# Earthquake Potential and Ground Motions for the Pillar Mountain Landslide, Kodiak, Alaska

by

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## INTRODUCTION

This report has been written in response to a request from the City of Kodiak for an estimate of the maximum earthquake accelerations that are likely in the vicinity of the city, so their potential for possibly triggering movement on the Pillar Mountain landslide may be considered. A warning of possible increased movement at the landslide, which lies above part of Kodiak Harbor, was issued two years ago (Kachadoorian and Slater, 1978), and since then several organizations have investigated various aspects of the situation further. This report deals with the regional geologic framework, the presently active geologic processes, the earthquake history, the potential for faulting along the two main types of faults that cut the region, and the likely accelerations from earthquakes on those faults.

## GEOLOGIC FRAMEWORK AND ACTIVE GEOLOGIC PROCESSES

The City of Kodiak is underlain by the Kodiak Formation, a firm dark-gray bedrock unit of Late Cretaceous age (Moore, 1969). This formation consists of thinly interbedded slate and hard impure sandstone (graywacke), believed to have originated from deep-sea trench deposits (Nilsen and Moore, 1979). The deposits were strongly compressed and mildly metamorphosed when they were squeezed between two tectonic plates which converged at the former trench. The outcrop of the boundary between the presently active Pacific and North American plates is farther seaward than the Kodiak Formation. It is at the Aleutian Trench, 170 km seaward from Kodiak.

Since its lithification, the bedrock at Kodiak Island has been uplifted from former great depth to the level of its present outcrops, and erosion has removed the covering materials. Glacial ice during the Pleistocene Epoch was the most recent major eroding agent. After stripping the terrain down to fresh bedrock, the moving ice carried nearly all the resulting debris offshore. Glacial abrasion smoothed the terrain and at most low-lying places on Kodiak Island left relatively gentle hillslopes. At Pillar Mountain, however, it carved an unusually steep slope, and that steepness is the principal cause for the Pillar Mountain landslide.

Southern Alaska is one of the most earthquake-prone areas in the world, and the convergence of the Pacific and North American plates causes the earthquakes (Lahr and Plafker, 1980). On the basis of computer analysis of worldwide plate-boundary slip vectors and seafloor-spreading rates, the Pacific plate at the Aleutian Trench near Kodiak is underthrusting the North American plate in the direction N. 24 W. at a long-term average rate of 6.7 cm/yr (Minster and Jordan, 1978). The upper surface of the underthrust plate lies approximately 25 km (15 mi) below the City of Kodiak and dips about 7° away from the ocean basin (von Huene and others, 1979). Farther to the northwest, where the upper surface of the underthrust Pacific plate reaches the base of the North American plate 85 km below the volcanoes of the Alaska Peninsula, the dip steepens gradually to 40°. Geologists infer that low-density magma derived from easily melted crustal layers on the descending plate rises buoyantly to produce the volcanoes.

## HISTORIC SEISMIC RECORD

The record of past seismicity is important both as a basis for determining the regional tectonic regime and for estimating the probable return time for great ($M_s \geq 7.7$) events. The distribution of earthquake epicenters near Kodiak Island since January 1967, based on the National Oceanic and Atmospheric Administration (NOAA) Environmental Data Service earthquake data file, are shown in Figure 1. A subset of these data with good depth control (precision of about 10 km for one standard deviation) is shown in cross section in Figure 2. The dominant feature to note on this cross section is the distribution of Benioff zone events which occur at or near the upper surface of that portion of the Pacific plate that has been thrust below Alaska. The earthquakes shallower than 40 to 60 km are predominantly thrust events and reflect slip at the interface between the underthrust oceanic and overlying continental plates. Great thrust earthquakes, such as the 1964 Prince William Sound shock, occur in this setting, that is, at shallow depth on the interface between the two plates. Below 40 to 60 km, earthquakes occur within the upper part of the underthrust oceanic plate and reflect brittle failure within the relatively cool downgoing plate rather than slip on the interface between the plates. Also seen in Figure 2 are shallow-focus earthquakes within the wedge of crust above the active megathrust zone and near the axis of the active volcanoes. The shallow earthquakes occur on smaller faults related to the main underthrusting along the shallow part of the Benioff zone.

There are limitations to the data available in the NOAA file for this region. The plot of magnitude versus time since 1900 in Figure 3 clearly reveals the incompleteness of the data set at small magnitudes during older times. Since the 1950's, for example, the magnitude threshold for earthquake location has improved from about 5 to about 2. The available data are not sufficient at the present time to assign with confidence the events shallower than 35 km to mapped or inferred faults, or to delineate near-surface faults on the basis of seismicity.

Old faults are ubiquitous on the island, and some earthquakes may take place along their reactivated strands (Pulpan and Kienle, 1979). But known faults with significant late Cenozoic displacement are confined to a zone along the southeast coast of the island--for example, 30 km from Kodiak at Narrow Cape (Moore, 1967)--or are still farther southeastward on the continental shelf along a zone parallel with the Aleutian Trench (Fisher and von Huene, 1980; von Huene and others, 1980).

The zone of surface deformation off the southeast coast of Kodiak Island is an extension of the zone of ancient faulting that was reactivated in part during the 1964 earthquake and came ashore to the northeast on Montague Island. The deformed zone parallels contour lines of equal elevation change accompanying the 1964 earthquake. The changes ranged from about 2 meters of subsidence at Kodiak to 2 meters of uplift on the shelf (Plafker, 1972; von Huene and others, 1972).

The near-surface earthquakes in the vicinity of Kodiak are within the thin wedge-shaped edge of the North American plate and probably result from strain changes both preceding and following great earthquakes. The lack of recognized young displacement on faults near the City of Kodiak suggests that the movement along faults there is small and infrequent, or possibly not consistently in the same direction, so as to cumulate during successive earthquakes.

Effects at Kodiak from the 1964 Prince William Sound earthquake of magnitude 8.5 have been well documented (Kachadoorian and Plafker, 1967). From the start of faulting at the earthquake focus under Prince William Sound, 450 km to the northeast, the rupture propagated southwestward passing under the City of Kodiak and approximately 150 km beyond to the southwest end of Kodiak Island. Although earthquakes similar to the 1964 earthquake are expected in the future, it is difficult to estimate their frequency of occurrence. Estimates of the average dip slip during the 1964 shock range from 7 meters inferred from the radiation pattern of seismic surface waves (Kanamori, 1970) to 12.2 meters calculated from geodetically and geologically measured horizontal and vertical displacements (Hastie and Savage, 1970). If the convergence between the Pacific and North American plate were to occur episodically in earthquakes similar to the 1964 event, then the long-term average convergence rate of 6.7 cm/yr (Minster and Jordan, 1978) would suggest a recurrence time of about 100 to 200 years. This estimate is a minimum because no allowance is made for plate convergence being accommodated in nonseismic plastic deformation or for the contribution of other large shocks somewhat smaller than the 1964 earthquake.

The historic instrumental record extends only back to 1897, and then only for the largest events. Sykes and others (1980) have reviewed many Russian documents in order to extend the record for large shocks back to the 1780's. By their analysis, large events producing strong shaking and numerous aftershocks occurred near Kodiak in 1788 (produced vertical deformation of the coastline, and landslides), 1792 (produced local tsunami), 1844, 1854 (produced local tsunami), and 1900. Although instrumental data are not available for the events prior to 1897, the descriptions of their effects suggested to Sykes and others (1980) that the magnitudes were most likely in the range 7.7 or above. Thus, the interevent time for great shocks in the vicinity of Kodiak based on sparse data from 1788 to 1964 has ranged from 4 to 64 years, and averaged 35 years.

## GROUND MOTIONS

Based on the historic record of seismicity and current knowledge of the seismotectonic setting, it is recommended that two types of earthquakes be considered in evaluating the seismic stability of the Pillar Mountain landslide. The first is a great earthquake on the Aleutian megathrust similar to the 1964 shock, occurring on the gently dipping interface between the Pacific and North American plates and extending directly beneath Kodiak. The other is a local M 6.5 shock occurring on an unspecified near-surface fault at a distance of 10 km from the site. These two events are chosen, not because they are the most probable earthquakes, but because they would produce the most severe shaking at the Pillar Mountain site.

During the past ten years, numerous instrumental recordings of strong ground motion have been obtained within a few tens of kilometers of faults elsewhere during earthquakes of about magnitude 6.5. Based on these data, the peak horizontal bedrock acceleration most likely to be expected at a site 10 km from the fault in a magnitude 6.5 earthquake is about 0.3-0.4 g (Boore and others, 1978; Boore and Porcella, 1980). The 90th percentile estimate of peak acceleration, which is the value that has only a 10 percent chance of being exceeded, is approximately twice as large. The duration of shaking, measured as the time interval between the first and last horizontal acceleration peaks equal to or greater than 0.05 g, is expected to be in the range of 10-20 seconds.

No instrumental recordings of strong ground motion have been obtained within 100 km of a fault during an earthquake of magnitude 8.0 or greater. At the time of the 1964 earthquake, no strong-motion seismographs were operating in Alaska. Thus, there are no instrumental data from great earthquakes to constrain estimates of shaking occurring on the Aleutian megathrust, 25 km beneath the site. Some investigators argue that ground accelerations close to the fault in a magnitude 8 earthquake are comparable to or not much greater than in a magnitude 6.5 shock. Others allow that near-fault accelerations may increase with magnitude above magnitude 6.5. In this case, the consequences of a sudden earthquake-induced landslide could be catastrophic, so presumably only a small risk of occurrence is tolerable. It would be reasonable therefore, to assume that the peak horizontal bedrock accelerations at the site during the postulated magnitude 8.5 earthquake would be significantly greater, perhaps by a factor of two, than those from the local magnitude 6.5 earthquake. The duration of shaking referred to the 0.05 g threshold amplitude of motion would also be substantially greater for the magnitude 8.5 earthquake, perhaps by a factor of three to five. During the 1964 earthquake, intense ground motion at Kodiak is reported to have lasted for approximately 2 1/2 minutes, with perceptible motion lasting an additional 2 to 3 minutes (Kachadoorian and Plafker, 1967, p. F19). What level of accelerations correspond to the intense phase of shaking is not known, however, the minimum perceptible level of acceleration is 0.001 g (Richter, 1958, p. 26).

The above estimates of peak horizontal accelerations for the two postulated earthquakes can be compared to probabilistic estimates taken from two recent maps of peak accelerations that include the Kodiak region. Woodward-Clyde Consultants (1978, v. 3, fig. 3-17) estimate the 100 year return-period peak horizontal acceleration to be about 0.3 g. Thenhaus and others (1979, plates 2 through 4) estimate peak accelerations of about 0.2, 0.4, and 0.6 g for return periods of 100, 500 and 2500 years, respectively. (There is about a 10 percent chance of exceeding the 100-year return-period value in 10 years, the 500-year value in 50 years, and the 2500-year value in 250 years.) Both of these studies assume that near-fault horizontal fault accelerations on rock do not exceed 1.0 g. Recent strong-motion recordings close to moderate-sized earthquakes (for example, Brady and others, 1980) suggest that this assumption may have to be modified once near-fault strong-motion records are obtained from earthquakes of magnitude 7 or larger.

As a parameter for use in evaluating slope stability, peak ground acceleration has limited utility. More important information is the duration of shaking above the critical acceleration, which is the acceleration needed to initiate sliding and which is a function of the geometry of the slide and the slip surfaces, the geotechnical properties of the slide materials, and local hydrologic conditions. If a physical model of the Pillar Mountain landslide were developed through further field investigations, then a dynamic analysis of its stability under earthquake loading could be undertaken and potential displacements during postulated earthquakes could be estimated (Wilson, 1979). For such analyses, representative time histories of bedrock accelerations would be needed. Representative time histories for the magnitude 6.5 shock could be selected from the suite of existing strong-motion recordings, but the time history for the magnitude 8.5 earthquake could only be approximated by a theoretical record synthesized from strong-motion data from smaller shocks.

## DISCUSSION

The thin-bedded slaty rocks of the Kodiak Formation at the landslide dip into Pillar Mountain. The slip surfaces of the bedrock blockslide consist of rupture zones containing disaggreagated fragments bounded by bedding cleavage and joints. Because the Pillar Mountain landslide is known to have moved, and because a total of about 20 meters of displacement has occurred on slip surfaces at its head, the critical acceleration has clearly been exceeded many times during the post-glacial period. If most of the movement of the blockslide has occurred during and immediately following great earthquakes, the average recurrence interval of 35 years for great earthquakes and the 10,000 years since the Pleistocene Epoch indicate an average movement on the order of 10 cm for one event.

Continued movement of this type causes less reason for concern than the possibility that a future earthquake or other process might reduce the resistance to sliding. If rock fragments are rotated into an unstable condition along a critically oriented slip zone, a high-speed rockslide along a slope of approximately $40^0$ might take place (Kachadoorian and Slater, 1978).

At the present stage of investigation, work should continue that will define the rupture surfaces on which movement has occurred in the past, giving special attention to the upper parts of the blockslide for surfaces of weakness that might favor a high-speed rockslide or rockfall. When that has been done, the accelerations of this report can be used to estimate the potential for generating a rockfall, and appropriate remedial action can be undertaken.

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Figure 1. Seismicity of Kodiak region, 1 January 1967 through July 1978. Triangles indicate focal depths of less than 50 km; crosses, 50 km or more. Smallest symbols indicate magnitudes of less than 3; intermediate, 3 to 6; largest, 6 or greater. Total of 655 shocks are plotted, of which only three are magnitude 6.0 or greater. Earthquake foci with poor depth control are included in the less than 50 km depth category.

Figure 2. Cross section of subset of seismicity shown in Fig. 1, projected on a vertical plane along line A-A'. Hypocenters determined by the University of Alaska and archived in the NOAA data file are shown for shocks from April 1976 through September 1977. These data better reflect the true depth distribution than do those of Fig. 1, because arrival times at local seismograph stations were used to determine the hypocenters. Symbol size indicates magnitude range, as in Fig. 1. Volcanic arc is indicated by V, Kodiak by K.

Figure 3. Seismicity in the area of Fig. 1, as recorded in the earthquake data file of the National Oceanic and Atmospheric Administration. Each event plots as a point at the corresponding time and magnitude. Events for which no magnitudes have been assigned are plotted on the horizontal axis. The vertical band in 1964 represents aftershocks of the great Prince William Sound earthquake.

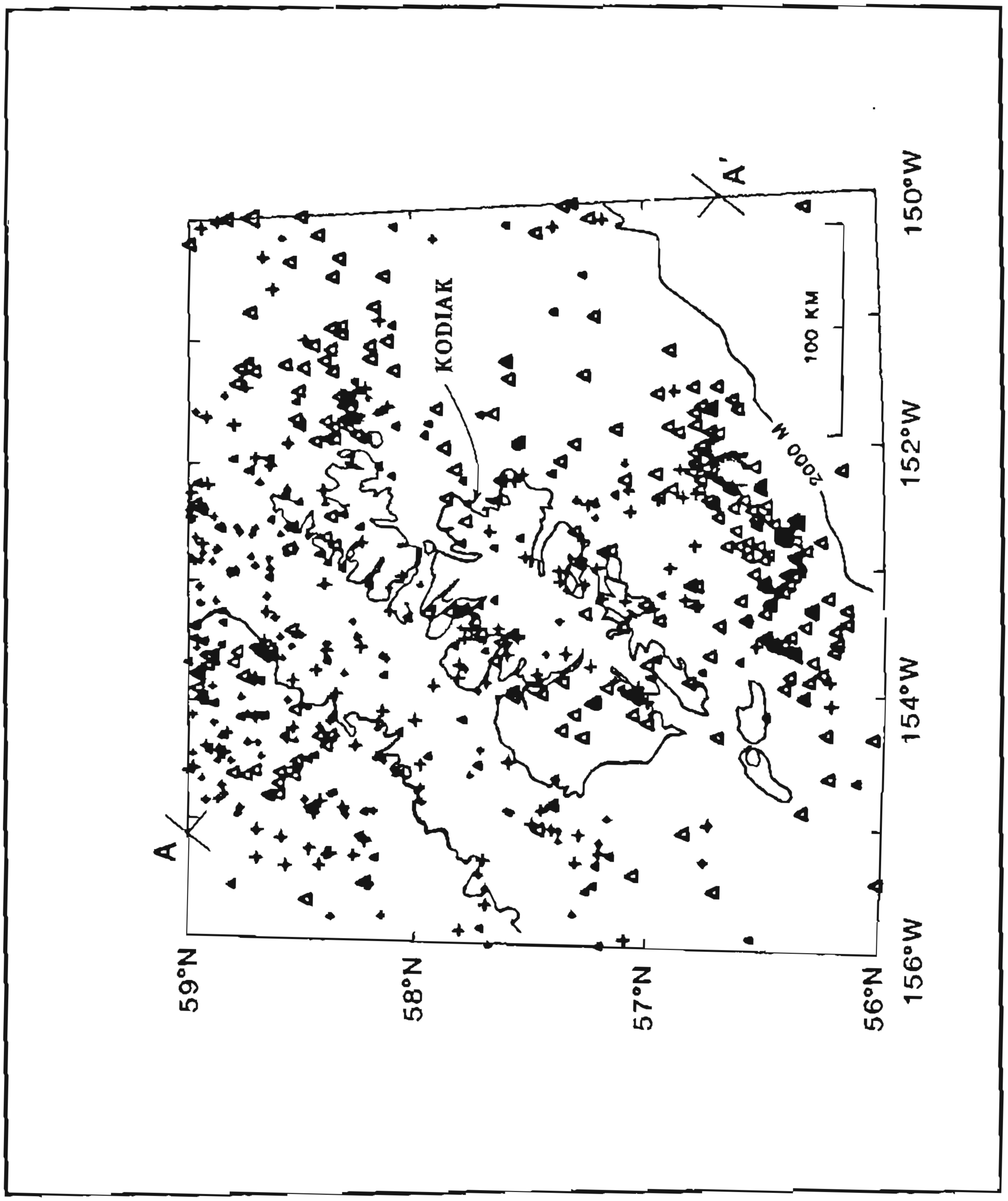

Figure 1.

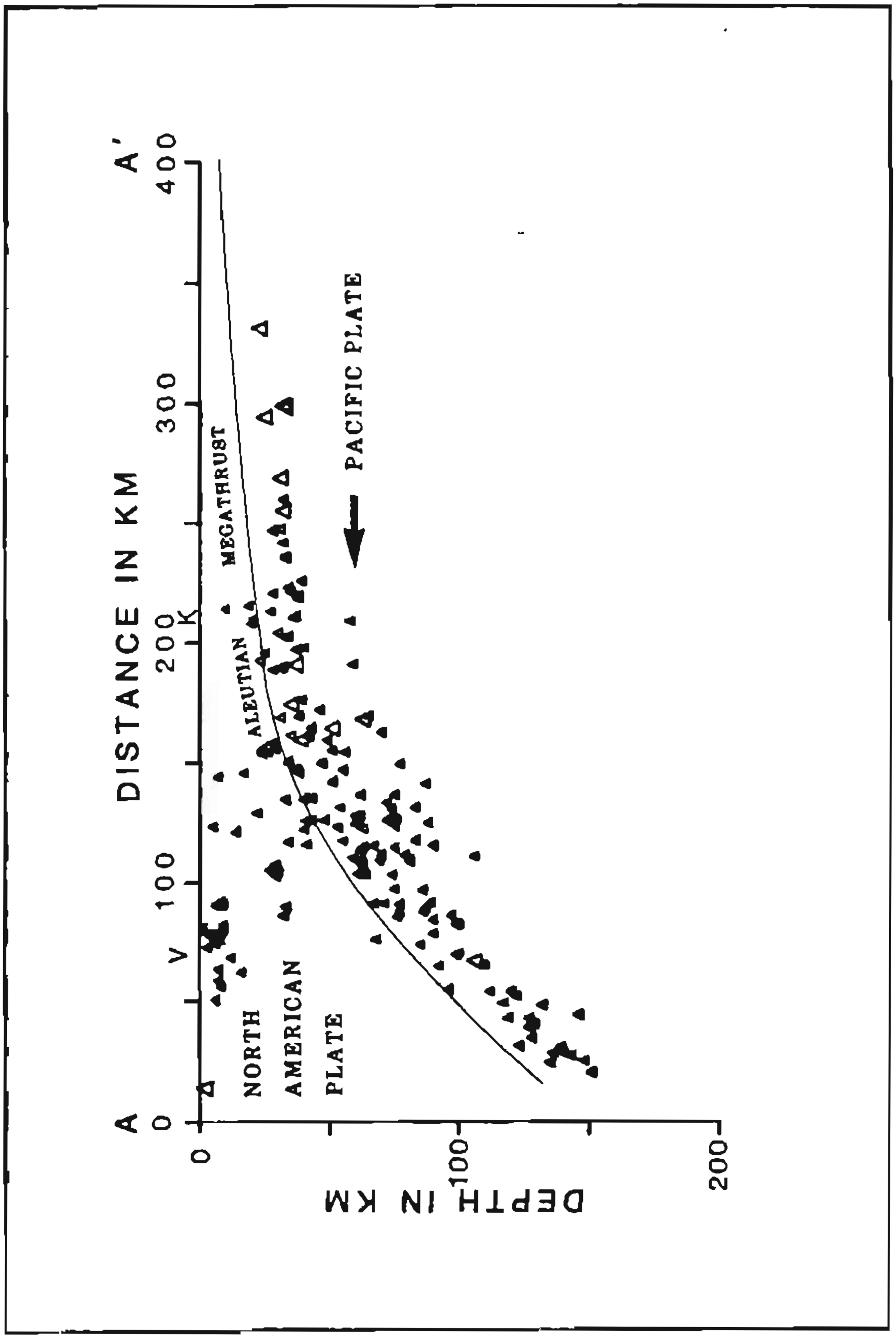
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Figure 2.

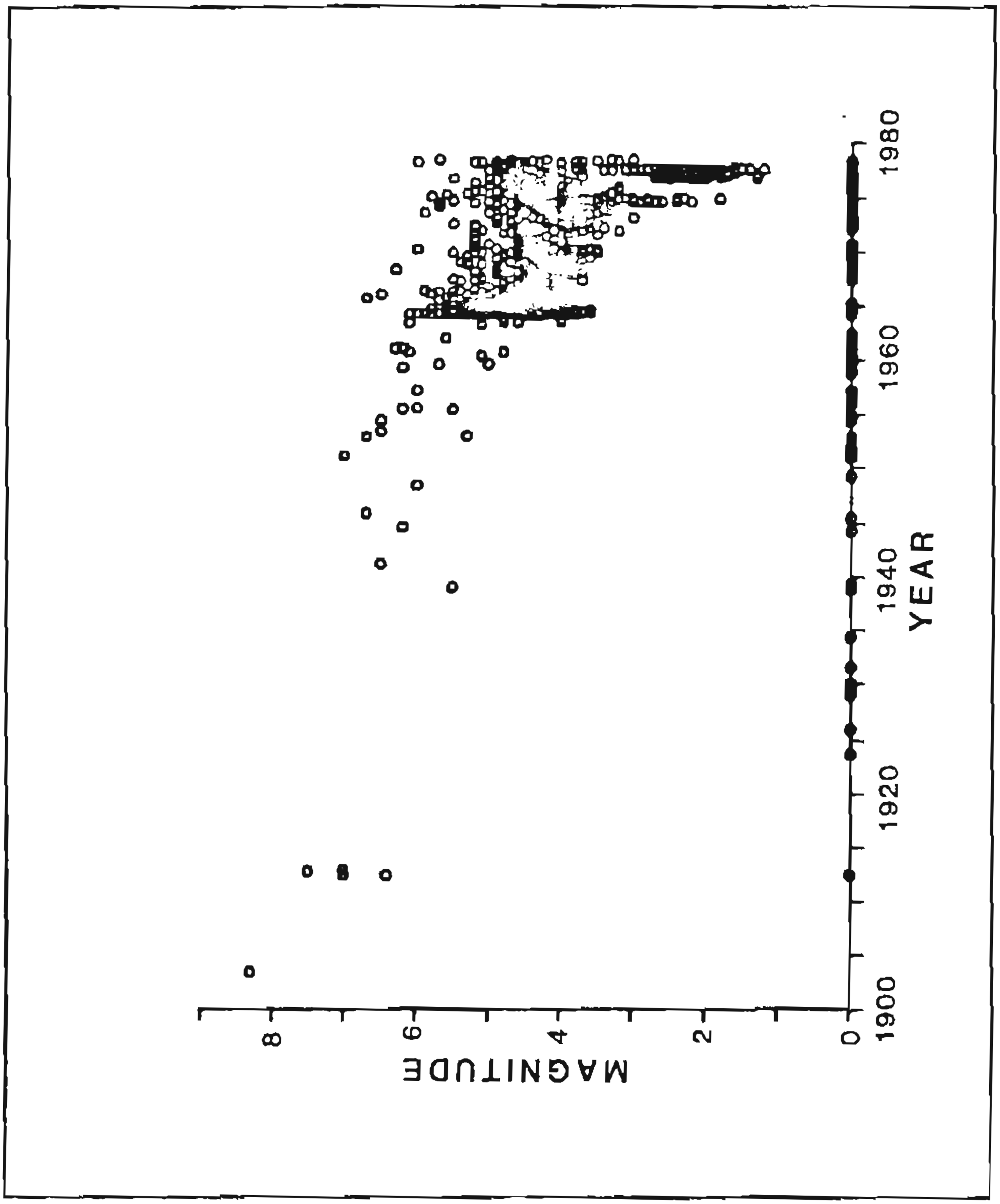

Figure 3.