6×10^9 m^3 of ejected material was made in the case of the eruption of Krakatoa in 1883 (*7*). Thus, even if the Mount Agung eruption involved 100 times less material than Krakatoa, the amount of airborne dust would still represent only about 1 percent of the total amount ejected.

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15 February 1965

Alaskan Glaciers: Recent Observations in Respect to the Earthquake-Advance Theory

Abstract. *Preliminary aerial photographic studies indicate that the Alaskan earthquake produced some rockfalls but no significant snow and ice avalanches on glaciers. No rapid, short-lived glacier advances (surges) are conclusively associated with this earthquake. Recent evidence fails to support the earthquake-advance theory of Tarr and Martin.*

After a series of strong earthquakes centered near Yakutat Bay, Alaska, in 1898, Tarr and Martin (*1*) reported nine glaciers which made short-lived, rapid advances (surges) (*2*). They proposed that ice and snow, shaken from the mountains in the upper regions of the glaciers, had caused a "flood" wave and that this wave traveled from source to terminus in periods of less than 1 year to 11 years, the delay being dependent upon the length of each glacier. Despite the fact that few observations were made in the upper portions of the glaciers where the avalanching was supposed to have occurred, the earthquake-advance theory has gained widespread acceptance.

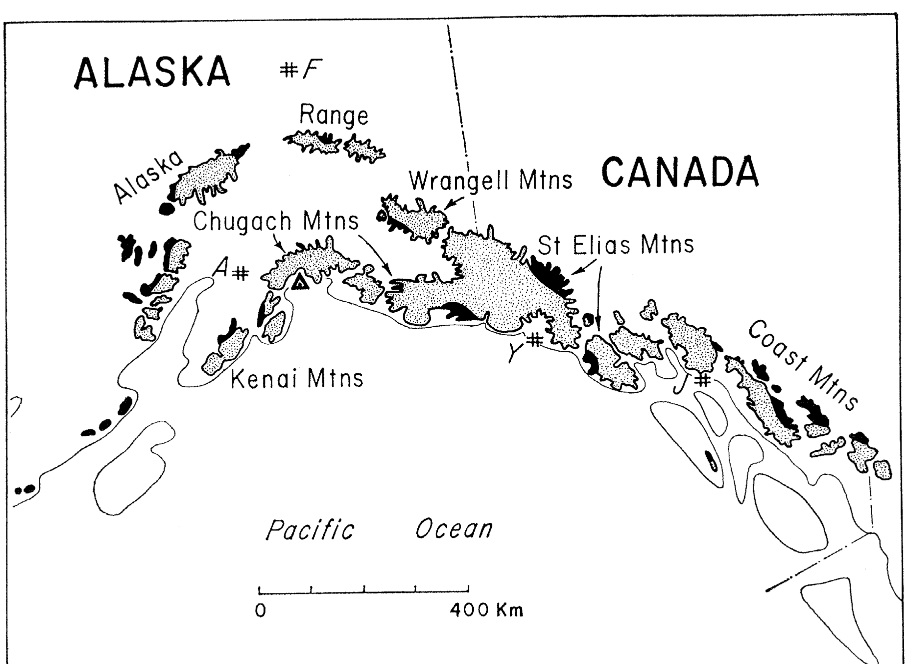

Fig. 1. Locations of major glacierized areas in south-central Alaska. Dotted areas were visually examined and the major features photographed in 1964; black areas represent glacierized regions not observed in 1964. Cities or towns: *F*, Fairbanks; *A*, Anchorage; *Y*, Yakutat; *J*, Juneau. Epicenter of 1964 earthquake indicated by triangle.

The epicenter of the Alaska earthquake of 27 March 1964 (magnitude 8.4 to 8.6) (*3*) occurred in the heavily glaciated Chugach Mountains (Fig. 1). Thirty-eight glaciers over 20 km in length and many hundreds of smaller glaciers exist in the region where the shaking was most intense. This is an area ideally situated to provide evidence which might verify the theory of Tarr and Martin. Observations in 1964 permit an immediate test of Tarr and Martin's theory in that (i) if extensive snow and ice avalanching did occur it should be readily observable, and (ii) if the earthquake caused any abrupt surging as described by Tarr and Martin the beginning stages of it in the higher reaches of the glacier should now be sufficiently developed to be detectable. The situation has, therefore, attracted the attention of many glaciologists and geologists (*4, 5*).

In 1960, 1961, 1963, and 1964, I made aerial examinations of nearly all of the glaciers in Alaska and western Canada (Fig. 1), by visual inspection and with vertical and oblique photography. More than 500 large glaciers and several thousand smaller ones were observed in late summer during the course of each study. Therefore any changes in nearly all of the more prominent glaciers could be analyzed. The following features were given careful attention: evidence of avalanching (snow, ice, or rock), position of the glacier terminus, the amount of crevassing which might denote changes in the rate of flow, evidence of changes in the surface levels of the ice both in the accumulation and ablation areas, movement and deformation of surface features such as medial moraines, changes in the marginal streams and lakes in ice-blocked valleys, and evidence of changes in glacier surface drainage and outlet streams.

The results of this study are clear. The earthquake had little visible immediate effect on the glaciers, except for some localized rockfalls. Practically no changes in terminus configurations, drainage patterns, surface levels, or glacier activity were observed which might not have occurred in these glaciers in any normal year. The examinations in 1964 in other areas and photography taken in previous years provide satisfactory bases for comparison. Evidence of significant snow and ice avalanching even on very steep slopes was not found during the August observations. Minor snow and ice avalanches had occurred in all

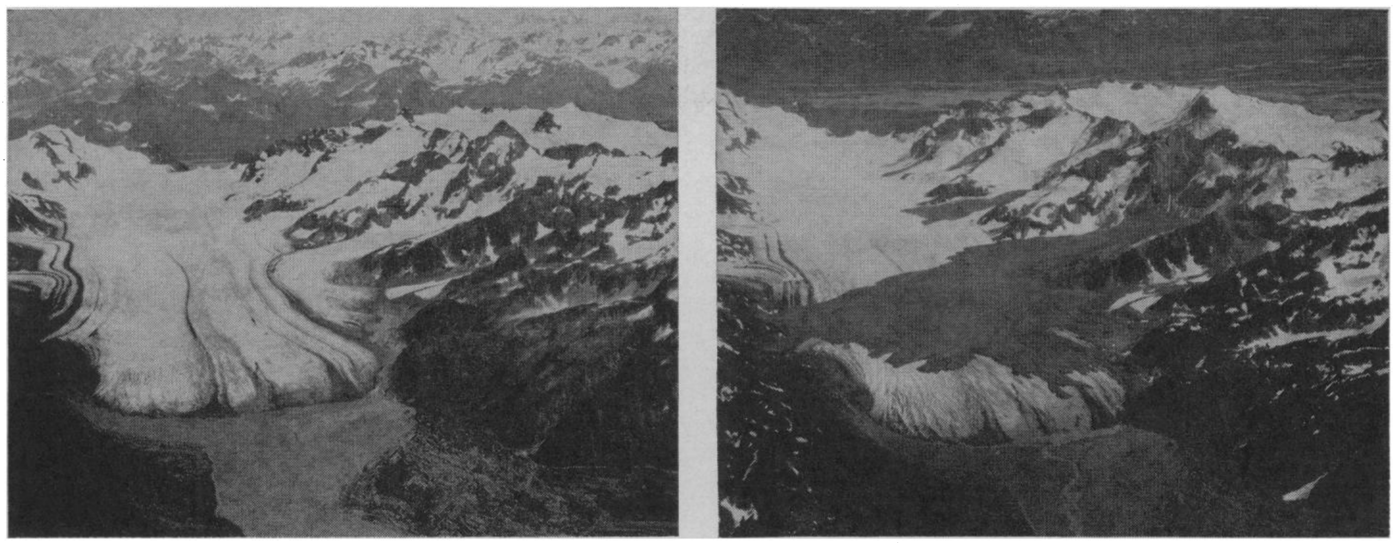

Fig. 2. Sherman Glacier, Alaska, as seen on 27 August 1963 (left) and on 24 August 1964 (right). Photos by Austin S. Post.

areas, but only to the extent expected in the course of a normal winter and spring.

Photographs taken within a week after the earthquake (*6*) also show little evidence of abnormal snow avalanching or other changes in the glaciers. Plafker considered that the amount of the snow shaken down on the glaciers was so small that it could not have a significant effect on the regimes of the glaciers.

Except for many minor rockfalls, evidence of extensive rock avalanching was found only in the Copper River region 160 km east of the epicenter. Large rock slides came to rest on the following glaciers:

1) Sherman Glacier (Fig. 2), 13 km in length: a debris flow covered about 18 km^2 (about 20 percent of the glacier surface) of the lower portion of the glacier.

2) Sioux Glacier, 10 km long: about 33 percent of the glacier surface was covered by a series of rock avalanches. The debris flows on the Sherman and Sioux Glaciers are briefly reported elsewhere (*5*).

3) Saddlebag Glacier, 6 km long: rockfall debris covered about 20 percent of its surface.

4) Johnson Glacier, 11 km long, and unnamed small glacier immediately north: numerous small debris flows.

5) Schwan Glacier, 23 km long: one tributary received debris covering about 15 km^2.

6) Stellar and Bering Glaciers, about 5700 km^2 in area: numerous small debris flows covered a total of not more than 30 km^2 of glacier surface.

7) Martin River Glacier, 48 km long: the largest branch received three large rock avalanches in the upper part of the valley.

With the possible exception of the last-named glacier, no effect of the debris on the activity of the glaciers could be detected. Although this material by insulating the ice has reduced its melting, no other immediate changes in glacier regimen could be observed. The Martin River tributary displayed evidence of rapid movement, and a lowering of the surface in the upper portion of the glacier amounting to 15 to 20 m had recently occurred as shown by its relation to unaffected marginal ice affixed to bedrock. The ice was highly crevassed in all earlier views, so it could not be determined with certainty if the 1964 movement was abnormally increased. No notable changes in the lower glacier could be found by comparing vertical photography taken in 1963 with that taken in 1964.

In order to evaluate the effects of the 1964 earthquake in regard to the earthquake-advance theory, it is necessary to identify the type of glacier

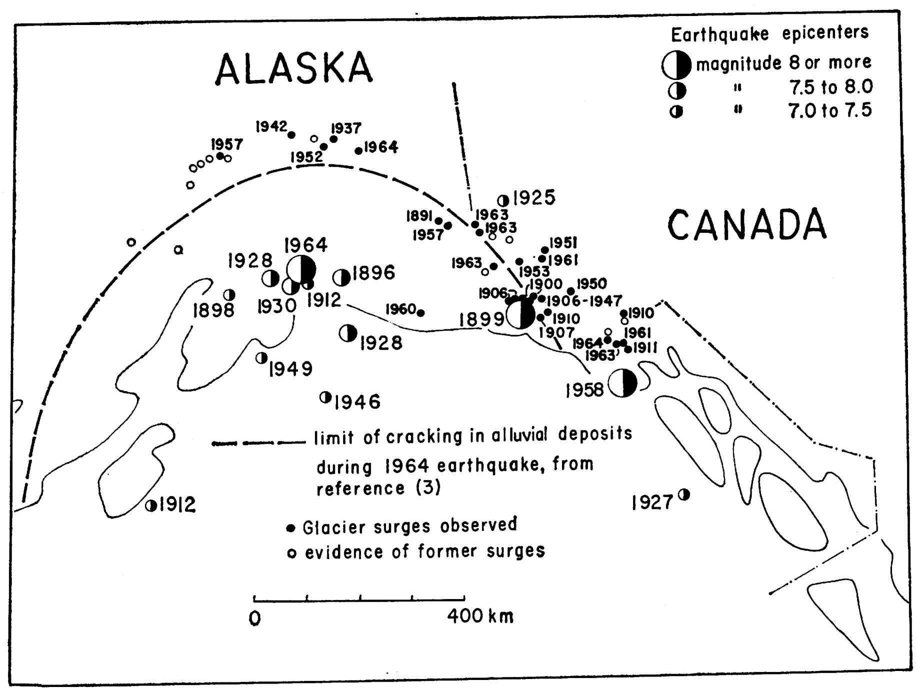

Fig. 3. Locations of all epicenters of recorded earthquakes of magnitude 7.0 or more and locations of glaciers which show evidence of past or present surges. The center of greatest earthquake activity is in the western Chugach Mountains near the site of the 1964 earthquake. No glacier surges of the type described by Tarr and Martin have as yet been reported in this area. No correlation of glacier surges either in time or geographical position to any earthquake later than 1899 is readily apparent (*9*).

behavior cited by Tarr and Martin and then to search for other examples of this behavior which show a clear association, or lack thereof, with the 1964 earthquake.

Aerial investigations since 1960 in Alaska and Yukon, and earlier work on the rapid advances of the Muldrow, Black Rapids, and Susitna Glaciers (*7*), have led to the identification of a type of glacier behavior (here called surges) which can be clearly distinguished from normal, climatically induced advances. A typical surge occurs as follows:

After a relatively long interval (of the order of 15 to 100 years) of virtual stagnation in the terminal area, an abrupt kinematic wave from the upper glacier moves very rapidly downvalley. This results in a rapid transfer of ice from the upper regions toward the terminus, and the surface of the glacier is chaotically broken. A surface displacement of 4 km or more often takes place in a single year. The ice discharge may lower the surface of the ice as much as 60 m in the upper part of the glacier. This overrides or thrusts ahead the stagnant ice at the terminus. Only in exceptional cases does the glacier advance beyond its former limit. The active period of these surges generally does not appear to exceed 3 years, regardless of the size of the glacier. Such surges may occur repeatedly in a single glacier; distinctive medial-moraine patterns or surface textures frequently provide evidence of three or more former surges. Conterminous glaciers and even individual branches in a single large glacier may not surge at the same time. Surging glaciers are rare but have been reported in many parts of the world (*8*).

All features of the nine glacier advances described by Tarr and Martin are typical of surges as described above. Thus a special search was made in 1964 for new surges. Except for the Martin River tributary glacier mentioned earlier, only the Variegated, Butler, and Art Lewis Glaciers showed any evidence of starting surges in 1964. Photographs of them show no abnormal avalanching. These glaciers are all in the St. Elias Mountains, about 450 km from the earthquake epicenter, and on the limit of the area where earthquake shaking caused cracking in alluvial deposits (Fig. 3).

Surges of other glaciers which have been observed since 1960 include the following: Klutlan and Walsh Glaciers (St. Elias Mountains), surged between 1960 and 1963; Gakona Glacier (Alaska Range) and "Tika" Glacier (near the Fairweather Range) both started surges in 1963 and were chaotically broken and evidently moving rapidly in 1964.

All of my observations suggest that the 1964 earthquake induced little significant snow and ice avalanching. Five months after the earthquake I found only one glacier which had been subjected to abnormal avalanching and which also showed some evidence of the beginning of a surge.

Other evidence which casts doubt on the earthquake-advance theory includes (i) a lack of correlation in time and space between earthquakes and glacier surges since Tarr and Martin studies (Fig. 3), (ii) the fact that two of Tarr and Martin's nine glaciers head in open basins where appreciable avalanching is unlikely, and (iii) a breakdown of Tarr and Martin's correlation between glacier lengths and time delays since the earthquake, when these lengths are measured on modern, accurate maps.

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2. The term "advance" is frequently technically incorrect as the affected glaciers do not always advance beyond their former limits. The term "surge" is here used to describe sudden, large-scale, short-lived glacier movements whether a terminal advance occurs or not.
3. A. Grantz, G. Plafker, R. Kachadoorian, *U.S. Geol. Surv. Circ. No. 491* (1964); A. Grantz, G. Plafker, J. E. Case, *Program 1964 Annual Meetings, Geol. Soc. Am.* et al., Miami Beach, 19–21 Nov. 1964, p. 77.
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9. Many glacier surges have doubtless gone undetected since 1900 owing to the dearth of investigations between 1913 and 1960. The apparent concentration of surging glaciers in the early 1900's in the Yakutat Bay area shown in Fig. 3 is probably due at least in part to a concentration of investigations in that area at that time.
10. Investigations in 1960, 1961, and 1963 were sponsored by NSF grants to the University of Washington, Department of Atmospheric Sciences. The 1964 studies were sponsored by the U.S. Geological Survey. W. Fairchild, D. Sheldon, and J. Wilson provided skilled piloting on aerial photographic missions in difficult terrain. Publication authorized by the Director, U.S. Geological Survey.

27 January 1965

Split-Twig Figurines from Northern Arizona: New Radiocarbon Dates

Abstract. *Recently released radiocarbon dates for split-twig figurines from Marble Canyon, Arizona, are 4095 ± 100 years ago; they substantiate previously determined dates of 3530 ± 300 and 3100 ± 110 years ago. A recently excavated site in Walnut Canyon, Arizona, extends the geographical range of the figurines. The dates of samples from this site are 3500 ± 100 and 3880 ± 90 years ago. It is hypothesized that the figurines were magicoreligious artifacts related to the Pinto complex of the Desert Culture.*

In 1958 a detailed study was published (*1*) of the "Grand Canyon Figurine Complex," represented by distinctive and well-constructed animal effigies made of split willow (*Salix* sp.) twigs (see Fig. 1). In that paper the first radiocarbon dating of these artifacts, and dates of 3100 ± 110 and 3530 ± 300 years ago, were reported. Eleven discoveries from at least nine separate sites in the Grand Canyon and adjacent areas of northern Arizona and southeastern Nevada were described. It was postulated that, although "no material was found associated with the split-twig figurines which would allow for definite placement with any established archaeological complex in the Southwest or the Basin," they were magicoreligious objects that "may have been part of the widespread Desert Culture."

In the summer and fall of 1963, two new collections of split-twig figurines were made in northern Arizona by Euler and Olson. Euler, in a visit to Stantons' Cave, the site at which some of the first-reported of these enigmatic artifacts were found, recovered ten complete and ten fragmentary specimens. This site (Ariz. C:5:3 in the Arizona State College Archaeological Survey) is on the Colorado River at an elevation of 2785 feet (847 m); it is in the inner gorge of Marble Canyon and is approximately 50 km upstream from the boundary of Grand Canyon National Park. The huge limestone solution cavern contained no surface evidence of human occupation except the figurines, which were found in three separate caches near the entrance, under large rockfalls from the ceiling of the cave. The artifacts conformed in every respect to those previously reported, ranging in length from 7.5 to 19.0 cm. Seven of them were pierced through the body by unsplit twigs 8.9 and 31.0