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SEISMIC EVIDENCE FOR GLACIER MOTION

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ABSTRACT. Unusual seismic signals with weak P phases and well-developed monochromatic shear-wave trains have been recorded and their sources located near College Fiord, Alaska. Epicentral determinations show that they originate on or near glaciers. Some of the events have equivalent earthquake magnitudes of 2.0 to 2.5. These energy sources seem to be compatible with spasmodic glacier movement. Smaller events occur often—as many as 60 per day.

RÉSUMÉ. *Preuves sismiques des mouvements glaciaires.* Des signaux sismiques inhabituels avec de faibles phases P et des traces d'ondes de cisaillement monochromatiques bien développées ont été enregistrées, leurs sources décelées près de College Fiord, Alaska. Les déterminations d'épicentre montrent qu'ils prennent naissance sur ou près des glaciers. Certains de ces phénomènes ont des magnitudes de 2,0 à 2,5 dans l'échelle des tremblements de terre. Les énergies mises en jeu semblent compatibles avec les mouvements spasmodiques des glaciers. De plus faibles mouvements se produisent souvent, jusqu'à 60 fois par jour.

ZUSAMMENFASSUNG. *Seismischer Nachweis für Gletscherbewegung.* Ungewöhnliche seismische Signale mit schwachen P-Phasen und gut entwickelten monochromatischen Scherwellenzügen wurden aufgezeichnet; ihr Quellpunkt wurde nahe beim College Fiord in Alaska lokalisiert. Epizentrische Bestimmungen zeigen, dass sie von oder neben einem Gletscher stammen. Einige der Vorgänge entsprechen Erdbebenstärken von 2,0 bis 2,5. Diese Energiequellen scheinen mit ruckartigen Gletscherbewegungen vereinbar zu sein. Schwächere Vorgänge ereignen sich oft — bis zu 60 mal pro Tag.

INTRODUCTION

Seismic events with weak P phases but well-developed monochromatic shear-wave trains are often recorded on the University of Alaska's high-gain seismic station SCM in southern Alaska (Fig. 1). Occasional large events are also recorded on some of the National Oceanographic and Atmospheric Administration's Palmer Seismological Observatory stations. These additional data permit determination of their source areas. What may be similar events have been reported from south-east Alaska and British Columbia (G. C. Rogers, Victoria Geophysical Observatory; personal communication from J. Davies) and apparently from Antarctica (Adams, 1971). However, we know of no published study in which sufficient data were accumulated to allow accurate source locations.

EVENT DESCRIPTION

The events considered in this study typically show a weakly developed P phase and an almost monochromatic, non-dispersive, well-developed wave train propagating at shear-wave velocities (Fig. 2). The period of this distinctive wave train is normally about 0.6 s and the ground motion at recording stations seems to exclude their interpretation as surface waves. Some of the larger events have been recorded as far away as station PJD, 420 km from the source, and show no dispersion. Smaller events with the same characteristic monochromatic wave train and a P phase so weak as to be undetectable are often recorded at station SCM. The source of these weak events is probably the same as that for the larger events which were recorded well enough to allow location.

FREQUENCY OF OCCURRENCE

Although complete tallies of the events have not been kept, there are several time periods during which useful data on their occurrence were obtained as an adjunct to other studies. Daily counts for two of these time periods are shown in Figure 3. Station SCM is closer to the source area and of higher gain than the Palmer stations, so one should not compare the level of

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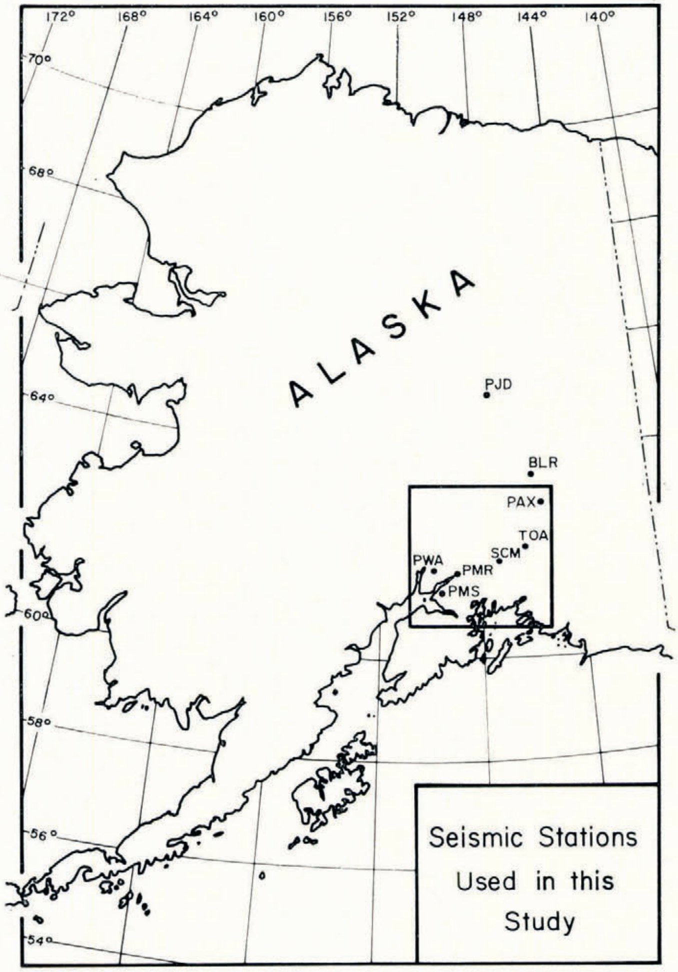

Fig. 1. Index map of Alaska showing the area of Figure 5. Stations PMR, PMS, PWA and TOA are operated by NOAA's Palmer Seismological Observatory. Stations SCM, BLR and PJD are operated by the Geophysical Institute of the University of Alaska.

activity of the two time periods. Although the smaller events recorded at SCM are often difficult to distinguish from "background noise", they often occur in large numbers (Fig. 4), as many as 60 per day.

No data have been compiled to investigate seasonal variations in frequency of occurrence. However, these events have been noticed throughout the year.

Location of events

To determine the source area of these unusual events, all of the larger ones which occurred during the time periods shown in Figure 3 were scaled from both the Palmer Observatory and the Geophysical Institute records. Due to the very weak nature of the P phases, only 12 of the events were recorded well enough at nearby stations to allow epicenter determination. A notable event which occurred in 1968 (Fig. 2) was also included and these 13 events were processed with the Geophysical Institute's routine earthquake epicenter-location computer

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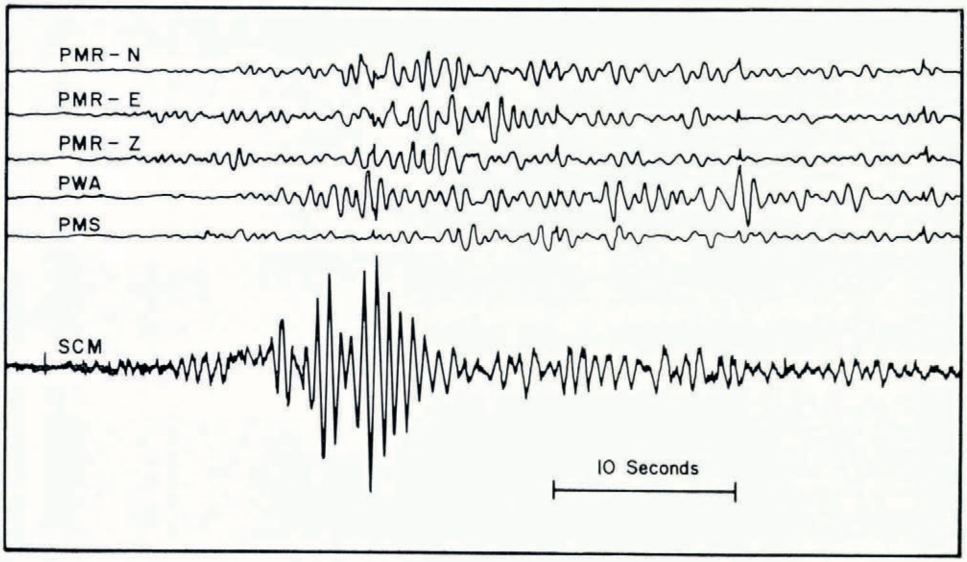

Fig. 2. Example of typical event (event 1 in Table I).

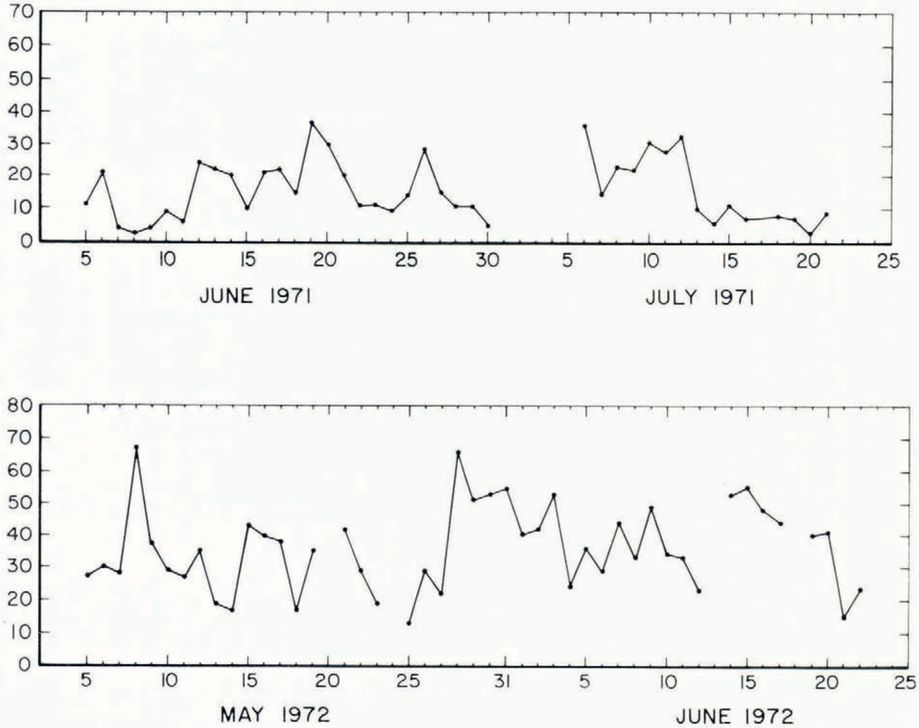

Fig. 3. Daily occurrence of events. Top curve obtained from Palmer records, bottom curve from station SCM. Missing data are due to incomplete records or high background noise.

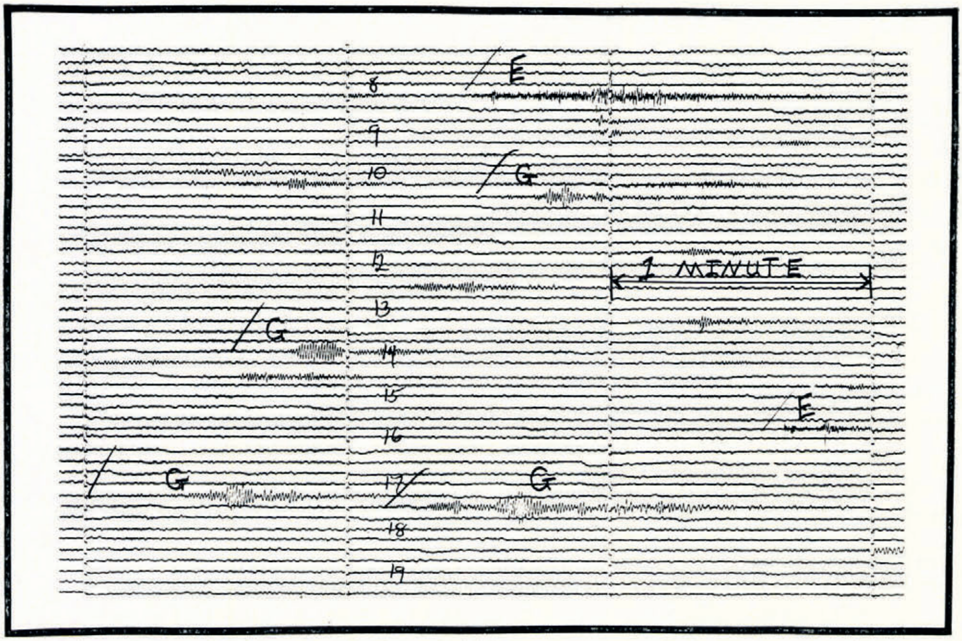

Fig. 4. Record sample from 28 May 1972. Signals marked "E" are earthquakes, the larger glacier signals are marked "G".

Fig. 5. Epicenters of the events. Numbers refer to Table I.

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program which is based on P-phase transit times. The locations of the events are shown in Figure 5 and other parameters are given in Table I. Most of the events are clustered on or near Harvard Glacier at the head of College Fiord and all but two of the events yielded a surface source.

TABLE I. EVENT PARAMETERS

Event number	*Date*	*Origin time*	*Depth* km	*Standard deviation**	*Magnitude*	*Comments*
1	20 May 1968	09 : 28 : 46.0	15	0.0	2.1	Fair to poor readings. Magnitude hand calculated (see text)
2	16 June 1971	14 : 22 : 34.8	0	0.2	2.1	
3	19 June 1971	06 : 26 : 12.0	0	0.6	2.1	
4	22 June 1971	09 : 28 : 25.5	0	0.8	1.9	
5	25 June 1971	19 : 08 : 14.4	0	0.2	2.0	
6	6 July 1971	13 : 47 : 33.1	0	0.2	1.7	
7	9 July 1971	06 : 54 : 54.6	0	0.3	2.1	2nd arrivals difficult to identify. Up to six "beats" in wave train at PMS
8	10 July 1971	19 : 33 : 48.9	0	0.2	1.7	
9	16 July 1971	10 : 13 : 55.4	0	0.3	2.5	
10	23 July 1971	09 : 19 : 01.8	250	0.0	1.6	Multiple event? Many "beats" at PWA
11	17 May 1972	07 : 16 : 08.5	0	0.2	2.0	
12	3 June 1972	06 : 46 : 23.9	0	0.2	3.0	Magnitude from one station only
13	9 June 1972	10 : 16 : 34.8	0	0.0	1.8	

* Standard deviation in seconds for the P-phase transit-time residuals.

Event 1, located north-west of the cluster at a depth of 15 km, has a signature similar to events located on the glacier and may be slightly in error. Event 3 is probably not from Harvard Glacier as the signal character (Fig. 6) and the order of P-phase arrivals at the stations indicates a different source. Event 7 is definitely from a source near the mouth of College Fiord and, unlike events from Harvard Glacier, was first recorded at station PMS. Other events too small to locate but with similar signature and arrival times have been observed, although the source area for event 7 is not as prolific as the Harvard Glacier area. Event 9 probably represents another source for these events, although no others have been located there and none has been noted on the records to have similar character. Event 10 has first P-phase arrival at station PMR and a character different from the events near Harvard Glacier. However, the calculated depth of 250 km and the rather poor quality of the P phase indicates possible error in location and it seems prudent to disregard event 10.

Figure 6 contrasts typical events 2 and 5 from the group on Harvard Glacier with the anomalous events 3, 7, 9 and 10 as recorded at SCM. The differences in signature characteristics are readily apparent and, in addition, event 7 was noted to have a very unusual signature at PMS, the station closest to that event.

Similarities of signature for the many small events recorded at SCM show that the great majority of them originate in the Harvard Glacier area, with a few coming from the area near the mouth of the fiord.

A few rare events similar in appearance to those from College Fiord have been recorded at stations BLR and PAX. The S minus P times of these small events and the order of arrival at the two stations dictate a source within the Alaska Range, although none of the events has been large enough to locate. We speculate that the common signal forms of these events indicate a mechanism similar to the source in the College Fiord area.

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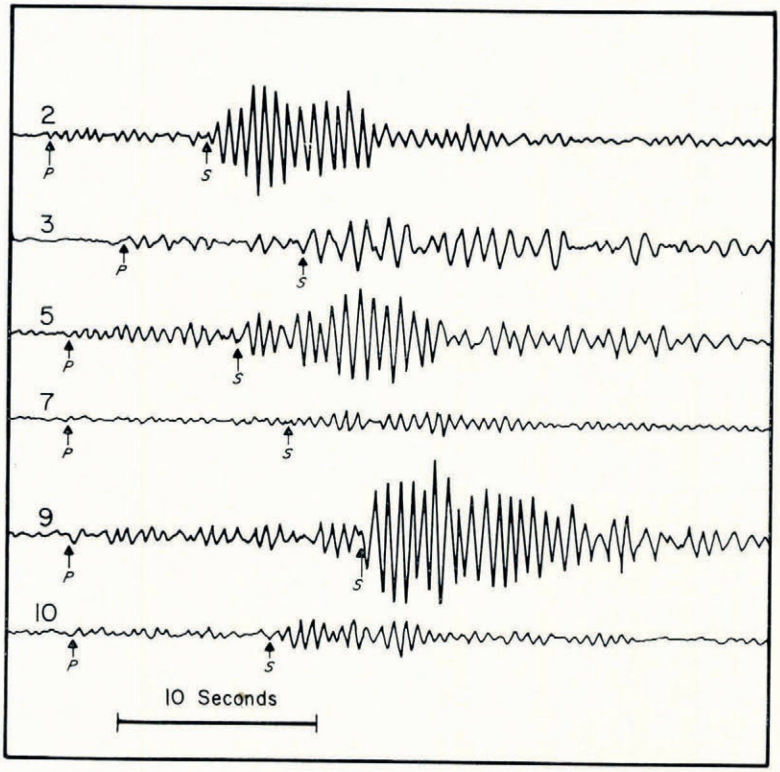

Fig. 6. Comparison of signature of typical events from Harvard Glacier (events 2 and 5) and events not located on Harvard Glacier. All records are from station SCM.

The uncommon monochromatic shear-wave train is a source characteristic since it propagates in different azimuths and to a distance of 400 km (for the larger events) conserving its signature. The peculiarities of this predominantly shear-type source will be further investigated.

Magnitude and energy

The Richter magnitudes computed for the event of 20 May 1968 at stations SCM, BLR and PJD were 2.3, 2.0 and 2.1, respectively. For an earthquake of magnitude 2.1, the energy, E (in ergs), calculated from the empirical formula (Richter, 1958, p. 366)

$$\log_{10} E = 11.4+1.5M$$

is $10^{14.5}$ erg ($10^{7.5}$ J). If one assumes that these events are produced by glacier motion, it is instructive to calculate the amount of motion required to provide this much seismic energy. Applying this formula to the events in this study will give only a rough estimate of the total energy involved because little is known of the conversion efficiency of glacier potential energy to seismic energy.

If an area A of the glacier bed is stressed by the yield stress Y of the ice, the displacement on release of the stress is d and, if the seismic efficiency is e, then the energy available is

$$AYde = E.$$

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Specifying reasonable upper limits for unknowns, A and e, will give a lower limit for d. Thus, assuming a yield strength of 1 bar, $Y = 10^5$ N m^{-2}, and using the calculated energy $E = 10^{7.5}$ J, we have $Ade \simeq 300$ m^3, so that if we suppose A not more than 1 km^2 and e not more than 10%, we find that d is not less than 300×10^{-5} m or $d \simeq 3$ mm. Although these figures are based on some assumptions that may not be valid, they appear reasonable and are at least within a few orders of magnitude of reality and indicate that measurement of seismic energy release for a substantial time period could give an indication of the total mass movement on a glacier.

We hypothesize that these unusual seismic events are due to glacier movement and that the movements associated with some events may be quite large. Although all the events we have been able to locate have been near glaciers in marine environments, we do not feel that they are produced by calving because the locations are well inland with the exception of event 7. Also the weak events of similar character from the Alaska Range exclude calving as an essential source.

Harvard Glacier, where most of the events are produced, is the most active glacier in the Prince William Sound area (personal communication from Larry Mayo, U.S. Geological Survey).

The very nature of these events excludes several sources. For example, earthquakes at comparable distances give records which have a much higher frequency content and are not at all monochromatic. The very weak P phases and pronounced S phases of these events are unlike those of any other event observed by the authors.

Conclusions

There is every indication that the unusual seismic events generated in the College Fiord–Harvard Glacier area are associated with glaciers. The energy of the largest events and the frequency of occurrence of the smaller events indicates that jerky, short-lived rapid motion could significantly contribute to the total movement of the glacier.

Acknowledgements

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