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AIR-GUN DATA ACQUIRED AT ONSHORE STATIONS DURING THE LOS ANGELES REGION EXPERIMENT (LARSE) 1994

Submitted By

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ABSTRACT

This report describes the acquisition and reduction of deep-crustal onshore-offshore seismic refraction/wide-angle reflection data in the Inner California Borderland-Los Angeles metropolitan region, conducted in October 1994 as part of the Los Angeles Regional Seismic Experiment (LARSE). LARSE is a cooperative study of the crustal structure of southern California involving earth scientists from the U.S. Geological Survey (USGS), California Institute of Technology (Caltech), the University of Southern California (USC), the University of California Los Angeles (UCLA), and other institutions of the Southern California Earthquake Center (SCEC). During LARSE, the R/V *Ewing*'s 20-element air gun array, totaling 137.7 liters (8470 cu. in.), was primarily used as a seismic source for wide-angle recording along three main onshore-offshore lines centered on the Los Angeles basin and the epicenters of the 1933 Long Beach and 1994 Northridge earthquakes. The LARSE onshore-offshore lines were each 200-250 km long, with the offshore source lines being between 90 and 150 km long. The 22,128 air gun signals generated by the *Ewing* were recorded by an array of 174 PASSCAL Reftek recorders deployed at 2 km intervals along all three of the onshore lines and 9 ocean bottom seismometers (OBSs) deployed along two of the lines. The *Ewing*'s 4.2-km, 160-channel, digital streamer was also used to record approximately 1250 km of 40-fold multichannel seismic-reflection data.

To enhance the fold of the wide-angle data recorded onshore, mitigating against cultural and wind noise in the Los Angeles basin, the entire ship track was repeated at least once resulting in fewer than about 660 km of unique trackline coverage in the Inner Borderland. Portions of the seismic-reflection lines were repeated up to 6 times. The marine air-gun signals were recorded by portable land recorders which were deployed in continuous recording mode. With the use of accurate GPS timing at both sources and receivers, seismograms were extracted from the continuously recorded data. In this report, we describe the equipment and procedures used to acquire the onshore-offshore seismic refraction/wide angle reflection data, discuss the reduction of the data, and present reduced travel-time seismic sections of the acquired common-station-gather profiles. A more complete description of the marine seismic data collected by the *Ewing* is available in Brocher et al. (1995) and ten Brink et al. (1996). A third portion of the full LARSE experiment involved onland explosive sources collected by onland portable recorders which is described in Murphy et al. (1996). Local earthquakes which occurred during the acquisition of the air-gun data are described in Okaya et al. (1996). A separate LARSE experiment in 1993 to collect earthquakes over a several week period along Line 1 is described in Kohler et al. (1996).

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INTRODUCTION

The seismic earthquake hazards posed by blind thrust faults in southern California have been reported by a number of investigators (Stein and King, 1984; Stein and Yeats, 1989; Wright, 1991; Crouch and Suppe, 1993; Davis and Namson, 1994; Shaw and Suppe, 1994; Shaw et al., 1994). Crustal seismic reflection and refraction/wide angle reflection methods are valuable and necessary tools for imaging the structural framework associated with blind thrusts, and can provide constraints for large-scale balanced crustal cross sections used to map thrust ramps in the subsurface. Both the damaging 1971 M_L 6.4 San Fernando and 1994 M 6.7 Northridge earthquakes occurred on blind thrusts (U.S. Geological Survey and the Southern California Earthquake Center, 1994). The damaging 1987 M 5.9 Whittier Narrows earthquake (Hauksson et al., 1988) was also on a blind thrust fault.

This report describes the collection of refraction/wide-angle reflection (R/WAR) profiles in the metropolitan Los Angeles region as part of the Los Angeles Regional Seismic Experiment (LARSE). LARSE is a cooperative study of the crustal structure of southern California involving scientists from the U.S. Geological Survey (USGS), California Institute of Technology (Caltech), the University of Southern California (USC), the University of California Los Angeles (UCLA), and other institutions of the Southern California Earthquake Center (SCEC). Seismic refraction/ wide-angle reflection profiling in the greater Los Angeles area, conducted during 13-21 October, 1994, used the R/V *Ewing*'s 137.7 liter (8470 cu. in) air gun array and onland IRIS/ PASSCAL portable seismic recorders. The R/V *Ewing* fired 22,128 air gun shots into 174 land-based stations which were subdivided into three major land arrays (Lines 1-3, Fig. 1a) during the LARSE work.

At the heart of LARSE was the collection of three long onshore-offshore transects involving sources along marine Lines 1 to 3 which provided air gun signals for land recorders deployed as inline land arrays (Figure 1A). R/WAR Line 1 involved marine sources trending NNE-SSW from the center of San Clemente Island through Seal Beach, the Los Angeles basin, San Gabriel Mts., and the Mojave Desert, passing near the epicenters of the 1933 M 6.3 Long

Beach, 1987 M 5.9 Whittier Narrows, and 1991 M 5.8 Sierra Madre earthquakes. Line 2 involved sources trending N-S along the western shores of San Clemente and Santa Catalina Islands through the Santa Monica Mts., west San Fernando Valley, San Gabriel Mts, and the Mojave Desert, passing through the 1994 Northridge earthquake epicenter. Marine sources for Line 3 trending ENE-WSW from northwest of San Nicolas Island crossed the center of Los Angeles basin (Wright, 1991). These three major R/WAR lines provide a regional reconnaissance of the crustal structure centered on the Los Angeles basin; in addition they provide specific information about the crustal structure in the vicinity of four recent, damaging earthquakes in the greater Los Angeles region. Special care was taken to acquire large segments of these lines late at night (2300 L to 0500 L) (all local times given herein are Pacific Standard Time), causing us to repeat parts of Lines 1 and 2 up to 5 times (Figures 2A and 2B). The planned ship track was altered throughout the cruise in order to maximize the acquisition of onshore-offshore data during late-night hours.

Line 1 (Fig. 1a). was the major focus of LARSE, extending through Seal Beach, the Whittier (Puente) Hills, San Gabriel River Canyon, Mescal Creek, El Mirage Lake, and Harper's Lake. Line 2 extended from Malibu through the western San Fernando Valley (1994 Northridge earthquake epicenter) into the western Antelope Valley of the Mojave desert. Line 3 extended from El Segundo to Redlands as an east-west cross line to the other transects. All three land arrays required a total of 174 stations. Portable instruments capable of recording continuously were deployed at the stations. Vertical component (4-1/2 Hz) sensors were attached to the portable instruments. The stations were operated and maintained for seven days, requiring two sets of service runs. Data were retrieved at the end of the acquisition period by returning the instruments to the instrument center based in Glendora, California where the data were downloaded to archive 8-mm cartridge tape. Data reduction was conducted at USC and at Caltech after the completion of the field experiment.

The R/V *Ewing* acquired at the same time several deep-crustal seismic-reflection profiles on the continental shelf of the Inner California Borderland, in the vicinity of Los Angeles, stretching from the 32°38'N to 34°N and from 119°45'W to 117°40'W (Figure 1b). A more complete description of the marine acquisition is available in Brocher et al. (1995) and ten Brink et al. (1996)

DATA ACQUISITION

The track of the R/V of *Ewing* is subdivided into sixteen ship-track lines (Table A). The ship tracks involved multiple passes along the three lines (Table B). Differing numbers of air-gun shots and line lengths characterize these ship tracks (Brocher et al., 1995) All air-gun shots were recorded by the land-based portable recorders.

Instrumentation on the R/V *Ewing* for Sources

Multichannel seismic-reflection profiling on the *Ewing* was performed using a 20-element, 137.7 liter (8470 cu. in.) air-gun array and a 160-channel, 4.2-km-long digital Digicon streamer. The air-gun array, composed of Bolt air guns, was generally towed at depths between 8 and 10 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 (Brocher et al., 1995).

Air-gun shot times recorded in the navigation files were from the air-gun fire command time determined from a Magnavox GPS clock. The Magnavox Global Positioning Satellite (GPS) receiver for the ship was located above the ship's bridge about 47.8 m forward of the stern of the ship, roughly 87.4 m forward of the center of the air gun array. Given jitter in the air-gun firing times (less than a millisecond), these shot times are considered accurate to within a millisecond. The air guns were generally fired during turns to permit the onshore recording of the air-gun signals; air guns were shut off only when turning within the 3-mile California State limit.

Navigation on the *Ewing* was based on redundant Magnavox GPS receivers operated in selected availability mode: the GPS locations were smoothed over a ten-minute window and updated using the Furuno course and speed log. This navigation was written to a separate 3480 cartridge tape and is estimated to be accurate to within 25 meters.

Files containing air-gun origin times and final air-gun locations were sent from the *Ewing* via e-mail to all LARSE investigators on a daily basis (Table C). These origin times were used to examine the quality of data recorded onshore by the three deployments of Refteks. The reduction and playback of wide-angle data during the field experiment were instrumental in the decision to repeat Line 1 numerous times to insure that this line was recorded during late-night hours when onshore noise conditions were lower within the Los Angeles basin. Communications with both land- and shore-based LARSE personnel was generally achieved using cellular phones.

Lines 1-3

Line 1, between Seal Beach and the northern Mojave Desert, had 86 land stations including two stations each on Santa Catalina and San Clemente Islands. Line 2, between Malibu and the western Antelope Valley, had 47 stations, and Line 3, east-west through the Los Angeles basin, had 41 stations (Fig. 1a). Location coordinates with ±10 m accuracy were obtained by differential GPS surveying. Tables D, E, and F provide latitude/longitude and UTM coordinates for seismographs in Lines 1, 2, and 3, respectively. Table G describes the station numbering convention for all three lines.

Instrumentation for the Land Arrays

The ability to collect onshore-offshore seismic data using marine air-guns is predicated on the use of seismic instruments capable of collecting large volumes of data via continuous recording. Sufficient PASSCAL Reftek instruments were made available by the Incorporated Research Institutions for Seismology (IRIS). These instruments were able to collect several days of continuous data at high sample rates. The LARSE experiment used a total of 215 Reftek instruments assembled from the following organizations: IRIS/PASSCAL (182), Southern California Earthquake Center (18), Los Alamos National Laboratory (5), and the University of Texas at El Paso (10). These instruments had a variety of specifications which are summarized in Table H.

Recording Instrumentation and Timing

The Refteks were deployed in continuous-mode acquisition. In-field instrument data capacity was a major constraining factor given the anticipated seven days of *Ewing* air-gun source time. Only the vertical components of the L-28 (4.5-Hz) sensors were recorded. The sampling rate was 10 msec (100 sps), for a Nyquist frequency of 50 Hz. Data compression in the instrument was employed. The instruments in general had sufficient storage capacity to collect the entire set of ship sources.

Power for the instruments was provided by large-capacity car batteries (110 amp-hr), sufficient to last the entire field deployment. Field checking was conducted to replace batteries as necessary.

Accurate timing was provided using the Global Positioning System (GPS). Fifty-seven instruments had internal GPS units. Additional instruments had external GPS units attached for the duration of the experiment. The clocks of the remaining instruments were set upon initial deployment, during site visits, and upon instrument retrieval.

Land Field Operations

The deployment, maintenance, and retrieval of the three land arrays were conducted by the USGS, USC, University of Texas El Paso (UTEP), and Caltech personnel. These activities were performed in coordination with the R/V *Ewing*'s activities.

The deployment of the three lines was conducted in the two days immediately prior of the departure of the *Ewing* from the port of Long Beach (Table J). The USGS and USC deployed 86 stations on Line 1. The USGS and UTEP deployed 47 stations in Line 2. Caltech deployed the 41 stations in Line 3. The instruments with attached GPS were programmed to start on the first day of *Ewing* air-gun shooting; instruments with no attached GPS were started immediately upon installation. The *Ewing* traversed line 01 (Fig. 2a) without the MCS streamer, firing the air-guns every 60 seconds, in order to avoid signal overlap at the ocean-bottom seismographs (OBS's). At San Clemente Island, the streamer was deployed and Lines 01R, 01X, 01Y were shot with a shot interval of 20 seconds (Tables A, B), lines 3 (03, 03R) and 2 (02, 02R, 02X, 02Y, 02Z) were shot with transit lines in between (TR1, TR2) (Tables A, B; Fig. 2a, 2b). Finally, due to poor acquisition conditions during most passes on Line 1, including wind and daytime recording for all but line 1Y (one half of the offshore part of Line 1), Line 1 was reshot (lines 1A, 1B; Tables A, B; Fig. 2a). Land recorders were serviced approximately twice each during the 8 days of air-gun shooting.

Data Archival

Data were transferred from the Reftek instruments to archive 8-mm cartridge tapes using SUN computer workstations located at the field center in Glendora, California. Four workstations were configured with PASSCAL software and 8-mm cartridge tape drives. A dozen persons were employed over a 1-1/2 day period to perform the data transfer. The data were transferred to the field tapes in Reftek field format for subsequent translation and reduction to be conducted after the completion of the field experiment.

DATA REDUCTION

Organization of Data: Two Data Products

The LARSE data were first reduced as common-receiver-gathers (CRGs)--one for each land station, each containing as many as 22,128 seismograms, representing shots on all 16 shiptracks (Tables A, D). This set of data is termed "Product 1".

Although organizationally simple, Product 1 is unwieldy if used for the analysis of any one ship track. The data were next resorted by the 16 individual ship tracks. This set of data is termed "Product 2". A more complete description of both products is provided below and in Tables L through N.

Data Reduction

The data reduction steps are illustrated in Fig. 3. The data were originally collected in continuous mode in 10-minute time windows. An amplitude debias and instrument timing (clock drift) corrections were applied to each time window. Individual seismograms were then extracted from the entire set of data windows using the air-gun shot times provided by the *Ewing*. UTM coordinates were obtained from the source and receiver latitude/longitude values; the WGS-84 spheroid and UTM zone 11 were used in the calculations. Using the source-receiver offset computed from the UTM values, a reduced travel-time correction (linear moveout) of 6.0 km/s was applied to each seismogram. Product-1 CRGs were produced in SEG-Y format followed by a resort of the data into Product-2 CRGs.

In order to reduce such a large volume of data in an efficient manner, new software was created at USC which was compatible with software provided by IRIS/PASSCAL. Table K describes this software in more detail.

Product One: Common Receiver Gathers

The CRGs for Product 1 contain the entire data set in its simplest form. For any station in Lines 1-3 , the entire set of seismograms produced by all 22,128 *Ewing* air-gun shots are contained in the station's CRG. Table L describes the internal characteristics of a CRG and describes which seismograms are associated with which ship tracks.

Product 1 consists of seismograms in SEG-Y format. Each seismogram is 30 sec in length (3000 samples at 10 msec sampling). Since the data is reduced by 6.0 km/sec, $t_{reduced} = 0$ is at sample 500 so that the first sample in the seismogram is at $t_{reduced} = -5.0$ sec (actually, $t_{reduced} = -4.990$ sec). The last sample of the data is at $t_{reduced} = 25.0$ sec. The ship and recorder locations in both latitude/longitude and UTM coordinates are saved in the trace headers. The source-receiver offset used in the reduced travel-time correction as well as the actual time shift (i.e., $\Delta t = \text{offset}/6 \text{ km s}^{-1}$) are also saved in the trace headers (see Table N).

There were a total of 174 gathers in Lines 1-3. These gathers are numbered in sequential order as 1-86 for Line 1 (south to north), 87-133 for Line 2 (south to north), and 134-174 for Line 3 (west to east). Gathers 1 and 2 arefrom stations located on San Clemente Island (south to north); and gathers 3 and 4 from Santa Catalina Island (south to north). Tables D, E, F, and L provide the assignment of cumulative gather numbers for all three lines.

Due to the deployment of two separate instruments at stations 08 and 32 (Line 1), there is an organizational difference between a "common-receiver gather" (CRG) and a "common station gather" (CSG). There are 174 unique CRGs whereas there are 172 CSGs. These numbers are stored in the SEG-Y trace headers as separate values.

Product Two: Common Receiver Gathers by Ship Track

The large number of seismograms/CRG in Product 1 makes Product 1 unwieldly. For example, in order to extract seismograms for ship track #1 (Line 01, Table A), seismograms 1-653 must be winnowed from the CRG. In order to obtain Line 01 for all stations, all 174 CRGs must be read. One must sort through the 25 8-mm cartridge tapes of Product 1 in order to access all 174 CRGs for a single ship track. Product 2 represents such a sort.

Description of SEG-Y Headers in Data Archive

Many of the pertinent parameters which describe the data or the LARSE field parameters are contained in the SEG-Y trace headers of both Products 1 and 2. Table N provides a full list of the SEG-Y trace headers and identifies in bold-formatted text which headers contain values specific to the LARSE experiment. Certain SEG-Y header fields were redefined in order to store such experiment-specific information These redefinitions were chosen to be consistent with the IRIS/PASSCAL and IASPEI versions of SEG-Y. LARSE-specific information includes air-gun source depth, source time, source shot-point number, source location (in both latitude/longitude and UTM coordinates), station stake number, station location (latitude/longitude and UTM), Line number (1-3), instrument number, instrument type, and sensor type. Data-reduction parameters include clock-correction time shifts, reduced travel-time shifts, reducing velocity, and instrument amplitude debias. Data-format values include number of samples in the seismogram and time of first sample the reduced travel time correction. Data indexing values include CRG # (1-174), CRG # within the Lines 1 (1-86), Line2 (1-47), and Line 3 (1-41), seismogram # within the CRG, ship track number, seismogram # within the ship track, and common-station gather # (CSG).

The source and receiver coordinates and elevations, whether in degrees or UTM coordinates are provided relative to the WGS-84 spheroid, the spheroid used in the reduction of the GPS survey data.

DESCRIPTION OF THE DATA

The onshore-offshore data vary in quality based on the following factors: time of acquisition (day or night), prevailing weather conditions, proximity to noise sources in the Los Angeles region (freeways, machinery), near surface conditions, and gross geology under the receiver sites (e.g., sedimentary rocks, basement rocks). The *Ewing* air-gun sources in general were sufficient to propagate as far as 200+ km.

Due to the continuous sources by the *Ewing* and continuous recording on Lines 1-3, the data includes not only 2-D inline profiles (Product 2) but 3-D cross-line profiles (Product 1) (Figure 1). Fig.4 illustrates the 3-D behavior of the source-receiver geometry for all three lines. In each figure, the source-receiver offset distance is divided by 6 km/s in order to plot the nominal arrival time of the Pg phase for all *Ewing* sources at each station in a given line. Water depth, basin sediments, receiver elevations, etc. will, of course, affect actual arrival times.

When the *Ewing* was moving radially toward/away to the station (i.e., inline to the station's array), strong linear moveout is visible. When the *Ewing* was moving in a more oblique to transverse direction, the source-receiver distance changed less rapidly as did the arrival time. Because the *Ewing* collected Lines 03 and 03R by sailing away from the coastline at El Segundo then doubling back on its track, the Pg traveltime curves for these two lines have a symmetric appearance. However, since the traveltime is plotted as a function of shot number, when the

Ewing source interval changed (e.g., line 01 to line 01R and line 02 to line 02R), resulting norminal Pg arrival times are asymmetric (Fig. 4). (Note: offset/ 6 kms^{-1} is plotted in Fig. 4; whereas actual traveltime minus offset/6 kms^{-1} is plotted in Product 1).

The nominal Pg arrival-time plot of Fig. 4 can aid in the identification of phases PmP and Pn as well as Pg. For example, PmP is likely to be most visible when the source-receiver distance is near the distance for critical Moho reflection; thus, one would look within a specific window of arrival time. Pn will appear as a first arrival only beyond the crossover distance, and one would look within another window of arrival time

Representative portions of each of the 174 CRGs are displayed in the Appendix. For the CRG at each station, a portion of the sources which are inline to the station's array is displayed. For Line 1 (stations 1-86), *Ewing* Lines 1Y and 1B are shown. For Line 2 (stations 87-133), Line 02 is shown and for Line 3 (stations 134-174), Line 03 is shown. The variations in data quality are observable.

In general, Pg is visible in most CRGs except those in the heart of the Los Angeles basin and San Gabriel and San Fernando valleys. The PmP phase is observable in the offset ranges of 60-100 km. Beyond this offset distance, a Pn arrival can be seen at selected stations.

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