Los Angeles Region Seismic Experiment (LARSE), California - Off-shore Seismic Refraction Data

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TABLE OF CONTENTS

SUMMARY .................................................................................................................. 1
RATIONALE FOR THE EXPERIMENT .................................................................. 1
EXPERIMENTAL DESIGN ...................................................................................... 1
LOG OF THE EXPERIMENT .................................................................................... 3
SPECIFICATIONS OF THE USGS OBS ............................................................... 6
SPECIFICATIONS OF DALHOUSIE OBS DATA ............................................... 6
COMMENTS ON DATA COLLECTED BY DALHOUSIE OBS .............................. 7
DATA FORMAT ......................................................................................................... 7
RECORD SECTIONS ................................................................................................. 8
DATA REPOSITORY ................................................................................................. 9
REFERENCES ........................................................................................................... 9
ACKNOWLEDGMENTS .............................................................................................. 9

TABLES

TABLE 1. Page 5. Start and end times and locations of lines shot by R/V Ewing and recorded by OBS

TABLE 2 Page 5. Locations and elevations of Ocean Bottom Seismometer and land stations.

FIGURES

Figure 1. Page 2. Location of offshore seismic refraction profiles. In Italic - OBS which did not record data. Inset - Overview of offshore-onshore part of the experiment and locations of earthquakes.

Figure 2. Page 4. Photographs of Canadian OBS ready for deployment (above) and USGS OBS during deployment.


Figure 22. Page 29. Monitor channel (channel 150) of MCS Line 2 from the R/V Ewing
SUMMARY

Nine Ocean Bottom Seismometers (OBSs) were deployed in the Inner California Borderland as part of the Los Angeles Region Seismic Experiment (LARSE). The data recorded by these OBSs were intended to delineate the offshore continuation of crustal structure under the Los Angeles Basin. The experiment, conducted in October 1994, was a cooperative study involving scientists from the U.S. Geological Survey, Caltech, the University of Southern California, the University of California Los Angeles, and the Southern California Earthquake Center (SCEC). The offshore wide-angle seismic experiment was the first such experiment in the area since 1958. The data quality recorded on the OBSs was very good with high signal-to-noise ratio on PmP arrivals in the majority of the OBSs. The total OBS data recovery rate for both deployments was about 80%. This report details the experimental design, the data format, the processing steps and other information pertinent to data analysis and modeling. It also presents seismic refraction records of the offshore area recorded by OBS and selected surrounding land stations.

A World-Wide-Web site has been established for the OBS component of the LARSE experiment showing the location of the experiment, samples of the data, and a short version of this report. The site can be found under http://obs.er.usgs.gov.

RATIONALE FOR THE EXPERIMENT

Combined offshore-onshore seismic experiments have become standard in recent years, because of the understanding that geological provinces cross from land to sea, and because marine air-gun sources are safe, highly repeatable, and inexpensive relative to land explosions (Brocher, 1995). The LARSE experiment recorded air-gun blasts generated by the R/V Ewing at seismographs deployed on land along two north-south lines crossing the Los Angeles region. The OBS component, designed to give the seismic velocity structure under the seismic source, is needed for accurate analysis of the land portion of the lines.

A second reason for the offshore component of the experiment is to delineate the seismic velocity structure of the offshore California Borderland province. An accurate velocity model there should enable refinements of the velocity model used to locate earthquakes. An accurate velocity model can be used to predict focusing of energy from earthquakes caused by low-velocity regions, favorably oriented seismic reflectors, and local site-amplification.

There has previously been only one large-scale refraction experiment offshore the Los Angeles basin, but the data were sparse, were not digitally recorded, and were analyzed by one-dimensional ray-tracing models (Shor and Raitt, 1958). The crust was determined to be 24-km-thick in the area between Catalina and San Clemente Islands increasing to 30 km on shore and decreasing to 18 km under the Patton Ridge close to the continent-ocean boundary (Shor and Raitt, 1958). The crust in their model had a P-wave velocity of 6.7±0.1 km/s below a depth of 6 km across the entire Borderland province. Because of the geological structure of the area (thin or missing sedimentary cover underlain by the highly diffractive Catalina Schist), multichannel seismic reflection (MCS) techniques have failed to image the deep crust (Bohannon and Geist, in press). Wide-angle reflection and refraction techniques retain the high density of ray paths that characterize MCS techniques, but are expected to yield larger amplitude reflections according to ray theory, as the critical angle of incidence is approached or exceeded.

EXPERIMENTAL DESIGN

Two offshore-onshore lines, oriented north-south and centered on the Los Angeles basin at the epicenters of the 1933 Long Beach, the 1987 Whittier-Narrows, and the 1994 Northridge earthquakes, were recorded during the experiment (Figure 1). The onshore-offshore lines were
Figure 1. Location of offshore seismic profiles. In Italic - OBS which did not record data. Inset - Overview of offshore-onshore part of the experiment and locations of earthquakes.
each 200-250 km long, with the offshore lines being between 90 and 150 km long, respectively. The offshore section of Line 1 extended from Seal Beach to San Clemente Island crossing the Catalina Ridge near the SE tip of Catalina Island (Figure 1). The offshore section of Line 2 extended from Santa Monica to 40 km south of the ridge containing San Clemente Island (San Clemente Ridge) passing near the NW tips of Catalina and San Clemente Islands. The onshore parts of the lines were recorded by 170 PASSCAL Reftek recorders and the offshore parts were recorded by the OBSs and by 4 PASSCAL Reftek stations on San Clemente and Catalina Islands.

The R/V Maurice Ewing's 20-element air gun array, totaling 137.7 liters (8470 cu. in.), was used as a seismic source for the wide-angle seismic recordings (Brocher et al., 1995). The array, composed of Bolt air guns, was generally towed at depths between 8 and 10 meters. The ship-to-gun distance varied for each gun to minimize fouling the air-gun towing harnesses and to optimally separate the air bubbles created by the air gun array: the center of the air gun array was towed approximately 87.4 meters behind the Magnavox Global Positioning Satellite (GPS) receiver of the ship. The width of the air gun array across the beam of the ship was 33.8 meters. The sizes of the air gun chambers varied from 145 cu. in. (2.4 liters) to 875 cu. in. (14.2 liters) to provide a tuned outgoing source wavelet. Air gun shot times recorded in the navigation files were from the air gun fire command time determined from a Magnavox GPS clock. Given the less than a millisecond jitters in the air gun firing times, these shot times are considered accurate to within a millisecond. The Ewing fired the array at a slow rate (every 60 and 90 seconds along Lines 1 and 2, respectively) to minimize acoustic-wave interference from previous shots in the OBS data (Table 1). These rates correspond to shot intervals of ~150 meters and ~225 meters, respectively. The Ewing repeated portions of these lines up to 5 additional times with a repetition rate of 20 seconds (which corresponds to ~50 meters shot interval) to enhance the fold of the wide-angle data recorded onshore. Multichannel seismic reflection data were also recorded during these additional passes by the Ewing's 4.2-kilometers, 160-channel, digital streamer.

The OBSs were deployed from and recovered by the R/V Yellowfin, a 76-foot vessel operated by the Southern California Marine Institute, a consortium of universities in Southern California, and based in San Pedro, California. Seven of the OBSs were operated by the USGS Eastern Marine and Coastal Team, Northeastern Section; the two additional OBSs were loaned for the LARSE experiment by Dalhousie University, Halifax, Nova Scotia (Figure 2). The sensors, used by the two different OBSs were nearly identical, yielding nearly matched instruments for the experiment. Separate OBS deployments were made along Lines 1 and 2 (Table 2). Each OBS deployment recorded air gun signals only along the line on which it was deployed. Shots were recorded continuously from a pre-programmed time on four channels (vertical geophone, two horizontal geophones, and a hydrophone). USGS OBS data were recorded at a sampling interval of 10 milliseconds and Dalhousie OBS data were recorded at a sampling interval of 5.73 milliseconds. Data from USGS OBSs were later separated to 60 sec long traces starting after each shot, and those of the Dalhousie OBS to 30 sec long traces. For the most part, the OBSs were concentrated on the northern ends of these lines, to help resolve the velocity structure nearest the Los Angeles Basin. One OBS on the Line 2 deployment was deployed to the southwest of San Clemente Island in an attempt to record reversed upper mantle refractions (Pn).

LOG OF THE EXPERIMENT

Nine OBSs along Line 1 were deployed on 12 October 1994 after being programmed to begin recording at 1600 UTC on JD 286 (0900 L on 13 October 1994). These OBSs recorded during both OBS and MCS passes of Line 1 (Lines 01 and 01R) made by the Ewing, and were recovered in the night and morning of 14-15 October 1994. Eight OBSs were immediately recovered from this deployment and all 8 provided useful data for Lines 01 and 01R (as well as for part of Line 01X). OBS C1 was found floating at the surface after being lost for about 4 days. This OBS apparently did not stay attached to its anchor and released shortly after impacting the sea floor,
Figure 2. Photographs of Dalhousie University OBS ready to be deployed (above) and USGS OBS being deployed (left).
recording only 10 shots of Line 01. The other OBSs recorded a total of 653 shots during Line 01 and 2310 shots during Line 01R.

The remaining eight OBSs were deployed along Line 2 between 0900 and 1800 UTC on JD 290 (0200 and 1100 L on 17 October 1994), and were programmed to begin recording at 0200 UTC on JD 291 (1900 L on 18 October 1994). The OBSs were recovered between 0215 and 1420 UTC on JD 292 (night and morning of 19-20 October) and thus recorded both OBS and MCS passes of Line 2 (Lines 02R and 02X); four OBSs recorded at least part of MCS Line 02Y (Table 1). Two OBSs, C9 and A2, were not immediately recovered from this deployment (Table 2). Both were found floating at the sea surface after the LARSE MCS experiment ended. OBS A2 recorded 100 shots (12%) of Line 02R before it released prematurely. OBS C9 stayed on the sea floor for nearly a day, and recorded 550 shots of Line 02R (representing 66% of the line). OBS C_ failed to record any useful data during this deployment (Table 2). The other OBSs recorded a total of 721 shots during Line 02R and 1296 shots during 02X.

### Table 1. Start and End Times and locations of lines shot by R/V Ewing and recorded by OBS

<table>
<thead>
<tr>
<th>Line No.</th>
<th>UTC Start of Line</th>
<th>Lat. (N)</th>
<th>Long. (W)</th>
<th>UTC End of Line</th>
<th>Lat. (N)</th>
<th>Long. (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01*</td>
<td>286:1849</td>
<td>33 38.191</td>
<td>118 07.055</td>
<td>287:0541</td>
<td>32 56.869</td>
<td>118 25.333</td>
</tr>
<tr>
<td>01R</td>
<td>287:1155</td>
<td>33 49.475</td>
<td>118 07.194</td>
<td>288:0124</td>
<td>33 37.276</td>
<td>118 11.621</td>
</tr>
<tr>
<td>01X</td>
<td>288:0028</td>
<td>33 36.951</td>
<td>118 11.505</td>
<td>288:0632</td>
<td>33 15.103</td>
<td>118 15.692</td>
</tr>
<tr>
<td>02R**</td>
<td>291:0155</td>
<td>32 38.36</td>
<td>118 43.386</td>
<td>291:1956</td>
<td>33 59.187</td>
<td>118 35.040</td>
</tr>
<tr>
<td>02X</td>
<td>292:0202</td>
<td>33 58.996</td>
<td>118 34.911</td>
<td>292:0404</td>
<td>33 26.080</td>
<td>118 40.439</td>
</tr>
<tr>
<td>02Y</td>
<td>292:0405</td>
<td>33 26.06</td>
<td>118 40.465</td>
<td>292:1231</td>
<td>33 59.090</td>
<td>118 35.130</td>
</tr>
</tbody>
</table>

* 60 sec shot time interval  
** 90 sec shot time interval

### Table 2. Locations and elevations of Ocean Bottom Seismometer and land stations

<table>
<thead>
<tr>
<th>OBS Name</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>33 34.0844</td>
<td>118 08.7095</td>
<td>97</td>
</tr>
<tr>
<td>A1</td>
<td>33 31.1492</td>
<td>118 09.8185</td>
<td>321</td>
</tr>
<tr>
<td>A2</td>
<td>33 26.5097</td>
<td>118 11.5804</td>
<td>723</td>
</tr>
<tr>
<td>A_</td>
<td>33 21.0082</td>
<td>118 13.4897</td>
<td>711</td>
</tr>
<tr>
<td>C_</td>
<td>33 16.8277</td>
<td>118 15.1957</td>
<td>177</td>
</tr>
<tr>
<td>C1*</td>
<td>33 12.8067</td>
<td>118 16.5421</td>
<td>1134</td>
</tr>
<tr>
<td>C9</td>
<td>33 06.7002</td>
<td>118 20.1462</td>
<td>1158</td>
</tr>
<tr>
<td>C4</td>
<td>33 01.0848</td>
<td>118 23.2386</td>
<td>798</td>
</tr>
<tr>
<td>C3</td>
<td>32 56.3934</td>
<td>118 25.2850</td>
<td>1191-1196</td>
</tr>
<tr>
<td>LS1</td>
<td>32 52.6583</td>
<td>118 27.0350</td>
<td>-528%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OBS Name</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS89</td>
<td>34 04.7350</td>
<td>118 34.167</td>
<td>-480%</td>
</tr>
<tr>
<td>C4</td>
<td>33 58.6342</td>
<td>118 34.9445</td>
<td>77</td>
</tr>
<tr>
<td>C3</td>
<td>33 53.0789</td>
<td>118 36.0271</td>
<td>79</td>
</tr>
<tr>
<td>C9*</td>
<td>33 47.8420</td>
<td>118 37.0280</td>
<td>833</td>
</tr>
<tr>
<td>A1</td>
<td>33 42.9050</td>
<td>118 37.8090</td>
<td>705</td>
</tr>
<tr>
<td>A2*</td>
<td>33 35.2470</td>
<td>118 39.3110</td>
<td>618</td>
</tr>
<tr>
<td>LS4</td>
<td>33 26.8900</td>
<td>118 32.8500</td>
<td>-534%</td>
</tr>
<tr>
<td>A3</td>
<td>33 21.9648</td>
<td>118 40.6503</td>
<td>1200</td>
</tr>
<tr>
<td>C_</td>
<td>33 12.4439</td>
<td>118 41.3244</td>
<td>1330-1340</td>
</tr>
<tr>
<td>LS2</td>
<td>33 00.5200</td>
<td>118 34.0466</td>
<td>-159%</td>
</tr>
<tr>
<td>D_</td>
<td>32 55.2289</td>
<td>118 42.5562</td>
<td>1210-1215</td>
</tr>
</tbody>
</table>

*OBS was not immediately recovered but was found drifting a few days after the others were retrieved. C9 recorded useful data on line 2 before drifting off, but Line 1 C1 and Line 2 A2 did not.

#OBS failed to record data.
When a range of depths is given, the depth-sounder on the Yellowfin could not provide more accurate readings at these depths.

Land stations (designated by L#) have negative depth. Reftek elevations for stations L4 and L89 are relative to the WGS84 spheroid. At Reftek L89, Geoid is 34.9 m below spheroid, and at L4 -36.3 m, hence these amounts were added to the elevation. Elevations for Stations L1 and L2 were taken off the topographic map.

The premature releases of the OBSs were caused by a manufacturing defect (hydrogen embrittlement) of the plated steel springs, which tie the OBSs to their bottom weight. As a result, springs ruptured spontaneously and the OBS floated to the surface.

**SPECIFICATIONS OF THE USGS OBS**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>width</th>
<th>Height</th>
<th>Weight in air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere and external sensors</td>
<td>0.69 m (27&quot;)</td>
<td>0.97 m (38&quot;)</td>
<td>92 kg (248 lb.)</td>
</tr>
<tr>
<td>at launch (with anchor)</td>
<td>1.02 m (40&quot;)</td>
<td>0.97 m (38&quot;)</td>
<td>119 kg (320 lb.)</td>
</tr>
</tbody>
</table>

**Release**

12.5 kHz Acoustic command with range capabilities.

**Sensors**

3 axis gimbaled 4.5 Hz geophones (Mark Product L-15B) hard mounted inside the sphere, 1 external hydrophone OAS E-2S.

**Recording system**

Continuous digital recording at 100 samples/sec from a pre-programmed start time on 4 channels (3 geophones +1 hydrophone). Data logger - "Tattletale 6" with 1 MByte memory buffer and 200 MByte of hard disk.

**Dynamic range**

72 dB (AD converter) + 30 dB step gain range for each data point.

**Data handling**

Binary with header information for each 1 MByte of data. Data is transferred from the hard disk to an Exabyte tape drive after each deployment via a 486 PC.

**Clock**

Oven crystal oscillator accurate to $10^{-8}$. Oscillators are interfaced with GPS clock for accurate calibration before and after deployment.

**Power supply**

72 Alkaline batteries providing +24 V, +12 V, and -12 V for 10 days deployment.

**SPECIFICATIONS OF THE DALHOUSIE UNIVERSITY OBS**

**Housing/Platform**

Uses existing design of Bedford Inst. of Oceanography OBS with a maximum water depth of 5 km. Weight in air: instrument - 82 kg; anchor - 55 kg. Size - 1.1 m high; 1.2 m long; 0.6 m wide.

**Release**

12.5 kHz Acoustic command + timed backup

**Sensors**
3-component geophone package (oil filled): 4.5 Hz (Mark L-15B; 380 Ohm coil w/ 0.7 damping). Hydrophone (OAS E-2SD)

**Sampling rates / dynamic range**
23, 11.5, 5.7, 2.9, 1.4 milliseconds @ 16 bit (AD7716 Sigma-Delta ADC)

**Gain**
Fixed settings hardware selectable geophones (69-93 dB); hydrophone (46-70 dB)

**Data storage**
2 Mb RAM stored as separate files on 540 Mb Connor HD w/ OTAK adapter to TT7. Capable of recording 4.6 days @ 5.7344 milliseconds sampling of 4 channels (16 bit). Data is transferred to a 486PC via TT7 parallel interface to AT-DIO-24 (100 kbyte/s).

**Clock**
Austron 1115 OCXO 5 MHz (drift<1 milliseconds/day)

**Power supply**
4 C-cell lithium (clock). Estimated lifetime >10 days; 12 D-cell NiCad (disk drive); 10+8, D-cell alkaline (analog+digital) acoustic release; 2, 9-volt alkaline (electronics); 4+4, 9-volt alkaline (pinger+release).

**COMMENTS ON DATA COLLECTED BY DALHOUSIE OBS**

(1) Data was separated into separate files for the following OBS and lines: OBS C_: Line 01 (complete), 01R (complete), 10X (complete); OBS A_: Line 01 (complete), 01R (shots 105-610 only); OBS D_: Line 02R (complete), 02X (shots 101-1100 only); OBS C_: no data. These data have also been archived by Dr. Keith Louden, Dalhousie University in Halifax, Nova Scotia. Data length for each trace is 30 sec beginning at the time of the shot, but Dr. Louden can produce longer data lengths upon request.

(2) Data were slightly clipped for very close shots. Some traces have small dc-biases.

(3) In converting from the internal OBS data files to SEGY, there are few (5-10) missing shots. If a shot occurred while the data logger was writing to the hard disk, the shot would not have been recorded. Corrected files with gaps inserted in the proper offsets will be available shortly upon request from the senior author.

**DATA FORMAT**

Trace header format on SEGY files of all OBS files are as follows:

- Byte position 1 = trace # (a number from 1 to the # traces in the file).
- Byte position 5 = trace # as above.
- Byte position 9 = shot # (from navigation data).
- Byte position 13 = channel # (1 = vertical geophone, 2 and 3 = horizontal geophones, and 4 = hydrophone).
- Byte position 29 = trace id code (1 for seismic data)
- Byte position 31 = # of vertically stacked traces (1 for 1 trace)
- Byte position 33 = # of horizontally stacked traces (1 for 1 trace)
- Byte position 35 = data use (1 for production)
- Byte position 37 = Shot-receiver offset (Offsets are negative for all shots occurring south of each OBS location and positive for all shots occurring north of each OBS location)
Byte position 41 = receiver elevation (negative value of the OBS depth)
Byte position 65 = water depth of receiver (OBS depth)
Byte position 73 = source longitude (in seconds)
Byte position 77 = source latitude (in seconds)
Byte position 81 = OBS longitude (in seconds)
Byte position 85 = OBS latitude (in seconds)
Byte position 89 = coordinate units (2 for seconds of arc)
Byte position 109 = delay recording time (0 in this case)
Byte position 115 = # samples in this trace
Byte position 117 = sample interval (in microsecs, e.g., 10,000 or 5,733)
Byte position 119 = gain type (1 for fixed)
Byte position 125 = correlated (1 for not correlated)
Byte position 141 = alias filter frequency (in hertz)
Byte position 143 = alias filter slope (dB/octave)
Byte position 157 = year of shot
Byte position 159 = day of year (Julian)
Byte position 161 = hour of day
Byte position 163 = minute
Byte position 165 = second
Byte position 167 = time basis code (2 for GMT - GMT used for all time references)
Byte position 169 = trace weighting factor (data values are recorded with the least significant bit corresponding to 10's of microvolts for a weight factor of 14)
Byte position 181 = milliseconds of the shot time

The following header locations were mapped, when the SEGY tapes were read into the Promax 5.1 software:
Byte position 53 = receiver elevation
Byte position 81 = receiver longitude
Byte position 85 = receiver latitude
Byte position 155 = OBS Channel number (1-4).

The Ewing's navigation files in ASCII text have the following format:

94 286 18:49:17.73600101 N 33 38.1910 W -118 07.0551 LA01:

where yr - year, JD - Julian day.

RECORD SECTIONS

We present wide-angle seismic sections recorded by the instruments listed in Table 2 for Line 1 (Figures 3-11) and Line 2 (Figures 13-21). The sections were recorded by the vertical geophone of the OBSs (channel 1) and of the land seismometers (PASSCAL Reftek). For the OBSs, data from channel 4 (hydrophone) may have slightly higher frequency content at small offset than channel 1, but their amplitudes decay more rapidly with offset. The quality of data from channels 2 and 3 (horizontal geophones) is generally poor. Denser data (every 50 m) were recorded by all instruments during other passes of the ship over the profiles (Lines 01R, 01X, 01Y, 02X, 02Y), but the data are similar in quality to the data presented here.

We also include seismic reflection profiles for these two lines on which we annotated locations of the OBSs and the projected locations of the land instruments. The MCS data for Line 01 (Figure 12) are a brute stack (courtesy of Kim Klitgord, USGS). The profile for Line 02 (Figure 22) is a single-channel monitor extracted aboard the R/V Ewing from channel 150, which is 412.5 m behind the center of the airgun array.
The processing sequence for the record sections presented in Figures 3-11 and 13-21 is as follows:

- Reading SEGY tape
- Modification of header location definition
- Linear Moveout correction at 6 km/s (except for Reftek data)
- Trace DC removal
- Minimum phase spiking deconvolution
- Butterworth band pass filter 1-3-15-18 Hz
- 2-D spatial filter over 3 traces and 3 time samples (The weight of the filtered sample is double that of the surrounding 9 samples)
- Trace equalization
- Automatic gain control with a 500 milliseconds window
- Wiggle trace and variable area plot with a section gain of 90 and a clip of 140

DATA REPOSITORY

Data are available for all four channels of each OBS for the lines listed in Table 2. Please contact the senior author at tel. 508-457-2396. Additional copies reside at the USGS in Menlo Park (with Dr. Gary Fuis, tel. 415-329-4758) and at the Southern California Earthquake Center (with Dr. David Okaya, tel. 213-740-7452). Data from the Dalhousie instruments are also available from Dalhousie University (Dr. Keith Louden, tel. 902-424-3557).

REFERENCES


ACKNOWLEDGMENTS

We thank Captain Jim Cvitanovich and the crew of the R/V Yellowfin for their excellent work and for their hospitality during the cruise. We thank Don Newman, Southern California Marine Institute, for coordinating the marine operation. Greg Miller, Dave Foster, and Robert Iuliucci were responsible for the successful operation of the OBS. Gary Fuis, Dave Okaya, Rob Clayton, and Tom Henyey helped coordinate our activities with the land-based wide-angle recording. David Okaya and Joyjeet Bhomik reduced the land seismometer data and Kim Klitgord provided the brute stack profile of Line 01. Dann Blackwood and Jeff Zwinakis reduced the seismic sections photographically. Debbie Hutchinson and Bob Bohannon provided useful reviews of this report.

This work was supported by the National Earthquake Hazards Reduction Program, the USGS Marine and Coastal Program, the National Science Foundation, and the Southern California Earthquake Center.
Line 01 OBS C

Reduced time (T - X / 6.0) in seconds

Shot-Receiver offset in kilometers
Reduced time \( T - \frac{X}{6.0} \) in seconds

Figure 8.
Two-way time in seconds

Location of seismometers

Catalina Fault

Line 01r MCS REFLECTION

Scale in kilometers

Two-way time in seconds
Reduced time $(T - X/6.0)$ in seconds