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Seismic sub-bottom profiling study of recent sedimentation in Flathead Lake Montana

Jerry Kogan
The University of Montana

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A SEISMIC SUB-BOTTOM PROFILING STUDY OF RECENT SEDIMENTATION IN FLATHEAD LAKE, MONTANA

by

Jerry Kogan

B.A., Dartmouth College, 1969

Presented in partial fulfillment of the requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1980

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

Date May 26, 1980
ABSTRACT

Kogan, Jerry, U., M.S., Spring, 1981 Geology
A Seismic Sub-bottom Profiling Study of Recent Sedimentation in Flathead Lake, Montana

Director: Dr. Anthony Qamar

Seismic sub-bottom profiles of recent sediments in Flathead Lake have revealed several types of deformed structures underlying a twenty to thirty foot thick package of undisturbed lacustrine deposits. The disturbed areas are found on gradual, 1 to 5 degree, slopes on either side of a deep north-south trough found on the eastern side of the lake. Sediments on the broad shelf lying to the west of the trough generally are undeformed. Erosional unconformities, truncated beds, disordered or chaotic zones, and folded and fragmented layers are the principal types of deformation. Undeformed layers underlying many of the structures indicate that disruption was the direct result of surficial processes such as block slumping, mass flows, or erosion. Similar style folding of large piles of sediments was produced by rapid movements. Deformation appears to have been caused by several discrete events.

Similar events have not recurred during the deposition of the undisturbed sedimentary drape. The sedimentation rate of the lake has not yet been definitively determined. A fairly high rate of sedimentation (1 - 1.5 cm./yr.) has been suggested, and if it is correct, the drape would represent less than a thousand years of undisturbed sedimentation. In this case large earthquakes would have been responsible for deformation. However, if Flathead Lake's sedimentation rate is similar to the average rate of other large intermontane lakes in the region (1 mm./yr.), deformation occurred over 10,000 years ago, and may have been associated with the last advance and retreat of the Cordilleran Ice Sheet.

While the deformation does not give direct evidence for recent active faulting under the lake, the alignment of structures on both sides of the eastern trough suggests that active faulting may have been responsible for the oversteepening of its slopes.
ACKNOWLEDGEMENTS

I wish to thank the members of my thesis committee, Dr. Anthony Qamar, Dr. Johnnie Moore, and Dr. George Woodbury for their discussions and critical suggestions. I also thank Dr. John Shaw and Dr. Norm Hyne for their helpful correspondence. This study was partially supported by a Geological Society of America Penrose Grant and a grant from the Environmental Protection Agency.
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Profiles 6 and 22
Profiles 15, 35L, and 48
Profile 17
Profiles 20 and 21
Profiles 23 and 24
Profiles 27 and 51
Profiles 28 and 30
Profile 31
Profiles 34A and 34D
Profiles 35A, 35C, 35D, and 35F
Profiles 35G, 35J, 35J, and 35K
Profiles 45 and 47
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Flathead Lake (Fig. 1) is located south of Glacier National Park in northwestern Montana. The bedrock in the surrounding region is part of the Precambrian Belt Supergroup, and has been subject to Laramide thrusting and post-Laramide block faulting (Johns, 1970).

The modern form of Flathead Lake is a product of the last major stade of the Cordilleran Ice Sheet (Stoffel, 1980). The Polson terminal moraine, formed during the retreat of Pinedale ice some 10,000 - 14,000 years ago (Stoffel, 1980) impounded the lake, to a higher level than at present (Johns, 1971). The level slowly decreased as the river cut through the moraine. The Kerr Dam, constructed in 1938, several miles below the outlet, has stabilized the lake's level.

Flathead Lake occurs at the intersection of two major structural provinces of western North America: the Rocky Mountain Trench and the Intermountain Seismic Belt. The lake is near the southern end of the Rocky Mountain Trench, a linear north-northwest trending trough, bounded on one, and sometimes both sides, by normal faults, which extends without interruption almost a thousand miles to the northern end of British Columbia (Leech, 1966; Mudge, 1970). The Intermountain Seismic Belt is a zone of high earthquake activity.
FIG. 1
FLATHEAD LAKE LOCATION MAP

BRITISH COLUMBIA  ALBERTA

EUREKA  ROCKY MTN. TRENCH  WHITEFISH RANGE

SALISH RANGE

KALISPELL  FLATHEAD LAKE

POLSON

MONTANA

SWAN RANGE

MISSION RANGE

IDAHO

115 W

MISSOURI 114 W

OVANDO +47 N

113 W

0 50 KILOMETERS 0 25 MILES

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running through southern Nevada, Utah, Eastern Idaho, and west-central Montana, and terminating at Flathead Lake in northwest Montana (Smith and Sbar, 1974).

The seismic activity of the Intermountain Seismic Belt has been associated with the Basin and Range extensional tectonic regime. In Nevada, southern Oregon, and Western Utah recent faulting has followed two principal orientations with north-northeast trending normal faults and west to northwest trending right lateral strike slip faults (Liviccari, 1979; Smith and Sbar, 1974).

The seismic activity around the lake conforms to the pattern of most of the Intermountain Seismic Belt with a relative preponderence of small earthquakes and microearthquake swarms, and far fewer large magnitude events than would be expected considering the rate of seismicity (Qamar and Breuninger, 1979; Smith and Sbar, 1974). Two recent magnitude five earthquakes have occurred there in 1952 and 1975 (Qamar and Breuninger, 1979), and two microearthquake surveys taken around the lake in 1969 and 1971 have located swarms centered on its southwestern side, just to the north and south of Big Arm Bay (Sbar, et al, 1972; Stevenson, 1976). Fault plane solutions for these swarms have not yielded consistent orientations.

The most prominent faults found near the lake are the Mission and Swan faults (Fig. 2). These are north to north-northwest trending normal block faults active in the late Tertiary and possibly the Quaternary (Pardee, 1950). The east side of the lake corresponds
Heavy lines represent known and suspected active faults (from Witkind, 1977). Dashed lines represent suspected active faults, based on gravity data and microearthquake locations (Stickney, 1980). Faults within dotted line are not necessarily active (mapped by Harrison, et al., 1974).

Ticks are on downthrown side of normal faults.
closely with the Mission Fault, which extends along the west front of the Mission Range, where it has several kilometers of offset, and proceeds northward, with decreasing offset, until it disappears in the alluvium of the Kalispell Valley north of Flathead Lake (Johns, 1970). Stickney (1980) found gravitational evidence for the continuation of a splay of the Mission Fault for several miles under the alluvium with about 600 meters of offset. On the basis of microearthquake locations and fault plane solutions, he suggested that the fault may still be active. Stickney also used gravity data to postulate the extension of the Kalispell normal fault to the north edge of the lake. The Kalispell and Flathead faults bound the Flathead graben, which Stickney estimated to have 700 meters of relief. Several smaller normal faults on the west side of the lake also trend northwest to north-northwest (Harrison et al., 1974). Immediately south of Big Arm Bay is a cluster of north to north-northeast trending normal faults (Harrison et al., 1974). This change in pattern, coupled with the measurement of a steep gravity gradient on the southern side of Big Draw, a valley filled with glacial outwash just west of Big Arm, has led to the suggestion that the Big Draw Fault, a major west to west-northwest trending right lateral strike slip fault (Witkind, 1977), should be extended several kilometers eastward into the region of the lake, either into Big Arm Bay or along its southern shore (Lapoint, 1971).
The predominant fault orientations around the lake are north-northwest, and are consistent with the trend of the Canadian Cordillera. However, north of Flathead Lake the Rocky Mountain Trench and other zones of the Canadian Cordillera are seismically inactive (Milne and Davenport, 1969). If the lake's most recent seismic activity is directly related to Basin and Range tensional stresses, then it is possible that minor faults, whose orientations correspond to faults in the southern Basin and Range Province, may show evidence of very recent movement.

The sediments of Flathead Lake provide an unbroken record of deposition at least 10,000 years old. If recent faulting in the bedrock under the lake is reflected in the sediments, these would provide excellent evidence for associating recent earthquake activity with crustal movement. Distinct patterns of faulting might make it possible to show whether the extensional tectonic regime with which the Intermountain Seismic Belt is associated expresses itself in faults which correspond to its predominant patterns of seismicity, or relieves its stress along pre-existing lines of structural weakness.

In the summer of 1980 a sub-bottom seismic profiling study was conducted in order to find evidence of recent faulting in the lake sediments. The profiles showed a wide range of sedimentary deformation structures within the lake. The present lack of long cores limited the specificity of interpretations, but it is expected that a future coring program will be undertaken to test this study's conclusions, which are made solely on the basis of the profiles.
The study was conducted with an Edo-Western HiFACT Sub-bottom profiling system, which was operated at a frequency of 3.5 kHz. The system's components were a model 515H transducer, 615 recorder, and 248E transceiver. Using steel poles, ropes, cables, and a small pulley, the transducer was mounted to the gunwales of a 22 ft. boat. In operation it was submerged five feet below the hull. Interference from the boat's engine was minimized by a cone shield around the transducer. The acoustic pulse length was 2.0 msec. with a keying rate of 1200 pulses per minute. The 3.5 kHz signal frequency allowed a vertical resolution of 1.5 feet. Signal power gave useful reflections from a section of sediments 200 feet thick. Signals penetrating more than 200 feet of sediments had very low amplitudes. After keying each pulse, the recorder digitized the incoming signal. The processing system allowed for variable settings of gain adjustments to compensate for signal attenuation with time. It also permitted a range of time scales and delays. With an appropriate time-delay, as much of the water column as desired could be removed, thus utilizing the full width of the paper records to display the sedimentary pile. The records were burnt into electrosensitive paper by a pair of revolving styluses, which produced traces of variable density proportional to the amplitude of the reflected signals.
The records were produced with a vertical scale of distance rather than time. The velocity of sound through fresh water is 1.45 km/sec., and through recent lake sediments is about 1.5 km/sec. (Dobrin, 1976; Otis et al, 1977). An internal compensator in the recorder was adjusted to a velocity of 1.5 km/sec. to produce a vertical distance scale. Hence, the error in depths is less than 3%, or about 10 feet in the deepest portions of the lake.

The overall quality of the profiles was excellent. The vertical scale was exaggerated approximately twenty times, thus emphasizing the details of minute structures. Other than the splicing needed to eliminate the offsets due to time-delay changes, it was not necessary to modify the profiles by additional processing. Diffraction patterns were uncommon and obvious, and had much steeper slopes than any structures (Fig. 3). Migration (Dobrin, 1976) would not have significantly changed the profiles due to the actual low angles of all slopes. Multiples were generally too weak to mask the stronger deep reflections, and did not interfere with structural interpretations. The slight errors in depths and thicknesses caused by the approximation of a uniform acoustic velocity for water and shallow sediments were insignificant for the purposes of this study.

Seventy profiles were made (Fig. 4A), with two areas receiving especially heavy coverage. These were Big Arm Bay and the east side of the lake between Yellow Bay and Woods Bay. Because of the high earthquake activity in its vicinity, Big Arm Bay was where disturbed zones and deformed structures had been anticipated; however, it
Fig. 3. If sound waves are traveling from a diffracting point source to the surface at a constant velocity, it is possible to simulate a diffraction pattern by a simple geometric construction. Point A lies immediately above the diffracting point, D. At point X the signal would appear to arrive from source Y, whose apparent vertical distance, XY, is equal to the actual distance to the diffracting point, XD. For a given depth it is possible to find the shape of a diffraction pattern by determining the apparent depth of Y for a series of X's. Such a pattern has been superimposed on the profile. Its extreme steepness is the result of the 36-fold vertical exaggeration of this profile. The slopes of the reflectors are not as steep as those of the pattern, and thus were not produced by diffractions.
FIG. 4A FLATHEAD LAKE BATHYMETRY AND PROFILES

NUMBERS REFER TO DEPTHS OF CONTOURS

CONTOUR INTERVAL: 40 FT.

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turned out that the east side of the lake had the greatest amount of sediment deformation.

On short traverses of a mile or less landmarks at each end were located on a map, the boat was kept at a constant speed, and was navigated as nearly as possible in a straight line. On longer traverses positions were checked by sextant sightings taken at about every mile.

In mapping the profile lines sextant sightings were plotted with a triple arm protractor, and all segments between landmarks and/or sextant sightings were assumed to be straight lines traversed at a constant velocity. In most profiles the sediment surface and prominent reflecting layers were highlighted and digitized for additional computer processing.

A set of computer programs was written and used to convert the digitized data into profile data files consisting of a series of x,y points for each line, with x representing the horizontal distance, in feet, from the start of the profile, and y, the depth. The coordinates were scaled to correspond to true map position and were adjusted for variations in boat speed and drift (via sextant sights), vertical scale changes and delay offsets (Appendix 1). From these data files line drawings of each digitized profile were plotted on a Calcomp Plotter (Appendix 2).
CHAPTER III

RESULTS

Character of Reflectors

Two different patterns of reflections were evident in the profiles. These were coherent signals indicating layered reflectors and "incoherent" signals showing no layering. While each reflection pulse does not necessarily correspond to an individual bed, structures shown by the layered reflectors do match those of the actual sediments. Incoherent signals can be produced by a variety of conditions: 1) structural patterns can seem to disappear with depth because of a loss of signal strength; 2) bedrock or sediment layers with a high acoustic absorption can return disordered signals; 3) a structurally amorphous sediment would show no discernable patterns in its reflections; and 4) layered patterns can also be destroyed by certain types of deformation of the sediments. In this study the terms "chaotic", "amorphous", and "disordered" will be used non-genetically and synonymously to describe reflecting zones with no discernable layering.

Bathymetry and overview of sediment patterns

The bathymetry determined from the profiles corresponded closely with that derived from two previous unpublished bathymetric surveys conducted by Silverman, et al (1970) and Moore (1979). Small discrepancies are probably due to errors in contouring between widely
spaced (1 to 2 km.) profile lines. Because of the lake’s very irregular bottom topography, contour lines approximated between traverses are bound to be somewhat erroneous. Other differences probably are the result of the failure of previous surveys to use sextant sightings as a means of checking position on the longer traverses. However, errors in all cases are small, and for the purposes of this study, the bathymetric map printed by Silverman, et al (1970) is perfectly adequate (Figs. 4A and 4C).

The most prominent feature of the lake bottom is a deep elongate trough which extends from the southeast end of Flathead Delta, down the eastern side of the lake, and into Skidoo Bay (Fig. 4B). The alignment of the trough corresponds with that of the Flathead graben described by Stickney in the Kalispell Valley, and is clearly its southern continuation. Depths of the trough range from 300 to 370 feet. Slopes into the deepest part are gradual in the north and increase to the south, especially on the east side. The trough is filled by chaotic reflectors with no discernable layering, covered by 20 to 30 feet of smoothly layered reflectors (Fig. 5). The thickness of the chaotic filling is variable. It is thinnest near the north and south ends of the trough, and in these areas is underlain by folded and deformed beds. Most of the deformed structures found in the lake were in the trough and on its more gradual slopes.

The slopes on both sides of the trough contain a mixture of layered reflectors and chaotic zones (Fig. 5). Some layered reflectors are clearly truncated and unconformably overlain by more
FIG. 4B
SUB-SURFACE TOPOGRAPHIC DOMAINS OF FLATHEAD LAKE
(FROM JOYCE, 1980)

DELTA
TRANSITIONAL SLOPES
WESTERN SHELF
EASTERN TROUGH
POLSON BAY

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NUMBERED PROFILES ARE REFERED TO IN TEXT OR DISPLAYED IN APPENDIX.

CONTOUR INTERVAL: 40 FT.

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PROFILE 47

DISTANCE (FT.)

DEPTH (FT.)

0 6844 13688 20532 27376 34220

TRUNCATED BEDS

FOLDED BEDS

TROUGH FILLING

KEY:

- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES
recent lake sediments. Several benches on the eastern slope have a variety of deformed structures which subsequently will be discussed in more detail.

To the west of the trough is a moderately deep and flat area called the western shelf. Its depths range from 160 to 240 feet. It is characterized by undisturbed packages of horizontal, layered reflectors, showing some localized and limited zones of deformation.

The lake has four large bays. Skidoo Bay, the deepest of these, is the southern end of the main trough which is terminated by Finley Point, a bedrock peninsula partially covered by morainal till. Most of the bay is 280 to 320 feet deep. The slopes on the east and west side of the bay are extremely steep, while at the southern end the slope is more gradual but much more irregular. Like the rest of the trough, the bay has a variably thick filling of chaotic reflectors beneath a drape of undisturbed layers. In its thinner areas, the chaotic zone can be seen overlying layered reflectors which are folded and fragmented.

Big Arm Bay on the west side of the lake has a small basin 160 feet deep, but most of the bay is shallower. Its sediments give smooth layered reflections, and appear to be generally undeformed. Disruptions with wrinkling and fracturing of parts of the sediment package are found in a few areas on the north side of the bay. Minor wrinkling of sediments on and at the base of slopes is common throughout the bay.
Much of Kalispell Bay is covered by the extensive Flathead River delta. Over the 40' deep foredelta and the delta slope the acoustic signal was unable to penetrate more than a few feet into the sediments. Apparently it was being absorbed by a highly attenuating zone underlying the uppermost layer of sediments. Signal penetration improved at the base of the delta slope, but still no sedimentary layering could be distinguished for as much as a mile from that point. The transition to a package with clearly discernable layering was extremely sharp (Fig. 6, Profile 20). Thus the sedimentary structures caused by the slumping and turbidity flows commonly associated with deltas are not apparent in these profiles. Other than the delta, and some small hummocks at its base which probably resulted from slumping (Joyce, 1980), Kalispell Bay had no notable features.

Polson Bay is extremely flat and shallow, with depths of about 25 to 30 feet. The character of the records below the surface layer was inconsistent. In some areas a hundred foot package of layered reflectors would clearly be evident, and then would abruptly disappear, with all of the reflections below a thin surface layer becoming amorphous (Fig. 6, Profile 48). The abruptness of the change is not geologically logical, and it is likely that the reflecting beds are present but are masked by a highly scattering near surface layer. This signal incoherence occurred both in the shallow sediments of Polson Bay and in the sediments at the top, slope, and base of the delta. It was never a problem in other areas and does not seem to have been caused by any mechanical irregularities. Extremely shallow
SECTION OF PROFILE 20

DEPTH (FT.)

DELTA
HIGH SIGNAL ABSORPTION
SEGMENT SHOWN IN PHOTO
SHARP TRANSITION FROM LAYERED TO CHAOTIC ZONE

DISTANCE (FT.)

SEGMENT SHOWN IN PHOTO

SECTION OF PROFILE 48

DEPTH (FT.)

HIGHER SIGNAL ABSORPTION
SUDDEN LOSS OF REFLECTORS

DISTANCE (FT.)

KEY:
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

10342  12232

6116
Sediments can be above wave base during storms. Prodelta sediments are constantly affected by turbidity flows and bottom currents. According to Otis et al (1977), acoustic scattering is caused either by a high gas or a high sand content in sediments. Shallow and deltaic areas both have higher sand contents than open lake sediments. Water samples taken from Polson Bay have shown that storm waves there do entrain fine silts and clays as suspended load (Stewart, 1980). Sands deposited on foredeltas are brought downslope and into the prodelta by slumps and turbidity flows. Thus sand layers are the most probable cause of the amorphous signals in Polson Bay and around the delta.

**Types of structures**

Sedimentary Drape. The most recent sedimentary processes are producing layered reflectors in all areas of the lake except on the delta. These reflectors are 20 to 30 feet thick and are clearly discernable when they overly deformed sediments (Figs. 7-21). They are undeformed and drape over irregularities, smoothing them out with time. The exact base of this sedimentary drape is apparent only over deformed structures. On any given profile it usually can be correlated from one structure to another by tracing individual layers. The records do not show each echo as an individual wave pattern, but approximate amplitudes only by the intensity of the markings. This makes lake-wide correlations very difficult. However, the base of the
drape can sometimes be correlated between parallel profiles by tracing it through a perpendicular profile intersecting both of them. Coupled with the overall consistency of its thickness, this correlation implies that the base of the drape is a time line. The thickness of its sediments represents a distinct period of deposition, with varying thicknesses produced by differing sedimentary rates throughout the lake.

Shallow cores taken from locations throughout the lake show that the drape is composed of horizontally bedded couplets of brown silt and black clay (Joyce, 1980). The thickness of the couplets is variable, but averages from 1 to 2 cm. Some silt layers are 6 cm. thick, and in all cores silts tend to predominate over clays. The sharpest boundaries are those of silts overlying clays. While all couplets are clearly not represented by individual reflectors, the pattern of layering is accurately reproduced.

Undeformed Packages. Normal and apparently undisturbed patterns of lacustrine sedimentation are evident over much of the western shelf. In many areas packages of horizontal layered reflectors at least 200 feet thick are present (Fig. 7). In these areas the drape is indistinguishable from underlying layers and so the conditions of deposition were probably very similar to present ones. The depositional environment was extremely stable, and was unaffected by the processes which caused deformation in other parts of the lake.
Truncated Beds. Horizontally layered reflectors represent horizontally bedded sediments. Bedded sediments do not suddenly stop unless they are deposited against a wall. Otherwise they tend to be continuous, and generally follow the topography they overlie. Thus abrupt truncations of layered reflectors where no obstructions are present, are clear indications of erosion or sediment deformation. The two types of truncations are erosional unconformities and sudden losses of coherence resulting from sharp transitions from layered to disordered sediments. In Profile 35J (Fig. 8) good reflectors dissolve into a chaotic zone. Underlying beds are continuous, and were unaffected by the disruption. The forces which affected the beds by disrupting their layering and possibly removing some sediment must have originated at or near the surface. Profile 30 (Fig. 9) shows a similar pattern. Both the chaotic zone and the adjoining reflectors are underlain by continuous beds. Deeper bedrock motion is clearly not the cause of disruption.

The alignment of beds in Profile 35G (Fig. 10) suggests that some lake sediments have been removed. Terminated beds dip to the east on a westerly dipping slope. Either there once must have been deposition in the area above the present slope, or a large block of sediments has been uplifted. If uplift has occurred it may have been caused by bedrock faulting or the backward rotation of a gliding slump block (Dingle, 1980). The profile does not provide the evidence necessary to make the distinction.
In Profiles 6 and 17 (Figs. 11 and 12) it is clear that large amounts of sediment have been removed. In each section a 60 to 80 foot package of reflectors is truncated. All truncated layers are now unconformably overlain by the base of the undisturbed drape.

Where underlying beds are continuous, it is evident that the cause of bed termination must have been surficial. Several examples are ambiguous, but in no case is there evidence which conclusively shows that bedrock movement directly raised the sediments. Scouring or block fracturing caused by massive slumping are the most likely processes to have truncated the beds.

Chaotic Zones. Any zones that do not show layering are termed chaotic. The term is non-genetic. Till could appear just as chaotic as lake-beds that have been disrupted by mass movement. However, coring done in association with sub-bottom profiling in a wide variety of lakes (Hyne et al, 1972; Otis et al, 1977; St.John, 1973) has demonstrated that undisturbed lake sediments almost always produce layered reflections on a profile. In the following examples chaotic zones are associated with other features that indicate that some disruption has occurred.

A single chaotic layer is found over much of the southern half of the western shelf (Fig 13). It lies in a well defined and limited zone within a horizontal package of layered reflectors that is near slopes, but not necessarily right beneath them. At its edges there is
SECTION OF PROFILE 6

FAULTS?
SEGMENT SHOWN IN PHOTO
TRUNCATED BEDS
CHAOTIC ZONE FILLING

KEY:
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

FIG. 11 DEPTH (FT.)

DISTANCE (FT.)

18368 9184
SECTION OF PROFILE 17

TRUNCATED BEDS

SEGMENT SHOWN IN PHOTO

STEEPLY DIPPING BEDS

CHAOTIC TROUGH FILLING

KEY:
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

W.  E.

DEPTH (FT.)

-100-
-200-
-300-
-400-

DISTANCE (FT.)

46560

58200

FIG. 12

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SECTION OF PROFILE 6

FIG. 13

DEPTH (FT.)

DISTANCE (FT.)

SEGMENT SHOWN IN PHOTO

FRAGMENTED AND THICKENED
CHAOTIC ZONE

KEY:
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

45920
36736
an abrupt transition from smooth layered reflectors to fragmented and chaotic ones. It is also characterized by a slight thickening of the sedimentary pile. The implication of these features is that the chaotic zone was formerly an undisturbed pile of flat reflectors which were then fragmented. The layering of the reflectors has not been completely obscured, and many small blocks can be seen folded and offset by minor vertical faults. These produced a horizontal shortening and vertical thickening of the layer in response to horizontal compressive forces.

The slight topographic rise is gradually being smoothed out by the sedimentary drape. The underlying beds sag under the thickened layer, but the amount of depression decreases with distance below the chaotic zone. Thus the younger overlying sediments and the older underlying beds have not been affected by the compressional forces which formed the chaotic layer. This deformation was most likely caused by a slight downslope slippage of large sediment blocks, with fracturing occurring at a zone of weakness, in what was, at that time, the top of the sedimentary pile.

Profile 35D (Fig. 14) is typical of the eastern shelf which drops off into the main trough. The slopes lying to the west of the truncated beds have chaotic zones with an extremely irregular or knobby topography underlying the recent sedimentary drape. Some of the high points or knobs are clearly made up of layered reflectors, and a column of such reflectors can be followed all of the way down through the sedimentary pile, through the surrounding chaotic zone and
FIG. 14

PROFILE 35D

KEY:
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

SEGMENT SHOWN IN PHOTO

KNOB UNDERLAIN BY HORIZONTAL REFLECTORS

DEPTH (FT.)

DISTANCE (FT.)
into a deeper area where it becomes part of a continuous set of layered reflectors. Sedimentary processes do not build up narrow columns of flat lying beds which jut up above the surrounding area. These high knobs could not have been deposited in isolation. Since their beds do not drop off to the sides, they represent undisturbed remnants of what had formerly been a broad horizontally layered area. Some sediments were removed and others disrupted, and since continuous and uniformly sloping deep layers underly the knobby chaotic area (Fig. 15), the disturbance must have been propagated from the surface, rather than the bedrock.

Almost all troughs in the lake contain a chaotic filling. Profile 35K (Fig. 16) illustrates a common pattern of trough filling, with deep beds on the sides of the trough sloping down, into, and perhaps under the chaotic filling. Shallower beds often are truncated (Fig. 12). The thickness of the trough filling is variable, and ranges from 20 to more than 200 feet. Small troughs are often completely leveled. In some areas of the deep trough deformed sediments underly a relatively thin chaotic filling (Figs. 5 and 17); in others the thickness of the chaotic zone exceeded the penetration limits of the profiler. Whatever process filled the troughs is not presently active, since all troughs are covered by the layered undeformed sedimentary drape. But Profile 21 (Fig. 18) shows more than one episode of trough filling. In this case a smooth reflecting sedimentary drape was deposited for a short period of time after the formation of the chaotic and knobby filling. Then another chaotic
FIG. 15

KEY:

- CONTINUOUS DEEP REFLECTORS
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

DISTANCE (FT.)

DEPTH (FT.)

KNOB UNDERLAIN BY HORIZONTAL REFLECTORS
TRUNCATED BEDS
SEGMENT SHOWN IN PHOTO

PROFILE 351

W. E.
SECTION OF PROFILE 30

**KEY:**
- Layered Reflectors
- Undeformed Sedimentary Drape
- Chaotic Zones

**SEGMENT SHOWN IN PHOTO**

**FOLDED LAYERS UNDERLYING CHAOTIC TROUGH FILLING**

**DISTANCE (FT.)** 23856 to 31808
THIN SEDIMENTARY DRAPE LYING BETWEEN TWO ZONES OF CHAOTIC TROUGH FILLING

KEY:
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

FIG. 18
DEPTH (FT.)
-400 -
-300 -
-200 -
-100 -

DISTANCE (FT.) 19848
13232 26464
episode filled in all remaining low areas.

Neither the composition of the trough filling nor the processes which formed it can be determined unambiguously from the profiles. With a mode of deformation so different from underlying and overlying sediments, the filling is clearly not made up of autochthonous lake sediments deformed only by differential compaction. They have been transported, possibly off of the delta and side slopes by a combination of slumps and mass flows, or perhaps through glacial action. Large volumes of sediment appear to have been removed from the slopes of the trough. In Profile 17 continuous and flat underlying layers imply that a block of sediment 60 to 80 feet thick and over a thousand feet wide has been removed. Removal of sediments definitely widened the trough, but it is unclear whether it was first deepened before being filled. The two possible conditions are illustrated in Fig. 19. One situation postulates a trough that was formerly narrower and deeper. In this case slumping from the sides filled in the center. Alternatively, the trough could have been deepened by the same erosive forces which scoured its sides. Subsequently it could have been partially filled by some amorphous material. The profiles show deeper layers which do not appear to be truncated, sloping down steeply under the edge of the chaotic filling. This may be the result of loading; however, since these layers cannot be traced all of the way under the trough, they do not show whether or not scouring took place at that level. In some profiles the amount of material removed from the slopes appears to exceed the amount of

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FIG. 19

CASE 1
TROUGH FILLED BY SLUMPS

BEFORE

AFTER

LAYERS ON THE SIDE OF THE FILL DIP UNDER IT.
LAYERS UNDERLYING THE TROUGH SHOULD BE CONTINUOUS, (THEY MAY BE FOLDED).

CASE 2
TROUGH FIRST SCoured, THEN FILLED

BEFORE

AFTER

LAYERS ON THE SIDE OF THE FILL ARE TRUNCATED.
VOLUME OF FILL IS NOT RELATED TO THE APPARENT AMOUNT OF EROSION.
chaotic filling in the trough. Substantial settling and compaction of slumped sediments could have occurred as a result of dewatering or an erosional agent could have carried away sediments within the trough. There is no evidence of how closely linked in time the erosion and the deposition were. They may have been stages of a single event or the result of two separate events. The profiles often do not show the base of the chaotic filling, and thus it would be impossible to attempt a quantitative balance of the volumes of scour and fill. The thickness of the trough filling tends to increase going south, at least up to the north edge of Skidoo Bay. Unpublished records from a previous airgun survey conducted by Wold et al (1970) show disturbed bedding underlying layers of chaotic filling over 200 feet thick in the trough south of Yellow Bay. Thus it is possible that some portion of the eroded sediments were moved to the southern part of the trough.

Foldlike Structures. Underlying the chaotic filling in many troughs are folded or wrinkled reflectors. In each case the folds maintain constant angles of slope through the sedimentary pile. In a depositional environment this similar style of folding can only be produced by rapid deformation. Gradual processes produce structures that are filled and smoothed at the surface by deposition while deformation is taking place, resulting in structures that level out from bottom to top. Rapid deformation would produce consistent structures through the pile, or, if promulgated from the surface, may show a smoothing downwards.
The most unusual folded structure is found in a minor trough on a bench at the base of the bedrock slope of the eastern shore. The sediments appear to form columns that are curved convexly upward (Figs. 20 and 8). The curvature at the edges is actual and not the result of diffraction patterns. The consistency of slopes and curvature through the column is readily apparent. To have formed such patterns from bedrock movement would require a series of closely spaced and narrow down-dropped and up-thrown blocks. A more likely explanation is that the structures were produced by small sudden movements of blocks of sediment sliding down the bedrock slope (Dingle, 1980). The convex form may be the result of buckling due to minor compression.

The folds in Profile 30 (Fig. 17) are more normal looking, since they have a clear syncline as well as an anticline. They are found in the northern part of the main trough and indicate that at least slightly prior to the trough filling, compressional forces were exerted on the deeper sediments. The profiles do not indicate the source of these forces, however considering the associated kinds of deformation, it seems likely that the compression was caused by blocks of sediment slipping slightly downslope into or along the trough.

A north south profile of the shelf on the east side of the trough shows blocks of flat reflectors separated by synformal troughs filled with chaotic sediments (Fig. 21). The high flat layers appear to be undisturbed lake sediments. The slope on either limb of the synforms is maintained through the sedimentary pile with no evidence of gradual
trough filling prior to the chaotic filling. Unlike the other folds, these structures do not appear to have been caused by horizontal compression. No compressional deformation is apparent in the undisturbed blocks. More likely vertical forces were involved. Subsidence may have occurred under the synformal troughs, or uplift may have raised the blocks. East-west profiles across the eastern shelf show it to be an area of slumping. On more gradual slopes the blocks slid intact, sometimes with a rotational component raising the downslope end; on steeper slopes sedimentary structure was disrupted. The profile is in the area of this slope change. The undisturbed layers are probably on gradual slopes of less than 2 degrees, with the troughs sagging into steeper areas.

Faults. Many of the structures previously discussed may have been directly caused by active faulting propagated from the bedrock through the sediments. These include the synformal troughs and some examples of the truncated and upraised beds. Unfortunately, none of these structures provide conclusive evidence for faulting. They could also have been caused by various types of mass movement. On the other hand, there is conclusive evidence, primarily from continuous underlying beds, that many other structures were directly caused by surficial processes, such as slumping. Individual structures have little or no continuity. Even in areas where parallel profiles were no more than a half mile apart, they showed considerable variety of structural patterns. Most of the structures found were formed
rapidly; movement along faults usually is protracted in small increments over extended periods of time. Upper layers tend to fill in and mask irregularities, so it is not until after their deposition that fractures will begin to show. The older and deeper the layer is, the longer it will be subject to fracturing. Thus in a lake any gradual and continuous process of deformation would show increasing disturbance with depth. Since earthquake activity has not abated recently, faulting associated with it should still be going on; yet there is no clear evidence that the drape is being deformed.

A structure found on a slightly upraised ridge some distance west of the main trough shows some evidence of being formed by a gradual process (Fig. 11). As in several of the other examples, the evidence is ambiguous, and is only suggestive not conclusive. The steepest slopes appear to be in a thin chaotic layer under 30 feet of sediments. Structures that are steepest in the uppermost sediments are produced by surficial agents. However, the pronounced thickening of several underlying layers within the graben calls for a gradual process of formation. Perhaps the slopes underlying the chaotic layer are offset, and while the slopes appear to decrease with depth, the throw actually increases. The difficulty of tracing deeper beds through the graben, and the limits of the profile's depth penetration combine to open a wide field for untestable conjecture. Nevertheless, the strongest argument for fault control in this case is that it is difficult to explain slumping as a mechanism for subsidence in the center of a ridge. There may be slopes or irregularities running
perpendicular to the profile, but nearby profiles do not show this.

One structure from one profile cannot prove that active faulting of lake sediments is taking place, but it certainly suggests that the possibility cannot be dismissed.
CHAPTER IV

CONCLUSIONS

Most of the structures discussed so far lie immediately beneath the base of the undisturbed sedimentary drape. These are the most pronounced structures seen in the profiles. Other disturbances are occasionally seen deeper in the sedimentary package. Most often these are wrinkled layers which rapidly smooth upward and disappear before the next episode of deformation. Occasionally unconformities are found in deeper layers (Fig. 8). Patterns of deeper disturbances are not sustained by later deformation. Episodes of deformation have occurred several times. In each case they have been smoothed out by subsequent lake sedimentation.

The sedimentary drape which is the most modern sedimentation in the lake is undeformed, and thus represents a distinct period of time during which no episodes of deformation have occurred.

All of the folds maintain their slope angles from the bottom to the top of a package. Unconformities are sharply defined with no evidence of intervening lake sedimentation. These structures could not have been caused by gradual processes such as differential compaction or slow persistent faulting. They provide unambiguous evidence that short discrete events were responsible for much of the deformation in the lake.
When the vertical exaggeration of the profiles is removed, it is evident that, in all cases, deformation has occurred on extremely gradual slopes. It is not possible to determine the precise slope of the bedrock underlying the sediments. But, judging from the sediments themselves, it seems that downward movement on slopes of 1 to 2 degrees has caused wrinkling, folding, buckling, and fracturing, while still preserving the layering. On slopes greater than 2 to 2.5 degrees mass movement generally has disrupted layering.

A hypothetical east-west cross section of the lake's bottom (Fig. 22) gives the general alignment of features. Most of the structures are clearly the result of surficial processes, such as slumping and possibly scouring. No structures could be shown unambiguously to have been propagated directly from bedrock faulting through the sedimentary pile.

There is an obvious north-northwest alignment to the general pattern of deformation (Fig. 23). The eastern trough is clearly an extension of the fault controlled Flathead graben. The steepness of the trough and the recent deformation on both of its sides suggest that the graben is still being actively faulted. By creating unstable slopes that slumped during a disturbing event, recent active faulting may have been responsible for deformation. Alternatively, the unstable slopes may have been produced by normal depositional processes, with faulting responsible only for the events that triggered deformation. In this case the alignment of slump structures along either side of the trough does not necessarily prove that
HYPOTHETICAL W-E CROSS-SECTION SHOWING ALIGNMENT OF MAJOR DEFORMED STRUCTURES

KEY:
- LAYERED REFLECTORS
- UNDEFORMED SEDIMENTARY DRAPE
- CHAOTIC ZONES

W.                   E.

0                   35000
DISTANCE (FT.)

DEPTH (FT.)

THICKENED CHAOTIC LAYER

CHAOTIC TROUGH FILLING

FOLDED BEDS

TRUNCATED BEDS

KNOBBY TOPOGRAPHY

CONTINUOUS DEEP REFLECTORS

CONVEX COLUMNS

FIG. 22

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Dots are in locations where the sedimentary drape is relatively thin, and overlies deformed structures or other interesting features, which may be reached and sampled with a 20 foot long corer.
north-northwest trending faults are still active.

Several isolated occurrences of deformation in Big Arm Bay could have been produced by localized faulting. But since they are found immediately beneath the drape, they were produced at the same time, and, most likely, by the same events which affected the rest of the lake. Perhaps the recent earthquake activity in that area is related to crustal movement that is not being translated through bedrock to the surface.
A rate of deposition for recent sedimentation in the lake has not been determined, and this presents the major difficulty in specifying the kind of event which caused the deformation. A previous study by Joyce (1980) has estimated the rate to be 1 to 1.5 cm/yr. This estimate, which is tenuous, was based on couplets from a single core, which could not be correlated with adjacent cores, and which may not have represented annual deposits.

There are too many factors involved in sedimentation rates for comparisons with other lakes to be especially meaningful. Flathead Lake does have a relatively large drainage area. But topography, rock resistance, and climate also play important roles in determining the quantities of sediment transported into the lake. Other major mountain lakes such as Lake Tahoe (Hyne et al, 1974), Yellowstone Lake (Otis et al, 1977), Okanagan Lake (St. John, 1973), and Garibaldi Lake (Matthews et al, 1976) have had sedimentation rates reported to be .1 to 1 mm/yr. This is at least an order of magnitude lower than Joyce's estimate. On the other hand, Gilbert (1975) has found varved couplets in Lillooet Lake, B.C., which range in thickness from 1.6 to 9.3 cm. Seven per cent of Lillooet Lake's drainage basin is still covered by active glaciers, and this may explain its much higher rate of sedimentation. Varved deposits from Pleistocene glacial and proglacial lakes often have couplets roughly one to ten cm. thick (Shaw, 1977; Curry et al, 1977), thus the high rate of sedimentation
in Lillooet Lake may be primarily the result of active glacial erosion.

The undisturbed sedimentary drape which overlies all of the deformed structures ranges from 10 to 40 feet in thickness, with an average thickness of about 25 feet. With a sedimentation rate of 1 cm/yr, the drape would represent a thousand years of deposition. A lower rate of 1 mm/yr would mean that the last major disturbance occurred ten thousand years ago. In addition to changing the ages of the deformed structures by an order of magnitude, the different depositional rates affect the range of its possible causes: about ten thousand years ago the last glacier to cover the lake was receding.

If the lower rate of sedimentation is accurate, there are a variety of possible causes for many of the disturbed features. Glaciers do not always scour to bedrock. Otis et al (1977) claim that in Yellowstone Lake the Bull Lake and Pinedale stades caused negligible scouring of the lake sediments. On a smaller scale, lake sediments uncovered during the last twenty to thirty years by the retreating Austerdalsisen Glacier in Norway show no evidence of deformation, or even of having been overridden (Theakstone, 1976). In another area till has been found deposited over slightly sheared lake beds (Hansen, et al, 1961). Thus it is possible that sediments underlying the drape could have been deposited in a pre-Pinedale lake, dammed by an older and possibly no longer apparent moraine. Loading and partial scouring of slope sediments could have been caused by normal ice movement during the glacial advance. Slumping could have
been associated with the glacial retreat, when sediments on the scoured and oversteepened slopes of the trough became unstable. Trough filling could be till or deltaic outwash shed from the retreating glacier into its proglacial lake. Deeper ice buried by proglacial lake sediments shed by a retreating glacier has been shown to stay frozen for significant periods of time (Gustafson, 1975). It’s gradual melting can cause the formation of a variety of structures in the overlying sediments including convexly curved mounds, grabens, and back dipping blocks (Shaw, 1977; Gustafson, 1975). In an introduction to a bibliography of articles dealing with penecontemporaneous deformation of sediments, Sims (1978) states that it is becoming increasingly evident that many structures which in the past were assumed to be tectonically derived could also have been produced as a result of glacial action.

The profiles do provide some evidence that seriously weakens the argument for a glacial origin of the structures. Terminal moraines extend all of the way across the valley at Polson and completely across the lake at Finley Point and the Narrows; yet there is no evidence of till or glacial disturbance in large areas of the western shelf, which have very thick, smooth, and undeformed packages of lake sediments. The profiles also show no evidence of a lakewide layer of till, which should have been deposited by a retreating glacier. If the main trough was scoured by glacial action, folds underlying it should show some evidence of being dragged or overturned to the south, but they don’t.
A 1 cm/yr rate of sedimentation would preclude any glacial influence in the formation of the structures immediately underlying the drape. Regardless of the time of their occurrence, the disturbing events could have been very large earthquakes. If the time of deformation was no more than one, or even several, thousand years ago, a major earthquake could have been the only possible cause.

Much research has been done on the formation of small scale features which result from the liquifaction of unconsolidated sediments subject to violent shaking (Kuenen, 1958; Sims, 1975), but few studies deal with resulting large scale structures, aside from their grossest details. The most pertinent work was done in the aftermath of the great Alaskan earthquake of 1964. The tremors caused massive subaqueous slumping and gravity flows, primarily off of the fronts of deltas. Studies of the Copper River Delta, Alaska, by Reimnitz (1972) and Reimnitz and Marshall (1965) showed a general steepening of all delta slopes. The steepest slopes, with inclinations of up to 9 degrees had very irregular and hummocky topographies. Long gradual slopes showed blocks of coherent reflectors offset by slump scars with slopes of 5 to 2.5 degrees, and up to 100 feet of dip slip. The reflectors in the blocks showed a very slight upward convexity. Erosion by the tsunami and seiches followed by a return to normal patterns of deposition terminated many of these structures with unconformities. Similar structural patterns were evident in Kenai Lake, Alaska, where McColluch (1966) compared pre-earthquake and post-earthquake lake bottom configurations. Slides
came off of the margins of all deltas in the lake. Slump scarps were curved concavely upward, implying that rotational slumping had occurred. Areas of deposition could be clearly distinguished by their rough bottom topography. In profiles the volume of material removed exceeded the volume of material deposited at the base. Lateral spreading was shown to have accounted for some of the difference. The rest must have been the result of compaction. Sliding produced two types of major waves, one of which interacted with the slide debris, entraining much of its material, and transporting it across low slopes, as far as 5000 feet away from its source.

Deformational patterns in Alaska sound very similar to those found in Flathead Lake. Unfortunately, most of the profiling work done in Alaska was with instruments that either did not penetrate beneath the lake bottom, or did so with such low resolution, that it is not possible to see the fine points of structures, such as their layering, or lack of it.

Based on what happened in Alaska, one or more major earthquakes around Flathead Lakes could have caused slumping of blocks of sediment on gradual slopes and a complete loss of cohesion of sediments on steeper slopes on the front of the delta and the sides of the main trough. In this case all of this eroded material would now make up the chaotic trough filling.
Such a scenario adequately accounts for all of the structures and the localization of deformation, but it has other serious weaknesses. Alaska has a history of extremely large earthquakes. Nothing on that scale is known ever to have occurred anywhere around Flathead Lake. Smaller earthquakes have been common around the lake, yet there is no evidence of any recent small scale slumping. Yellowstone Lake has had some of the highest magnitude earthquakes of the region occur in its vicinity, yet studies have described no structures similar to those found in Flathead Lake (Otis, et al, 1977). The magnitude 7.1 earthquake at Hebgen Lake caused major landslides and lake seiches. Yet little evidence of any major subaqueous slumping or of other significant changes in the lake's sediments was found in bottom profiles (Jackson, 1964). The strength of the 1964 Alaska earthquake was at least an order of magnitude greater than anything known to have occurred in the Northern Rocky Mountain region. These smaller earthquakes do not seem to have comparable effects on unconsolidated sediments. Any argument that requires a magnitude 8 earthquake to have occurred near Flathead Lake in the last thousand years is somewhat questionable. However, it is very possible that differences in patterns and rates of sedimentation along with slope instabilities resulting from fault movements might have made Flathead Lake more susceptible to slumping than either Yellowstone or Hebgen Lakes, and perhaps all that was necessary to trigger deformation was a magnitude 6.5 to 7 event.
If an accurate rate of sedimentation is provided by further studies, it would be extremely helpful in resolving which type of event caused the deformation. 20 foot long cores may be able to penetrate below the drape in selected areas and determine the composition of the chaotic trough filling. Fig. 23, which shows the general distribution of deformed structures, also proposes several suitable coring sites where a relatively thin drape overlies a deformed structure (Several such sites are also noted in the line drawings in Appendix 2). Microstructures in sedimentary layers immediately below the base of the drape may provide useful evidence. Small load casts, stringers, and heave-up structures found beneath the unconformity, even in undeformed sediments, would indicate that liquifaction had taken place (Sims, 1975). Such structures, confined to individual stratigraphic horizons, but spread over large areas of the basin which had not had slumping or slope failure would provide conclusive proof of large scale earthquake activity. On the other hand, microstructures with uniformly oriented overturned folds and faults would have been caused by shear stresses most probably due to glacial overriding. Also they should be overlain by at least a thin layer of till.

Through its recent past Flathead Lake sediments have been subject to periodic episodes of deformation. The shallow nature of the disturbances does not necessarily eliminate the possibility that one or both sides of the trough are being faulted as Stickney's (1980) microearthquake evidence suggests. In Prince William Sound, Alaska,
and Yellowstone Lake evidence for faulting was also surprisingly sparse (Von Huene et al, 1967; Otis et al, 1977). Holocene sediments in Prince William Sound were not deformed even in zones where active faults could be projected from land into the sound. Similarly Flathead Lake sediments may be responding to bedrock tectonism without extensive internal deformation. The fact that Holocene deposition has not filled the trough, and the alignment of slumps and scours on both of its sides may be evidence for active faulting of the Flathead graben. Alternatively, unstable sediments could have been left on the slope by normal depositional processes.

Sets of deformed structures similar in detail to those found in Flathead Lake have not been described in other published articles. Since few other lacustrine sub-bottom profiling studies have produced records with the same detail and resolution, it is not yet possible to judge how unique these features are.
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APPENDIX 1

Computer Programs for Digitizing and Plotting Line Drawings of Profiles
GUIDELINES FOR DIGITIZING PROFILE LINES IN THE CORRECT FORMAT.

The first two points in any sequence are the end reference points of a segment. These should be digitized at the base of the white margin at the top of the page at the end points of a profile segment small enough to fit on the digitizing table. These points will be interpreted as water level. Before digitizing, ensure the profile should be aligned so that the Y values of the reference points are within ±5 inches of each other.

Delay changes, line numbers, and vertical scales are put in through the use of the menu package described in John Schumiton's DATA.2D program. Delay changes and line numbers must be put in after the digitized point that they refer to. Vertical scale lengths must be put in after the first point digitized following the reference points. Sections with different vertical scale lengths should be treated as separate segments, with a new set of reference points. The first three spaces of the menu are for the delay (a two digit delay must have a 0 in the first space). Space 4 is always a blank. Spaces 5-7 are for the line number. Space 8 is left blank. And spaces 9-11 are for the vertical scale length of the profile.

FLAG #2 is used to conclude line segments.
FLAG #3 is used after the completion of a profile segment.
FLAG #1 is used for deleting incorrect points.

After the digitized data is transmitted, run SEG.PGM to put the menu in the correct format. Then execute PGC.ED to create a data file with actual distances and depths of the points of the lines. The data file for any line is named ED*.DAT (* represents a two or three digit line number). The file title, direction, and map distance in inches are placed in the file directory KSST.Dat. Plots of the profile line drawing can then be produced on the Calcomp Plotter at any scale by the program KGCS.FOR.

PGC.ED takes digitized measurements from the data file ED*.DATE and converts them to measurements, in feet, of the distance from the beginning of the profile and the depth below water level. The program asks for:
1) the name of the output data file; 2) the distance from the start of the profile to any sextant readings and to the end of the profile, measured in inches plotted on a 12.5", 7.5", and (3) the profile alignment. It temporarily stores the coordinates in arrays XIST and YIST, while counting the number of point, Y, as then placed in the first line of the designated data file, along with the line number. These are followed by the X,Y coordinates of every point of the line (in feet).

DIMENSION XIST(50), YIST(50), XMPP(10)
DOUBLE PRECISION: FRV, INVE

500 FORMAT('2H,1D4,1H OF INPUT DATA FILE: ','$'
600 FORMAT('FRV','$'
700 FORMAT('TYPE 300')
800 FORMAT(2H,4H OF OUTPUT DATA FILE - 10 CHARACTERS

1 OR LESS (EXAMPLE: YP8545.DAT '$_$'
900 FORMAT(2H,4H)
1000 OPEN (UNIT=2, DEVICE='DSK', ACCES='SEQ', NDF='ASCII', FILE='YIST')
1100 OPEN (UNIT=3, DEVICE='DSK', ACCES='SEQ', NDF='ASCII', FILE='XIST')

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TYPE 130.

130 FORMAT (X, "INPUT MAP DISTANCE IN INCHES(3 DEC. PLACES)
1 OF START OF PROFILE, SE XTANT RDGS, IF ANY, AND END
2 OF PROFILE. (EXAMPLE: 10.0, 8.24, 12.58) "
ACCEPT 1, (XMAP, I=1, 19)

100 FORMAT (C30) TYPE 120.

120 FORMAT (I9, "IS THE PROFILE NORMA L (DELAY AND SCALE
1 LENGTH AT BOTTOM OF PAGE) OR REVERSED (BY AND SL
2 AT TOP OF PAGE)? TYPE N OR R: ")
ACCEPT 1, (XMAP, I=1, 19)

110 FORMAT (C4) C

DO 95 K=1, 20.
XMAP=XMAP(K)-XMAP(K-1)
TYPE 200, XMAP

2000 FORMAT (I9, F9.2) C

READ DIGITIZED END POINTS OF PROFILE SEGMENT.
READ (5,2.) X,Y,7,4,SL

XREF1=X
YREF1=Y
READ(5,1) X,Y,7,4,SL
YREF2=Y

C LOOP FOR COMPILING ALL OF THE LINES WITH IN A SEGMENT
DO BY J=1, 2
NEXT=
I=0

C LOOP DIGITIZES DIGITIZED DATA OF INDIVIDUAL LINE
C SEGMENTS, AND STORES IN ARRAY.
DO I=1, 6.
READ(5,2) X,Y,7,4,SL
IF (X.EQ.99.99) GO TO 5.

C NUMBER OF VERTICAL FEET PER INCH OF PROFILE
IF (SL.N.EQ.0) VSCAL = SL/9.1
IF (SL.EQ.0) VSCAL = 0
GO TO 53

GO TO 98

53 YREF3=I
X,Y,7,4,SL
TNUM=
C CHECKS EACH LINE TO SEE IF A NEW DELAY FACTOR HAS BEEN PUT IN.
54 IF (X.EQ.99.99) GO TO 3;
READ(5,2) X,Y,7,4,SL

DELY=1

C CONVERTS DIGITIZED VALUES TO COMPLETED VALUES IN FEET.
30 X=((-((Y-YREF1)/XREF1-YREF1)))*XMAP(K-1)+2000.
Y=((-((Y-YREF1)/YREF1-YREF1))*YMAP(K-1)+2000.

C FACTOR WHICH CORRECTS FOR DIFFERENT ALIGNMENT OF
C PROFILE IN SEGMENT OR SECTION "UNITS."
IF (ALIGN.EQ.1) Y=Y+(1*VSCAL.)
YDIST(I)=X
YDIP(I)=Y
N=N+1;

70 CONTINUE
GO TO 52.

48 NEXT=1
50 WRITE (6,18) I=1, 20
25 F ORMAT (F9.1, F9.1)
DO 60 I=1, 20
60 WRITE (6,18) XDIST(I), YDIP(I)

20 FORMAT (F9.2, F9.2, I9)
IF (Y.EQ.99.99) GO TO 99
IF (X.EQ.99.99) GO TO 99
CONTINUE
GO TO 98

90 CONTINUE
STOP

99 END
FOR: F0P takes data files of digitized profiles and plots
profile line drawings on a Calcomp Plotter. The drawings
can be plotted from left to right or right to left with
any horizontal and vertical scales which will not exceed
the limits of the plotter. The standard scale for both axes
is 1"=2'-, 1:2:1 vertical exaggeration in the profile
can be obtained by requesting horizontal and vertical scale
multipliers: .5, it would give the
same exaggeration in a profile one half the size.

DIMENSIONS: LIST(Y),YSP(X), Y1(F)
DOUBLE PRECISION DATA
COMMON/SCAL/30(35)
91 CALL F0L((5,3))
c
PROTAM: SNS FOR LINE NUMBER AND LCWS FOR DATA FILE.
99 TYPE: 16
140 FORMAT(1X,"LINE NUMBER "S)
ACCEPT 16, F0MPL, PLT
150 FORMAT(13,1,4)
OPEN(UNIT=5,DEVICE="DSK",ACCESS=",SEQI",MODE=",ASCII",
IF(LIST=",STAT",AAT")$)
DO 17 1=1,33
READ(5,27)FILLET/FILLET
27 FORMAT(13,2,4)
IF(FILLET=",1",2)GO TO 67
IF(FILLET=",1",2)F0MPL, PLT)-AND. (FILLET=",0", F0MPL))GO TO 87
GO TO 37
67 FILLET=":"
IF(FILLET=",0", F0MPL)GO TO 127
17 CONTINUE
TYPE 47
47 FORMAT(1X,"FILE NOT FOUND")
GO to 97
87 FEPEAT 17, F0MPL(3)
107 FORMAT(5,5,1)
GO to 37
117 FEPEAT 17, F0MPL(3)
127 FORMAT(3,5,1)
37 FEPEAT 57, F0MPL/DIR/MAP
57 FORMAT(3,5,1)
TYPE 157, F0MPL/DIR/MAP
157 FORMAT(1X,5,5,5/15,5,5)
CLS()"(UNIT=5,DEVICE=",DSK",ACCESS=",SEQI",MODE=",ASCII",
1 FILE="VAMS")
TYPE 10
1000 FORMAT(1X,"PUT" LOCATION OF PLOT ORIGIN, HORIZONTAL AND
1 VERTICAL SCALE MULTIPLIERS, AND DIRECTION PROFILE
2 SHOULD = HPLOT( EXAMPLE: 2,2,1,2,6-L-A)/S"
ACCEPT 2,0, ,A,F,10XP,V10XP,POIR
2000 FORMAT(5,5,1)
S(1)=F
S(2)=0
S(3)=X19,M,XEXP
S(4)=(S2/255.)X10XP
S(5)=S(1)
S(6)=X10XP*2,0,.
IF ("DIR ".EQ. "R-L") GO TO 205
GO TO 217

200   S(5)=S(5)
S(6)=0

210   S(7)=-50.
S(8)=5.
S(9)=1.
S(10)=1.
S(11)=15.
S(12)=5.
S(13)=1.
S(14)=2.
S(15)=1.

CALL LILI ("DISTANCE (FT.)",14,"DEPTH (FT.)",11,11,11,0,9)

XPI=clipboard(5,1,1)
YP1=clipboard(5,2,1)
CALL PLOT(XPI,YP1,3)
XPI=clipboard(5,1,1)
YP1=clipboard(5,2,1)
CALL PLOT(XPI,YP1,3)

PTIT(1)="RI"
PTIT(2)="LC"
PTIT(3)="IR"

CALL TITEL (PTIT,35,3)
READ(5,15,90=15)NUM

DO 40 I=1,NUM
READ(5,2,X,Y

40   CONTINUE
CALL PLINE(PIST,YP1,NUM,1,1,2)
GO TO 35

45   TYPE 24

240   FORMAT(1X,"DO YOU WISH TO HAVE OTHER PLOTS DUNE ON THE
1 SAME SCREEN? ANSWER Y OR "N")
ACCEPT 2X, MORE

250   FORMAT(1X)
IF ("Y".EQ. "Y") GO TO 99
XPP=XPI+1
IF (DIR.EQ. "R-L") XPP=XPI+1

CALL PLOT(XPI,YP1,N99)

97   STOP

END
APPENDIX 2

Line Drawings of Selected Profiles
Key for Line Drawings.

- **Undeformed sedimentary drape**
- **Chaotic Zone**
- **Layered Reflectors**
- **Area where the sedimentary drape overlies deformed structures, and is thin enough to allow a 20 foot long corer to penetrate into the disturbed zone.**

A single layer of dots near the top of the sedimentary pile, with nothing shown beneath it, denotes an area of high signal absorption.

Most profiles have a 20:1 vertical exaggeration with a horizontal scale of 1"=4000'. To allow an uncut display Profiles 6 and 27 were plotted with a 23:1 vertical exaggeration and a horizontal scale of 1"=4651'. For the same reason Profiles 22 and 51 have a 22:1 vertical exaggeration and a horizontal scale of 1"=4444'.

North or East is always on the right side of the profile, and South or West is always on the left. The profile title gives the direction of travel. Zero on the distance scale designates the start of the profile. Zero on the depth scale is at water level.

See Figure 4C for location of lines.