The Yavapai-Mazatzal boundary: A long-lived tectonic element in the lithosphere of southwestern North America

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ABSTRACT

A seismic reflection profile crossing the Jemez lineament in north-central New Mexico images oppositely dipping zones of reflections that converge in the deep crust. We interpret these data as a Paleoproterozoic bivergent orogen, centered on the Jemez lineament, that formed during original Proterozoic crustal assembly by collision of Mazatzal island arcs with Yavapai proto–orth American continent at ca. 1.68 1.65 Ga. The two major sets of reflections within the Yavapai-Mazatzal transition boundary dip at 15° 20°, and we interpret them as part of a south-dipping thrust system and as a north-dipping crustal-scale duplex that formed synchronously with the thrust system. The upper crust shows structures recording a succession of tectonic and magmatic events from the Paleoproterozoic to the Holocene. Notable among these structures is a system of nappes that formed during development of the bivergent orogen. Elements of the nappe system are exposed in Rocky Mountain uplifts and have been dated as having formed at 1.68 Ga, at depths of 10 km and at temperatures of >500 °C. We also see continuous bright reflections in the upper part of the middle crust that we associate with basaltic sills that postdate accretion. The data show that the Yavapai-Mazatzal suture is low angle (~20°), an observation that explains why the boundary between the provinces has previously been so hard to define in the surface geology. The Jemez lineament overlies the root of this bivergent orogen that we also suggest is a Paleoproterozoic zone of weakness that has subsequently acted as a conduit for magmas and a locus of tectonism.

Keywords: inherited features, low angle boundary, transition zone, deep seismic profile, bivergent orogen.

INTRODUCTION

A widely accepted model for growth of the southwestern United States emphasizes Proterozoic southward accretion of juvenile lithosphere to the North American continent between 1.8 and 1.6 Ga (Hamilton, 1981; Bowring and Karlstrom, 1990). This model has subsequently been challenged by evidence for pre 1.8 Ga crust south of the Wyoming craton (Hawkins et al., 1996; Hill and Bickford, 2001), suggesting that recycling of previously accreted crust could have been a prominent process in the early stages of the tectonic history of the southwestern United States. Whereas locations with evidence for pre 1.8 Ga inheritance are found either proximal to Archean terranes (Hill and Bickford, 2001) or in the Mojave province (Hawkins et al., 1996), no evidence for an inherited component is found in either the Mazatzal province or most of the Yavapai province. This circumstance suggests that, at least in these provinces, the accretionary model remains the most plausible option.

The assembly boundaries, i.e., the sutures between accreted island arcs and oceanic fragments within these provinces, have always been difficult to identify. In spite of the large number of studies carried out in the southwestern United States, there is no agreement on the location and the nature of the Yavapai-Mazatzal boundary and no explanation for its transitional character. Likewise the significance of major tectonic lineaments in today's lithosphere has been controversial. The Jemez lineament, originally defined as an alignment of Tertiary–Quaternary volcanic centers (Mayo, 1958), is a northeast-trending, ~100-km-wide zone characterized by active uplift (Wisniewski and Pazzaglia, 2002), low seismic velocity in the mantle (Dueker et al., 2001), and repeated reactivation (Aldrich, 1986). Its southern edge also coincides approximately with the southern edge of a 300-km-wide transition zone between the Yavapai (1.8–1.7 Ga) and Mazatzal (1.7–1.6 Ga) Proterozoic provinces (Karlstrom and Humphreys, 1998). This paper presents new deep-crustal seismic reflection results across the Jemez lineament of New Mexico. On the basis of seismic and geologic data, we argue that the Jemez lineament represents both a Paleoproterozoic suture zone and a long-lived intracontinental tectonic and magmatic boundary.

The 170-km-long seismic reflection line (Fig. 1) was acquired in 1999 as part of the National Science Foundation Continental Dynamics Program within the Rocky Mountains Project (CD-ROM; CD-ROM Working Group, 2002). The profile, recorded with a 1001-channel system and Vibroseis sources (CDP [common depth point] interval = 12.5 m; source interval = 100 m; 8–60 Hz sweep), extends north-south just east of the Rocky Mountain Front Range faults, following the eastern edge of the outcrops of Proterozoic rocks in the Sangre de Cristo Mountains, and extends south of Las Vegas onto the Great Plains east of the Pedernal Hills (Fig. 1). The poststack depth-migrated seismic image (Fig. 2), although

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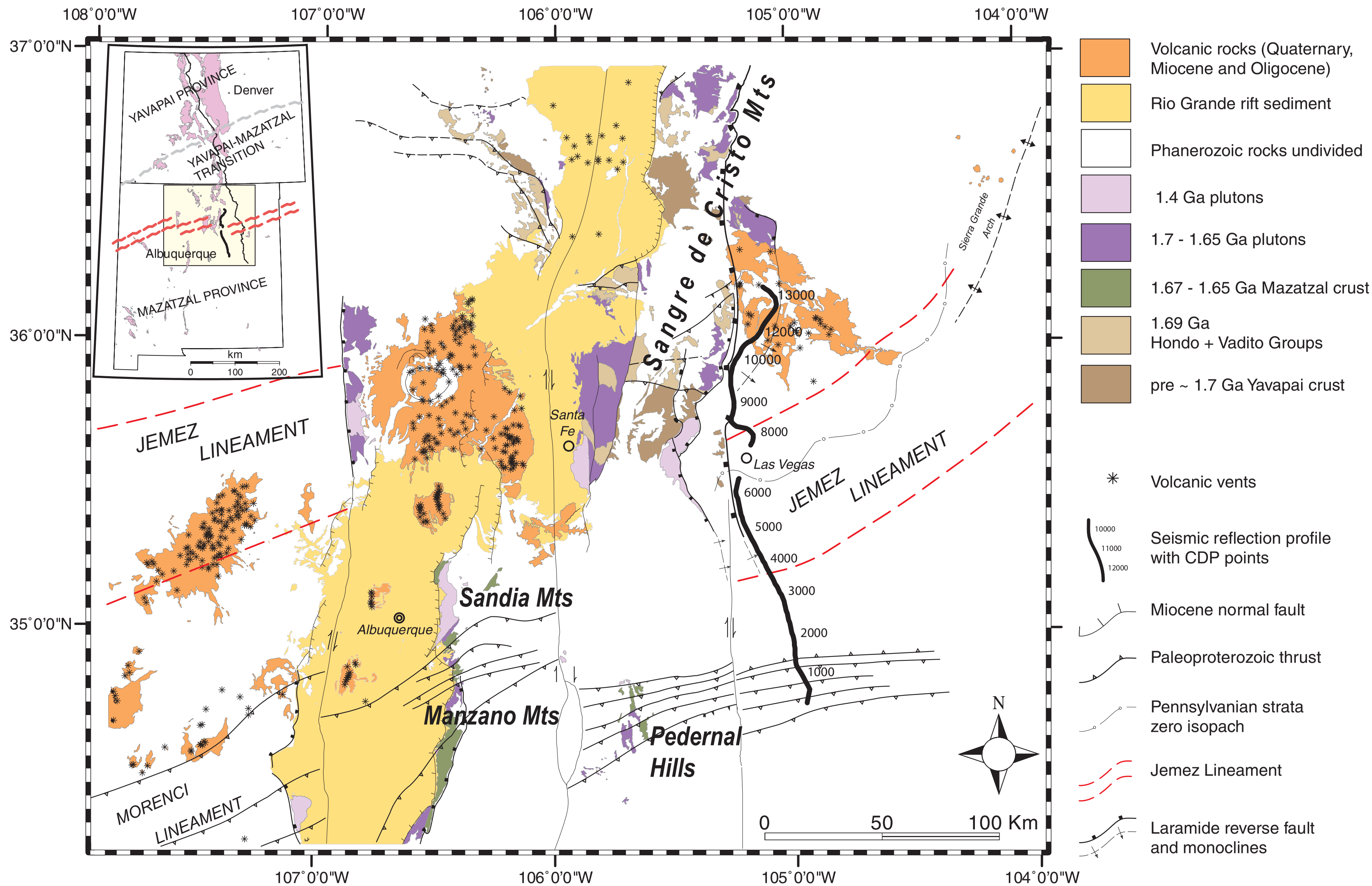

Figure 1. Simplified geologic map of the northern New Mexico showing basement rocks, Tertiary–Quaternary volcanic centers and Rio Grande rift sediments. CD-ROM seismic line is shown with CDP numbers (thick solid line). OVF—Ocate volcanic field; JMVF—Jemez Mountains volcanic field, MTVF—Mount Taylor volcanic field.

complicated, can be interpreted on the basis of present knowledge of the evolution of southwestern North America developed from surface mapping, geochemistry, and geochronology.

The striking features of the profile are (1) the prominent undeformed reflection at the base of the Paleozoic sedimentary rocks north of the Jemez lineament and the absence of this reflection to the south, (2) simple, bright, subhorizontal reflections in the upper and middle crust, (3) the change in the dip of reflectivity north and south of the Jemez lineament in the middle crust, and (4) the absence of significant Moho reflectivity. These features are described below from shallowest to deepest and are then discussed from oldest to youngest.

OBSERVATIONS

In the northern part of the profile, at shallow depth (2 km), a single high-amplitude and laterally continuous event (identified as A in Fig. 2) separates almost undeformed sedimentary rocks from folded and faulted basement structure. Depth to basement in the north is 2 km (1.2 s). This reflection shallows over the Sierra Grande uplift near Las Vegas, New Mexico, and in the south appears only intermittently at the shallowest resolvable depths (~300 m).

Immediately beneath the sedimentary cover in the north is a group of undulating coherent reflections (B1 in Fig. 2) extending to ~8 km depth that, upon close examination, are seen to be made up of a number of short reflection segments. The undulating reflectors disappear into a featureless region south of CMP 10500. South of CDP 6000 the basement is very shallow; the upper 2 km of the image bears a band of bright but diffuse reflectivity (B2) fading into a weakly reflective upper crust at 8–10 km depth. The continuity of this transparent region is interrupted by a system of bright, nearly continuous, reflectors at 10–12 km depth (C) that form an arch in the section over a length of >100 km. The apex of the arch is beneath Las Vegas, New Mexico. To the south, between CDP 1250 and CDP 2250 are three south-dipping reflections (E) traceable at depths of 2 to 10 km.

At depths of >8 km, the differences between the northern and the southern part of the profile are even more remarkable. In the northern section the bright reflectors (C in Fig. 2) at 12–15 km overprint a southward-dipping 8-km-thick band of reflectors (D1) that extends from 9 km depth at the northern edge of the profile, to ~33 km depth near CDP 11000, a distance of ~48 km. South of Las Vegas and below 10 km, the section exhibits numerous north-dipping continuous reflections (D2) that delineate a duplex. The duplex occupies the entire middle crust, having a maximum thickness of 27 km and a length of >50 km. The structure ends in the north at a depth of 30–35 km (CDP

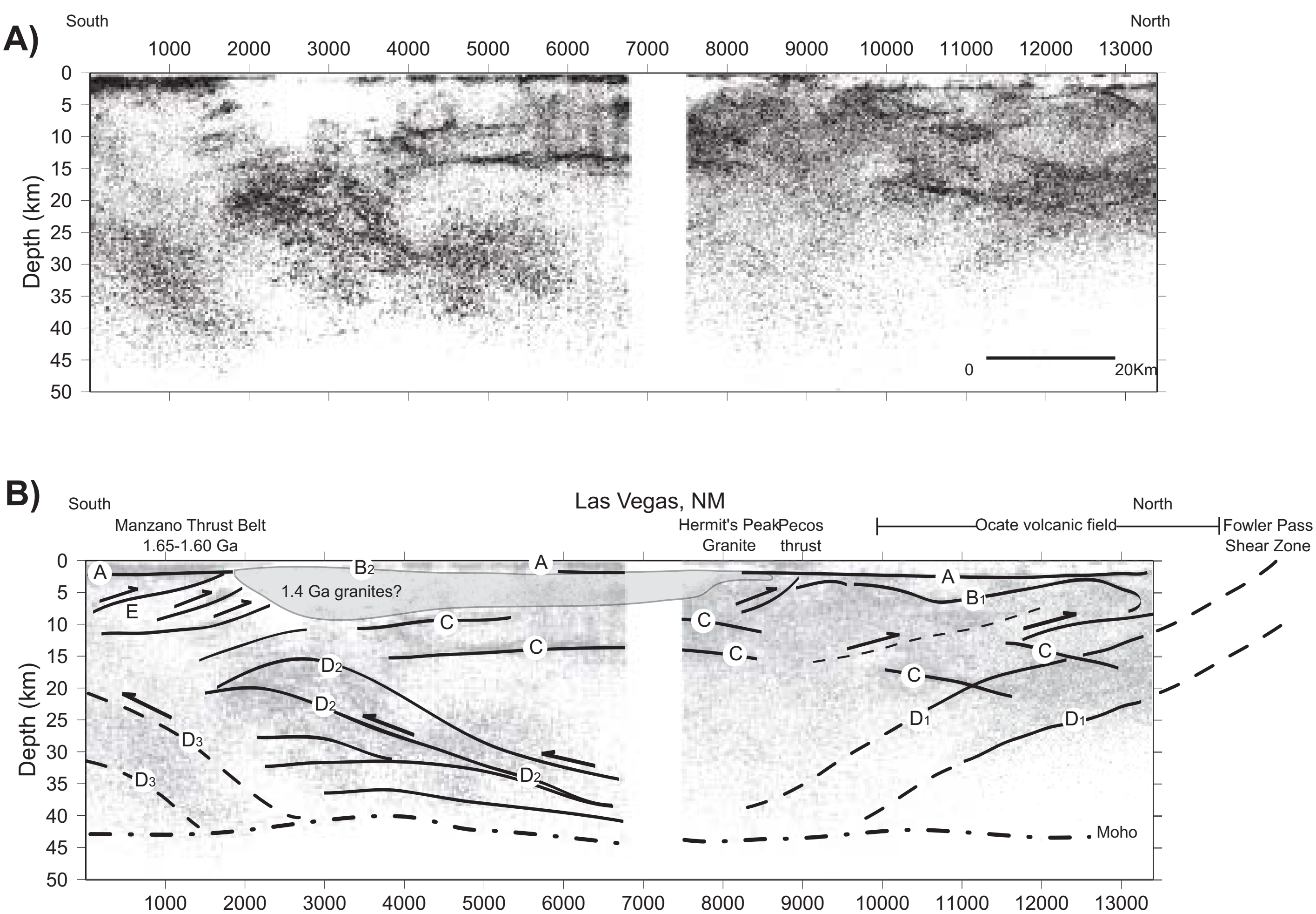

Figure 2. (A) Depth-migrated CD-ROM seismic reflection profile. Depth conversion computed at 80% of stacking velocities. (B) Interpreted seismic profile. Reflectors: A—Great Unconformity; B_1 and B_2—supracrustal Proterozoic rocks; C—Proterozoic or Cenozoic mafic sills; D_1 and D_2—bivergent Paleoproterozoic suture (1.68–1.65 Ga) with opposing dips; E—Manzano thrust belt (1.65–1.60 Ga).

5800–6000). South of CDP 2000, yet another set of north-dipping diffuse reflectivity (D3) enters the profile at a depth of 25 km and fades out at depth of 43 km. At the northernmost end of the line, the reflectivity is generally absent below ~30 km. In the center and the south, reflections are present to depths as great at 40–43 km, but do not define continuous reflecting surfaces.

INTERPRETATION OF SEISMIC DATA

From borehole data, surface outcrops, and geologic maps, we interpret with certainty reflector A as the Great Unconformity, above which is an almost undeformed section of Phanerozoic sedimentary sequences (Powell, 1875; Baltz, 1999). The lack of topography and deformation of the unconformity and the overlying sedimentary rocks suggests that little deformation occurred east of the Front Range faults in the sedimentary section as far south as CDP 6000. The Great Unconformity is not well imaged to the south because the sedimentary cover is much thinner (~450–1200 m) and is cut by late Paleozoic high-angle faults that extend into the underlying Precambrian rocks (Broadhead and King, 1988). We interpret the base of reflectivity (B2, Fig. 2) as the contact between Precambrian rocks and inferred granitic crust (see below).

We interpret the undulating horizon and overturned fold (B1 in Fig. 2) imaged just below the Great Unconformity at a depth of 3–5 km (CDP 9000–13500) as the subsurface expression of Proterozoic nappes that crop out in the Laramide uplifts to the west (Fig. 1). Exposed in these ranges are the lower limb and part of the hinge of a north-facing nappe, imbricated by several south-dipping, top-to-the-north ductile thrusts and cored by the 1.68 Ga Guadalupita granitic gneiss (Riese, 1969; Read et al., 1999). Remarkably, the seismic data image the entire nappe, the seismic signature of which probably originates from a 1200-m-thick quartzite layer (Ortega Formation), a regional stratigraphic marker in the 1.69 Ga Hondo Group. South of CDP 9000 (Pecos thrust), where the reflectivity loses coherence, lies the ca. 1.4 Ga Hermit's Peak granite (Read et al., 1999). Although the extent of this magmatic body to the south is unknown, we speculate that the lack of reflectivity at this depth across most of the southern sector of the profile is due to the presence of upper-crustal granitoids that intruded the crust during different Proterozoic tectonic events. Exposures of 1.4 Ga granites in the Manzano and Sandia uplifts (Priest and Sandia plutons) suggest that the subsurface bodies were most likely emplaced during the 1.4 Ga "anorogenic" magmatic event (Karlstrom and Humphreys, 1998), although an age of 1.65 Ga cannot be ruled out.

The reflectors labeled E in Figure 2 are the southernmost identified on the profile, and their interpretation relies on the structures observed in outcrops of Proterozoic rocks in the Pedernal Hills and the Manzano Mountains (60 km and 120 km to the southwest, respectively). Here 1.65 Ga south-dipping imbricate thrust faults are documented as part of the Manzano thrust belt (Thompson et al., 1991).

Interpretation of the deeper reflection packages (D1 and D2 in Fig. 2) is based on comparison of the seismic image to models for orogenic development (e.g., Willet et al., 1993) that are consistent with the island-arc collision model for development of the Southwest (see Karlstrom and Humphreys, 1998). We interpret the southward-dipping reflection package (D1) and the crustal duplex structure (D2) as a 1.65 Ga Paleoproterozoic bivergent orogenic belt created by collision of Mazatzal island arcs with the Yavapai margin that was already accreted to the proto–North American continent. The 45-km-thick suture zone represents the crustal expression of the lithospheric boundary between the Yavapai and the Mazatzal provinces. Teleseismic results across the Jemez lineament in New Mexico (Dueker et al., 2001) show a south-dipping low-velocity body extending into the mantle to a depth of 120 km, consistent with southward subduction of the Yavapai lithosphere under the Mazatzal arc. The geometry of the D1 reflectivity suggests top-to-the-north thrusting, imbricating Mazatzal supracrustal rocks onto Yavapai basement. Such an interpretation is supported by the observation that the projection to the surface of the D1 reflectivity occurs in the Cimarron Mountains where the Proterozoic Fowler Pass shear zone crops out. This shear zone is considered a fundamental Proterozoic crustal boundary as it juxtaposes profoundly different rock types characterized by diverse deformation histories (Grambling and Dallmeyer, 1993). Although no constraints on activity before 1.4 Ga exist, the oldest fabric on both sides of the fault is ca. 1.7 Ga (Carrick, 2002). We therefore suggest that the D1 reflectivity is the continuation at depth of a proto–Fowler Pass shear zone that juxtaposed the supracrustal Mazatzal rocks with Yavapai packages during the early stages of the suturing.

In this interpretation the north-dipping crustal duplex system (D2 in Fig. 2) would have been emplaced during island-arc–continental collision. According to surface geology, rocks above the D1 thrust are tectonically and magmatically mixed elements of both the Yavapai and Mazatzal provinces (e.g., Shaw and Karlstrom, 1999). In the subsurface, the suture zone itself likely consists of highly deformed, structurally mixed metasedimentary, metavolcanic, and metaplutonic rocks, tectonized during large-scale translation of one island arc onto another. Local surface outcrops show that the precollision Yavapai crustal rocks extend southward to about CDP 6500. South of this point, 1.67–1.65 Ga rocks exposed in the Sandia Mountains and the Pedernal Hills belong to the Mazatzal province. We suggest therefore that the rocks that constitute the duplex imaged at middle-crust depth are part of the Mazatzal arc terrane and that they were backthrust southward during the collision at 1.67–1.65 Ga between the Yavapai continent and the Mazatzal island arc. The amalgamation of the island arc to the continent produced the bivergent suture that we observe in the crust today. Continued convergence led to northward movement along the Manzano thrust belt (reflector E) at 1.65–1.60 Ga onto previously deformed Mazatzal terrane rocks.

We interpret the bright arched reflections (C in Fig. 2) that crosscut the seismic profile as mafic intrusions, on the basis of their high amplitude, geometry, and depth range. Reflectors with these characteristics have been interpreted as mafic intrusions on many other seismic profiles around the world, often corroborated by surface extrusive rocks or documented well data (e.g., Goodwin et al., 1989; Ross and Eaton, 1997; Papasikas and Juhlin, 1997). Furthermore, preliminary calculation of the polarity of the bright reflections (C) indicate that they have the same polarity as that of the Great Unconformity (A), which is known from well data to have a positive impedance contrast. This observation likely rules out molten magma as a possible origin for the reflectors.

Crosscutting relationships in the seismic data demonstrate only that the sills postdate accretion. However, regional geology suggests that they are likely to be Mesoproterozoic or late Tertiary in age. In southeastern New Mexico, a major mafic magmatic episode led to the intrusion of the 1.1 Ga Pecos Mafic Intrusive Complex (Keller et al., 1989; Adams and Miller, 1995). Additional evidence for mafic magmatism of this age comes from well data, 50 km southeast of our profile, where an age of 1090 Ma has been obtained for a gabbro intruding metasedimentary and metavolcanic rocks of the Debaca sequence (Amarante et al., 2000). Reflectors similar to those seen in the CD-ROM data tie gabbro in the well to industry reflection data (Amarante et al., 2000). Another possibility is that the intrusions are ca. 1.3 Ga in age and are associated with bimodal magmatism in the Southern Granite-Rhyolite province as observed in the Texas Panhandle (Van Schmus et al., 1993; Barnes et al., 2002).

Alternatively, nearby surface exposure of basalt and basaltic andesites of Tertiary to Quaternary age (Baltz, 1999; Green and Jones,

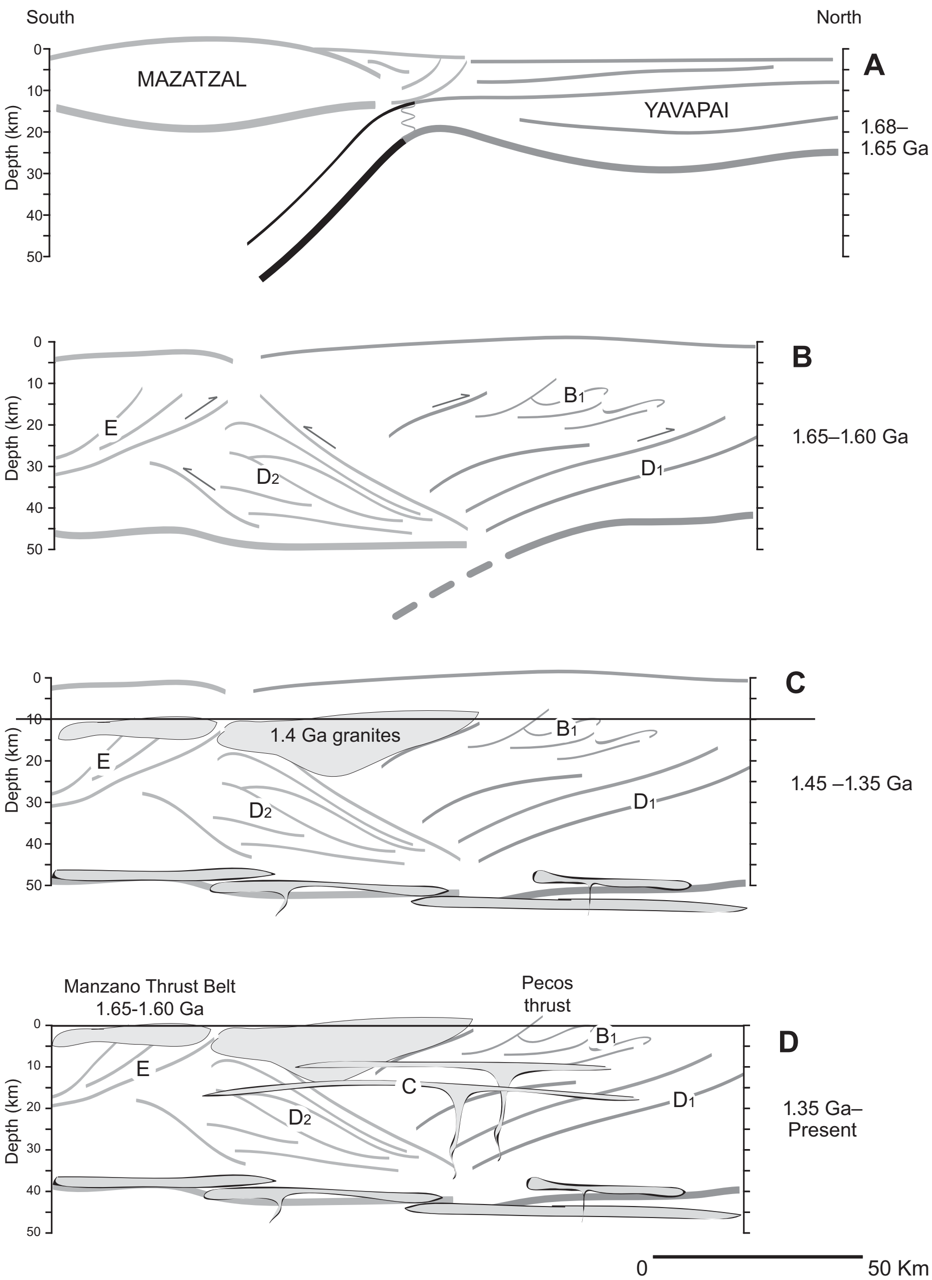

Figure 3. Tectonic model. (A) Subduction of the Yavapai margin generates the Mazatzal volcanic arc. Mazatzal sediments are deposited over Yavapai basement (1.70 Ga). (B) Mazatzal arc collides with the Yavapai margin, and as deformation progresses, bivergent structures nucleate (1.68–1.65 Ga). (C) At 1.4 Ga a regional anorogenic magmatic event affects the stable lithosphere, producing 10 km of uplift and subsequent denudation and the emplacement of granitic and basaltic magma. (D) Mafic sills intrude the cratonic lithosphere, possibly exploiting the presence of the preexistent Proterozoic suture (1.1 Ga to Holocene).

1997), indicate that the bright reflections could represent the intrusive counterpart of the extrusive rocks observed along the Jemez lineament. The northern part of the line crosses into the Ocate field, a Quaternary volcanic center that is one of several basaltic complexes that define the Jemez lineament. The eruptive center exposes a suite of basaltic and intermediate-composition lavas (ranging from alkali olivine basalts to dacites) 8.3–0.8 Ma in age. The petrology of these volcanic rocks is indicative of crustal contamination by mixing of a basaltic melt with a crustal granodiorite (Nielsen and Dungan, 1985). This finding suggests that these intrusions have ponded at several crustal levels before reaching the surface, perhaps exploiting preexisting faults or zones of weakness of Precambrian or/and Laramide age. The observation that the bright reflections do not seem to be affected by the Mississippian–Pennsylvanian uplift that shaped the Great Unconformity supports a young age for the intrusions.

The lower crust and the Moho are not well defined by individual reflections or strongly reflective zones: rather reflectivity just dies off at Moho levels, and at Moho depth only scattered reflectivity is observed. Amplitude-decay calculations suggest that the lack of Moho reflectivity is not attributable to poor signal penetration but rather to a nonreflective lower crust. Nearly spatially coincident CD-ROM seismic refraction data detect the Moho at 43–45 km, the depth at which reflective packages terminate on the profile we describe (Snelson, 2001). The refraction data show intermittently strong wide-angle reflections. Despite careful processing and analysis, no strong reflectors appear in the higher-frequency (8–60 Hz) vertical-incidence data as Moho depths are reached.

DISCUSSION

Interpretations of reflector A, the Great Unconformity, and reflector B1, a Precambrian nappe structure, are well correlated with local and regional geology. Such is not the case with the interpretations of reflection package D1 and D2, the Precambrian suture, which is model based, or reflection C, a Tertiary–Quaternary or Proterozoic magmatic feature, which are based on reflection character, borehole data, and surface evidences.

The duplex reflectors (D2) and the north-dipping reflectivity (D1) imaged at middle- and lower-crust depths could have a variety of origins. We propose that (1) they represent, respectively, a crustal duplex system and a crustal-scale thrust zone that accommodated the underthrusting of the Yavapai crust beneath the Mazatzal crust during the Mazatzal orogeny (Conway and Silver, 1989) and (2) they record the impressive shortening associated with the orogenic collage. The Alpine orogeny is a modern analogue whose scale is similar to the tectonic model for the Mazatzal-Yavapai collision (Fig. 3) The geometry of the reflectivity (oppositely dipping reflections on both sides of the suture) and the scale of the observed suture (the structures are imaged along a 170-km-long profile and appear to continue beyond the northern end) show a close similarity with the structures observed in the Alps both by seismic images and surface geology (Schmid et al., 1996). In the Alpine system, further compression after the collisional stage led to the formation of a bivergent orogen with a southern and a northern foreland and the propagation of thrusting in both directions. We propose a similar scenario, in which the Mazatzal arc—created by the 1.68–1.65 Ga subduction of the passive margin of the Yavapai block—eventually collided against the Yavapai margin and imbricated the Yavapai crust and the Mazatzal arc's sedimentary cover above the subduction system (Fig. 3A). Continued convergence caused the Mazatzal arc to overthicken by way of a system of north-dipping crustal duplexes and the subsequent activation of the south-dipping Manzano thrust belt (1.65–1.60 Ga) (Fig. 3B). The juvenile lithosphere underwent a regional heating event 200 m.y. after the assembly; the heating was likely driven by mantle melting and resulted in the emplacement of voluminous granitic bodies in the crust (Fig. 3C). The thermal event produced a 10 km surface uplift and the eventual subsequent erosional denudation.

CONCLUSIONS

The seismic data show two Paleoproterozoic crustal structures that we interpret as a bivergent orogen formed at an accretionary suture. The features have survived subsequent Proterozoic and substantial Phanerozoic tectonism. This new image of a Proterozoic bivergent suture also sheds light on the long-standing puzzle of why the boundary between Yavapai crust to the north and the Mazatzal crust to the south is so broad and transitional. Clearly, the entire crust is composed of Yavapai and Mazatzal material that has been tectonically mixed within the orogen.

This suture has persisted in the crust as a zone of weakness, allowing magma penetration until the present as evidenced by modern local extrusive rocks. The boundary zone appears spatially correlated with bright crosscutting reflections that we interpret as Middle Proterozoic or Tertiary–Quaternary basaltic intrusions. Teleseismic results (Dueker et al., 2001) show that the crustal suture zone is underlain by a region of mantle having low compressional and shear velocities. This mantle anomaly is a likely source of present-day basaltic magma generation.

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