Marine Seismic-Reflection Data Acquired in the San Francisco Bay Region, 1991–97

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CONTENTS

Abstract

Between 1991 and 1997, the U.S. Geological Survey conducted seismic-reflection studies of earthquake faults in the San Francisco Bay region. The goal of these studies was to investigate the positions and structure of the region's strike-slip faults, from shallow subsurface depths down through the entire crust, using various seismic-reflection techniques with overlapping resolution and depths of penetration. The deep-crustal and midcrustal geometry of the San Andreas and Hayward Faults was the focus of the three-phase Bay Area Seismic Imaging eXperiment (BASIX) run in 1991, 1995, and 1997, which utilized large airgun arrays and widely distributed hydrophone receivers to obtain seismic-reflection images of these faults to 22-km depth. A combination of higher-resolution seismic-reflection methods were used to study the shallow crust. A small airgun multichannel system was used to acquire seismic-reflection profiles with 1 to 2 km of penetration for detailed fault and shallow-structure studies. Very high resolution images of approximately the shallowest 25 m of the subsurface were collected along many of the multichannel tracklines, using a surface-towed, electromechanical ("boomer") source and a vertically oriented transducer array. All seismic data were digitally recorded, processed, and archived. Positional data were acquired by using the Global Positioning System in either nondifferential (early 1990s) or differential (mid-1990s and late 1990s) mode.

Introduction

From the early 1970s through 1990, the U.S. Geological Survey (USGS) routinely collected marine multichannel seismic-reflection data for use in regional geologic-framework studies. Most of this work was conventional, two-dimensional marine profiling, using a 2.4-km multichannel hydrophone streamer and an array of 5 or 10 airguns totaling more than 32 L in volume. Since 1991, however, the focus of USGS marine research has shifted to shallow-water studies relevant to coastal processes, shallow aquifers, and geologic hazards. These programmatic changes necessitated the development of equipment and methods more suitable to shallow-water operation and near-surface targets, including new high-resolution systems and novel uses of conventional seismic-reflection systems. In the San Francisco Bay region, long segments of the San Andreas and related earthquake faults lie submerged beneath shallow coastal and inland waters. Beginning in 1991, the USGS conducted a series of marine seismic-reflection studies, using new systems and methods designed to image the region's geologic structures and fault geometry, as summarized in table 1.

BASIX–1

The first Bay Area Seismic Imaging eXperiment (BASIX–1) was the first attempt to use marine seismic-reflection profiling to define the deep-crustal structure and fault geometry of the San Francisco Bay region. This experiment, which was designed to investigate a model proposed by Furlong and others (1989) that the network of major regional earthquake faults are structurally linked by a horizontal fault beneath San Francisco Bay, was conducted in September 1991 by the USGS in collaboration with the University of California, Berkeley, Stanford University, Penn State University, and Lawrence Berkeley Laboratory (McCarthy and Hart, 1993).

Although options for a large-scale seismic-reflection study in the San Francisco Bay region are severely restricted by dense urban development, the bays and delta that dissect the region provide accessible pathways that cross the major faults. These inland waters were used for BASIX–1 and the followup experiments in 1995 and 1997, BASIX–2 and BASIX–3, respectively. The research vessel *S.P. Lee* was used as the main platform for BASIX–1 data acquisition. A 12-airgun 96-L source array and a 120-channel digital seismic recording system were installed on the *S.P. Lee*. Because heavy ship traffic, shallow water, and rapidly changing tidal currents combined to make the use of a

Table 1.—Summary of marine seismic-reflection data collected in the San Francisco Bay region, 1991–97.

Date Cruise ID	Vessel	Data Description	Comments
Sept. 1991 L1–91–NC BASIX–1	*S.P. Lee*	60–120-channel data; radio telemetered from single hydrophones buoyed at 100–200-m intervals along shot tracklines; 50-m shot interval; 12-gun 96-L airgun array; source-receiver offsets, max 20 km; 16-s record length; 4-ms sample interval.	Stacked profiles and common-receiver gathers from San Francisco, San Pablo, and Suisun Bays, the Sacramento River delta, and 10 km out the Golden Gate. Low signal-to-noise ratio. Good upper-crustal structural imaging in eastern part of delta. Deep (6–10 s) reflectivity observed in central San Francisco Bay. Map: figure 1; data example: figures 2–4.
Sept. 1991 L1–91–NC BASIX–1	*S.P. Lee*	Single-channel vertical incidence records of the BASIX–1 airgun shots acquired with a towed 50-m hydrophone streamer. 5-s record length; 4-ms sample interval.	Profiles acquired along most of the BASIX–1 shot tracklines. Much less noise than in buoyed-hydrophone data. Map: figure 1.
Apr. 1995 G1–95–SF BASIX–2	*Robert Gray*	48-channel stationary streamer laid directly on the bay floor. 12-gun 96-L airgun array; ~200 m shot int. Radio trigger link. Source-receiver offsets, max 20 km; 16-s record length; 4-ms sample interval	Three streamer deployments in central and southern San Francisco Bay designed to better define the deep reflectivity observed on BASIX–1 data and to test the bottom cable recording technique. Records show drastic reduction in noise relative to BASIX–1. Map: figure 5; data example: figure 6.
Sept. 1997 M1–97–SF BASIX–3	*McGaw* and *Auriga*	48-channel stationary streamer laid directly on the bay floor. 12-gun 96-L airgun array; ~200 m shot interval. Radio-trigger link. Source-receiver offsets, max 20 km; 16-s record length; 4-ms sample interval.	Five streamer deployments made to extend the BASIX–2 data into San Pablo and Suisun Bays and to provide data acquired with the receiver array perpendicular to the San Andreas and Hayward Faults. Map: figure 5; data example: fig. 6.
High-resolution data available at URL http://geopubs.wr.usgs.gov/open-file/of00-494/			
July 1993 J8–93–SF	*David Johnston*	24-channel 150-m-long streamer; two 0.65-L airguns; ~50–200-Hz bandwidth; 6–12-fold, with 3.12-m common-depth-point interval; 1–2-s record length; 2-ms sample interval.	Nine good-quality multichannel seismic profiles in southern San Francisco Bay imaging the San Leandro Basin to 1 km depth. Map: figure 8.
May 1994 J2–94–SF	*David Johnston*	24-channel 150-m-long streamer; two 0.65-L airguns; ~50–200-Hz bandwidth; 6–12-fold, with 3.12-m common-depth-point interval; 2-s record length; 2-ms sample interval.	Data acquired in four areas: southern San Francisco Bay, San Pablo Bay, Sacramento delta near the town of Pittsburg, and a single east-west profile out the Golden Gate. All good quality except San Pablo lines. Map: figure 8; data example: figure 9.
May 1994 J2–94–SF	*David Johnston*	Surface-towed sled system; single channel; “boomer” source; inline cone receiver array; ~1,000–4,000-Hz bandwidth; 200-ms record length; 0.0625-ms sample interval (16 kHz).	Very high resolution profiles acquired concurrently with most of the 1994 multichannel seismic profiles except the Golden Gate line. Good quality with 25-m penetration, except San Pablo data, which are obscured by shallow gas. Owing to recording problem, data have low dynamic range. Map: figure 8; data example: figure 10.
June 1995 G2–95–SF	*Robert Gray*	24-channel 150-m-long streamer; two 0.65-L airguns; ~50–200-Hz bandwidth; 6–12-fold, with 3.12-m common-depth-point interval; 2-s record length; 2-ms sample interval.	Grid of high-quality multichannel profiles outside Golden Gate imaging San Andreas and San Gregorio Fault zones to >1-km depth. A few fair-quality profiles in central San Francisco Bay and the Sacramento River delta. Map: figure 8.
Mar. 1997 J4–97–SF	*David Johnston*	24-channel 240-m-long streamer; 0.57./0.57-L dual-chamber airgun; ~50–200-Hz bandwidth; 6–12-fold, with 5.0-m common-depth-point interval; 2-s record length; 2-ms sample interval.	A single southern San Francisco Bay profile across the San Leandro Basin acquired to test improvements made to the high-resolution multichannel seismic system. Map: figure 8; data example: figure 11.

conventional kilometers-long towed hydrophone streamer unfeasible, individual floating hydrophones with radio telemetry units were used as receivers. These receivers were anchored at 100- to 200-m intervals adjacent to the ship tracklines to record airgun blasts (fig. 1) and transmit the data back to the shipboard recording system. Each day of the experiment, 60 to 120 receivers were deployed by using several small boats. The airguns were fired at night along the receiver array and off end to distances of approximately 20 km. Over a 2-week period, 1,030 receiver stations were occupied, recording a total of 11,634 airgun blasts at a 50-m shot spacing. Telemetrically received data were recorded at a 4-ms sample interval to a 16-s record length. Receiver deployments began at the east limit of the experiment, near the town of Rio Vista, and progressed daily to the west, through Suisun Bay, San Pablo Bay, southward through San Francisco Bay and westward 10 km beyond the Golden Gate. Airgun tracklines were constrained to the relatively deeper (>8 m) water of the dredged shipping channels.

Data quality varies significantly along the individual BASIX–1 tracklines (fig. 2). Noise from tidal currents and strong winds dominates most of the far-offset data. Noise bursts, presumably from the hydrophones jostling in the choppy water, are common. Additional degradation of the far-offset data could be due to transmission noise in the radio signal from the hydrophone receivers to the recording ship. As a result, extensive editing of the data was necessary. After eliminating the noisiest data traces, a custom automatic noise-burst editor was applied, followed by conventional seismic-reflection processing steps. Data were gained, band-pass-filtered at 14 to 44 Hz, and sorted to common-midpoint gathers; then, normal moveout velocities were picked and applied. Residual statics were calculated and applied, and the data were stacked at an average of 65-fold. A 50-m single-

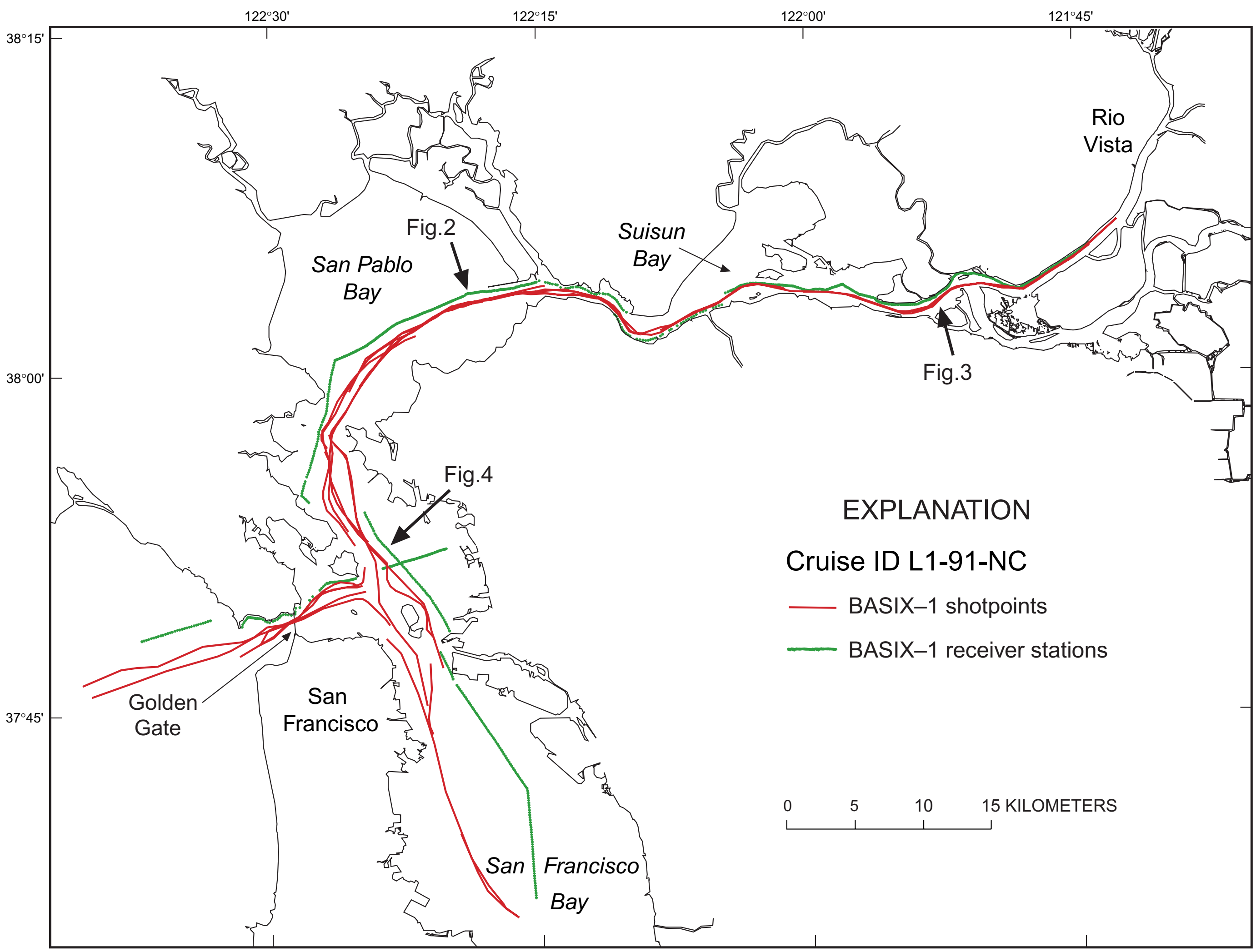

Figure 1.—Gulf of the Farallones and San Francisco Bay region, Calif., showing locations of major faults and tracklines of high-resolution multichannel seismic-reflection records acquired for this study. Shaded area, general area of the San Gregorio Basin as defined here; hachured area, the Bodega Basin of McCulloch (1987, 1989). Rectangle denotes area of figure 6.

channel streamer was towed behind the *S.P. Lee* along most of the airgun tracklines to record vertical-incidence data to 5-s two-way traveltime. These profiles are much less noisy and provide better upper-crustal images than the stacked buoyed-hydrophone data.

Few laterally continuous reflections are evident in the BASIX–1 data. However, on one 20-km section at the east edge of the study area (fig. 1), a 4-s-two-way-traveltime (10–12 km) zone of coherent, continuous reflections can be clearly seen (fig 3). These data help define the structure of the Kirby Hills Fault (see Parsons and others, this volume). The only other area with continuous high-amplitude reflections is central San Francisco Bay, where a zone of horizontal reflections between 6- and 10-s two-way traveltime are observed on both the stacked profile and the receiver gathers. A representative receiver gather from central San Francisco Bay is shown in figure 4. The high-amplitude reflections at 6- to 7-s two-way traveltime were interpreted by Brocher and others (1994) to originate at 18- to 21-km depth on a horizontal detachment fault linking the San Andreas and Hayward Faults. This interpretation is supported by the observation that the zone of reflections between 6 and 10 s is visible only on receiver gathers between these two faults and so is unlikely to result from a regional deep-crustal reflector. BASIX–1 airgun data were also recorded on an array of land seismometer stations (Brocher and Moses, 1993) and ocean-bottom seismometers (Holbrook and others, 1996) deployed throughout the region, which show a similar distribution of possible deep-crustal and midcrustal reflectivity. However, the low signal-to-noise ratio of many of the marine data makes it difficult to map the lateral extent of the reflectivity with certainty, using only the data from BASIX–1.

BASIX–2

A subsequent field program was proposed in 1995 to attempt to solve the noise problems encountered during BASIX–1 by using bottom-cable hydrophone receivers.

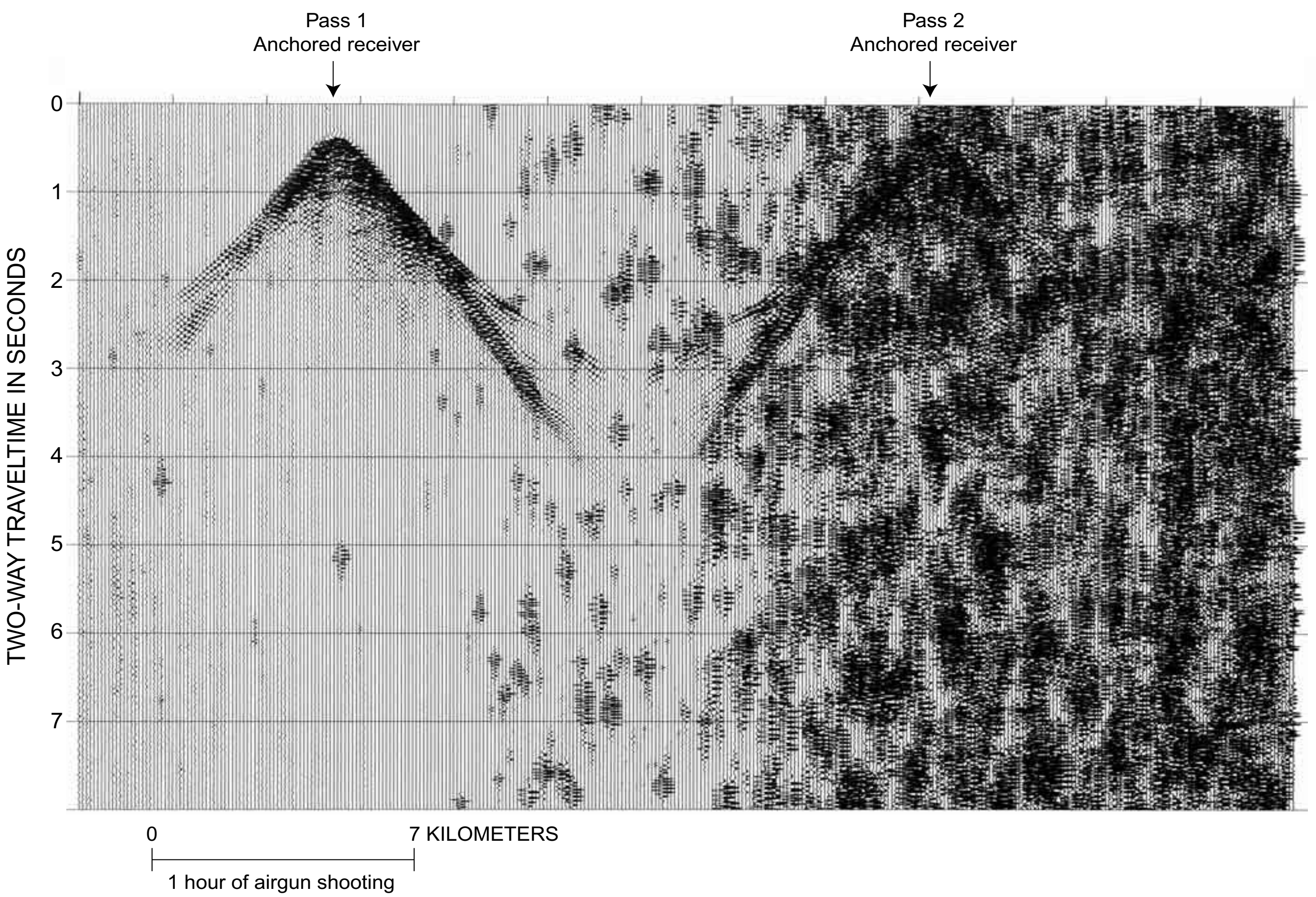

Figure 2.—Part of a single common-receiver gather from San Pablo Bay (see fig. 1 for location) recorded during 5 hours of airgun shooting during BASIX–1. No amplitude scaling has been applied to illustrate noise problems. Airgun ship made two passes by anchored hydrophone receiver. During second pass, noise from tidal currents and surface waves increased to the point where high-amplitude noise bursts completely dominate record.

Deploying long arrays of hydrophones directly on the bay floor could enhance the signal-to-noise ratio of the deep-crustal reflection data in several ways. Hydrophones enclosed within a flexible cable lying in contact with the soft muddy bottom of the bay would not be as strongly affected by strong tidal currents and choppy waters as were the floating hydrophones used in 1991. In addition, linear arrays of hydrophones would be used for each recorded channel, diminishing random noise in favor of coherent-reflection energy arriving vertically from below. Finally, the stationary-receiver spread would be wired directly to the recording system, eliminating noise introduced by radio telemetry.

BASIX–2, which was conducted by the USGS in April 1995, was planned to be a relatively small pilot study of the bottom-cable recording technique that, if successful, would lead to a much larger program. The field-operations budget was thus too small to allow the work to be contracted to a geophysical-data-acquisition company or to lease the specialized equipment needed for bottom-cable recording. USGS personnel and equipment had to be used as much as possible. The USGS owns a 2.4-km-long oil-filled hydrophone streamer designed to be towed behind a recording ship during conventional open-ocean seismic profiling. This streamer was modified for use as a 48-channel bottom cable by taping 2,400 0.45-kg lead weights at 1-m intervals along its length. The weighted streamer and its storage reel was mounted on a 9- by 18-m leased barge, along with the multichannel recording system in a portable van. A 12-airgun array, deployment gantry, air compressor, and shot controller were installed on a second 9- by 21-m barge.

Three sites were chosen in central and southern San Francisco Bay for deployment of the weighted streamer (fig. 5). These sites overlapped all the hydrophone-station locations from BASIX–1 that recorded deep reflectivity. Operational considerations also influenced the locations of the deployment sites. To minimize risk of damage to the streamer during deployment or recovery, existing side-scan-sonar data were reviewed to ensure that the sites were flat and that no debris or rocky outcrops existed along each 2.4-km-long deployment line. Because each deployment location was to be

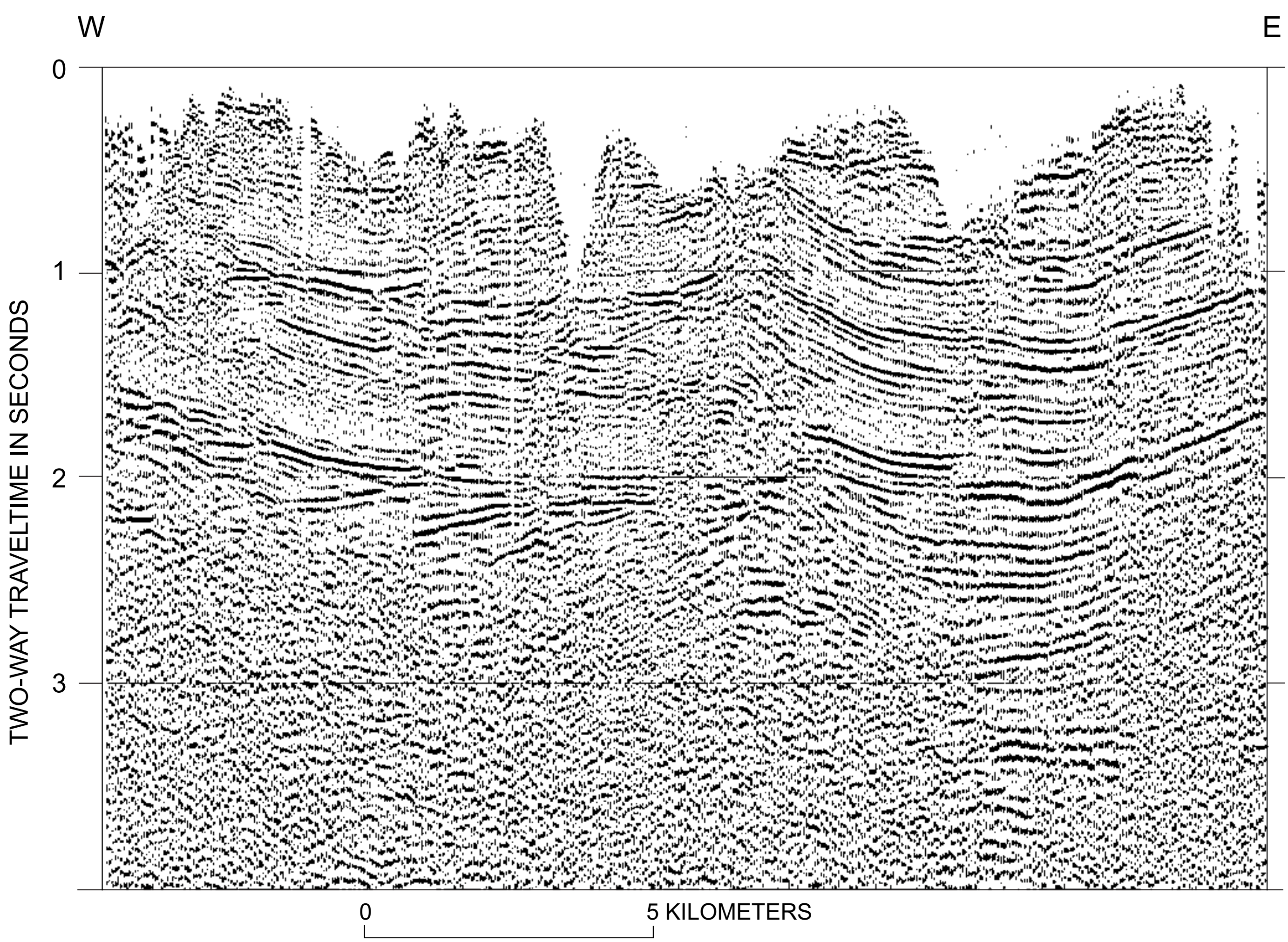

Figure 3.—Approximately 65-fold stacked section of BASIX–1 data from west to east across the Kirby Hills Fault (see fig. 1 for location). Extensive noise editing that was applied before stacking has caused gaps visible in upper 1 s of record.

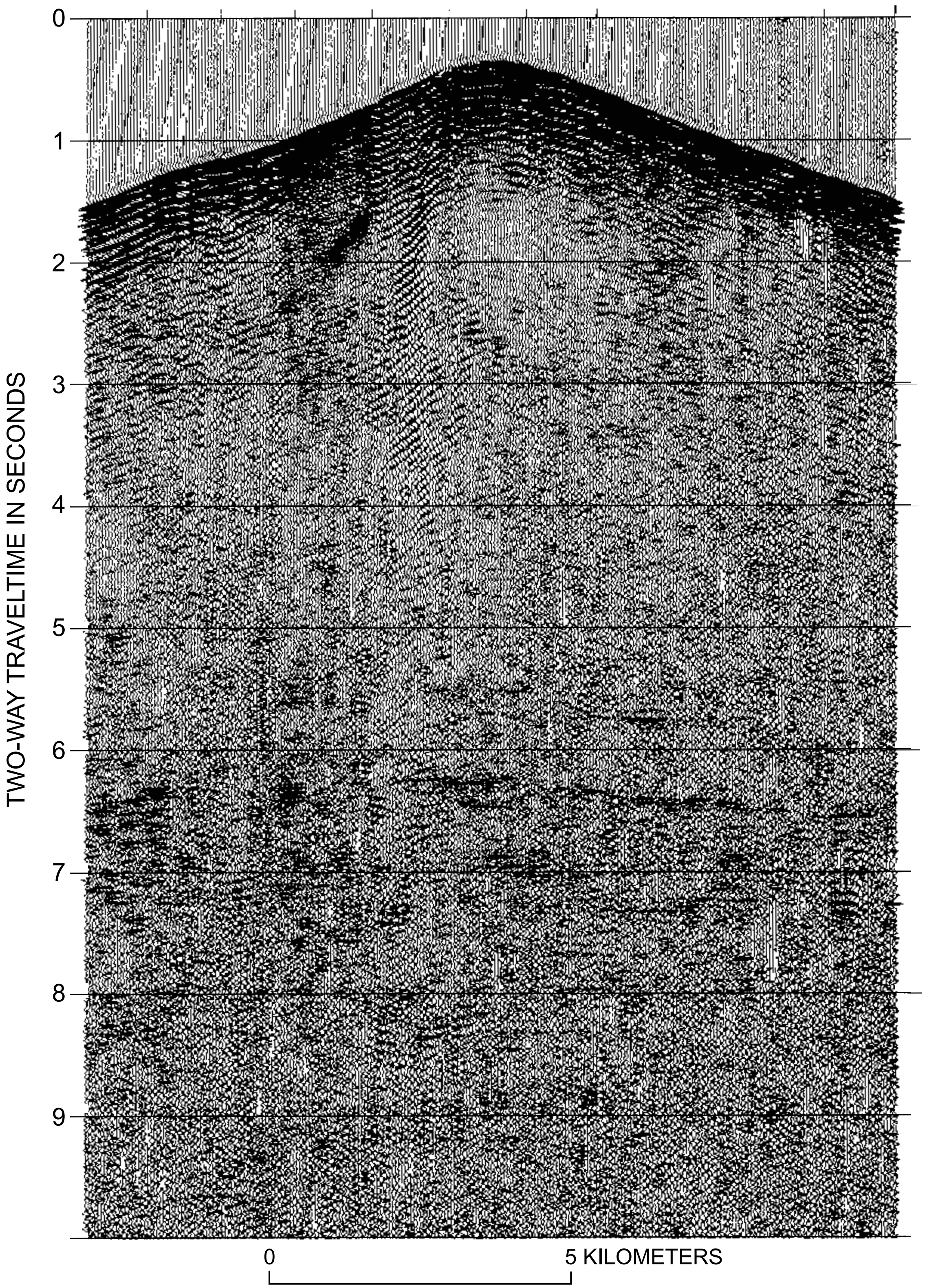

Figure 4.—Common-receiver gather from central San Francisco Bay (see fig. 1 for location) recorded during BASIX–1. Although this record has a low signal-to-noise, it shows a zone of coherent horizontal reflectivity between 6- and 8-s two-way traveltime. One major goal of BASIX–2 and BASIX–3 was to determine origin of this reflectivity.

occupied for 1 to 2 days, the deployment lines were chosen to be parallel to tidal currents so as to reduce the possibility that the streamer might roll a significant distance if pushed perpendicularly by a strong current. The lines were in water depths greater than about 5 m to allow vessel access during deployment and recovery, and the shipping channel was avoided in case the streamer might float up off the bottom in the turbulence of a passing ship and be damaged.

The field operation for BASIX–2 was complex and fairly awkward. The procedure using equipment mounted on barges was the least expensive way to test bottom-cable recording in San Francisco Bay and was not intended to be a prototype for future work. The motor vessel *Robert Gray* was contracted to move the barges as needed for data acquisition, and to house all personnel during the experiment. The *Robert Gray* towed the recording barge along the deployment lines as the streamer was rolled off its reel and laid onto the bay bottom in a straight line; the recording barge was then anchored at the end of the streamer. Airgun shooting was accomplished by the *Robert Gray* towing the shooting barge past the stationary streamer and to about 20 km beyond the ends of the deployment lines as the airguns were fired at a 90-s (approx 200 m) interval. A radio-trigger link synchronized the gun firing with the data recording. A total of 1,241 shots were recorded at the three deployment sites during 8 days of shooting.

BASIX–2 data quality is much higher than that of BASIX–1. High-amplitude reflections are conspicuous between 6- and 10-s two-way traveltime on shot records from each of the deployments (fig. 6). The BASIX–2 data suggest a highly reflective lower crust beneath San Francisco Bay,

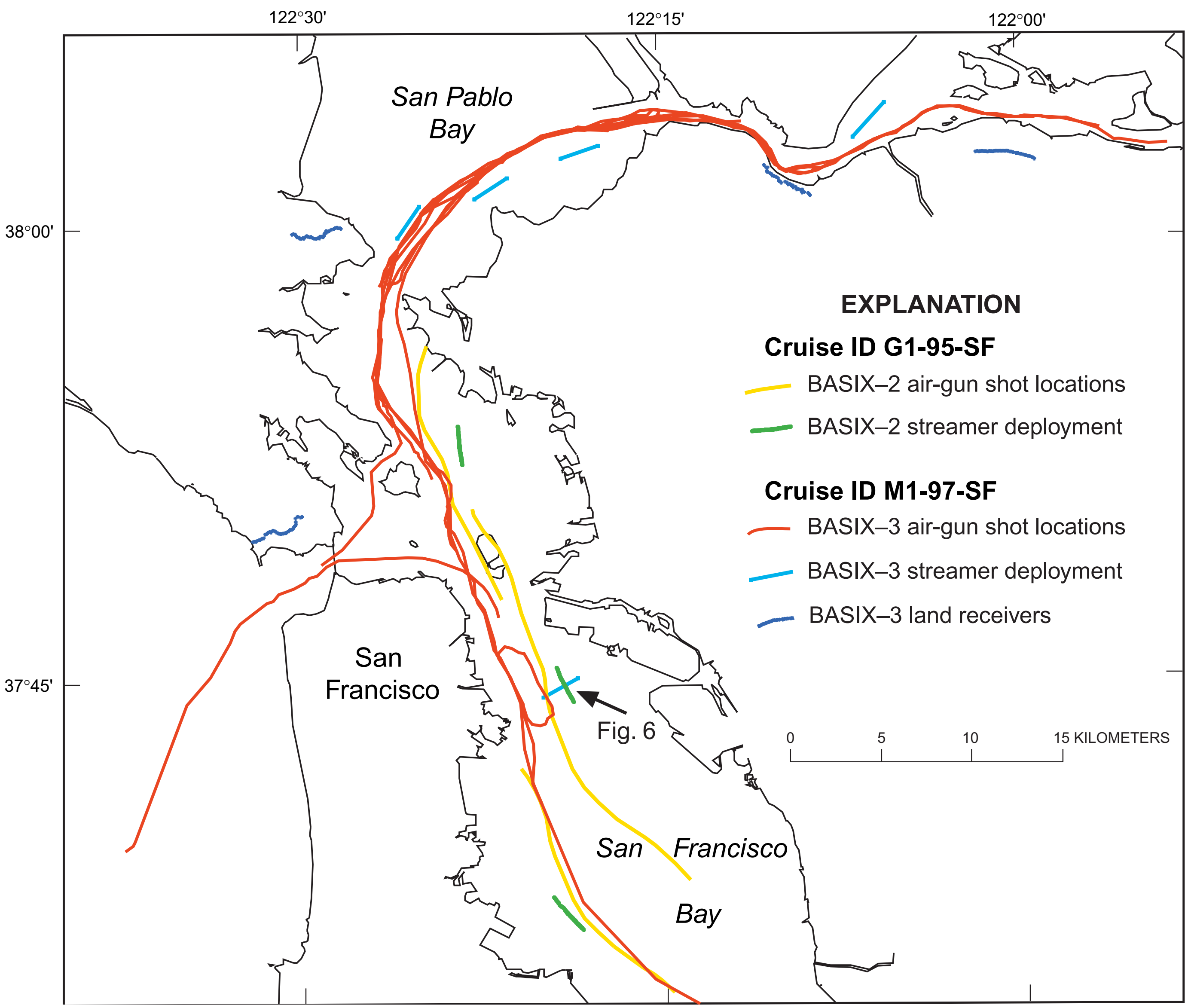

Figure 5.—San Francisco Bay region, showing locations of BASIX–2 (1995) and BASIX–3 (1997) airgun tracklines and hydrophone-streamer deployments, BASIX–3 onland geophone-receiver stations, and data example from figure 6.

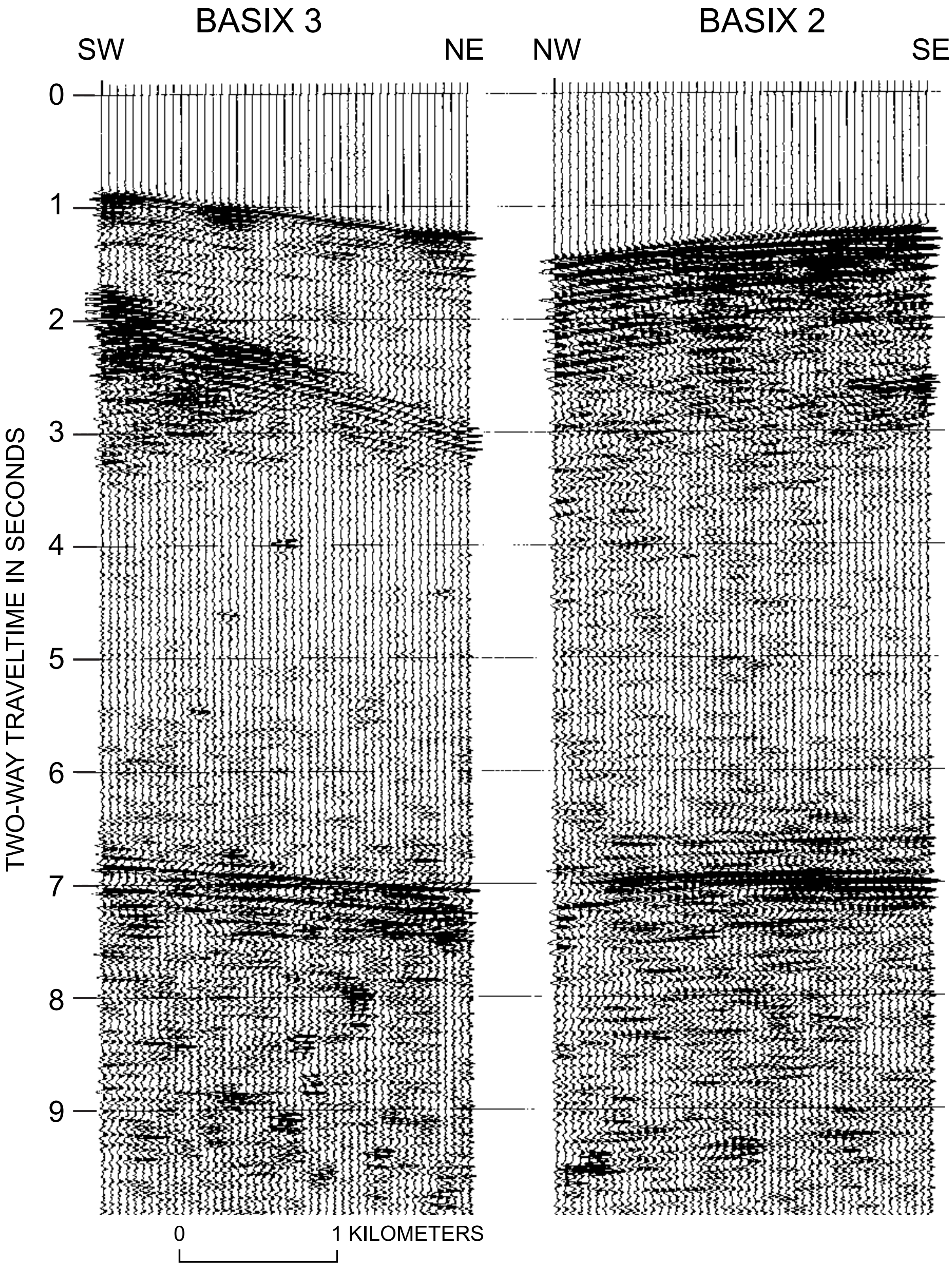

Figure 6.—Single-shot gathers from BASIX–2 and BASIX–3, showing records from airgun shots at similar locations (fig. 5). Orientation of hydrophone streamer for BASIX–3 record is perpendicular to that of BASIX–2 record. Difference between the two records in moveout of reflection event at 7-s two-way traveltime has been analyzed to determine that reflection originates from steeply dipping San Andreas Fault plane.

in support of the model of a detachment-fault connection between the San Andreas and Hayward Faults. However, this interpretation is inconsistent with data acquired on the San Francisco peninsula in 1995 (Parsons, 1998), when large chemical-explosive sources were recorded on a spread of land seismometers deployed orthogonal to the San Andreas Fault. Those data showed conspicuous reflections at 12- to 14-s two-way traveltime but not at 6- to 10-s two-way traveltime, as seen on the BASIX–2 data. Parsons (1998) concluded that the reflections on land came from a 70º-SW.-dipping Hayward Fault between 18- and 24-km depth. A similar out-of-plane origin for the BASIX–2 reflections was considered, but the acquisition geometry of BASIX–2 did not allow distinction between horizontal and dipping fault-plane reflectors because the deployment lines and shooting tracklines nearly paralleled the region's major faults (Parsons and Hart, 1999; see Parsons and others, this volume).

BASIX–3

BASIX–3, which was completed in September 1997, used the same airgun source array and weighted hydrophone streamer as BASIX–2, although the field operation was modified to increase efficiency and allow better access to new deployment lines. Two ships, instead of barges, were contracted to carry and deploy the equipment. The streamer reel and recording van were put on the research vessel *McGaw*, and the airgun system was installed on the motor vessel *Auriga* (fig. 7). A small tugboat was used to help maneuver the *McGaw* during streamer deployment and recovery and to help set the four-point anchoring system that held the *McGaw* in place during acquisition.

Five streamer-deployment lines were occupied (fig. 5), and a total of 2,751 airgun shots were recorded during 10 days of shooting. The southernmost deployment was just south of the San Francisco-Oakland Bay Bridge at a right angle to one of the 1995 BASIX–2 lines, to determine the orientation of the deep reflection events observed in the BASIX–2 data by comparing the arrival times across these two orthogonal spreads (fig. 6). Deployments were also made in San Pablo Bay and Suisun Bay to provide data east of and crossing the Hayward Fault. Analysis of the entire BASIX–2 and BASIX–3 data sets indicates that most, if not all, of the high-amplitude reflectivity at >6-s two-way traveltime

Figure 7.—Motor vessel *Auriga*, with 12-airgun source array, working in San Pablo Bay (see figs. 1, 5) during BASIX–3.

results from steeply dipping reflectors interpreted to be fault planes (Parsons and Hart, 1999; see Parsons and others, this volume). The San Andreas and Hayward Faults are interpreted to be vertical to about 10- to 12-km depth, then to dip toward each other at 60º and 70º, respectively, beneath San Francisco Bay to the base of the crust. The fault planes cannot be mapped with the BASIX data below the base of the crust at about 25-km depth.

High-Resolution Data

Work began in 1993 on a multichannel seismic system capable of imaging geologic structures to 1- to 2-km depth with a spatial resolution of 5 to 10 m in relatively shallow water environments (Childs and others, 2000). The main components of this system were a small airgun source, a short 24-channel streamer, and a compact PC-based digital recording instrument. The initial streamer was of solid-core construction with "thin film" cylindrical hydrophones of polyvinylidene fluoride plastic, which is characterized by high sensitivity and a broadband (5–5,000 Hz) frequency response. The streamer was 150 m long, with a 6.25-m group interval and one hydrophone per channel. The source was a pair of 0.65-L airguns with "wave shape" kits installed in their chambers to suppress the bubble pulse. Navigation software developed by the USGS provided trackline following and position logging. Positioning was accomplished with a single Global Positioning System receiver with an absolute position accuracy of approximately ±30 m. Relative positions, from fix to fix, were accurate to within a few meters.

In July 1993, this system was installed on the USGS research vessel *David Johnston* for field trials in southern San Francisco Bay. The major difficulty encountered during the field trials was proper ballasting of the streamer to allow it to "fly" just below the water surface but not contact the bay floor when working in water as shallow as 2 m. Then, nine seismic-reflection profiles were recorded (cruise J8–93–SF, fig. 8). The shot-firing interval for these lines was either 6.25 or 12.5 m. Factors limiting the firing interval were air-compressor capacity and the shot-processing time required by the recording system. At speeds below 1.8 m/s, the 6.25-m fire interval could be maintained; higher speeds (generally tidally controlled) necessitated the longer shot-firing interval. Resulting common-midpoint data were either 12- or 6-fold, with a 3.125-m common-midpoint interval. Data were recorded at a 1-ms sample interval to a 2-s record length. The data-processing sequence used to create stacked profiles from the field data is SEG–Y (Barry and others, 1974) input and resampling to 2 ms, trace edit, geometry assignment, bandpass filter (50–200 Hz), automatic gain control (100-ms window), water-bottom mute, frequency-wavenumber filter (50–200 Hz, ±2,400 m/s), spiking deconvolution, common-midpoint sort, stacking-velocity analysis, normal-moveout correction, stack, and SEG–Y output.

Data quality of the 1993 tests was high, allowing imaging of structure deeper than 1 km in places. On the basis of this success, in May 1994, detailed surveys using the research vessel *David Johnston* were run over southern San Francisco Bay near San Bruno Shoal (Marlow and others, 1998), over the Kirby Hills Fault where it crosses the western part of the Sacramento River delta (see Parsons and others, this volume), and over the Hayward-to-Rodgers Creek Fault stepover in San Pablo Bay. A subsequent cruise was conducted in June 1995, using the motor vessel *Robert Gray*, over the offshore extension of the San Andreas Fault system west of the Golden Gate (fig. 8; table1; see Bruns and others, this volume). All data were processed using a sequence similar to that listed above. Differential GPS navigation used during the 1995 cruise improved absolute positional accuracy to approximately ±10 m.

In 1994, very high resolution reflection profiles were acquired concurrently with the airgun data. The instrument used to acquire these profiles consisted of a source and a receiver mounted together on a 2-m-long catamaran sled towed behind and to the side of the survey vessel. The source was a wideband (500–4,500 Hz) electrodynamic "boomer" that generated a single positive-pressure transient of as much as approximately 218 dB referenced to 1 μPa at 1 m; the receiver was a line-in-cone hydrophone array oriented to maximize vertical-incidence reflected energy. Data were recorded digitally at 16-kHz sampling rate to a record length of 200 ms, at a repetition rate of 2 to 4 "pings" per second. Low power levels from the analog-signal conditioner resulted in recorded data with a relatively low dynamic range (<30 dB); however, a vertical resolution of >50 cm to a subbottom depth of ~25 m and a lateral resolution of ~1 m were achieved.

Part of a multichannel seismic profile acquired in 1994 in the Sacramento River delta crossing the Kirby Hills Fault Zone is shown in figures 9 and 10. The steeply dipping near-surface sedimentary deposits are imaged at better than 10 times the multichannel seismic resolution by the very high resolution data. This combination of data-acquisition systems allows interpretations of the uppermost 1 or 2 km of crust to be tied to the shallowest subsurface. These data have been used in fault investigations of the Kirby Hills Fault zone (see Parsons and others, this volume) and southern San Francisco Bay (Marlow and others, 1996).

In March 1997, a single seismic profile was recorded in southern San Francisco Bay during tests of changes made to reflection profiling system to improve the penetration and data signal-to-noise ratio. A new 240-m solid-core hydrophone streamer and a dual-chamber generator-injector airgun were used. The streamer was of the same type as used previously but featured a 10-m group interval (240-m overall active length) and three hydrophones per channel. The airgun consists of a 0.57-L "injector" chamber timed to discharge a short time (typically, 20–30 ms) after the 0.57-L "generator" chamber so as to suppress the bubble pulse and create an optimal signal. This gun was fired as frequently as the air compressor would allow, typically at 10- to 12-s intervals. Stack fold therefore ranged from 4 to 12, depending on the vessel speed. A migrated version of this profile is shown in figure 11 to demonstrate the data quality and resolution that are achievable with this system in shallow water.

Conclusions

Modeling and analysis of the BASIX data sets is continuing to refine the interpretation of the crustal structure in the San Francisco Bay region. Refraction data from arrays of land seismometers deployed during BASIX–3, and data from the eastern streamer deployments of BASIX–3, have not yet been studied in detail. Although much work remains to be completed, results from BASIX have given the best picture yet of the deeply buried segments of the San Francisco Bay region's earthquake fault system.

The USGS high-resolution multichannel seismic and very high resolution systems have proved capable of acquiring high-quality seismic-reflection profiles in the shallow water of San Francisco Bay. These data combine to provide a continuous image of subsurface geologic structure and fault geometry that ties 5- to 10-m resolution and 1- to 2-km penetration with less than 1-m resolution in the uppermost few tens of meters.

The data described here are all available for download from the USGS Web site at URL http://walrus.wr.usgs.gov/reports/. Because of recent regulatory changes pertaining to the use of airgun sources within San Francisco Bay region waters (Childs and others, 1999), additional surveys of the type described here will probably not be undertaken.

Acknowledgments

The success of the USGS marine seismic programs in the San Francisco Bay region during the 1990s is largely attributable to the technicians, engineers, and staff at the USGS marine facility in Redwood City, Calif., whose work before and during the often-difficult field operations directly

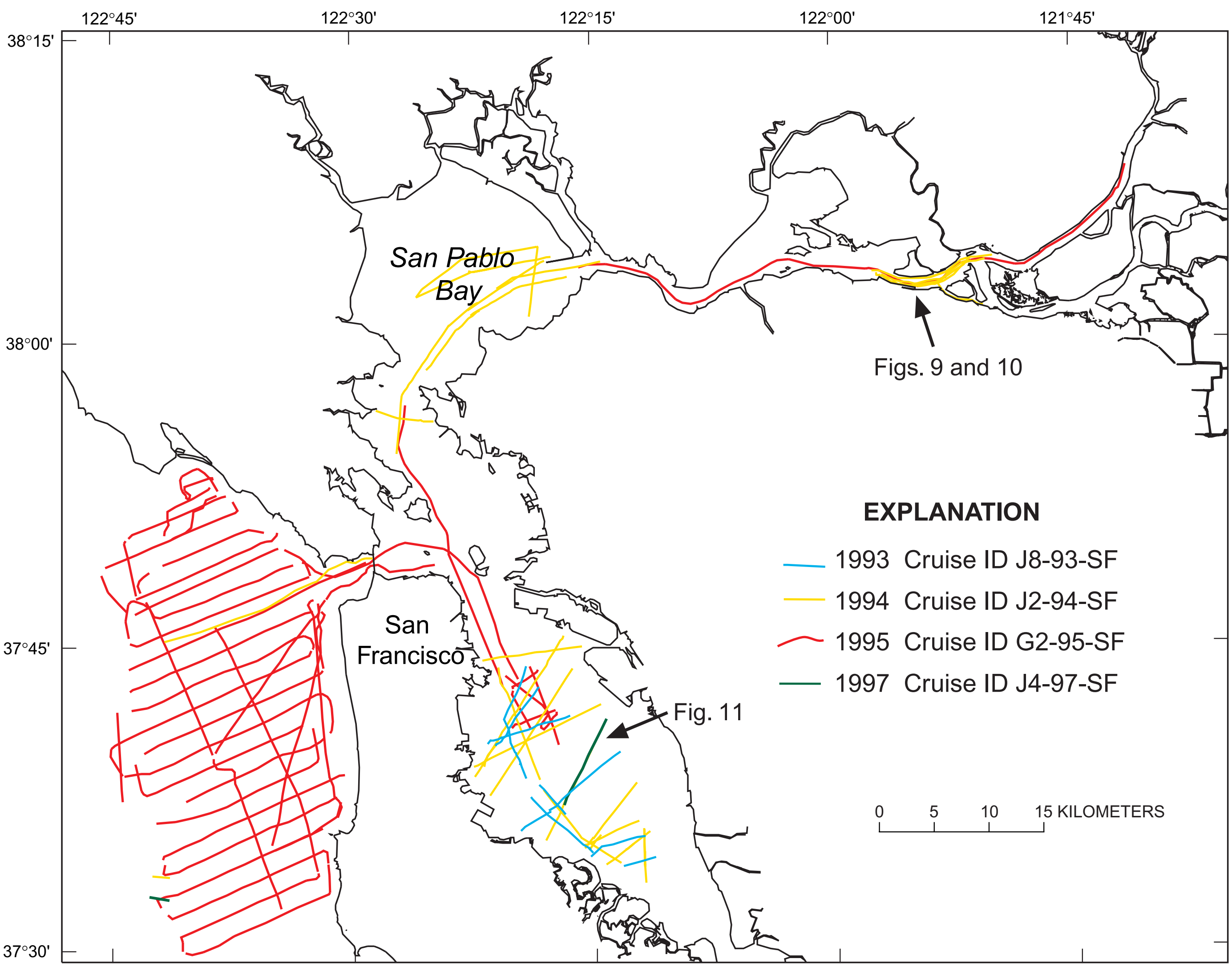

Figure 8.—San Francisco Bay region, showing locations of tracklines for four high-resolution marine seismic-reflection surveys completed from 1993 to 1997 and data examples in figures 9 through 11.

resulted in new data-acquisition capabilities and a comprehensive regional data set collected with minimal time lost to technical problems. In particular, we thank Steve Wallace, Kevin O'Toole, Hal Williams, Walt Olson, Dave Hogg, Larry Kooker, Bill Robinson, Mike Boyle, Fred Payne, Sue Hunt, Gerry O'Brien, and Gordon Smith, the master of the research vessel *David Johnston*. We are grateful to Diane Minasian for her work in preparing all the maps and figures for this chapter.

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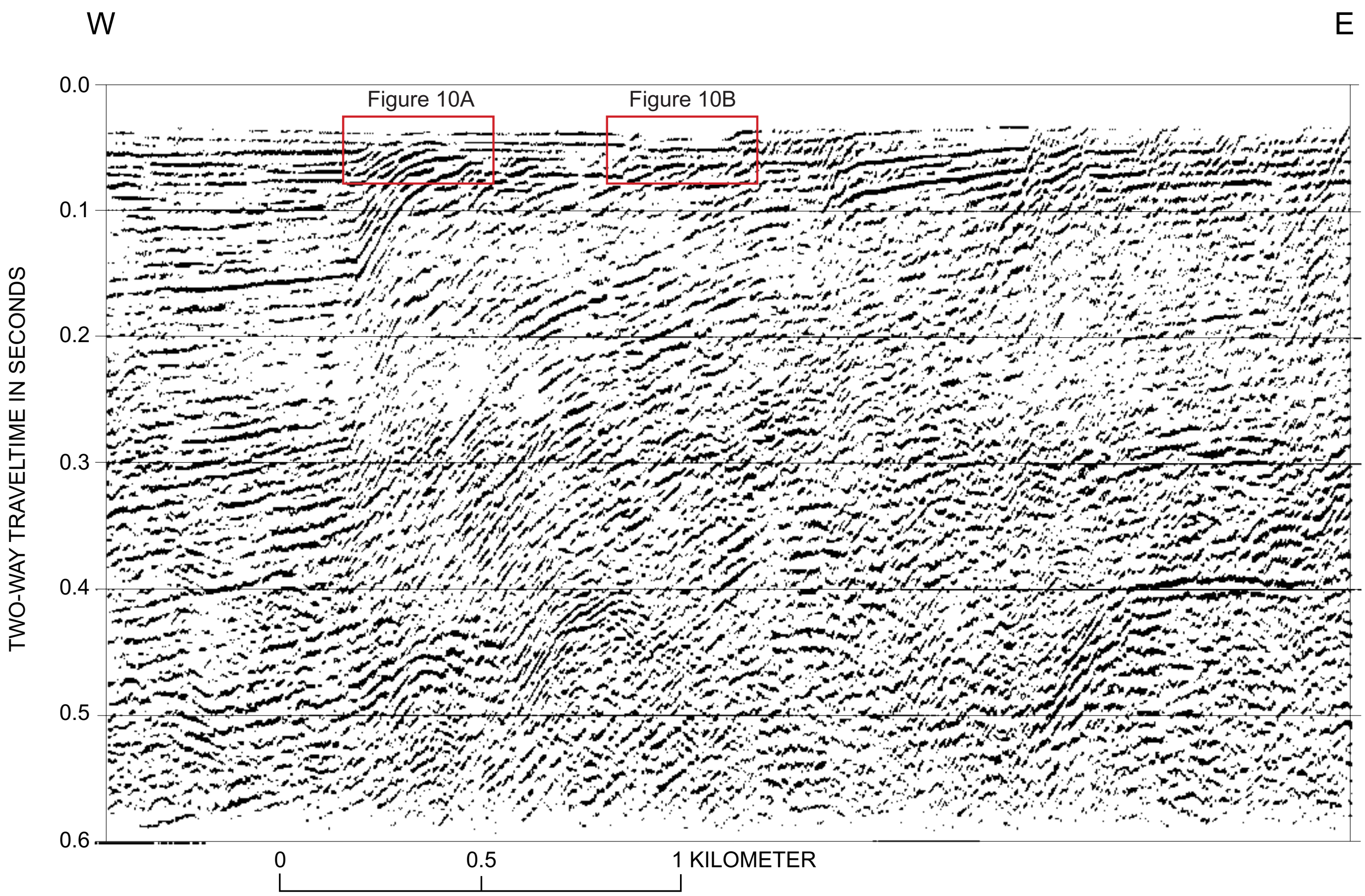

Figure 9.—Section of a high-resolution multichannel seismic profile acquired in the Sacramento River delta crossing the Kirby Hills Fault zone (see fig. 8 for location), showing approximately 500 m of penetration. Two rectangular boxes indicate coverage of coincident very high resolution data examples in figure 10.

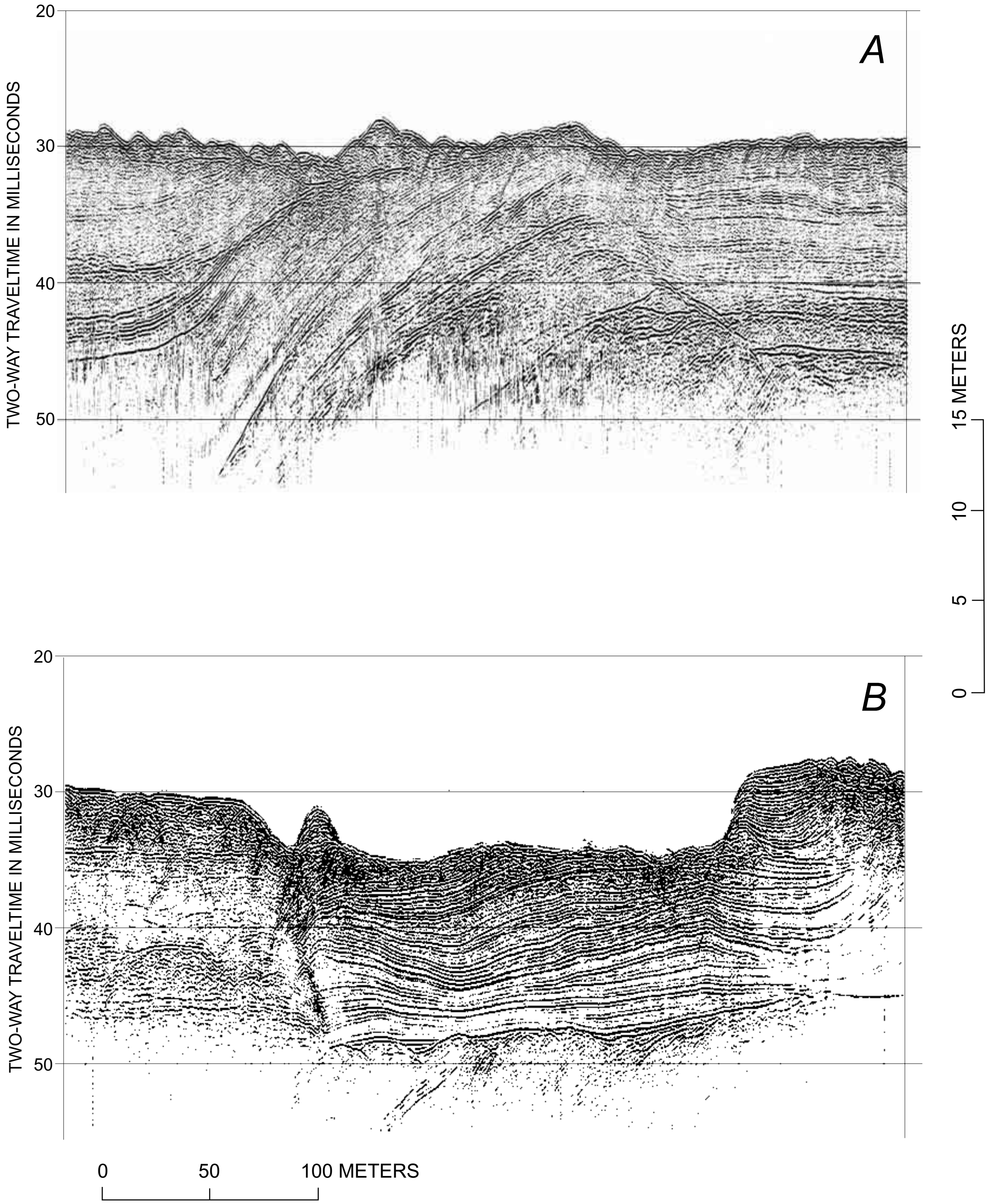

Figure 10.—Two sections of a very high resolution seismic reflection profile acquired in 20 to 25 m of water in the Sacramento River delta near the Kirby Hills Fault (see fig. 8 for location), showing a "zoomed in" image of two zones (*A*, *B*) outlined in figure 9. These data, which have more than 20 m of subbottom imaging with approximately 30 cm of vertical resolution, allow interpretations to be extended to shallowest subsurface in much greater detail than is possible with multichannel seismic data alone.

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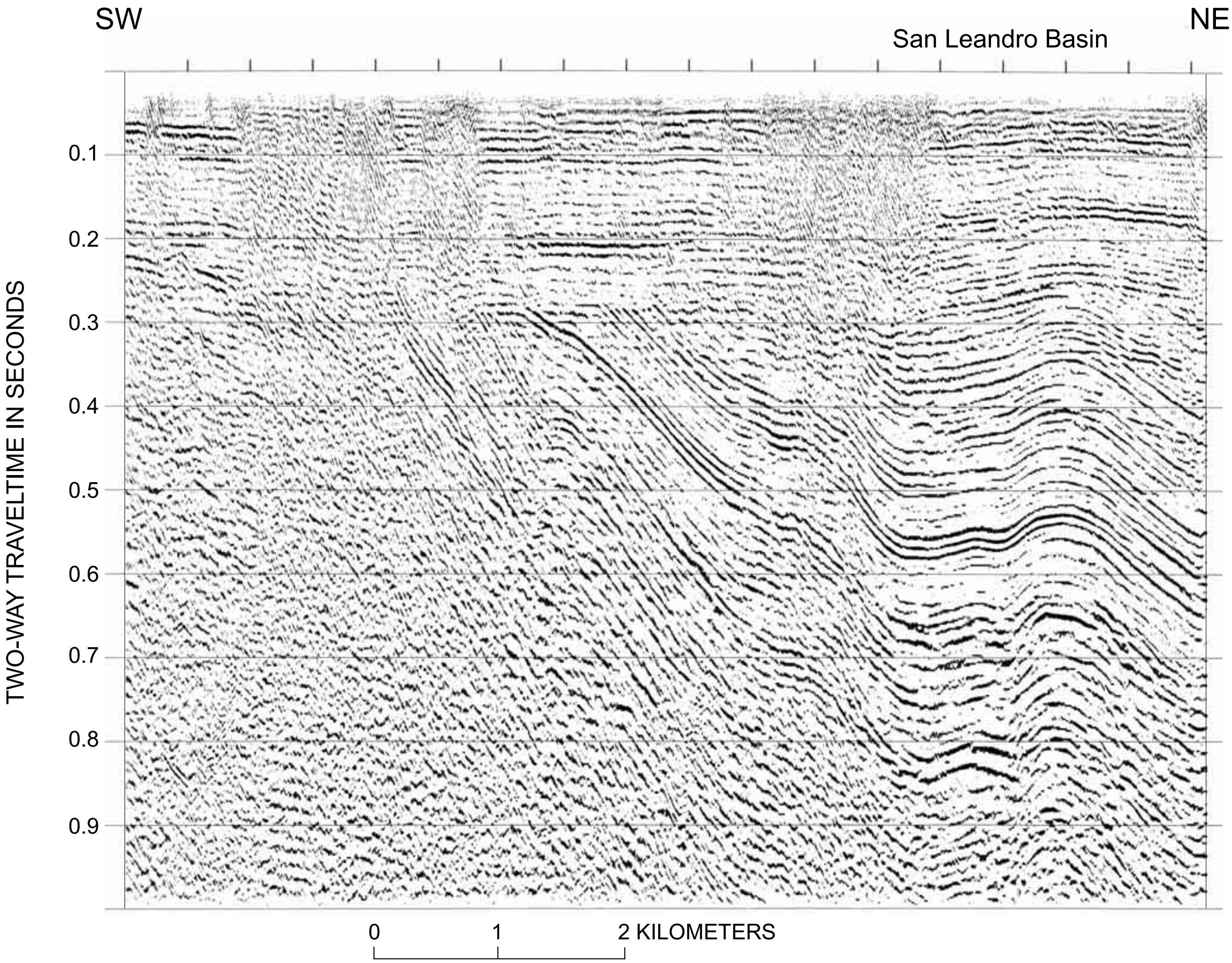

Figure 11. Migrated multichannel seismic-reflection profile acquired in southern San Francisco Bay (see fig. 8 for location). This airgun line shows approximately 1 km of penetration into folded sedimentary deposits of the San Leandro Basin.