

CDROM Interstation Pn Study Along the Rio Grande Rift

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Upper mantle velocities in the regions of the Rio Grande rift and the Southern Rockies were investigated using Pn waves from the broadband seismic data obtained from the Continental Dynamics - Rocky Mountain (CDROM) experiment. A velocity of 7.8 +/- 0.1 km/s on the eastern flank of the Rio Grande rift in New Mexico was measured from epicentral distance vs. travel time data for ten Pn measurements from a south-western New Mexico earthquake that was in-plane with the southern CDROM line. Thirty-two interstation Pn measurements were made using eight western United States earthquakes. Using these measurements another bulk velocity estimate was made by solving for the best-fit velocity for interstation distances and travel times; this method also shows that the upper mantle beneath the Rio Grande rift has a slow velocity of 7.8 +/- 0.1 km/s. This low velocity is consistent with the high heat flow in the Rio Grande rift area and the evidence of modern rifting. Individual measurements made in the north end of the southern Rocky Mountains are near the global average Pn value of 8.1 km/s.

1. INTRODUCTION

The Continental Dynamics - Rocky Mountain (CDROM) passive source seismic experiment studies the effects of the assembly, stabilization, and reactivation of the western United States by providing constraints on the modern crust and mantle structure. The present day mantle structure may reflect past tectonism and/or a reactivated tectonic regime. More specifically, the seismic velocity of the upper mantle can help us determine the physical state of the upper mantle and the presence of current tectonic activity.

Two simultaneous deployments of 48 seismometers continuously recorded seismic activity from April of 1999 until June of 2000. The broadband instruments recorded local, regional and teleseismic earthquakes. The seismic stations

were arranged in two NNE-SSW trending lines, which coincide with the active seismic source studies. Station locations are provided in Figure 1 and Table 1. The combination of the passive-source and active-source studies will provide us with both a detailed understanding of the shallow subsurface and a glimpse at the deeper structure of the mantle. The northern seismic line extended from Rawlins, Wyoming to Steamboat Springs, Colorado and traversed the ancient suture zone between the Archean Wyoming province and the Proterozoic Yavapai province. The southern line extended from the San Luis Basin in Colorado to Las Vegas, New Mexico and crossed the suture zone between the Yavapai province and the younger Mazatzal province. The southern line is also very proximal to the Rio Grand rift and the recent tectonism in the Jemez lineament.

The southern deployment was in place from April of 1999 until March of 2000 and the northern line was in place from June of 1999 until June 2000. Periods of bad weather and equipment malfunction caused some power outages, especially at the beginning of the experiment, but for the most part a good signal was continuously recorded throughout the experiment. The deployment consisted of 25 instruments

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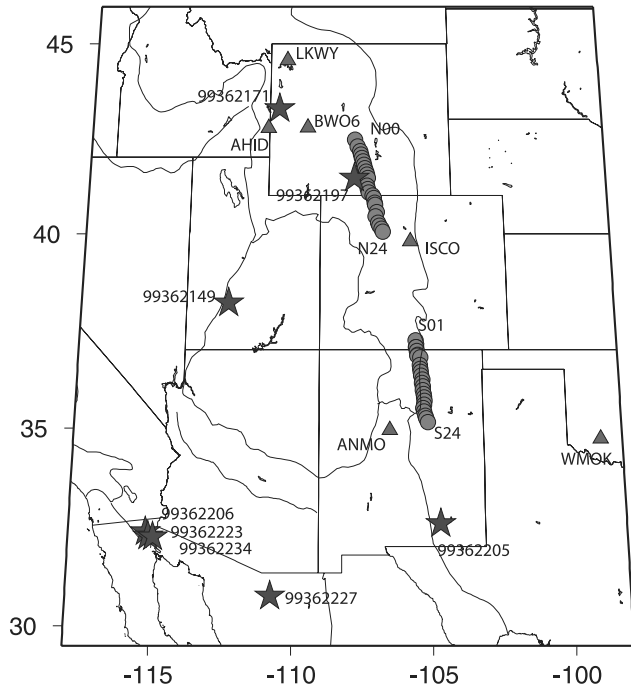


Figure 1. Map showing the location of the CDROM stations and the earthquakes used in this study. The stations are shown as circles and the earthquakes are shown as stars. The station spacing is approximately 10 km.

across the northern suture zone and 23 across the southern suture zone. The instruments included 27 STS-2 seismometers, 15 CMG3T seismometers and six CMG40T seismometers. The sampling rate of the experiment was 25 samples/sec for the beginning (April - October) of the experiment and then was reduced to 10 samples/sec. The sampling rate was reduced because inclement weather would prevent the sites from being visited in the winter; therefore a lower sampling rate was needed in order to preserve field disk space. The stations were arranged in a linear, north-northwest trending array with station spacing at approximately 10 km. This short interstation distance was necessary in order to document possible abrupt changes in the mantle that may correspond to terrane boundaries.

This study contributes to the spirit of the Continental Dynamics project by providing an independent data set that can be used to enhance the findings of researchers working in other areas of seismology and earth science. The upper mantle seismic velocities obtained in this study could potentially enhance the crustal and upper mantle seismic velocity models developed by the researchers working on the active source seismic data. The active source studies often use PmP, a reflected phase, to determine the depth to the Moho, but this phase offers little information on the upper mantle velocities.

The results from this study will provide an additional constraint for the near-surface structural model.

2. INTERSTATION PN STUDY

The arrangement of the CDROM stations in a NNW-SSE linear array was a tradeoff between crossing the province boundaries in a normal sense and recording teleseismic events for in-plane tomography and other analysis. However, it severely limited the number of events that could be used for interstation velocity analysis. Interstation velocity analysis has the advantages of reducing error due to earthquake mislocation and constraining the measured velocities to a finite location. The interstation Pn analysis requires an earthquake to be within three degrees of the same great circle path as two seismic stations. In order to create more suitable interstation paths, the study was supplemented with data from IRIS Global Seismographic Network (GSN) station ANMO and United States Geological Survey - United States National Seismograph Network (USGS - USNSN) stations AHID, BW06, ISCO, LKWX and WMOK.

The locations of the earthquakes that were used in this study are shown in Figure 1 and Table 2. These locations were taken from the USGS Preliminary Determination of Epicenters (PDE) bulletin. The seismic phase of most interest in this study is Pn. Pn is a refracted body wave that travels in the uppermost mantle. It is the first arrival when station-earthquake distances are between 2 and 16 degrees [Beghoul and Barazangi, 1989]. When the source-station distance is less than 2 degrees the first arrival is Pg, when the distance is greater than 16 degrees the first arrival is P. The minimum distance where Pn becomes the first arrival is known as the crossover point. The crossover point depends on a variety of factors such as crustal thickness and velocity and mantle velocity. Pn arrivals were picked on stations that had a clear Pn arrival and that were on the same great circle path as another station for that same event. The stations were determined to be on the same great circle path as the events when the azimuth between the stations was within three degrees of the azimuth from each station to the event. A difference of three degrees provokes a velocity difference of less than 1% over our average interstation distance. There were eight earthquakes that fit the requirements for the study; these eight events produced 32 velocity measurements. The velocities were calculated by dividing the distance between the two stations by the difference in the Pn arrival time at the two stations (t_a and t_b) as shown in equation (1)

$$Velocity = distance\ between\ stations / (t_a - t_b) \quad (1)$$

Calculated velocities are given in Table 3. All of the velocities in Table 3 fall within an acceptable range of Pn values and

were picked from clear Pn arrivals. Velocities that were < 7.4 km/s or > 8.5 km/s were discarded due to an obvious error in selecting the phase. The northern CDROM stations produced velocities from 7.87 km/s to 7.99 km/s. The southern CDROM velocities ranged from 7.48 km/s to 8.4 km/s with a mean of 7.9 km/s. The uncertainties for this study were estimated by using the extrema of possible arrival time picks to find the maximum and minimum possible velocity. The average Pn velocity uncertainty was 0.04 km/s.

Due to a small number of events, it was difficult to determine variations in Pn velocity on similar interstation paths. There were three repeat paths in the study with a standard deviation of 0.02 km/s. Ten stations, and one event, 99362205, (Located in SE New Mexico, 75 miles SE of Roswell, New Mexico, May 30, 1999, ml=3.9, depth = 10 km) produced twenty-two measurements. Four of the eight events produced only one measurement each and three events produced two measurements.

Only three events were in locations suitable for the interstation analysis using the northern stations. Event 99362149 (located in SW Utah, January 2, 1998, ml = 4.5, depth = 5 km) gave a velocity of 7.94 km/s between AHID and LKWY. Event 99362171 (located in western Wyoming, June 20, 1998, ml = 4.4, depth = 0 km) provided a velocity of 7.99 km/s between BW06 and ISCO. Event 99362197 (located in south-

ern Wyoming April 6, 1999, ml = 4.3, depth = 10 km) gave a velocity of 7.87 km/s between ISCO and WMOK.

Event 99362205, located in southern New Mexico, was nearly perfectly aligned with both the northern and southern CDROM lines. Unfortunately, the northern stations had not yet been deployed at the time of this event and the event was only clearly recorded at ten southern stations. The other events used for the southern station analysis (99362206, 99362223, 99362227, 99362234) were located in northern Mexico and all utilized station ANMO in the interstation measurements. Event 99362227, located in northern Mexico at a SW azimuth from the CDROM south line, gives a particularly low velocity of 7.6 km/s and is discussed further in the next section.

Since event 99362205 was recorded at the most stations and was aligned with the southern CDROM line we calculated the upper mantle velocity in the Rio Grande rift region with data from that event. We plotted epicentral distance vs. the total phase travel time for event 99362205, shown in Figure 2. The scatter in the data set is rather insignificant, ± 0.2 s. This small amount of variation can be caused by lateral variations in earth structure such as topography on the moho, station elevation, and slight differences in the Pn picks.

We also calculated the upper mantle velocity using all of the southern interstation travel time and distance data from the

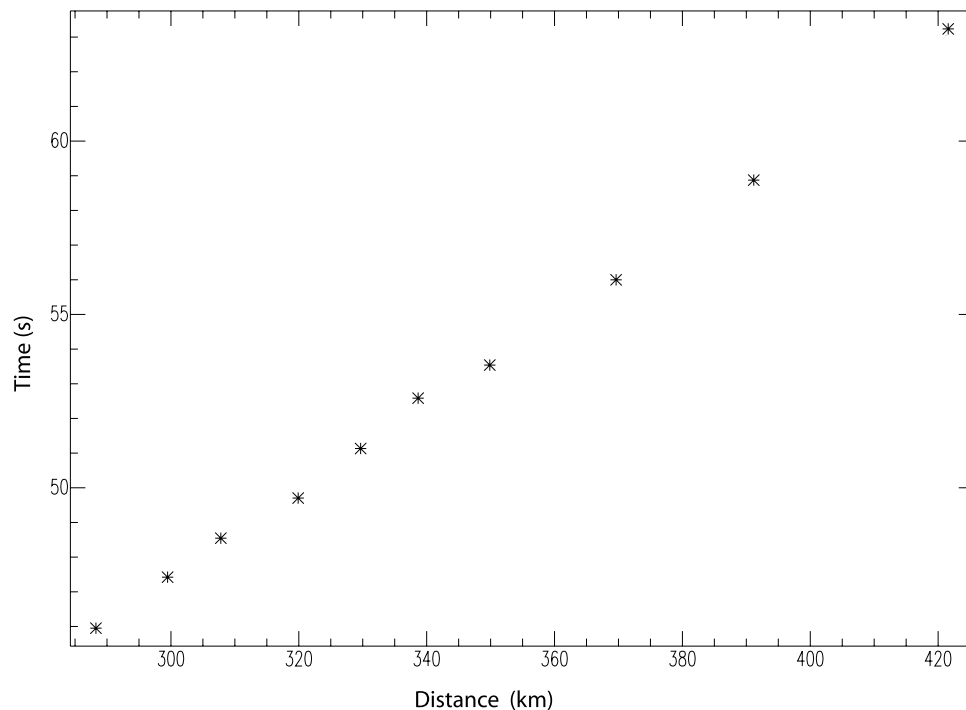


Figure 2a. Plot showing epicentral distance vs. Pn travel time for event 99362205. Ten stations recorded a clear Pn arrival for this event.

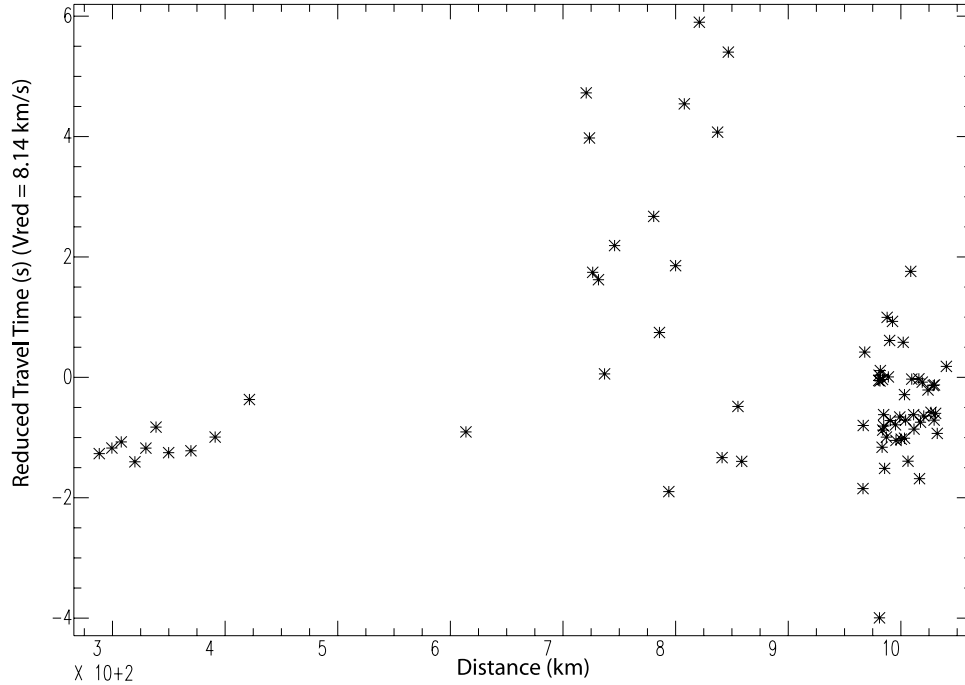


Figure 3. Reduced velocity plot showing data from the eight stations used in the interstation study. Each data point represents the distance between a two-station pair plotted against the interstation travel time. The best fit velocity for the data set is 7.83 ± 0.12 km/s.

eight western US events. We plotted interstation distance vs. interstation travel time. A Pn velocity of 7.8 ± 0.12 km/s best fit this data. The data is shown in a reduced velocity plot with a reduction velocity of 7.83 km/s in Figure 3.

3. DISCUSSION

We characterize the upper mantle in the Rio Grande rift area using the velocity of 7.8 ± 0.1 km/s. This velocity was achieved through two methods: calculating the best-fit line through our distance vs. travel time data for one event (99362205) and by using all of the interstation travel time and distance data available for the southern stations. The individual velocity measurements can be seen plotted at the interstation midpoints in Figure 4. The particularly low velocity produced by event 99362227 may be due to an interstation path that lies almost entirely within the Rio Grande rift. The NE-SW alignment of the ray path from event 99362227 is in the direction of the dominant fast SKS polarization direction for the region (Fox and Sheehan, this issue) thus the slow Pn velocities are inconsistent with the regional mantle anisotropy. Robust Pn estimates for the region are not available. A Moho dipping down to the north could also produce slow Pn velocities along this path. However, the Moho

imaged by CDROM receiver functions beneath the CDROM South line (where the majority of our interstation paths are) is nearly flat [Zurek and Dueker, 2001; Karlstrom et al., 2002]. The Rio Grande rift has a thin crust, slow Pn velocities, and high heat flow. Previous unreversed seismic profiles show the Pn velocity beneath the southern Rio Grande rift is about 7.7 km/s [Olsen et al., 1979]. The northern portion of the rift exhibits a Pn velocity of 7.7–7.8 km/s, which is much slower than the velocity of 8.2 km/s reported for the Great Plains [Stewart and Pakiser, 1962] but is very similar to the values of 7.7 km/s reported in the Basin and Range [Keller et al., 1976]. A Rayleigh wave dispersion study [Sinno and Keller, 1986] also shows low Pn velocities (7.7 km/s) in the Rio Grande rift. The low Pn velocity we observe is consistent with the Pn velocities in other tectonically active areas [Hearn et al., 1991]. The Basin and Range province displays a similar Pn velocity of 7.8–8.0 km/s [Hearn et al., 1991]. The Snake River Plain also displays a low Pn velocity (7.9 km/s), this is due to thermal heating. Heat flow measurements in the Rio Grande rift are varied and complex, but in general they are very high at about $75\text{--}125$ mWm⁻². Near surface anomalies can locally elevate heat flow measurements up to 160 mWm⁻² [Keller et al., 1990]. These high heat flow values are consistent with a low Pn velocity. The velocities measured adjacent

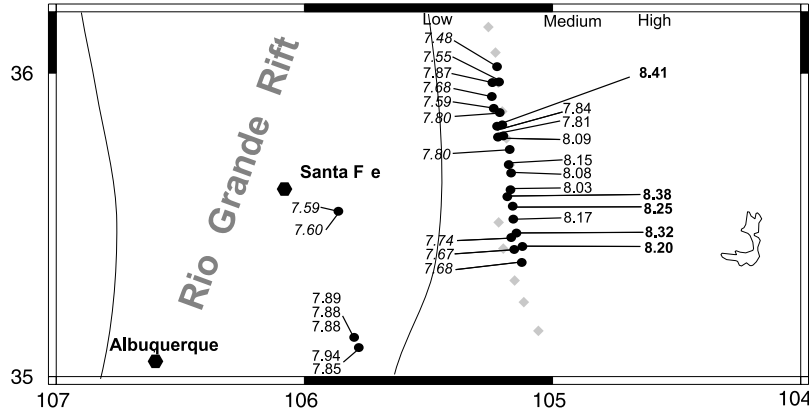


Figure 4. Pn velocities plotted at the midpoint of the stations used for calculation. Italicized numbers represent velocities < 7.8 km/s, regular numbers are velocities between 7.8 and 8.2 km/s, bold numbers are > 8.2 km/s.

to the Rio Grande rift are comparable to the velocities measured in the Eastern Great Basin making it hard to distinguish between the two provinces based on upper mantle Pn velocities. The presence of high mantle temperatures in a rifted area was also shown to exist beneath the Kenya rift [Fuchs *et al.*, 1997; Prodehl *et al.*, 1994]. The rift exhibits low velocities of 7.5–7.8 km/s while the adjoining unrifted craton has Pn velocities of 8.1–8.3 km/s. This is similar to the slow velocities of the Rio Grande rift and the adjoining Great Plains.

We have showed the upper mantle velocities surrounding the Rio Grande rift are slower than the surrounding Great Plains. The slower velocities can be attributed to elevated mantle temperatures and/or partial melt. Davis *et al.* [1993] find an 8% velocity reduction from the global average beneath the Rio Grande rift. This velocity reduction is attributed to 1% partial melt. We see only a 3–4% velocity reduction, at a shallower depth observed by Davis *et al.* [1993]. There is a strong correlation in between elevated upper mantle temperature and low Pn velocities [Hearn *et al.*, 1991; Black and Braile, 1982]. It seems clear that the low Pn velocities we are observing are also strongly correlated to a raised mantle temperature.

We also tested whether individual Pn velocity measurements could be interpreted or if they may be influenced by Moho topography. The individual velocities measured have a variance of 6%. These variations may be due to changes in the upper mantle, but they also might be due to variations in Moho topography. We are using relatively short interstation path lengths for this study, therefore a small variation in Moho topography may represent a considerable percentage of the total path length. The CDROM refraction/wide angle reflection study [Rumpel, 2001] and receiver function study [Zurek, 2001] show a maximum crustal thickness variation of 5 km over the area we are observing. Using forward modeling we

measure the potential influence of Moho topography on velocity over our average interstation path length of 90 km. We see that 5 km of Moho topography can influence the apparent Pn velocity by up to 7% of 8.0 km/s. Our measured velocities vary 6% from 8.0 km/s therefore we cannot believe individual velocity measurements for they may reflect Moho topography and not the state of the upper mantle. The results of Zurek *et al.*, [2001] show a coarse picture of Moho topography. Our undulating pattern of results may reflect this topography variation as well as variations on a smaller scale.

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