Sedimentology, stratigraphy, and geochronology of the Proterozoic Mazatzal Group, central Arizona

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ABSTRACT

Quartzite, conglomerate, and shale of the Mazatzal Group record the filling of a Proterozoic intra-arc basin in central Arizona. U-Pb ages of zircons from rhyolite ash-flow tuff indicate that deposition began at 1701 ± 2 Ma. Basal deposits of the newly defined Pine Creek Conglomerate formed in an alluvial-fan setting, synchronous with the final phase of extrusive rhyolite volcanism and active faulting. After volcanic activity ceased, shallower-slope braided-stream environments developed in early Deadman Quartzite time. Subsequent marine transgression produced shallow subaqueous deposits of the upper part of the Deadman Quartzite. These were overlain by prodelta sediments of the Maverick Shale, indicating a phase of basin deepening. Finally, the Mazatzal Peak Quartzite was deposited as the basin shoaled again, first to shallow-marine and subsequently to fluvial conditions.

The quartzite is diagenetic quartz arenite, originally deposited as lithic arenite and lithic arkose. The provenance was initially restricted, and earliest sediment was derived mainly from the subjacent Red Rock Group. When tectonic activity ceased, however, the surrounding highlands were planed down by erosion, and detritus from a wider variety of source rocks was funneled into the basin. This included contributions from arc-related supracrustal rocks of the Payson Ophiolite and East Verde River Formation, and finally a granitic basement input. Detrital quartz in the lower part of the Mazatzal Group is largely monocrystalline, and volcanic in origin. Polycrystalline quartz, associated with detrital feldspar and of probable continental affinity, is concentrated in the uppermost parts of the sequence.

The life span of the intra-arc basin was on the order of 30 m.y., from the formation of the Payson Ophiolite at 1.73 Ga to the deposition of the upper Mazatzal Peak Quartzite sometime after 1.70 Ga. The pre-Mazatzal Red Rock Group represents the last stages of volcanic arc activity, and the Mazatzal Group records the transition from orogenic to nonorogenic sedimentation in central Arizona.

Keywords: arc, Arizona, orogeny, Proterozoic, U-Pb correlation.

INTRODUCTION

The Mazatzal Group of central Arizona (Fig. 1) is the uppermost stratigraphic unit of the Proterozoic tectonic block known as the Mazatzal block (Karlstrom and Bowring, 1993) (Fig. 2) and represents the transition from tectonically active arc and marginal-basin environments to a stable continental regime (Bowring and Karlstrom, 1990; Karlstrom and Bowring, 1988; Karlstrom et al., 1987). Information about the age and stratigraphy of these sedimentary deposits is therefore fundamental to understanding the later stages of crustal stabilization in this region.

The Mazatzal Group (Fig. 3) consists mainly of quartzite and pelite; localized conglomerate and ash-flow tuff are found near the base of the sequence (Conway and Silver, 1989; Wilson, 1939). There is no consensus as to the regional extent of the basin or its tectonic setting. Conway and Silver (1989) stated that it may have been a passive continental margin, continental-interior basin, or a continental-rift basin in the early stages of ocean-basin formation. Others have proposed a backarc (Condie et al., 1992) or intra-arc (Dann, 1997; Dann and Bowring, 1997) setting for the supracrustal package of which the Mazatzal Group is a constituent. Some workers envisage a large-scale basin with a regional east-trending (Trevena, 1979) or northeast-trending (Conway and Silver, 1989) shoreline. Others suggest that sedimentation in the Mazatzal Group and other Proterozoic sedimentary se-

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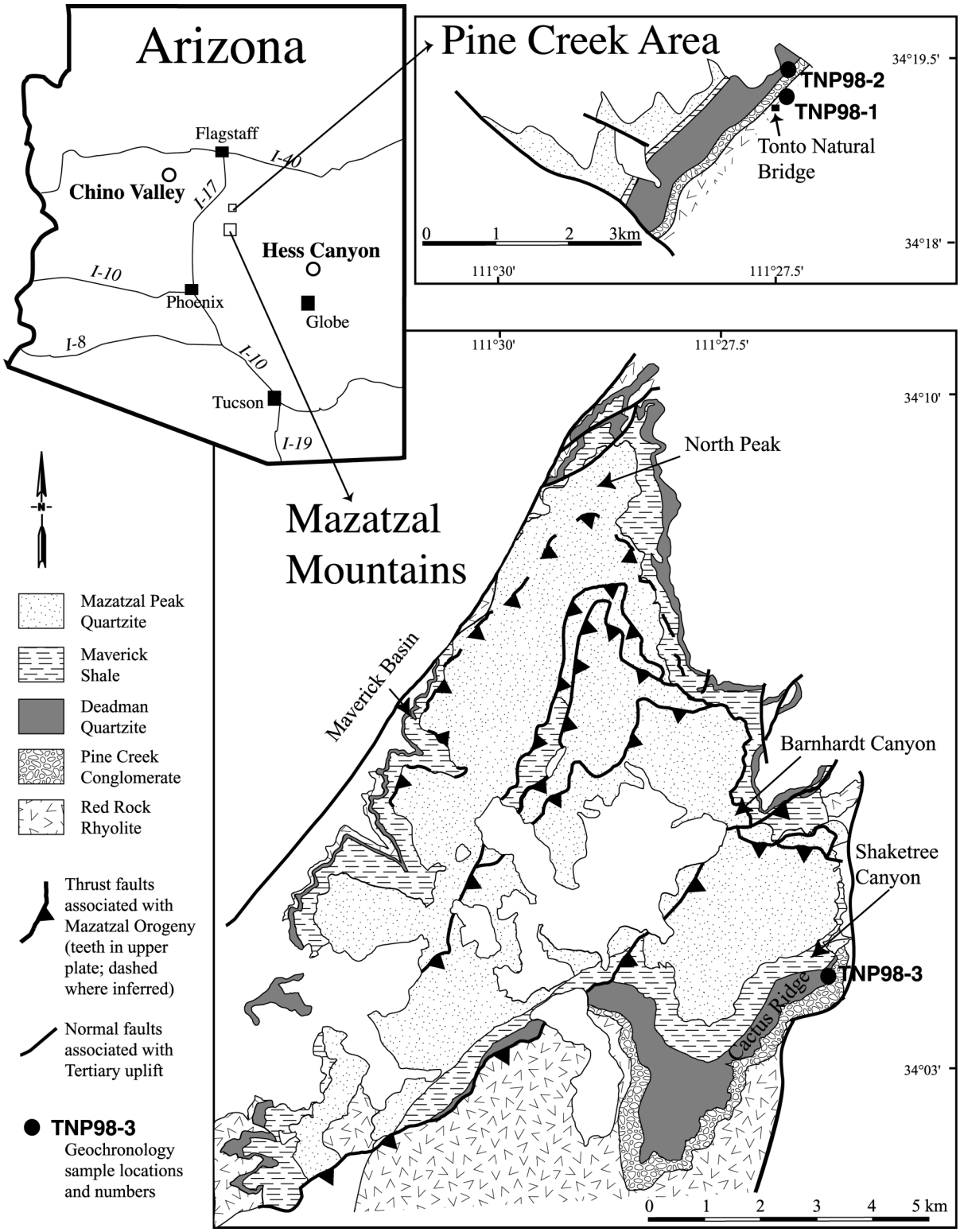

Figure 1. Geologic maps of Mazatzal Group outcrop areas, generalized after Wrucke and Conway (1987), Puls and Karlstrom (1991), and Doe (1991a).

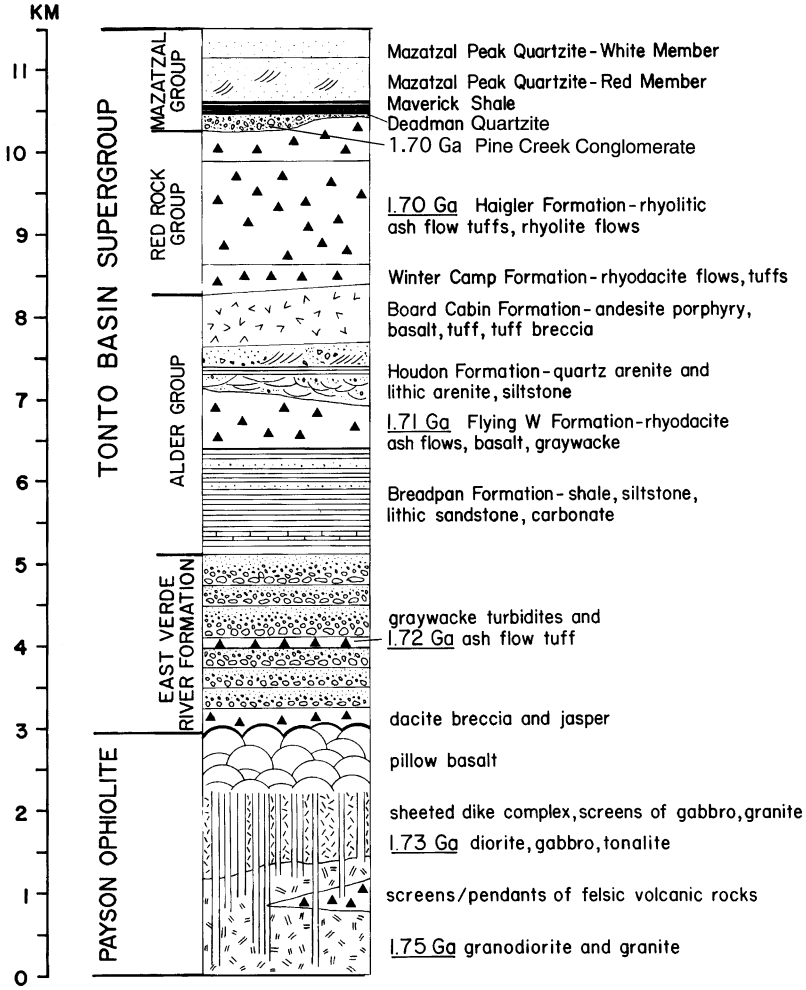

Figure 2. Stratigraphy of the Mazatzal block, modified after Karlstrom and Bowring (1993) to include the Pine Creek Conglomerate.

quences in Arizona may have occurred in response to active faulting at basin margins and that subsidence and sedimentary accumulations may have been localized (Bayne, 1987; Middleton, 1986). A fuller understanding is hampered by incomplete stratigraphic control. In particular, the lack of correlation between the Mazatzal Mountains and Pine Creek sections (Wilson, 1939; Wrucke and Conway, 1987) means that there is no basis on which to reconstruct and interpret the regional sedimentology and facies architecture.

In this contribution, we propose a precise stratigraphic correlation between specific formations in the Mazatzal Mountains and the stratigraphically undivided Mazatzal Group rocks in the Pine Creek area (Fig. 1). We report geochronologic data from both areas that support this correlation and also constrain the age of onset of sedimentation. By using detailed measured sections to refine interpretation of the environments of deposition, and petrographic and geochemical data to analyze sediment provenance, we present a tectonic model for the setting and evolution of the Mazatzal Group basin.

MAZATZAL GROUP STRATIGRAPHY

The Mazatzal Group lies with angular unconformity on the volcanic Red Rock Group and other Proterozoic units (Wilson, 1939; Conway et al., 1987) (Fig. 2). Measured thicknesses range from 670 m (Wilson, 1939) to 840 m (Doe, 1991b; Doe and Karlstrom, 1991) in the Mazatzal Mountains and from 1079 m (Trevena, 1979) to 1160 m (Wilson, 1939) in the Pine Creek section (Fig. 3). These thicknesses are minima because the top of the sequence has been removed by erosion.

The Mazatzal Group was first described in the Mazatzal Mountains, where it is divided into Deadman Quartzite, Maverick Shale, and Mazatzal Peak Quartzite (Conway, 1976; Wilson, 1922, 1937, 1939; Wrucke and Conway, 1987) (Figs. 1, 3); a fourth formation, the Hopi Springs Shale, was proposed by Doe (1991a, 1991b), but this unit is likely to be a structural repeat of the Maverick Shale (Wrucke and Conway, 1987; Puls and Karlstrom, 1991), and so is not included here. Wilson (1937, 1939) stated that neither the Deadman Quartzite nor Maverick Shale was present at Pine Creek and that the entire sequence was equivalent to the Mazatzal Peak Quartzite. Wrucke and Conway (1987) reported that parts of the sequence bore lithologic resemblance to and might be correlative with the Deadman Quartzite and Maverick Shale and therefore designated the Pine Creek strata as Mazatzal Group undivided. Subsequently, Doe (1991b) proposed a correlation between the lower Deadman Quartzite in the Mazatzal Mountains and the basal conglomerate at Pine Creek, but referred the rest of the Pine Creek section to Mazatzal Group undifferentiated. We extend the Mazatzal Group stratigraphy to the hitherto undivided section at Pine Creek (Fig. 3) on the basis of our stratigraphic descriptions as well as the generalized logs of Wilson (1937) and Trevena (1979).

Proposed New Formation: The Pine Creek Conglomerate

At Cactus Ridge in the Mazatzal Mountains, ~300 m of conglomerate and quartzite underlie the Deadman Quartzite (Fig. 3). These strata were assigned to the Deadman Quartzite by Wrucke and Conway (1987), and mapped as Deadman Quartzite, lower member, by Doe (1991a). Doe (1991b) and Doe and Karlstrom (1991) showed that the conglomeratic unit is separated from the overlying quartzite by several meters of rhyolite ash-flow tuff and in some places by local unconformity, which suggests that the conglomerate might in fact be a separate formation. The conglomerate at Pine Creek (Fig. 3 and GSA Data Repository Fig DR1[1]) is lithologically and sedimentologically identical to that in the Mazatzal Mountains. It is also separated from overlying quartzite by an ash-flow tuff, which is the same age as that at Cactus Ridge (Figs. 4, 5).

We interpret the conglomerates to be correlative and to constitute a distinct formation, the

[1]GSA Data Repository item 2002136, Figures DR1–DR4 and text, are available on the web at http://www.geosociety.org/pubs/ft2002.htm. Requests may also be sent to editing@geosociety.org.

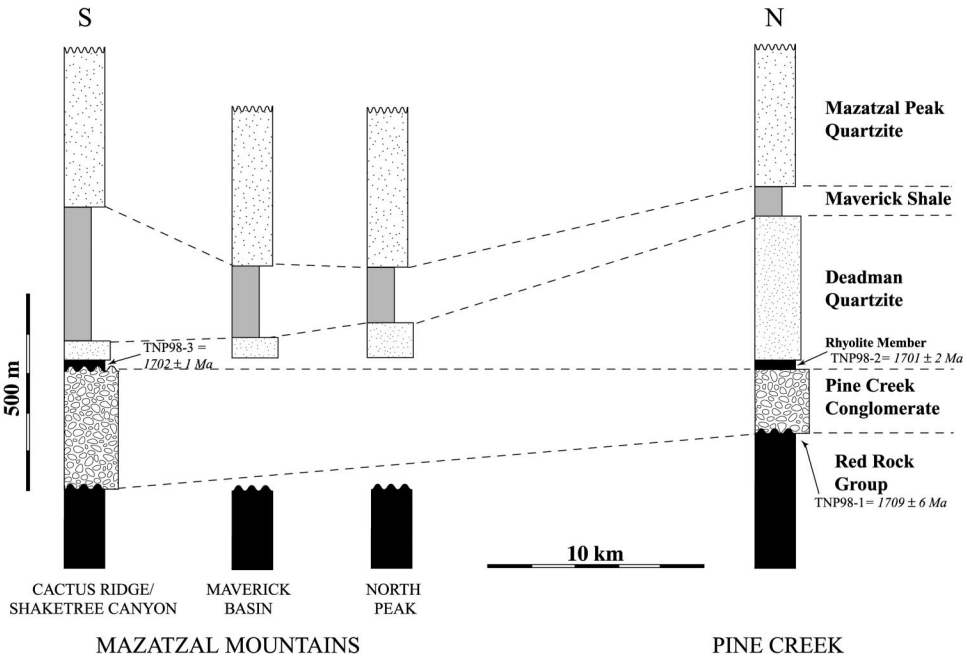

Figure 3. Stratigraphy of the Mazatzal Group, showing regional correlation and thickness trends from north to south. Vertical exaggeration is 20:1. The horizontal scale represents present-day distance north to south. Mazatzal Group thicknesses from Wilson (1939), Trevena (1979), Doe (1991b), and this study. The Rhyolite Member of the Deadman Quartzite is chosen as the horizontal datum. Ages are from this study (Table 1, Fig. 4). Red Rock Group thicknesses are not implied.

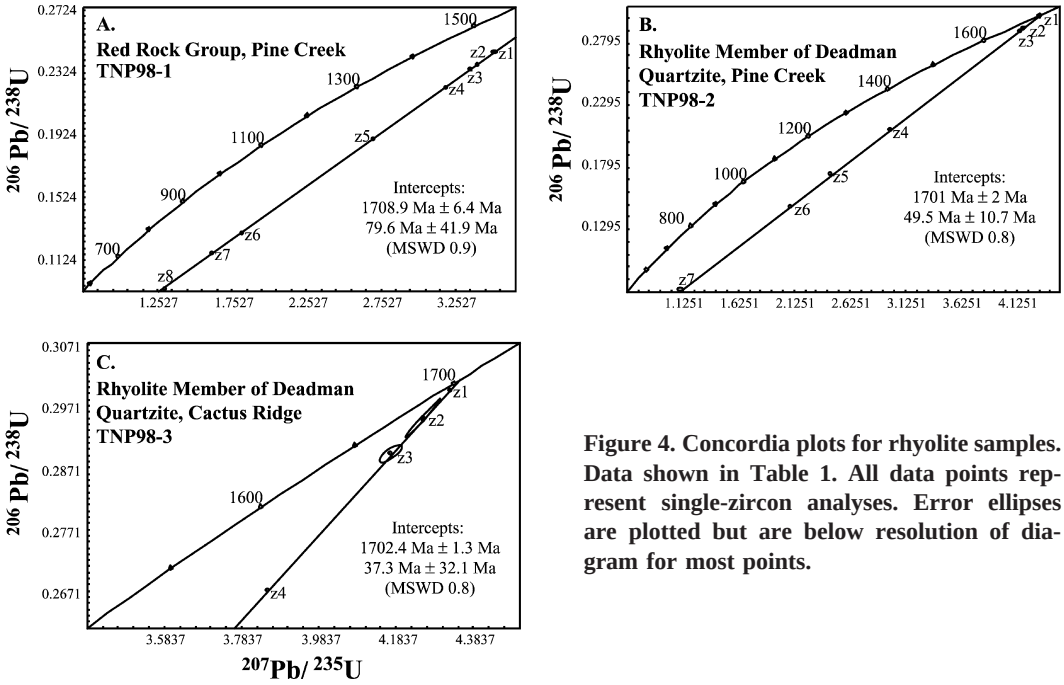

Figure 4. Concordia plots for rhyolite samples. Data shown in Table 1. All data points represent single-zircon analyses. Error ellipses are plotted but are below resolution of diagram for most points.

Pine Creek Conglomerate, which is the basal unit of the Mazatzal Group. The Pine Creek Conglomerate is best exposed and most accessible in Pine Creek, at Tonto Natural Bridge State Park (Fig. 1; 34°19.5′N, 111°27.3′W), and we designate this the type locality.

GEOCHRONOLOGY

The age of the Mazatzal Group is not well constrained, and current understanding is based largely on reported ages from unpublished data. The sedimentary sequence sits with angular unconformity on the ca. 1.70 Ga volcanic Red Rock Group (Karlstrom and Bowring, 1991; Silver et al., 1986), and predates the ca. 1.65 Ga Mazatzal orogeny during which it was deformed into a series of folds and thrusts (Conway and Silver, 1989; Karl-

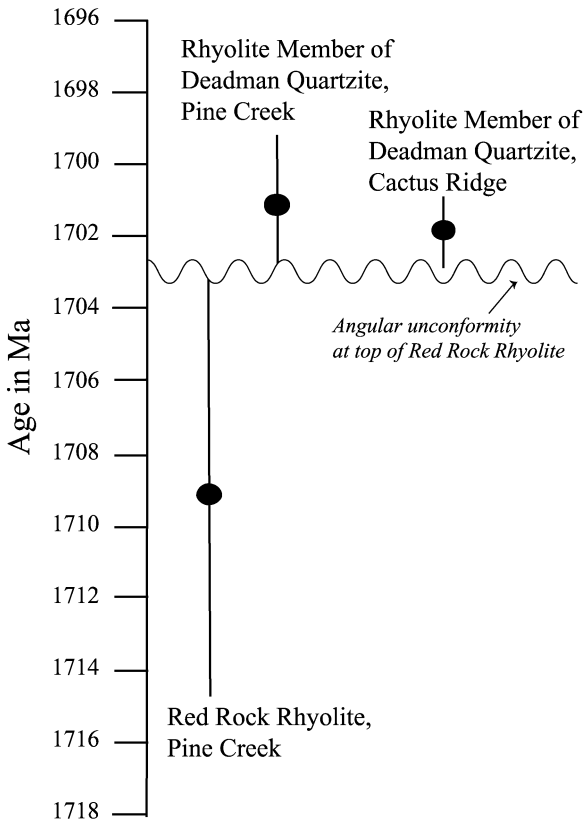

Figure 5. Rhyolite age brackets (error bars are 2σ). The Pine Creek and Cactus Ridge samples are indistinguishable; the Red Rock sample is slightly older.

storm and Bowring, 1991; Wilson, 1939). The age of the rhyolite ash-flow tuff in the section at Pine Creek (Fig. 3) has been reported as 1715 ± 15 Ma (L.T. Silver, personal commun. in Conway, 1976), and was later amended to 1695 ± 15 Ma (Karlstrom and Bowring, 1991).

The aims of this analysis were to establish a precise age for the onset of Mazatzal Group sedimentation and to test the stratigraphic correlation between the Pine Creek Conglomerate units in the Mazatzal Mountains and at Pine Creek. We dated samples of ash-flow tuff from both localities, as well as the uppermost Red Rock Group at Tonto Natural Bridge in Pine Creek (Fig. 1).

Zircons were euhedral with bipyramidal terminations, clear, and colorless to slightly pink in hue. They were 50–150 μm long and stubby in morphology, with length to width ratios 2:1 to 3:1. Single crystals were selected on the basis of size and clarity and then air-abraded (Krogh, 1982). U-Pb analyses were performed at the Massachusetts Institute of Technology, by using methods described in detail by Schmitz and Bowring (2001).

Results

All samples experienced varying degrees of recent Pb loss and are discordant (Fig. 4, Table 1). Data points are strongly collinear, however (MSWD [mean square of weighted deviates] values are <1 for all samples), and the three samples yield quite precise upper-intercept ages, which we interpret as crystallization ages. The lower intercepts are poorly constrained and probably reflect Pb loss related to Tertiary uplift of the Mazatzal Mountains (Scarborough, 1989).

The data do not show any age inheritance. The Proterozoic continental crust in Arizona is juvenile, and the proposed basement to the Mazatzal Group and related supracrustal rocks is ca. 1.75 Ga (Karlstrom and Bowring, 1988; Fig. 2 herein). Inheritance of zircon from the local crust would, therefore, be difficult to detect.

Nine single-crystal analyses of zircons from the Red Rock Group define a discordia array with an upper-intercept age of 1709 ± 6 Ma (Fig. 4A), which is consistent with the previously reported age of 1700 ± 6 Ma (Silver et al., 1986). Seven zircons were analyzed from the ash-flow tuff at Pine Creek, giving an age of 1701 ± 2 Ma (Fig. 4B), and four zircons from the ash-flow tuff at Cactus Ridge in the Mazatzal Mountains produced an identical upper-intercept age of 1702 ± 1 Ma (Fig. 4C).

The overlap between our data and the age determination of Silver et al. (1986) suggests that the age of the Red Rock Group is between 1703 and 1706 Ma (Fig. 5). The rocks from Pine Creek and Cactus Ridge are slightly younger and geochronologically indistinguishable from each other. They may represent either a single ash-flow event or two separate but closely related events. In either case, the ages confirm that onset of deposition of the Mazatzal Group was at about 1701 Ma.

SEDIMENTOLOGY AND STRATIGRAPHIC CORRELATIONS

Structural complications preclude the measurement of complete sections through the Mazatzal Group (Anderson and Wirth, 1980; Doe, 1991b). The detailed sedimentology is therefore represented by short logs from undisrupted sections.

Pine Creek Conglomerate

This basal unit of the Mazatzal Group is found at Pine Creek and in the Cactus Ridge area of the Mazatzal Mountains (Figs. 1, 3). Its localized occurrence and variable thickness indicate either patchy deposition or penecontemporaneous erosion. There is an unconformity—the only one known within the Mazatzal Group—between this unit and the Rhyolite Member of the overlying Deadman Quartzite on Cactus Ridge.

Description

The Pine Creek Conglomerate is a fining-upward sequence. In the type section at Pine Creek (Fig. DR1, stratigraphic log; see footnote 1), basal cobble and boulder conglomerate are followed by pebble conglomerate with interbedded quartzite, overlain in turn by coarse- to fine-grained quartzite with occasional pebbly layers. The unit is ~160 m thick at Pine Creek (Fig. 5). At Cactus Ridge it is at least 300 m thick and may be up to 450 m thick in some places (Doe, 1991b; Prendergrass, 1984).

Imbrication is common in the conglomerate where clast shapes are appropriate to show it, but in most cases the sphericity of the clasts precludes imbrication. The conglomerate ranges from well sorted to poorly sorted and

TABLE 1. U-Pb ANALYSES OF SINGLE ZIRCON CRYSTALS FROM THE RED ROCK RHYOLITE AND INTRAFORMATIONAL RHYOLITES FROM THE MAZATZAL GROUP

		Concentration				Error—2σ (%)						Age (Ma)				
Sample fractions	Mass[†] (μg)	U (ppm)	Pb (ppm)	$^{206}Pb/^{204}Pb$[‡]	$^{208}Pb^{*}/^{206}Pb$	$^{206}Pb/^{238}U$[§]	% err	$^{207}Pb/^{235}U$[§]	% err	$^{207}Pb/^{206}Pb$[§]	% err	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Corr. coeff.	Pb[#] (pg)
Red Rock Group rhyolite at Pine Creek (sample number TNP98-1; location 34°19.33' N, 111°27.29' E)																
z1	3.1	224.5	57.9	2628.1	0.113	0.24528	(0.17)	3.52100	(0.18)	0.10411	(0.05)	1414.1	1531.9	1698.7	0.96	4.1
z2	1.5	302.4	73.7	2409.0	0.089	0.23747	(0.15)	3.40682	(0.17)	0.10405	(0.08)	1373.5	1506.0	1697.6	0.90	2.9
z3	2.9	259.7	63.1	4598.0	0.102	0.23416	(0.09)	3.35653	(0.11)	0.10396	(0.06)	1356.3	1494.3	1696.0	0.84	2.5
z4	2.5	366.5	85.1	2944.4	0.104	0.22249	(0.17)	3.19256	(0.18)	0.10407	(0.06)	1295.0	1455.4	1698.0	0.94	4.4
z5	1.4	330.3	67.0	991.1	0.114	0.18929	(0.31)	2.70169	(0.33)	0.10352	(0.10)	1117.5	1328.9	1688.1	0.96	5.6
z6	3.3	674.0	92.8	1290.4	0.097	0.12916	(0.12)	1.81847	(0.13)	0.10211	(0.05)	783.1	1052.1	1662.9	0.92	13.5
z7	3.7	985.4	126.3	781.4	0.099	0.11637	(0.09)	1.62166	(0.11)	0.10107	(0.06)	709.6	978.6	1643.8	0.83	32.9
z8	0.9	2279.6	231.6	849.2	0.089	0.09439	(0.17)	1.30464	(0.19)	0.10025	(0.09)	581.4	847.8	1628.7	0.88	13.9
Rhyolite Member of Deadman Quartzite at Pine Creek (sample number TNP98-2; location 34°19.6' N, 111°27.3' E)																
z1	1.5	193.5	73.1	243.3	0.094	0.30171	(0.30)	4.33178	(0.38)	0.10413	(0.21)	1699.8	1699.4	1699.0	0.83	22.8
z2	2.0	38.0	11.7	673.3	0.124	0.29149	(0.34)	4.18784	(0.44)	0.10420	(0.26)	1649.0	1671.6	1700.2	0.82	2.2
z3	2.2	68.5	20.7	1270.1	0.108	0.28926	(0.18)	4.15711	(0.23)	0.10423	(0.13)	1637.8	1665.6	1700.8	0.81	2.2
z4	1.3	232.3	50.8	1849.1	0.111	0.20936	(0.13)	2.99001	(0.16)	0.10358	(0.09)	1225.4	1405.1	1689.3	0.84	2.2
z5	2.3	203.4	37.8	1128.3	0.127	0.17358	(0.33)	2.44813	(0.34)	0.10229	(0.09)	1031.8	1256.9	1666.1	0.96	4.6
z6	2.5	89.8	13.8	819.4	0.109	0.14713	(0.26)	2.09977	(0.29)	0.10351	(0.11)	884.9	1148.7	1687.9	0.92	2.7
z7	2.5	856.5	77.6	575.6	0.097	0.08117	(0.16)	1.11019	(0.21)	0.09920	(0.13)	503.1	758.3	1609.1	0.80	18.6
Rhyolite Member of Deadman Quartzite at Cactus Ridge (sample number TNP98-3; location 34°04.20' N, 111°25.85' E)																
z1	2.0	176.8	54.9	3146.6	0.097	0.30058	(0.10)	4.32416	(0.12)	0.10434	(0.07)	1694.2	1698.0	1702.7	0.79	2.2
z2	0.9	92.0	33.7	201.9	0.111	0.29609	(1.01)	4.25391	(1.03)	0.10420	(0.18)	1671.9	1684.5	1700.2	0.98	8.4
z3	0.8	29.0	8.8	495.4	0.108	0.29026	(0.48)	4.16983	(0.69)	0.10419	(0.45)	1642.8	1668.1	1700.1	0.76	0.9
z4	3.0	220.8	62.3	1564.5	0.097	0.26812	(0.18)	3.85171	(0.20)	0.10419	(0.09)	1531.3	1603.6	1700.1	0.89	7.0

Note: Total procedural blank for Pb ranged from 0.65 to 3.7 pg and <1.0 pg for U. Blank isotopic composition: $^{206}Pb/^{204}Pb = 19.10 \pm 0.1$, $^{207}Pb/^{204}Pb = 15.71 \pm 0.1$, $^{208}Pb/^{204}Pb = 38.65 \pm 0.1$. Corr. coeff.—correlation coefficient. Age calculations are based on the decay constants of Steiger and Jäger (1977). Common-Pb corrections were calculated by using the model of Stacey and Kramers (1975) and the interpreted age of the sample. Sample numbers are keyed to Figure 1.

*Radiogenic Pb.

[†]Sample weights are estimated by using a video monitor and are known to within 40%.

[‡]Measured ratio corrected for spike and fractionation only.

[§]Corrected for fractionation, spike, blank, and initial common Pb. Mass fractionation correction of 0.15%/a.m.u. ± 0.04%/a.m.u. (atomic mass unit) was applied to single-collector Daly analyses and 0.12%/a.m.u. ± 0.04% for dynamic Faraday-Daly analyses.

[#]Total common-Pb in analyses.

is generally clast supported with a sandy matrix. It is poorly structured or massive, with occasional crude horizontal layering on a decimeter scale. Diamictite is rare, as is grading. Bedding is often lenticular over tens of meters or less.

The quartzite in the upper part of the Pine Creek Conglomerate and the interbedded sandy layers in the conglomerate are well sorted and usually show low-angle cross-bedding, trough cross-bedding, or flat lamination (although in some beds, recrystallization combined with a lack of grain-size contrast make traction structures difficult to distinguish). Paleocurrent directions indicated by cross-bed foresets are southward.

Interpretation

The coarse clastic sediment and local unconformities of the Pine Creek Conglomerate reflect the final stages of Proterozoic tectonic instability in the Mazatzal region and mark the transition from active volcanism and uplift to the tectonic quiescence of later Mazatzal Group sedimentation.

The depositional setting is clearly terrestrial, but there is some disagreement about the specific nature of the environment. Trevena (1979) considered the Pine Creek section (TB1–TB4 of Trevena, 1979) to represent possible alluvial-fan deposition. Bayne (1987) and Bayne and Middleton (1987) suggested that it records a distal-fan or proximal braidplain environment. Anderson and Wirth (1980) interpreted the conglomerates at Pine Creek and Cactus Ridge as high-energy, channelized, fluvial sediment.

We propose that the Pine Creek Conglomerate in toto represents a proximal alluvial-fan depositional environment. The prevalence of sorting and traction structures in the conglomerate and associated quartzite indicates that it is mostly water laid. Sedimentation was dominated by hyperconcentrated flood flows (most of the conglomerate) and high-energy, unidirectional, aqueous flows (recorded by the quartzite); occasional noncohesive mass-flow events also occurred (Bayne, 1987). This set of processes is consistent with an alluvial-fan environment (Blair and McPherson, 1994). The complete lack of mud and silt indicates that fine material was washed through the system, implying a significant depositional slope that provided no opportunity for ponding. Deposits are highly variable in thickness (Fig. 3), consistent with very proximal, localized fan deposits from a rapidly uplifted source area. This interpretation is also supported by localized faulting and meso- to macroscale channelization (Anderson and Wirth, 1980; Doe and Karlstrom, 1991).

Deadman Quartzite

The Deadman Quartzite overlies the Pine Creek Conglomerate. Where the Pine Creek Conglomerate is absent, the Deadman Quartzite rests on the Red Rock Group with angular unconformity (Wrucke and Conway, 1987; Dann, 1991). It is sedimentologically homogeneous throughout the area (Fig. DR2, stratigraphic logs; see footnote 1), but thins from north to south (Fig. 3). Ash-flow tuff of the Rhyolite Member marks the base of the unit in both the southern Mazatzal Mountains and the Pine Creek area (where we define the Deadman Quartzite for the first time) and is the same age in both places (Figs. 4, 5).

Description of Rhyolite Member

The Rhyolite Member ranges in thickness from 1 to 15 m (Doe, 1991b; Wilson, 1937, 1939) (Fig. DR2). On Cactus Ridge at the TNP98–3 site (Fig. 1), where there is an an-

gular discordance between the Pine Creek Conglomerate and the Deadman Quartzite, the Rhyolite Member fills irregular small-scale topography on the eroded Pine Creek Conglomerate surface. The rhyolite consists of banded ash-flow tuff containing abundant flattened pumice fragments that are molded around unbroken quartz phenocrysts. Straight-sided, downward-tapering cracks in the upper surface of the tuff contain infiltrated sand from the overlying quartzite, indicating that the Rhyolite Member formed a depositional surface. Doe (1991b) recognized several distinct ash-flow units in Shaketree Canyon, but elsewhere in the southern Mazatzal Mountains there is generally only one thin tuff (1–2 m) at this stratigraphic position. At Pine Creek, a single 15-m-thick flow-banded unit is recognized (Wilson, 1939; Wrucke and Conway, 1987).

Interpretation of Rhyolite Member

It is not possible to establish whether the Rhyolite Member represents a single eruptive event or several local, laterally discontinuous units, but the age equivalence of the dated units at Cactus Ridge and Pine Creek indicates that they constitute a marker horizon (Fig. 5). The Rhyolite Member is volumetrically minor and represents the very last expression of volcanism in the Mazatzal Group basin.

Description of Quartzite Sequence

Overlying the rhyolite is well-sorted, coarse- to fine-grained quartzite, with occasional pebble conglomerate (dominated by rhyolitic clasts) and rare siltstone (Fig. DR2). The quartzite sequence exhibits dramatic thickness variations. Measured thickness in the Maverick basin is 28 m (Wilson, 1939) to 46 m (Trevena, 1979). In the vicinity of Barnhardt Canyon, stratigraphic thickness changes from 6 m to 35 m over a lateral distance of 500 m (Doe, 1991b; Doe and Karlstrom, 1991). In the Pine Creek area, thickness is 334 m (units 23–27 in the undivided section of Wilson, 1939, p. 1147) to 432 m (units TB6–TB14 in the undivided section of Trevena, 1979, p. 341 et seq.).

The Deadman Quartzite preserves abundant sedimentary structures. Traction structures found throughout the Mazatzal Mountains and at Pine Creek include upper-flow-regime flat lamination and both trough and tabular cross-bedding on scales from a few centimeters to tens of centimeters. Wave ripples are common in the Mazatzal Mountains, but at Pine Creek are found only at the very top of the unit. Wrinkle marks and desiccation cracks are reported only in the Mazatzal Mountains (Fig. DR2). Laminated siltstone occurs at some localities in the Mazatzal Mountains, but is volumetrically minor. Mudstone occurs as millimeter-scale mud drapes and rip-up clasts. There is some pebble conglomerate, especially at Pine Creek, and clasts include rhyolite and vein quartz. At Pine Creek, parts of the section are characterized by convolute bedding, disrupted bedding, and overturned beds. The disrupted sediments include normally graded beds as well as units with small-scale trough and tabular cross-bedding.

Interpretation of Quartzite Sequence

The sequence at Pine Creek (TB6–TB14 of Trevena, 1979) has been interpreted as a braidplain deposit (Trevena, 1979; Bayne, 1987). The dominance of trough and tabular cross-bedding and a lack of marine indicators indicate alluvial sedimentation, but a substantial depositional slope is implied by the presence of soft-sediment deformation and event sedimentation (represented by the graded beds). We therefore conclude that the Deadman Quartzite at Pine Creek was deposited on an alluvial fan rather than on a braidplain, but that it represents a more distal or lower-slope environment than the underlying Pine Creek Conglomerate. The appearance of wave ripples at the top of the Pine Creek section suggests an up-section facies change that we interpret as a transition to shallow-marine conditions.

For the sequence in the Mazatzal Mountains, Trevena (1979) proposed either a nearshore-marine or lacustrine setting. The thickness and coarseness of the unit, and especially the absence of silt and mud, are inconsistent with a lacustrine setting. The abundance of wave ripples and desiccation features, in addition to the sorting, grain size, and range of traction structures, strongly suggests a nearshore-marine environment for these deposits.

The Deadman Quartzite forms a southward-thinning clastic wedge from Pine Creek to the Mazatzal Mountains (Fig. 3). The regional sedimentology indicates that it preserves a facies transition from braided fluvial in the northeast to shallow marine in the southwest. It also records a probable south-to-north marine transgression, resulting in the up-section facies transition in the Pine Creek section from fluvial to shallow marine.

Maverick Shale

The Maverick Shale rests conformably on the Deadman Quartzite. Stratigraphic thickness increases from north to south (Fig. 3), on the basis of thickness measurements in areas of lowest strain. In the Pine Creek area, where we formally define it for the first time, it is <100 m thick (equivalent to units TB15–TB17 in the undivided section of Trevena, 1979, p. 341 et seq., and units 18–22 of Wilson, 1939, p. 1146–1147; broken out as unit Xmsq on map of Wrucke and Conway, 1987). At North Peak in the Mazatzal Mountains (Fig. 1), it is ~150 m thick (Wilson, 1939; this study). In the Maverick basin, it is ~150–200 m thick (Wilson, 1939; Trevena, 1979; Puls, 1986; Doe, 1991b), and in the Cactus Ridge area, it is 250–500 m thick (Trevena, 1979; Wilson, 1939). There also appears to be an increase in stratigraphic thickness from ~200 m at North Peak to 250 m in the southern Mazatzal Mountains. The Maverick Shale grades up section into the overlying Mazatzal Peak Quartzite (Figs. DR3 and DR4; see footnote 1).

Description

The Maverick Shale consists of shale, siltstone, and varying amounts of interbedded quartzite (Fig. DR3, stratigraphic log; see footnote 1). In the thin Pine Creek sequence, shale is subordinate to siltstone and silty quartzite, whereas in the Mazatzal Mountains, shale and siltstone dominate.

The lower parts of the sequence in the Mazatzal Mountains consist mainly of finely laminated shale and muddy siltstone. Normal grading (fine sandstone to siltstone) occurs in many of the thin layers. The number and thickness of quartzite interbeds increases up-section, and the uppermost 10 m consists of ~60% quartzite and 40% siltstone (Trevena, 1979). The quartzite shows abundant traction and erosion features. Wave ripples, including symmetric, current-modified, and interference ripples, are common on quartzite bedding planes, and small-scale trough cross-bedding and scour-and-fill structures are abundant. Current-ripple cross-lamination and fine-scale flat lamination occur in fine-gained quartzite and siltstone. Load casts and flame structures are found at shale-quartzite interfaces. Desiccation cracks are common in the mudstone toward the top of the unit, and herringbone cross-stratification is also found. Tabular cross-sets are generally limited to the uppermost parts of the sequence, where the thickest quartzite beds occur. The tops of cross-bedded deposits are often reworked by wave ripples that are in turn draped by fine sediment.

The thinner Maverick Shale in the Pine Creek area is dominated by fine-grained

quartzite, silty quartzite, and siltstone. The fine-grained beds are generally horizontally laminated, with occasional small-scale cross-lamination. The quartzite shows cross-bedding with abundant wave ripple marks and occasional mud drapes.

Interpretation

The regional facies associations suggest a southward-prograding marine deltaic system. This interpretation is supported by the southward thickening (Fig. 3), the southward facies transition from shallow- to deep-water sedimentation, and the upward coarsening of the formation, in addition to the suite of sedimentary structures and the facies associations above and below.

The sequence in the Mazatzal Mountains records a transition from sub–wave-base suspension sedimentation to traction sedimentation by unidirectional currents, bidirectional currents, and waves. Soft-sediment deformation suggests rapid deposition. Herringbone cross-stratification, abundant wave ripples, and desiccation features indicate very shallow water in late Maverick Shale time tidal influence and periodic emergence. The abundant large-scale tabular and trough cross-sets suggest a strong unidirectional flow component to the system. The initial deep-water sedimentation style of finely laminated, thin, normally graded beds is consistent with a prodelta environment. Subsequent traction-dominated sedimentation represents shoaling due to basinward migration of the delta front.

The thinner and relatively coarse Maverick Shale sequence in the Pine Creek area is lithologically very similar to the upper sand- and silt-rich parts of the Mazatzal Mountains section. It contains abundant wave ripples and cross-bedding, representing proximal delta-front and probable distributary-mouth-bar environments.

Mazatzal Peak Quartzite

The transition from the Maverick Shale to the Mazatzal Peak Quartzite is conformable and gradational. In the Mazatzal Mountains, ~400 m of quartzite are preserved in the type section at Maverick basin (Fig. 1) (Wilson, 1939). Trevena (1979) measured 500 m in Barnhardt Canyon, but this section was subsequently found to be structurally thickened (Doe, 1991b; Doe and Karlstrom, 1991). In the Pine Creek area, where we define the Mazatzal Peak Quartzite for the first time, 320 m (units TB17–TB21 in the undivided section of Trevena, 1979, p. 341 et seq.) to 575 m (units 1–17 of Wilson 1939, p. 1146) remain beneath the pre-Mississippian angular unconformity. Thickness trends in the Mazatzal Peak Quartzite cannot be evaluated because the top of the sequence has been eroded.

Description

There are distinct differences between the lower and upper parts of the Mazatzal Peak Quartzite in the Mazatzal Mountains (Fig. DR4, stratigraphic log; see footnote 1). In the lower Mazatzal Peak Quartzite (corresponding to the ''red member'' of Wrucke and Conway, 1987), both symmetric and interference wave-ripples are abundant. Cross-beds are generally unidirectional, but herringbone cross-lamination sets, generally separated by thin mud laminae, also occur. Dune-scale reactivation structures are plentiful and often preserve mud drapes. Rare hummocky cross-stratification occurs. Desiccation cracks are common, both on flat-lying mud layers and on thin mud drapes over ripples. Thin sections of low-matrix quartzite near the base of the unit show bimodal sand grain-size distributions.

The abundance of wave ripples and desiccation features decreases up section, and horizontal lamination and trough cross-bedding become the characteristic structures. Conglomerate with crude horizontal bedding and occasional graded bedding occurs over a restricted interval in the middle of the sequence. Small- to medium-scale scours with gravel fill also occur, and larger-scale channelization is indicated by beds that are downcutting and lenticular over several meters. Fining-upward cycles of conglomerate, cross-bedded sandstone, and siltstone, ranging from 10 cm to ~150 cm, are common. The uppermost quartzite (corresponding to the ''white member'' of Wrucke and Conway, 1987) is dominated by trough and tabular cross-bedding with sets commonly thicker than 0.5 m. Sandstone grains are more rounded in the upper than in the lower Mazatzal Peak Quartzite.

At Pine Creek, the lower Mazatzal Peak Quartzite contains wave ripples and herringbone cross-stratification. Traction structures in the quartzite are dominated by low-angle trough and tabular cross-bedding, with some planar lamination. In the middle and upper parts of the section, granule and fine-gravel layers and lenses up to 1 m thick display crude horizontal stratification and trough cross-bedding. A few siltstone layers up to 4 cm thick also occur. These are generally flat-laminated but also contain current-ripple cross-lamination.

Interpretation

The Mazatzal Peak Quartzite and the underlying Maverick Shale constitute a single sedimentary package representing a prograding deltaic system. The abundance of marine indicators and unidirectional flow features, in addition to the transitional relationship with the underlying Maverick Shale, indicates that the environment of deposition of the lower Mazatzal Peak Quartzite was a coastal delta front. The dominance of unimodal current structures suggests a river-dominated delta, with superimposed tidal and wave effects (Reading and Collinson, 1996). The bimodal grain-size populations in some of the cross-bedded quartzites suggest an eolian component (Folk, 1971), consistent with a coastal setting. This interpretation is broadly similar to that of Trevena (1979), who interpreted the lower Mazatzal Peak Quartzite in the Mazatzal Mountains as a transitional, terrestrial, or near-shore environment representing a high-energy delta or fluvial system. The Namurian cyclothems of western Ireland (Pulham, 1989) are a good analogy for the Maverick Shale and lower Mazatzal Peak Quartzite.

Trevena (1979) interpreted the upper part (''white member'') of the Mazatzal Peak Quartzite in the Mazatzal Mountains as a near-shore-marine deposit. However, the complete lack of marine indicators, the dominance of tabular and trough cross-bedding, and the frequency of gravelly channels suggest that these rocks in fact record the transition to fully terrestrial, braided, fluvial sedimentation of the delta-plain environment. Similar facies are seen at the top of the unit in the Pine Creek area, where they have been interpreted as braided-stream deposits (Trevena, 1979). The upper Mazatzal Peak Quartzite differs from the classic Phanerozoic delta plain because, in the absence of vegetation to stabilize fine sediment, no overbank or levee deposits are preserved, and the characteristic soils and peats are likewise absent.

PETROLOGY AND PROVENANCE

The Mazatzal Group Composition Paradox

The Mazatzal Group is the final unit in an arc-related orogenic supracrustal sequence that includes the Payson Ophiolite, East Verde River Formation, and Alder Group (Fig. 2). The elapsed time between pre-Payson-ophiolite rifting and deposition of the Mazatzal Group is <40 m.y. (Dann and Bowring, 1997; Karlstrom and Bowring, 1993; Wrucke and Conway, 1987). The Mazatzal Group is known to

have been derived from a recently uplifted hinterland consisting of plutonic, volcanic, and metamorphic rocks (Bayne, 1987; Cox and Lowe, 1995; Doe and Karlstrom, 1991; Karlstrom and Bowring, 1993; Neet and Knauth, 1989; Trevena, 1979), but the quartzite is consistently described as ''quartz arenite'' or ''mature quartz arenite'' (Conway et al., 1987; Conway and Silver, 1989; Karlstrom et al., 1987; Trevena, 1979; Wrucke and Conway, 1987). Interpretation of the tectonic setting is therefore problematic (Bayne, 1987; Conway et al., 1987; (Conway and Silver, 1989). There are rare examples of quartz arenite in volcanically active basins (Busby-Spera, 1988; Riggs and Busby-Spera, 1990), but there are no modern examples of quartz arenite–*dominated* sedimentation in such environments, nor in basins with substantial relief and active faulting; nor are such associations known from other Proterozoic localities (Van Schmus et al., 1993b). In addition, the lack of an older inherited component in the rhyolite U-Pb data (Fig. 4, Table 1) indicates little or no cratonic influence, making the association with quartz arenite even more difficult to reconcile.

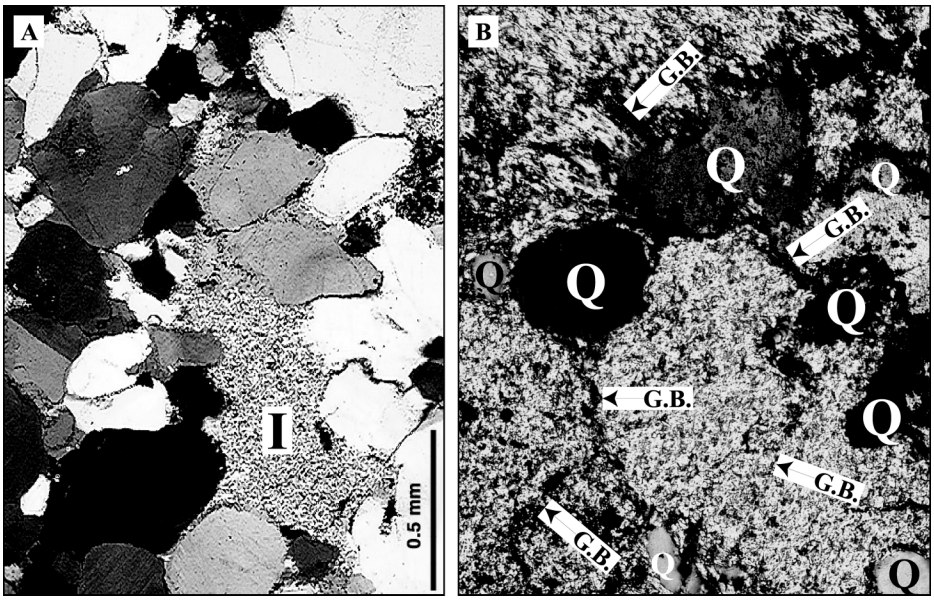

Figure 6. Photomicrographs of Mazatzal Group quartzite showing textural relationships between preserved detrital grains and pseudomatrix. Fields of view are 2 mm. (A) Pseudomatrix (labelled "I") is an interstitial, sand-sized clot representing the labile detrital grain from which it formed. (B) Detrital grains (labelled "Q") surrounded by pseudomatrix. This is not a diamictite: the sample is cross-bedded, and the preserved detrital grains are well sorted. The pseudometrix preserves relict grain boundaries (labelled "G.B.").

Resolving the Paradox: Pseudomatrix and Normative Analysis

The key to the composition paradox is in the diagenetic history of the Mazatzal Group quartzite, in which phyllosilicate matrix averages 12% and ranges up to 33% by volume (Table DR2, point-count data; see footnote 1). This phyllosilicate material is interpreted as secondary pseudomatrix, formed by the in situ mechanical and chemical alteration of labile framework grains (Dickinson, 1970), for the following reasons. (1) The large proportions of fine-grained material are inconsistent with the sedimentology of the quartzite: all samples were taken from tabular or trough cross-bedded rocks with well-sorted framework-grain populations and should therefore have a maximum of 1%–4% primary matrix (Visher, 1969). (2) Textural criteria (Dickinson, 1970) indicate a diagenetic origin: matrix commonly occurs as interstitial clots, occupying spaces equivalent in size to the preserved detrital grains, with wispy apophyses extending between adjacent rigid grains (Fig. 6A), and in many cases, well-sorted detrital grains ''float'' in sericitic pseudomatrix that preserves relict lithic textures (Fig. 6B). (3) Microprobe analyses of matrix show negligible within-sample K_2O variability, indicating that the components were homogenized during diagenesis (Trevena, 1979).

The pseudomatrix problem prohibits petrographic interpretation of original composition. The apparent maturity of the Mazatzal Group quartzite is an artifact of postdepositional modification, and most of these rocks are diagenetic quartz arenites (sensu Anderhalt, 1986; Chandler, 1988; Cummins, 1962; McBride, 1985; Milliken, 1988). Ternary diagrams of preserved detrital minerals show only quartz and chert (Fig. 7A), leading to the false conclusion that the Mazatzal Group sediments were mineralogically mature.

Normative analysis (Cox and Lowe, 1996)—combining petrographic (Table DR2) and chemical (Table DR3, X-ray fluorescence [XRF] analyses of quartzite; see footnote 1) data—permits recreation of the primary mineral assemblage (Data Repository text shows methodology; see footnote 1). The data indicate that precursor detrital grains included both feldspar (F*) and lithic (L*) fragments (Table DR2; see text footnote 1). Protoliths to the quartzite contained up to 10% feldspar (mostly K-feldspar, with minor plagioclase) and up to 24% lithic fragments. Therefore, although a subset of the samples is composed of true quartz arenite, the majority were lithic arenite and lithic arkose. The original framework-grain compositions plot in the recycled-orogen field (Fig. 7B), which is well in keeping with the known provenance and active-plate-margin setting of the Mazatzal Group.

Detrital Quartz

Monocrystalline grains dominate the detrital quartz population in the Pine Creek Conglomerate and Deadman Quartzite (Table DR2; see text footnote 1). Grains are mostly angular or subrounded, and volcanic phenocrystic quartz is very abundant. The volcanic grains preserve the idiomorphic bipyramidal shape characteristic of rhyolitic quartz, have few or no fluid inclusions, and include resorption embayments on a variety of scales (Fig. 8). Preservation is best in the Pine Creek Conglomerate, where reworking was minimal. Deadman Quartzite grains are generally more rounded, so many of the delicate embayment features and straight crystal faces have been modified. However, embayed grains still make up ~10% of the quartz population in the Deadman Quartzite, and the probable volcanic origin of a substantial proportion of the nonembayed grains is attested to by their lack of internal strain and the scarcity of fluid inclusions. In spite of the degree of induration and overall deformation of the rock package, the quartz grains

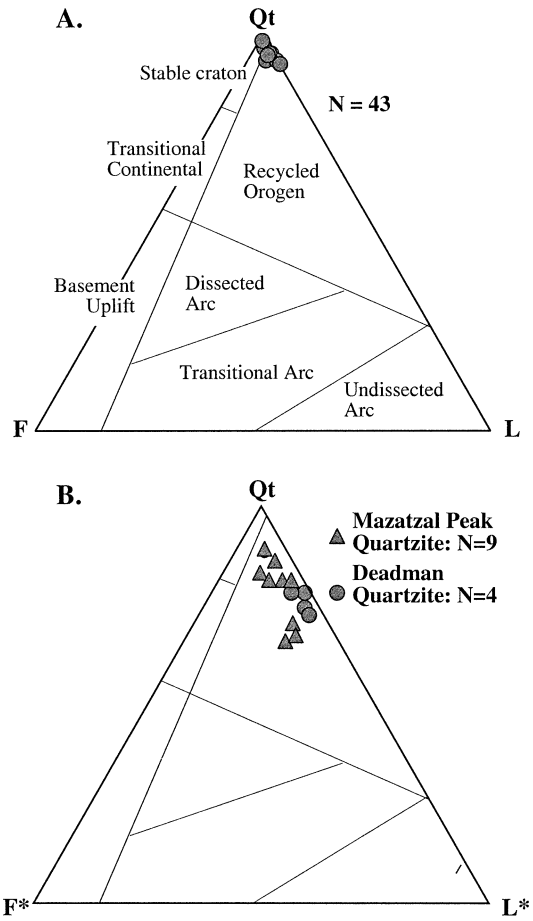

Figure 7. Petrologic data for quartzite from the Mazatzal Group. Complete data are shown in Table DR2 (see text footnote 1). Ternary diagram fields are from Dickinson and Suczek (1979) and Dickinson (1985). (A) Petrographic point-count data collected by using a modified Gazzi-Dickinson technique (Cox and Lowe, 1996). Data points cannot be distinguished because they tend to plot on top of one another. Only 6 of 43 data points plot outside the stable craton field. (B) Normative data combining petrographic and chemical analysis (method of Cox and Lowe, 1996) for 13 randomly chosen samples. F* and L* represent preserved detrital grains plus grains reconstructed by normative analysis. There is a very marked difference between the tight clustering of the points in Figure 7A and the much more variable and immature compositions of the samples plotted in Figure 7B. Restored detrital compositions plot in the recycled orogen field, indicating derivation of the sediment from an uplifted, metamorphosed continental hinterland.

in the lower part of the Mazatzal Group generally have only slightly undulose extinction.

In the Mazatzal Peak Quartzite, the quartz population is different. The average abundance of polycrystalline quartz is still very low, but up to 14% of the quartz population in individual samples may consist of polycrystalline grains (Table DR2; see text footnote 1). Grains are generally less angular, and predepositional fluid inclusions and strongly undulose extinction are common. Embayed monocrystalline grains and grains with crystal faces do occur, but they are much less common than in the Deadman Quartzite.

Provenance Interpretations

The Mazatzal Group received sediment from three distinct sources, the relative contributions of which varied through time. Varied petrologic indicators show that the provenance, dominated originally by subjacent volcanic rocks of the Red Rock Group (volcanic quartz and silicified rhyolitic fragments), evolved through time to include fine-grained orogenic rocks of the Payson Ophiolite and East Verde River Formation (labile grains with Fe + Mg ± Ca ± Na, now in pseudomatrix), and finally granitic basement rocks (polycrystalline quartz, and K-feldspar in pseudomatrix).

Volcanic quartz is most common in the Pine Creek Conglomerate, is less so in the Deadman Quartzite, and is least abundant in the Mazatzal Peak Quartzite. Conversely, the abundance of polycrystalline grains and internally strained, undulose grains (from granitoid rocks and/or recycled quartzite; Basu et al., 1975) and fluid-inclusion–rich grains (probably vein quartz; Folk, 1974) increases up section.

The preponderance of well-preserved volcanic quartz grains in the Pine Creek Conglomerate and Deadman Quartzite suggests derivation from the immediately subjacent rhyolite. In contrast, the major source for the quartz in the Mazatzal Peak Quartzite was the continental hinterland and/or the exposed plutonic roots of the rhyolitic volcanic complex; the quartzite shows only a minor contribution from the volcanic rocks themselves. Grain rounding increases up section, indicating longer travel times and greater sediment reworking, reflecting progressive reduction of the regional topography. These detrital quartz patterns suggest that the initial volcanic topography associated with the Red Rock Group, possibly enhanced by local faulting as suggested by Middleton (1986), formed a barrier to sediment transport such that the Mazatzal depocenter was initially narrowly circumscribed. With cessation of uplift, erosion wore down the highlands and opened the basin to input from a wider hinterland, including arc rocks of the Mazatzal block supracrustal series and, ultimately, continental basement.

The boulders and cobbles of the Pine Creek conglomerate consist almost entirely of rhyolite (Bayne, 1987; Cox and Lowe, 1995). Boulders and cobbles of quartzite and jasper-rich iron formation also occur, but in spite of the proximity of the sources for these rocks (the Alder Group, East Verde River Formation, and Payson Ophiolite), and their mechanical and chemical resistance, their abundance is very low (<10%) (Bayne, 1987; Cox and Lowe, 1995; Doe and Karlstrom, 1991), suggesting that the basin catchment area was extremely limited, and that the sediment sources were very local.

In Deadman Quartzite time, the now-muted volcanic terrain produced less gravel and a higher proportion of sand. Greater reworking

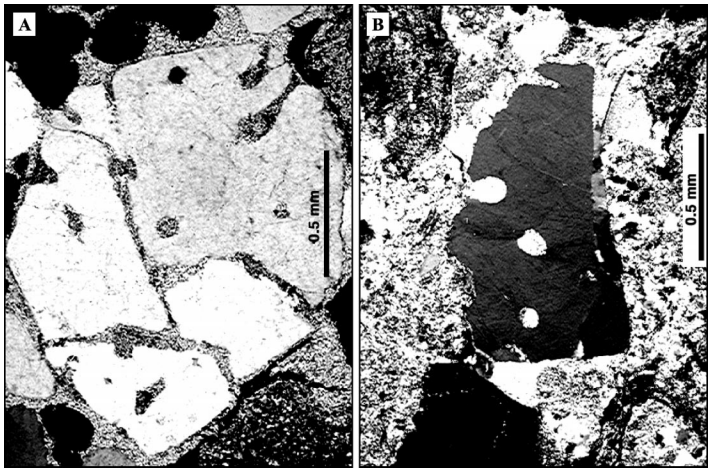

Figure 8. Photomicrographs showing volcanic quartz phenocrysts as detrital grains in Mazatzal Group quartzite. (A) Deadman Quartzite at Pine Creek. (B) Deadman Quartzite at Shaketree Canyon.

resulted in more rounding of sand-sized grains. Detrital quartz was still dominated by rhyolite-derived chert and volcanic quartz, but the sand also originally contained ~20% labile lithic fragments (Table DR2). The labile material, preserved now only as a chemical signature in the pseudomatrix, suggests that by Deadman Quartzite time detritus from mafic volcanic rocks and graywackes of the East Verde River Formation and Payson Ophiolite was reaching the Mazatzal Group depocenter. Detrital feldspar was rare, in part because of the lack of sand-sized feldspar phenocrysts in the Red Rocks Group and related rocks. The lack of feldspar is significant, however, because it also indicates that there was no substantial granitic input to the depositional basin at this time.

The Mazatzal Peak Quartzite also contained an average of about 15% labile lithic fragments prior to pseudomatrix development, with an inferred source in the Payson Ophiolite and East Verde River Formation. In contrast to the Deadman Quartzite, however, it also contained up to 10% detrital feldspar (Table DR2, Fig. 7B). The feldspar component, in combination with the abundance of polycrystalline quartz and undulose, fluid-inclusion–bearing monocrystalline quartz, indicates an increasing granitic basement source contribution. Maverick Shale mudrocks have a well-developed negative europium anomaly, and high field strength elements are moderately enriched relative to transition elements, consistent with a predominantly continental source (Cox et al., 1995). The generally fine grain sizes and the lack of conglomeratic indicate a low-lying hinterland, and suggest that continued erosional flattening of the posttectonic landscape opened the depocenter to sediment from a wider catchment area.

DISCUSSION AND CONCLUSIONS

The Mazatzal Group is part of a Middle Proterozoic volcano-sedimentary succession formed during the accretion of central Arizona. The Mazatzal Group records the final stages of the process, as volcanism and tectonic activity gave way to quiescent conditions, and erosive processes dominated over uplift in the sediment source areas.

Overview of the Proterozoic Mazatzal Depocenter

Sediment source areas were to the north and northeast throughout deposition of the Mazatzal Group, and the deepest parts of the basin were to the south (Trevena, 1979; Bayne, 1987). The depocenter was close to the continental margin, and transitions between terrestrial and marine environments took place over very short stratigraphic intervals. The preserved along-strike extent of the sedimentary sequence is on the order of 30 km, but because of subsequent tectonic fragmentation, the original size of the basin is unknown.

From the clast sizes in the Pine Creek Conglomerate, it is apparent that the initial topographic expression of the basin margins was rugged and that the source highlands were proximal to the depocenter. Active faulting and rhyolitic volcanism produced substantial relief in the vicinity (Wrucke and Conway, 1987), although there is little local relief beneath the Mazatzal Group deposits (e.g., Trevena, 1979). The main phase of volcanism and tectonic activity effectively ceased at ca. 1.70 Ga, the approximate age of formation of the sub–Mazatzal Group unconformity (Karlstrom and Bowring, 1993). The unconformity (mapped by Wrucke and Conway, 1987) is locally marked by concentrations of hematitic detritus and thin (<1 m), strongly ferruginous sandstones with uneven bases. The Pine Creek Conglomerate formed on this surface as an apron of coarse alluvial detritus. The very small clastic contribution from nearby resistant lithologies (such as the Alder Group quartzite) implies an extremely limited catchment area and a marked watershed during Pine Creek Conglomerate time.

The predominance of event sedimentation in the Pine Creek Conglomerate is indirect evidence for minor uplift in the source area. The terminal tectonic event in the Mazatzal area is marked by local, small-scale angular discordance between the Pine Creek Conglomerate and the intraformational rhyolite of the overlying Deadman Quartzite. The cessation of uplift and the wearing down of the basin margins are reflected in the fining-upward character of the clastic succession from Pine Creek Conglomerate through Deadman Quartzite and in the progression from coarse alluvial-fan to sandy braided-stream environments recorded in these rocks. From the Deadman Quartzite upward there is no evidence for any tectonic disturbance in the Mazatzal Group basin.

Sand-dominated terrestrial sedimentation was followed by a marine transgression that produced shallow-marine deposits of cross-bedded and wave-rippled sandstone, now forming the upper part of the Deadman Quartzite. The Maverick Shale records a subsequent transition to deeper-water, largely sub–wave-base sedimentation. This deepening was probably due to rising sea level because the contact with the Deadman Quartzite is conformable and there is no evidence in the Maverick Shale for any kind of fault-related sedimentation. Progressive shallowing and a return to shallow-water sedimentation, probably coastal, are preserved in the gradual transition to the desiccation cracks, wave ripples, and herringbone cross-lamination of the lower Mazatzal Peak Quartzite. Subsequent marine regression or delta progradation resulted in the braided-stream deposits of the upper Mazatzal Peak Quartzite.

Continued low relief in the hinterland is reflected in the lack of coarse clastic material from the Deadman Quartzite through the Mazatzal Peak Quartzite. In addition, petrologic

characteristics indicate increased sediment reworking and a more cosmopolitan set of source lithologies through time, suggesting that as topography was worn down, the basin catchment area widened.

Interpreting the Tectonic Setting of the Mazatzal Group: The State of the Debate

The false sediment maturity and implied cratonic setting indicated by the preserved detrital minerals (Fig. 7A) leading to characterization as ''mature quartz arenite'' (Conway et al., 1987; Conway and Silver, 1989; Karlstrom et al., 1987; Trevena, 1979; Wrucke and Conway, 1987; Karlstrom and Bowring, 1993; Van Schmus et al., 1993b) has prompted interpretations such as a passive-margin (Karlstrom and Conway, 1986) or continental-shelf environment (Conway et al., 1987; Conway and Silver, 1989; Trevena, 1979) for the Mazatzal Group sedimentary rocks. These interpretations are at odds, however, with the regional and underlying geology, because the Mazatzal Group is closely associated in space and time with rocks that are understood to represent Andean-type arcs and orogenic events and because the sediments are partly coeval with rhyolitic volcanism (Condie, 1982; Condie and Chomiak, 1996; Dann, 1997; Dann and Bowring, 1997; Karlstrom and Bowring, 1991, 1993).

The diagenetic destruction of provenance information has also had wider-ranging effects on paleogeographic interpretations: For example, the apparent absence of feldspar in the proximal Mazatzal Group and its presence in the more distal Pinal Schist in southeastern Arizona has prompted the suggestion that either high-level subrhyolitic plutons or basement granite of an older orogenic terrane must have been locally exposed in the Pinal basin (Conway and Silver, 1989).

Tectonic settings suggested for the Mazatzal Group include an active margin (no specific plate setting given) (Trevena, 1979); basin-and-range–type transtensional basins or half grabens (Bayne, 1987); a semistable, subsiding continental environment, either the margin of a continental nucleus or a continental-interior basin (Conway and Silver, 1989; Wrucke and Conway, 1987); synorogenic deposition in response to 1.70 Ga orogenesis in the Yavapai block (no specific plate setting given) (Karlstrom and Bowring, 1991, 1993); and a backarc basin (Condie et al., 1992).

The basin-and-range–type and stable continental-interior interpretations are based on the voluminous rhyolite of the Red Rock Group immediately preceding and locally coinciding with deposition of the thick sequence of Mazatzal Group ''quartz arenite'' (Bayne, 1987; Conway and Silver, 1989; Wrucke and Conway, 1987). However, there are no known environments, past or present, in which rhyolite and quartz arenite are volumetrically codominant. In addition, ductile deformation and metamorphism were ongoing northwest of the Mazatzal depocenter, which is difficult to reconcile with a passive-margin or stable continental-interior setting (Karlstrom et al., 1987). Synorogenic sedimentation (Karlstrom and Bowring, 1991, 1993; Condie et al., 1992) fits well with the geologic history of the region, but the existing models do not explain the abundance of ''mature continental sediment,'' and therefore are not fully satisfactory (Karl Karlstrom, 1991, personal commun.).

Interpreting the Tectonic Setting of the Tonto Basin Supergroup

The tectonic setting of the Mazatzal Group can be better understood by examining it in relation to the rocks with which it is regionally associated. The Mazatzal Group is the final installment of the Tonto Basin Supergroup (Fig. 2), a supracrustal sequence on the Mazatzal block (Karlstrom and Bowring, 1988) that has been interpreted to represent a continental-margin arc environment sensu lato (Condie and Chomiak, 1996; Condie et al., 1992). Interpretations for the various formations, however, while reasonable in the context of each individual unit, are mutually inconsistent when viewed as a series. The lowermost unit is the Payson Ophiolite (Fig. 2), an autochthonous complex of gabbros, sheeted dikes, and submarine basaltic volcanic rocks interpreted as an intra-arc assemblage formed by rifting of older arc crust (Dann, 1991, 1997). The overlying supracrustal rocks of the East Verde River Formation and the Alder Group have been interpreted to represent an island arc (Wrucke and Conway, 1987), a backarc basin (Karlstrom and Bowring, 1993), or continental-margin backarc basin (Condie et al., 1992). The tectonic setting of the Mazatzal Group is unsettled, as discussed in the preceding section.

An Intra-Arc Origin for the Payson Ophiolite and Tonto Basin Supergroup

We propose that the supracrustal package including the Payson Ophiolite and the Tonto Basin Supergroup (Fig. 2) formed in a continental or near-continental intra-arc basin and that the Mazatzal Group represents the extinction stage and final infill of the basin. This setting explains the association of the Mazatzal Group with the orogenic supracrustal rocks below it, is consistent with the composition of the Mazatzal Group itself, and fits with established tectonic models for the southwestern United States (Van Schmus et al., 1993a). More specifically, it is fully in keeping with the stratigraphy of the Mazatzal block (as defined by Karlstrom and Bowring, 1988).

Intra-arc successions may be difficult to differentiate from backarc successions because they share many of the same features (Marsaglia, 1995). They are end members of a tectono-sedimentary spectrum, as many backarc basins originate by intra-arc rifting (Smith and Landis, 1995). Backarc basins, however, represent advanced spreading and generation of oceanic crust and hence achieve bathyal or abyssal water depths. Sedimentary facies within them are therefore almost entirely submarine and are dominated by volcaniclastic or resedimented detritus in turbidites or pelagic deposits (Marsaglia, 1995; Klein, 1985). Overall facies patterns commonly indicate progressive deepening through time. Intra-arc basins, in contrast, do not achieve the same width and depth, because oceanic crust formation may be initiated but complete arc separation is not achieved. Sediments, in consequence, include both deep- and shallow-water deposits, and the sedimentary system may in fact be emergent (Busby-Spera, 1988; Riggs and Busby-Spera, 1990; Smith and Landis, 1995; Smith et al., 1987). Eustatic effects can produce patterns of deepening and shoaling as well as intrabasinal shifts from continental to marine facies (Houghton and Landis, 1989; Smith and Landis, 1995). These eustatic effects are not generally seen in backarc basins because the greater water depths buffer the system against relatively small-scale sea-level changes.

The Mazatzal block stratigraphy (Fig. 2) is more consistent with an intra-arc than with a backarc setting. The Payson Ophiolite records partial but incomplete oceanic crust formation within magmatic arc/nascent continental crust because screens of granitic crust remain in the sheeted-dike complex, and the ophiolite gabbros intrude that same granitic basement (Dann, 1997). The relatively high granite to mafic rock ratio implies limited extension that was not sustained over a long period and indicates incomplete arc separation. Volcano-sedimentary rocks of the East Verde River Formation were deposited on the floor of the newly formed intra-arc basin, and the repeti-

tive Bouma-cycle turbidites, with associated siltstone and bedded jasper, record the deepest-water sedimentation in the basin's history. The Alder Group is also largely volcanogenic, including both mafic and felsic components, but it has a higher terrigenous contribution. It contains abundant turbidites, but progressive shoaling produced cross-bedded quartzite near the top. The Red Rock Group records a change to voluminous high-silica rhyolite volcanism, which is not characteristic of backarc settings. Finally, the largely postvolcanic Mazatzal Group represents both reworking of older volcanogenic material and an increased continental crustal component in sedimentary environments ranging from shallow marine to emergent.

Mazatzal Group Sedimentation as the Final Phase of the Intra-Arc Basin

The interpretation of the Mazatzal Group as representing the waning stages and final infill of the intra-arc basin resolves a number of the controversies surrounding the composition and associations of the sequence. First, the composition of the quartzite is consistent with a mature intra-arc setting. We have shown that these rocks include a significant proportion of altered lithic fragments and feldspar, reflecting the orogenic and basement rocks in the source area (Fig. 7, Table DR2), but they are also quartz rich (although not quartz arenite). In mature intra-arc basins, especially those proximal to continents, some quartz-rich sediment and even pure quartz arenite may be deposited (Smith and Landis, 1995). Microcline- and quartz-bearing sediments occur in immature, Marianas-type arc assemblages in the Klamath Mountains (Lapierre et al., 1985), and continental molasse and red-bed sediments are closely associated with Mesozoic arc volcanic rocks in the central Andes (James, 1971). Thick basin fills of terrigenous sediment, derived from plutonic and sedimentary source rocks, are interpreted to occupy submerged, fault-bounded basins along the Aleutian arc (Scholl et al., 1975), and pure quartz arenite, derived from the cratonic hinterland, is intimately interbedded with contemporaneous silicic volcanic rocks in the Jurassic arc-graben system of the southwestern United States (Busby-Spera, 1988; Riggs and Busby-Spera, 1990).

Second, the composition of the penecontemporaneous volcanic rocks is consistent with an intra-arc setting. Thick silicic accumulations are not uncommon in extensional arc settings where continental crust is available for partial melting. Modern examples include rhyolite of the Taupo volcanic zone in New Zealand (Wilson et al., 1984), the Tonga-Kermadec arc (Ewart et al., 1977), and dacitic to rhyolitic ignimbrites in the High Cascades (Smith et al., 1987). Recently accreted continental basement and a thick sediment pile were available to produce the Red Rock Group rhyolite (Fig. 2).

Third, the timing of sedimentation with respect to volcanism is very important. The time gap between the Red Rock Group and the Mazatzal Group is small (Fig. 5), but marked by a substantial angular unconformity (Karlstrom and Bowring, 1993; Wrucke and Conway, 1987). The only volcanic event during Mazatzal Group time is the volumetrically small eruptive pulse of the Rhyolite Member at the beginning of deposition of the Deadman Quartzite time. Anderson and Wirth (1980) have pointed out that the source for volcanic detritus in the Mazatzal Group is subjacent and that there was no direct volcaniclastic contribution to the basin. In addition, other than the small local angular discordance between the Pine Creek Conglomerate and the Deadman Quartzite, there are no internal unconformities. The Mazatzal Group is therefore essentially a postvolcanic sequence, which is consistent with the extinction of the arc and the transition to a stable continental setting.

Fourth, there is a marked and progressive up-section change in sediment provenance, which we interpret to represent rapid sedimentary response to changing tectonic, and hence topographic, conditions in the region. The nature of this change, toward continental dominance and high levels of sedimentary reworking, is consistent with the extinction of the intra-arc basin as a tectonic entity and the final infill by sediment, and also represents the final accretion and stabilization of this segment of the continental crust in the southwestern United States.

Relationship to Other Proterozoic Sedimentary Sequences in Arizona

The interval 1.70 to ca. 1.60 Ga was characterized by the final stages of craton stabilization at the then-southern margin of the North American craton. Several areas in Arizona preserve quartzite or quartzite-shale sequences overlying rhyolitic volcanic rocks. The issue of the relationships among those sequences is central to understanding the regional tectono-sedimentary system during craton formation.

The strata of the Mazatzal Group have been correlated with lithologically similar Proterozoic units in the Chino Valley and Hess Canyon areas (Fig. 1), and an east-trending shoreline, with a north-south transition from terrestrial to marine, has been proposed (Anderson and Wirth, 1980; Conway and Silver, 1989; Karlstrom et al., 1987; Trevena, 1979; Wilson, 1939). More recent geochronological studies, however, have indicated that the various units may be substantially different in age. U-Pb data from detrital zircons in quartzite in the Chino Valley sequence yield concordant ages of ca. 1660 Ma (Chamberlain, K.R., 2000, personal commun.), which is younger than the 1771 Ma onset of sedimentation in the Mazatzal area. Similarly, the rhyolitic Redmond Formation, which underlies the quartzite and shale of the Hess Canyon Group, was previously correlated with the Red Rock Group (Anderson and Wirth, 1980; Livingston, 1969; Trevena, 1979), but U-Pb data from the Redmond Formation indicate that its age is 1.66 Ga (Karlstrom and Bowring, 1991; Karlstrom et al., 1990), also significantly younger than the 1.70 Ga Red Rock Group.

The similarity of the rhyolite–sedimentary rock sequences, in spite of the disparity in their ages, suggests that the southern edge of the continent was episodically and locally tectonically active in the waning stages of arc activity and that sedimentation took place at local depocenters. The environments of deposition vary among these sequences, from largely fluvial in the Chino Valley area, to mixed fluvial and marine in the Mazatzal area, to exclusively marine in the Hess Canyon sequence (Trevena, 1979). There was undoubtedly sedimentation in the intervening times and the intervening areas, but because of either penecontemporaneous erosion due to the ongoing volcanism and faulting or the vagaries of preservation in the modern central Arizona Transitional Zone, those deposits have not been preserved. In all cases, the Middle Proterozoic quartzite sequences in Arizona have erosional tops, suggesting a final culminating phase of regional uplift and erosion.

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