U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

DATA REPORT FOR THE 1991 BAY AREA SEISMIC IMAGING EXPERIMENT (BASIX)

By

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INTRODUCTION

Seismicity in the San Francisco Bay Area has increased dramatically during the past decade following a long period of quiescence associated with the 1906 San Francisco earthquake. This increased seismicity is best illustrated by the October 17, 1989, 7.1 M earthquake along the Loma Prieta segment of the San Andreas fault (SAF). Future earthquake concerns focus on two possibilities: 1) that the Loma Prieta earthquake has loaded the Peninsula segment of the SAF, and 2) that the historical pattern of large paired quakes -- involving faults along the Peninsula and the East Bay -- may be about to repeat itself. Fault occurrences of paired earthquake activity between the Peninsula and East Bay have been documented in the last century and in the early 1900's (Table 1). Although these periods of paired seismicity may be fortuitous, it is possible that the network of faults that bound the San Francisco Bay Area are linked structurally and are all part of an evolving fault system, as proposed by Furlong and others (1989; Fig. 1).

TABLE 1
PAIRED EARTHQUAKES

1936	M6.8	Hayward Fault, northern segment
1938	M7.0	San Andreas Fault, south San Francisco
1865	M6.5	San Andreas Fault, southern Santa Cruz Mts.
1868	M6.8	Hayward Fault, southern segment
1906	M8.3	San Andreas Fault
1911	M6.5	Calaveras Fault
1989	M7.1	San Andreas Fault, Santa Cruz Mountains
?	?	?

To test the Furlong and others (1989) model and to obtain fundamental information on the crustal structure and fault geometries that underlie the San Francisco Bay Area, the U.S. Geological Survey (USGS), in conjunction with the University of California, Stanford University, Pennsylvania State University, and Lawrence Berkeley Laboratory, conducted a major seismic reflection investigation in the fall of 1991 utilizing the marine waterway system that dissects the Bay Area (Fig. 2). This study, known as the Bay Area Seismic Imaging eXperiment, or BASIX, consisted of three complementary seismic reflection and refraction profiling methods: high-resolution seismic reflection profiling, wide-angle reflection/refraction profiling, and multichannel seismic profiling. The high-resolution, shallow-penetration data were acquired to constrain near-surface faulting, while the wide-angle reflection/refraction data were acquired to constrain the deep-crustal velocity structure of the crust. The focus of this report are the multichannel, seismic reflection data which were acquired to image structures throughout the crust down to the Moho.

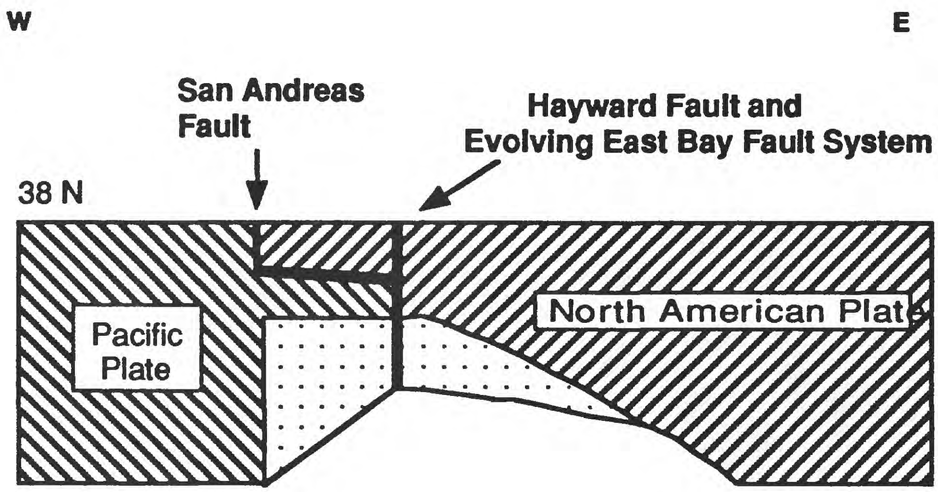

Fig. 1. Schematic drawing of the lithospheric structure and fault configurations in the vicinity of San Francisco. The surface plate boundary occupies the approximate position of the previous western edge of North American plate, but the deeper shear zone boundary is offset to the east (~40 km). Newly forming faults sit above the deeper eastern segment. Stippled region is asthenospheric mantle that has cooled and accreted to adjacent lithosphere. Cross section is approximately 200 km (width) by 60 km (depth) in extent. Figure adapted from Furlong and others (1989).

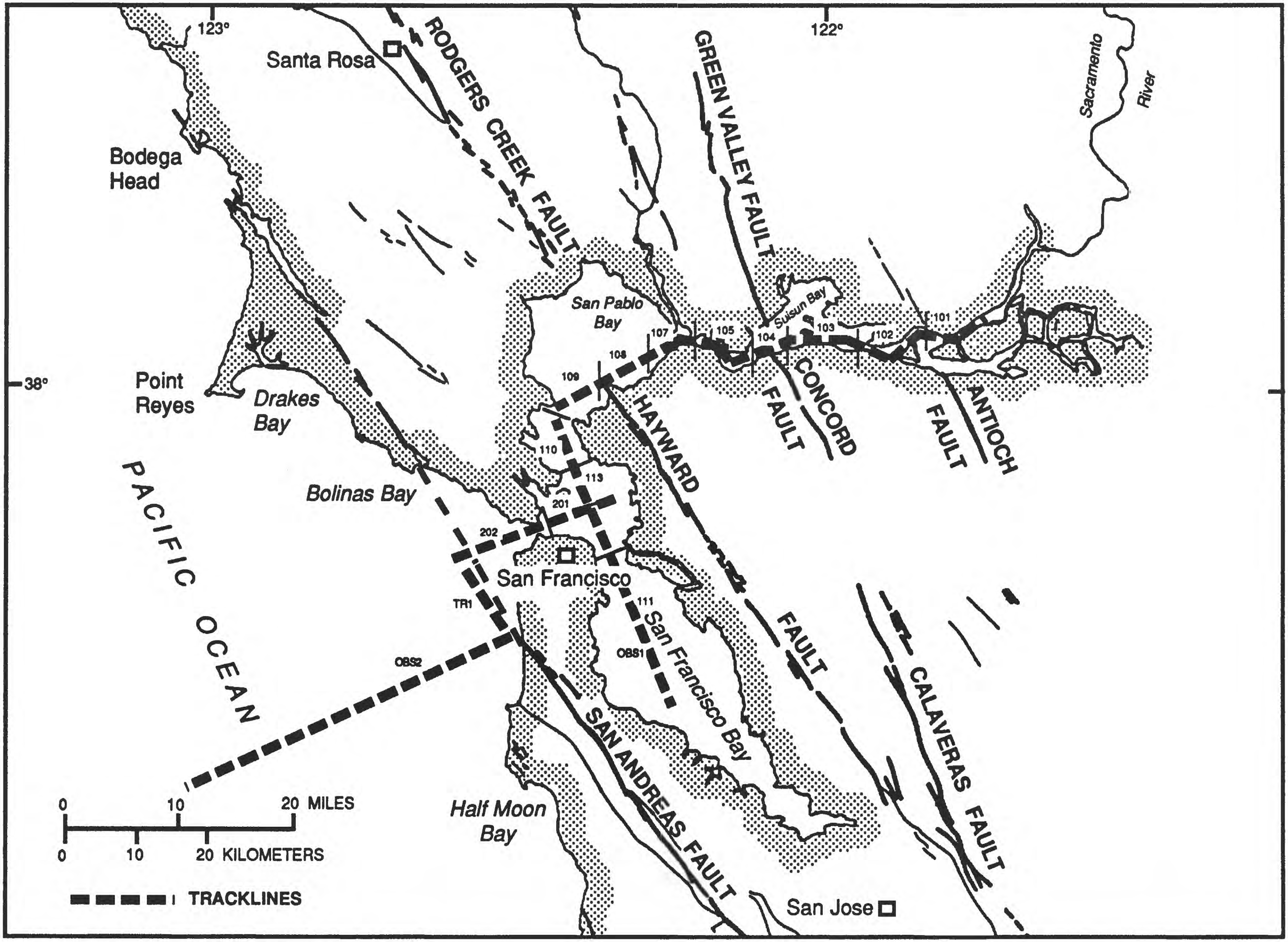

FIGURE 4. Index map showing location of BASIX seismic study. Individual lines are numbered.

INSTRUMENTATION

The Seismic Source

The seismic source consisted of a 12-element, 2000 psi, 5828 cu. in. (95.6 liters), airgun array towed from the U.S. Geological Survey's research vessel, the *S.P. Lee* (Fig. 3). Airgun sizes were selected to maximize the peak-to-peak amplitude (85.3 bar-m) and the peak-to-bubble ratio (12.7) while maintaining maximum volume. Because of the shallow-water environment for most of the experiment, airguns were towed at an average depth of 7.6 m (25 ft); depths were maintained by buoying each gun with a separate Norwegian buoy. The airguns were fired at 50-m intervals in the inland and Golden Gate profiles (lines 101-113, OBS1, and 201-202) and at 75 m for the offshore transit and continental margin profile (TR1 and OBS2). Shooting was conducted during night-time hours when ship traffic and ambient noise were a minimum. Acquisition was timed so that the ship moved against the tide as much as possible; this resulted in minimum speed over the ground (approximately 3.5 knots) as well as maximum control and maneuverability of the vessel. A total of more than 11,634 airgun shots were fired during the fourteen-day experiment (Appendix A).

The Receiver Array

The seismic energy was recorded on hydrophones moored to the edge of the dredged shipping channel in the bay. The hydrophones and associated telemetry receivers, known as Telseis (Fig. 4), were leased from Fairfield Industries. The Telseis units were equiped with an antenna and a transmitter, which radioed the analog seismic data to a 120-channel, DFS-V recording system on the *S.P. Lee*. Separate radio frequencies had to be licensed for each of the 120 Telseis units (72-79 MHz band). Sixty to 118 of these units were used on any given night; battery limitations often required keeping half of the Telseis units onboard the Lee for recharging in preparation for the following night's shooting. In addition to the Telseis receivers, a short two-channel streamer was also deployed off the fantail of the Lee; this streamer provided a near-offset image of the crust. All data were recorded to 16 s two-way traveltime at a 0.004 s sample rate. A listing of the number of Telseis deployed each night, the group spacing, and the number of shots is provided in Appendix A.

Navigation

Navigation was based on two independent systems. The land-based Del Norte radio-navigation system was the primary method used for positioning and resulted in station locations accurate to ± 1 m. Up to 9 transponders were positioned in the area of operation so as to provide sufficient control for triangulation. These stations were moved daily as the survey moved from east to west. The Del Norte system proved successful throughout most of the study, but there were some areas where reception was limited and station coverage was not sufficient to provide an accurate fix. In these regions locations were determined from a single Global Positioning System (GPS) receiver. Because this GPS system did not operate in differential mode, absolute station accuracy was approximately ± 100 m -- relative positions from station to station, however,

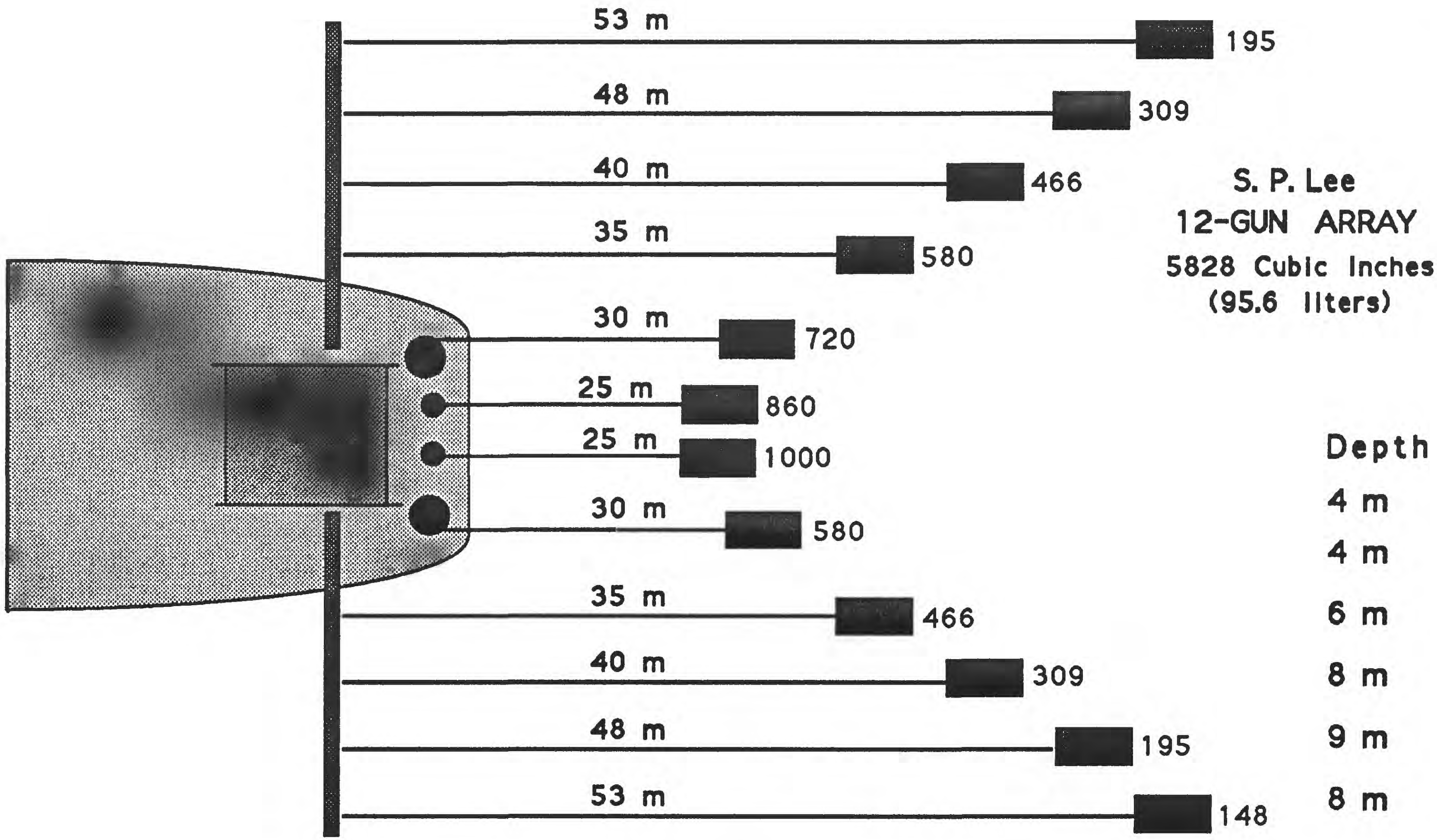

Figure 3. Schematic diagram showing the stern of the *S.P. Lee* and winged airgun deployment configuration. Individual chamber sizes are listed in cubic inches. The chamber sizes were selected to maximize the peak-to-peak amplitude (85.3 bar-m) and the peak-to-bubble ratio (12.7) while maintaining maximum volume.

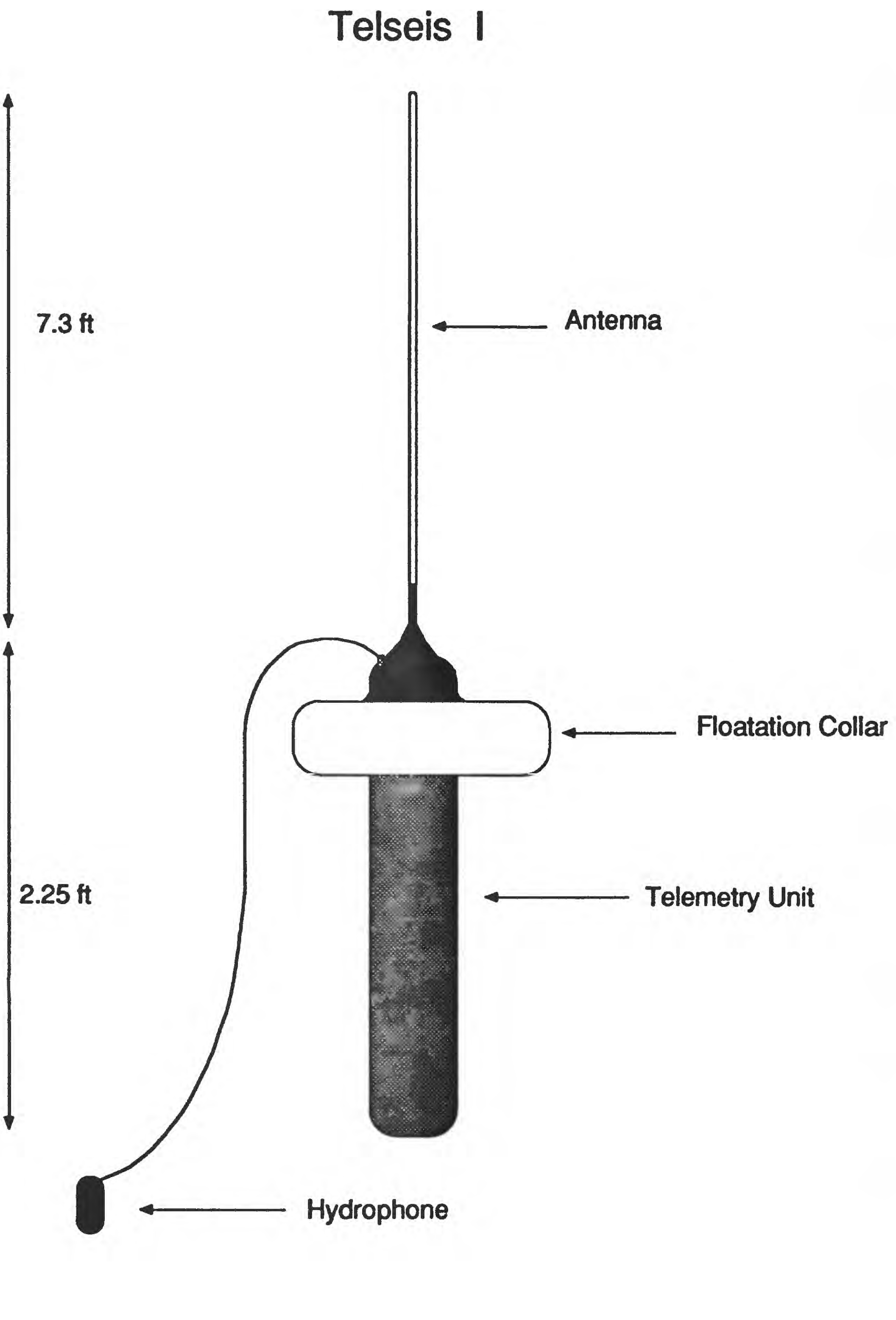

Figure 4. Schematic sketch of Fairfield Technologies Telseis I seismic telemetry exploration system.

were accurate to within a few meters. Navigation for lines 202 and OBS2 seaward of the San Andreas fault was accomplished using a combination of GPS operated in a selected availability mode and rho-rho Loran-C; positions are considered accurate to within 150 to 200 m.

METHODOLOGY

The BASIX investigation was designed to take advantage of the extensive marine waterway system that dissects the San Francisco Bay Area. A total of 140 km of multichannel reflection data were acquired across this region (Fig. 2) during 14 nights of profiling. Although each night of profiling is assigned a different line number, several of the lines overlap and they were thus processed together as merged profiles. All totaled, there are four distinct segments to the experiment. The first segment begins in the Sacramento River near Rio Vista and proceeds west through Honker, Suisun, and San Pablo Bays (lines 101 through 110; Figs. 5, 6, and 7). The next two segments run north-south from Richmond to Angel Island (line 113; Figs. 8a and 9), and from the Bay Bridge to just north of the San Mateo Bridge (line 111; Figs. 8b and 10). The fourth and final segment begins in the vicinity of Alcatraz Island and extends west underneath the Golden Gate bridge, 6 km into the open waters of the Pacific (lines 201-202; Figs. 11 and 12).

The shallow water depths and abundant ship traffic in the San Francisco Bay region precluded using a standard towed-streamer approach to seismic data acquisition. Instead, 60 to 118 independent Telseis receivers were moored to the edge of the dredged shipping channel at 100 to 200 m intervals for a fixed spread of 6 to 12 km in length. Each day the receiver array was repositioned, and each night the *S.P. Lee* steamed along the hydrophone array, with its airgun array firing.

The day-to-day small-boat operations began first with the retrieval of the Telseis instruments deployed the previous day. This process utilized a fleet of 4-5 small boats that ranged in size from 6 to 15 m. Once retrieved, the instruments were brought back to the *S.P. Lee* for recharging. The *R.V. David Johnston* trailed behind these small vessels and recovered the associated buoys and anchors. At this time the *David Johnston* also recorded navigational fixes, which were required in order to check for possible drift of the instrument sites during the night; although anchors were used to maintain instrument position, currents were strong enough in a few areas to move the anchors between deployment and retrieval.

Once the instrument retrieval was complete, the *David Johnston* would begin laying out the next line segment. A Global Positioning System (GPS) and Del Norte triangulation system were used to measure the 100- or 200-m distance separating instrument sites. The receiver line was positioned so as to minimize bends in the profile and to keep the buoys out of the active shipping channel. At each site, anchors were deployed and navigation fixes were taken; the anchored sites were marked by orange buoys. The smaller boats followed behind and clipped the recharged Telseis units with cabled hydrophones to these buoys. The hydrophones were weighted so as to minimize movement on the seafloor.

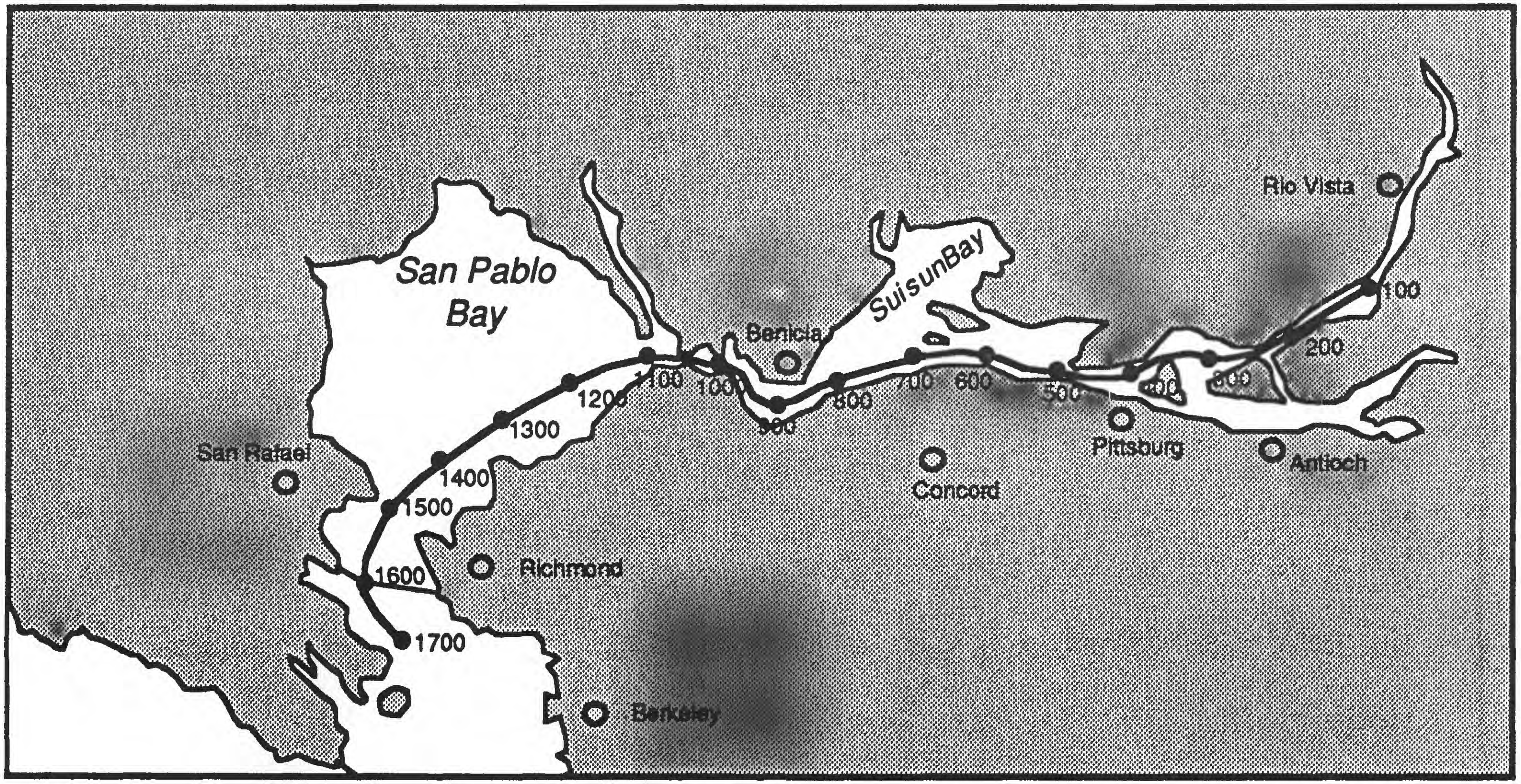

Figure 5. CDP locations for lines 101 through 110.

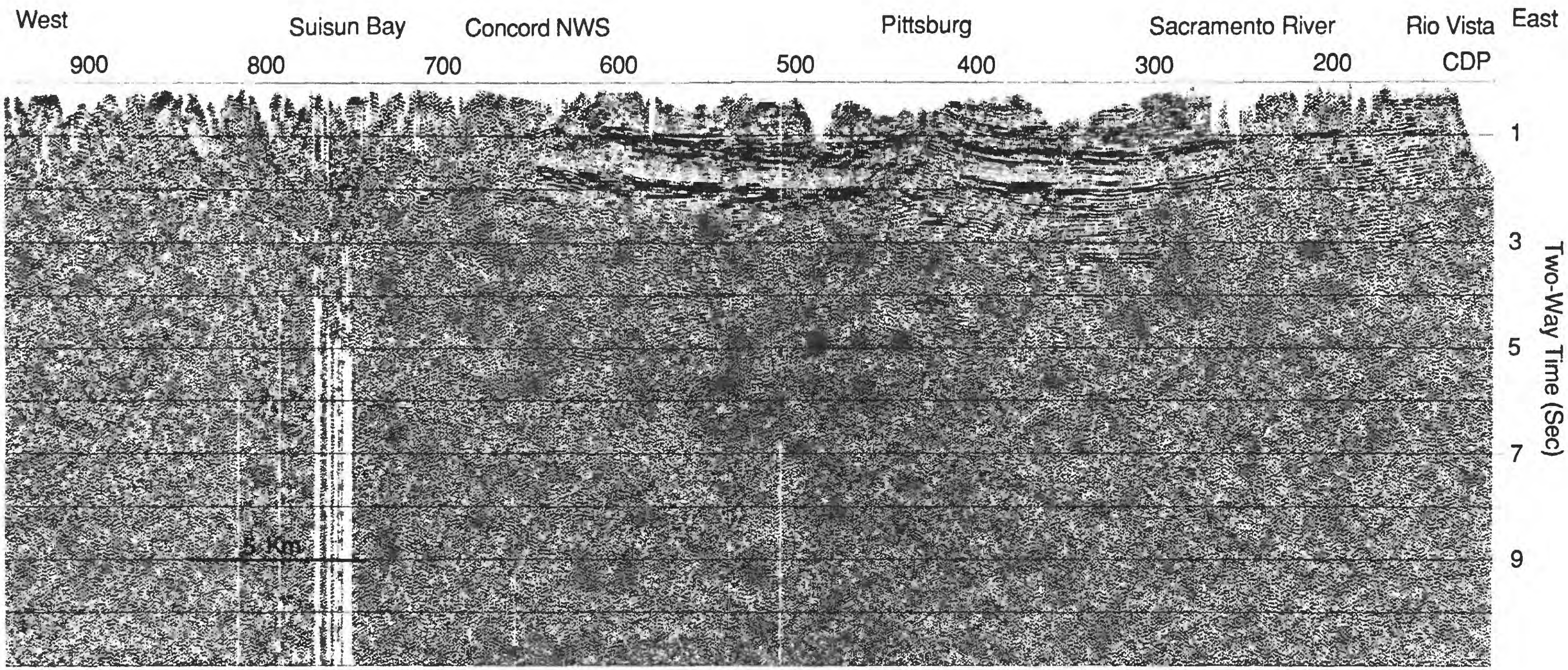

Figure 6. Final stack of BASIX lines 101-105, recorded across Suisun Bay and up the Sacramento River towards Rio Vista.

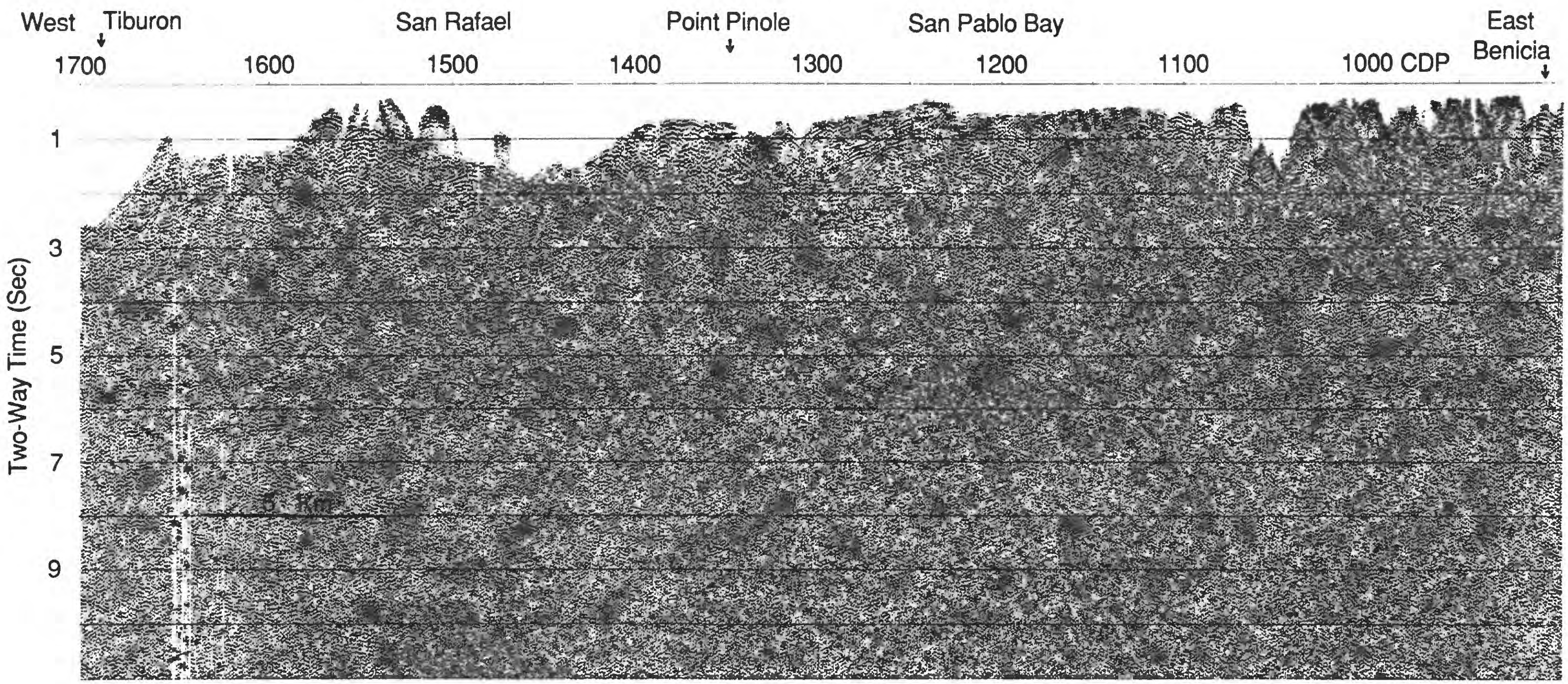

Figure 7. Final stack of BASIX lines 107-110, recorded across San Pablo Bay.

A.

B.

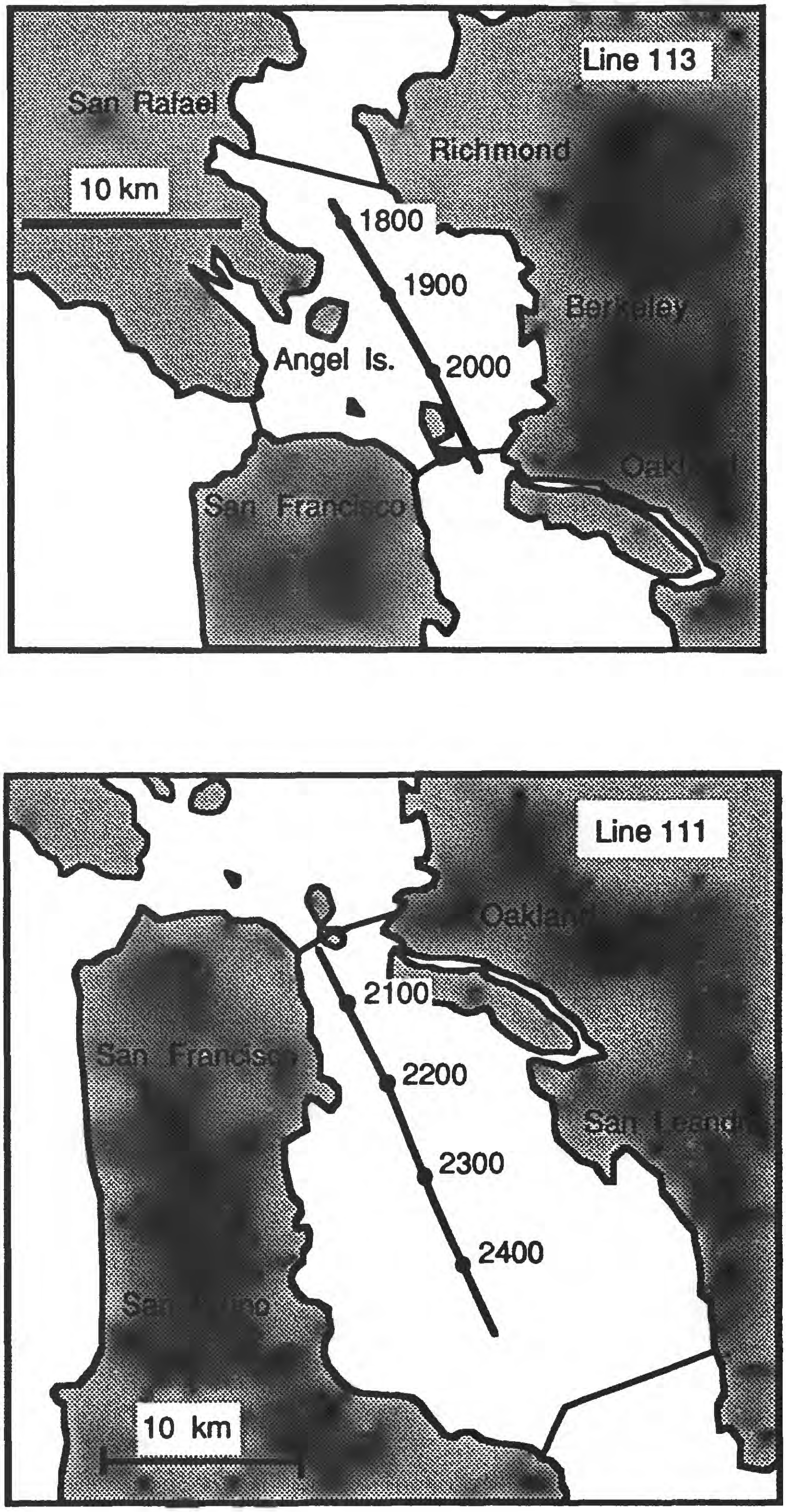

Figure 8. CDP locations for (A) Line 113, and (B) Line 111.

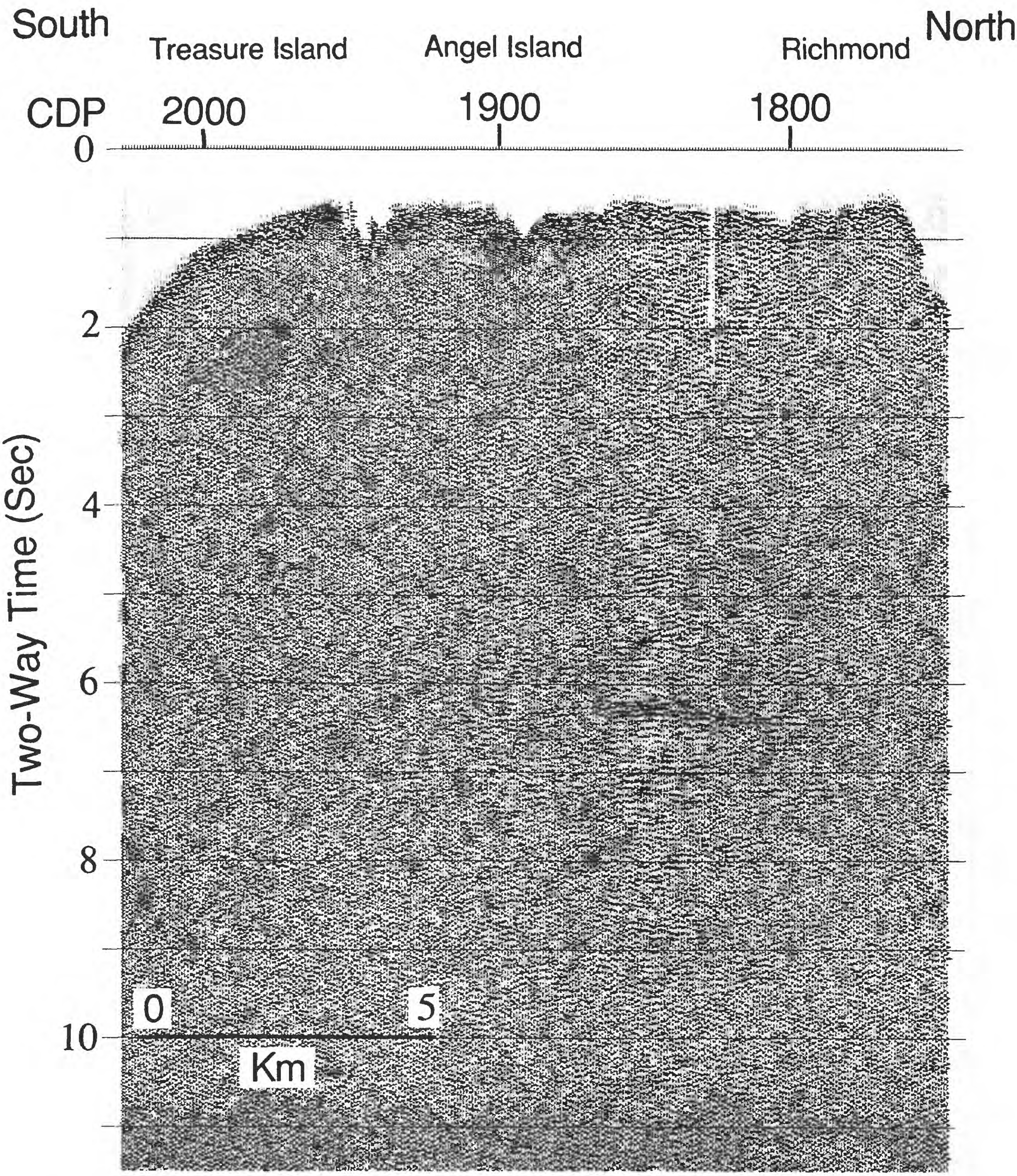

Figure 9. Final stack of BASIX line 113, recorded across central San Francisco Bay.

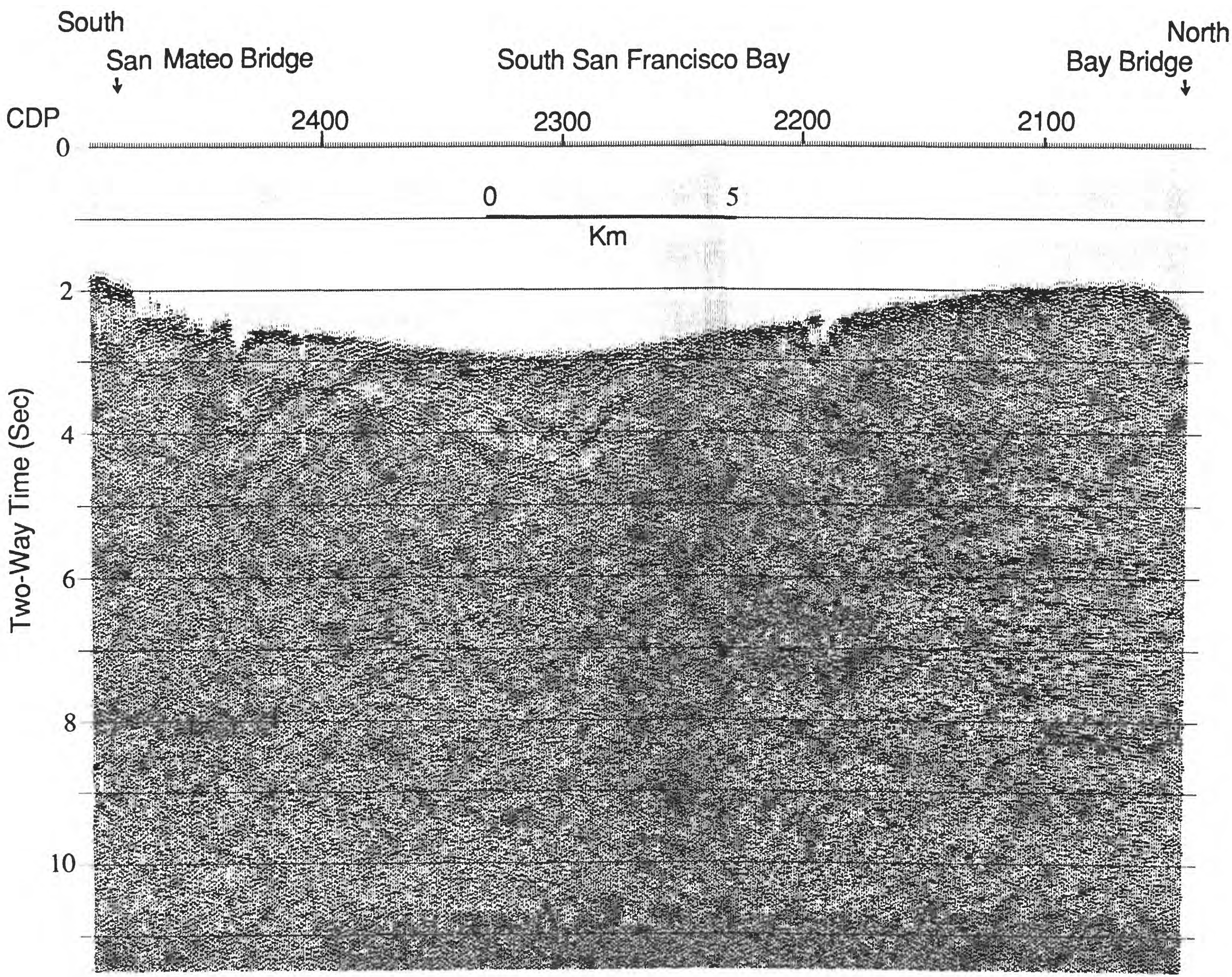

Figure 10. Final stack of BASIX line 111, recorded across south San Francisco Bay.

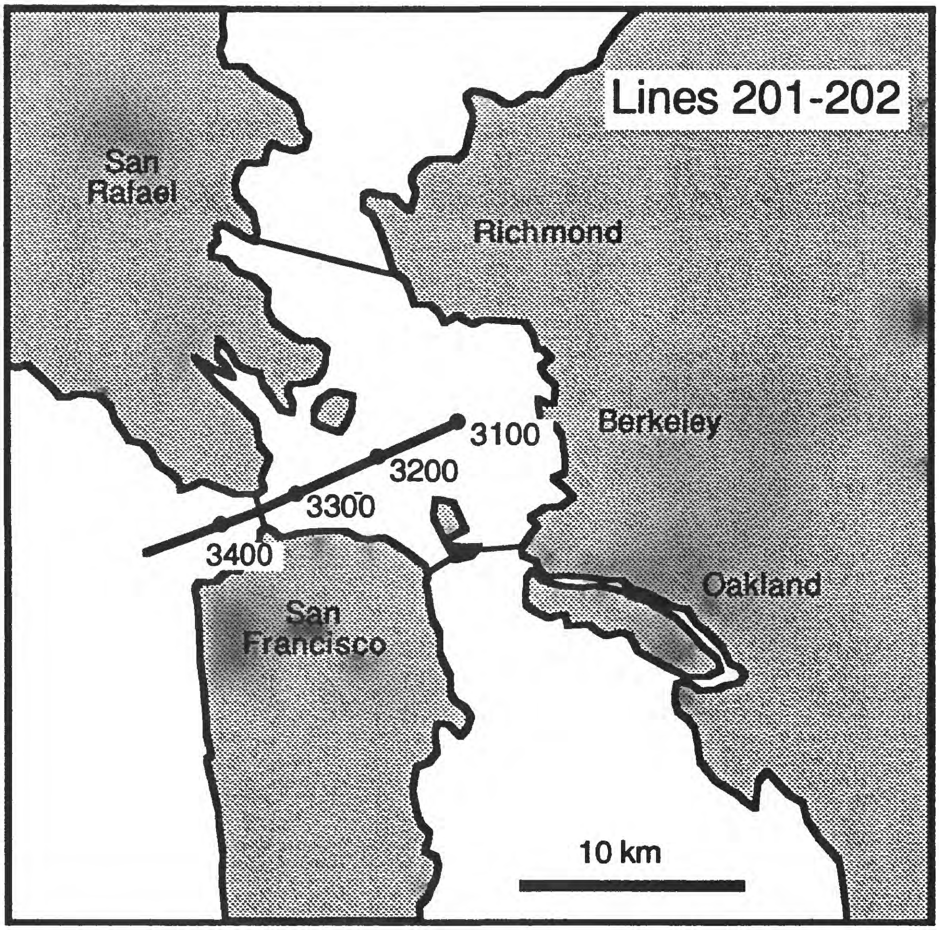

Figure 11. CDP locations for lines 201-202.

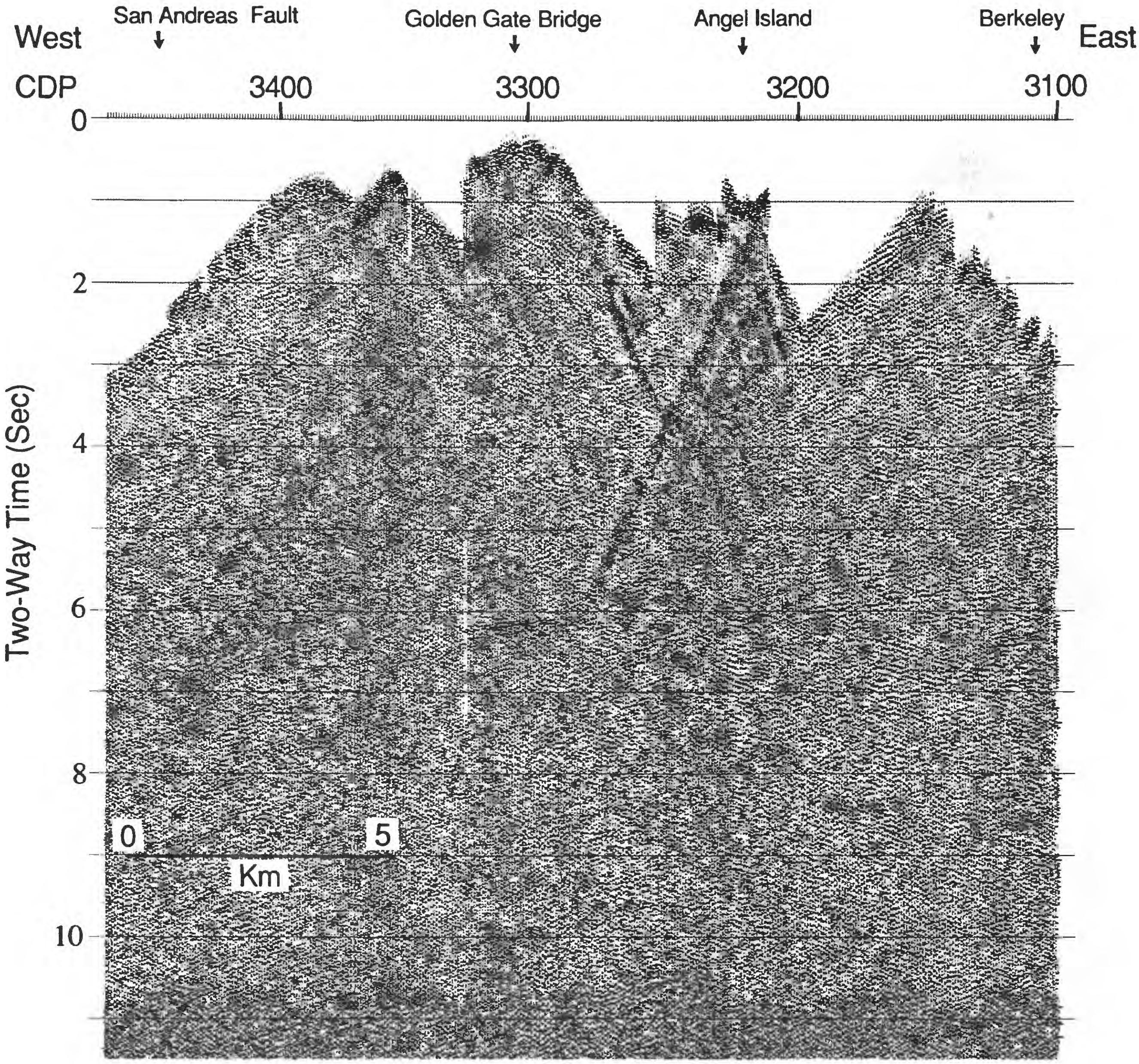

Figure 12. Final stack of BASIX lines 201-202, recorded from east to west, across the central San Francisco Bay and west of the Golden Gate bridge.

The final phase of operation was airgun profiling. Profiling was conducted during night-time hours so as to take advantage of reduced ship traffic and lower levels of ambient noise. Each night the *S.P. Lee* acquired approximately 24 km of reflection data by looping through the receiver array twice. Along 10 of the 13 multichannel lines (Appendix A) the *S.P. Lee* fired the airgun array while steaming first from east to west and then, reversing course, duplicated the line by steaming from west to east, further doubling the number of airgun shots available for stacking of the seismic signal. Although the receiver array averaged 6 km in length, the *Lee* continued profiling for approximately half a spread length on either side of the array (approximately 12 km total for each pass) so as to maximize offsets and fold. Two passes through the array typically required 10-12 hours; profiling was timed so as to acquire as much data as possible while operating against the tides. Slack tides proved to be the best time for profiling due to the reduced currents and therefore reduced noise conditions.

In addition to the 13 reflection lines acquired in San Francisco Bay and the Golden Gate region, the airgun array on the *S.P. Lee* was used primarily as a seismic source for wide-angle profiles recorded along three other lines: the N-S trending line OBS1 in San Francisco Bay; a short transit leg, line TR1 southwest of the Golden Gate; and the E-W trending line OBS2 on the continental margin (Fig 2). Lines OBS1 and OBS2 were obtained along two separate deployments of 6 USGS ocean bottom seismometers (OBS) deployed by investigators from the USGS Branch of Atlantic Marine Geology and Woods Hole Oceanographic Institution (Holbrook and ten Brink, 1991; Brocher and others, 1991). The shot interval along line 112/OBS1 was 50 m. The shot interval for lines TR1 and OBS2 was approximately 75 m. Line OBS2 was located coincident to seismic reflection line 13 of Lewis (1990) in order to provide deep structural control on the continental margin west of the San Andreas fault (Fig. 2). The reader is referred to Holbrook and others (1993) and Brocher and Moses (1993) for a discussion of these wide-angle data.

DATA REDUCTION

After acquisition, the data were demultiplexed, and the 16-s records with 4 ms sample intervals were truncated and resampled to 12-s records with 8 ms sample intervals. The data were then sorted to common receiver gathers for editing. Once the navigation data were reduced, the shot-receiver offsets and midpoints were calculated and inserted into the trace headers. Trace editing, which was the most effort-intensive part of the data reduction process, followed.

There were several sources of noise that required different editing techniques. Because of the use of a telemetry recording system, data drop-outs resulted when radio communication was hampered by land barriers and large ship-to-receiver distances. Signal was rarely present beyond 6 km offsets. The crooked nature of the reflection profile also resulted in a smearing of midpoints out of the plane of the common midpoint (CMP) profile. Even though the data were binned using a crooked line geometry, offsets perpendicular to the plane of the profile needed to be restricted to minimize smearing. (Note that because the receivers were on the edge of the shipping channel and the *Lee* profiled down the center of the channel, zero offset data were rarely acquired. A certain amount of smearing was thus required by the geometry of the study.) In-plane offsets were typically restricted to 6 km, and out-of-the-plane mid-point scattering was restricted to ± 0.5 km (except lines 201-202, which had up to a ± 1 km midpoint scatter).

A second source of noise was the jostling of the hydrophones during times of strong currents. As tides increased during the night, noise on the receiver gathers also increased, often overwhelming any seismic signal (Fig. 13). This noise appeared as hundreds of individual spikes of approximately the same amplitude as the first-arrival refractions. A noise reduction algorithm was developed to edit these noise spikes. The algorithm was designed to compare the amplitude of a reference trace with the average amplitude of adjacent traces (the number of which is specified by the user). When the ratio of the amplitude of the reference trace exceeded that of the surrounding traces by a user-designated amount, that sample was zeroed (compare Fig. 13 with Fig. 14 to see the effect of this noise editing routine).

Although these two editing techniques reduced the noise content of the data set significantly, areas still remained where either there was no signal or where coherent noise (i.e.: refractions) obscured weak reflections. Manual editing for each receiver gather was thus required to further reduce the noise content of the data. This manual editing was done twice, once for receiver gathers and once following sorting to CMP gathers.

Once the editing was complete, the data volume was approximately one tenth of the original volume (reduced from 790,000 traces to 95,535 traces); this equates to a reduction in the nominal fold from 500 to approximately 65. Although this reduced the effectiveness of the stacking process, the final image was improved simply due to the absence of the dominant noise.

Additional processing steps for the BASIX data included first-break mutes, sorting to CMP gathers (using the crooked-line geometry), automatic gain control (1-s gate), velocity analysis, surface-consistent statics, residual velocity analysis, normal moveout, stacking (variable fold, average is approximately 40), and bandpass filtering (14-44 Hz). Both surface-consistent statics and detailed trace editing were important steps in generation of the final stack.

The data are written to two 8mm Exabyte tapes. The first tape contains the edited receiver gathers (12 s, 8 ms sample rate), with geometry applied so that the data can be resorted into CMP order. Receiver locations were unique, and the dataset is written as a single SEG-Y volume. The second tape contains stacked data (12 s, 8 ms sample rate) of the complete transect. This tape was also written as a single SEG-Y volume, but consists of four separately processed line segments. A line identifier is included in the SEG-Y header, allowing each segment to be extracted by unique CMP or line segment. These two data tapes are available from the National Geophysical Data Center at the following address:

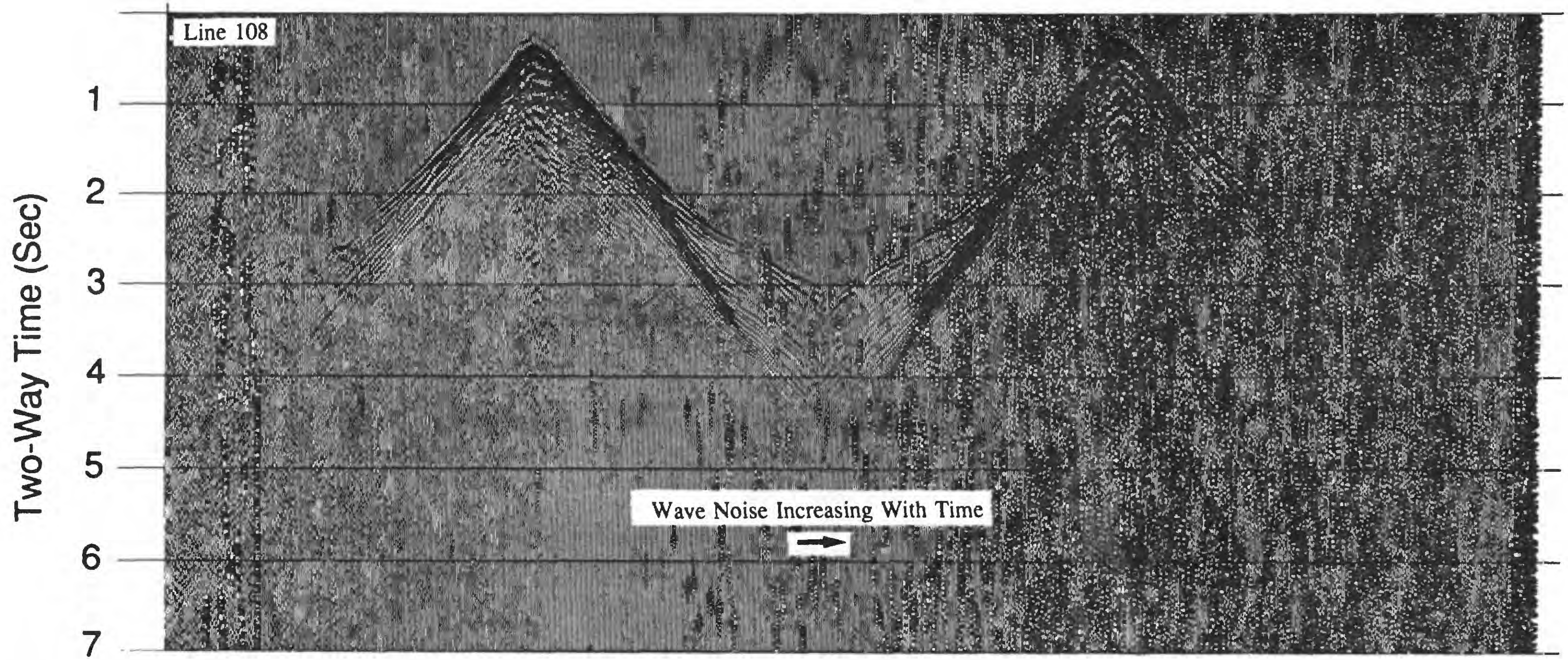

Figure 13. A single common receiver gather from San Pablo Bay recorded during two passes of the *S.P. Lee.* No scaling has been applied in order to illustrate noise problems. The 744 traces shown on this gather are from six hours of shooting. Noise from tidal currents and surface-wave action increased during the night.

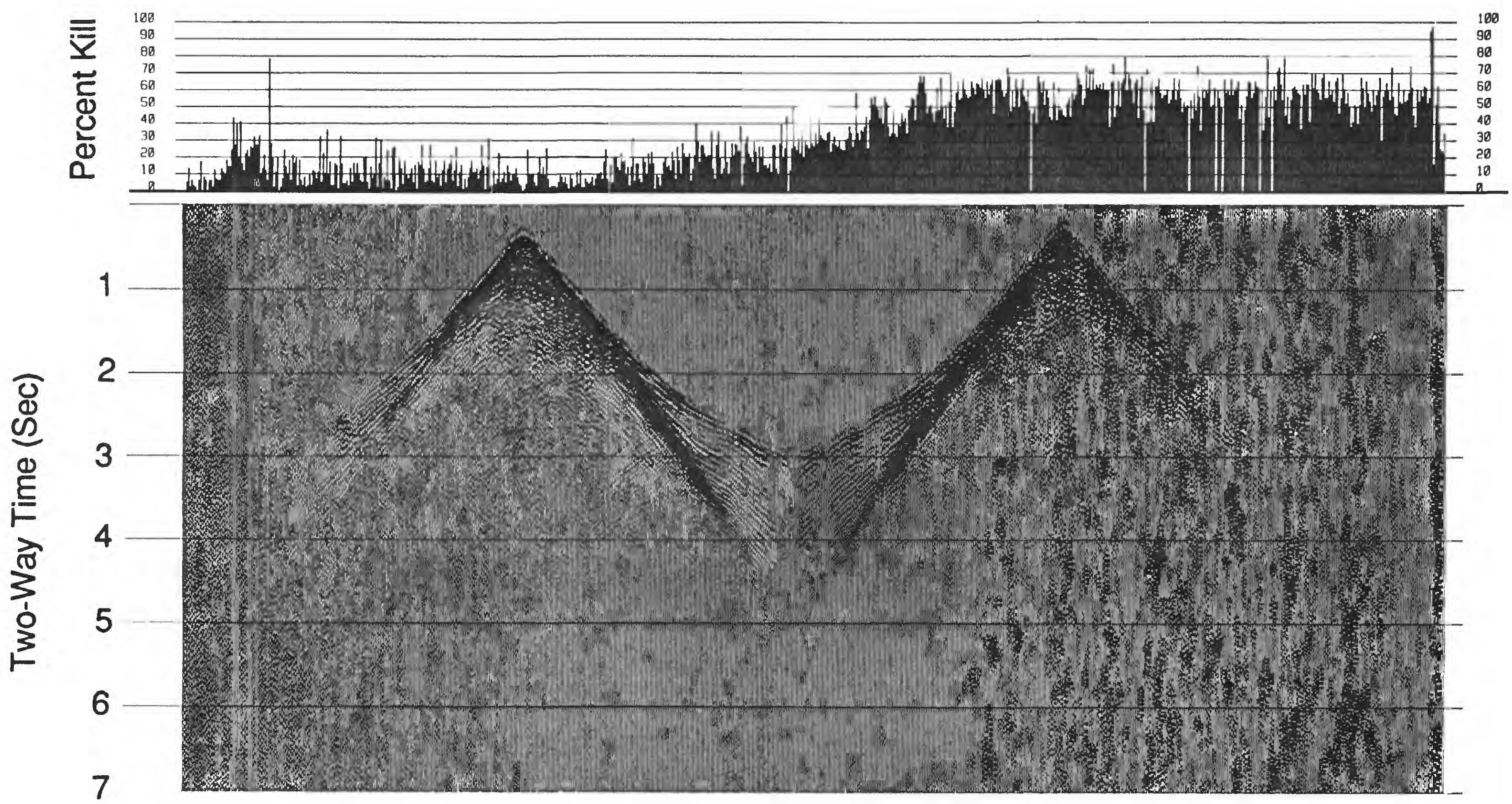

Figure 14. Common receiver gather (Figure 13) after application of automatic noise burst editing software. The amplitude of a sliding window on each trace is compared to the same time windows on adjacent traces, and anomalously high values are zeroed. Coherent energy such as reflection and refraction events are not affected by this editing. The bar chart above the record shows the percentage of each trace that has been zeroed.

National Geophysical Data Center
NOAA/EGCI
325 Broadway
Boulder, CO 80303
Telephone: (303) 497-6123.

The EBCDIC trace headers for each of the three data tapes are listed in Appendices B and C.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Captains Alan McClenaghan and Gordon Smith and the members of the scientific staff and crew of the *S.P. Lee* and the *David Johnston*, respectively, for their efforts during the acquisition of the BASIX data. In addition, we are indebted to Steve Higgins, George Knudson, Mike Pawlik, and John Stein of Fairfield Industries for their technical assistance during the experiment. Bob Tasto of the California Department of Fish and Game, Diane Windham and Michael Thabault of the National Marine Fisheries Service, Dick McCarthy of the California Coastal Commission, Mary Bergen of the State Lands Commission, Susan Ryan of the U.S. Army Corps of Engineers, Tom Tobin of the Seismic Safety Commission, Patrick McClellan of the San Leandro Office of Earthquake Preparedness, and Nancy Wakeman of the Bay Conservation and Development Commission all provided invaluable guidance during the permitting phase of this study. John Brezina of Brezina and Associates monitored the airgun operations for any potential environmental impact. The U.S. Coast Guard monitored all *S.P. Lee* and small-boat operations and provided important communication links between the BASIX activities and commercial ship traffic. The California Department of Transportation is acknowledged for providing the research vessels *Maco*, and *D.B. Marsh* for use in this study; Edward Fagan and Maurice Ruiz of Caltrans are especially acknowledged for their adept handling of the *D.B. Marsh*. Eric Geist wrote the noise burst editing routine, while Jon Childs, Rich Clymer, and Eleni Karageorgi contributed to the analysis of the seismic reflection data. Jon Childs and Tom Parsons provided helpfuls reviews of this manuscript.

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Appendix A

Line #	Location	Date	#Shots	Group Int.	#Telseis	#Passes
101	Rio Vista	9/4/91	723	100	118	2
102	Antioch	9/5/91	483	100	118	1
103	Suisun Bay	9/6/91	599	100	118	1
104	Martinez	9/7/91	165	100	60	1
105	Carquinez	9/8/91	946	200	60	2
107	San Pablo Bay	9/10/91	878	100	60	2
108	San Pablo Bay	9/11/91	869	100	60	2
109	San Pablo Bay	9/12/91	856	100	60	2
110	San Rafael	9/13/91	855	200	60	2
111	South Bay	9/14/91	791	200	105	1.5
OBS1	South Bay	9/15/91	871	0	0	0
113	Berkeley	9/16/91	907	200	60	2
201	Alcatraz	9/17/91	609	100	80	2
202	Golden Gate	9/18/91	956	100-200	71	2
TR1	Pacifica	9/19/91	102	0	0	1
0BS2	Cont. Margin	9/20/91	1024	0	0	1
Total:			11,634			

APPENDIX B
TAPE #1 -- SEG-Y EBCDIC REEL HEADER
<u>BASIX EDITED RECEIVER GATHERS:</u>

```
C 1  BRANCH OF PACIFIC MARINE GEOLOGY          U. S. GEOLOGICAL SURVEY
C 2  BASIX: BAY AREA SEISMIC EXPERIMENT        SURVEY_ID: L1-91-NC
C 3  AREA: SAN FRANCISCO BAY                   YEAR COLLECTED: 1991
C 4  LINES: 101 TO 202                         TRACES IN DATASET: 95535
C 5  REEL ID: BSXRECED                          8MM LOW-DENSITY (2.5 GB)
C 6  SAMPLE INTERVAL: 8 MSEC                   SAMPLES/TRACE: 1500
C 7  TRACE INTERVAL: 50 METERS                 TIME RANGE: 0 TO 12 SEC
C 8
C 9  THIS SEG-Y TAPE CONTAINS COMMON-RECEIVER SORTED AND NOISE EDITED
C10  DATA FROM ALL BASIX LINES. HEADER NAME IS REC-STAT: BYTES 187-188
C11  LINE 101 INCLUDES RECEIVER GATHERS 1-110
C12  LINE 102 INCLUDES RECEIVER GATHERS 111-207
C13  LINE 103 INCLUDES RECEIVER GATHERS 208-307
C14  LINE 104 INCLUDES RECEIVER GATHERS 312-430 (EVEN NUMBERS ONLY)
C15  LINE 105 INCLUDES RECEIVER GATHERS 384-502 (EVEN NUMBERS ONLY)
C16  LINE 107 INCLUDES RECEIVER GATHERS 504-563
C17  LINE 108 INCLUDES RECEIVER GATHERS 564-623
C18  LINE 109 INCLUDES RECEIVER GATHERS 624-683
C19  LINE 110 INCLUDES RECEIVER GATHERS 684-804 (EVEN NUMBERS ONLY)
C20  LINE 113 INCLUDES RECEIVER GATHERS 806-924 (EVEN NUMBERS ONLY)
C21  LINE 111 INCLUDES RECEIVER GATHERS 926-1144 (EVEN NUMBERS ONLY)
C22  LINE 201 INCLUDES RECEIVER GATHERS 2101-2180
C23  LINE 202 INCLUDES RECEIVER GATHERS 2181-2260
C24
C25  SHOT NUMBERS ARE LOCATED IN HEADER BYTES 9-13
C26
C27
C28  FUNDING FOR THIS WORK PROVIDED BY THE:
C29  NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM  (NEHRP)
C30
C31  ***********************************************************
C32
C33  FOR FURTHER INFORMATION, CONTACT:
C34
C35          PATRICK HART OR JILL MCCARTHY
C36          U. S. GEOLOGICAL SURVEY, M/S 999
C37          345 MIDDLEFIELD RD., MENLO PARK, CALIFORNIA  94025
C38          (415)  853-8300
C39
C40
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APPENDIX C
TAPE #2 -- SEG-Y EBCDIC REEL HEADER
BASIX STACKED PROFILES:

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C 1   BRANCH OF PACIFIC MARINE GEOLOGY                    U.S. GEOLOGICAL SURVEY
C 2   BASIX: BAY AREA SEISMIC IMAGING EXPERIMENT          SURVEY_ID: L1-91-NC
C 3   AREA: SAN FRANCISCO BAY                             YEAR COLLECTED: 1991
C 4   LINES 101 TO 202                                    TRACES IN DATASET: 2678
C 5   REEL ID: BSXSTK                                     8MM LOW-DENSITY (2.5 GB)
C 6   SAMPLE INTERVAL 8 MSEC                              SAMPLES/TRACE: 1500
C 7   TRACE INTERVAL: 50 METERS                           TIME RANGE: 0 TO 12 SEC
C 8
C 9   THIS SEG-Y TAPE CONTAINS STACKED DATA FROM ALL BASIX LINES
C10   LINES 101-110    CDP RANGE  111-1705    LINE_ID: 101    NTRACES: 1587
C11   LINES 113        CDP RANGE 1747-2046    LINE_ID: 113    NTRACES: 282
C12   LINES 111        CDP RANGE 2049-2493    LINE_ID: 111    NTRACES: 456
C13   LINES 201-202    CDP RANGE 3104-3465    LINE_ID: 201    NTRACES: 353
C14
C15   CDP AND LINE_ID ARE DEFINED IN THE FOLLOWING HEADER BYTES:
C16
C17   HEADER         STARTING        LENGTH        VARIABLE
C18                  BYTE            (BYTES)       TYPE
C19
C20   CDP            21              4             INTEGER
C21   LINE_ID        191             2             INTEGER
C22
C23
C24
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