Seismic Investigation of the Yavapai-Mazatzal Transition Zone and the Jemez Lineament in Northeastern New Mexico

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A new seismic reflection profile of the Precambrian lithosphere under the Jemez Lineament (JL) (northeastern New Mexico, USA) shows impressive reflectivity throughout the crust. The upper crust is characterized by a 2 km thick undeformed Paleozoic and Mesozoic sedimentary sequence above the Precambrian basement. At a depth of 5–8 km, undulating reflections image a Proterozoic nappe cropping out in the nearby Rincon Range. To the south the upper crust is seismically transparent except for south dipping reflections at 2–10 km depth. The middle-lower crust, from 10–45 km depth, shows oppositely dipping reflections that converge in the deep crust (35–37 km) roughly at the center of the profile. To the north the reflectivity dips southward at 25° to a depth of 33 km before fading in the lower crust. In the southern part of the profile a crustal-scale duplex structure extends horizontally for more than 60 km. We interpret the oppositely dipping reflections as the elements of a doubly vergent suture zone that resulted from the accretion of the Mazatzal island arc to the southern margin of the Yavapai proto-craton at ~1.65–1.68 Ga. Subhorizontal high amplitude reflections at 10–15 km depth overprint all the reflections mentioned above. These reflections, the brightest in the profile, are interpreted as mafic sills. Although their age is unconstrained, we suggest that they could be either 1.1 Ga or Tertiary-aged intrusions related to the volcanic activity along the JL. We further speculate that the Proterozoic lithospheric suture provided a pathway for the basaltic magma to penetrate the crust and reach the surface.

1. INTRODUCTION

Geologic and geophysical investigations in the southwestern US suggest that Proterozoic accretionary boundaries have had a persistent influence on the tectonic and magmatic evolution of the Southern Rocky Mountain lithosphere for as long as 1.8–1.6 Ga since initial continental assembly. Here, the northeast-striking fabric established during cratonic assembly has provided, to varying degrees, a preferred path for the modification of the lithosphere during the various Phanerozoic orogenic and magmatic events that modified the western margin of the North American plate.

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During cratonic assembly, tectonic elements of various scales up to lithospheric-scale were incorporated in the Laurentia super-continent and the boundaries between these elements persisted as shallowly to steeply dipping structural and chemical boundaries, some of which appear to have been reactivated during subsequent magmatism or/and tectonic deformation. Geophysical, geological and geochemical data show that these northeast-striking boundaries influenced the sedimentation throughout the Paleozoic, for example, controlling the location of mineralization and mantle-derived magmatism in the Tertiary (see Colorado Mineral Belt, Jemez Lineament as examples) [*Tweto and Sims*, 1963].

Despite the long-lived influence of some of these assembly boundaries, the details of the nature, structure, and tectonic role of these features have not been determined clearly. The southern segment of the Continental Dynamics of ROcky Mountains (CD-ROM) active source seismic experiment [*Prodhel et al.,* this volume] targeted the boundary separating the Yavapai and Mazatzal terranes, two Paleoproterozoic island arc terranes with different geochemical signatures. As discussed below, the location and nature of this boundary is still hotly debated. We have interpreted from the reflection profiles that the Yavapai-Mazatzal boundary in central New Mexico represents a doubly vergent accretionary suture and that it coincides with the modern-day Jemez Lineament, a Tertiary-Quaternary volcanic trend stretching from Arizona across New Mexico to southern Colorado. From the regional point of view the geometry of the features recognized in the seismic data provides an explanation for the elusive and diffuse character of this boundary. More generally the coincidence of the Proterozoic suture with the Tertiary volcanic centers of the Jemez Lineament suggests that collision zones play a persistent (and active) role in the evolution of the lithosphere. In the case of the Proterozoic suture studied, the weakness zone in the crust, and likely in the mantle, acted as a locus of tectonism and provided a preferred pathway for the mantle to penetrate the crust. The seismic data document a multifaceted tectonic history with crustal scale structures that have survived since continental accretion, and Tertiary igneous structures that are an expression of the processes that modify the lithosphere today.

2. THE YAVAPAI-MAZATZAL TRANSITION-ZONE

The Southern Rocky Mountains region has experienced a complex geologic history recording lithospheric assembly during Paleo-Proterozoic time (1.8–1.6 Ga), intracratonic magmatism during the Mesoproterozoic (1.44–1.35 Ga), incipient rifting (1.1–0.5 Ga), development of the ancestral Rockies during the Paleozoic (350–290 Ma) and, more recently, Laramide tectonism during the Cretaceous-Paleogene (75–45 Ma) and Tertiary extension, magmatism and uplift [see *Karlstrom and Humphreys*, 1998 for a review].

The Proterozoic continental assembly produced an area of accretion ~1200 km wide that includes major crustal provinces defined on the basis of their composition and age: the Archean Wyoming Province (with protoliths and deformation between 2.5–3.5 Ga), the Mojave Province (pre-1.8 Ga crustal material to a 1.75 Ga arc), the Yavapai Province (1.76–1.72 Ga juvenile arc crust deformed during 1.70 Ga Yavapai orogeny) and the Mazatzal province (1.7–1.6 Ga supracrustal rocks) (see Karlstrom et al., [this volume] for a review). The exposed boundaries separating these provinces have a general northeast strike but exhibit extremely different characters. Unlike the Cheyenne belt, which abruptly separates the Archean and Proterozoic crust, boundaries between the Proterozoic terranes of the Mojave and Yavapai and Yavapai and Mazatzal are diffuse and transitional zones where changes include isotopic (Pb and Nd) differences of the crust, timing of deformation (before 1.7 Ga for the Yavapai Province, between 1.66 and 1.60 Ga for the Mazatzal Province), and character of crustal xenoliths (P-T paths and rock types). The Yavapai-Mazatzal crustal boundary in the Southern Rocky Mountains is a 300 km wide region with tectonically intermixed rocks of the two provinces. The northern edge of the transition zone is defined by the northern limit of the Mazatzal-age (1.7–1.65 Ga) deformation in southern Colorado [*Shaw and Karlstrom*, 1999]. The southern margin of the transition zone coincides approximately with the Jemez Lineament in northern New Mexico.

3. THE JEMEZ LINEAMENT

The Jemez Lineament is defined on the basis of the NE-trending alignment of Tertiary-Quaternary volcanic centers [*Mayo*, 1958] of variable-width extending more than 800 km from the White Mountains-Springerville, Arizona, volcanic field at the southern margin of the Colorado Plateau, through the Jemez Mountains [*Aldrich*, 1986], to the Raton-Clayton center and into the western Great Plains of New Mexico. The volcanic rocks along the lineament range in age from 16.5 Ma to 1200 B.P. [*Gardner and Goff,* 1984] and are dominantly basaltic with a few silicic volcanoes. The alkali basalts show great petrologic variation along the lineament, attributed to distinct source zones in the mantle, different crustal contaminants and variable differentiation. Petrologic observations on the alkali basalts at the northeastern end suggest a cratonic mantle source that is distinct from the asthenospheric signature of the magmas in the southern end of the lineament [*Perry et al.*, 1987]. The volcanic activity along the Jemez lineament exhibits no time progression: volcanism began at 13.2 Ma in the middle of the lineament, at about 9.8 Ma at the southwestern end, and at 8.2 Ma at the northeastern limit.

Karlstrom and Daniel [1993] have proposed that the Jemez Lineament is a broad zone coinciding with the southern edge of the Yavapai-Mazatzal crustal boundary in northern New Mexico, as it also corresponds to a band of northeast-trending magnetic highs located south of the volcanic centers [*Zietz*, 1982] that exhibit right lateral offsets across north-striking faults.

Tomographic studies of the mantle underneath the Jemez lineament in New Mexico show a pronounced low-velocity anomaly of 1–2% within the regional 5–7% low-P-wave-velocity zone. The anomaly is 200 km long and 100 km wide and lies in the depth range of 50–160 km [*Spence and Gross*, 1990] suggesting the presence of melt in upper mantle rocks. Similar conclusions come from a *Dueker et al.*'s [2001] tomographic investigation, which also images a south-dipping low-velocity anomaly between depths of 100 and 300 km.

Tectonic activity along the Jemez Lineament is also recorded by incisions along the Canadian River in northeastern New Mexico. These geomorphic features support a Plio-Pleistocene arching and flexure along the Jemez Lineament with uplift rates of ~0.06–0.07 mm/yr [*Wisniewski and Pazzaglia*, 2002].

4. CD-ROM YAVAPAI-MAZATZAL TRANSITION-ZONE PROFILE

One of the two CDROM reflection profiles collected in 1999 [*Prodhel et al.*, this volume] was designed to investigate the crust of the Jemez Lineament and the transition zone between the Yavapai and Mazatzal Provinces. The profile extends north and south of the town of Las Vegas, New Mexico, which sits at the southern edge of the Jemez Lineament. The data were acquired with Vibroseis® sources and 1001 active recording channels on a 25 km-long seismograph array, with a 25 m group interval, and 100 m source interval. Nominally the array configuration was a 10 km/15 km split spread. Sweep frequencies ranged 8–60 Hz and sweep time was 20 s. A "listening" time of 45 s resulted in record lengths of 25 s. The profiles extend north-south for approximately 170 km, just to the east of the Front Range Fault that borders the Proterozoic outcrops of the Sangre de Cristo Mountains (Figure 1), and between the volcanic centers that define the Jemez Lineament and the band of magnetic highs. Exposures of uplifted Precambrian rocks in the Sangre de Cristo Range west of the seismic line show complex polyphase deformation and metamorphism that include several episodes of Paleoproterozoic shortening and Mesoproterozoic emplacement of plutons at middle and upper crustal depths.

4.1. Seismic data processing

The seismic processing sequence (Table 1) focused on improving the S/N ratio by removing organized noise. In order to account for differences in outcrops north and south of Las Vegas, we chose different filter parameters for the two segments of the southern CD-ROM profile. However the processing parameters of the two seismic segments are very similar, permitting the combination of the final migrated sections into a composite display.

The seismic data generally exhibit good S/N ratio with reflections visible at offsets up to 14 km and up to 10 s time on shot gathers. The most commonly identified noise on the data includes reverberations generated in the subsurface, surface (Rayleigh) waves, air waves, 60 Hz electrical power-line noise, and incoherent ambient or cultural noise.

After correlating the data, we resampled to 6 ms and assigned a crooked-line geometry. The common-midpoint bin size is 12.5 m. Careful trace editing and air-wave mutes preceded a frequency-wavenumber filter applied to mitigate surface wave noise. We applied prestack static elevation corrections to source and receivers using a constant replacement velocity of 3800 m/s shifting the traces to a final reference datum elevation of 2200 m.

We applied predictive deconvolution to the data in order to reduce the surface and inter-bed reverberations present in the seismic records. Trace autocorrelations indicated that the dominant period of the main reverberation was about 70 ms for the northern part of the profile (north of Las Vegas) and about 65 ms for the southern part (south of Las Vegas). Our tests showed that a prediction distance of 42 ms and 30 ms gave the best results for the northern and the southern sectors respectively, with deconvolution-operator lengths of 500 ms (north) and 200 ms (south) and a white noise level of 0.1%.

A time-variant bandpass filter (8-12-45-55 Hz at t=0-3 s, 8-12-38-42 Hz at t= 3-6 s to 8-12-32-36 Hz at t=6-20 s) attenuated power line noise and frequencies outside the bandwidth of interest. We applied an automatic gain control (AGC) function with a time gate of 1 s in order to increase the amplitude of weak reflections and to gain deeper portions of the data.

We performed velocity analysis using common velocity stacks (CVS) and common-midpoint (CMP) velocity spectrum analysis in order to determine normal move-out corrections (NMO). We used CVS to develop a preliminary stacking velocity field, which we then refined with velocity-spectrum measurements made every 600 m along the profile. Velocity estimates deteriorate below 8–10 s. Data were then NMO-corrected and stacked. On the stack section, we identified several prominent reflections then computed and applied surface-consistent residual static corrections to prestack data, followed by another velocity-spectrum analysis to further refine the stacking velocity field. The results of the processing are shown in Figure 2.

We depth migrated the stacked section to 60 km using a Kirchhoff algorithm. For depth migration we converted the final stack-

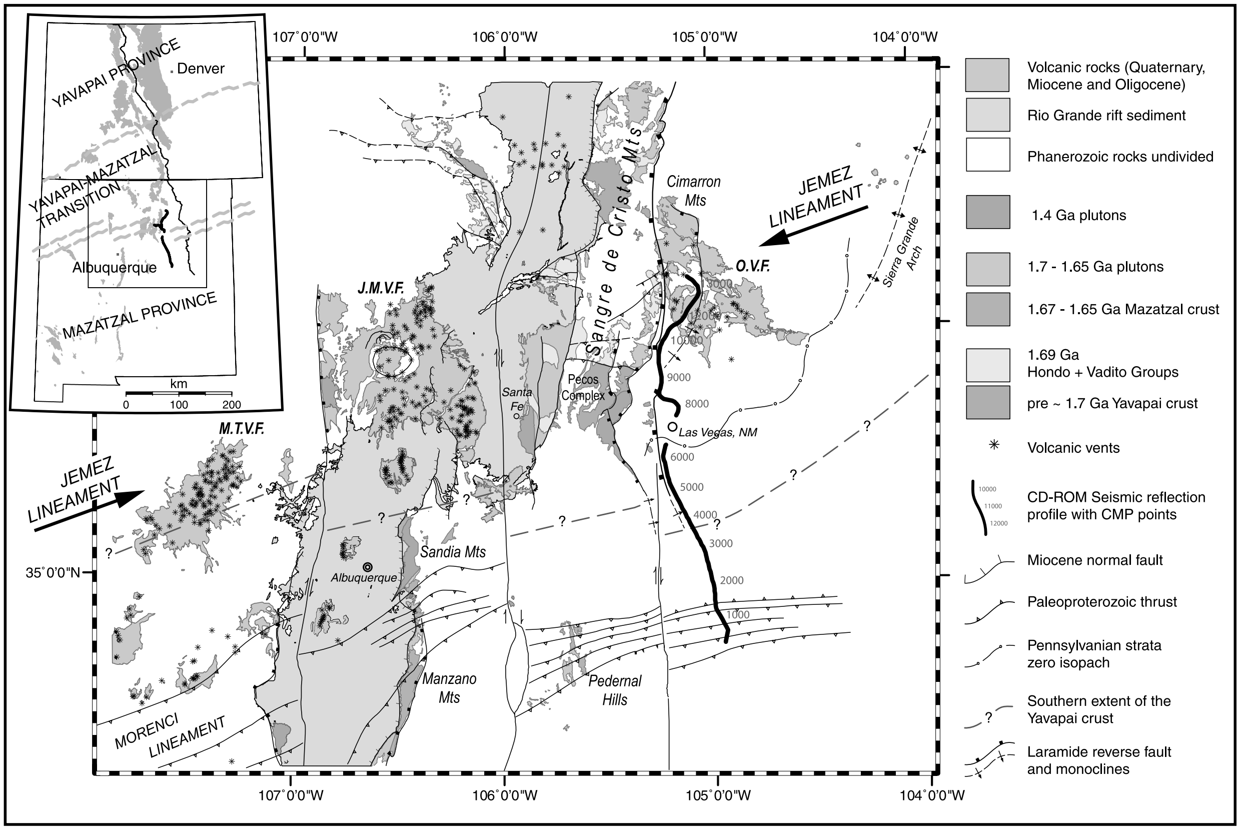

Figure 1. Location map showing the two segments of the CD-ROM seismic lines, the Jemez Lineament and the Proterozoic outcrops in the area of investigation. **M.T.V.F.-** Mount Taylor Volcanic Field, **J.M.V.F.-** Jemez Mountain Volcanic Field, **O.V.F.-** Ocate Volcanic Field.

ing velocities to interval velocities in depth. This velocity field was then smoothed and reduced in magnitude. We performed several migrations, testing different fractions (90% – 80%) of the migration velocity field. We also migrated the data with the refraction velocity model obtained from the CD-ROM seismic refraction profile recorded almost coincident with the reflection profile [*Snelson*, 2002; *Levander et al.*, this volume; *Prodhel et al.*, this volume]. Migration with the refraction velocity model led to overmigration of shallow (0–20 km depth) events while correctly migrating the deeper portion of the profile. The final velocity function resulted in the integration of both fields (velocity field determined by CMP analysis reduced by 10% from 0–35 km and refraction velocities for depths >35 km). The section was adequately migrated to 60 km, with an aperture of 20 km. For display purposes, traces were equalized along the seismic profile, amplitudes were squared and the absolute value of each sample was plotted (Figure 3).

4.2. Observations

Figure 3a is the depth-migrated profile shown to a depth of 50 km. The seismic image exhibits impressive reflectivity at upper-middle crustal depths with conflicting dips, some reflections at lower crustal depths, and a reflection-free upper mantle. This structurally complicated image is consistent with the long and complex geologic history of this area. Reflectors are identified as A-E in Figure 3b.

At shallow depth (2 km), a single high-amplitude, subhorizontal and laterally continuous event crosses the northern half of the profile (Figure 3b: Event A). Above this marker is an almost undeformed sedimentary section that gradually thins southward until it disappears south of ~CDP 8000. At the very southern end of the profile (~CDP 0–2000) the same sedimentary packages are visible again at a depth of 2 km for a distance of 25 km.

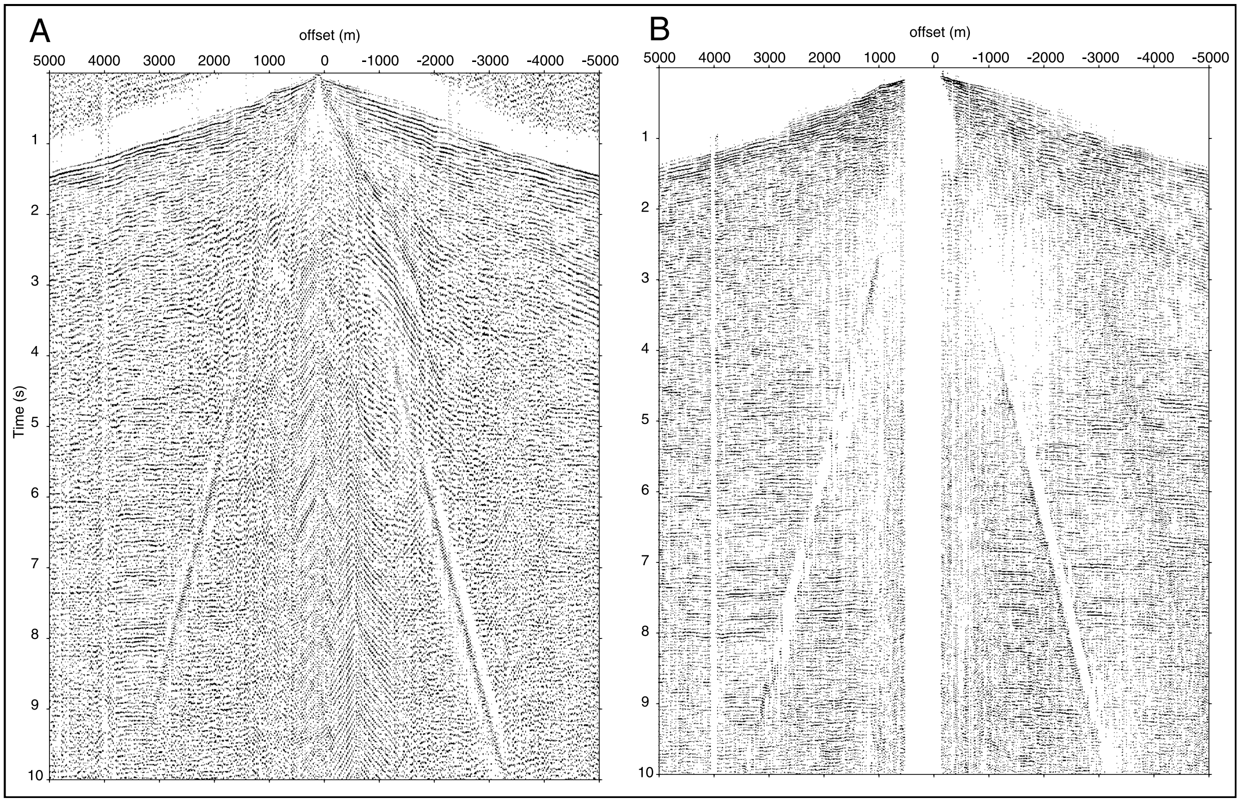

Figure 2. Comparison between the same shot gather pre a) and post b) seismic processing. Air-wave as well as low frequency surface-wave noise is removed from the processed data and reflections emerge throughout the middle and lower crust.

In the north beneath the discontinuity (A) and extending to 8 km depth are other continuous strong reflections that depict a gently to strongly folded and faulted structure (B1, CDP 9500–13500). Figure 4 shows the northern end of this feature and the overlying unconformity (A). To the south, this reflectivity dies out into a featureless region south of CMP 9500. South of Las Vegas, NM (~CDP 7000, Figure 3), the upper crust appears mostly transparent except for three south dipping reflectors at 3–10 km depth (E, Figure 3) at the southern end of the profile (CDP 0–2500).

At 8–14 km depth is a system of bright nearly continuous reflections (C, Figure 3) that form an arch extending more than 100 km with an apex beneath Las Vegas (CDP 7000). In the north these bright reflections are visible at CDP 10000–12500 at 14–25 km depth, where they overprint an 8 km-thick band of south-dipping reflectors (D1). The D1 reflectors extend from 10 km depth at the northern edge of the profile, to ~33 km depth near CDP 11000, a distance of about 34 km. No additional reflectivity is observed at lower and middle crustal depths in the north. To the south, the entire middle and lower crust is occupied by continuous north-dipping bright reflections (D2) that delineate what we interpret to be a crustal duplex. The structure has a maximum thickness of 27–30 km and extends more than 50 km (CDP 1500–6800), thinning to 10 km at about 33 km depth at CDP 6800. South of the crustal duplex, another set of north-dipping reflectors enters the profile at 25 km depth and is traceable down to a depth of 43 km at CDP 2000 (D3).

Despite careful processing and analysis (see discussion below) no clear and continuous reflections from the Moho discontinuity were detected. To the south, the reflectivity dies out uniformly at about 40–45 km whereas to the north only scattered reflectors can be traced below 33 km depth.

4.3. Interpretation

The interpretation (Figure 3b) of reflectors A and B is based on borehole data, surface outcrops and projections from geologic maps [*Baltz*, 1999]. Reflector A can be interpreted with certainty as the Great Unconformity, above which is an almost undeformed section of Phanerozoic sedimentary sequences [*Powell*, 1876]. The Great Unconformity and the overlying sedimentary rocks exhibit almost no deformation for a distance of 90 km except for the southward thinning of the Phanerozoic

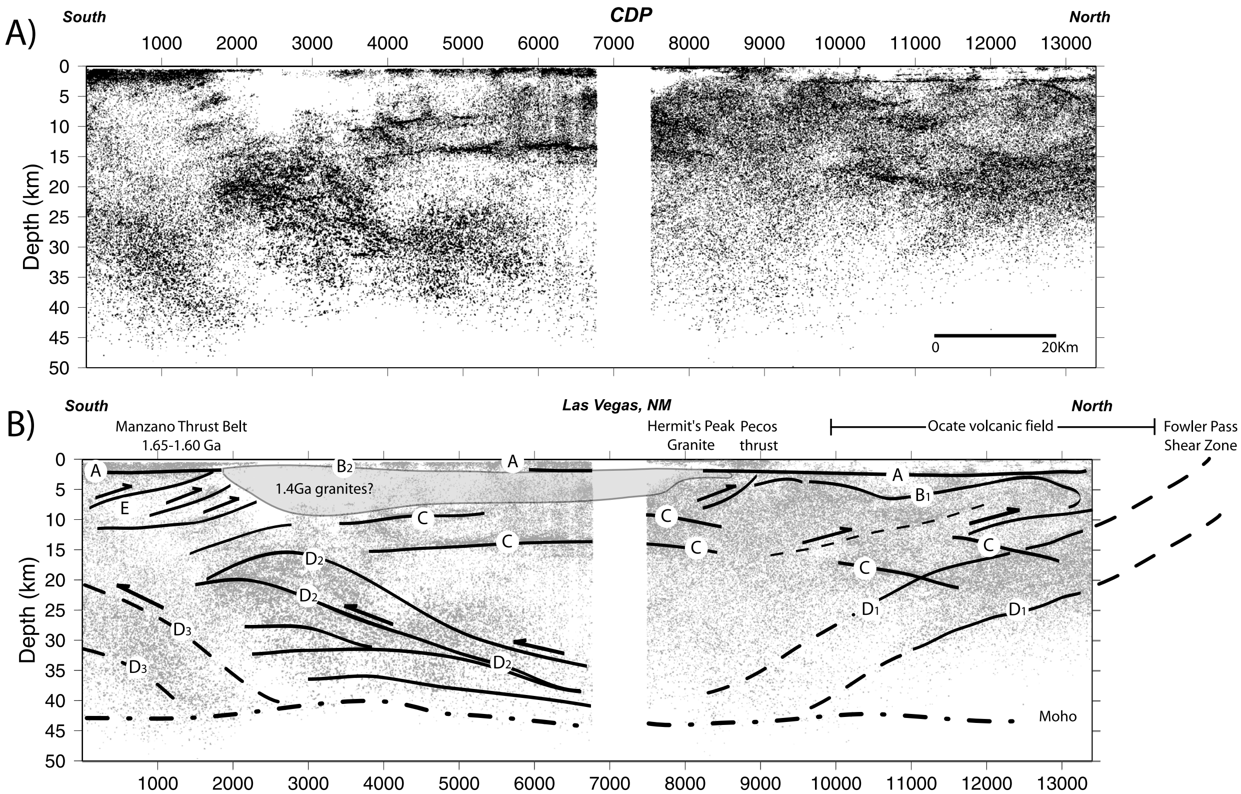

Figure 3. a) Seismic profile migrated displayed to a depth of 50 km; b) Interpretation. A) Great Unconformity; B1) Allochtonous Proterozoic supracrustal rocks; B2) top of the "granitic" crust; C) Proterozoic (1.1 Ga) or Tertiary mafic intrusions; D1, D2, D3) Proterozoic doubly vergent suture associated with the arc-continent collision during the 1.68–1.65 Ga Mazatzal orogeny; E) Manzano thrust belt (1.60 Ga).

sequences due to the uplift associated with the Sierra Grande arch. The uniformity of the Great Unconformity and overlying sediments shows that little deformation occurred this far east after the Pennsylvanian-Mississippian. The absence of shallow, well-organized reflections between CDP 1800–5000 is partially due to late Paleozoic high-angle faults that dissect the sedimentary cover and the underlying Precambrian rocks [*Broadhead and King*, 1988], obliterating the seismic signal. The base of the shallow reflectivity (B2) is interpreted as the contact between the Precambrian basement and the inferred granitic crust (see below).

We interpret the undulating horizon and overturned fold (B1), imaged just below the Great Unconformity at a depth of 3–5 km, as the subsurface expression of Proterozoic nappes that were uplifted by Laramide thrusts in the Rincon Range (southern Sangre de Cristo Mountains) to the west (Figure 1). Exposed in these ranges is the lower limb and part of the hinge of a north-facing fold-nappe that is imbricated by several south-dipping, top-to-the-north ductile thrusts, and that is cored by the 1.68 Ga Guadalupita granitic gneiss [*Riese*, 1969; *Read et al.*, 1999]. The granite, exposed at the Guadalupita and El Oro domes, intruded the supracrustal rocks and deformed synchronously with the overturned fold [*Read et al.*, 1999]. The seismic image (Figures 3 and 4) exhibits remarkable correspondence with the surface geology, showing clearly the reflections that compose the whole nappe on the northern end of the profile (CDP ~9000–13700), with the overturned limb defined by a 1200 m-thick quartzite layer (Ortega Formation), a regional stratigraphic marker in the 1.69 Ga Hondo Group. The section exposed in outcrops shows that the bedding of the recumbent fold is pervasively deformed in tight parasitic folds and suggests that the structure imaged by the seismic section is, in fact, the envelope of these folds. This horizon is cut by several Precambrian age thrust faults that sole at depths of 7–8 km. The seismically transparent crust above the Ortega Formation is likely a result of a dominant vertical foliation that overprints and obscures any previous geometry, producing a transparent or diffractive seismic response [*Levander et al.*, 1994]. Geobarometry and geothermometry data [*Read et al.*, 1999] indicate that the nappe formed at a paleodepth of

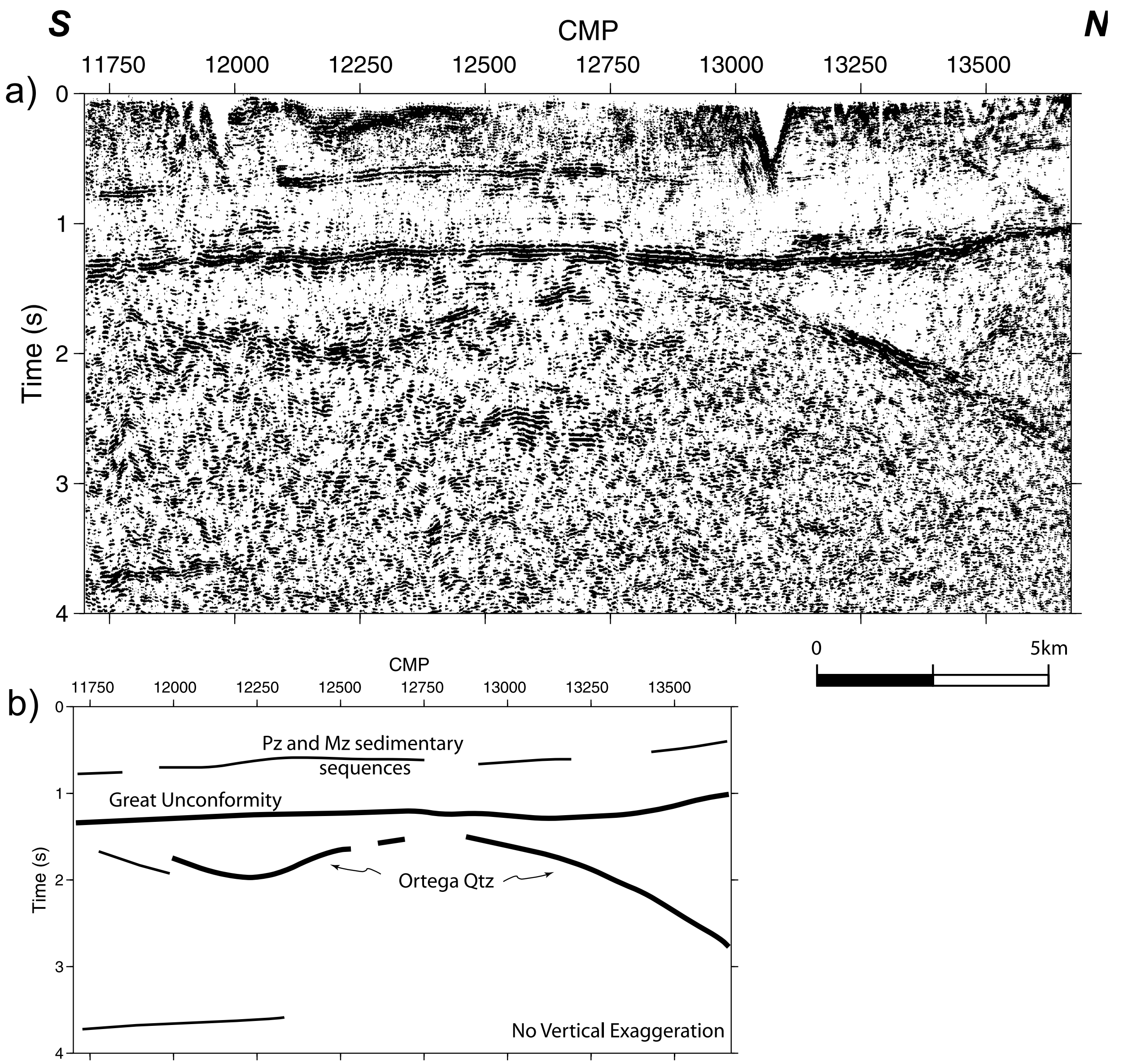

Figure 4. a) Detail of the nappe structure; b) Interpretation. The nappe is outlined by the ~1200 m-thick cross-bedded nearly pure quartzites of the Ortega Formation. The Proterozoic nappe shows a remarkable correspondence with the compressive structure outcropping at the Rincon Range, to the west. The Pennsylvanian-Mississippian Great Unconformity separates the Paleozoic and Mesozoic sedimentary rocks of the Las Vegas basin from the Proterozoic basement rocks.

12–18 km (4–6 kbar pressure and 650 °C), making it a mid-crustal, likely brittle-ductile transition zone structure.

Where the reflectivity loses coherence south of CDP 9000 (Figure 3), the south-dipping Pecos Thrust ductile shear zone crops out above the ~1.4 Ga Hermit's Peak granite [*Read et al.*, 1999]. Due to the lack of continuous Proterozoic outcrops south of Las Vegas, the extent of this magmatic body is unknown. However we suggest that the transparent upper crust imaged by the seismic profile from CDP 2000 to CDP 8500 is made up of granitic bodies that intruded the crust during several Proterozoic tectonic events. Granitic plutons, 1.4 Ga in age, are exposed in numerous locations in New Mexico and particularly in the Sandia and Manzano Mountains (Priest and Sandia plutons), 120 km west of the seismic profile. Although a 1.6 Ga age cannot be ruled out, we speculate that the granitic bodies were emplaced during the 1.4 Ga "anorogenic" magmatic event [*Karlstrom and Humphreys*, 1998].

Since none of the deep reflectors (D1, D2 and D3) reaches the surface within the length of the seismic profile, or can be unambiguously associated with any nearby outcropping structure, the interpretation of the deeper portion of the profile is based on the island arc collision model for growth of the southwest U.S. [*Hamilton*, 1981; *Bowring and Karlstrom*, 1990] and mechanical models for development of doubly-vergent compressional orogens [e.g. *Willet et al.*, 1993]. The southward-dipping reflection package (D1) and the crustal duplex structure (D2) define a doubly-vergent compressional orogen that we speculate formed during the 1.65 Ga Paleoproterozoic collision of the Mazatzal island arc with the Yavapai proto-continent, synchronous with the mid to upper crustal nappe structure (events B1) lying above its northern half. The main elements of the orogen, D1 and D2, are interpreted respectively as a north-verging, south-dipping shear zone system associated with the thrusting of Mazatzal supracrustal rocks above the Yavapai basement and as a north-dipping south-verging duplex structure that accommodates the back thrusting of the Mazatzal tectonic units. The suture zone occupies the present thickness of the crust for a length of 170 km and represents the crustal expression of the lithospheric boundary between the Yavapai and the Mazatzal provinces. Rocks above the suture are tectonically and magmatically mixed elements of both the Yavapai and Mazatzal provinces, whereas we speculate that rocks below (D1) are Yavapai basement. Such an interpretation is supported by exposures of the Fowler Pass shear zone in the Cimarron Mountains, north of the profile, which may be the projection to the surface of D1 reflectivity.

The Fowler Pass shear zone is considered a fundamental Proterozoic crustal boundary as it juxtaposes profoundly different rock types characterized by diverse deformation histories: high-grade quartzites and syenites (interpreted as derived from a supracrustal passive-margin environment) to the south, and greenschist-grade calc-alkaline arc rocks and greenstones (associated with a convergent margin environment) to the north [*Grambling et al.,* 1993]. The shear zone has a long history of reactivation (*Carrick*, 2002) and, although no constraints on activity before 1.4 Ga exist, the oldest fabric on both sides of the fault is ca. 1.7 Ga (Andronicos, pers. comm). According to surface geology, rocks above D1 are mixed metasedimentary, meta-volcanic and meta-plutonic rocks related to both the Mazatzal and the Yavapai blocks, tectonized during large-scale thrusting of an island arc onto the southern edge of the proto-North American continent. To the south, the duplex structure is probably formed by Mazatzal basement rocks thrust to the south to accommodate shortening associated with the arc-continent collision. The north-dipping reflectivity labeled D3 could represent the deeper portion of an outer back thrusting system. At a much shallower depth, the three south-dipping reflectors (E) south of CDP 2500, underlying the Great Unconformity reflector and truncated by it, are interpreted as the eastward continuation of the 1.65–1.60 Ga Manzano Thrust Belt [*Thompson et al.*, 1991], exposed at the Manzano Mountains and Pedernal Hills, 120 km and 60 km west of the seismic profile respectively.

The interpretation of the complex set of bright reflections (C on Figure 3) relies mainly on their seismic character (high amplitude, continuity, depth range, etc.) and on observations from both surface exposures and well data. The reflections stand out clearly on individual field records as well as on the depth-migrated section, with amplitudes of 9–10 dB above the background reflectivity (Figure 6). We interpret them as mafic intrusions, based also on the evidence of many other seismic profiles around the world that imaged reflectors with similar attributes [e. g. *Goodwin et al.*, 1989; *Ross and Eaton*, 1997; *Papasikas and Juhlin*, 1997]. The age of these intrusions is more difficult to constrain and we propose two alternative possibilities: Mesoproterozoic or Tertiary. Evidence for a major mafic magmatic episode in New Mexico of 1.1 Ga age comes from outcrops in the Pecos Mafic Intrusive Complex [*Keller et al.*, 1989; *Adams and Miller*, 1995] and from well data where a 1.09 Ga gabbro intruded metasedimentary and metavolcanic rocks of the Debaca sequence [*Amarante et al.*, 2000]. On the other hand, Tertiary to recent basaltic magmatism is widespread in this region and is both associated with the Rio Grande rift and with the Jemez Lineament [*Baltz*, 1999; *Green and Jones*, 1997]. Although the Rio Grande rift magmatism has not affected the area where the seismic profile is located, the northern part of the seismic profile crosses into the Quaternary Ocate volcanic field, one of the centers that define the Jemez Lineament. The composition of the exposed lavas ranges from alkali olivine basalts to dacites 8.0–0.3 my in age and indicates crustal contamination by mixing of a basaltic melt with a crustal granodiorite [*Nielsen and Dungan*, 1985] suggesting that these magmas have ponded at several crustal levels during their ascent through the crust. We speculate that they have used preexisting zones of weakness or faults of Precambrian or/and Laramide age as conduits from the mantle. These observations indicate that the complex, layered, bright reflections could represent the intrusive counterpart of the extrusive rocks associated with the Jemez Lineament. Due to the very recent age of the magmatic activity, it is also possible that the bright reflections correspond to molten magma.

Lower crustal reflectivity changes along the profile and fades out at about 40–43 km south of Las Vegas. To the north, the reflective packages terminate shallower at about 33–35 km and only intermittent reflectivity is observed in the lower crust. No reflections from the Moho are detected along the pro-

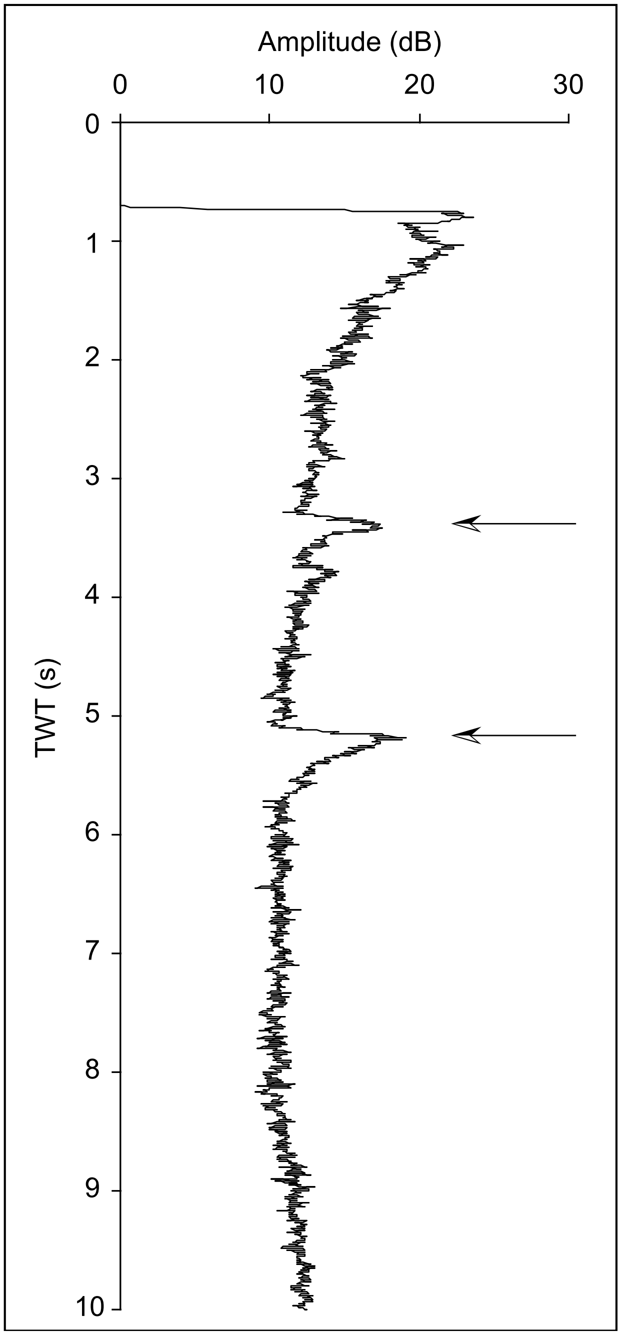

Figure 6. Amplitude plot of the bright reflections (C) roughly at CDP 5200. Amplitude decay curve is averaged over several traces of a shot gather. Arrows indicate the locations of the bright reflections where the amplitudes are 9–10 dB above the background reflectivity. The slight increase of amplitude strength at the bottom of the curve (~9 s) is due to the reflectivity of the duplex structure (reflectors labeled D2 in Figure 3).

file. CD-ROM seismic refraction data, collected parallel to the reflection profile at a distance of 50 km, show a 43–45 km thick crust [*Snelson*, 2002; *Levander et al.*, this volume], in good agreement with the observation of the termination of the lower crustal reflectivity on the reflection profile.

The absence of continuous Moho reflections was investigated through analysis of amplitude and frequency decay patterns [*Barnes*, 1994]. Analyses were performed on shot gathers with minimal processing. Decay plots of the southern and the northern segment of the profile show that amplitude values are above the noise levels down to 17 s time to the north and down to 18 s to the south, after which no further decay is observed (Figure 5 a and b). Coincident refraction data detect the Moho at about 13.5 s (TWT) along the reflection profile, the depth at which the deepest reflectivity is observed on the stacked section. Moho reflections are also visible at short offsets in the refraction data at frequencies of 1–6 Hz, well below the frequency range of the reflection data. The analysis therefore shows that signal penetration is adequate to image the Moho and upper mantle reflectivity and that the lack of strongly reflective zones or reflections at these depths is probably a genuine geologic feature.

5. DISCUSSION

Interpretation of reflector (A), the Great Unconformity, and (B1), a remarkable Precambrian nappe structure, are well correlated with local and regional geology. The Great Unconformity is a province-wide feature well documented in local stratigraphic studies [*Baltz*, 1999]. The nappe is an accretionary structure in the paleo-middle crust that we discuss further below.

The interpretation of deeper portion of the profile (i.e. reflection package (D), the Precambrian suture) is based on the accretionary model for the continents [*Hamilton*, 1981] and geodynamic models of bivergent orogens [*Willet et al.*, 1993]. The interpretation of the almost flat bright events (C) as the Proterozoic or Tertiary-modern magmatic features is based on circumstantial geologic evidence and the reflection character.

The accretionary model for the lithospheric growth of the southwestern US invokes the southward amalgamation of island-arc lithospheric fragments to the craton along a northeast-striking continental margin [*Karlstrom and Bowring*, 1990]. In this setting we interpret reflectors (D1 and D2) and the overlying nappe structure (B) as part of a lithospheric suture that resulted from the collision of the Mazatzal island arc and the Yavapai Province during the Paleoproterozoic. The north-verging structures (reflectors B and D1) and the south-verging crustal duplex (D2 reflectors) define the doubly vergent orogen that identifies at depth the northeast-trending boundary between the Yavapai and Mazatzal Provinces as defined by *Karlstrom and Bowring*, [1988]. The nappe

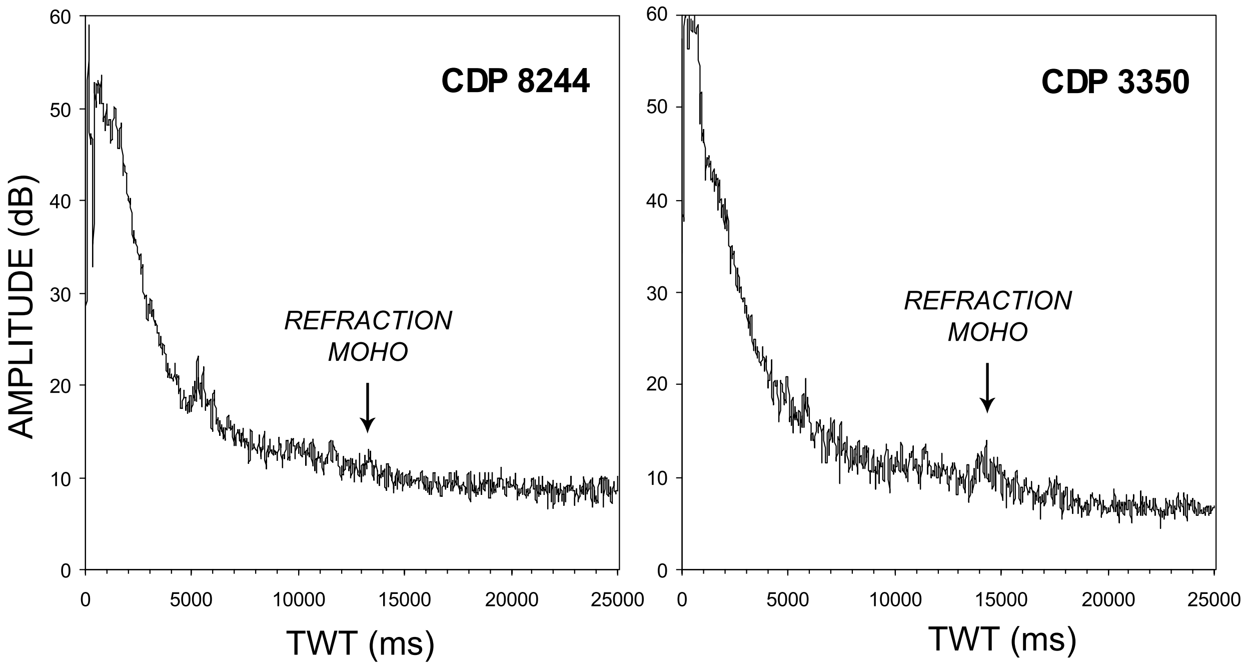

Figure 5. Amplitude-decay curves of two different CDP locations of the profile in Figure 3, north (CDP 8244) and south (CDP 3350) of Las Vegas. No processing was applied on analyzed data. Amplitudes were horizontally stacked and plotted. Amplitudes appear to flatten at about 17 s, well below the time of the Moho (~13.5 s) detected by the nearby CD-ROM refraction profile [*Levander et al.,* this volume; *Snelson et al.,* this volume]. An increase of reflectivity is observed at 14.5 s in the southern segment (CDP 3350) corresponding to the refraction Moho boundary. The bright reflections (C) are visible at ~5 s on CDP 8244.

structure, formed at paleo-midcrustal levels, deformed in the brittle-plastic region, and was probably at least partly decoupled from the deeper suture structures (D1) by a series of thoroughgoing thrust faults that deepen beneath the nappe into broader shear zones with decreasing seismic signature as the rheological regime becomes more ductile. Surface outcrops suggest that the uppermost part of the suture (above D1 and D2) is composed of intermixed metasedimentary, metavolcanic and metaplutonic rocks of both the Yavapai and Mazatzal terranes that were pervasively deformed in the ductile regime during the Mazatzal orogeny [*Conway and Silver*, 1989]. The geometry of the low angle accretionary structures that propagate throughout the crust provides an explanation for the diffuse character of the Mazatzal-Yavapai boundary.

The seismic fabric of the imaged Proterozoic suture resembles in scale and geometry that of younger doubly vergent orogens like the Alps. Similarly to the Alpine orogeny we infer that the collision between the Mazatzal arc and the Yavapai continent followed the subduction of the Yavapai passive margin and that the bivergent geometry was achieved through the continuous convergence after the collision [*Schmid et al.,* 1996].

The data presented here suggest that the region of penetration of the original Paleoproterozoic suture may have persisted as a crust-mantle weakness zone, acting as a conduit for magma ascent into the crust. The interpretation of zone (C) as a series of ponded mantle-derived basaltic intrusions is based on surface geology, the proximity of a source, as well as the strength and geometry of the reflections. In agreement with these seismic data, surface geology, and the teleseismic mantle seismic results [*Humphreys and Dueker*, 1994; *Zurek and Dueker*, this volume] we speculate that the Proterozoic suture has provided a mantle-crust pathway for recent magmatism, which developed the overprint of bright reflectivity (C).

6. CONCLUSIONS

The seismic data examined here cross the Cenozoic Jemez Lineament in northern New Mexico and show two Proterozoic-age crustal structures, forming what we interpret as part of a major bivergent accretionary suture, that have largely survived subsequent tectonism. The Proterozoic suture marks the boundary between the Yavapai crust below, and tectonically mixed Yavapai-Mazatzal crust of the transition region above.

We interpret the overprinting reflections as basaltic intrusions, spatially coincident with the extrusive rocks of the Tertiary-Quaternary Jemez Lineament volcanic centers and with the bivergent orogen, suggesting that the suture has persisted in the crust as a zone of weakness for magma penetration until the present. Teleseismic results [*Dueker et al.*, 2001] show low velocities in the upper mantle to 120 km depth suggesting that the suture persists into the mantle, providing a source for basaltic magma generation.

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