the fault trace is again concealed by landslides for a distance of almost 1½ miles until it reappears as a zone of fissures and tilted trees in the alluvial fan deposits of Braided Creek and the nearby streams. Individual fissures have as much as 4 feet of vertical displacement, the northwest sides invariably upthrown. At one point along this trace, the fault zone is defined by a 40- to 60-foot-wide swath of trees tilted at a uniform angle of about 70°, resulting from a southeastward surface tilt of 20°. Approximate vertical displacement across the zone, as calculated from its width and surface slope is 14½ to 22 feet.

North of Braided Creek the fault follows the contact between predominantly massive greenstone tuff along the base of the mountain front on the upthrown block and the alluvial flats on the downthrown side. At the most northerly point on this segment, where it strikes into the alluvial valley of Patton River, the fault is exposed in a dry creekbed as a 3-foot-wide zone of sheared, crumpled, and sericitized siltstone that strikes N. 10°E. and dips 67° northwest. On the flood plain immediately north of this outcrop, a vertical displacement of roughly 21 feet is indicated by an average 12° downslope tilt of the surface over a zone about 100 feet wide (determined from the tilting of trees).

PATTON RIVER VALLEY SEGMENT

The Patton River Valley segment of the Patton Bay fault is unique in that it is entirely in an area of low relief underlain by thick deposits of unconsolidated alluvium. A climax forest of Sitka spruce composed of imposing trees as much as 4 feet in base diameter and 140 feet in height occupies the entire valley floor except for the poorly drained swampy areas or active stream channels. Within this forest, the fault trace is defined by a remarkably persistent line of discontinuous surface cracks and associated tilted trees that can be traced to the northern margin of the valley, a distance of nearly a mile.

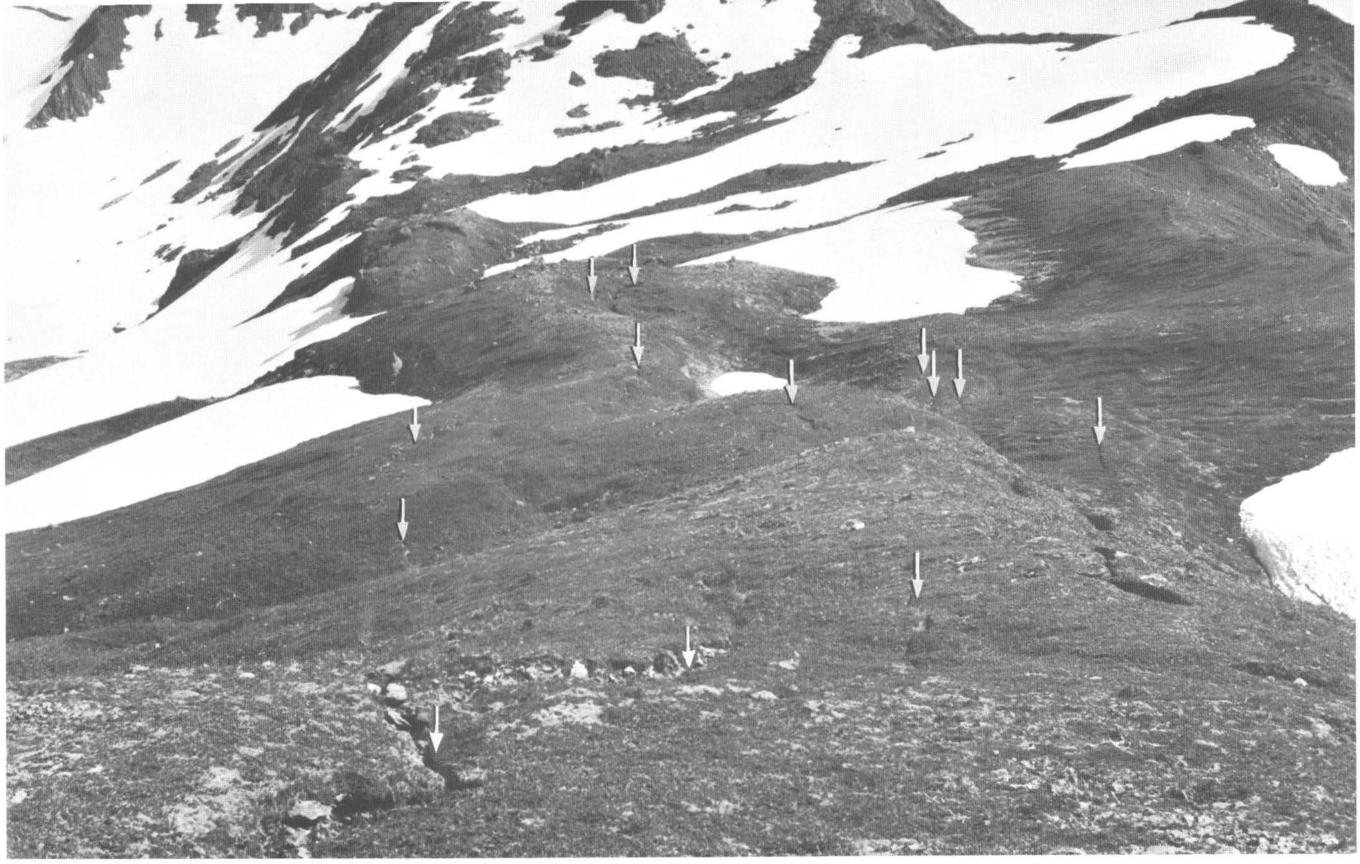
The cracks, which occur in peat moss and soil, are subparallel and trend N. 10° to 30° E. They are open 1 to 4 inches at the surface and show a few down-to-the southeast dip-slip displacements of 2 to 3 inches and no measurable strike-slip components. A minor set of cracks with a general N. 55° E. orientation was observed near the north end of the segment. All the cracks occurred in a well-defined zone a few hundred feet wide; no other newly opened cracks were found outside this zone in the same general area of the valley floor.

Tilted trees are associated with the line of cracks, particularly south of Patton River (fig. 20), where average tree heights of more than 125 feet make tilts of as little as 5° from the vertical readily apparent.

20.—Looking southwest along the Patton Bay fault in the alluviated valley of Patton River. The fault trace is indicated by the tilted giant Sitka spruce trees and by ground fissures that roughly parallel the zone of tilted trees.

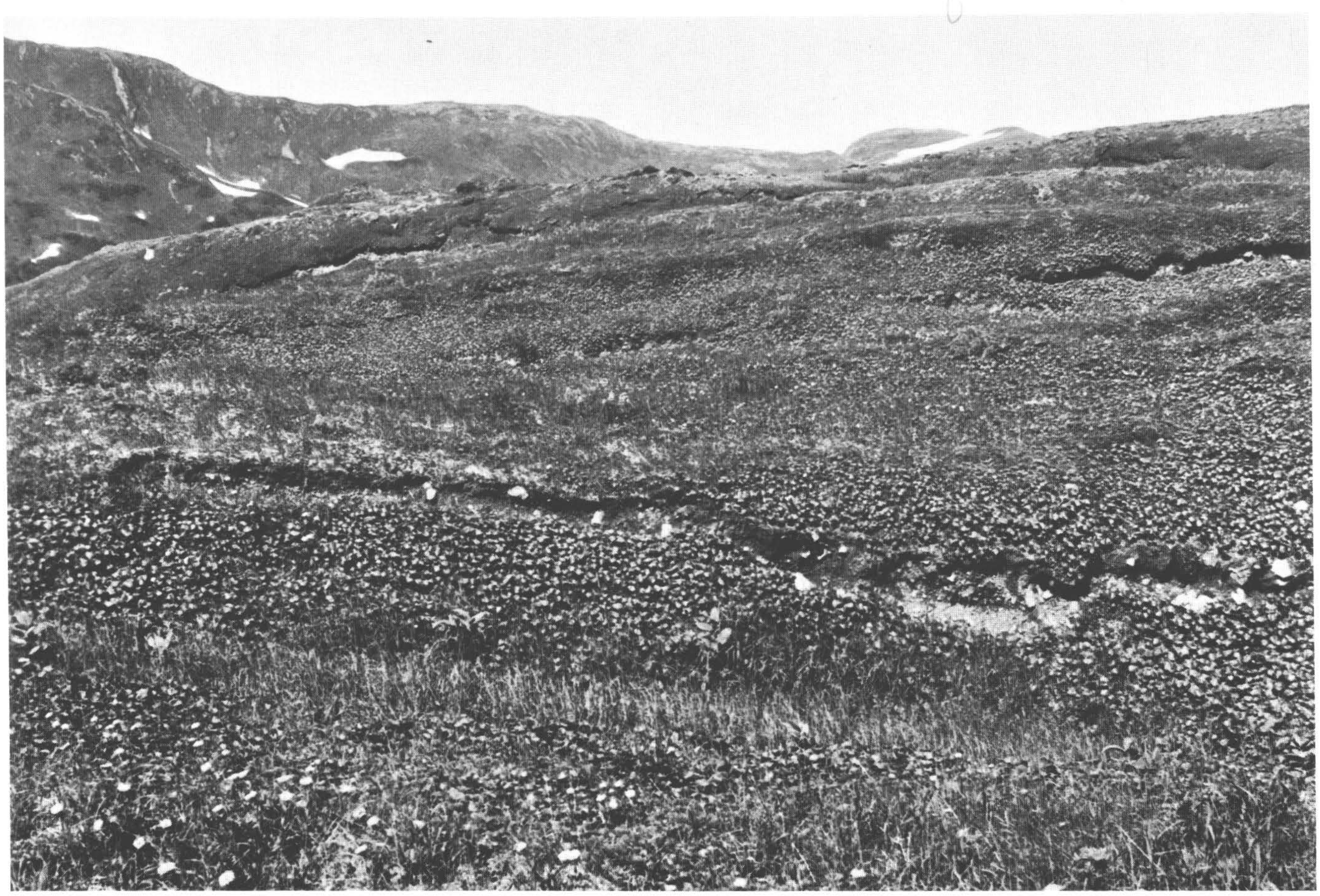
PATTON RIVER VALLEY TO PURPLE BLUFF

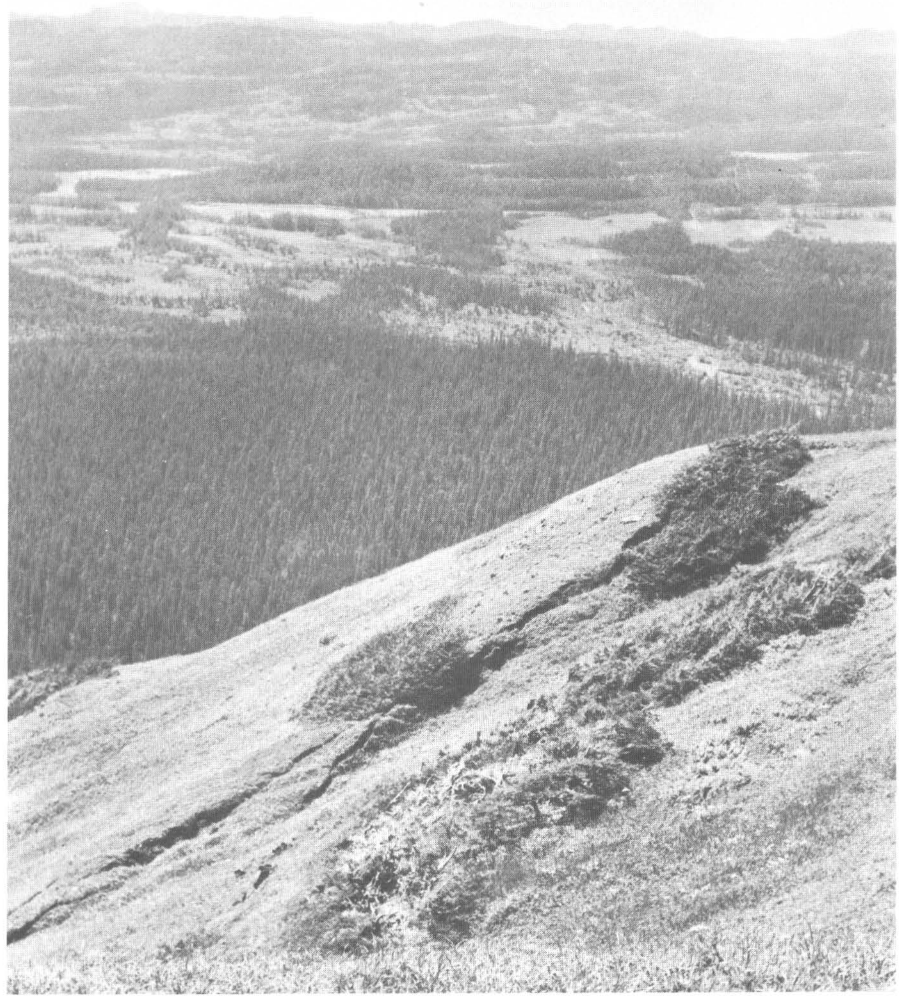
The character of the surface displacements along the Patton Bay fault zone changes markedly to the north of Patton River valley. In this 11-mile-long segment (pl. 1; figs. 21, 22), tectonic movements are strongly suggested by numerous peculiar subparallel northeast-trending fissures consisting of open cracks or normal faults with small vertical displacements that, for the most part, are uninfluenced by the topography. The southeastern margin of this zone of fissures is a conspicuous lineament, trending N. 30° E., similar to much of the Patton Bay fault to the south in that it forms a boundary between an imposing rugged ridge on the northwest and terrain of lower relief on the southeast, but different in not having a single continuous scarp or well-defined narrow zone of displacement. The character of the fissures in this segment suggests the possibility that the displacement here is taken up mainly by a broad anticlinal flexure of the upthrown block and that the longitudinal zone of extension cracks and minor normal faults results from local tensile stress along the crest of the flexure.



21.—Part of the zone of tectonic fissures at 3,000 feet altitude on the ridge summit north of Patton River. The fissures, some of which are indicated by arrows, could be traced almost continuously to the northeast through the peak (center of photograph) and the notch on the skyline to the left of the peak. alaska earthquake 115

22.—Subparallel minor normal faults within the area shown in figure 21. Note that some of these fissures coincide with preexisting linear scarps. alaska earthquake 116





23.—Minor normal faults along a preexisting linear groove on a steep ridge slope. The downhill side is uplifted 16 inches. Patton River valley visible in the background.

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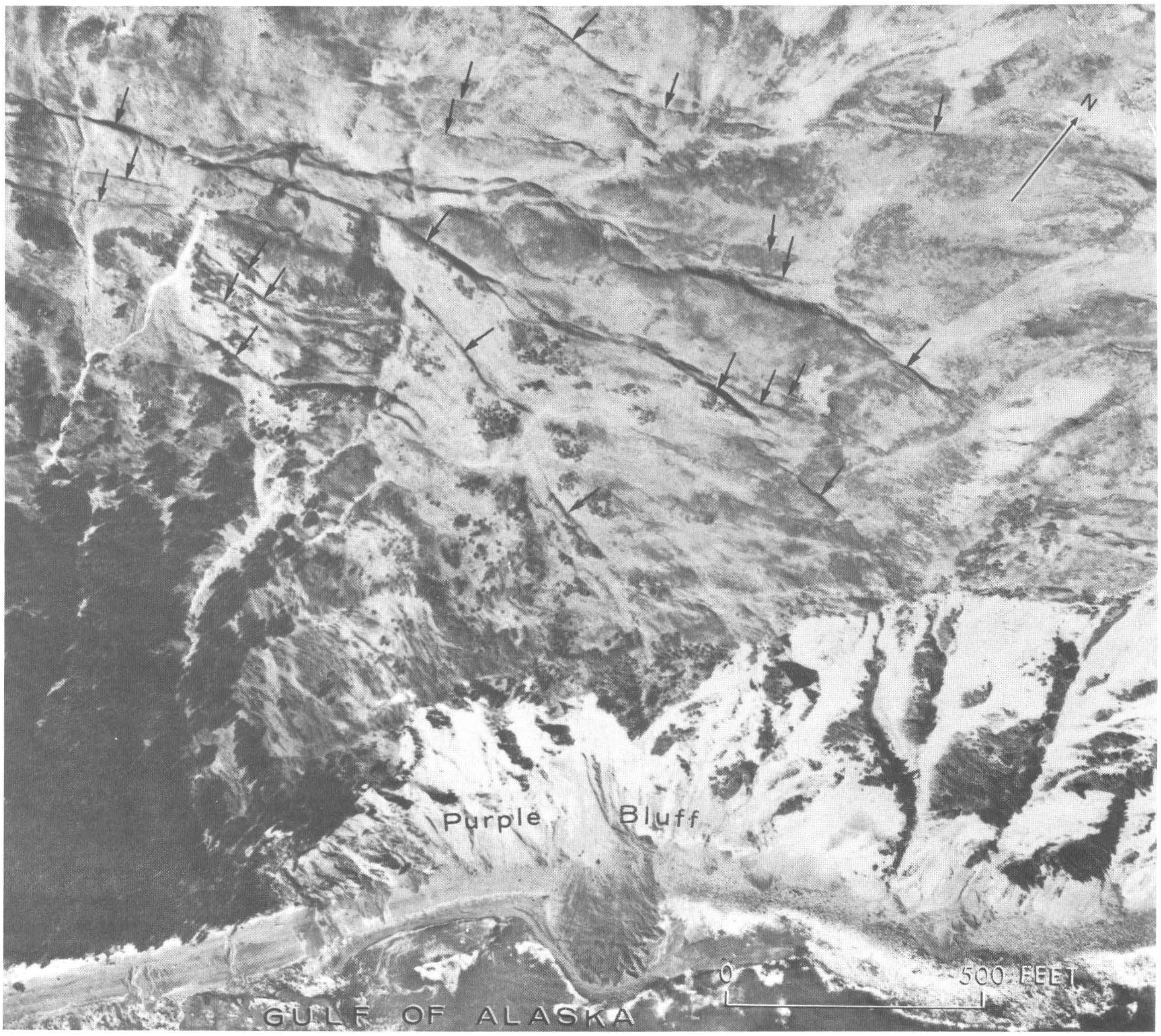
The fissures were studied in detail only at one locality on the ridge immediately north of the Patton River valley (pl. 1, profile *C–C′*). Here the fissures occur over a zone about 1,500 feet wide and are generally subparallel. Their average strike is N. 20° E. parallel to the ridge crest, although some individual fissures and segments of nonlinear fissures trend at an oblique angle to the zone—between N. 80° W. and N. 70° E. Some of the fissures are several hundred feet long and as much as 17 inches wide. Most are nearly vertical with dip-slip displacement of as much as 21 inches (figs. 21, 22; pl. 1, profile *C–C′*). The overall width of this zone of fissures is difficult to determine because cracks on the steep southeast-facing ridge slope cannot be readily differentiated from incipient landslides. The zone shown on plate 1, which is 3,000 feet wide, includes the entire area in which surface cracks of possible tectonic origin have been observed.

That the fissures on the ridge are tectonic features is indicated by (1) the linearity and lateral continuity of the zone; (2) the fact that most of the fissures displace bedrock; (3) the occurrence of some fissures in which uplift on the downhill side, in relation to the uphill, precludes the possibility of landslide origin (fig. 23); and (4) coincidence of many of the fissures with preexisting linear scarps in rock along which previous movements may have occurred.

The fissure zone could be readily followed northward from the area shown on profile *C–C′* of plate 1 across the highest peak on the ridge at an altitude of 2,200 feet. Beyond this point it is discontinuously evident from subparallel cracks and landslide scarps on the steep mountain slopes that were traced to Purple Bluff by aerial reconnaissance.

Two localities in this zone of fissures that were examined on the ground by L. C. Cluff of Woodward-Clyde-Sherard and Associates in July 1966 are worthy of special mention. One is at the slope break near the base of the ridge 2 miles north of the Patton River valley, where a southeast-facing scarp about half a mile long and 4 feet high displaces vegetation and soil. The length of this scarp and evidence of surface displacement suggest that it may be a fault. The second locality is at the northern end of the zone, where renewed vertical surface displacement of no more than a few inches occurred along several preexisting lineaments that extend inland from Purple Bluff for a distance of about 1,600 feet (figs. 2, 24). Some of these fissures near the upper edge of the bluff may be along the heads of gigantic landslide blocks, but most of them, including many with relatively uplifted downhill sides, seem to be



24.—Vertical aerial photograph in the vicinity of Purple Bluff showing conspicuous lineaments (arrows) along the inferred northeastward extension of the Patton Bay fault. Renewed displacement occurred on some of these lineaments after the 1964 earthquake. A large earthquake-induced landslide may be seen at the base of the high bluff at bottom center. Photograph by U.S. Coast and Geodetic Survey, August 25, 1964.

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of tectonic origin. The fissures strike about N. 30° E. and intersect the coast at an acute angle immediately north of Purple Bluff. No detailed studies of shoreline displacement were made across the zone of fissures at the coast; the available measurements of shoreline changes (fig. 2) suggest that the displacement here is no more than a few feet or that there may be no displacement at all.

An alternative possibility is that the fault may once again be offset en echelon to the southeast and that it continues northeastward as a submarine feature. Although there is no direct evidence for such an offset, the precipitous linear coast of Montague Island northeast of Purple Bluff, a concentration there of aftershock activity, and the occurrence of abrupt submarine scarps in the vicinity of Hinchinbrook Island (Van Huene and others, 1966) are suggestive of possible active faulting in this area.

SUBMARINE EXTENSION OF PATTON BAY FAULT

Subsequent to the discovery of the faults on Montague Island, the U.S. Coast and Geodetic Survey made hydrographic and seismic surveys of the ocean floor southwest of the island. These surveys have revealed a prominent southeast-facing bedrock scarp 40 to 90 feet high that is in line with, and inferred to be a continuation of, the Patton Bay fault (fig. 2). Comparison of detailed bottom soundings taken in 1927 with others taken after the earthquake in 1964 indicates that the vertical uplift of the bottom on either side of this scarp is in the same sense as, and is comparable in amount to, that recorded on land for a distance of at least 17 miles southwest of the point where the fault strikes out to sea near Neck Point (Malloy, 1965a, p. 1048–1049; 1965b, p. 22–26). The hydrographic surveys do not come closer than 6½ nautical miles to the fault trace on land, so it is not known whether the onshore and offshore segments of the fault scarp are a continuous strand or perhaps are offset en echelon.

Malloy (1965b, figs. 6, 7) believes that a sharp 18-foot-high break in slope on the continuous sounding and seismic profiles closest to shore may represent the 1964 movement; an underwater photograph of what appears to be fresh breakage of the sea floor at this locality tends to support this interpretation. It is also significant that the vertical displacement across the submarine scarp indicated by the bathymetric surveys is compatible with the displacement of 20 to 23 feet measured across the scarp and warped upper plate along the nearby shore at the southern end of the fault.

The fault probably continues farther southwestward, although the 1964 reconnaissance surveys did not track it as a continuous scarp beyond the limits of the pre-1964 hydrographic survey, which was confined mainly to shoal waters. The lines of evidence discussed below suggest that the Patton Bay fault may be but the northern end of a fault, or of a system of discontinuous faults, that extends southwestward an additional 300 miles to the area offshore from Sitkalidak Island in the Kodiak Island group.

1. That this postulated line of faulting is along a narrow zone of probable maximum submarine uplift is inferred from the spatial distribution and runup heights of the seismic sea waves associated with the earthquake (Van Dorn, 1964, fig. 6; Plafker and Mayo, 1965, p. 11; Plafker and Kachadoorian, 1966, p. 38–39). The waves clearly were generated on the Continental Shelf within the zone of regional uplift by vertical displacements of the sea floor. The direction of travel and reported arrival times of the initial wave crest—the crest that struck the shores of the Kenai Peninsula nearest to Montague Island within 19 minutes and the southeast coast of Kodiak Island within 38 minutes after start of the earthquake—indicate that the wave crest was generated within the regional zone of uplift along one or more line sources in a narrow elongate belt that extends southwestward from Montague Island approximately along the axis of maximum uplift shown in figure 1. Furthermore, the similarities in maximum wave runup heights along physiographically comparable segments of coast, both on the Kenai Peninsula opposite Montague Island and on Kodiak Island, suggest that the vertical sea-floor displacements which generated the waves in these two areas may be of the same order of magnitude.
2. The inferred zone of fault displacement also has an especially large concentration of features that seem to be a result of recent subbottom tectonic movements (D. F. Barnes, unpub. data, 1966; Von Huene and others, 1966). These features include sharply defined submarine fault scarps similar to those near Montague Island, subbottom discontinuities that displace possible Holocene deposits, and small folds in the Holocene deposits.

25.—View southwest along Hanning Bay fault. Northwest block (right) has overthrust the southeast block. Note warped surface and overhanging muskeg mat on the scarp in the foreground. Tree in the background has been tilted by the overthrusting. Location shown in figure 27. alaska Earthquake 119

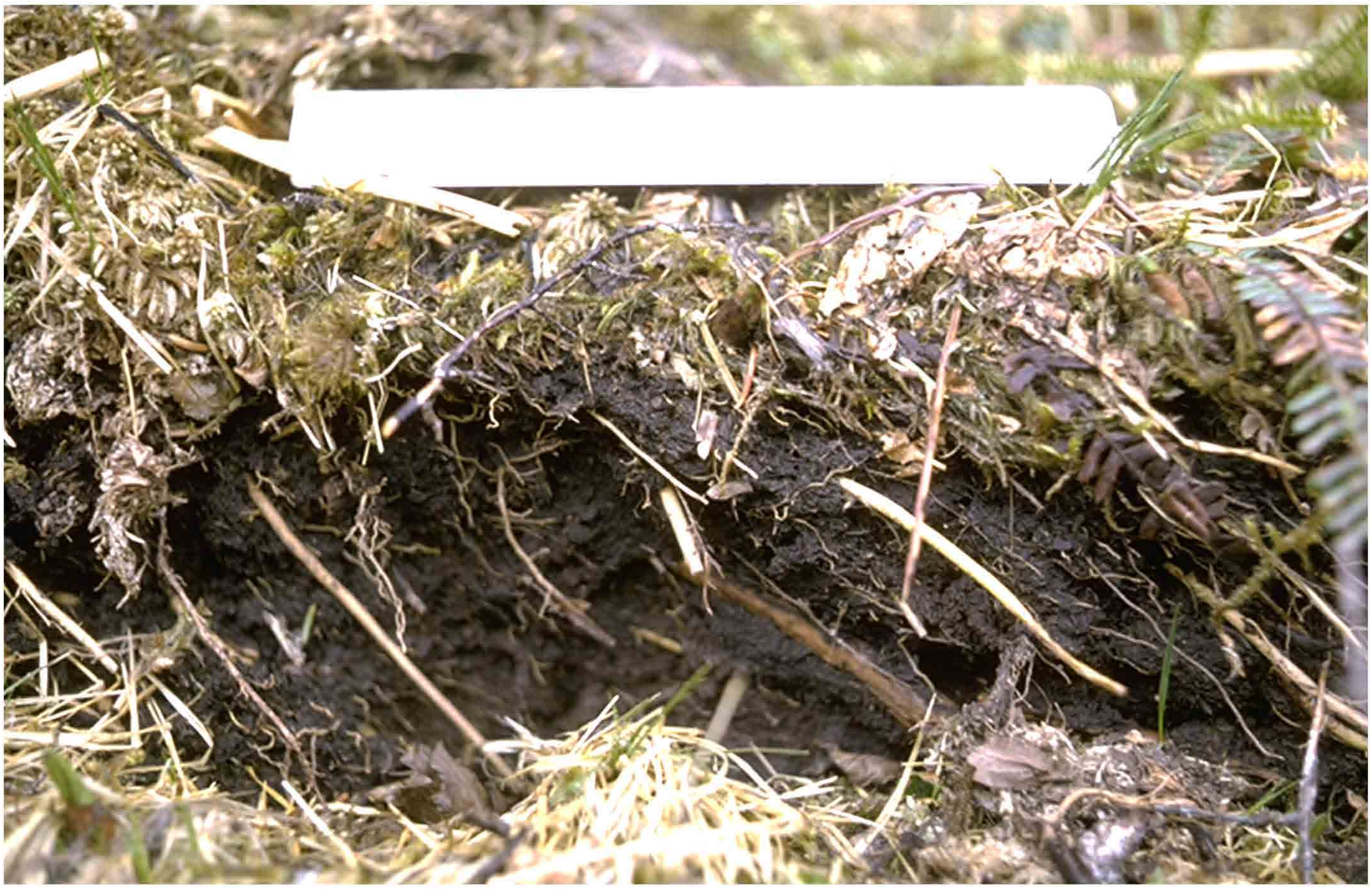
3. The concentration of aftershock activity and release of seismic-wave energy which apparently occurred in this area could indicate postearthquake fault adjustments (S. T. Algermissen, written commun., March 1965). Much of the seismic-wave energy released during the aftershock sequence was contained in the six recorded aftershocks shown in figure 1 with Richter magnitudes equal to or larger than 6.0 (as determined by the U.S. Coast and Geodetic Survey). Of these, two were almost directly in the postulated fault zone, one was on its southwestward projection in the Trinity Islands, two were northwest of the belt in positions where they could conceivably lie on the down-dip extension of northwest-dipping reverse faults, and only one was clearly unrelated to this postulated belt of extreme uplift and faulting.

HANNING BAY FAULT

The Hanning Bay fault extends about 4 miles from the south shore of Hanning Bay almost to MacLeod Harbor (pl. 2; figs. 25–39). After the earthquake, the fault trace was exceptionally well exposed along nearly its entire length, either as a single steep scarp or as a narrow zone of surface warping. Descriptions of surface features along the fault are divided geographically into three segments as follows: (1) south of Fault Cove, (2) Fault Cove, and (3) Fault Cove to Hanning Bay. Places referred to, including the locations of illustrative photographs and diagrams, are shown by the map and photomosaic on plate 2. Vertical displacements relative to sea level at and near the fault are shown on plate 2 and are contoured at a smaller scale in figure 2.

SOUTH OF FAULT COVE

The mile-long segment of the Hanning Bay fault south of Fault Cove trends N. 35° E. and is marked by a southeast-facing



26.—Overhanging scarp of Hanning Bay fault in glacial till dipping 80° northwest. About 4 inches of left-lateral displacement is indicated by the rake of roots extending across the scarp. Scale is 6½ inches long. Location shown in figure 27.

scarp in surficial deposits, tilted or toppled trees, and gaping extension cracks. The scarp is clearly visible along the extreme southern part of the fault where it crosses open ground along a slight preexisting break in slope. The fault trace is marked by a scarp as much as 5½ feet high; the surficial muskeg layer and underlying glacial till on the northwest block has ridden up and over the southeastern block to form a prominent pressure ridge (fig. 25). Where visible beneath the surface vegetation, the overhanging scarp in till dips about 80° NW. At its southern end the scarp becomes progressively lower and finally disappears. No indication of fault displacement was found anywhere along the north shore of MacLeod Harbor—an area which was examined in some detail.

The displacement is entirely dip-slip except for about 4 inches of left-lateral strike-slip displacement near the south end of the fault. The lateral component of movement is indicated by rootlets that trend obliquely across the scarp (fig. 26), by the rake of striations in the fault plane, and by the regular right-handed en echelon arrangement of gaping fissures that follow the general course of the flexure but intersect it at an angle of about 15° (fig. 27). The absence of lateral displacements elsewhere along the fault, or of systematically offset drainage across the fault trace, demonstrates that the strike-slip component of displacement during this earthquake and during earlier movements was relatively minor.

27 (left).—Segment of Hanning Bay fault trace looking northeast showing surface flexture 3 to 5 feet high broken by gaping sub-parallel right-handed en echelon cracks, 3 to 6 feet apart. Gullies that intersect the scarp at right angles show no evidence of lateral offset that would suggest strike-slip displacement. Arrow indicates location of figure 25.

North of the locality shown in figure 27, the fault trace trends in a N. 35° E. direction along the heavily timbered channel of a small stream, which drains into the beach-barred lake at the shore. For most of this distance the fault parallels the northwest edge of the stream channel except at one point where it cuts across a meander and through a small bedrock hill on the opposite side of the creek. The trace is clearly marked by a break in slope with associated ground cracks and a swath of tilted and downed trees whose crowns all point toward the relatively downthrown block. In one locality the slope break is 8½ feet high and 24 feet wide; right-handed en echelon tension cracks trending N. 15° E. at the top of the slope are as much as 1 foot wide and 6½ feet deep.

At the north end of this segment, the fault scarp forms the linear southwest shore of the beach-barred lake. An overhanging scarp that dips 80° northwest displaces glacially derived pebble-cobble gravel in a blue-gray silty-clay matrix. Striations in the soft clay are in the direction of dip.

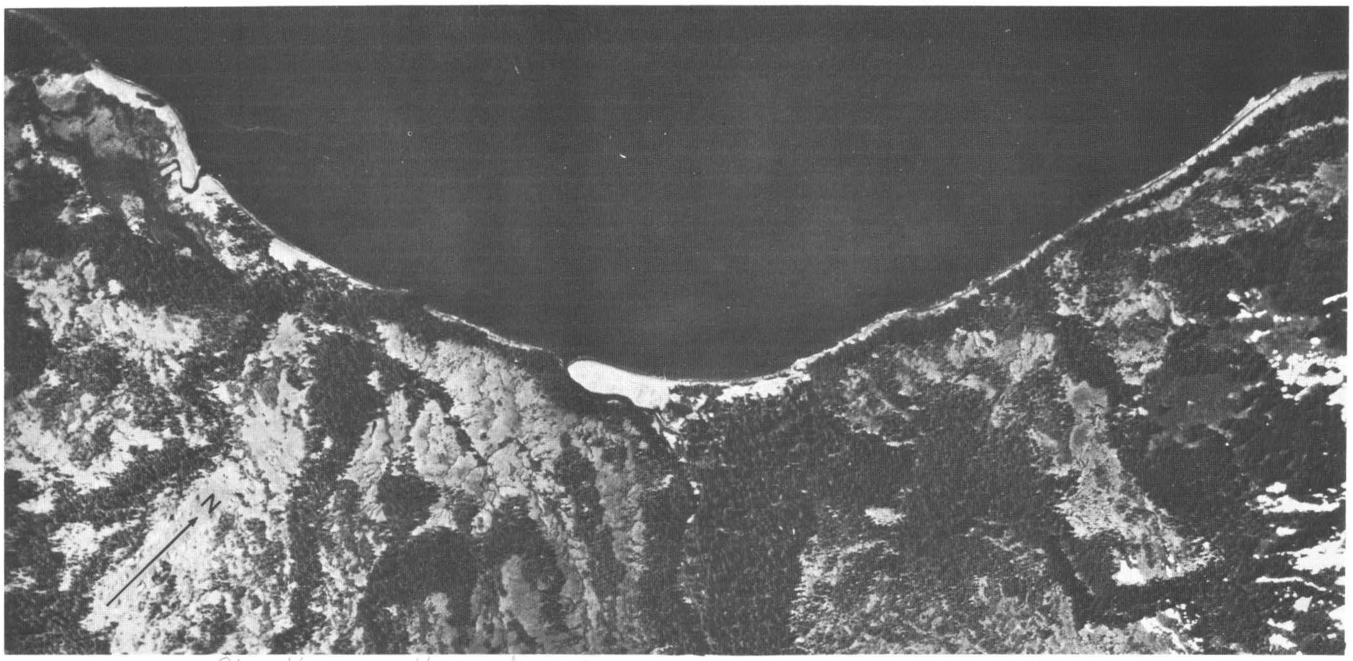
AT FAULT COVE

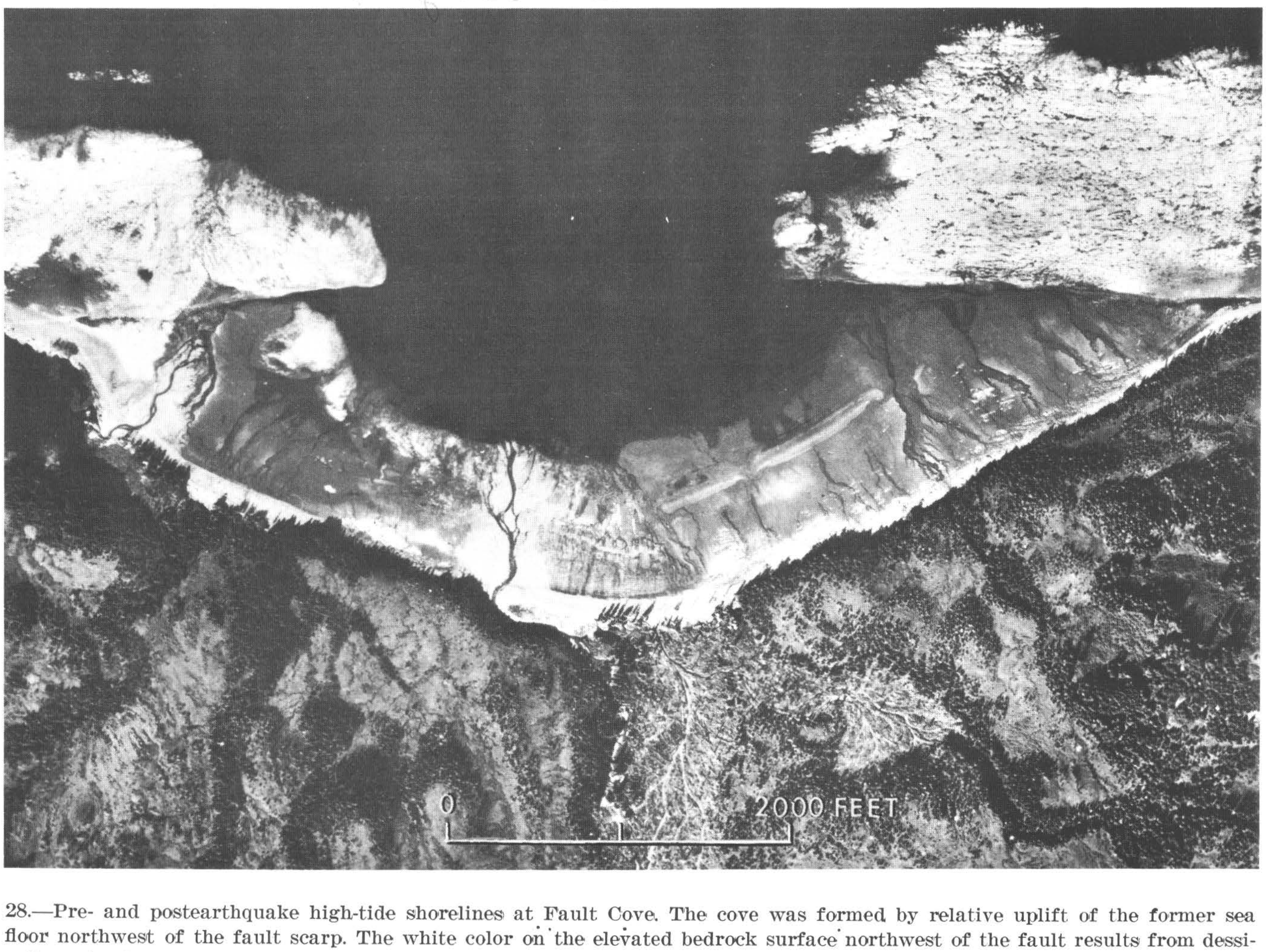
By far the most spectacular segment of the Hanning Bay fault is the part shown in figure 28 (next page). It crosses a former inconspicuous embayment in the coastline, which has been transformed by vertical displacement during the earthquake into a shallow cove (christened Fault Cove). The movement produced a single continuous scarp 1.4 miles long that displaces bedrock and sediments of the former sea floor and beach deposits along the shore. The fault trace curves gradually from N. 35° E. to N. 45° E. as it crosses the cove. At extreme low tide it is exposed at the surface almost continuously except for the permanently submerged part at the cove entrance which, however, is readily visible from the air (fig. 29).

The existence of a preearthquake submarine scarp in bedrock at this locality is clearly indicated by the fact that unconsolidated deposits were ponded on the shoreward side of the scarp, whereas bare rock is exposed almost everywhere else on the upthrown block.

Along the south shore of Fault Cove, the scarp is a prominent southeast-facing break in slope about 8½ feet high; marine sand and pebble-cobble-boulder gravel that constitute the beach prism have slumped across the scarp and thereby concealed the actual fault surface (fig. 30). Linear strand lines on the uplifted beach, and bands of marine sand and gravel on the former submarine part of the beach that cross the fault at an oblique angle, show no evidence of lateral offset.

The part of the fault trace along the north shore of Fault Cove in the area seaward from the former beach prism is marked by an abrupt scarp in bedrock or in bedrock mantled with a thin veneer of unconsolidated marine deposits. The scarp trends either parallel to the strike of bedding planes in the bedrock or intersects them at an acute angle of less than 10°. It varies in height from 12½ to 13½ feet, and along most of its length it consists of slumped bedrock and the overlying unconsolidated deposits (fig. 31). Segments of the scarp that originally were vertical or overhanging have subsequently slumped back to the steep angle of repose shown in figure 31. In part, the slumping was accelerated by undercutting of the scarp toe and by removal of slump debris both by stream runoff diverted along the uphill-facing scarp and by current scouring. A shallow pond oc-





28.—Pre- and postearthquake high-tide shorelines at Fault Cove. The cove was formed by relative uplift of the former sea floor northwest of the fault scarp. The white color on the elevated bedrock surface northwest of the fault results from dessication of calcareous algae and other calcareous marine organisms. Upper photograph by U.S. Forest Service, June 8, 1959; lower photograph by U.S. Coast and Geodetic Survey, April 17, 1964.

29.—Hanning Bay fault at Fault Cove approximately at low tide. The northwest (right) block is uplifted as much as 16⅓ feet relative to the southeast block. Both blocks are uplifted relative to sea level. As a consequence, the cove is virtually dry at low tide, and the elevated beach and former offshore deposits are deeply dissected by streams. Veneer of unconsolidated deposits on the former submarine part of the downthrown block accumulated behind a preexisting fault scarp.

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30.—View southwest along Hanning Bay fault. Scarp 8½ feet high has displaced the elevated beach at south side of Fault Cove, and beach deposits draped across the scarp conceal the fault plane. Comparative photographs show that modification of the scarp was negligible between May 30, 1964 (above), and August 4, 1965 (below). Bottom photograph by M. G. Bonilla.

31.—Hanning Bay fault scarp 13½ feet high in bedrock at north side of Fault Cove. The fault dips at about 55° NW. (left), but slumping along the trace has formed a scarp that is nearly vertical or dips steeply southeast. The slumping process is accelerated by erosion along the base of the uphill-facing scarp. Location shown in figure 34.

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32.—View northwest toward cobble-gravel storm beach at north side of Fault Cove which was displaced 16⅓ feet vertically across the Hanning Bay fault scarp. Pond at right occupies a shallow tectonic depression. Photograph by M. G. Bonilla.

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cupies a tectonic depression along the scarp base immediately below the elevated beach berm.

At the one locality where the fault plane is exposed, it consists of a 1½-foot-wide zone of sheared siltstone and intensely shattered graywacke containing thin seams of interstitial clay gouge and quartz veinlets. Planar elements within the shear zone dip 50°–60° northwest and cut obliquely across the prevailing southeast dips of the bedding.

The maximum amount of measured vertical displacement along the Hanning Bay fault is at the uplifted beach ridge shown in figure 32; here the surface of the former beach berm was displaced 16⅓ feet. Maximum dip-slip displacement at this locality is almost 20 feet.

Bedrock in the upthrown block of the Hanning Bay fault in the area of maximum uplift was broken by numerous cracks that commonly trend at high angles to the fault trace. Individual cracks are as much as 200 feet long and 0.4 foot wide, and are open to depths of more than 7 feet (fig. 33). They are extension features without vertical or lateral displacement except for short sections where local caving has occurred. All but one of the cracks are in the upthrown block in a zone that extends 650 feet northwest from the fault scarp and 1,000 feet laterally along the scarp on the northeast side of Fault Cove. The largest and most continuous cracks are shown in figure 34. A careful search found no other newly opened cracks elsewhere in the exposed bedrock platform along the shore in either block except for one crack as much as 0.3 foot wide that opened along a preexisting fault in the uplifted surf-cut platform immediately south of Fault Cove.

The relationship of these exten-

33.—Near-vertical extension crack on uplifted block of Hanning Bay fault at Fault Cove. Crack is 0.2 foot wide and at least 7 feet deep. Hole in foreground is caused by local caving at the intersection of two cracks. Location shown in figure 34.

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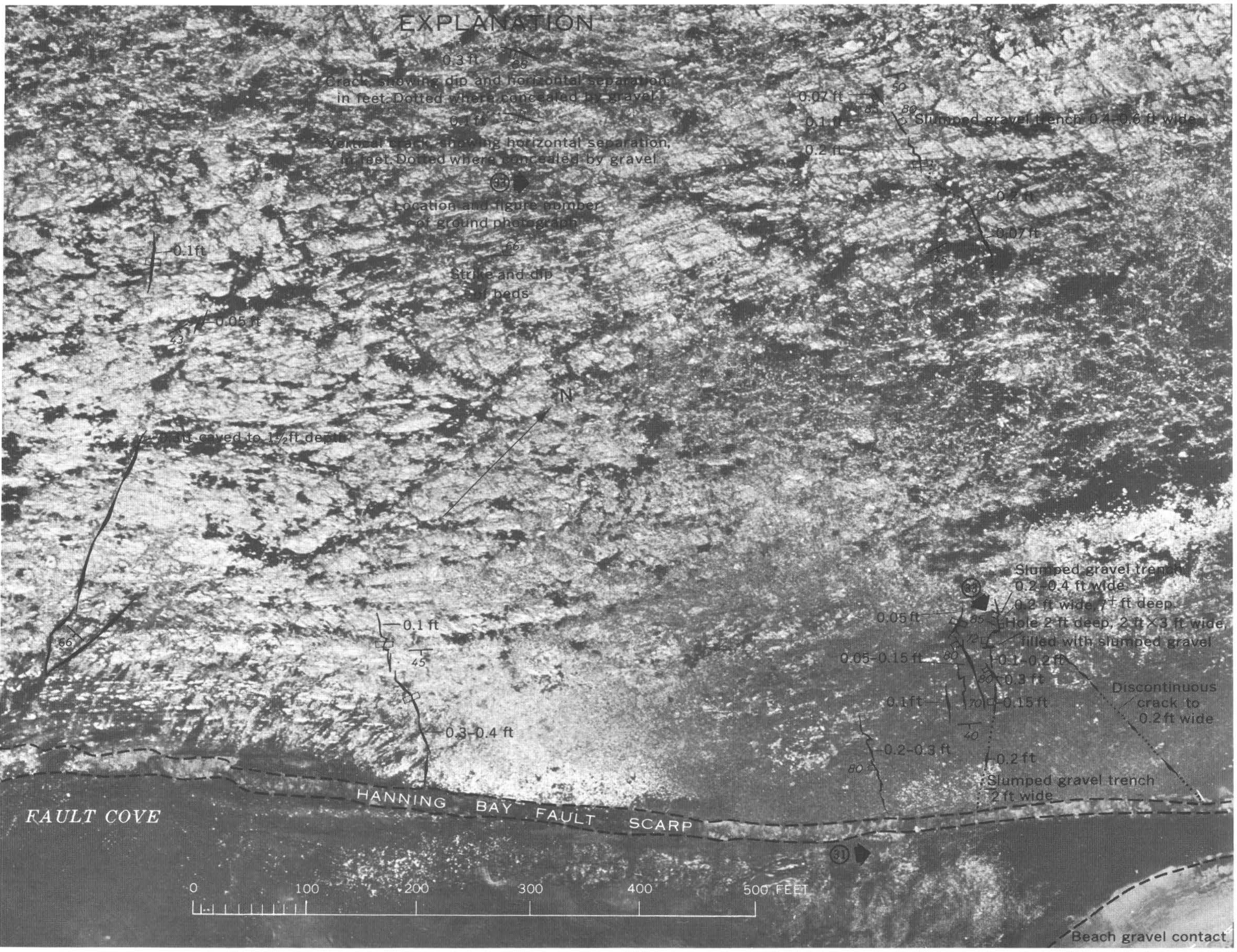

34.—Sketch map of the larger tectonic cracks in the upthrown block of the Hanning Bay fault at Fault Cove. Numerous smaller cracks in the same general area are not plotted. Location of photograph is shown on plate 2. Geology by M. G. Bonilla and George Plafker August 1, 1965. Base photograph by U.S. Coast and Geodetic Survey, July 28, 1964.

sion cracks to the Hanning Bay fault is uncertain. One possibility is that the cracks result from local tensional stresses due to surface flexing at the culmination of a distinct anticlinal warp that parallels the fault trace within the upthrown block in this area (fig. 2, profile *A–A′*).

FAULT COVE TO HANNING BAY

North of Fault Cove the apparent strike of the Hanning Bay fault swings to N. 50° E. as it crosses the 850-foot-high drainage divide between Fault Cove and Hanning Bay (fig. 35, next page). South of the divide, the fault trace follows along the northwest side of alined incised linear stream valleys that undoubtedly are controlled by a preexisting fault. The fault trace in this heavily timbered and topographically rugged segment is marked by a swath of fallen trees and brush, intermingled with debris from soil slips and small landslides (fig. 36). Ponds have formed where two small streams flow across the uphill-facing scarp (fig. 37). Soundings made near the scarp at the downstream end of these ponds, indicate a minimum vertical fault displacement of 10 feet.

North of the ponds, the fault scarp follows a peculiar course that is northwest of, and parallel to, the incised linear stream valley

35.—Hanning Bay fault north of Fault Cove. The average 65°-NW. (left) dip of this segment of the fault causes the trace (dashed) to be deflected uphill (right) as it crosses the 850-foot-high ridge between Fault Cove and Hanning Bay. The pond, at the intersection of the fault scarp and the former beach ridge, occupies a closed tectonic depression in the downthrown block.

36.—A typical swath of tilted and fallen trees in timbered areas along the Hanning Bay fault. The upthrown block was overthrust from left to right.

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37.—Pond more than 10 feet deep formed where a stream flows across the uphill-facing fault scarp (arrows). Streamflow is toward the observer. Rubble and tangle of fallen trees slid from the steep valley walls.

38.—Hanning Bay fault looking southwest from the bay. The fault trace on the ridge is marked by active landslides.

39.—Flexure and scarp with net vertical displacement of 7 feet in boulder-gravel beach along the Hanning Bay fault at south shore of Hanning Bay. Scarp 4 feet high in foreground is at the upper margin, and pond at right side of view is dammed against the base. The fault does not reappear on the north shore of Hanning Bay, which is visible in the background.

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that heads at the divide on the ridge (pl. 2). The actual rupture is well uphill from the valley bottom, and, at one locality, a zone of discontinuous scarps crosses a meadow on the ridge about 200 feet above the valley bottom. The main scarp is about 6 feet high in bedrock and trends N. 35° to 40° E. along the edge of the meadow at the break in slope on the ridge. Discontinuous subparallel scarps or flexures with two sets of associated extension cracks trending N. 25° E. and N. 75° E. are exposed in an area about 150 feet wide on the ridge summit within the upthrown block.

From the meadow the fault can be traced northward to the drainage divide as a line of scarps with associated landslides and tilted or fallen trees. The fault plane is exposed in a scarp 6 feet high on the northwest side of the prominent notch at the drainage divide (pl. 2; fig. 38). Its dip, as indicated by sheared argillite and brecciated soft sandstone, is 52° NW. This estimate is reasonably compatible with a dip of 65° for the fault plane at this locality, as calculated from the altitudes and relative positions on published topographic maps of the fault trace at the divide and at the shorelines of Fault Cove and Hanning Bay. (This calculation was not made on plate 2 because distortion of photographs used in making the planimetric map does not show these three points in their correct relative horizontal positions.)

From the drainage divide to the shore of Hanning Bay the fault trace is concealed beneath blocky talus derived from a large landslide on the uphill side of the fault (pl. 2, fig. 38). The landslide predates the earthquake, but a substantial amount of debris with freshly exposed surfaces was apparently shaken down during the earthquake.

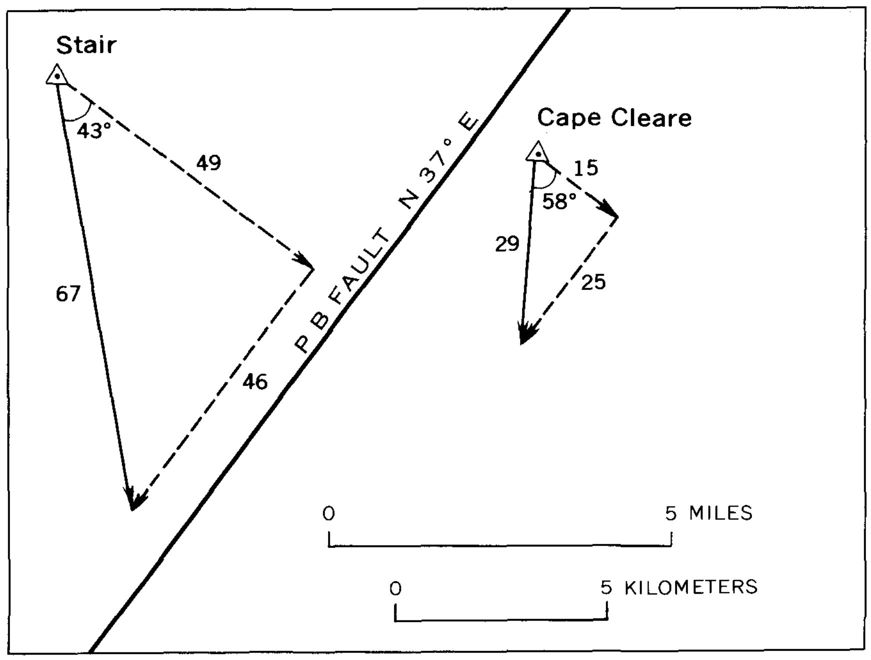
Where the fault crosses the uplifted boulder beach and former submarine platform along the shore of Hanning Bay, there is a pronounced flexure zone about 30 feet wide with a nearly vertical scarp as much as 5 feet high in boulder gravel at the head of the flexure (fig. 39). A small pond fills a depression in the downthrown block along the northeastern margin of this flexure, and the drainage is diverted along the base of the scarp, which faces upslope. Net vertical displacement across the fault zone is uncertain because many boulders have slumped along the scarp and the top and bottom of the flexure are not clearly defined. Measurements of the height of the barnacle line on either side of the zone indicate that the northwest block is upthrown about 7 feet in relation to the southeast block (pl. 2).

The fault apparently dies out somewhere beneath Hanning Bay. A detailed examination of the northeast shore along its projected strike did not reveal any of the features characteristics of the fault trace on land or any anomalous vertical displacements of the shoreline.

HORIZONTAL DISPLACEMENTS INDICATED BY GEODETIC MEASUREMENTS

A re-triangulation, by the U.S. Coast and Geodetic Survey, of part of the network of primary horizontal control stations in the vicinity of Montague Island suggests that both the horizontal shortening and left-lateral component of displacement in this area may be substantially greater than is indicated by the surface ruptures (Parkin, 1966, fig. 4).

Differences in displacement of two stations in the triangulation net—Stair (610) and Cape Cleare (553)—which straddle the Patton Bay fault as shown in figure 2, provide a geodetic check on the indicated fault movement obtained from field geologic studies. Station Cape Cleare is on the downthrown block 1 mile east of the fault trace; Station Stair is on the upthrown block 7 miles west of Station Cape Cleare and about 6 miles from the fault. Consequently, the indicated relative displacement between the two stations results from both movement on the fault and deformation of the crust between each of the stations and the fault.



40.—Orientation of horizontal displacement vectors (solid arrows) at triangulation stations Stair and Cape Cleare relative to the average strike of the Patton Bay fault. Dashed arrows are the indicated components of horizontal displacement perpendicular to, and parallel to, the fault. Numerals are horizontal displacement in feet relative to station Fishhook (40 miles northeast of Anchorage), which was held fixed in the adjustment. Triangulation data from Parkin (1966, table 1).

Unfortunately, the stations are not tied together directly across Montague Island, but rather are connected through a third-order triangulation net (containing a number of geometrically weak figures), which extends around the northeast end of the island. As a consequence, the original position of Station Cape Cleare relative to the remainder of the net is especially uncertain. Added to this uncertainty is the fact that during the earthquake all stations in this area experienced large differential vertical movements with resultant shifts in horizontal positions of the stations at high altitudes. Nevertheless, the general similarity in orientation of the two vectors and their striking difference in magnitude are suggestive of substantial relative movements between them.

As shown in figure 40, the principal vector of horizontal movement derived from the geodetic data is between N. 10° W. and N. 5° E. at an oblique angle to the fault system, whereas the direction indicated by the predominantly dip-slip displacements across the scarps is actually about N. 53° W., or approximately normal to the average strike of the faults. The re-triangulation data further indicate that the two stations moved 34 feet relatively toward one another in the direction of fault dip and that they were relatively displaced 21 feet in a left-lateral sense (fig. 40). The dip-slip shortening could have been taken up by bending of the upthrown block in addition to the fault displacement. The strike-slip displacement, on the other hand, should have been readily observable had it occurred along the fault. Absence of a large lateral-slip component on the fault suggests that either the displacement was taken up mostly by warping between the fault and the stations or, more probably, that an error has been introduced into this part of the triangulation adjustment through a slight clockwise rotation of displacement vectors.

SUMMARY AND CONCLUSIONS

The Patton Bay fault on land is represented by a complex system of right-handed en echelon reverse faults and associated flexures that has an average N. 37° E. strike. The fault at the surface dips about 85° NW. near its southern end and 50° to 75° elsewhere along the scarp. Displacement on the fault is almost entirely dip slip, the northwest side upthrown relative to the southeast side. The maximum measured vertical component of slip is 20 to 23 feet and maximum indicated dip slip is about 26 feet. A left-lateral displacement component of less than 2 feet near the southern end of the fault is probably a local phenomenon related to a change in strike of the fault that causes it to trend at a small oblique angle to the principal horizontal stress direction.

The fault system can be traced on land for 22 miles from shore to shore and is known to continue seaward to the southwest for at least 17 miles. Indirect evidence suggests that the fault system may extend southwestward on the sea floor more than 300 miles. The fault apparently dies out on its northwestern end but it could be offset en echelon in a right-handed sense and continue northeastward offshore from Montague Island at least as far as Hinchinbrook Island.

The Hanning Bay fault is a virtually continuous reverse fault with an average strike of N. 47° E., a total length of about 4 miles, and surface dips of 52° to 75° NW. Displacement is almost entirely dip slip except for a left-lateral strike-slip component of about a third of a foot near the southern limit of exposure. The maximum measured vertical component of slip is 16⅓ feet, and the maximum indicated dip slip is about 20 feet.

The reverse faults on Montague Island and the postulated submarine extension of the Patton Bay Fault lie within a tectonically important zone of crustal shortening and maximum known uplift associated with the earthquake. The principal horizontal stress direction is oriented roughly normal to the average strike of the faults in a general N. 53° W. to S. 53° E. direction.

The displacements that occurred along these two faults during the earthquake are large, but there are four convincing indications that the faults are not the primary features along which the earthquake occurred: (1) The lithology of the rock sequences is not significantly different on the two sides of the faults, as it commonly is along faults that form major tectonic boundaries. (2) Displacement along these known and postulated faults is insufficient to explain the areal extent of regional uplift—particularly the uplift seaward from the known and inferred trace. (3) Not enough movement occurred on these faults to account for the size and spatial distribution of the earthquake focal region, as defined by the aftershocks; this region extends in all directions far beyond the maximum conceivable limits of the known and postulated surface faults. (4) The epicenter of the main shock is roughly 90 miles away from the fault traces and in a position where it is not likely to lie on the down-dip projection of the fault planes.

Both the Patton Bay and the Hanning Bay faults on Montague Island are along prominent linear breaks in slope or linear stream valleys that, for the most part, were clearly visible on aerial photographs taken before the earthquake (Condon and Cass, 1958). Only the southern segment of the Patton Bay fault, for a distance of 3.3 miles, does not follow a well-established prior fault trace but instead breaks away from a pronounced scarp along which much of the previous movements undoubtedly occurred. Net Quaternary vertical displacement on and near the Patton Bay fault, as indicated by maximum topographic relief across it, could be 1,500 feet; it is probably no more than 100 feet on the Hanning Bay fault.

Many of the preearthquake scarps along these faults are sharp postglacial topographic features. The straight spruce trees along the faults, including many giants as much as 4 feet in base diameter that are probably 150 to 300 years old (J. Standerwick, U.S. Forest Service, oral commun., Oct. 4, 1966), indicate that no major displacement has occurred for at least that length of time.

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