PACE89

DATA REPORT FOR THE PACE 1989 SEISMIC REFRACTION SURVEY, NORTHERN ARIZONA

Submitted by
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1994

PASSCAL Data Report 94-013

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INTRODUCTION

In 1985 the U.S. Geological Survey (USGS) initiated a multi-disciplinary program to study the geologic and tectonic evolution of the southwestern United States. This study, referred to as the Pacific to Arizona Crustal Experiment (PACE), extends from San Diego, California, to Flagstaff, Arizona, and includes a wide range of geophysical and geologic studies such as gravity, magnetics, geochronology, tomography, field mapping, and paleomagnetics. Central to the PACE program has been the use of seismic refraction methods to constrain crustal thickness, rock composition, and crustal structure. The seismic refraction studies were initiated in 1985 mid-way along the PACE transect (Wilson and Fuis, 1987) and were extended to the northeast across the Transition Zone in 1987 (Larkin and others, 1988). The results of these studies have been integrated into a model of the crustal structure from the unextended Colorado Plateau to the highly extended metamorphic core complex belt (McCarthy and others, 1991; Wilson and others, 1991).

In September of 1989 the USGS, in conjunction with the University of Texas at El Paso, the University of Saskatchewan, the University of Arizona, the Air Force Geophysics Laboratory, Stanford University, and the Geological Survey of Canada, conducted a third seismic refraction experiment across the northeastern Transition Zone and the southwestern margin of the Colorado Plateau. When merged with the earlier PACE refraction profiles, the combined data set provides a complete transect from the highly extended metamorphic core complexes to the unextended Colorado Plateau (Fig. 1). This report describes the field operations for this 1989 PACE experiment and the types of data acquired.

GEOLOGIC BACKGROUND

The Colorado Plateau is a major tectonic and physiographic province in the southwestern United States that has behaved as a relatively stable, coherent block during much of the Phanerozoic (e.g., Lucchitta, 1989). A site of marine deposition during the Cretaceous, the Colorado Plateau now stands about 2 km above sea level and is actively deforming, as evidenced by earthquakes along its margins. Unlike the Basin and Range province and Rio Grande rift which have experienced approximately 1 km of uplift while simultaneously undergoing horizontal extension and internal deformation, the Plateau has remained a relatively rigid block, resistant to faulting and deformation. The greatest amount of uplift has been along the southwestern margin of the Plateau, where elevations are often 0.5 km greater than in the center.

Several mechanisms have been proposed to account for the recent uplift of the Colorado Plateau, including thermal expansion, crustal thickening, and delamination of the lithosphere. In order to evaluate each of these processes, however, the structure and thickness of the crust beneath the Plateau and the velocity structure of the upper mantle must be determined. The surface elevation is dependent on both the density and the thickness of the lithosphere, of which the crust is the buoyant component (e.g., Lachenbruch and Morgan, 1990). The thickness and average density (estimated from the average velocity) of the Plateau crust must thus be known in order to evaluate the thickness of the mantle portion of the lithosphere. Furthermore, because thermal expansion and crustal thickening via magmatism may

PACE: Pacific to Arizona Crustal Experiment

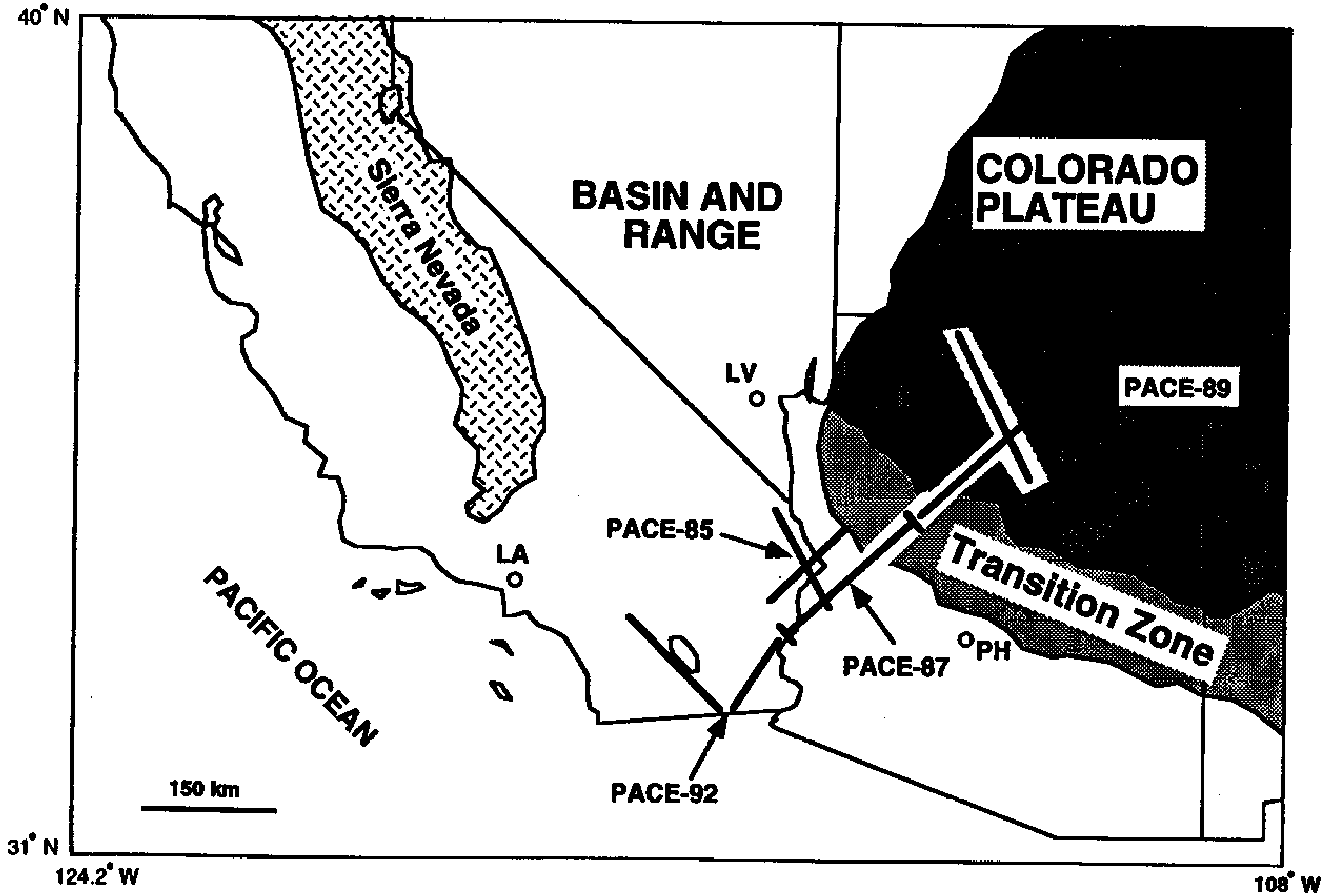

Figure 1. Location of the various PACE refraction experiments in southern California and Arizona. Two perpendicular profiles were collected in 1985 in southeastern most California, a single profile was collected in 1987 across western Arizona, and two perpendicular profiles were collected in both 1989 and 1992 to extend the transect northeast across the Colorado Plateau and southwest to the Salton Sea, respectively. Symbols used: LA, Los Angeles; LV, Los Vegas; PH, Phoenix.

contribute to the present elevations, the temperature conditions in the upper mantle must also be evaluated. The Pn velocity structure, obtained from refraction studies and from teleseismic studies (Beghoul and Barazangi, 1989), will bear directly on the question of the thermal state of the upper mantle and will permit a direct comparison between the upper-mantle lithosphere beneath the Basin and Range province, the Colorado Plateau, and the Great Plains.

The 1989 PACE seismic refraction experiment was designed to measure the crustal thickness at the southwestern margin of the Colorado Plateau. When combined with topography, gravity, heat flow, and seismicity, these results can then be used to constrain the mechanisms responsible for uplift. The seismic data acquired in this study are currently being analyzed. For initial results the reader is referred to: Benz and others (1990); Benz and McCarthy (in press); Howie (1991); Howie and others (1991); Parsons and others (1992); Johnson and Hartman (1991); Kohler and McCarthy (1990); McCarthy and Parsons (in press); Parsons and McCarthy (submitted), and Wolf and Cipar (1993).

DESCRIPTION OF SURVEY

Two refraction/wide-angle reflection profiles were acquired during the 1989 PACE experiment. The first profile, referred to as the Colorado Plateau profile (Fig. 2), was oriented NE-SW and extended 150 km from the northeastern end of the 1987 PACE study across Chino Valley, Arizona, to the western edge of the Navajo Indian Reservation, near Cameron, Arizona. This profile crossed the northeastern half of the Transition Zone and the southwestern margin of the Colorado Plateau. In addition to constraining crustal thickness and upper-mantle velocity, the study was designed to delineate structures in the crust associated with the transition from the unextended Colorado Plateau to the extended Basin and Range province.

The second refraction profile, referred to as the Grand Canyon profile (Fig. 3), was oriented NW-SE and was situated strictly within the Colorado Plateau physiographic province. This profile was positioned as far inboard into the Plateau as possible so as to constrain crustal thickness while avoiding the Plateau margin, where extensional processes may have modified crustal structure. The Grand Canyon profile also intersects the northeastern portion of the Colorado Plateau profile and thus provides axial control to the northeastern portion of this line.

In addition to the two main refraction profiles, a suite of independent "piggyback" studies were conducted by several investigators. Each of these studies is described later in this report.

The PACE 1989 experiment was unusual in terms of the collaborative nature of the study. Funding was provided by five principal organizations: the U.S. Geological Survey's Deep Continental Studies Program, the Air Force Geophysics Laboratory (AFGL), the University of Texas at El Paso (through a grant from the AFGL), the Gas Research Institute, and the National Science Foundation. The USGS, AFGL, and the University of Texas at El Paso provided primary funding for the two refraction/wide-angle reflection profiles. The Gas Research Institute, Arco Oil and Gas, and Amoco Production Company provided financial and field support for Stanford during the acquisition phase of the study, while the National Science Foundation provided data analysis support. The National Science Foundation also provided primary support for the acquisition and analysis of the University of Arizona's piggyback study.

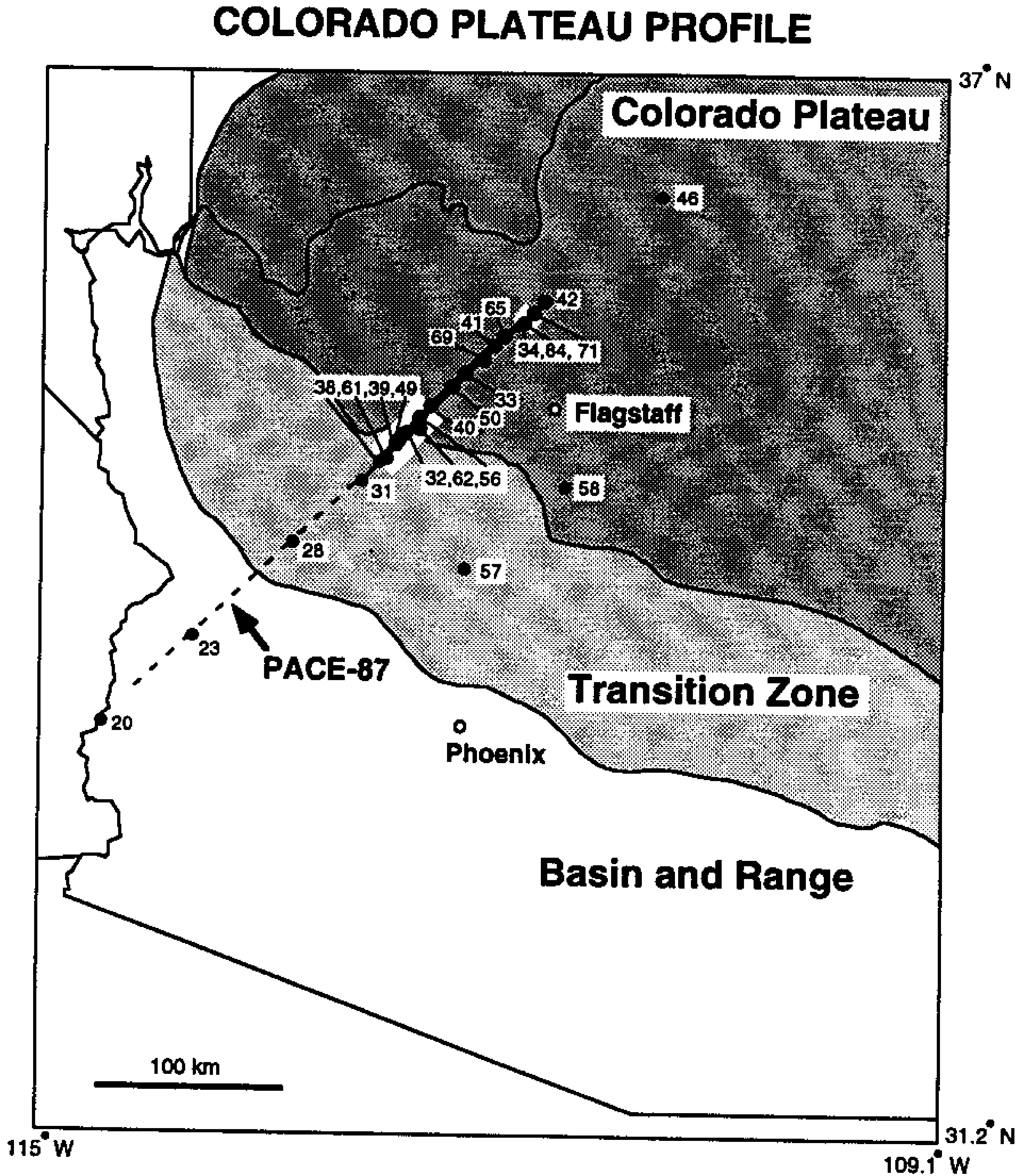

Figure 2a. Location of the PACE 1989Colorado Plateau profile. Black circles mark shotpoint locations; solid black line represents instrument deployment. Dashed line corresponds to location of 1987 PACE instrument deployment. White boxes denote the location of the Stanford (big box) and University of Arizona (small box) piggyback experiments.

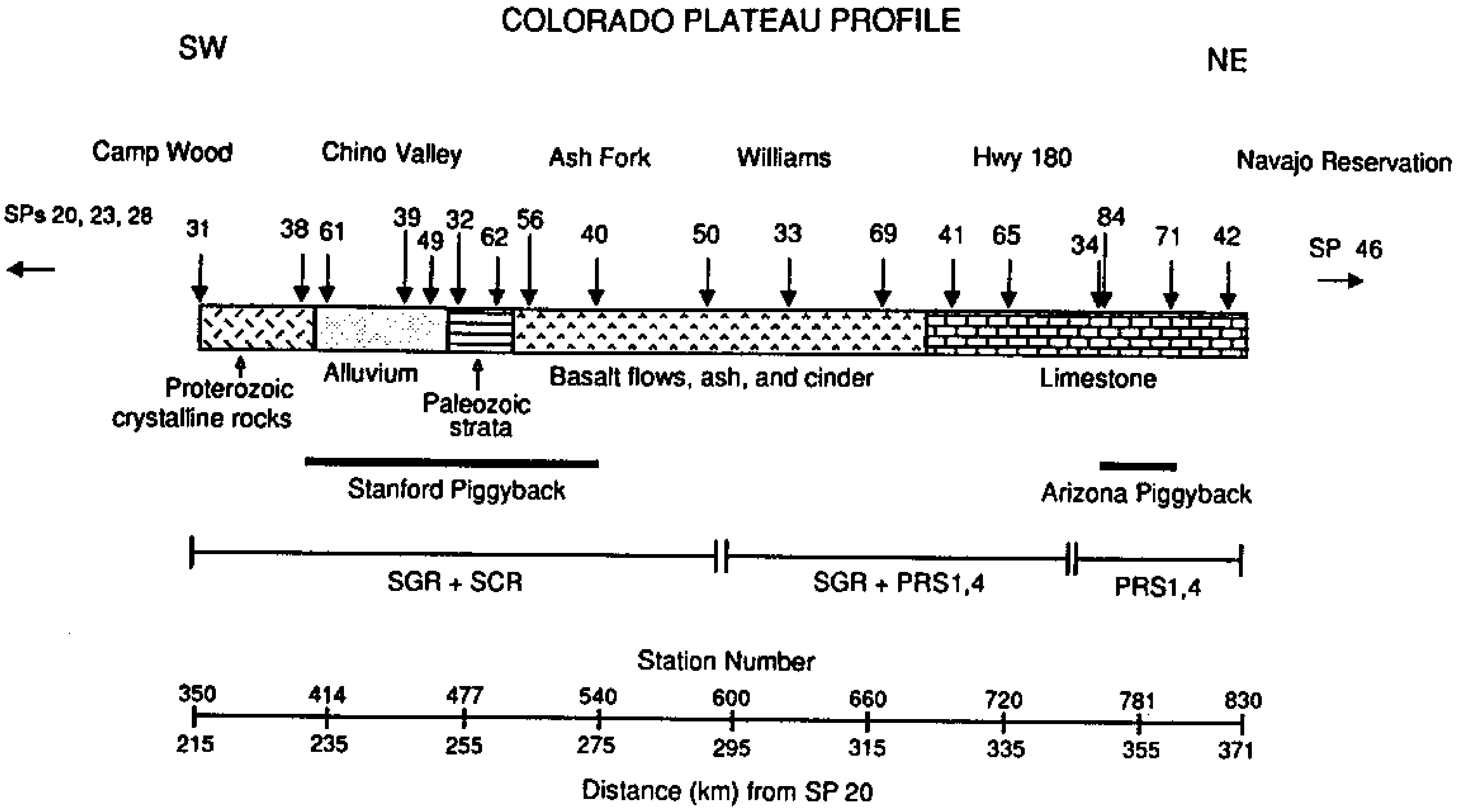

Figure 2b. Schematic diagram showing location of shotpoints (arrows), rock type (patterened squares), and receiver types on the PACE-89 Colorado Plateau Profile. Offset shotpoints are not plotted to scale. Receiver spacing is constant at 0.33 km . SGRs were interleaved with SCRs, PRS1s, and PRS4s to prevent large data gaps in the event of instrument failure. Data quality is affected by both receiver type and local surface geology (see text for more detailed discussion). The Grand Canyon profile intersects the Colorado Plateau profile on the northeast end of the line at SP 71, and the PACE-87 profile intersects the Colorado Plateau profile to the southwest, at SP 31. Location of Stanford University and University of Arizona piggybacks are shown.

The 1989 PACE experiment was also unusual in terms of the number of receiver channels deployed in the field. The USGS provided 120 analog seismic cassette recorders (SCRs), Stanford contributed 192 digital seismic group recorders (SGRs), the University of Texas, in conjunction with the University of Saskatchewan and the Geological Survey of Canada, provided 150 Canadian PRS1s and 13 PRS4s, and the Air Force Geophysics Lab contributed 30 DCS-302 Terra Technology digital cassette seismographs (the latter were deployed in-line on the Grand Canyon Profile only). All totaled, 462 receivers were used to record the Colorado Plateau profile and 490 stations recorded the Grand Canyon profile.

The Colorado Plateau Profile

The Colorado Plateau profile began at the northeastern end of the 1987 PACE profile and continued for 150 km across the northeastern half of the Transition Zone and the southwestern margin of the Colorado Plateau. The average instrument spacing along this profile was 333 m, and the average shot spacing was 10 km. A total of 24 shots were recorded; three of these shots were offset to the southwest of the recording line, one was offset to the northeast, and two were fan shots displaced approximately 80 km southeast of the receiver array (Fig. 2). The shots were detonated over a three-evening period. Locations of shot and receiver sites are listed in Appendixes A and B and are shown in Figure 2. Record-section plots are displayed in Appendix D.

The Grand Canyon Profile

The second refraction profile, referred to as the Grand Canyon profile, was oriented NW-SE and extended 150 km from just north of Flagstaff, Arizona, across the Grand Canyon, to Jacob Lake, Arizona (Fig. 3). This profile was designed both as a reflection profile with tight instrument and shot spacing, and a wide-angle profile with long receiver arrays and large shot-geophone offsets. To accomplish both of these objectives with a limited number of instruments, recorder spacing was varied along the length of the profile (Fig. 3b). At the southeast end of the line instrument spacing was 0.5 km for the first 20 km of the profile and then decreased to 0.1 km. The tight 0.1 km spacing was continued northwest for 35 km, before instrument spacing returned to 0.5 km for an additional 20 km. Across the Canyon, instrument spacing was further increased to 1.5 km. Seven backpackers deployed one instrument each down the south side of the Grand Canyon, while mules were used by the Air Force Geophysics Laboratory to deploy 15 instruments down the north rim. North of the Grand Canyon, 30 instruments were deployed by AFGL personnel at an average spacing of 1.2 km to Jacob Lake.

Shot spacing was also varied along the Grand Canyon profile (Fig. 3). Seven small shots were positioned within the 35-km-long dense, 0.1-km-spaced receiver grid, and an eighth fan shot was located approximately 10 km southwest of the line at the tie with the Colorado Plateau profile. The small, closely spaced shots provided near-vertical-incidence reflection data within the higher-resolution portion of the receiver array. Three larger explosive shots were also fired. Two of these were positioned on the north rim of the Grand Canyon -- one was located at the NW-end of the profile at Jacob Lake, and the other was located just north of the boundary of the Grand Canyon National Park. The third large shot was offset 75 km SE of the profile near Meteor Crater. These three large (3000-4000 lbs.) in-line shots provided the necessary shot-geophone offsets to record refractions and wide-angle reflections

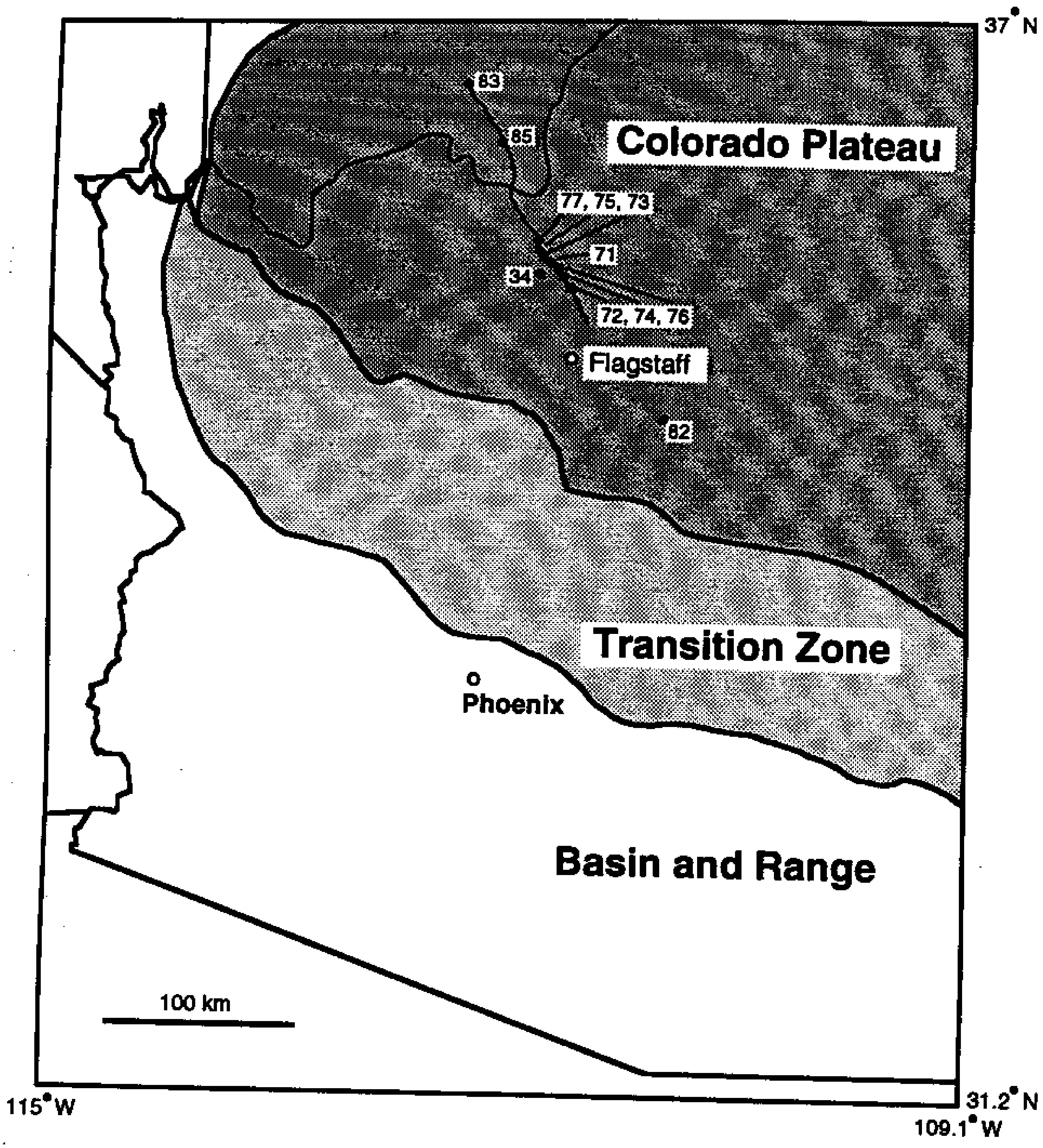
GRAND CANYON PROFILE

Figure 3a. Location of the PACE 1989 Grand Canyon profile. Black circles mark shotpoint locations (numbered); solid black line connecting shotpoints represents the approximate location of the receivers along the profile.

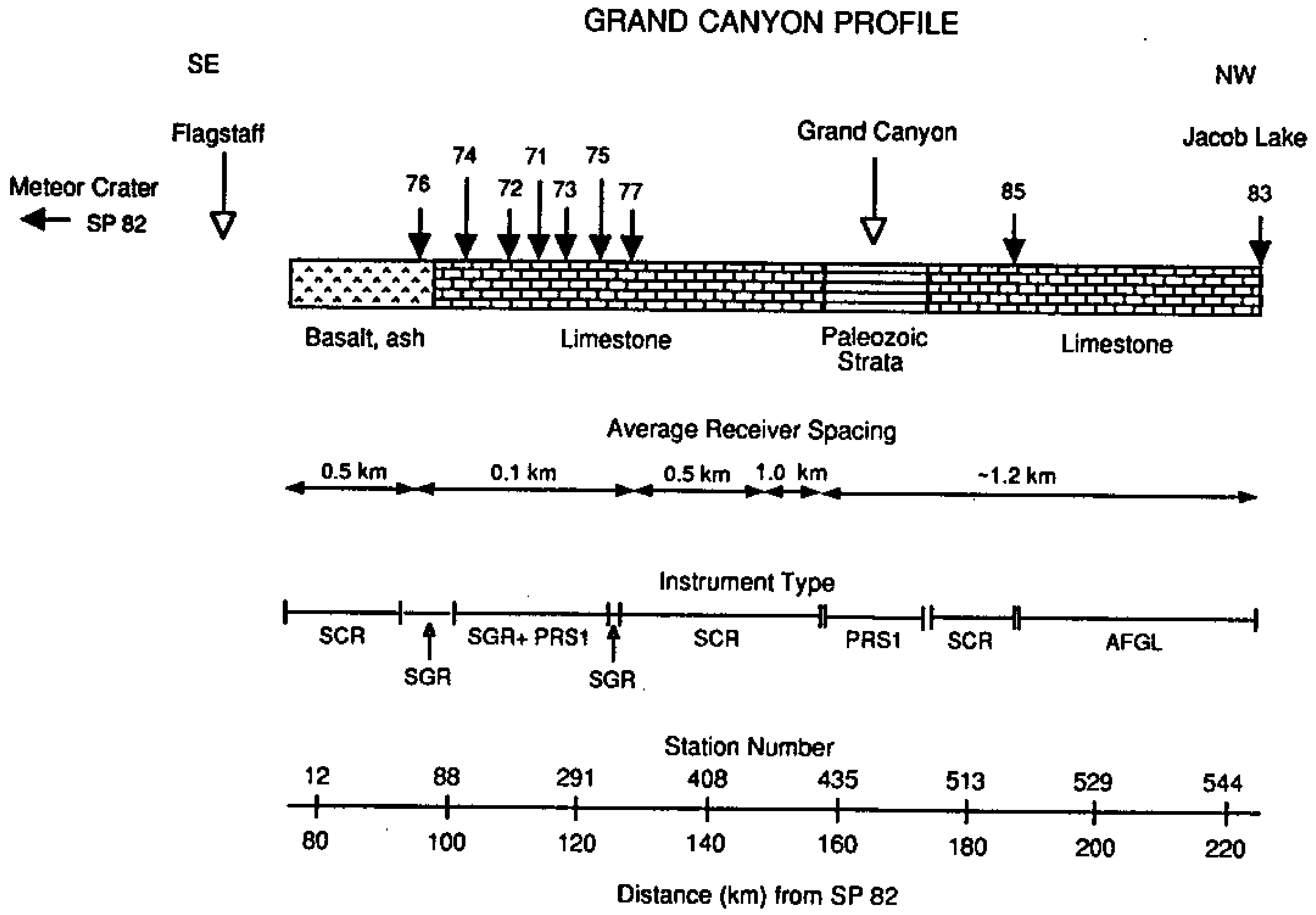

Figure 3b. Schematic diagram showing location of shotpoints (arrows), rock type (patterned squares), and instrument type along the Grand Canyon profile. Variation in receiver spacing is also shown. Note that instruments are spaced every 100 meters between SPs 76 and 77, and every to 1 to 2 km along the remainder of the profile. The location of SP 82 is not shown to scale. The Grand Canyon profile intersects the Colorado Plateau profile at SP 71. See text for details.

from structures deep in the crust. Locations of shot and receiver sites are listed in Appendixes A and B and are shown in Figure 3. Record-section plots are displayed in Appendix D.

A quarry blast from the Peabody Coal Company's Black Mesa mine, located ~150 km northeast of the recording array, was also recorded as a fan by the receiver array. Although energy carried from the shotpoint to the receiver array, the detonation time was not adequately determined, and thus these data have not been included in the data release, nor is the shot listed in the master shot list (Appendix A).

FIELD OPERATIONS

Drilling. Drilling commenced several months prior to the experiment so that the holes would be completed well before the experiment was to begin, and so that all the holes could be loaded in sequence. A total of 53 holes were drilled by Arizona Beeman Drilling Company between May and August of 1989. The holes were 8 inches in diameter and ranged between 100-200 feet in depth. Multiple holes were drilled at locations where larger shots were to be fired. At those sites the holes were perpendicular to the deployment line and spaced approximately 60 feet apart. Casing was necessary at several sites in order to keep the holes from caving in prior to loading.

Loading. Loading began two weeks prior to the experiment. Shot sizes ranged from 1000 to 8000 lbs. of explosives, and no more than 3000 pounds were loaded into an individual hole. Multiple holes were drilled where larger shots were desired. An Alpha Explosive pump truck from Lincoln, California, was used to load most of the holes. Several holes across the Kaibab Plateau were drilled into cavernous limestone and had to be loaded with bagged material from the pump truck to prevent loss through seepage and ground water circulation. A length of 50-grain primer cord with 1-pound cast boosters spaced at 8-foot intervals was lowered to the bottom of the hole. The pump truck pumped the material from the bottom of the hole up until the predetermined amount of explosive was in the hole, usually about 60 feet from the top. The remaining 60 feet was then filled with cuttings from the hole.

Shooting. After each hole was loaded, the primer cord was tied off inside a metal cap that fit over the top of the casing. This cap was then locked onto the casing via steel pipe through holes in the cap and top of the casing. The hole caps secured the hole until the shot was ready to be fired. A few minutes before shot time, an instantaneous detonator (cap) was attached to the primer cord and then to the shot line, which was wired to the shooting system about 500 feet away. The heart of the shooting system was the master clock, which had a minimal drift (< 4 milliseconds per day) and provided the time reference for the entire experiment. (In addition to the shots, the master clocks were also used to time the recording instruments.) Just before the shot time, the shooter charged up the blaster and pushed the fire button. At the shot instant, the master clock sent a pulse that fired the electronic cap and sequentially caused the primer cord, boosters, and blasting agent to detonate. The shot origin time, defined as the time that the cap fired; was typically 6 ms after the desired shot time, due to delays in the electronics. The shot times and charge sizes are listed in Appendix A and shot-hole information can be found in Appendix C. The reported shot times are accurate to within ± 1 ms.

Surveying. Two Global Positioning System (GPS) receivers (Trimble Navigation Path Finders) were used to determine locations and elevations for all receiver stations and most shotpoint sites. The GPS receivers were used in differential mode and provided horizontal locations accurate to within approximately 5 m and vertical positions accurate to within 10 m. PACE 1987 locations were used for those shots that were reoccupied from the earlier study (SPs 20, 28, 31, 32, 33, and 34). These 1987 locations were determined from 1:24,000 topographic maps and are accurate to within 50 m. For SP 23, two separate sites were used during the two studies. The 1989 site was located 0.5 miles to the east of the 1987 site in order to accommodate a much larger shot (6000 lbs. versus the 3000 lbs.) without damaging existing structures in the area. Because the 1989 site for SP 23 was displaced in a direction perpendicular to the receiver array, and because the shotpoint was offset a minimum of 135 km from the receiver array, the 1987 coordinates were used for the 1989 site. This then allowed the data from both studies to be merged into a composite record section with only a minimal (<100 ms) timing shift.

Instrument Recording. PACE 1989 was the first experiment to use the SGRs in a delay-turn-on programmable mode. For this reason the instruments were interleaved with SCRs and PRS1s on the Colorado Plateau profile to minimize the potential impact if the new turn-on method were to fail catastrophically. The SGRs were thus deployed every other station, beginning at the southwest end of the profile where they were interleaved with SCRs (Fig. 2b). Once all 120 of the SCRs were deployed, the PRS1s were inserted in the array, and they then alternated with the SGRs until finally only PRS1 instruments remained. The final 25 km of the Colorado Plateau profile consisted entirely of PRS1 instruments deployed every 333 m. Although this approach was adopted because it provided a minimum-risk approach to data acquisition, it did degrade the lateral trace-to-trace continuity of wide-angle reflections and refractions. This effect is evident in the record section plots (Figs. 8 to 31) and results from contrasting geophone and instrument responses (see discussion of data quality below).

On the Colorado Plateau profile the SGRs were programmed to record for 99 s with no turn-on delays. A maximum of 14 records could be written to the shorter (400-ft) cassette tapes given this record length and the 0.002-s sample rate. Other recording systems also had limitations. The Stanford piggyback effort utilized a recording system provided by Arco Oil and Gas Co. which required 2 to 3 minutes between shots to down-load its 800 channels of data to tape. The SCRs, on the other hand, recorded continuously in three 10-minute windows, and thus were better suited for short time intervals between shots. Given these various instrument restrictions and the large number of shots (24) on the Colorado Plateau Profile, the line was divided into three separate nights of recording, with tape swaps for the SCR and SGRs occurring each day following shooting. Even with 3 nights of shooting, not every instrument group was able to record all of the shots. The SCRs did not record SP 61, for example, which was a small shot added to the experiment by Stanford — fortunately, the dense Stanford array in the vicinity of this shot overlapped the SCRs and minimized the impact of this data loss. Similarly, the Stanford piggyback did not record several of the shots northeast of their receiver array, but they were able to record all of the shots within and southwest of Chino Valley.

Unlike the Colorado Plateau profile, the Grand Canyon profile was recorded in a single 24-hour period. The 12 shots on this profile (some with 60-s versus 99-s record lengths) could easily be recorded on a single SGR cassette tape. In addition, Stanford did not participate in this portion of the PACE study, and thus the limitations of the Arco recording system were not a factor. The only shotpoint that could not be recorded by all instrument types on the Grand Canyon profile was the Peabody Coal Company quarry blast. The SCRs did not have a sufficient number of recording windows to accommodate this daytime shot. The Terra Technology seismographs on the north rim of the Grand Canyon also did not record the quarry blast.

The instrument deployment strategy used on the Grand Canyon profile (Fig. 3b) contrasted somewhat with that described above for the Colorado Plateau profile. The SCRs and Terra Technology seismographs were deployed primarily at the southern and northern ends of the profile respectively, where instrument spacing averaged 0.5-1.2 km. The SGRs and PRS1s, in contrast, were deployed in the central 35-km-long higher-resolution portion of the study. As before, the SGRs and PRS1s were interleaved, although there were fewer PRS1s than SGRs and thus the southernmost 5 km of this dense array consisted entirely of SGRs. Because of their compact size and overall reliability, 15 of the PRS1s were also used in the ~15-km-long backpacker/mule deployment across the Grand Canyon.

INSTRUMENTATION

Five different types of recording instruments were used during this experiment: USGS's Seismic Cassette Recorders (SCR), Geological Survey of Canada's PRS1s and PRS4s, Stanford's Seismic Group Recorders (SGR), and the Air Force Geophysics Laboratory's DCS-302 Terra Technology seismographs. A general description of all but the DCS-302 TERATEKs is given here. For more detailed descriptions see Murphy (1988) regarding the SCRs and Asudeh and others (1992) regarding the PRS1s and PRS4s.

The SCRs are a six-chanel, single-component instrument consisting of a Mark Products L-4C 2-Hz vertical geophone, a set of three parallel amplifier boards with adjustable gain settings, a clock (temperature-compensated oscillator, TCXO) a VCO (voltage controlled oscillator), and a cassette recorder (Murphy, 1988; Fig. 4). The use of three parallel amplifier boards with gains set so that the dynamic ranges of the amplifiers overlap, affords a variable total dynamic range. The three data carrier frequencies, the clock carrier frequency, and a tape-speed compensation carrier frequency are summed and recorded on cassette tape. All three data channels and the time code signal (IRIG E) are frequency modulated. During the digitizing process, the cassette tapes are played back and the signals are demultiplexed and demodulated. To prevent accidental shifting of the data-carrier frequencies, the tape-speed compensation carrier frequency matches a locally generated reference frequency. A 12-bit analog-to-digital (A/D) converter converts the signals to digital data; the data are then sampled at 200 samples per second and are stored on optical disks. The amplitude response is roughly flat between 2 and 30 Hz (Fig. 5), and the approximate ground motion, $A_g(t)$, in cm/s, for this frequency range can be calculated from the following expression:

$$A_g(t) = 1.541 * 10^{-8} * 10^{(a/20)} D_m$$

where a = attenuation setting of the pre-amplifier (usually 12, 30, or 48); D_m = measured peak-to-peak amplitude in digital counts (Kohler and Fuis, 1989).

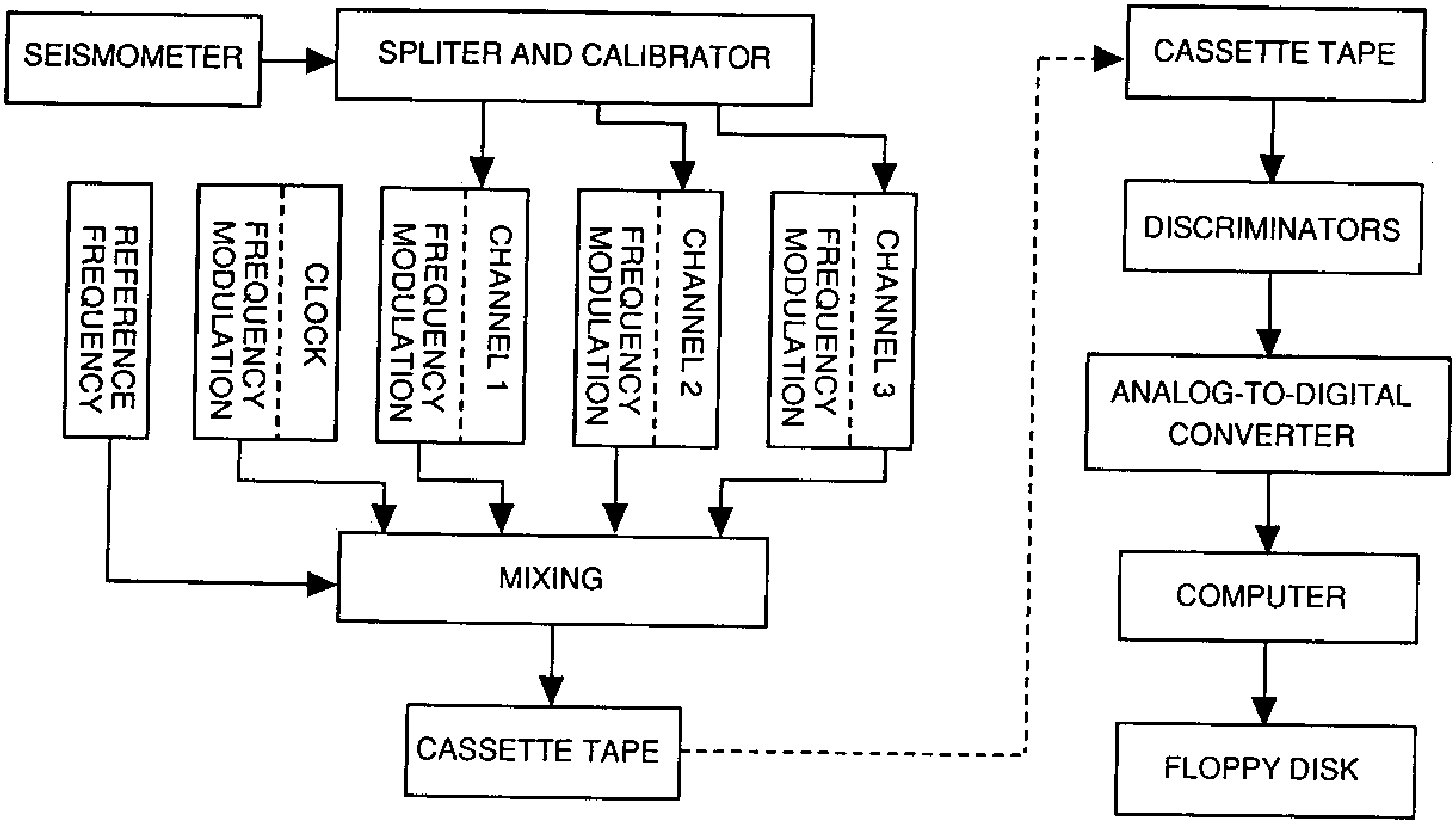

Figure 4. Schematic diagram of the Seismic Casette Recorder (SCR) data acquisition and processing system. Figure from Murphy and others (1993).

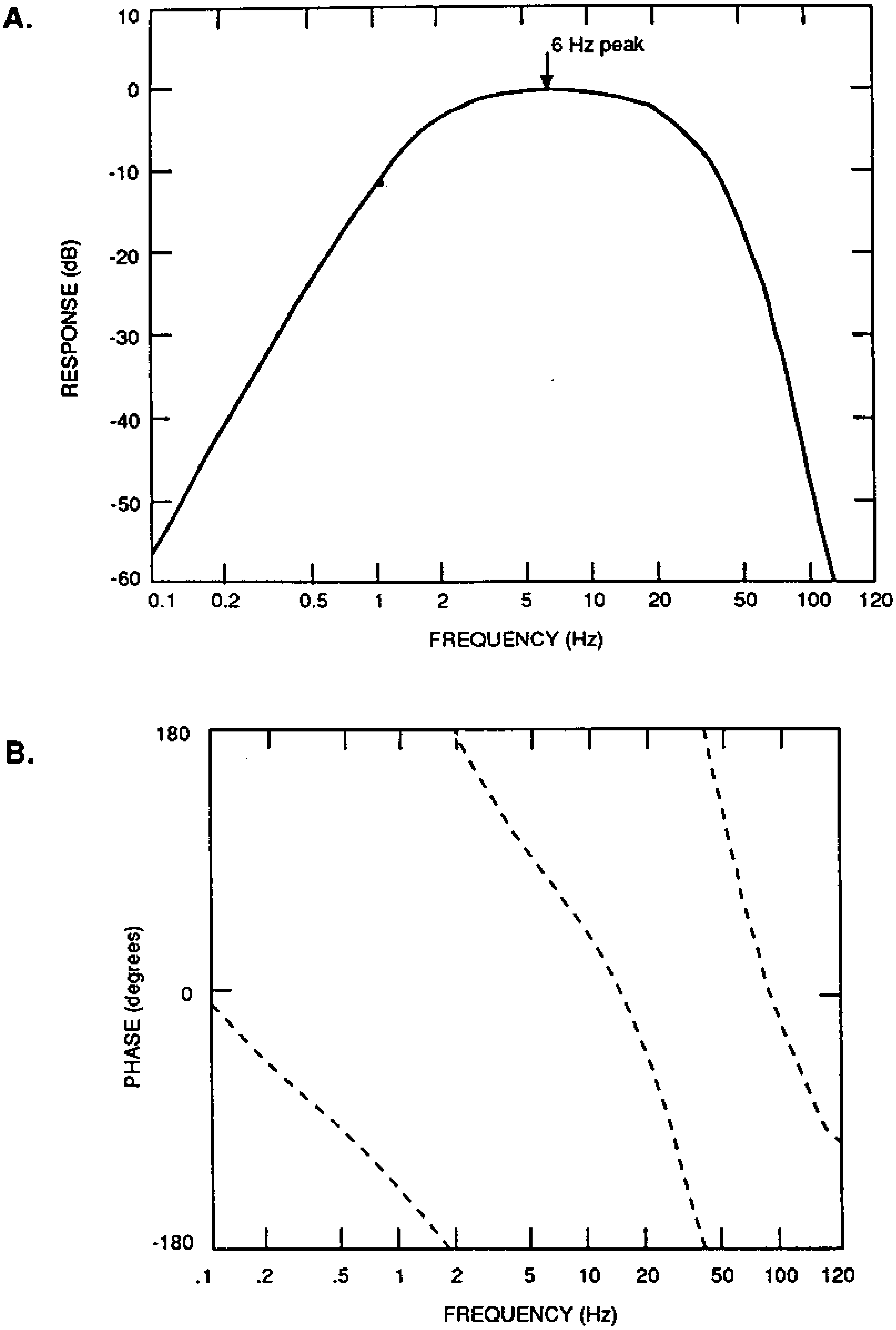

Figure 5. Theoretical amplitude (A) and phase (B) response for the USGS seismic cassette recorder (SCR) and digitizing system with a Mark Products L-4C geophone (2 Hz). (From Dawson and Stauber, 1986).

Phase characteristics are shown in Figure 5b. Prior to deployment, the clock in each unit is synchronized to a USGS master clock which drifts approximately 1 ms per day and is checked periodically against satellite clocks. When the cassette recorders are retrieved, a clock drift is measured and these data are used to calculate chronometer corrections at shot time (assuming linear drifts). Most clocks drift less than 20 ms during a 24-hour period.

The PRS1s (Asudeh and others, 1992) are also single-channel instruments that use a Mark Products L-4C 2-Hz vertical-component geophone. Automatic gain-ranging from 1 to 1024 in binary steps allows a total dynamic range for these instruments of 132 dB. Seismic data are sampled at 120 samples per second by a 12-bit A/D board and stored in memory (DRAM) until the data are uploaded to a PC. The response curves for the overall system are shown in Figure 6. The amplitude response peaks about 5 Hz. Timing is provided for each unit by a temperature-compensated oscillator (TCXO) that is synchronized to VCT via satellite during the programming (or downloading) process. After retrieval of the instruments, the clock drift is measured for each instrument and clock corrections are made assuming linear drift rates. Most clocks drift less than 20 ms during a 24-hour period. The PRS1s were designed by the Geological Survey of Canada and built by EDA Instruments Ltd. (now Scintrex Limited of Toronto). The PRS4s are similar but permit 3-channel recording capabilities.

The SGR III recorders were designed by Amoco Production Company, built by Globe Universal Sciences, Inc., and modified by the USGS. The seismograph is a single-channel digital seismic recorder with a theoretical dynamic range of 156 dB. Data are sampled at 500 samples per second by a 12-bit A/D board with gain ranging from 0-90 dB in 6 dB steps. The Stanford SGRs have been modified to turn on at pre-set times instead of using the standard radio turn on. Timing is provided by a temperature-compensated internal oscillator (TCXO) that is synchronized to a USGS master clock prior to deployment. Like the SCRs and PRS1s, most SGR clocks drift less than 20 ms during a 24-hour period. The digital data and the clock drift at the time of instrument retrieval are recorded on cartridge tape. The drift rates (assumed to be linear) are used to calculate chronometer corrections at shot time. For this experiment, the SGR III pre-amplifier was set to 50 mV, the low-cut filter was "out", and the 60-Hz notch filter was "in". Figure 7b shows the phase characteristics associated with these filter settings.

Three different geophone types were used in conjunction with the SGRs on the PACE-89 experiment. One hundred and seventy modified 6-phone (connected in-series) strings of Mark Products L-10B vertical-component phones (8 Hz) were the primary geophone used in the study. The total system response for this configuration is shown in Figure 7. In addition, 20 single Mark Products 8-Hz phones and 2 Mark Products L-4C 2-Hz vertical-component geophones were deployed. Although the single-phone 8-Hz strings were much simpler and faster to deploy, they produced about one-half the signal strength and are thus not recommended for future use. The L-4C 2-Hz phones were the most compatible with the SCR and PRS1 recorders. For this reason, the phones have since been used on several long-offset refraction experiments in conjunction with these other instruments. Because of the three types of geophone configurations used with the SGRs in the PACE 1989 study, amplitudes had to be corrected for geophone type (empirically-determined scalars of 4, 9, and 19 were applied for L-4C, single, and 6-string geophones, respectively). Co-location studies were also conducted following the experiment to derive an empirical scalar of

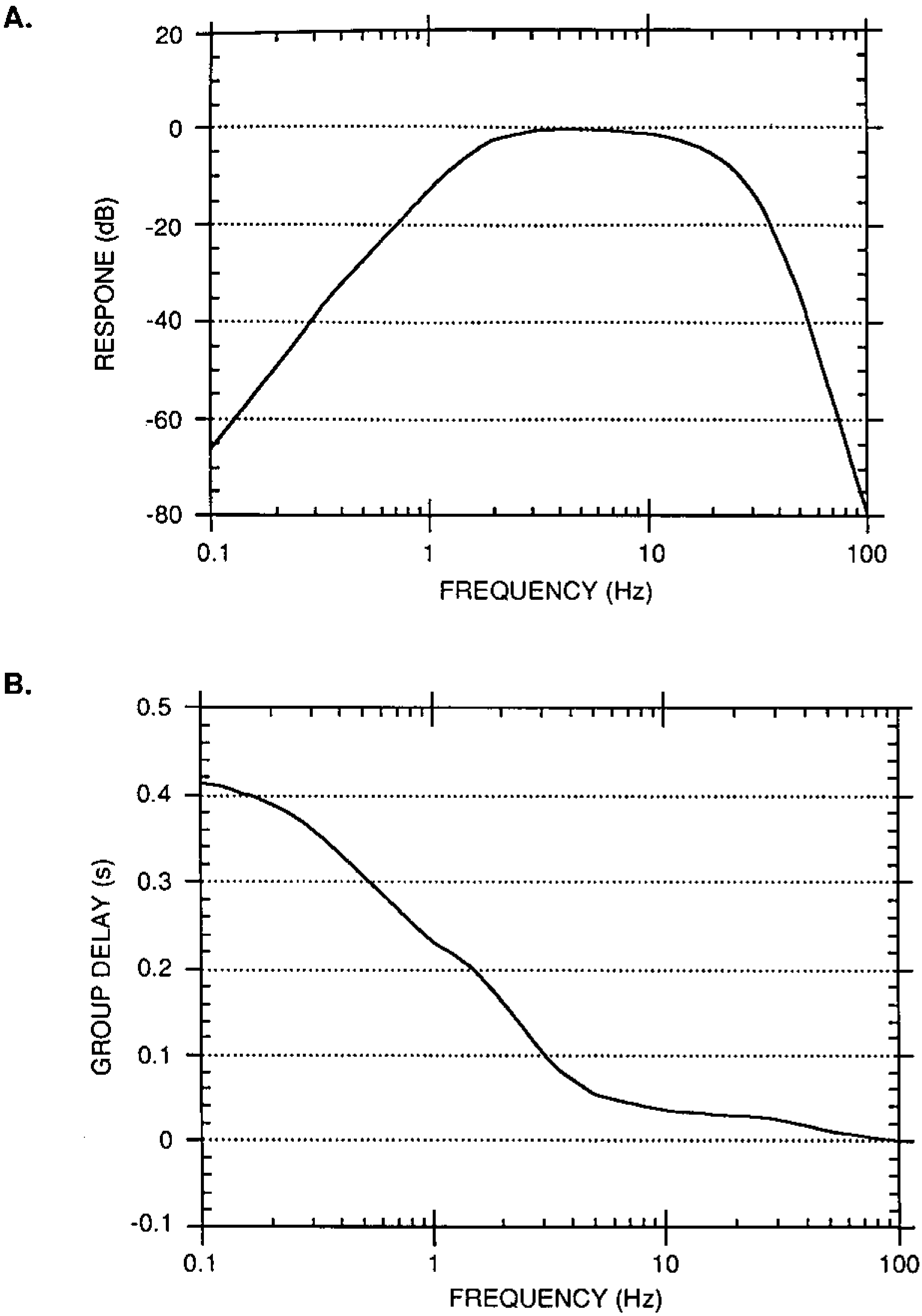

Figure 6. The amplitude (A) and phase (B) response for the PRS1 with the Mark Products L4-C geophone (2-Hz). Figure from Murphy and others (1993).

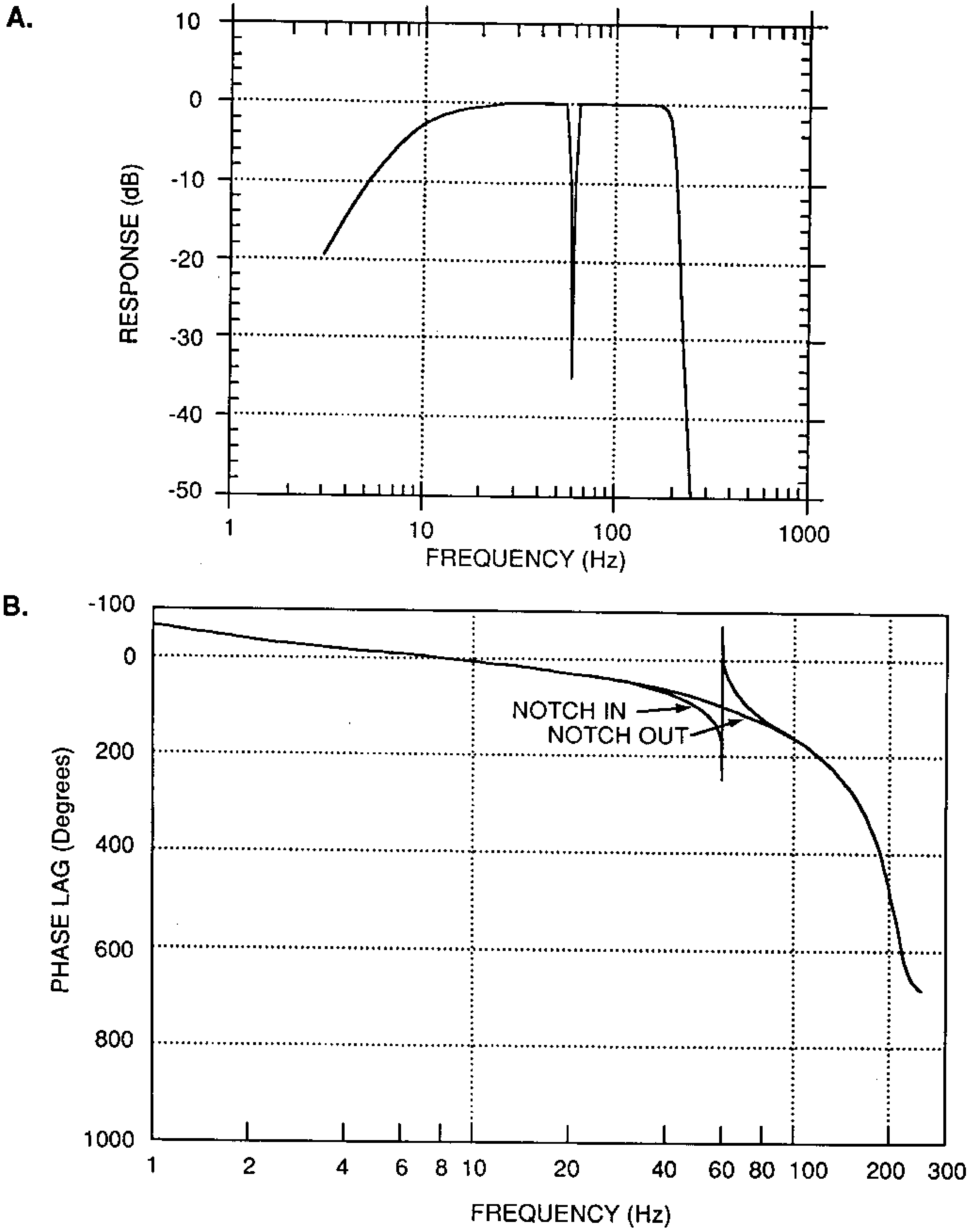

Figure 7. The amplitude response (A) and phase characteistics (B) of the SGR IIIs with filters as described in the text. The effect of the Mark Products L10-B geophone string is included in (A) but not in (B). Figure from Murphy and others (1993).

595200 which, when applied to the data, normalizes amplitudes to be approximately equivalent to SCR and PRS1 values (nm/sec/digital_count).

Many of the connectors used to link the geophones and SGR IIIs were wired incorrectly and yielded negative polarities for over half the SGRs. The SGR data were thus visually inspected for polarity reversals, and trace polarities were modified accordingly.

PIGGYBACK STUDIES

There were several smaller "piggyback" studies conducted during the 1989 PACE study. Each of these studies is described briefly below. Note that the data acquired in these piggyback studies is not included in the data release available through the National Geophysical Data Center.

Stanford. Stanford University deployed a 45-km-long recording array centered about Chino Valley, Arizona, to record the 24 shots of the Colorado Plateau profile. This piggyback study utilized an 800-channel GUS-1000 cable system provided by Arco Oil and Gas Co., and 210 two-channel SGR-IVs combined with 458 SGR-IIIs provided by Amoco Production Company and operated by Grant Norpac Inc. A total of 1678 channels were recorded at 924 stations with an average station spacing of 50 m. Areas with sensitive upper-crustal targets had station spacings of 25 m. Several short (1-5 km) 3-component arrays were positioned strategically along the 45-km reflection spread. Intermittent, short, closely spaced 3-component arrays were chosen over widely spaced 3-component stations covering the entire line so that P- and S-wave data could be compared at the same, close station spacing. Twenty-four large explosions were shot into the spread at offsets ranging from 0 to 250+ km. The Stanford reflection spread constitutes a 45-km-long high-resolution "window" embedded in the larger regional refraction array and has been used to assess the structural transition at the southwest physiographic margin of the Colorado Plateau (Howie and others, 1991; Howie, 1991; Parsons and others, 1992).

Arizona. The University of Arizona deployed a 192-channel, 9.6-km-long recording spread between shotpoints 84 and 71 along the azimuth of the Colorado Plateau profile (Johnson and Hartman, 1991). Station spacing was 50 m, with vertical- and horizontal-component geophones interleaved at alternating stations. This Arizona spread remained fixed during the course of the experiment, and thus this spread recorded in-line data during the shooting of the Colorado Plateau profile and fan data during the recording of the Grand Canyon profile. Multielement, 20-m geophone arrays were aligned along a NE azimuth; within the horizontal-component geophone arrays, elements were oriented parallel to the azimuth of the Colorado Plateau profile. Individual and composite shot records generally exhibit very high signal-to-noise ratios (S/N) for both P- and S-wave reflected and refracted arrivals. Although weak shear-wave arrivals are recorded on the vertical-component geophones, deployment of horizontal-component geophones resulted in much higher S/N for shear arrivals than would have been possible with the deployment of vertical-component geophones alone.

Williams Array. During the 1989 PACE experiment, the Solid Earth Geophysics Branch of the Geophysics Laboratory of the US Air Force, in conjunction with Weston Observatory of Boston College, operated a small aperture seismic array near the center of the NE-SW Colorado Plateau profile at Williams, Arizona, approximately 30 km west of Flagstaff (Battis, 1990). The 16-elements of the array were distributed along two cross arms of 435 and 350 m in length with the greater arm aligned with the trend of the main shot line. Data quality from this piggyback was only marginal due to the highly attenuating volcanic ash and cinder that blanketed the surface in the region.

North Rim Fan. The Air Force Geophysics Laboratory deployed 30 instruments from the north rim of the Grand Canyon to Jacob Lake, ~40 km to the NW (Wolf and Cipar, 1993). This spread remained approximately stationary during the shooting of the two PACE refraction profiles (some instruments were repositioned to different stations within the north rim array; see Appendix B). As a result, the shots from the Colorado Plateau profile were recorded as fans into the AFGL array, while the shots from the Grand Canyon profile were recorded in-line and extended this profile by 40 km. Only the AFGL data recorded in-line have been merged with the SCR-SGR-PRS1 data and are available through the National Geophysical Data Center.

Flagstaff Peaks. The University of Texas at El Paso, in conjunction with Texas A&M, deployed 27 PRS4 instruments in the vicinity of the San Francisco Peaks, parallel to, but off-axis from, the main Colorado Plateau profile. This spread is only 55 km long, but provides three-dimensional control to the structures determined from the Colorado Plateau profile (Durrani and others, 1992).

Meteor Crater Array. Following the recording of the two PACE refraction profiles, the PRS1 instruments were redeployed at 0.1-km-spacing in the vicinity of Meteor crater, 35 miles east-southeast of Flagstaff. Two small shots were fired into this array, which was located near the southern margin of the Colorado Plateau. These shots were co-located and were all approximately 100 lbs. each. The goal of this study was to try to image the deep reflections (16 s two-way traveltime) described by COCORP (Hauser and Lundy, 1989) with an explosive instead of a Vibroseis source.

Three-Component Recording. A limited number of three-component instruments were deployed at 2 km station spacing on both of the wide-angle reflection/refraction profiles. Ten of these instruments were GEOS and 18 were PRS4s (13 from the GSC and 5 from the USGS). These instruments were deployed across the northeastern portion of the Colorado Plateau profile (southwest of the tie with the NW-SE line) and the central portion of the Grand Canyon profile (centered about the tie with the NE-SW line). The vertical-component data from the PRS4s have been merged with the other vertical-component SCR, SGR, and PRS1 data and are available through the National Geophysical Data Center.

DATA QUALITY

Displays of the in-line shots recorded during the 1989 PACE experiment are presented in Figures 8 to 42. The data are reduced at 6 km/s (except for SP 20, which is reduced at 8 km/s) and are bandpass filtered from 7-35 Hz. The plots are pseudo-true amplitude: amplitudes are normalized within each trace and are laterally balanced to correct for the loss of energy with increasing distance away from the shot. Because of the difficulty in generating high-quality record-section displays when data are recorded at dramatically different trace spacings along a single profile, the cross-line plots, Figures 32 to 42 have been subsampled to a minimum trace spacing of 500 m. Thus, within the tightly spaced 0.1-km spaced portion of the receiver array, only one out of every five traces is plotted.

The record sections have several general characteristics that can be attributed to variations in the regional geology from the Arizona Transition Zone across the Colorado Plateau. In general, the first-arrival times are approximately flat (compare to the PACE 1985 and 1987 studies across the southern Basin and Range province), indicating only minor amounts of structural disruption of the upper crust. Two exceptions to this general rule are evident. On the Colorado Plateau profile, first arrivals are delayed approximately 0.2 s across Chino Valley due to the increase in slow-velocity sediments (e.g., see SP 31 between 35 and 50 km offset, Fig. 11). The opposite effect is seen on the Grand Canyon profile across the Grand Canyon. Here travel times are advanced 0.25 s due to the removal of slower-velocity Paleozoic strata (e.g., see SP 75 between 35 and 45 km offset, Fig. 37).

The single most important factor controlling data quality is the rock type at both the source and the receiver (see summary of lithologies and wet/dry conditions for each shotpoint in Figs. 2 and 3 and in Table C; see also Kohler and Fuis, 1992 for summary of relationship between shotpoint site condition and recording distance). Wet sources (e.g., SP 20, Fig. 8) produced the strongest seismic source. Shots located in hard rock sites such as granite (e.g., SP 31, Fig. 11) also produced good seismic energy. Shots fired in either dry alluvium (e.g., SP 61, Fig. 26) or volcanic cinder (e.g., SP 50, Fig. 22) were the least efficient. Limestone shotpoints were also not as effective as crystalline rock or saturated alluvium, due to the cavernous conditions at many of the shotpoints. Data recorded from limestone shotpoints typically have lower signal-to-noise ratios and are highly reverberatory (e.g., SP 77, Fig. 39).

Because rock type varies systematically across the PACE 1989 study area, there is a strong regional variation in data quality. The greatest signal-to-noise ratios were consistently recorded across the Arizona Transition Zone, where Precambrian crystalline rocks are exposed at the surface (Fig. 2b). Data quality decreases dramatically across the Colorado Plateau (between SPs 32 and 42, Fig. 2), where volcanic ash and cinder deposits of the Flagstaff volcanic field predominate. Similarly, because the shots of the Grand Canyon profile were situated almost exclusively within the limestone of the Kaibab Plateau (Fig. 3b), which is cavernous and elevated well above the regional water table, many of the recorded arrivals are reverberatory in nature and secondary reflections are rare.

One final factor that has affected phase correlation and data quality is instrument type. The different recording instruments each have a unique instrument response, and when these instruments are interleaved, the resulting waveforms have different phase and frequency characteristics. In the absence of any post-experiment wavelet processing, this results in a degradation in the trace-to-trace phase coherency. The SGRs were interleaved with SCR and PRS1 recorders across most of the Colorado Plateau profile. However, PRS1 instruments are deployed exclusively along the northeast 25 km of the profile (Fig. 2b), resulting in improved trace-to-trace coherence (e.g., see the improved data quality northeast of 130 km offset on SP 31, Fig. 11). Thus in the future, we recommend not interleaving different instrument types.

DATA REDUCTION

The raw data recorded by the SGRs, SCRs, PRS1, PRS4, and Terra Technology seismographs all had different sample rates, trace lengths, reduction velocities, instrument responses, and data-tape formats. Prior to merging these different data sets, the following data reductions steps were applied.

- Resample data to 8 ms

- Update miscellaneous headers
  - Write SP to bytes 17-20 (INT format) and to bytes 225 (ASCII format)
  - Write Shot to bytes 9-12
  - Write FFID to bytes 233-236 (ASCII format)
  - Write shot charge size to CHARGE, bytes 179-180.
  - Write azimuth (in degrees) to AZIMUTH, bytes 219-220
  - Write original offsets (SCR and PRS instruments) to XOFFSET, bytes 237-240.

- Write instrument type into header INSTRU (bytes 215-216)
  - 1=SCR
  - 2=SGR
  - 3=PRS1
  - 4=PRS4
  - 5=AFGL

- Modify CHAN in trace header (bytes 13-16)
  - CHAN = station number for Colorado Plateau profile
  - CHAN = (station number-2000) for Grand Canyon profile

- Apply DISCO geometry and write values into trace headers
  - Soffset (bytes 37-40)
  - Relev (bytes 41-44)
  - Selev (bytes 45-48)
  - Sdepth (bytes 49-52)
  - Sdatum (bytes 53-56)
  - Rdatum (bytes 57-60)
  - Sht-X (bytes 73-76)
  - Sht-Y (bytes 77-80)
  - Rec-X (bytes 81-84)
  - Rec-Y (bytes 85-88)
  - CDP-X (bytes 61-64)
  - CDP-Y (bytes 65-68)
  - CDP-Stat (bytes 181-182)
  - Sht-Stat (bytes183-184)
  - Rec-Stat (bytes 185-186)

- Apply Geophone gain corrections. Amplitudes converted to nm/s/digital_count.
  - Original gain corrections copied into header GAIN (bytes 177-178).
  - Once applied, INGCONST (bytes 121-122) reset to 1.
  - Gain correction information not available for AFGL seismographs.

- Apply drift corrections for SGR, PRS1, PRS4, and AFGL seismographs only.
  - Drift corrections already applied to SCRs during digitizing process.
  - Original drift values copied into header DRIFT (bytes 175-176).
  - Once applied, drift values reset to zero (header COR, bytes 217-218).

- Correct shot timing errors for SGRs and AFGL seismographs (shot timing errors were previously applied to SCRs, PRS1s, and PRS4s).
  - Shot timing errors ranged between 6 ms and 2132 ms.

- Reduce all data to 8 km/s, with each trace beginning at -1 s.
  - Store reduction time plus -1s time shift in TTRACE (bytes 209-212).
  - Create header TAPPLY (bytes 213-214) and set equal to 1.
  - To unreduce data, apply values in TTRACE (ms).
  - Sort data by shotpoint and offset.

- Update shot and receiver turn-on times in headers.
  - Adjust shot times to reflect ideal detonation times (no delays).
  - (SHOUR, bytes 191-192; SMINUTE, bytes 193-194; SSEC, bytes 195-196)
  - Adjust receiver turn-on times to equal ideal shot times (no delays or drifts).
  - (HOUR, bytes 161-162; MINUTE, bytes 163-1164; SECOND bytes 165-166).

- Additional corrections for the SGRs included:
  - Omit dead traces generated by transcriber.
  - Flip polarities on reversed geophone cables.
  - Correct amplitudes for different geophone types.
  - Edit data and delete bad traces.
  - Reset TRACEID header to 1 (bytes 29-30).

Forty-two seconds of data sampled at 8 ms were output to 8 mm Exabyte tapes in 32-byte IBM float format following the Geological Survey of Canada's Lithoseis 3.00 SEGY refraction format. These data are reduced at 8 km/s and begin at -1 s. Trace start times were modified to equal shot times; these trace start times have not been adjusted to account for the 8 km/s reduced times or the -1 trace start time. To unreduce the data, apply the times stored in the header "TTRACE" (bytes 209-212). Receiver and shot static corrections were computed and stored in the trace headers but were not applied to the data.

ARCHIVE DATA TAPE FORMAT

The Pace-89 data tape is written in standard SEG-Y 32-bit IBM floating point format (Barry and others, 1975). The data are written to 1600-bpi Exabyte tapes and each tape has the standard SEG-Y EBCDIC reel header. Minor modifications to the trace headers allow refraction data to be archived in this format. A list of the header fields used for this data set is shown below.

Trace Identification Header (total of 240 bytes)

Bytes	Header	Explanation	Length:	Type:
9 - 12	SHOT	Shot number	4	INT
13 - 16	CHAN	Channel	4	INT
17 - 20	SP	Shotpoint number	4	INT
21 - 24	CDP	Common depth point number	4	INT
29 - 30	TRACEID	Trace ID code (=1, seismic)	2	INT
25-29	SEQNO	Sequential trace number in gather	4	INT
37 - 40	SOFFSET	Signed shot-receiver offset	4	INT
41 - 44	RELEV	Receiver elevation (m)	4	INT
45 - 48	SELEV	Shot elevation (m)	4	INT
49 - 52	SDEPTH	Shot depth (m)	4	INT
53 - 56	RDATUM	Receiver datum statics	4	INT
57 - 60	SDATUM	Shot datum statics	4	INT
61 - 64	CDP-X	X coordinate of CDP (m)	4	FLT
65 - 68	CDP-Y	Y coordinate of CDP (m)	4	FLT
71-72	CO-SCAL	Scalar for all coordinates in bytes 41-68	2	INT
73 - 76	SHT-X	X coordinate of shot (m)	4	FLT
77 - 80	SHT-Y	Y coordinate of shot (m)	4	FLT
81 - 84	REC-X	X coordinate of receiver (m)	4	FLT
85 - 88	REC-Y	Y coordinate of receiver (m)	4	FLT
89 - 90	COORUNIT	Coordinate units (=1, meters)	2	INT
91-92	WVEL	Weathering velocity	2	INT
93 - 94	SUBWVEL	Subweathering vel (=6000 m/sec)	2	INT
109-110	DELAY		2	INT
115 - 116	NSAMPLES	Number of Samples (=5250)	2	INT
117 - 118	SRATE	Sample rate (=8 milliseconds/smp)	2	INT
119 - 120	GAINTYPE	Gain type	2	INT
121 - 122	INGCONST	Gain constant (=1)	2	INT
123 - 124	INITGAIN	Initial gain (=1)	2	INT
133 - 134	TSTYPE	Source type (5=borehole)	2	INT
157 - 158	YEAR	Receiver turn-on time, year	2	INT
159 - 160	DAY	Receiver turn-on time, day	2	INT
161 - 162	HOUR	Receiver turn-on time, hour	2	INT
163 - 164	MINUTE	Receiver turn-on time, minute	2	INT
165 - 166	SECOND	Receiver turn-on time, second	2	INT
175 - 176	DRIFT	Original drift values	2	INT
177 - 178	GAIN	Original gain constant	2	INT

179 - 180	CHARGE	Shot charge size (kg)	2	INT
181 -182	CDP-STAT	Surface station nearest to CDP	2	INT
183 - 184	SHT-STAT	Surface station nearest to shot	2	INT
185 - 186	REC-STAT	Surface station nearest to receiver	2	INT
187 - 188	SYEAR	Shot turn-on time, year	2	INT
189 - 190	SDAY	Shot turn-on time, day	2	INT
191 - 192	SHOUR	Shot turn-on time, hour	2	INT
193 - 194	SMINUTE	Shot turn-on time, minute	2	INT
195 - 196	SSEC	Shot turn-on time, second	2	INT
209 - 212	TTRACE	Time shift to unreduce trace	4	INT
213 - 214	TAPPLY	Flag (=1 since TTRACE in use)	2	INT
215 - 216	INSTRU	Instrument type	2	INT
217 - 218	COR	Drift values (reset to 0)	2	INT
219 - 220	AZIMUTH	shot-receiver azimuth (deg)	2	INT
221 - 222	BOX	Box number	2	ASCII
225 - 228	SP	Shotpoint number	4	ASCII
233 - 236	FFID	Field file identification number	4	ASCII
237 - 240	XOFFSET	Original SCR, PRS1 offset	4	INT

To obtain a copy of the PACE 1989 seismic data on SEG-Y Exabyte tape contact either of the following:

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

or:

IRIS Data Management Center
1408 NE 45th Street
Seattle, WA 98105
Telephone: (206) 547-0393

ACKNOWLEDGMENTS

Field Operations. The authors wish to express their appreciation to Beate Aichroth, Isa Asudeh, Mark Baker, Jonathan Begay, Harley Benz, Tim Cartwright, John Cipar, Tim Coté, Joseph Cotton, Coyn Criley, Chris Dietel, Lynn Dietz, Diane Doser, Don Farrell, Gary Fuis, Don Geddes, Chuck Gilbert, Mark Goldman, Greg Hajic, Zoli Hajnal and University of Saskatchewan students, Steve Harder, Pat Hart, Gordon Haxel, John Hendricks, Steve Hughes, Craig Jarchow, Gray Jensen, Klaus Joehnk, Ron Kaderabek, Uwe Kaestner, Werner Kaminski, Randy Keller, Jim Luetgert, Rob Luzitano, Carlos Montana, Walter Mooney, Mike Moses, Brennan O'Neil, Sue Priest, Dave Reneau, John Sass, Bob Schiemann, Raimund Stangl, Jean Taylor, George Thompson, Alan Walter, Theresa Williams, and Lorraine Wolf for their assistance in the field.

Instrument Development, Repair, and Data Reduction. Fred Fischer, Grey Jensen, and Reese Cutler adapted the SGRs for programable recording. Craig Jarchow assisted in SGR maintenance, modification, and development. Dale Richards and Janice Murphy assisted in data reduction and report preparation.

Pre-experiment Planning: Steve Larkin was responsible for much of the shotpoint permitting. George Billinsley, Phil Gans, and Gordon Haxel provided assistance in shotpoint site selection. Iris Barton, Jonathan Begay, and Jane Gray assisted in permitting SP 46 on the Navajo Indian Reservation. Helen Fairley and Barbara Phillips conducted the archeological and botanical studies the Navajo shotpoint.

Navajo and Hopi Indian Reservations: We would like to express a special thanks to the Navajo and Hopi Nations for providing access to Indian Lands. We are particularly grateful to the following individuals for their assistance: George Abe, Edward Begay, Irving Billy, Leonard Haskie, Byron Huskon, Richard Koch, Vernon Masayesva, Roger Paul, Patrick Ryan, Leroy Shingoitewa, Ivan Sidney, and Akhtar Zaman.

Access: Permission to record and shoot on private lands was graciously granted by: David Blair, William Cadasco (C.O. Bar Ranch), Merwin Davis (Chino Valley Land and Cattle Company), John and Linda Harper Jr. (Juniper Wood Ranch, Inc), Victor Howell (Babbitt Ranches), Kenneth Johnson, G.O. and Anita Lawdon, Lilo Perrin, Gene Polk (Kieckhefer Enterprises), Steve Powers, Roy Rager, and Terri Walker. Permission to record and shoot on public lands was granted by: Mike Howard, Coconino National Forest, Emilio Lujan and Dick Streeper, Prescott National Forest, Peter Kahon and Carey Price, Kaibab National Forest, John Davis, Grand Canyon National Park, and William Childress, Sue Richardson, and Roger Taylor, Bureau of Land Management.

Funding: The PACE 1992 seismic experiment was funded by five principal organizations: the U.S. Geological Survey's Deep Continental Studies Program, the Air Force Geophysics Laboratory (AFGL), the University of Texas at El Paso, the Gas Research Institute, and the National Science Foundation. Field support was provided by Arco Oil and Gas Company and the Peabody Coal Company. Instrumentation was provided by the Amoco Production Company and the University of Wyoming.

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