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アメリカ合衆国西部, シェラネバダ山脈内タホ湖底の活断層 ——音波探査機を用いた予備調査——

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Active Faults in Lake Tahoe, Western Part of the United States. — a Preliminary Report —

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Lake Tahoe sits astride the crest of the Sierra Nevada and is cut by the border between California and Nevada. Physiographic evidence has now long been the basis to interpret that Lake Tahoe occupies a fault graben. The steep and straight range fronts and scarps that bound the east, west, and northern edges of the basin have been referred to as the East, West and North Tahoe faults, respectively. Yet little is known about the rate and recency of faulting along the faults. Therefore we conducted the seismic reflection survey in this lake.

Survey of the area offshore of Sugar Pine Point provided evidence of a north-striking zone of faults that cut sediments of the lake bottom. The section displays a broad fault graben with near-surface sediments sharply truncated by faults. Nonetheless, the fault displacement of shallow sediments argues for relatively young displacements.

The faulting of young sediments is also indicated in the profiles collected within Crystal Bay. The profiling delineated a distinct northwest striking scarp in sediments that corresponds approximately with the offshore projection of the Incline Village Fault. The warping and faulting of the lake bottom sediments is consistent with a late Pleistocene to Holocene recency of movement.

Logistics limited the opportunity to conduct seismic reflection within Lake Tahoe to 2 days. The available time did not allow an accompanying effort to obtain sample cores from the sites to aid in directly determining the age of the sediments involved in the faulting and warping. Nonetheless, the profiles do preliminary but arguable evidence for very young faulting in Lake Tahoe. The results provided here should, at minimum, provide a springboard for future efforts.

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High Resolution Seismic Reflection Survey in Lake Tahoe: Observations Bearing on Faulting and Climate Change

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On September 25 and 26 of 1993, the opportunity arose to conduct a reconnaissance high-resolution seismic reflection survey in Lake Tahoe on the California-Nevada border astride the Sierra Nevada crest (**Figure 1**). The resulting seismic profiles lend some insight to issues related to both faulting and climate change in the vicinity of Lake Tahoe. As well, they point to viable research directions that can lead to a better understanding of Holocene climate in the western Great Basin. The results of the reconnaissance form the subject of this brief letter.

Lake Tahoe, with an average depth of 302 m and maximum depth of about 503 m, is the third deepest in the United States and believed to be the tenth deepest lake in the world. The Lake occupies 497 km^2 of a 1,310 km^2 drainage basin. With an average surface elevation of 1,897 m, it is the highest lake of its size in the United States. Physiographic evidence has long been the basis to interpret that the Lake occupies a fault graben [*Birkeland, 1963; Hyne et al., 1972; Le Conte, 1875; Louderback, 1911*]. The East, West and North Tahoe faults bounding the east, west, and northern edges of the basin (**Figure 1**) are marked by steep range fronts and escarpments [*Hawkins et al., 1986*]. Little is known about the rate and recency of faulting. For example, available maps and reports provide no evidence that the East Tahoe fault displaces Quaternary deposits where it is projected to cut the north [*Birkeland, 1963; Hawkins et al., 1986; Matthews, 1968*] and south shores of the Lake [*Armin and John, 1983; Burnett, 1967; Hawkins et al., 1986; Wagner et al., 1981*]. Similarly, the West Tahoe fault is well-defined in bathymetric maps but not reported to cut Pleistocene glacial deposits of Tahoe and Tioga age along the south shore of the Lake [*Hawkins et al., 1986*]. It is only along the North Tahoe fault that clear evidence of recurrent late Quaternary movement has been recognized. A reflection profile shows the fault cutting sediments of reportedly Holocene age, producing a 14 m escarpment at water depths of about 400 meters [*Hyne et al., 1972; Hyne, 1969*]. Thus, while the total relief and physiography across the Tahoe basin are comparable to other basins within the Basin and Range, which are well-known to be bounded by active faults, little information is available regarding the rate of fault activity within the Tahoe basin.

Upon reaching a level of 6,223 feet, the waters of Tahoe flow across a natural sill at Tahoe City into the Truckee River (**Figure 1**). The natural sill is composed of about 4 meters of sediments overlying Quaternary bedrock, based on cores taken from inside the outflow channel by the US Forest Service [*Hug, 1989*] and the US Bureau of Reclamation [*Hawkins et al., 1986*]. Geomorphic evidence [*Davis, 1976*] and the occurrence of submerged tree stumps with calibrated ^{14}C ages between 6,300 BP to 5,000 BP [*Lindstrom, 1990; Rose and Lindstroms, in press*] have been the basis for suggesting that the level of Tahoe did not reach the sill during the mid-Holocene between about 7,000 to 4,000 BP. The deepest documented submerged trees reported by Lindstrom are about 4 m (13 feet) beneath the natural sill level.

Several hypotheses can be offered to account for the submerged trees. First , a period of aridity caused the lake level to drop in the mid-Holocene. The hypothesis fits well with a body of evidence from the western US that documents a period of mid-Holocene aridity [*Lindstrom, 1990*]. Second, sedimentation during mid-Holocene may have effectively raised the level of the sill at the Truckee River outlet, resulting in the submergence and death of trees near the shoreline. Because the depth of sediments on the sill is 4 m, the process could account for a similar rise in lake level. However, preliminary tephrochronologic (J.O. Davis, *pers. comm.* to M.R.R.) and palynologic (J. West, Bureau of Reclamation, *pers. comm.* to M.R.R.) analysis of a core taken through the sill by the Bureau of Reclamation suggest the sediments on the sill are pre-Holocene in age and, thus, do not support the hypothesis. Thirdly, because (1) the basin is bounded by active faults, (2) vertical displacements resulting from large earthquakes in this region [e.g. *Scholz et al., 1986*] are similar to the degree of submergence of the tree stumps reported by *Lindstrom* [*1990*], and (3) active faults are mapped in the vicinity of the reported submerged trees (**Figure 1**), there also exists the possibility that the submergence of the tree stumps are due to earthquake displacements. It was thus with the intent of shedding light on the activity of faults in the Tahoe Basin and the relationship of known faults to the location of submerged trees that we took advantage of an opportunity to conduct a preliminary seismic reflection survey of the lake.

The survey was conducted out of Tahoe City, California on the Tahoe Research Group's vessel John LeConte, provided through the courtesy of Dr. John Reuter and Dr. Charles Goldman of the U.C. Davis Tahoe Research Group and captained by Mr. Bob Richards. The high resolution of the profiling system was provided by a transponder producing a multifrequency signal of 4-8 Khz, with a broad peak at about 6 Khz. The interval between signal pulses was set at 0.3 seconds and the energy radiated per pulse is about 36 joules. The wavelength of a 6 Khz signal is about 25 cm in water or water-saturated sediments (velocity-1.5 km/sec) which, in turn, is the approximate scale of features that can be resolved by the reflection profiler. The reflected signal was on dry paper of a belt conveyed recorder. The ship location was recorded in real time to a resolution of about <30 m using a Trimble Navstar Global Positioning system. The rapid attenuation of the high-frequency signal limits use of the system to water depths of less than 200 meters. The steep drop-off towards the center of the lake **(Figure 2)** limited our reconnaissance to the lake margins. The approximate ship track during the course of the 2-day investigation is shown in **Figure 1.** Only within the regions marked A, B, and C did our recordings provide evidence on faulting and prior lake levels, and it is those regions to which we limit the following discussion.

The most striking evidence of active faulting was observed offshore of Sugar Pine Point (Box A in **Figure 1**), where profiling documented a north-striking fault zone cutting lake bottom sediments. Details of the ship-tracks and the points where the ship crossed the fault zone are shown in **Figure 3**. Raw and interpreted sections of a reflection profile crossing the fault zone are shown in **Figure 4**. The section displays a broad fault graben with near-surface sediments sharply truncated by faults. It is reasonable to interpret that the faults are associated with the West Tahoe Fault **(Figure 1)**, although the major displacements along the West Tahoe fault are likely associated with the steep bathymetric escarpment that lies just east of the ship tracks. Assuming that the sedimentation rate at the site is between 0.1 and 1 mm/yr [*Hyne et al., 1972*] and that the breaks in sediment reach to within <1 to 2 meters of the surface, the fault offsets would appear to be less than 20,000 BP and perhaps Holocene in age. Coring of sediments at the site would be required to firmly date the time of last movement. Nonetheless, the fault displacement of shallow sediments argues for relatively young displacements.

Fault deformation of young sediments was also observed while profiling within Crystal Bay (Box B in **Figure 1**). Profiling delineated a distinct northwest striking scarp in sediments corresponding approximately with the offshore projection of the Incline Village Fault **(Figure 5)**. A profile of one of the fault crossing sections is shown in **Figure 6.** The profile shows an east-facing scarp of about a meter in height. Although the trend of the scarp observed offshore is not in perfect alignment with the mapped trace of the Incline Village fault, the warping and faulting of the lake bottom sediments is consistent with prior interpretations that the Incline Village Fault has moved during late Pleistocene [*Grose, 1986; Lewis, 1988; Lewis and Grose, 1988*].

Surprisingly, the most direct evidence regarding the past history of lake level did not arise directly from our search for active faulting but, rather, from an east-west profile across an unbroken section of sediments in Agate Bay that we collected on our final return to port (Box C in **Figure 1**). The portion of the profile provided in **Figure 7** shows a gently warped sequence of sediments with erosionally truncated folds. The erosional event was of sufficient force to remove at least 10 meters of sediment along the fold axes. The water-sediment interface in the profile is located at a depth of about 21 meters (63 feet). The depth of vigorous abrasion in oceans is related to the depth at which breaking waves form, which is at a maximum depth of about 10 meters [*Dietz and Menard, 1972*]. It seems most certain that wave action within Lake Tahoe is less than experienced along the margins of the major ocean basins. In that respect, it is reasonable to suggest that a lowering of the Lake by 10 meters or more below current lake level was required to subject the sediments directly to wave action and to produce the truncated section observed in **Figure 7.** A combined effort of profiling and coring for dateable material in this vicinity of the lake would be a viable approach to document both the extent and age of the lake lowering. As well, the profile demonstrates the existence of a thick package of sediments that is amenable to palynological, macrobotanical, micropaleontological, sedimentological, and geochemical studies which could also lend insight to past environmental changes in the Tahoe Basin.

In summary, our two-day reconnaissance confirms the relative recency of faulting in the Tahoe Basin. Although our observations of faulting are not along the main bounding faults principally responsible for the Basin formation, it is reasonable to suggest that the main bounding faults of the basin are similarly active. Because coseismic offsets during large earthquakes on normal faults like those bounding Tahoe appear dominated by the down-dropping of the hanging wall (basin) in comparison to uplift of the foot wall [*Barrientos et al., 1987*], one may well expect that large earthquakes have contributed in part to subsidence of the Tahoe Basin during the Holocene. As well, because average coseismic offsets during the largest earthquakes in the Basin and Range can reach several meters (10 feet) or more [e.g. *Scholz et al., 1986*] and the sites of submerged trees reported by *Lindstrom* [*1990*] are adjacent to the projections of strands of the East and West Tahoe faults (**Figure 1**), it is possible the submerged trees along the south shore result from tectonic subsidence. However, if so, the faults should have left clear evidence of displaced Pleistocene glacial deposits where they cut on to the south shore region of the lake. Such evidence has not, to our knowledge, been reported on existing maps of the area [*Armin and John, 1983; Burnett, 1967; Hawkins et al., 1986; Wagner et al., 1981*]. If the formation of the erosional truncation of the fold observed in Agate Bay **(Figure 7)** is contemporaneous with the age range of trees observed by *Lindstrom* [*1990*], explanation of the submerged trees by tectonic subsidence is improbable. The truncation is at a depth of 21 meters beneath the current lake surface. Even assuming that the depth of vigorous erosion in Tahoe is equivalent to that in the roughest oceans (i.e. 10 meters), the erosion of the fold would require a decrease in lake-level of at least 10 meters from the current level (6,223 feet). To account for a 10 m drop in lake-level by tectonic subsidence would require several or more nearby earthquakes. Agate Bay **(Figure 7)** is not located adjacent to any major known faults and the repeat time of large earthquakes on active faults in the Basin and Range is generally measured on times scale of 10's of thousands of years [e.g. *Wallace, 1987*]. Hence, the occurrence of several or more large earthquakes near this site since the mid-Holocene is unrealistic. A more reasonable interpretation is that the erosional event reflects an actual lowering of the lake due to a drier climate. The key to determining the depth to which the erosional unconformity extends and whether or not the age of the submerged trees correlate to the lake-lowering event represented by the erosional truncation resides in further seismic profiling, coring and dating of sediments along and near the profile.

Acknowldegements

Center for Neotectonic Studies Contribution #13

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Figure Captions

Figure 1. Map of Lake Tahoe showing ship tracks (gray lines along borders of lake), the locations (thick dashed and solid lines) of proposed major active faults [adapted from *Hawkins et al.* (1986) and W. Page (Woodward-Clyde Consultants, pers. comm.)], and the locations (stars) of sites of submerged trees reported by *Lindstrom* [*1990*]. Boxes A, B, and C mark sites of survey discussed in text or letter.

Figure 2. Bathymetric map of Lake Tahoe adapted from *Hyne et al* [*1972*]. Contour interval is 50 meters.

Figure 3. Contour and bathymetric map in vicinity of Sugar Pine Point. Area corresponds to Box B in Figure 1. A north-striking zone of faulting of young sediments (dotted ellipse) was delineated by seismic profiling along the ship tracks shown (solid lines). Station locations are numbered and correspond to those listed in Figure 4.

Figure 4. Original (top) and interpreted (lower) seismic profile along ship track including station 168 in Figure 3. Note vertical exageration. Faulting (solid lines) of shallow sediments extends to less than 1-2 meters beneath the lake bottom.

Figure 5. Contour and bathymetric map in vicinity of Crystal Bay. Area corresponds to Box A in Figure 1. A northwesterly zone of warping and faulting of young sediments (dotted ellipse) was delineated by seismic profiling along the ship tracks shown (solid lines). Station numbers are labeled and correspond to those given in Figure 6. The zone of offshore deformation is along strike of the previously mapped Incline Village Fault which has been interpreted to show late Pleistocene offset [*Grose, 1986; Lewis, 1988; Lewis and Grose, 1988*].

Figure 6. Original (top) and interpreted (lower) seismic profile along ship track including station 90 in Figure 5. Note vertical exageration. Faulting (solid lines) and warping produces a scarp in lake bottom that may be extension of onshore Incline Fault.

Figure 7. Seismic profile in Agate Bay shows a thick section of sediments that is gently folded and erosionally truncated at a depth of 21 meters beneath the level of the lake at the time of the survey (6223 ft). Truncation of the folds may indicate a severe lowering of the lake and, hence, significant drought, possibly during the Holocene.

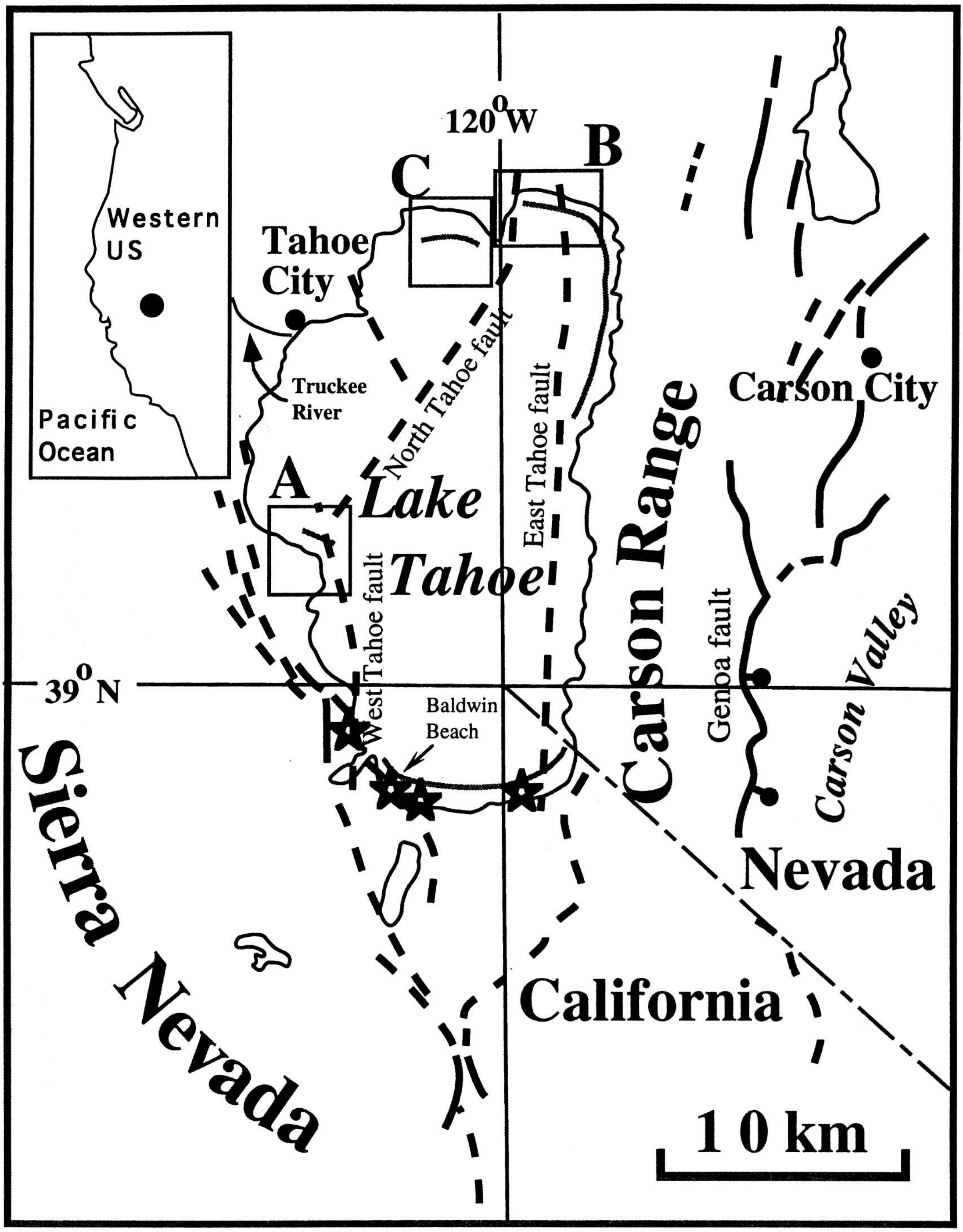
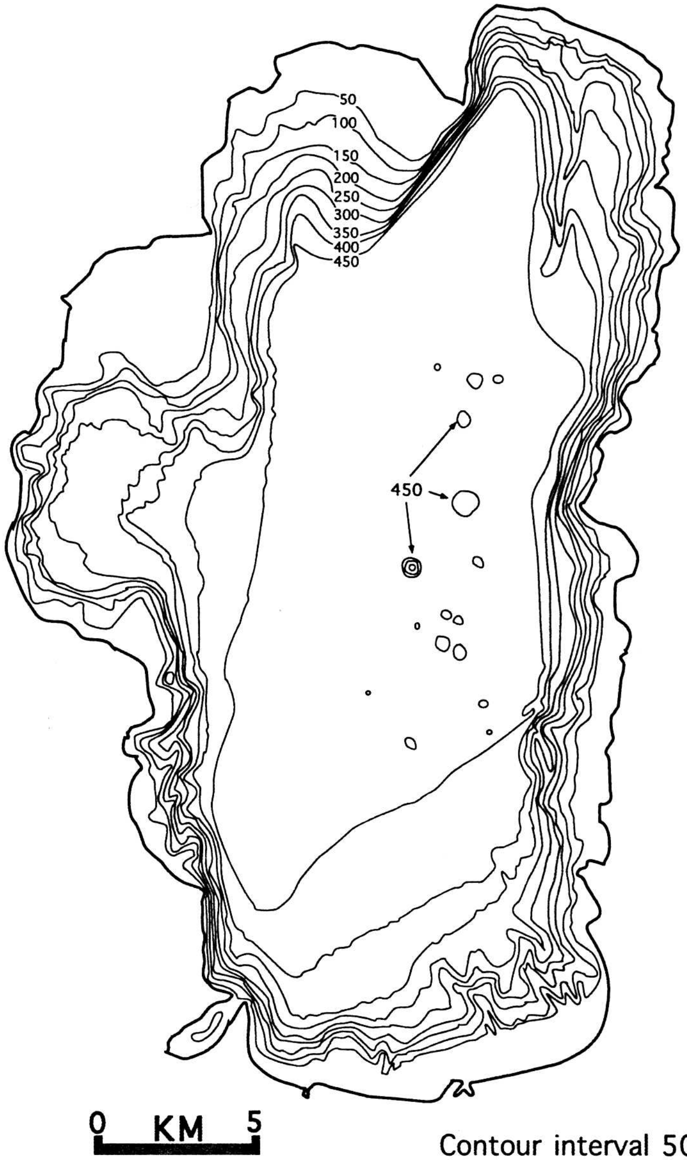

Western
US
Pacific
Ocean
120°W
B
C
Tahoe
City
Truckee
River
North Tahoe fault
East Tahoe fault
A
Lake
Tahoe
West Tahoe fault
Carson Range
Carson City
Genoa fault
Carson Valley
39°N
Baldwin
Beach
Sierra Nevada
Nevada
California
1 0 km

Fig. 1

Lake Tahoe Bathymetry



Contour interval 50 meters

Fig. 2

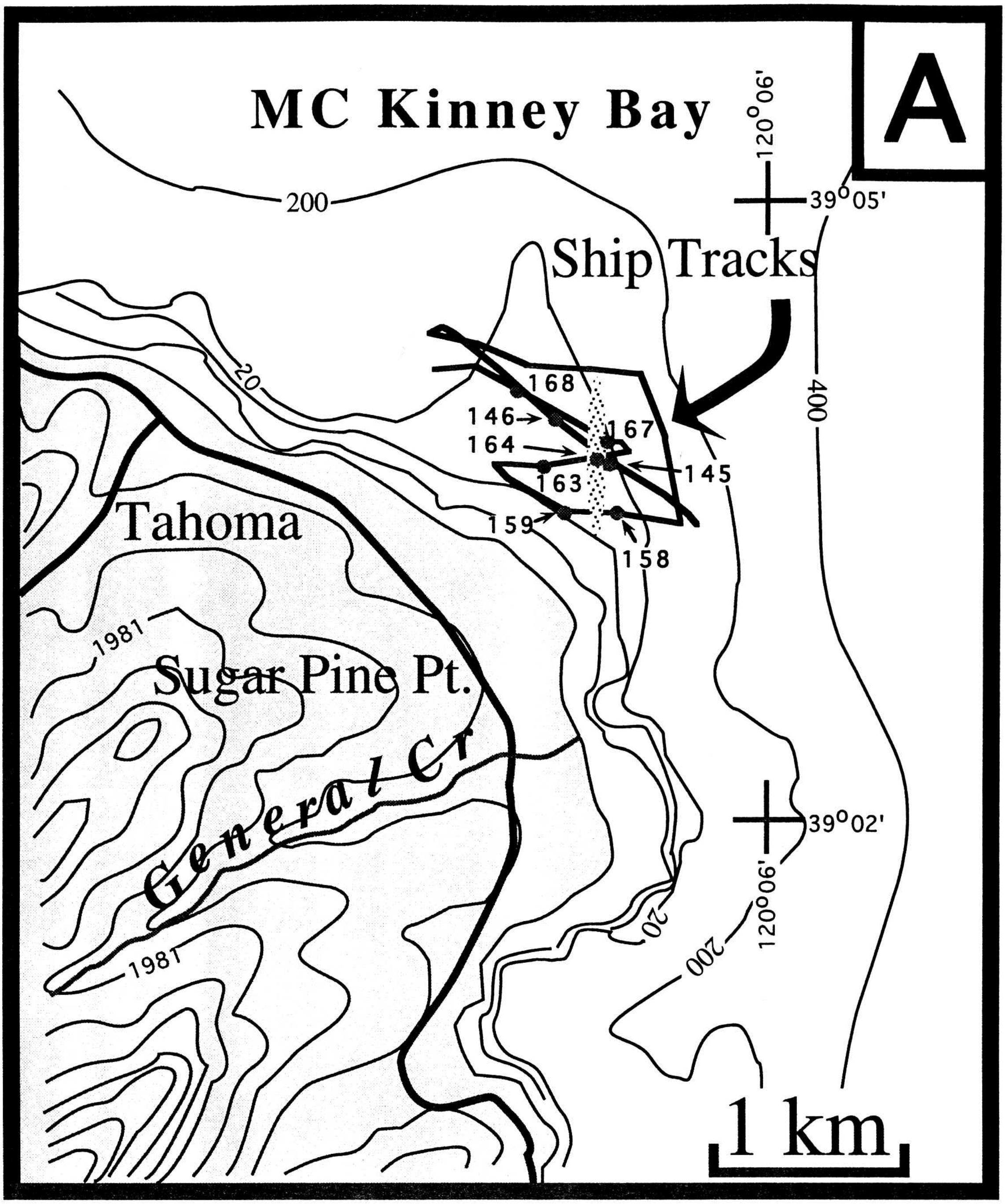

A
MC Kinney Bay
120°06'
39°05'
200
Ship Tracks
20
400
168
146
167
164
145
163
159
158
Tahoma
1981
Sugar Pine Pt.
General Cr
39°02'
120°06'
20
200
1981
1 km

Fig. 3

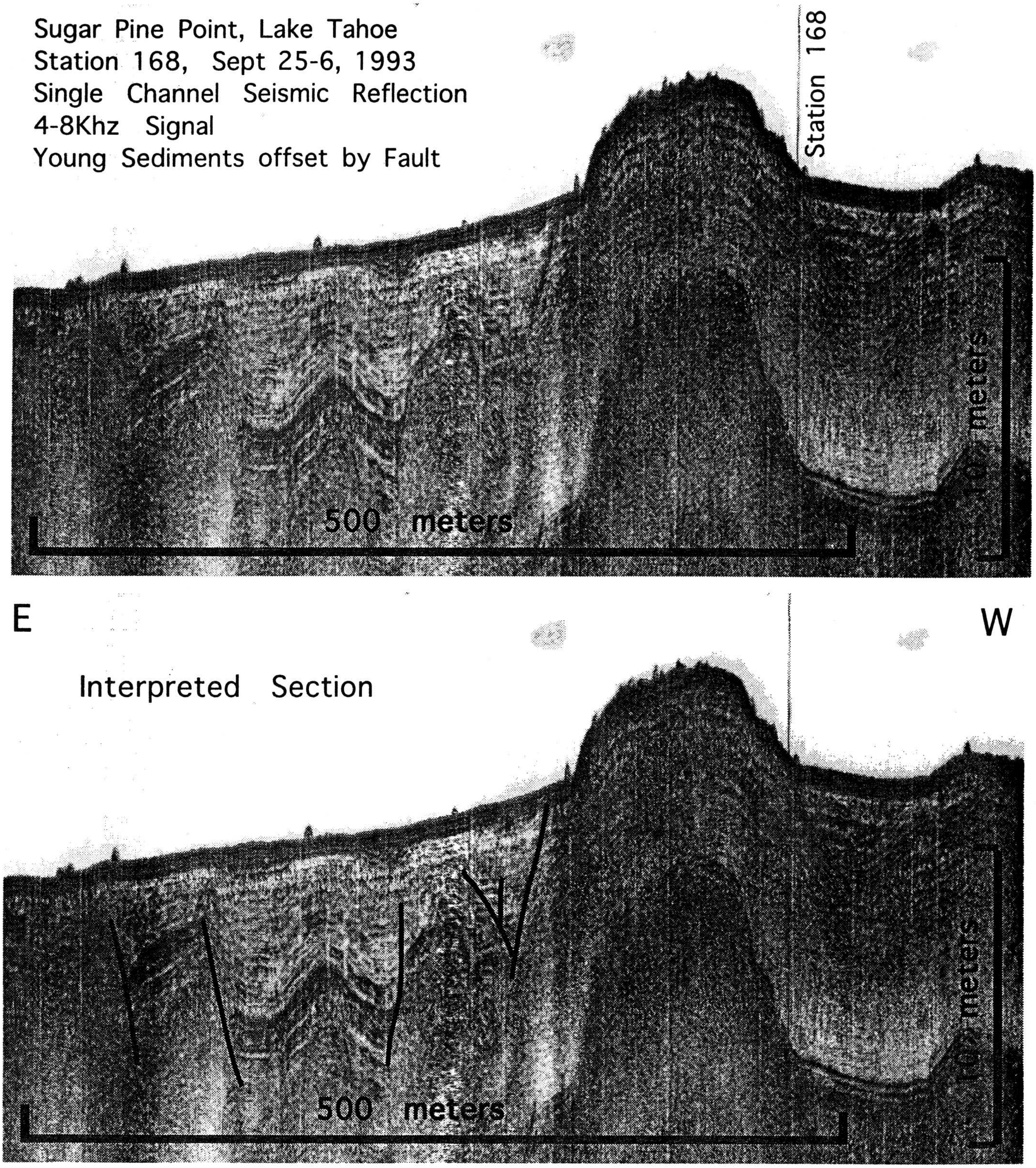

Sugar Pine Point, Lake Tahoe
Station 168, Sept 25-6, 1993
Single Channel Seismic Reflection
4-8Khz Signal
Young Sediments offset by Fault
Station 168
500 meters
10 meters
E
W
Interpreted Section
500 meters
10 meters

Fig. 4

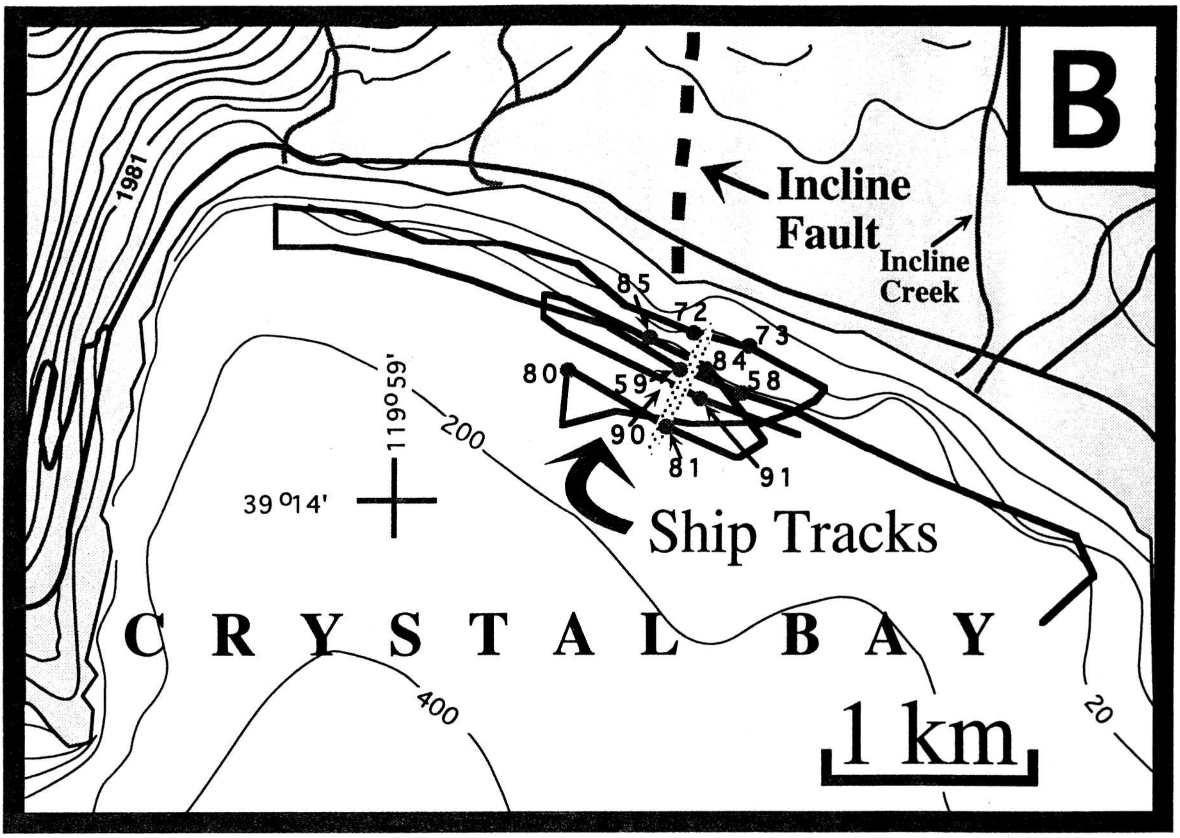

B
1981
Incline
Fault
Incline
Creek
85
72
73
80
84
59
58
90
81
91
119°59'
200
39°14'
Ship Tracks
C R Y S T A L B A Y
400
20
1 km

Fig 5

Crystal Bay, Lake Tahoe, Sept 25-6, 1993, Single Channel Seismic Reflection, 4-8Khz Signal, Scarp and Deformation of Young Sediments Possibly Produced by Offset on Incline Fault

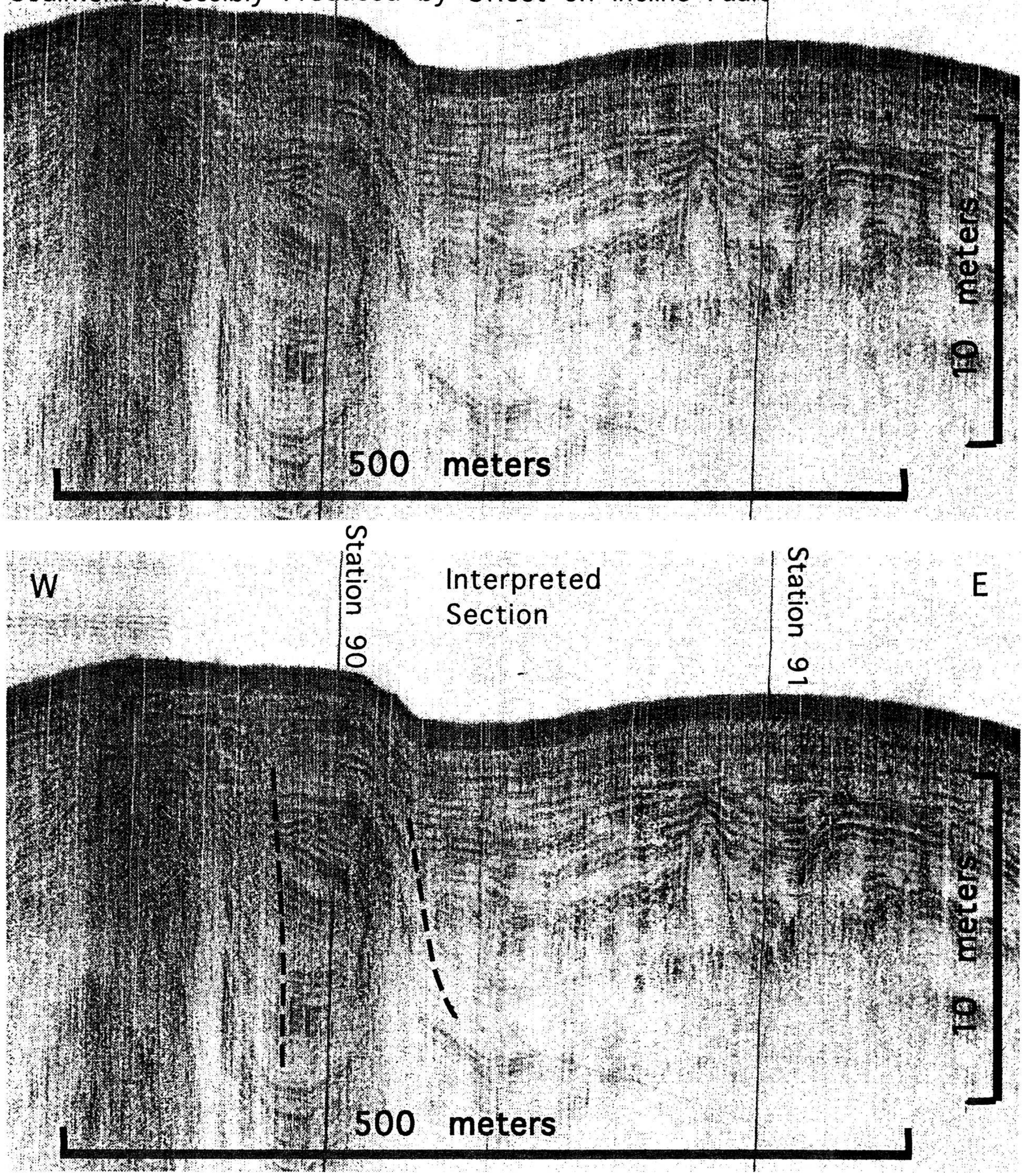
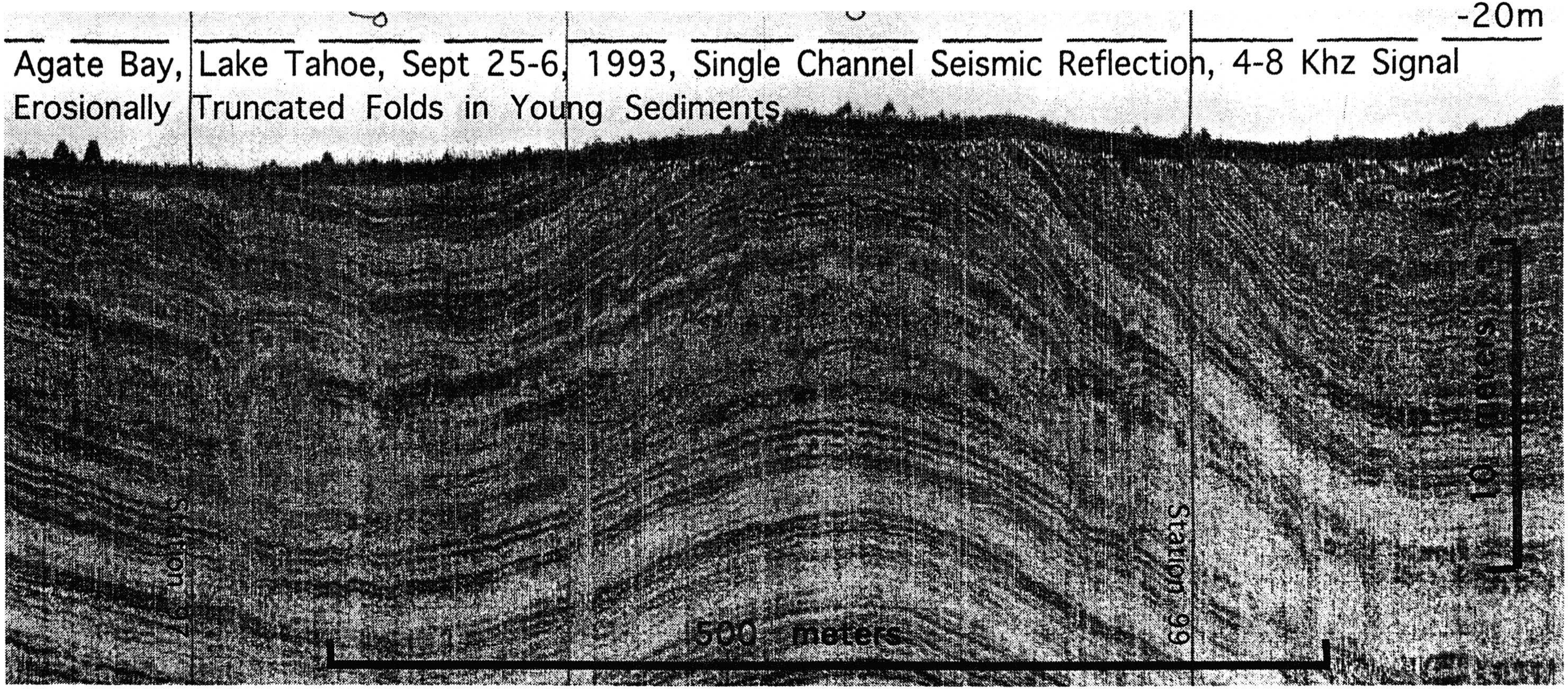


Fig. 6



Agate Bay, Lake Tahoe, Sept 25-6, 1993, Single Channel Seismic Reflection, 4-8 Khz Signal
Erosionally Truncated Folds in Young Sediments