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PRELIMINARY SURVEY OF MODERN GLACIOLACUSTRINE SEDIMENTS FOR EARTHQUAKE-INDUCED DEFORMATIONAL STRUCTURES, SOUTH-CENTRAL ALASKA

by

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INTRODUCTION

Bottom sediments of four lakes in South-Central Alaska were studied in the summer of 1975 for evidence of earthquake-induced deformation. The lakes are: Summit, Upper Trail, and Skilak, all on the Kenai Peninsula, and Eklutna, northeast of Anchorage (fig. 1). Interest in these lakes was stimulated by hypotheses developed from a study of sediments in Van Norman Reservoir, California, after the 1971 San Fernando earthquake (Sims, 1973). During that study three zones of deformational structures were found and correlated with moderate earthquakes that shook the San Fernando area in 1930, 1952, and 1971. Results of that study, coupled with the experimental formation of deformational structures similar to those from Van Norman Reservoir, led to a search for similar structures in Pleistocene and Holocene lakes and lake sediments in other seismically active areas. The lakes for this study were chosen specifically because of their location within the area affected by the 1964 Prince William Sound earthquake, and the probability of obtaining varved sediments which would allow counting of years between sedimentologic events.

SUMMARY OF DATA

Eklutna Lake

Eklutna Lake is situated approximately 45 km northeast of Anchorage (fig. 1) and lies in a glacially scoured basin. The lake is 11.3 km long and approximately 58 m deep at its deepest (fig. 2). An attempt was made to recover sediment samples from the distal (northwest) end of Eklutna Lake. Depth of water at the site (point A on fig. 2) is about 15 m. After several unsuccessful efforts to take core samples, SCUBA divers examined

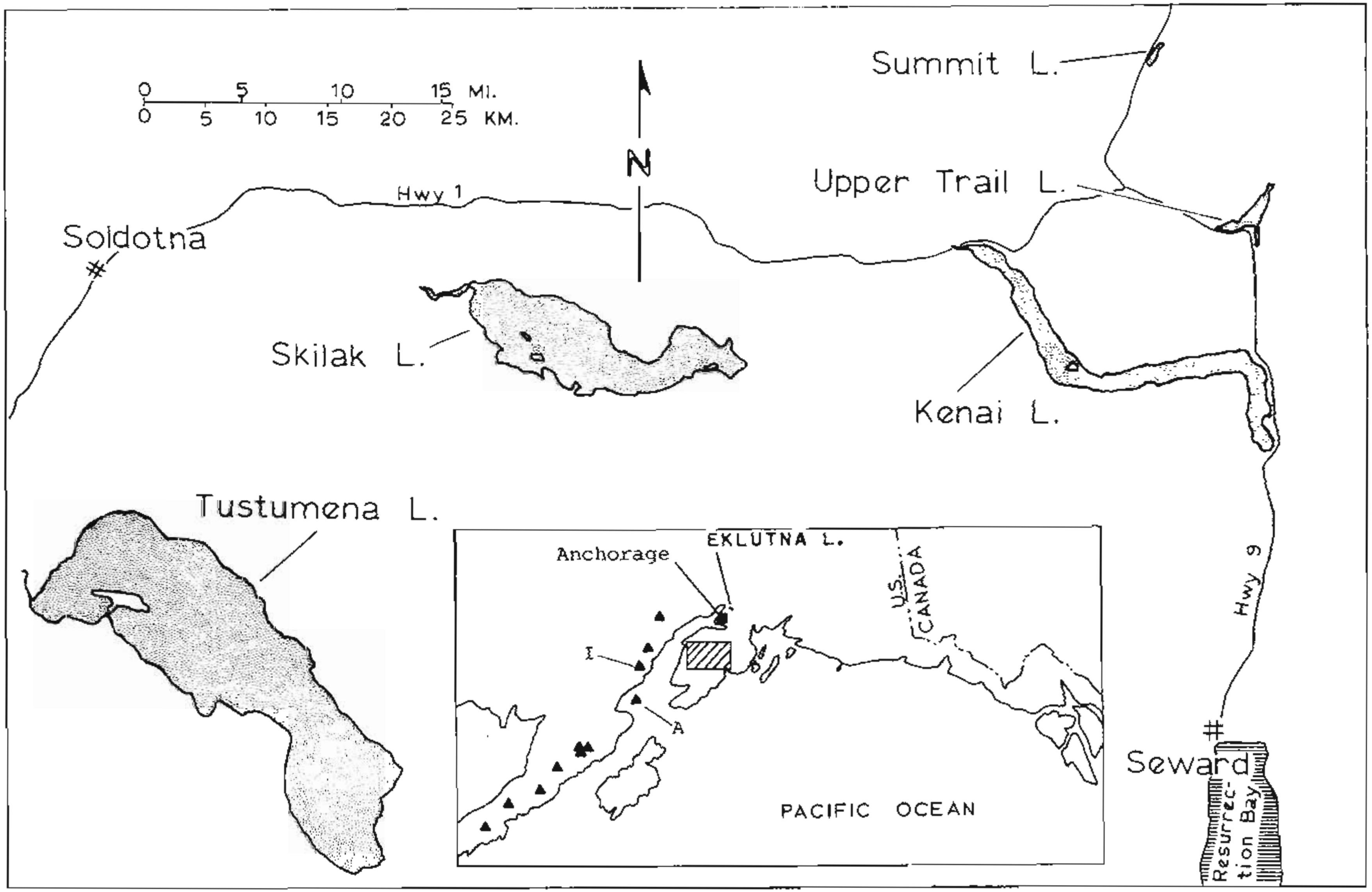


Figure 1. Map showing location of Eklutna (inset), Summit, Upper Trail, and Skilak Lakes, Alaska. Inset map shows location of historically active volcanoes (▲). I = Iliamna volcano, A = Augustine volcano.

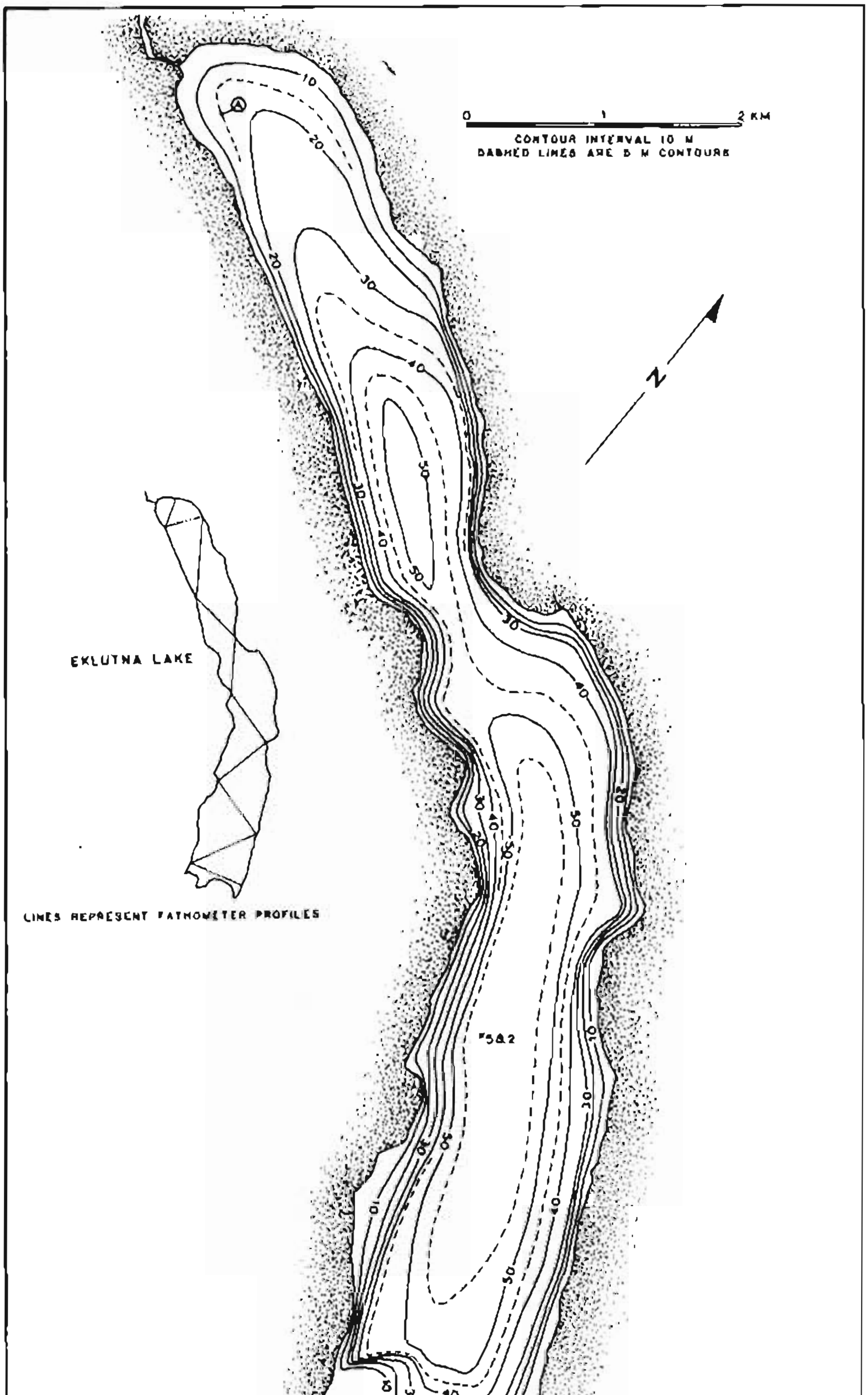


Figure 2. Bathymetric map of Eklutna Lake, Alaska.

the lake bottom and found gravel- and boulder-sized material as the predominant clast sizes. No more attempts were made to recover samples from Eklutna Lake because the clast size is too large to allow core sampling or formation of deformational structures (Sims, 1975).

Summit Lake

Summit Lake is situated on the Kenai Peninsula approximately 66 km south of Anchorage (fig. 1). The lake lies in a U-shaped glaciated valley and is approximately 2.3 km long and 20.5 m in maximum depth. The lake receives inflow mainly from Tenderfoot Creek, to the east, and drains to the northeast.

Two cores, 32 and 35 cm long, were recovered from Summit Lake (point A on fig. 3) in approximately 12 m of water. X-ray radiographic examination of the cores reveals three ash beds or probable ash beds in a sequence of poorly preserved rhythmites of clay and silt rich in organic material overlain by mud. The rhythmites are possibly annual layers (varves). Ash "beds" 3 to 15 mm thick are represented by ash grains disseminated in mud.

Upper Trail Lake

Upper Trail Lake is situated approximately 81 km south of Anchorage (fig. 1) and lies in a glacially scoured basin. The lake is approximately 6.3 km long and the depth greater than 42 m. A preliminary bathymetric map of the two western arms is shown in figure 4.

One core was recovered from Upper Trail Lake, in approximately 30 m of water (point A on fig. 4). The core is 84 cm long and contains disrupted varved sediments in the lowest 18 cm. The upper 66 cm of the core are un-

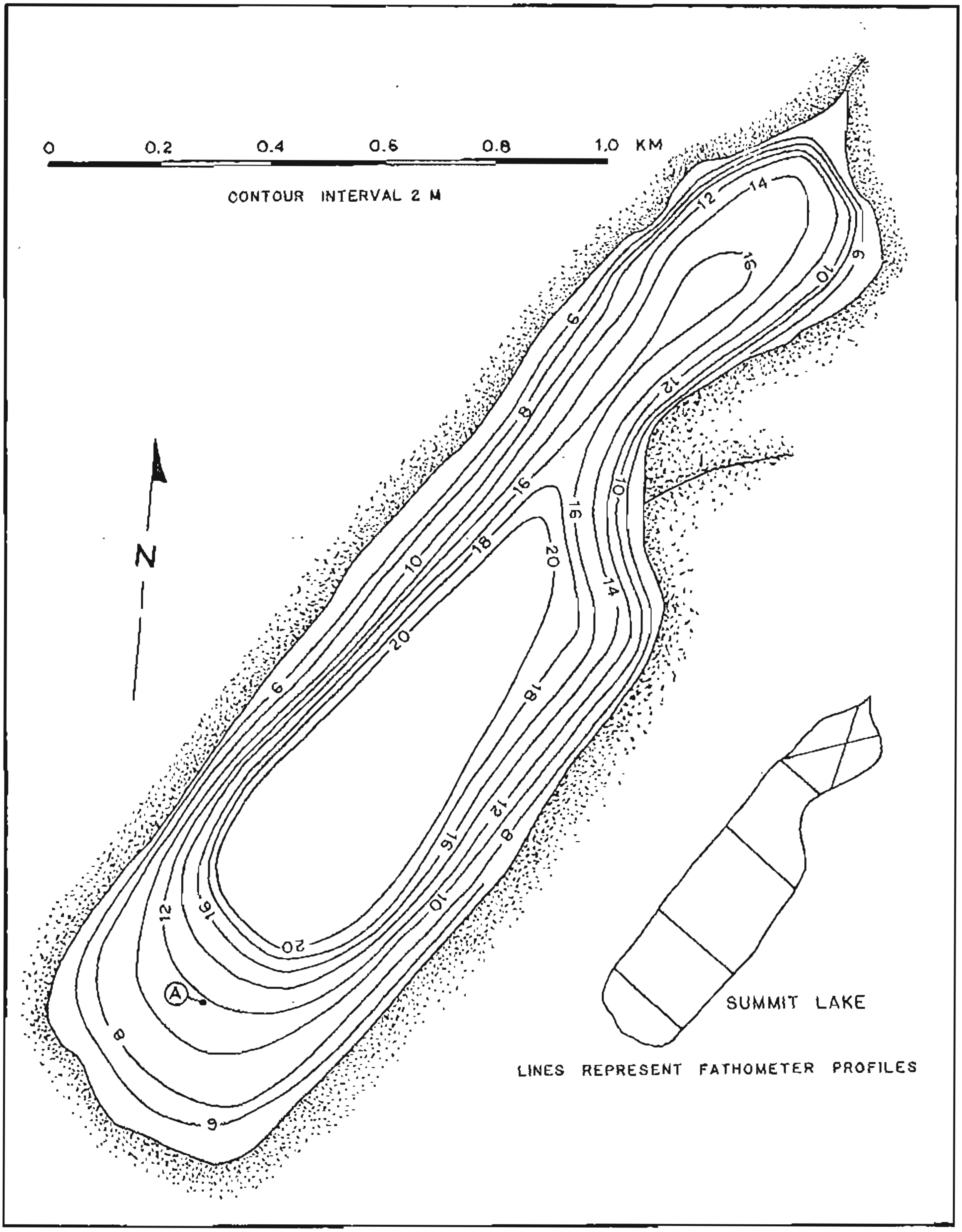


Figure 3. Bathymetric map and location of core samples from Summit Lake, Kenai Peninsula, Alaska.

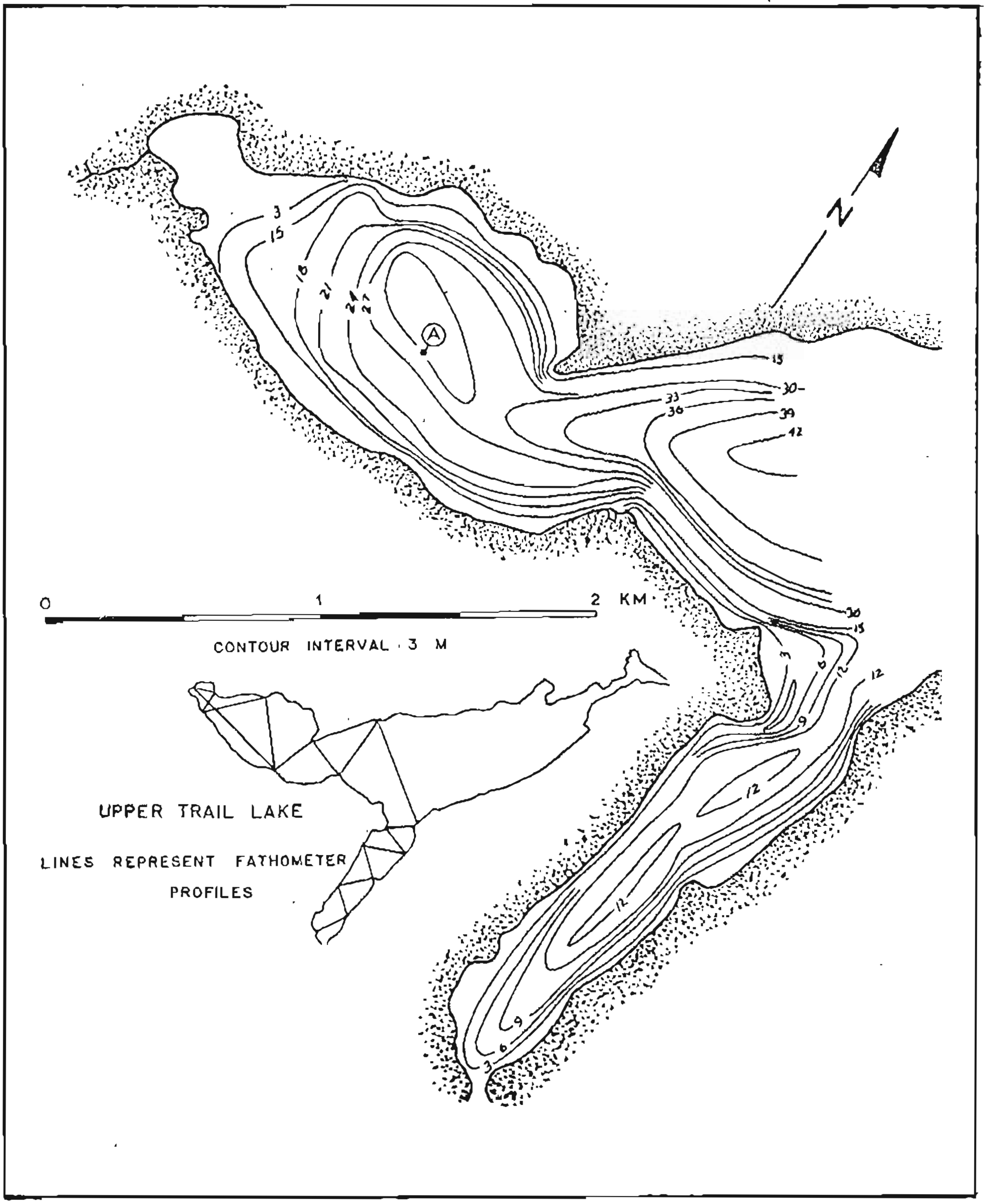


Figure 4. Preliminary bathymetric map and location of core sample from Upper Trail Lake, Kenai Peninsula, Alaska.

interpretable due to disruption of the sediment after sampling. The disruption of the sediments could be due to one or more of a number of factors, but most likely they are due to shaking during transportation from Alaska to California. Flowage structures in the lower part of the disrupted sediments indicate movement parallel to the core tube, which was transported in a horizontal position. Sediments in the core are composed of silt- and clay-sized particles. One possible ash bed is present in the lower portion of the core. This possible ash bed is at 82 cm and consists of widely scattered coarse silt to fine sand-sized grains. Other ash beds could be present but are uninterpretable due to the disruption of the sediments.

Skilak Lake

Skilak Lake is located on the Kenai Peninsula 85 km south of Anchorage (fig. 1). The lake is approximately 23.2 km long and greater than 120 m in maximum depth. The lake basin was glacially scoured and moraine dammed (Karlstrom, 1964). Major streams flowing into the lake are Kenai and Skilak Rivers. Skilak River contains meltwater from Skilak Glacier, a lobe of the Harding icefield. The lake drains to the west via the continuation of Kenai River. A preliminary bathymetric map (fig. 5) shows a buried moraine in the lake.

Five cores, from 29 to 80 cm in length, were removed from the west end of the lake 18 and 20 km from inflowing Kenai and Skilak Rivers respectively (fig. 5). The cores were taken on 15-16 August, 1975. Depth of water at the core sites is approximately 22 and 40 m. Cores 75-1 and 75-2 are from

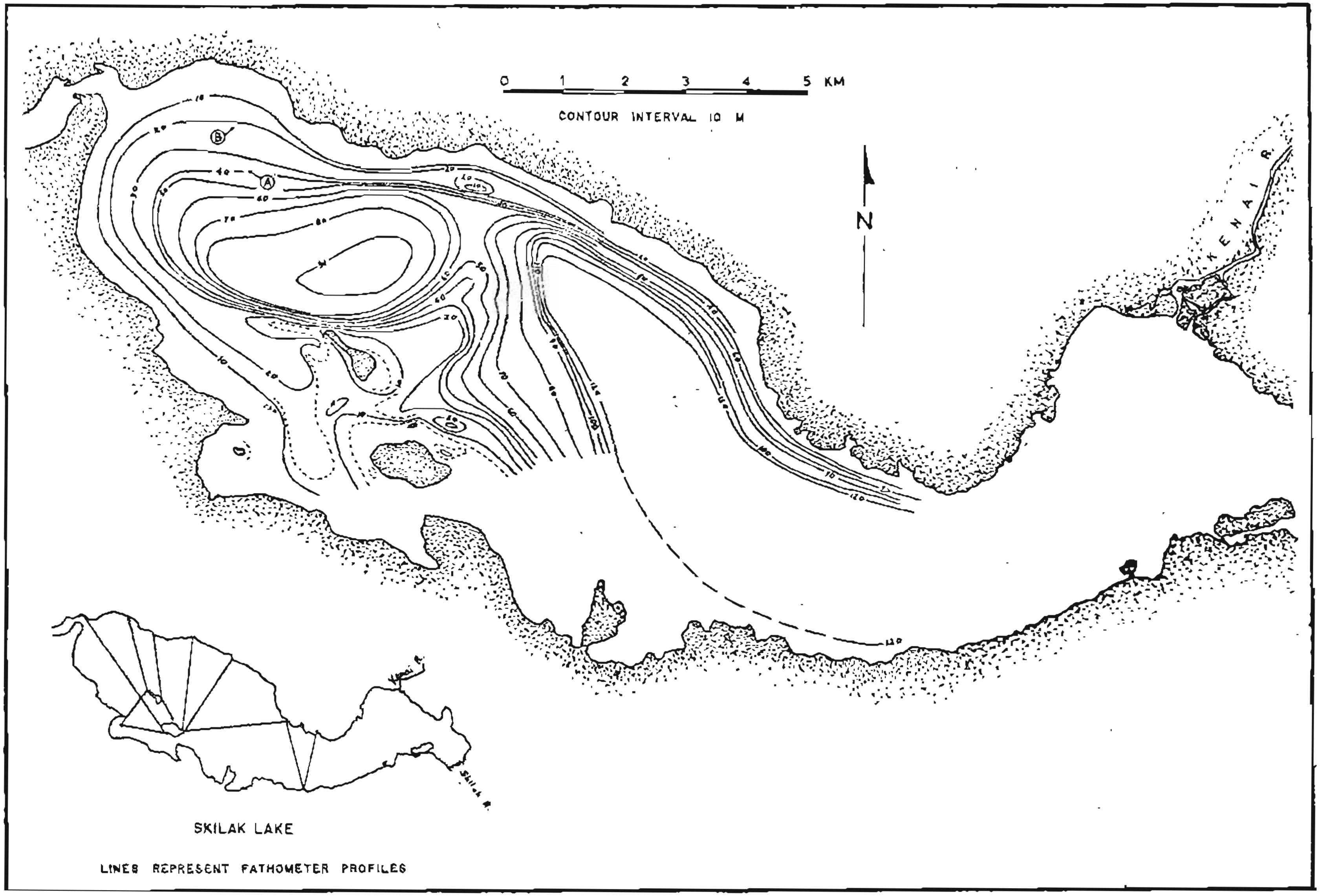


Figure 5. Preliminary bathymetric map and location of core samples from Skilak Lake, Kenai Peninsula, Alaska.

site A and cores 75-3, 75-4, and 75-5 are from site B (fig. 5). From the nearest shore to core site B the slope is approximately 1.7%.

The cores consist of varved lacustrine sediments and show that varves are presently being deposited in Skilak Lake. The sediments are light gray (5Y7/1) clays, fine silts, and interbedded volcanic ash. Varves are apparent on cut and polished dry surfaces and on X-ray radiographs, where they show as vague to distinct clay and clay-silt couplets 2 to 8 mm thick. The varves in these cores fit into Groups I and II of Ashley (1975). Group I varves are composed of winter (clay) layers thicker than summer (clay-silt) layers. Group II varves are of approximately equal proportions of winter and summer layers. Ashley (1975) states that these two groups of varves represent deposition in still water away from river mouths, where little sediment is received directly from density currents.

Counting of varves was done on X-ray radiographs of the cores. Counts were made between ash beds and sedimentation rates were calculated for each interval. There is variation in sedimentation rates within each core, but these variations are relatively consistent from core to core (fig. 6). Overall average rates of sedimentation for the cores is from 4.2 to 4.7 mm yr^{-1}. The sedimentation rate of 7.5 mm yr^{-1} for the top of core 75-5 is probably due to the lack of compaction of the most recent sediments.

Six ash beds are preserved in the cores from Skilak Lake (fig. 7). On X-ray radiographs ash beds appear as distinct, light (opaque to X-rays) fine-grained beds from 1 to 2 mm thick. When the ashes can be separated from the sediments in which they were deposited, they have colors ranging from light gray to grayish orange pink to pinkish white (10YR7/2 to 10YR8/2

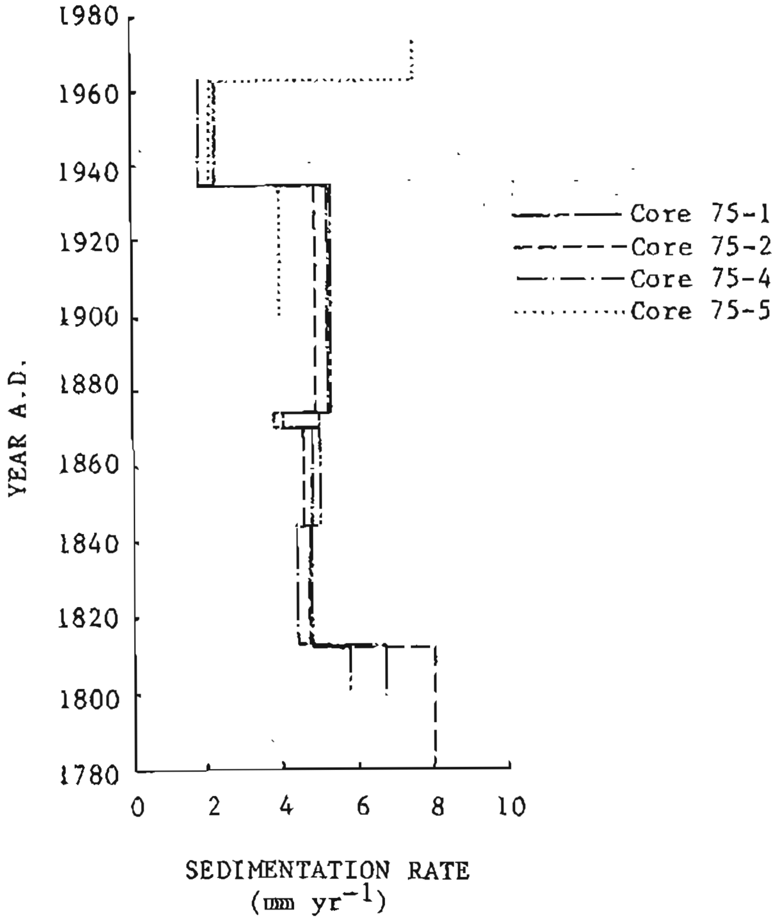


Figure 6. Variations in sedimentation rates between ash beds in cores from Skilak Lake, Alaska.

to 5YR8/2). Counts of the varves indicate that the ash beds were deposited approximately in 1816, 1845, 1870, 1875, 1935, and 1963 (fig. 7). These dates are in reasonable correspondence with eruptive histories of nearby volcanoes as developed by Grewingk (1850), Perry (1866), Coats (1950), and Detterman (1968). On the basis of varve counts, the 1963 and 1935 ashes are correlated with eruptions of Augustine Volcano, less than 175 km southwest of Skilak Lake. Assignment of the earlier ashes to their sources is more difficult. The 1816 (varve-count date) ash bed is possibly from the 1812 eruption of

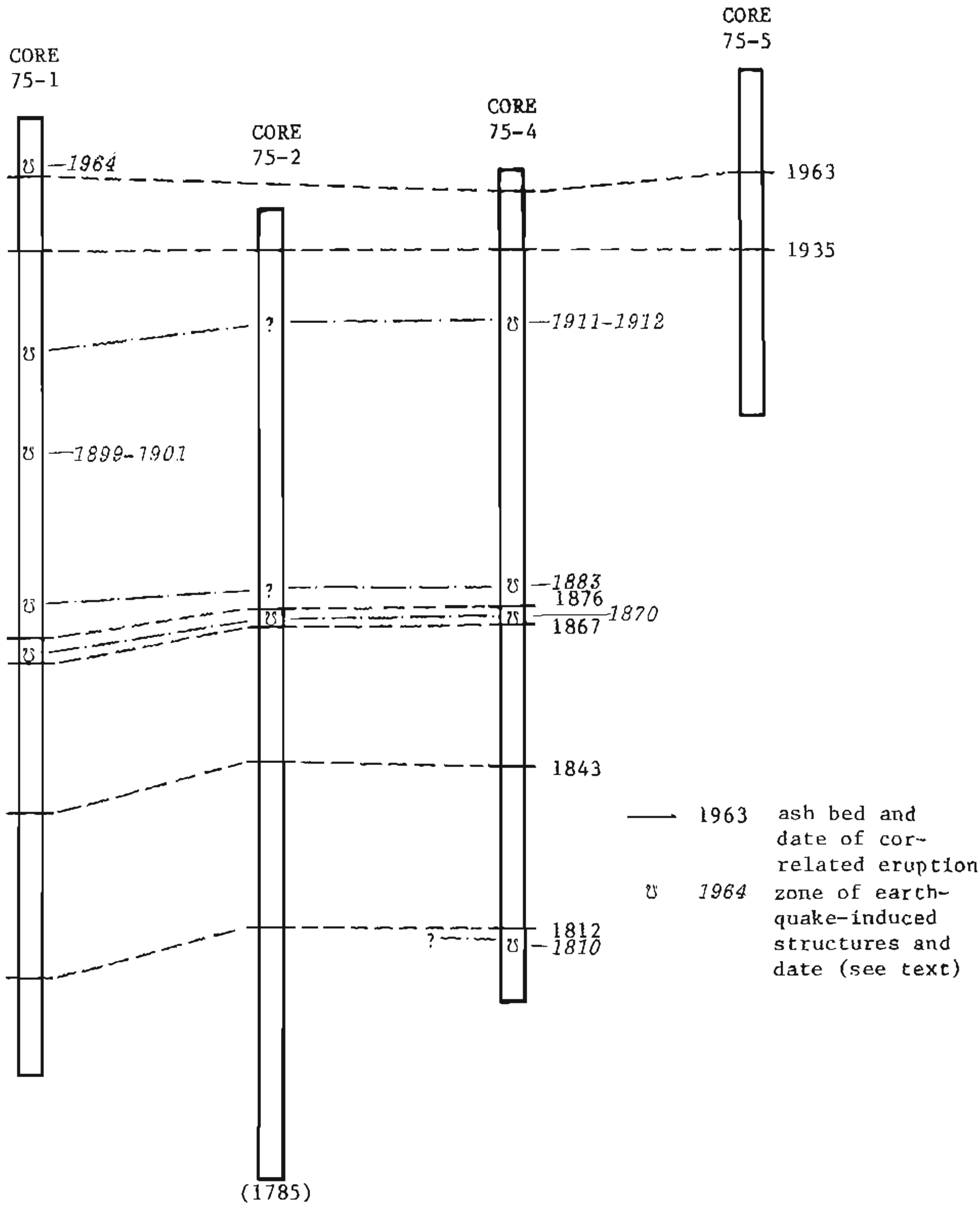


Figure 7. Correlation of ash beds and deformed zones in four cores from Skilak Lake, Alaska. The 1935 ash is used as a datum. Because of fracturing the upper 10 cm of core 75-4 have been reconstructed by the matching of varves. 1785 is the date of the oldest sediments in these cores.

Augustine Volcano and the 1845, 1870, and 1875 (varve-count date) ash beds are possibly from Iliamna Volcano's eruptions of 1843, 1867, 1876, respectively. However, other volcanoes or eruptive events from the above volcanoes could be the source of ash preserved in these cores. The sparse population of the area and presence of numerous active volcanoes makes ash correlations tentative at best. Another hinderance to correlations is the common thick fog or cloud coverage which can obscure volcanic activity and ash deposition in remote areas. On the assumption that the correlated ages of the ashes (fig. 7) are correct, the date for the oldest sediments recovered in the Skilak Lake cores is 1785 (Core 75-2).

Six zones of deformed sediments interpreted as formed by earthquakes were found by X-ray radiographic examination (fig. 7, Appendix). The structures are 2 to 14 mm thick and appear as thin wispy diapir-like distortions of laminations with a lack of directionality or as slight crenulations of the laminae. According to varve counts and ash chronologies, these deformed zones were produced in approximately 1810, 1870, 1883, 1899-1901, 1911-1912, and 1964. Dates of the older structures are uncertain due to possible errors in counting the varves.

DISCUSSION

Interlake correlation of ash beds and possible ash beds have not been made for two reasons. First, although the age of the sediments, and therefore the ash beds, is known for Skilak Lake, the general lack of varving in Summit Lake and accidental disruption of varves in Upper Trail Lake prevents age determinations of their contained ash beds. Second, the airfall ash histories for each lake could be significantly different from other lakes.

The latitudinal variation of active volcanoes west and southwest of Kenai Peninsula coupled with variations in prevailing winds cause localization of ash falls in the area of study. For example, the 1963 eruption of Mt. Spurr deposited ash in the Anchorage area but not in the vicinity of Summit, Upper Trail and Skilak Lakes (Wilcox, 1959, fig. 63).

Figure 8 shows the epicentral location and date of major earthquakes which may have affected the Skilak Lake sediments since 1899 and a few prior to 1899. However, a simple matching of deformed zones with their correlated dates and earthquake histories is potentially misleading. First of all, shaking intensities of MM VI or greater are probably required to cause deformation in silty sediments. Shaking intensities of earthquakes shown on Figure 8 are not known for the Skilak Lake area. Secondly, there are more seismic events than deformed zones in the Skilak Lake cores. The close timing of many shocks prevents unequivocal correlation of a deformed zone with a certain shock, such as the 1899-1901 and 1911-1912 deformed zones. Both of these zones could be correlated with at least four major shocks in the area (fig. 8). Only one earthquake may have affected the sediments in each zone enough to deform them, or each zone may represent the cumulative effects of more than one closely spaced shock. More precise knowledge of the distribution of shaking intensities is needed before any further correlation with historic earthquakes is attempted.

The criteria for recognition and interpretation of probable earthquake-induced structures in sediments given below are modified from Sims (1975):

1) The sediments containing deformational structures are in a seismically active area.

2) Sediments are sensitive to earthquake shaking.

3) Internal structure that suggests loss of strength in the sediments and disruption of laminae or other primary depositional structures.

4) The structures are restricted to a single stratigraphic interval that is correlative over a large area.

5) Similarity of deformational structures to those produced experimentally (Keunen, 1958, 1965) or those described by Sims (1973, 1975).

6) Absence of detectable influence by slopes or subaqueous slumps.

Deformational structures in the Skilak Lake cores satisfy criteria 1, 2, and 6. However, criteria 3, 4, and 5 are only partly satisfied. The internal structure of deformed zones in these cores in some cases indicates disruption of overlying laminae but often does not. Deformational structures described by Sims (1973, 1975) and produced experimentally by Keunen (1958, 1965) suggest downward movement or sags of overlying laminated sediments into weakened or liquified underlying sediments (ball and pillow structures or pseudonodules). These are possibly due to liquifaction of the underlying material during strong shaking of an earthquake.

Crenulations and diapir-like disturbances in these sediments are indicative of upward rather than downward movement. A possible explanation for this is the cohesiveness of the fine-grained underlying sediments. SCUBA divers encountered firm cohesive bottom sediments only a few centimetres below the lake bottom, indicating rapid development of cohesion and internal strength in the laminae. Therefore, during strong earthquake shaking the uppermost (possibly 1-3 cm) unconsolidated and less cohesive sediments can only move upward.

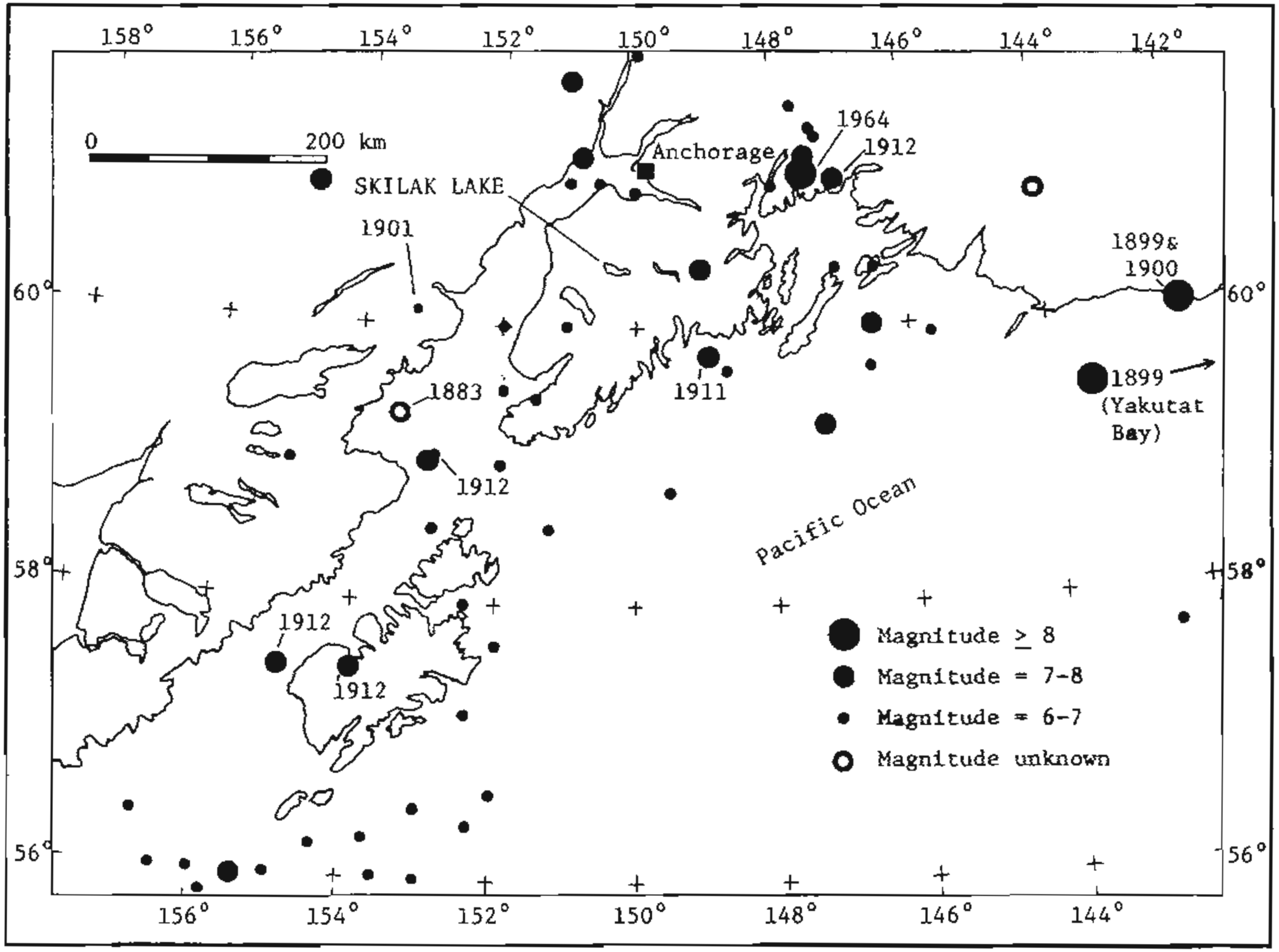


Figure 8. Earthquakes with magnitude ≥ 6.0 in the Prince William Sound area. Solid circles are for earthquakes from 1899-1964, open circles are for earthquakes prior to 1899 (magnitudes are unknown). Dated events are those which directly relate to this report. Modified after Wood (1966).

Reasons for the absence of deformational structures in similarly dated material are unknown. For example, the 1911-1912 structure is present in Cores 75-1 and 75-4 but not in Cores 75-2 or 75-5 (fig. 7). This may be related to the spacing between individual structures in a zone greater than the diameter of the coring apparatus (44 mm).

METHOD OF STUDY

Preliminary bathymetric maps (figs. 2, 3, 4, 5) were made to aid in selecting core sites. Core site selection adhered to criteria set forth by Sims (1975). Cores were obtained using a 1.0 m long piston sampler from a small boat or by manually pushing a rigid plastic tube into bottom sediments. All samples were retrieved in rigid plastic tubes which were sealed with plastic tape to prevent moisture loss. For examination the sediments were extruded and the core cut in half lengthwise using a "cheese cutter" type instrument. Lithologic and other sedimentologic data were then recorded (see Appendix for detailed descriptions). A 1 cm-thick slice was taken from the center of the core segment and an X-ray radiograph made to study the internal structures and fine details of the visible structures.

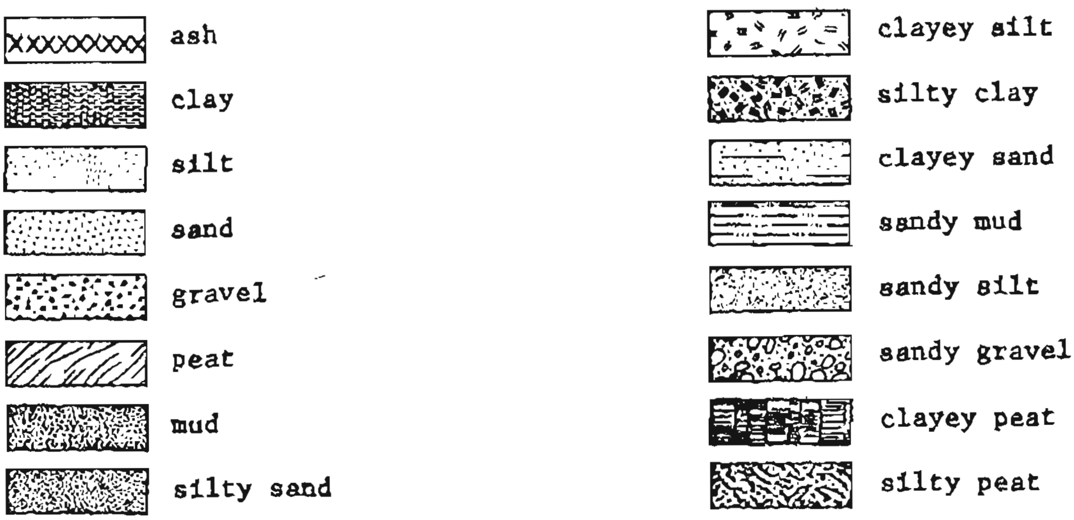
The X-ray radiographs were taken on 30 x 43 cm sheets of industrial X-ray film at 1:1 scale. Exposures to X-radiation ranged from 3 to 20 minutes at 45-55 KV and 3.5 ma.

After lengthwise splitting, samples were taken from one-half of the core for bulk mineralogy, fine grain size (<125μ diameter), and palynological analyses. The remaining core half was wrapped in plastic and retained for future use and reference. These samples and the radiographs may be examined by contacting: John D. Sims, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025.

GRAPHIC NOTATIONS USED IN STRATIGRAPHIC DESCRIPTIONS

The stratigraphic descriptions of each core are contained on individual sheets. The graphical notations used in the core descriptions and radiograph interpretations are modified from the methods of Bouma (1962). The conventions and symbols used follow: Those symbols marked* are also used in the column entitled Radiographic.

Lithology



v — *vivianite, an iron phosphate present in the sediments

interlaminated strata; dominant lithology on left (in this example, clayey peat and mud)

Varve Count

Varve counts are made from radiographs and are reported for indicated intervals.

Structure

graded bedding

load cast

earthquake-induced structure*

fault* (possibly due to sampling procedure)

interval in which structure occurs*

indistinct structure* ( )

Sedimentation Rate

Sedimentation rates are given for indicated intervals and are computed from varve counts within the given interval.

Fossils

fish scale*

fish bone*

gastropod*

clam*

wood oriented parallel to bedding plane

wood not parallel to bedding plane

plant fragment parallel to bedding plane

plant fragment not parallel to bedding plane

Radiographic

This column contains supplementary information derived from an analysis of information taken from X-ray radiographs. The notations used in this column are a combination of those marked by (*) under the headings Lithology, Bedding Plane Structure, and Fossils, plus some additional special symbols not previously used (list below):

granule - an X-ray opaque small body < 1 mm in diameter.

granule cluster - a regularly to irregularly shaped mass of granules.

pebble(⊙) - a large (> 3 mm diameter) X-ray opaque body.

mottle(s) - area(s) of low X-ray transparency of irregular shape and unknown origin.

bioturbation - animal burrows. The degree of sediment disturbance generally accompanies this note such as: heavy, slight, et.

$\Delta\delta$ - a difference in X-ray transparency between stratigraphic subunits due to compositional, grain size or other physiochemical differences.

fractured - physical breaking of the indicated part of the sediment slice that usually occurred during sample preparation prior to X-ray inspection.

Sample Number

Sample numbers identify samples taken for specific tests or supplementary data. Numbers are reserved for bulk mineralogy, fine grain size analysis (fraction < 125μ diameter), and palynological examination. Samples taken for other purposes are so indicated.

ACKNOWLEDGEMENTS

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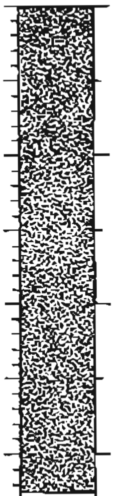
APPENDIX

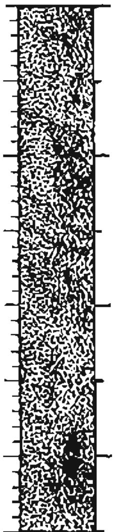
LAKE SUMMIT

CORE 75-1 DEPTH 0 cm. to 32.5 cm.

LITH.	cm.	VARVE COUNT	STRUCT.	SED. RATE	FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #
	0							
						Δδ		
						granules		
	10					ash	small fracture due to sampling	
						cemented zone		
						(ash?)		
	20					(ash?)		
					(22–32 cm interval marked)		22 cm - TD high organic (plant) content	
	30					Δδ		
	40							
	50							
	60							
	70							
	80							
	90							
	100							

LAKE SUMMIT

CORE 75-2 DEPTH 0 cm. to 35 cm.

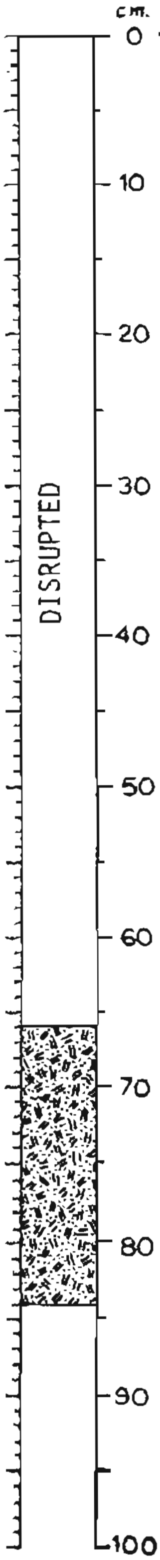
LITH.	VARVE COUNT	STRUCT.	SED. RATE	FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #
					Δδ granules ash cemented zone granules (ash?)	14-20 cm sediments are varved 20 cm - TD possible varving but obscured by high organic (plant) content	

cm. 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100

LAKE UPPER TRAIL

CORE 75-1 DEPTH 0 cm. to 84 cm.

LITH.	VARVE COUNT	STRUCT.	SED. RATE	FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #

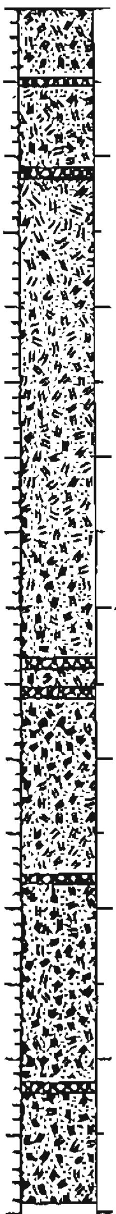


0-66 cm disrupted possibly during transportation from Alaska to California.

All of this core dried before exposure to X-radiation.

LAKE SKILAK

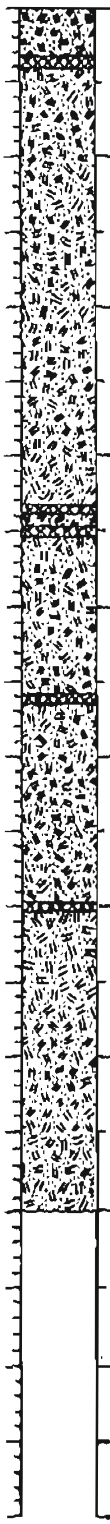
CORE 75-1 DEPTH 0 cm. to 79 cm.



Depth (cm)	VARVE COUNT	STRUCT.	SED. RATE mm/yr	FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #
0–5		ʊ				color of mud after drying is light gray (5Y7/1)	
5–11	27		2.2				
11–13	9 } 61		3.1 } 5.3				469(SEM) ash
13–20	19	ʊ					471(SEM), 470(SEM)
20–28	12	ʊ	6.5				
28–38	12		7.1				
38–44	9	ʊ					
44–46	5	ʊ	4.0			ash at 45.5 cm is light gray (10YR7/2) in color	468(SEM) ash
46–58	25		5.0				
58–72	29		4.8			ash at 58.0 cm is grayish orange pink (10YR8/2)	
72–79	12		5.8			ash at 72.0 cm is pinkish white (5YR8/2) in color	

LAKE SKILAK

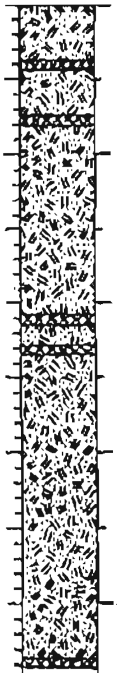
CORE 75-2 DEPTH 0 cm. to 80 cm.



cm.	VARVE COUNT	STRUCT.	SED. RATE mm/yr	FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #
0							
10	61		4.9				
20							
30	4	ʊ	3.8				
40	24		4.6				
50	28		4.8				
60							
70	25		8.0				
80							
90							
100							

LAKE SKILAK

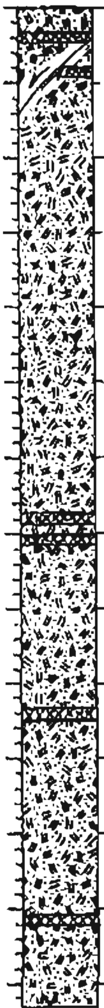
CORE 75-3 DEPTH 0 cm. to 44 cm.

LITH.	VARVE COUNT	STRUCT.	SED. RATE mm/yr	FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #
						varves in this core are extremely vague, therefore no counting of varves was made	

cm. 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100

LAKE SKILAK

CORE 75-4 DEPTH 0 cm. to 66.5 cm.

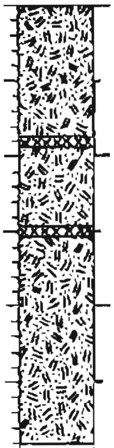


LITH.	VARVE COUNT	STRUCT.	SED. RATE mm/yr		FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #
							fault from 2-7 cm is from sampling procedure	
	20		3.0	5.2 (spans the next two rows)				
	15	ʊ	3.3					
	23		8.3					
	3	ʊ ʊ	5.0					
	24		4.8					
	31		4.4					
	9	ʊ	6.7					

cm. 0 – 10 – 20 – 30 – 40 – 50 – 60 – 70 – 80 – 90 – 100

LAKE SKILAK

CORE 75-5 DEPTH 0 cm. to 29 cm.



LITH. (cm.)	VARVE COUNT	STRUCT.	SED. RATE mm/yr	FOSSIL	RADIO-GRAPHIC	REMARKS	SPL. #
0–10	12		7.5				
10–15	28		2.1				
15–30	36		3.9				

cm. 0 10 20 30 40 50 60 70 80 90 100