



Proterozoic evolution of the Zuni Mountains, western New Mexico: Relationship to the Jemez lineament and implications for a complex cooling history

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PROTEROZOIC EVOLUTION OF THE ZUNI MOUNTAINS, WESTERN NEW MEXICO: RELATIONSHIP TO THE JEMEZ LINEAMENT AND IMPLICATIONS FOR A COMPLEX COOLING HISTORY

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ABSTRACT.— Exposures of Proterozoic crystalline rocks in the southwestern United States record the accretion of juvenile crust to the Archean/earliest Paleoproterozoic craton province along northeast-striking structural zones. The Jemez lineament of New Mexico and Arizona, an alignment of late Cenozoic volcanic centers, has been proposed as a tectonic boundary between two accreted Paleoproterozoic terranes. The Zuni Mountains of western New Mexico offer a unique opportunity to view the crystalline basement of the lineament. The most voluminous rocks within the range are calc-alkaline granitoids and related volcanic rocks that are consistent with Paleoproterozoic arc development. Geochemical data from ultramafic rocks within the central Zuni Mountains are consistent with an oceanic origin for these rocks, supporting the existence of a terrane boundary. However, shear zones in the Zuni Mountains record normal-sense, upper greenschist/lower amphibolite-grade deformation that occurred ca. 1430 Ma (indicated by ⁴⁰Ar-³⁹Ar data), rather than a Paleoproterozoic accretionary history. The Zuni Mountains also contain an undeformed, megacrystic granite that may be ca. 1.4 Ga. Northwest-striking diabase dikes in the Zuni Mountains record subsequent magmatism ca. 1.1 Ga. The Zuni Mountains were later uplifted during the Ancestral Rockies and Laramide orogenies. The long-lived tectonic and magmatic history recorded within the Zuni Mountains is evidence that the Jemez lineament is a crustal-scale zone of weakness, and is consistent with episodic reactivation of a Paleoproterozoic accretionary boundary.

INTRODUCTION

Precambrian rocks exposed throughout the Rocky Mountain and Basin and Range provinces record the accretion of juvenile material during the Paleoproterozoic, and voluminous A-type magmatism during the Mesoproterozoic. Arc accretion (ca. 1750 Ma to ca. 1650 Ma) occurred along generally northeast-trending structures (Condie, 1982; Karlstrom and Bowring, 1988), and this period resulted in the addition of Proterozoic crust onto the Archean craton from southern Wyoming to southern New Mexico, and eastward to Baltica. These rocks have been separated into three large provinces: Mojave, Yavapai, and Mazatzal, on the basis of differences in age and isotopic composition (Wooden and DeWitt, 1991). Boundaries between Paleoproterozoic provinces have been the subject of debate and have been discussed in numerous recent papers; the Jemez lineament of New Mexico and Arizona is a proposed boundary between the Yavapai and Mazatzal provinces.

The Jemez lineament, first identified and named by Mayo (1958), is marked by a prominent alignment of Cenozoic volcanic centers (see inset of Fig. 1). Several workers have postulated a Precambrian ancestry for the lineament (Aldrich et al., 1983, and references therein); U-Pb geochronologic data suggest that it marks the southward limit of pre-1.7 Ga crust (Wooden and Dewitt, 1991). The idea that the Jemez lineament is an important crustal boundary is supported by a long history of reactivation. For example, it may have served as a conduit for 1.4 Ga magmatism (Karlstrom and Humphreys, 1998); it influenced depositional environments for Permian sedimentary rocks (Aldrich et al., 1986); it appears to have controlled the distribution of large porphyry copper deposits of Laramide age (Aldrich et al., 1986); and it appears to coincide with a region of low-velocity mantle and possible zone of partial melting that has been inferred from teleseismic experiments (Karlstrom and Humphreys, 1998; Dueker et al., 2001). Seismic reflection experiments show oppositely-dipping zones of deep crustal reflectivity that pass from

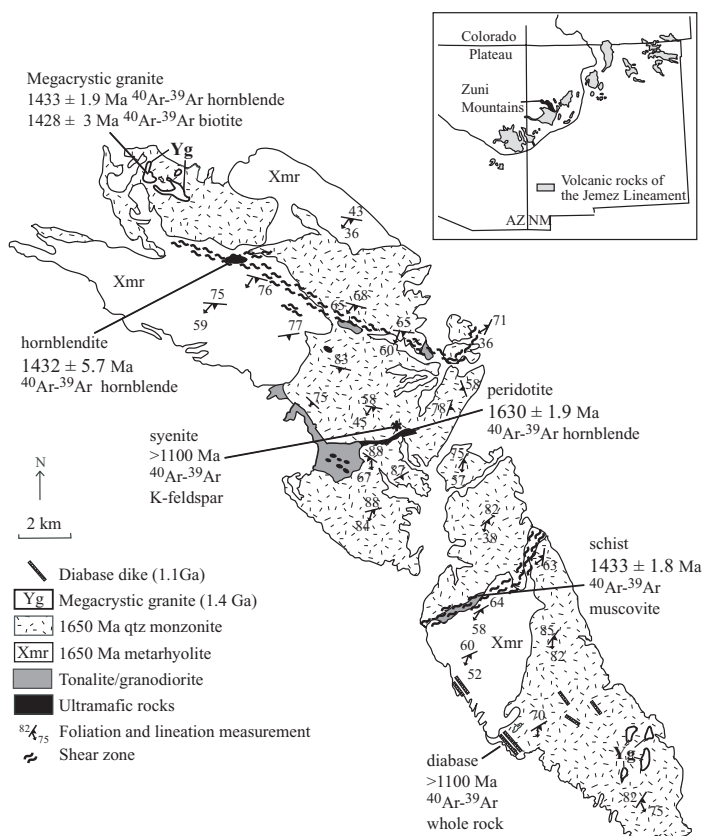


FIGURE 1. Generalized geologic map of Precambrian rocks from the Zuni Mountains, New Mexico. Adapted from Goddard (1966), Lambert (1983), and Mawer and Bauer (1989). Inset shows the location of the Zuni Mountains within the Jemez Lineament, adapted from Aldrich et al., (1986). Locations of samples for ⁴⁰Ar-³⁹Ar age analyses indicated by heavy lines.

the deep crust into the mantle under the Jemez lineament, further indicating a lithospheric-scale structure (Karlstrom and the CD-ROM Working Group, 2002). Therefore, the Jemez lineament may be a province boundary between the Yavapai (1.8-1.7 Ga) and Mazatzal (1.67-1.65 Ga) crustal provinces (Condie, 1982; Karlstrom and Humphreys, 1998).

The Zuni Mountains provide the best exposures of the crystalline basement beneath the Jemez lineament as well as an important window into the Proterozoic basement beneath the Colorado Plateau (Fig. 1). The Zuni Mountains consist of a northwest-trending, Precambrian-cored anticline that was uplifted during the Ancestral Rockies and Laramide orogenies (Aldrich et al., 1986). Geochemical, structural, petrographic and geochronologic data presented here shed new light on the origin of the Proterozoic rocks and structures within the Zuni Mountains. Our goals are to elucidate the early tectonic history of the Jemez lineament, to evaluate the Jemez lineament as a Paleoproterozoic province boundary using data from the Zuni Mountains, and to describe the variety of ^{40}Ar - ^{39}Ar cooling ages observed within the range.

Previous work done in the area includes a 1:31,680 scale map by Goddard (1966), a master's thesis on the occurrence of fluorite veins by Emanuel (1982), a master's thesis on the occurrence of ultramafic rocks by Lambert (1983), and an examination of deformation and shear sense by Mawer and Bauer (1989).

PRECAMBRIAN ROCK UNITS OF THE ZUNI MOUNTAINS

The Proterozoic rocks of the Zuni Mountains are predominantly meta-igneous (Mawer and Bauer, 1989). The oldest rocks exposed within the Zuni Mountains are ultramafic bodies that are unfoliated and consist of hornblende and serpentinized peridotite. They crop out in eight individual lenses (100-300 m long by 25-60 m wide) and in one elongate body that is about 100 m wide and trends east/northeast for almost 2 km (Fig. 1). The peridotite bodies are surrounded by quartz monzonite, granodiorite and/or metarhyolite at every locality. Field relations suggest that the serpentinite was intruded by the quartz monzonite and that contact metamorphism and metasomatism produced hornblende along the margins of the largest serpentinite body and several of the smaller lenses.

Relict clinopyroxene and orthopyroxene are present in some ultramafic samples, and the former existence of olivine is deduced from serpentine-oxide pseudomorphs; based on this mineralogy, the protolith is assumed to have been a lherzolite. Serpentinization and subsequent metamorphism produced an assemblage of talc, serpentine group minerals, chlorite, dolomite, actinolite, spinel, and hornblende. Despite the extensive alteration, the relict lherzolite fabric is still preserved. No demonstrable cumulate textures were observed in thin section, in hand sample, or in outcrops of up to 300 m in diameter (Lambert, 1983); nor is there any variation in primary mineralogy from sample to sample. Cr/Ni ratios for the Zuni Mountain peridotites range from 0.6 to 2.3, and MgO/MgO+FeO ratios fall between 0.59 and 0.74 (Table 1).

The most abundant rock types in the Zuni Mountains are quartz monzonite and an associated metarhyolite, both of which yield U/Pb zircon dates of 1655 Ma (Bowring and Condie, 1982)

(Fig. 1). These rocks are calc-alkaline, (Fig. 2, Table 1) similar in age to numerous 1.65 Ga granitoids in the Sandia-Manzano uplift, and are likely part of a large 1650 Ma batholithic complex in the northern Mazatzal province. Less voluminous are calc-alkalic granodiorite bodies that show magma-mingling textures between mafic and intermediate phases (Fig. 1).

Although ca. 1.4 Ga A-type plutons are voluminous throughout the Southwest, none have previously been identified in the Zuni Mountains. However, an unfoliated, megacrystic, biotite-hornblende granite crops out in several small bodies within the southernmost and northernmost parts of the range (Fig. 1). This megacrystic granite is similar in mineralogy and appearance to the regional 1.4 Ga suite. Goddard (1966) interpreted the outcrops as feeder stocks to a granitic body that had been structurally higher, but they may also represent the top of a pluton.

Other volumetrically minor rock types in the Zuni Mountains include diabase dikes along northwest-striking faults, and a brick-red syenite that was previously reported to be Cambrian in age (McLemore and McKee, 1989; Fig. 1).

DEFORMATION WITHIN THE ZUNI MOUNTAINS

In the southwestern United States, voluminous A-type granites intruded the juvenile Paleoproterozoic crust ca. 1430 Ma and often utilized or reactivated older structures (Karlstrom and Humphreys, 1998). The plutons are commonly megacrystic, with rapakivi textures, and although their geochemistry is most consistent with generation in an extensional environment (Frost and Frost, 1997), several workers have documented well-developed, reverse-sense shear zones that are parallel to the flow foliation (Duebendorfer and Christensen, 1995; Nyman et al., 1994; Selverstone et al., 2000). The Zuni Mountains contain both a pluton and a shear zone network that are likely ca. 1430 Ma in age.

Most of the Proterozoic rocks of the Zuni Mountains have a strong penetrative foliation and associated stretching lineation (Goddard, 1966). The dominant foliation strikes west/northwest in the northwestern part of the main range, is variable in the central part of the range, and strikes northeast in the southern part of the range (Fig. 1). Two shear zones, characterized by zones of more intense foliation, lineation development, and hydrothermal alteration, have been identified in the Zuni Mountains. The most continuously exposed shear zone is in the northern part of the range (Fig. 1). Although Goddard (1966) originally mapped the shear zone as discontinuous zones of high strain, our field work indicates that the northern shear zone is continuous and exposed for 8 km along strike (Fig. 1). Its western segment is about 500 m wide, strikes west/northwest, and dips steeply to the southeast. At its eastern end, the shear zone bends sharply and strikes northeast, dips steeply to the west, and is exposed for another 2 km (Fig. 1). The transition between these two orientations occurs in the central Zuni Mountains, where it appears that the shear zone has been folded, with a fold axis plunging moderately to the southwest (Fig. 3). All foliation orientations show a consistent top-to-the-southwest (normal sense) mineral elongation lineation, indicating that the flow direction was parallel to the fold hinge. The consistency of lineations around the

TABLE 1. Whole-rock analyses of samples from the Zuni Mountains done by XRF analysis at the University of New Mexico. Oxides listed as weight percent, trace elements listed as parts per million. †: Iron reported as FeO total. Samples collected for geochemistry were thoroughly cleaned of any weathered rind, jaw crushed, and pulverized to 100 mesh with a ceramic bowl. X-ray fluorescence (XRF) analysis for trace elements was done with pressed powders, and XRF analysis for major elements was determined with fused disks. Estimates of error are 1-3% for major elements is, 3-10 % for minor elements, and 10-50 % for trace elements.

	granodiorite	qtz monzonite	qtz monzonite	ultramafic	ultramafic	ultramafic
SiO ₂	69.77	64.46	59.20	43.30	30.88	41.44
Al ₂ O ₃	15.67	17.24	20.16	3.51	22.98	5.86
FeO [†]	3.20	4.00	4.84	15.79	18.37	15.09
MnO	0.07	0.06	0.09	0.26	0.30	0.24
MgO	1.40	1.70	2.41	36.69	26.30	33.36
CaO	3.79	4.89	6.17	0.19	0.09	3.77
Na ₂ O	3.38	4.63	3.69	0.01	0	0.05
K ₂ O	2.11	2.00	2.11	0	0	0
TiO ₂	0.45	0.74	0.95	0.19	0.88	0.12
P ₂ O ₅	0.15	0.27	0.39	0.06	0.20	0.06
Cr	18	40	69	2558	63	1331
Co	36	14	5	199	159	208
Ni	18	27	28	1131	100	1059
Cu	41	48	628	36	30	33
Zn	45	28	41	200	201	168
Rb	88	79	91	25	24	24
Sr	384	403	629	5	6	18
Y	33	23	22	6	9	5
Zr	166	148	227	2	11	0
Nb	16	22	21	11	11	11
Ba	786	605	1570	0	4	21

fold suggests that the folding of the shear zone was coeval with the normal-sense (top-to-the-southwest) deformation. The hinge region is characterized by a strong L-tectonite, which also suggests that shearing and folding were synchronous. A second shear zone in the southern Zuni Mountains contains a similar change in orientation along strike (Fig. 1). Its western segment strikes east/northeast and dips steeply to the southeast for about 3 km, and its eastern segment strikes north/northeast and dips steeply to the west for about 4 km. As with the shear zone in the northern Zuni Mountains, both segments have a consistent southwest-plunging lineation that also indicates top-to-the-southwest (normal) sense of shear. The transition between these two segments is sharp and is also interpreted to be folded. Regional foliations are parallel to the orientations of both shear zones (Figs. 1, 3).

Reliable sense of shear indicators (Fig. 4) include S/C and C-C' fabrics in both the fine-grained metarhyolites and coarser-grained quartz monzonite. These fabrics are typically defined by the alignment of biotite and muscovite, and by a shape-preferred orientation of quartz grains. Sigma and delta porphyroclasts (quartz) with recrystallized tails are well developed in the metarhyolite and quartz monzonite. Rare mica fish and asymmetric crenulations defined by folded micas in fine-grained samples also indicate sense of shear. All shear sense indicators indicate normal-sense shear (in present-day coordinates), even though the orientation and dip of the foliation varies.

Meta-igneous rocks of both shear zones were examined for quartz and feldspar microstructures to evaluate deformation mechanisms and to infer temperatures accompanying deformation (e.g., Hirth and Tullis, 1992). In the coarser-grained

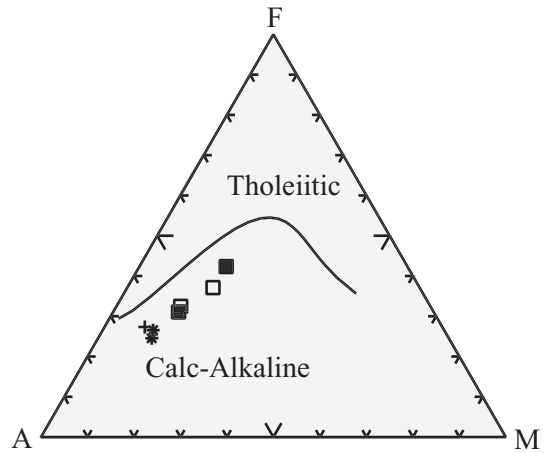


FIGURE 2. AFM diagram for quartz monzonite (open squares from this study; stars from Lambert, 1983) and granodiorite (filled squares from this study; crosses from Lambert, 1983).

samples, deformation is most easily recognized in the deformed quartz and feldspar phenocrysts and quartz veins (Fig. 4). Quartz phenocrysts and veins exhibit a variety of microstructures indicating different deformation mechanisms. Undulose extinction is present in virtually every quartz grain examined, and large relict quartz phenocrysts are commonly flattened and elongated parallel to the extension direction or to C planes within a given section (Fig. 4). Dynamic recrystallization in rocks from the Zuni Mountains shear zones is evidenced by mutually interpenetrating (bulging) subgrain walls (grain boundary migration recrystallization) and well-developed core and mantle structure (subgrain

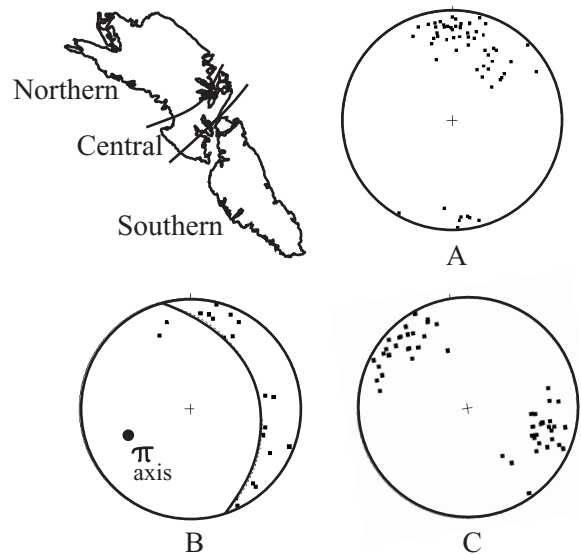
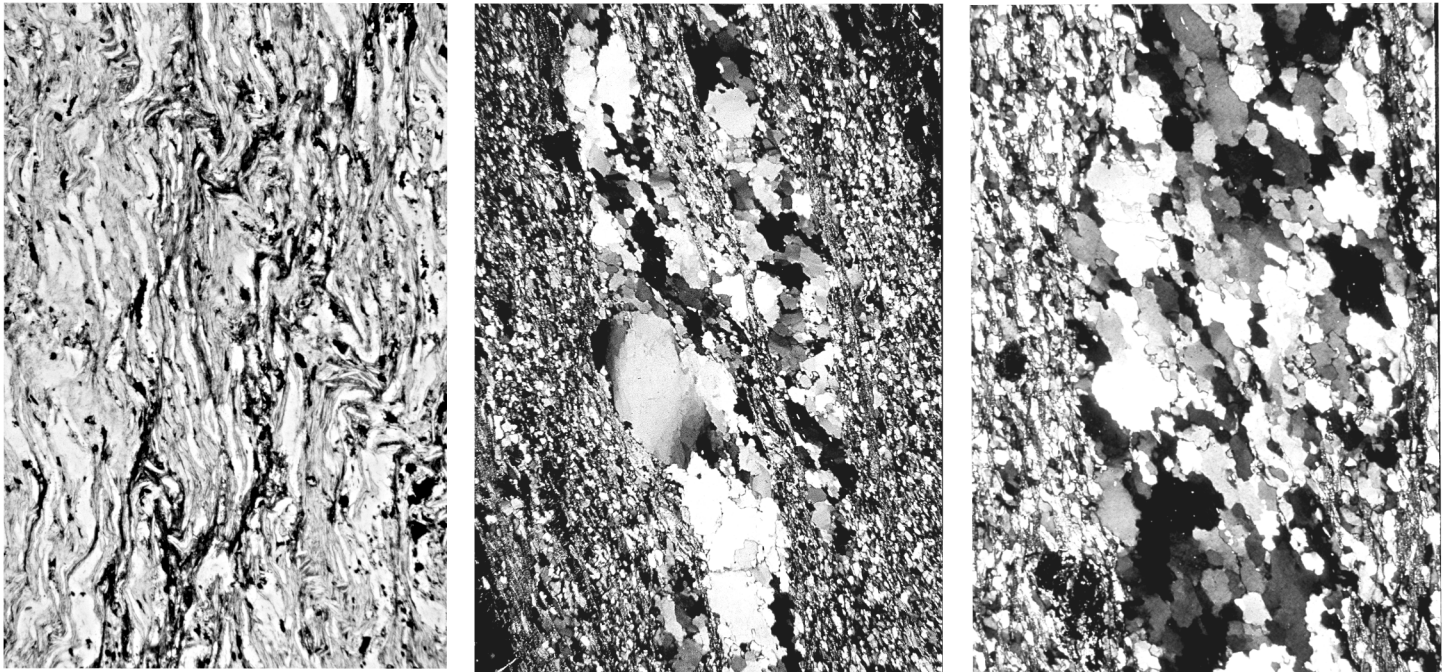


FIGURE 3. Lower-hemisphere, equal-area projections of poles to foliation for domains indicated by map (upper left). A: Plot from the northern Zuni Mountains showing a steep, west/northwest-striking foliation. B: Plot from the central Zuni Mountains showing a southwest-plunging π axis. C: Plot from the southern Zuni Mountains showing a steep, north-east-striking foliation.



NE

SW

FIGURE 4. Photomicrographs from the Zuni Mountains. Right: Recrystallized quartz vein from quartz monzonite. Shape preferred orientation of recrystallized grains with respect to the vein edges defines an S/C fabric that indicates top-to-the-SW sense of shear. Grain boundary migration recrystallization is indicated by bulging grain boundaries, subgrain development and undulose extinction. Field of view is 4 mm. Center: Asymmetric quartz porphyroclasts in metarhyolite. Tails indicate top-to-the-SW sense of motion. Subgrain rotation recrystallization can be seen as flattened quartz grains and core and mantle structure. Field of view is 8 mm. Left: Asymmetric folds and quartz porphyroclasts in mica schist. Asymmetries indicate top-to-the-southwest (normal) sense of shear. Field of view is 2 mm.

rotation recrystallization; Hirth and Tullis, 1992). The new, small grains typically show a shape-preferred orientation and a lattice-preferred orientation, and can be seen bulging into each other, indicating that both grain-boundary migration and subgrain rotation recrystallization occurred simultaneously (Hirth and Tullis, 1992). No fully annealed quartz grains are present. In contrast, all the feldspars observed were boudinaged (brittle), and a small number of feldspar crystals showed undulose extinction. No other indicators of dynamic recrystallization were observed in feldspar crystals from the Zuni Mountains.

Temperature during deformation can be estimated from the microstructures preserved in the samples, although variable strain rate or the presence of water can also affect the development of microstructures. Quartz develops undulose extinction through dislocation glide at or below 300°C, and becomes fully annealed above about 700°C (Passchier and Trouw, 1996). Hirth and Tullis (1992) found that both dislocation glide and dislocation climb (plus other recovery mechanisms) occurred in quartz above 400°C in experimental studies, and that flattening of quartz grains is common at mid-greenschist conditions. Feldspar begins to develop undulose extinction between 300° and 400°C, and does not begin to recrystallize significantly until a temperature of about 500°C is attained (Passchier and Trouw, 1996). These data bracket the temperatures of the textures observed in the sheared Zuni Mountain samples to about 400-500°C, which agrees with the grade of metamorphism observed by previous workers (Lambert, 1983; Mawer and Bauer, 1989).

⁴⁰AR-³⁹AR THERMOCHRONOLOGY OF THE ZUNI MOUNTAINS

Several samples containing a variety of K-bearing minerals were dated with the ⁴⁰Ar-³⁹Ar age spectrum technique (Figs. 1, 5).

Sample preparation and irradiation: Minerals were separated by standard heavy liquid, magnetic, and hand-picking (HP) techniques. Groundmass was concentrated by HP fragments free of visible crystals. Separates were loaded into a machined Al disc and irradiated in two separate packages (NM-116, NM-128) for 100 h in L67 position, Ford Reactor, University of Michigan. Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts, 1990) relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987).

Instrumentation: Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system. Megacrystic granite biotite and hornblende crystals were step heated by a 50-watt Synrad CO₂ laser. K-feldspars were step heated in Mo resistance furnace.

Furnace analysis: Reactive gases removed during a 10 to 240 minute heating with a SAES GP-50 getter operated at ~450°C. Additional cleanup (1-4 min) following heating with two SAES GP-50 getters, one operated at ~450°C and one at 20°C. Gas also exposed to a W filament operated at ~2000°C.

Laser analysis: Reactive gases removed during a 4-min reaction with two SAES GP-50 getters, one operated at ~450°C

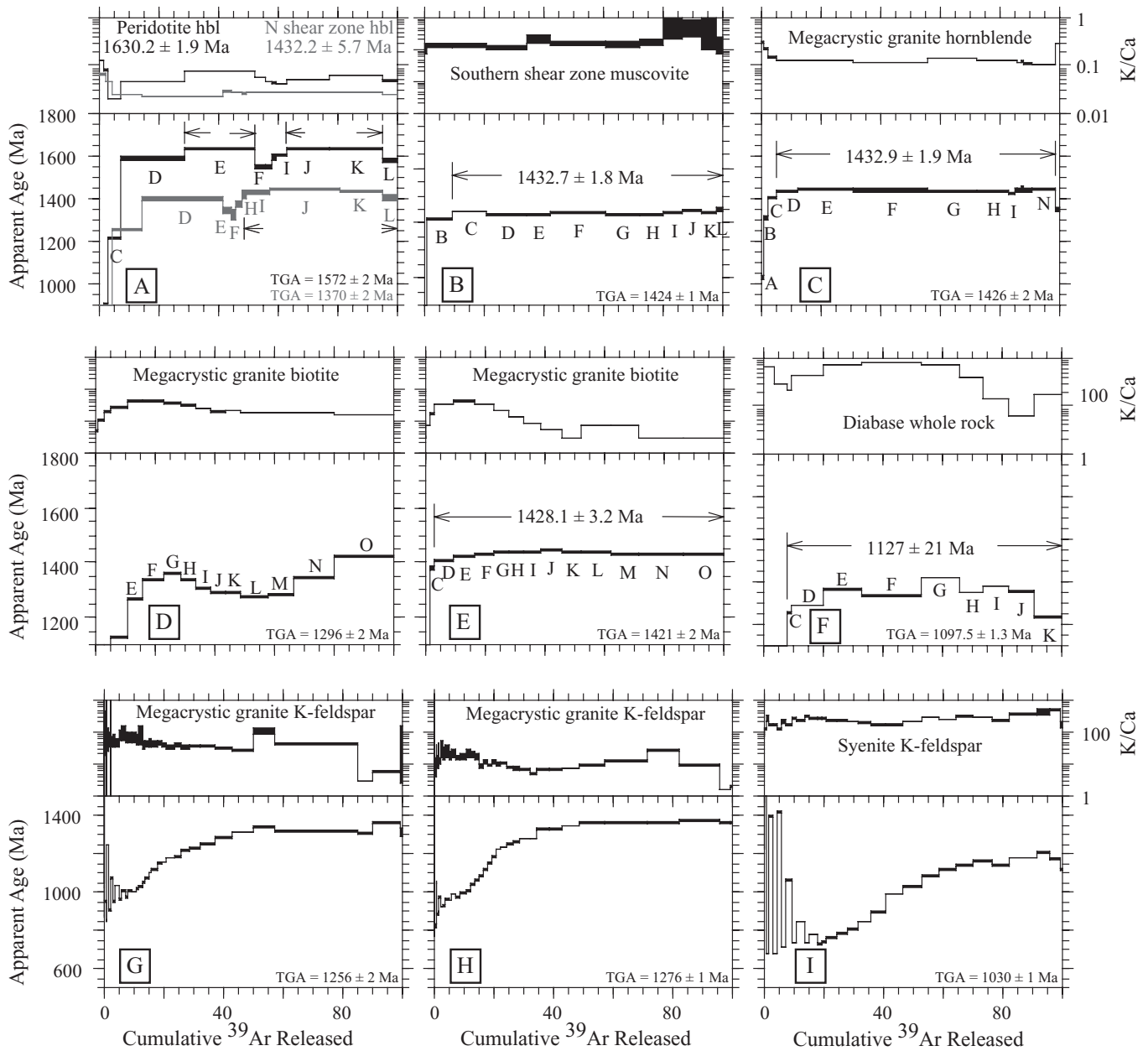


FIGURE 5. Diagrams showing Argon age spectra (left axis) and K/Ca (right axis) vs. cumulative ³⁹Ar released for ten samples from the Zuni Mountains. See Figure 1 for sample locations. Preferred ages and total gas ages (TGA) are shown for each analysis. Arrows indicate steps used for the assigned preferred ages. Errors are reported at 1σ and individual steps are plotted at 2σ. See text for discussion.

and one at 20°C. Gas also exposed to a W filament operated at ~2000°C and a cold finger operated at ~140°C.

Analytical parameters: Electron multiplier sensitivity averaged 1.2x10⁻¹⁶ moles/pA for laser and 2.0x10⁻¹⁶ moles/pA for furnace. Total system blank and background: Laser = 200, 0.3, 0.1, 0.5, 0.8 x10⁻¹⁷ moles for masses 40, 39, 38, 37, 36, respectively.

Total system blank and background: Furnace = 120, 0.5, 0.1, 0.6, 0.6 x 10⁻¹⁷ moles for masses 40, 39, 38, 37, 36, respectively. J-factors determined to a precision of ± 0.1% by CO₂ laser-fusion of four single crystals from each of four radial positions around the irradiation tray. Correction factors for interfering nuclear reactions were determined using K-glass and CaF₂ and are as

follows: NM-116 (⁴⁰Ar/³⁹Ar) K = 0.0266±0.0005; (³⁶Ar/³⁷Ar) Ca = 0.00027±0.00001; and (³⁹Ar/³⁷Ar) Ca = 0.00070±0.00002. NM-128 (⁴⁰Ar/³⁹Ar) K = 0.02495±0.00025; (³⁶Ar/³⁷Ar) Ca = 0.00027±0.00001; and (³⁹Ar/³⁷Ar) Ca = 0.00070±0.00002.

Age calculations: Integrated age calculated by combining isotopic measurements of all steps. Integrated age error calculated by combining errors of isotopic measurements of all steps. Preferred age is inverse-variance-weighted mean of selected steps. Preferred age error is inverse-variance-weighted mean error (Taylor, 1982) times root MSWD where MSWD>1. Preferred and integrated ages incorporate uncertainties in interfering reaction corrections and J factors. Decay constants and isotopic abun-

dances following Steiger and Jäger (1977). All errors reported at $\pm 1\sigma$, unless otherwise noted.

Hornblende from the Zuni Mountains serpentinite/hornblendite yields a somewhat disturbed age spectrum (Figure 5A, black). The three oldest steps that have similar K/Ca values are combined to yield a preferred age of 1630.2 ± 1.9 Ma. The age spectrum disturbance is probably caused primarily by low argon retentivity impurities, as the age variations correlate with variations in the K/Ca values. The method of combining noncontiguous steps from an age spectrum is uncommon, but a recent data set reveals agreement in ages for hornblendes with complex spectra and hornblende with flat spectra, and appears to support this data-processing method (Schneider et al., in press).

Hornblende from the northern shear zone also yields a complex age, but is significantly younger than hornblende from the peridotite body (Fig. 5A, gray). The final five heating steps of hornblende from the northern shear zone yield a preferred age of 1432.2 ± 5.7 Ma. A synkinematic muscovite from the southern shear zone yields a fairly flat spectrum with a preferred age of 1432.7 ± 1.8 Ma (Fig. 5B).

A hornblende sample from the undeformed, megacrystic granite yields a simple age spectrum and a well-defined age of 1432.9 ± 1.9 Ma (Fig. 5C). Two biotite samples from the megacrystic granite were also analyzed and yield highly contrasting age spectra (Figs. 5D, 5E). One biotite has an overall undulatory spectrum whereas the other biotite is fairly flat with an age of 1428 ± 3 Ma. No age is assigned to the undulatory spectrum and its complexity is interpreted to reflect significant alteration to chlorite and consequent argon loss. Two K-feldspar samples from the megacrystic granite yield nearly identical age spectra that show a substantial age gradients from approximately 900 to 1350 Ma (Figs. 5G, 5H).

The brick-red syenite that is found in the central Zuni Mountains (Fig. 1) yields a K-feldspar age spectrum with an age gradient ranging between ca. 700 and 1180 Ma (Fig. 5I). Some of the initial steps in the K-feldspar spectrum are anomalously old and also record an alternating old/young pattern for isothermal heating steps. This behavior is associated with excess argon that is presumably hosted in fluid inclusions (cf. Harrison et al., 1994). The age of the syenite cannot be precisely determined from the argon analysis.

The final argon age spectrum result is from a diabase dike located in the southern Zuni Mountains (see Fig. 1). A whole-rock sample from the diabase dike was analyzed because its fine grain size prevented mineral separation; it yields a complex spectrum (Fig. 5F). Following a steep initial age gradient, approximately 90% of the remaining spectrum then yields a noisy pattern and an imprecise preferred age of 1130 ± 20 Ma.

DISCUSSION

The basement rocks of New Mexico and Arizona consist of Paleoproterozoic arcs that were gradually amalgamated during ongoing accretion; the Zuni Mountains are no exception. The 1650 Ma quartz monzonite and metarhyolite (Bowring and Condie, 1982) show calc-alkaline affinities when plotted on an

AFM diagram (Fig. 2, Table 1), and are interpreted to be part of an arc complex. Although the Zuni Mountains lie in a proposed location for the Yavapai/Mazatzal terrane boundary, the deformation in the Zuni Mountains does not appear to reflect Paleoproterozoic accretion onto Laurentia.

The origin of the ultramafic rocks in the Zuni Mountains is unknown. Possible models include formation either as part of an ophiolite complex or as cumulate horizons in arc-related plutons. Dismembered ophiolites or portions of ophiolites can be found along tectonic boundaries around the world (Coleman, 1977; Rampone et al., 1991; Peltonen et al., 1996; Smith and Harris, 1996;). The mantle and crustal ultramafic sections of ophiolites are typically serpentinized during exposure to seawater (Coleman, 1977). MgO/MgO+FeO ratios for peridotite sections of an ophiolite typically range from 0.80 to 0.70 (Coleman, 1977), and Cr/Ni ratios are typically 1 to 3 (Fig. 6; Lugovic et al., 1990; Smith and Harris, 1995; Rampone, 1996; Melcher et al., 2002). Crustal cumulates of peridotite from arc settings are not as common as ophiolite-associated peridotites, but several examples do exist in Alaska, the former Czechoslovakia, and Finland (DeBari and Sleep, 1991; Jelinek and Dudek, 1993; Peltonen, 1995). These plutons typically show a rhythmic layering (centimeter to kilometer scale) of peridotite and gabbro, with increasing amounts of plagioclase towards the stratigraphic top of the intrusion. The ultramafic cumulates typically have Cr/Ni ratios >3 (Fig. 6), and MgO/MgO+FeO ratios show greater variability than are observed in ophiolites (DeBari and Sleep, 1991; Jelinek and Dudek, 1993; Peltonen, 1995).

The Zuni Mountains peridotites are not associated with any other rock types that would point directly to an ophiolitic origin (i.e., pillow basalts, sheeted dikes, deep-sea sediments), nor are they associated with gabbros or textural features that might support a cumulate origin in an arc setting. The pervasive serpentinization is consistent with a sea floor history, although serpenti-

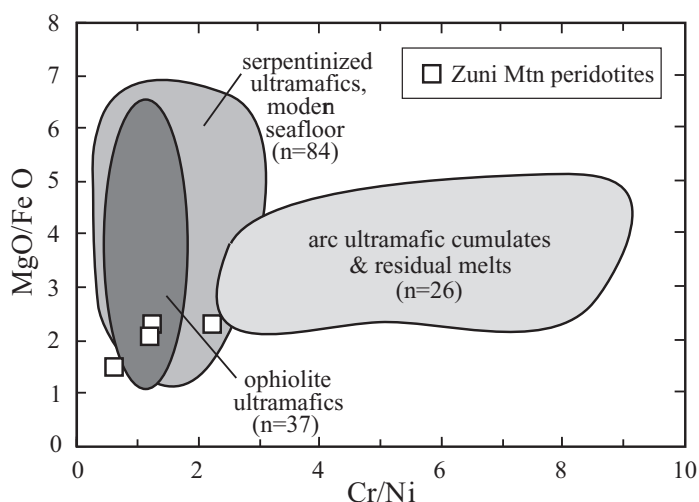


FIGURE 6. Plot of Cr/Ni values of the Zuni Mountains peridotite compared to Cr/Ni values for ultramafic cumulates and ophiolite ultramafics. Data from Coleman (1977), Lugovic et al. (1990), DeBari and Sleep (1991), Jelinek and Dudek (1993), Peltonen (1995), Smith and Harris (1995), Rampone (1996), and Melcher et al. (2002).

nization can occur in other settings. The Cr/Ni ratios of the Zuni Mountains peridotites are more similar to oceanic peridotites than to arc cumulates, although the Mg/Fe ratios are ambiguous (Fig. 6, Table 1). Alteration during serpentinization is more likely to have affected Mg/Fe ratios than Cr/Ni ratios. Based on the pervasive serpentinization, lack of cumulate features, and low Cr/Ni ratios, we currently favor formation of the Zuni peridotites in an oceanic setting. A more detailed geochemical study is necessary, however, to tightly constrain the origin of the protolith.

Hornblende from hornblendite found along the margin of the largest peridotite body yields an ^{40}Ar - ^{39}Ar age spectrum of 1630.2 ± 1.9 Ma (Fig. 5A, black). Field relations indicate that the hornblendite was likely formed by contact metamorphism of the serpentinized peridotite during the intrusion of the 1650 Ma quartz monzonite. The Paleoproterozoic age from the hornblendite mostly likely records cooling after contact metamorphism, and the crystallization age of the peridotite is unknown.

Shear zones in the Zuni Mountains are variable in orientation and appear to have been folded during normal-sense deformation at upper-greenschist/lower-amphibolite grade conditions. The mineral elongation lineation is down the plunge of the fold hinge, suggesting that a zone of non-coaxial deformation was folded by the shortening direction of a progressive strain field. This event has several possible tectonic interpretations: the shear zone network may record local extension due to pluton emplacement; the shear zones may record a regional extensional regime associated with the emplacement of the ca. 1.4 Ga A-type granites, as proposed by Frost and Frost (1997); or the shear zones may record the conjugate extensional direction to an overall contractional stress field at ca. 1.4 Ga, as proposed by Nyman et al. (1994). Given the limited exposure of these shear zones and the homogeneity of the sense of movement and conditions of deformation, it is difficult to choose a preferred tectonic interpretation. However, the steep lineation associated with these shear zones is not compatible with bulk crustal thinning.

Micas and amphiboles from the shear zones and the megacrystic granite reveal a tight age cluster at ca. 1432 Ma. However, the occurrence of the Paleoproterozoic hornblende in the central part of the Zuni Mountains indicates that the entire range could not have been heated above 500°C at ca. 1432 Ma. Because Paleoproterozoic hornblende cooling ages are preserved, we interpret the ca. 1430 Ma ^{40}Ar - ^{39}Ar ages from within the shear zone to reflect the timing of deformation. We also interpret the megacrystic granite to be a ca. 1.4 Ga pluton, but a detailed study of its geochemistry and U/Pb zircon geochronology is needed to establish it as part of the Mesoproterozoic A-type suite.

The analytically indistinguishable hornblende (1433 ± 2 Ma) and biotite (1428 ± 3 Ma) ages from the undeformed granite indicate that it cooled from 550°C to at least 350°C within the resolution of the age dating method. The rapid cooling indicated by this sample suggests that the regional 1432 Ma ambient temperature was below about 350°C . This relatively low regional 1.4 Ga temperature is also supported by the preservation of the Paleoproterozoic hornblende age from the peridotite. Evidently, there were steep lateral thermal gradients such that hornblende could be reset within the shear zone, but hornblende from the perido-

tite did not undergo argon loss. The ca. 500°C temperatures that would be required to degas hornblende in the northern shear zone are slightly higher than the ca. 450°C temperature of deformation indicated by quartz/feldspar microstructures. One possible explanation is that the deformation outlasted the thermal maximum, and therefore the microstructures record the final stages of the deformation. The microstructures may also have been influenced by varying strain rates and/or the presence of fluids.

Detailed interpretations of the K-feldspar age spectra are beyond the scope of this paper, but we summarize some possible thermal histories that explain the shape of the K-feldspar spectra (Figs. 5, 7). Thermal histories that yield model spectra matching the measured age spectra recorded in the Zuni Mountains indicate cooling below about 275°C by 1350 Ma. Following this, the region either cooled quite slowly with temperatures falling to about 150°C by 900 Ma, or the region cooled below about 150°C by about 1300 Ma and was reheated to a peak temperature of about 225°C at ca. 1100 Ma, followed by cooling to about 150°C by 900 Ma (Fig. 7). Either of these thermal histories can create model age spectra that have the 900 to 1350 Ma age gradients. Either thermal history is geologically plausible with the overall slow-cooling history recording long-term crustal stability as suggested by Hodges et al. (1994) for central Arizona. Alternatively, the region could have experienced some burial between about 1300 to 1100 Ma similar to the Unkar group sediments deposited in the Grand Canyon region (Timmons et al., 2001). Sediments greater than 1100 Ma are preserved in the Tucumcari basin in eastern New Mexico (Amarante et al., 2000) as

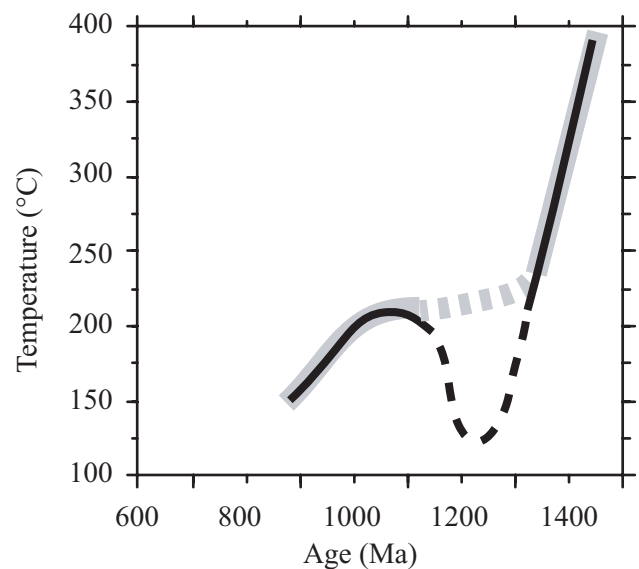


FIGURE 7. End-member thermal histories derived from multiple diffusion domain modeling (Lovera et al., 1989) of K-feldspar from the undeformed, megacrystic granite found in the Zuni Mountains. Model shown in gray assumes that the region has only undergone cooling, whereas model shown in black accounts for possible reheating. Dashed line records temperature and time periods that are not constrained by the model. Slow-cooling model implies long-term crustal residence at $\sim 225^\circ\text{C}$. Reheating model may be indicative of possible Mesoproterozoic burial and/or a thermal disturbance associated with Grenville tectonism.

well as in west Texas, and thus provide some indication that burial could have occurred in other New Mexico locations such as the Zuni Mountains. However, no sedimentary rocks of this age are preserved in western New Mexico.

Thermochronology has also revealed another tectonic event recorded in the Zuni Mountains. A diabase dike that occurs in the southern part of the area along a northwest-trending fault (Fig. 1) yields an ^{40}Ar - ^{39}Ar whole-rock age of at least 1100 Ma, which is interpreted to be the time of its emplacement. We suggest that the majority of the complexity of the age spectrum is caused by recoil of ^{39}Ar from relatively high-K sites into relatively low-K sites, and that the bulk age of 1130 ± 20 Ma represents the age of the diabase dikes. The imprecise age could suggest that the diabase dikes found in the Zuni Mountains are correlative with other 1100 Ma dikes in the region or that the diabase dikes are significantly older. The diabase dikes exposed in the southern Zuni Mountains are similar in composition, orientation and appearance to the ca. 1100 Ma dikes in Arizona (Hammond, 1990), and we suggest that the Zuni Mountain diabase dikes belong to the regional suite of ca. 1100 Ma dikes.

A syenite body found in the central Zuni Mountains, previously thought to be Cambrian in age, is also ca. 1100 Ma or older. Previous mapping (Goddard, 1966; McLemore and McKee, 1989) interpreted this syenite body to be correlative with known Cambrian syenites in New Mexico; however, our data indicate that this unit is at least 1100 Ma. This interpretation is drawn from the final steps of the age spectrum that climb to apparent ages of about 1100 Ma. Because of closure temperature considerations we cannot determine how much older the syenite is (if it is indeed older), but based on field relations we tentatively suggest that it is a hydrothermally altered version of the 1650 Ma quartz monzonite.

Today, the Zuni Mountains are the core of a northwest-trending anticline uplifted both during the Ancestral Rockies orogeny and the Laramide orogeny (Aldrich et al., 1983), indicating that the area has remained in the upper crust during the Phanerozoic.

The location and nature of the boundary between the Yavapai and Mazatzal terranes has been the subject of considerable debate. Shaw and Karlstrom (1999) proposed that the boundary is a diffuse zone of deformation, rather than a single structure. Selverstone et al. (1999) used data from crustal xenoliths to argue that an abrupt boundary does exist in the subsurface, but lies to the north of the Jemez lineament beneath the Four Corners region. The Zuni Mountains, on the southern edge of the Jemez lineament, show evidence for repeated deformation and magmatism from Paleoproterozoic through Cenozoic times. Peridotite bodies within the area may indicate the locus of original terrane-bounding structures, but no demonstrably Paleoproterozoic structures were documented. This study thus does not resolve the debate over the location of the Yavapai/Mazatzal boundary, but does demonstrate the repeated tectonic and magmatic activity that has characterized the Jemez lineament zone since the Paleoproterozoic.

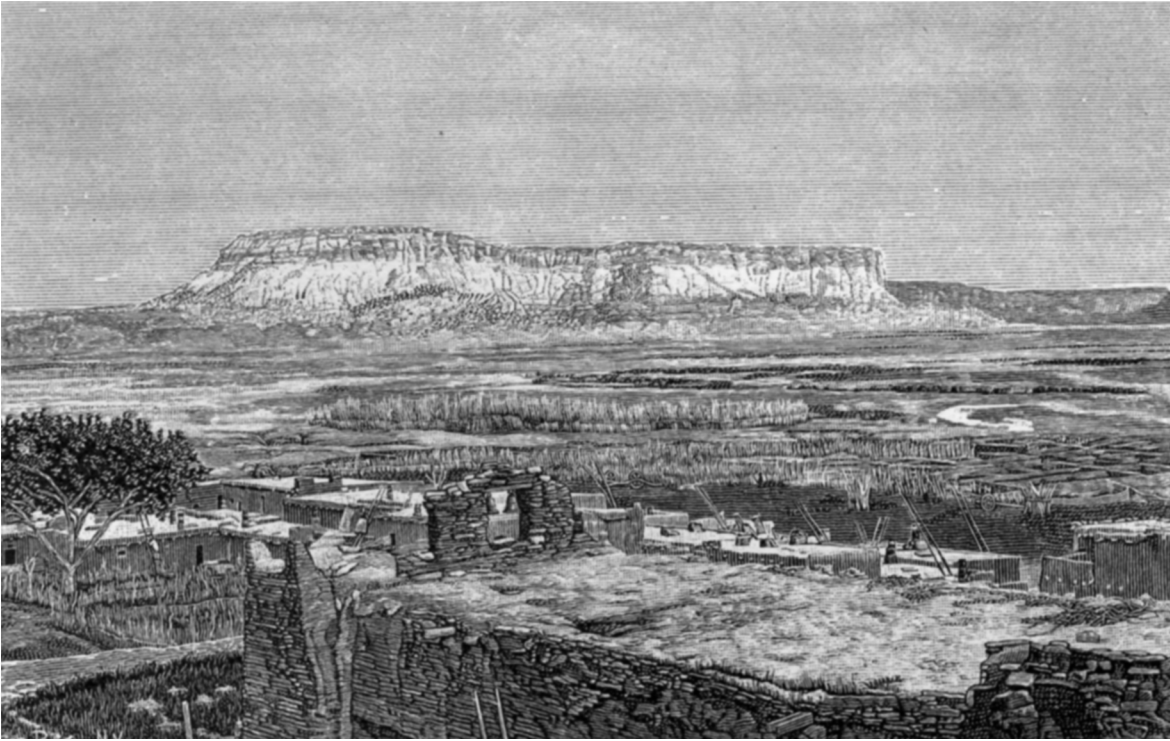
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Dutton's (1885, fig. 10) woodcut photograph of the Zuni Sandstone, described as "Toyalané, a butte composed of the upper members of the Jura-Trias system, as seen from the housetops of Zuñi."