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CRUSTAL STRUCTURE DETERMINED FROM A NEW WIDE-ANGLE SEISMIC PROFILE IN SOUTHWESTERN NEW MEXICO

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Abstract—In February 1999, a test of new seismic instruments was conducted using the Tyrone Mine near Silver City as an energy source. This test produced a high-quality, although unreversed, seismic section extending 145 km south from the Tyrone Mine. A number of crustal seismic phases, including P, Pg, PcR, PmP, and SmS, are easily seen in the seismic section. These phases allow us make a one-dimensional, velocity-depth interpretation of the crust under southwestern New Mexico. The crustal thickness is 35 km, at least 2 km thicker than the crust either to the east or west. The thicker crust is reflected in the higher topography in southwest New Mexico.

INTRODUCTION

A better understanding of crustal structure is a key element to efforts to interpret the complex tectonic history of the southwestern New Mexico region. Seismic surveys provide important constraints on crustal structure, and the Phelps-Dodge open-pit copper mine at Tyrone, New Mexico, has been the source of energy for several deep-crustal seismic profiles (Fig. 1). These profiles extend to the west (Gish et al., 1981), to both the northeast and southeast (Sinno et al., 1986) and to the north (Schneider and Keller, 1994; Snelson et al., 1998). In February 1999, we again used the Tyrone mine as the energy source for a seismic profile extending to the south. The purpose of the experiment was an operational field test of new, lightweight, low-cost, single-channel seismographs (Texans) acquired by the University of Texas at El Paso. It was also an opportunity to collect a high-quality, crustal-scale data set with a minimum of effort and expense.

Previous seismic profiles from the Tyrone mine often required several blasts and multiple fieldtrips to collect. In this case, the seismic data along the new profile were collected in less than 12 hrs including driving time to and from El Paso, instrument deployment and pickup, and recording. The seismic profile extends from the Tyrone mine to the Mexican border crossing at Antelope Wells (Fig. 2), a distance of 145 km with a nominal station spacing of 500 m. A total of 296 instruments were deployed, almost an order of magnitude more than on previous profiles. This field test produced an unreversed, but high-quality, wide-angle seismic profile, the first crustal seismic data collected with these new instruments.

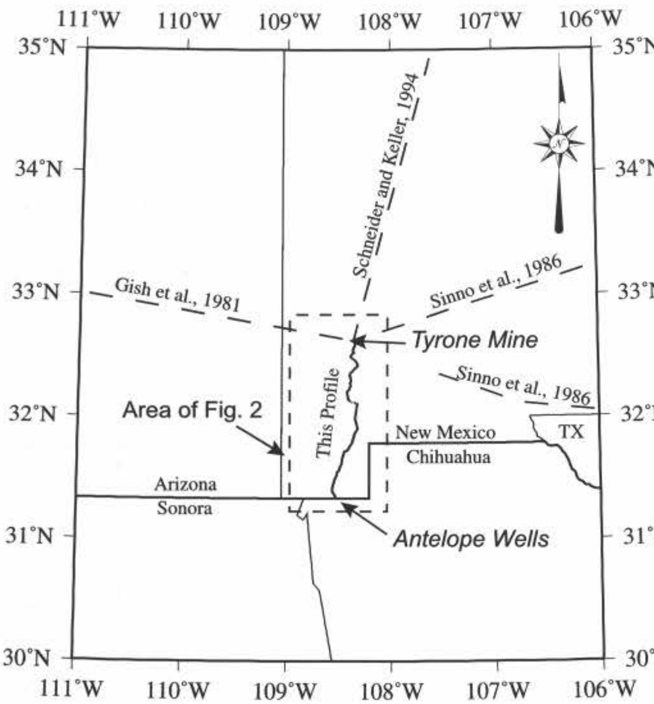

Figure 1. Index map showing the location of the wide-angle seismic profile discussed in this paper and earlier profiles in the area.

TECTONIC SETTING

Interpreting geophysical models of crustal structure requires an understanding of the major tectonic events that have affected the region. The crust of southwestern New Mexico formed during the late Proterozoic toward the end of a period of continental growth. This accretionary regime formed the North American craton (Laurentia) as we think of it today (Hoffman, 1988; Karlstrom and Bowring, 1988). The Grenville orogeny at about 1.0 Ga marked the end of this major period of continental growth (Mosher, 1998). Perhaps as a result of this last phase of accretion, widespread extension and magmatism occurred across southern New Mexico (Adams and Keller, 1994a). From a larger perspective, this accretion was part of the formation of a supercontinent (Rodinia, e.g., Dalziel, 1997). Rodinia broke up soon after it formed, and a passive continental margin formed along the Ouachia trend and to the south in Mexico. This margin can be traced southward from the Big Bend region of Texas to the vicinity of Chihuahua City, Mexico, where it turns westward, crossing the State of Sonora, and appearing again in exposures in southeastern California (Moreno et al., 1994; Speed, 1994; Stewart, 1988; Stewart et al., 1990). A strong northwest-striking structural grain seen in Laramide and older tectonic features in southwestern New Mexico (e.g., Seager and Mack, 1986; Kluth, 1986; Ross and Ross, 1986) and apparent in gravity maps (Fig. 2) and magnetic anomalies (DeAngelo and Keller, 1988) of the region may have originated at this time. For example, the Triassic basins along the East Coast of the U.S. are parallel to, and 500 km inboard from, the modern continental margin. A similar geometry would place a series of northwest-trending grabens in southwestern New Mexico in the Neoproterozoic–early Paleozoic. The formation of the Pedregosa basin and uplifts during the Ancestral Rocky Mountains orogeny during Mississippian and Pennsylvanian time also followed northwest trends in southwestern New Mexico (Kluth, 1986; Ross and Ross, 1986). The Laramide orogeny affected southwest New Mexico extensively (e.g., Seager and Mack, 1986; Drewes, 1978) and recent seismic reflection data (Chang et al., 1999) document some of the major Laramide faults in the subsurface. Mid-Tertiary volcanism greatly affected the crust in southwestern New Mexico. For example, a seismic and gravity study of the Datil-Mogillon volcanic field showed that there is crustal thickening and a ~10-km-thick batholith associated with this feature (Schneider and Keller, 1994).

The formation of the Basin-and-Range/Rio Grande rift is an ongoing process that produced the landscape that we see today. Defining the boundaries of the southern part of the Rio Grande rift is an ongoing process that was a major motivation for this study. Since the early work of Decker and Smithson (1975), Ramberg et al. (1978), Cook et al. (1979), and Seager and Morgan (1979), the southern extent of the Rio Grande rift has been the target of several geophysical experiments and studies (e.g., Sinno et al, 1986; Daggett et al., 1986; Keller et al., 1990; Adams and Keller, 1994b; Roberts et al., 1994). Gravity and seismic models indicate gradual crustal thickening from east to west in southwestern New Mexico and suggest that the western boundary of the rift

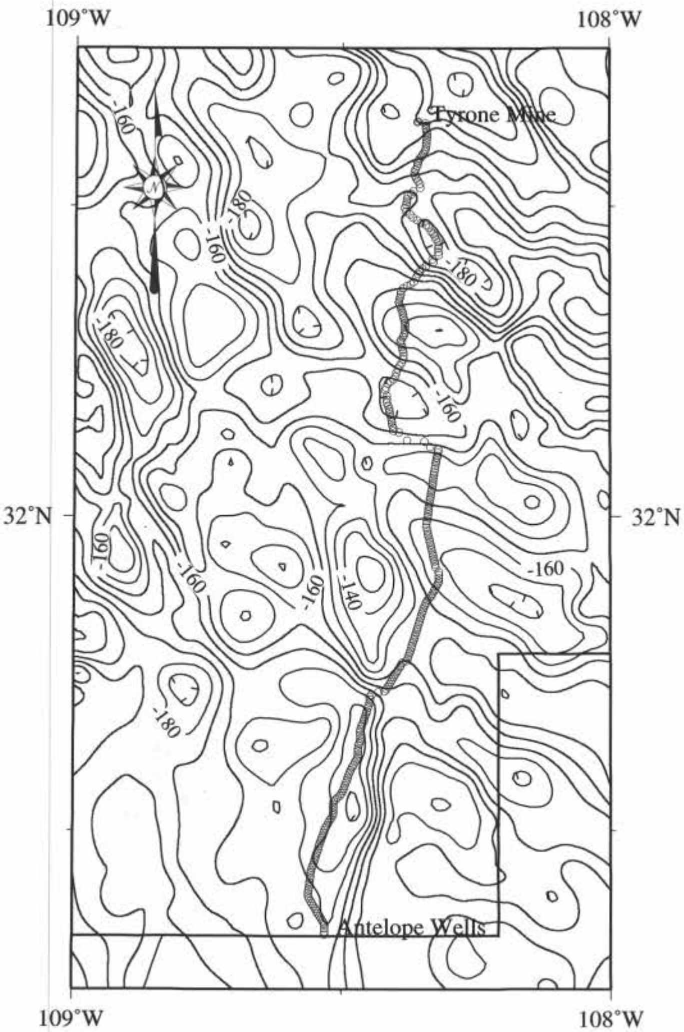

Figure 2. A Bouguer gravity map in the area of the seismic profile showing the lack of a regional gradient along the length of the profile. Contour interval is 5 mGals. Seismic stations are shown as circles.

is near Deming; however, more crustal-scale information is needed in southwestern New Mexico and adjacent parts of Arizona to provide a definitive answer to this question. This study is a first step in providing the new data required.

PROCESSING AND INTERPRETATION OF THE SEISMIC DATA

The first step in the processing flow of data from the new seismic instruments is to retrieve the data collected and convert them into a format that can be accessed by a seismic-data processing package. During this step, previously surveyed location information is integrated with the seismic data, the desired time window of data is cut from the larger record, and clock corrections, although small, are applied. The data were then bandpass filtered (4–20 Hz) to remove noise, gained to compensate for attenuation, and plotted with a reducing velocity of 6.0 km/s (Fig. 3) to give arrivals a more horizontal moveout.

The seismic profile is not reversed and there is little evidence from the gravity data (Fig. 2), such as a north–south regional gradient, to indicate significant crustal thickening or thinning in the north–south direction. These data are therefore interpreted using the assumption that the deep crustal structure of the earth in this area consists of flat-lying layers of uniform thickness. This assumption greatly simplifies the interpretation by reducing the number of variables in the model. Based on refracted and reflected arrivals present in the seismic section (Fig. 3), a three-layer earth model overlying the upper mantle was considered adequate to describe the generalized crustal structure in this area. Because of the limited data available, travel-time curves were calculated analytically assuming the three-layer model above and fitted by trial and error to the data on the seismic section.

The uppermost layer consists of sedimentary and/or volcanic rocks with a modeled thickness of 1.0 km and P-wave velocity of 5.1 km/s. The direct arrival that travels within this layer is labeled as P on Figure 3. Arrival times due to this layer vary considerably over the length of the profile because of near surface horst-and-graben structure and the southward increase in thickness of pre-Cenozoic strata. Grabens with substantial Tertiary basin fill are seen as delays in the first arrivals from the Pg phase (upper crustal refraction) in Figure 3. For example, between 50 and 60 km, Tertiary basin fill delays the Pg arrival nearly one second. The Pg arrival is picked where it arrives earliest, where the Tertiary basin fill is shallowest. The second layer is the crystalline upper crust with a thickness of 22 km and a P-wave velocity of 5.88 km/s. It corresponds to a combination of the two upper crustal layers observed by Gish et al. (1981) and Sinno et al. (1986) and the upper and middle crustal layers of Schneider and Keller (1994). The refracted arrivals traveling in the upper part of this layer are labeled Pg on the record section and the reflection from the bottom of this layer is labeled PcR (Fig. 3). We see no evidence, such as a reflected arrival between P and PcR, to resolve two layers in this part of the crust. The third layer is the lower crust with a thickness of 12 km. Below this layer is the Moho and the reflection from it is labeled PmP on the record section. The thickness of the crust south of the Tyrone mine is ~35 km, somewhat thicker than the 31–33 km found by Gish et al. (1981), Sinno et al. (1986), and Schneider and Keller (1994). This however may be due to the fact that this seismic profile is unreversed.

An additional arrival seen on the record section (Fig. 3) is a reflected S-wave arrival from the Moho (SmS). S-waves are not usually recognized on seismic sections where only the vertical component of ground motion is recorded. This is because the seismograms are too widely spaced for S-waves to appear as coherent arrivals. Because of the 500 m station spacing in our profile, the S-waves appear as a strong coherent arrival on the record section from 55 km offset to the end of the line at 145 km. S-waves can also be recognized by their low apparent velocity of approximately 4 km/s, that is drastically different from the high velocities of P-wave arrivals. The SmS arrivals are modeled well with an upper crustal S-velocity of 3.5 km/s and a lower crustal S-velocity of 3.8 km/s.

CONCLUSIONS

Results from this wide-angle profile differ from previous results in the area (Gish et al., 1981; Sinno et al., 1986; Schneider and Keller, 1994) in that only a single layer is observed in the upper and middle crust. This may be due to a change in geology or because the reflection from the interface between the upper and middle crust, which is weak at best, may be obscured by the long wavetrain generated by the ripple blast used in the mine. The depth to the lower crust is 23 km and corresponds well with the results of both Sinno et al. (1986) and Schneider and Keller (1994). The modeled Moho depth of 35 km is at least 2 km greater than seen in nearby studies. At Tyrone, the crust is thicker than either to the east (Sinno et al., 1986) or the west (Gish et al., 1981). Our results may indicate a gradual thickening of the crust in the area south of Tyrone toward the Sierra Madre Occidental. This crustal thickening is reflected in the average topography that is higher along this seismic profile than along the profiles to the east and west. This profile crosses the Continental Divide twice and lies within 30 km of the Continental Divide throughout its length. The crustal thickness of 35 km is about 5 km greater than observed in the adjacent areas of the Rio Grande rift and Basin-and-Range province in central Arizona.

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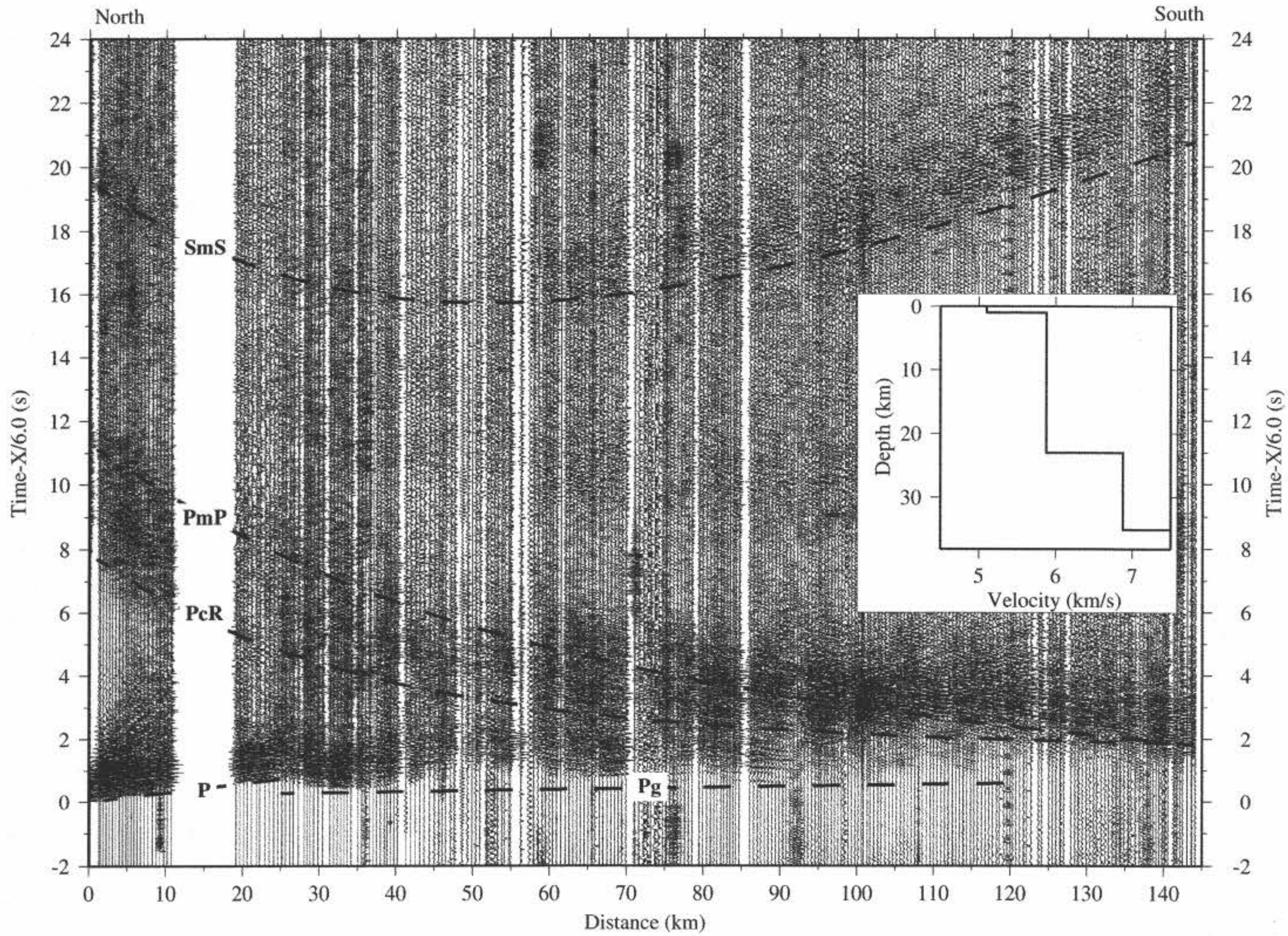

Figure 3. The wide-angle seismic section plotted with a reducing velocity of 6.0 km/s. Modeled arrivals are indicated with black dashed lines. P is the direct arrival traveling in the uppermost layer. Pg is the refracted arrival traveling in the second layer. PcR is the reflected arrival from the bottom of the second layer at a depth of 22 km. PmP is the reflected arrival from the Moho at a depth of 35 km. SmS is the reflected S-wave arrival from the Moho. Inset contains velocity-depth model derived from these arrivals.

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