Correlation of Jurassic eolian strata between the magmatic arc and the Colorado Plateau: New U-Pb geochronologic data from southern Arizona

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ABSTRACT

Mature quartz-rich sandstone interbedded with Mesozoic magmatic-arc strata in southern Arizona has been previously considered correlative with the eolian Pleinsbachian to Toarcian Navajo Sandstone on the Colorado Plateau. New U-Pb zircon data from the Mount Wrightson Formation in the Santa Rita Mountains and from the strata of Cobre Ridge in the Pajarito Mountains and in the Arivaca area in southern Arizona support the hypothesis that sand derived from the Navajo Sandstone probably did gain access to the magmatic arc and further indicate that sands extending from younger eolian units on the Colorado Plateau are probably present as well.

The Mount Wrightson Formation accumulated from ~190 Ma to 170 Ma, corresponding to late Pleinsbachian to Aalenian time (time scale of Harland, 1990). Isotopic ratios from zircon fractions from the lower member of the Mount Wrightson Formation define a discordia line with lower intercept of 184 ± 8 Ma. The lower member is approximately coeval with the 188 ± 2 Ma Piper Gulch monzonite, dated by Asmerom and others (1990), which intrudes it. The middle and upper members of the formation yield somewhat less precise dates that indicate deposition between 183 ± 2 Ma and ≈170 Ma. Quartz-rich sandstone occurs in all three members, though most abundantly in the middle and upper members, and in many places contains sedimentary structures diagnostic of eolian sedimentation. Our results suggest that sands related to Lower Jurassic Navajo ergs and Middle Jurassic Temple Cap ergs gained access to the arc.

The age of the strata of Cobre Ridge is ~170 ± 5 Ma. Eighteen fractions taken from three samples of the tuff lie in a cluster near concordia. A best-fit age of 169 Ma is based on near concordance of one fraction and on model discordia trajectories using assumed upper intercepts. Sandstone horizons interbedded within the strata of Cobre Ridge in many cases contain sedimentary structures diagnostic of eolian sedimentation and, although quartz rich, in general have more volcanic detritus than sandstones in the Mount Wrightson Formation. The interval between 165–175 Ma corresponds to the Aalenian and Bajocian stages and is within the time span represented by the Temple Cap and Page sandstones of southern Utah and northern Arizona. Sandstone interstratified with the strata of Cobre Ridge may be correlative with either of those units. The possibility cannot be discounted, however, that unconsolidated or weathered Navajo-equivalent sands from the upper member of the Mount Wrightson Formation were recycled into the strata of Cobre Ridge.

These results support the models (Busby-Spera, 1988; Riggs and Busby-Spera, 1990, 1991), suggesting that during Early to Middle Jurassic time the magmatic arc in southern Arizona was low standing and did not constitute an impediment to the south and southwestward movement of continental sediments. We suggest that much of the region between the Colorado Plateau and the arc was topographically low, and that tectonic and volcanic basins within the arc provided traps for windblown mature sands for as long as 35 m.y. We speculate that Early to Middle Jurassic tectonic subsidence within the magmatic arc may have been more continuous than subsidence on the Colorado Plateau, thus providing a depocenter in which major tectonically induced unconformities that characterize the Mesozoic record in the back arc are masked by ongoing volcanic activity.

INTRODUCTION

Mature, quartz-rich sandstones interstratified with volcanic rocks of a Jurassic continental magmatic arc (Coney, 1979; Dickinson, 1981; Tosdal and others, 1989) have been identified from the Sonoran Desert of Mexico and southern Arizona through the Mojave Desert of western Arizona and southeastern California, to the Sierra Nevada of eastern California and adjacent ranges in Nevada (Hewett, 1956; Grose, 1959; Knight, 1970; Cooper, 1971; Drewes, 1971c; Haxel and others, 1980a, 1980b; Marzolf, 1980, 1982; Busby-Spera, 1984; Riggs, 1987; Segerstrom, 1987; Fig. 1). Early workers in the Sonora-Mojave regions (Hewett, 1956; Grose, 1959; Cooper, 1971; Drewes, 1971c) proposed that these sandstones, many of which contain high-angle, large-scale cross-stratification, are correlative with Mesozoic eolian sandstone units on the Colorado Plateau. Specifically, thick eolian sandstone in eastern California was stratigraphically correlated with the Aztec Sandstone, the western continuation of the Navajo Sandstone (McKee, 1979; Porter, 1987; Blakey and others, 1988).

The first reliable dating of volcanic rocks interstratified with eolian sandstone in southern Arizona was done by Wright and others (1981), who obtained U-Pb ages of 190–195 Ma on volcanic rocks in the Baboquivari Mountains (Fig. 1). Wright and others (1981) and Bilodeau and Keith (1986) proposed that these eolian quartzarenites are coeval with the Lower Jurassic Navajo Sandstone. Bilodeau and Keith (1986) further suggested that the association of craton-derived eolian quartzarenite and volcanic strata is so unusual that in all probability all eolian strata associated with Mesozoic volcanic strata in southern Arizona and eastern California are correlative with each other and with the Aztec and Navajo Sandstones.

We present here results of a study undertaken to test the hypothesis that major eolian intervals interstratified with volcanic sequences in southern Arizona are coeval, and to suggest correlative(s)

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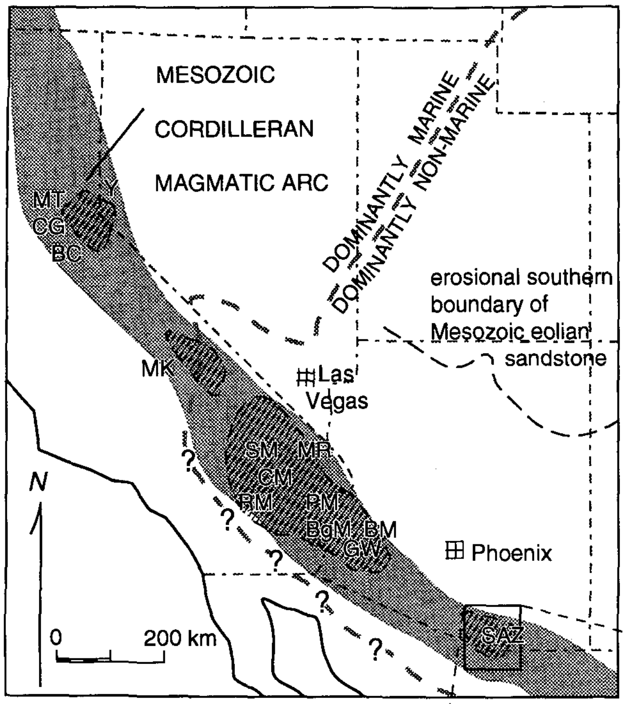
A



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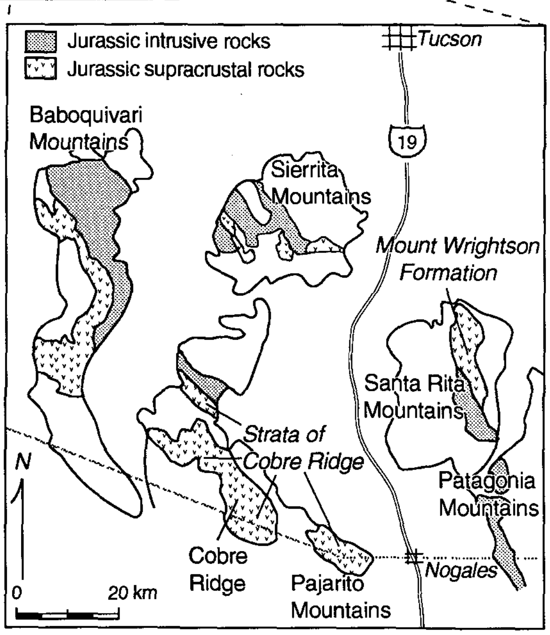

Figure 1. A. Generalized map of the western United States showing inferred original extent of Mesozoic magmatic arc. Quartz-rich sedimentary strata interstratified with magmatic arc deposits *shown in diagonal pattern*. Initials: MT, Mount Tallac; CG, Cisco Grove; Y, Yerington; BC, Blackwood Canyon; MK, Mineral King; SM, Soda Mountains; CM, Cowhole Mountains; RM, Rodman Mountains; MR, Mescal Range; BgM, Big Maria Mountains; PM, Palen Mountains; BM, Buckskin Mountains; GW, Granite Wash Mountains; SAZ, southern Arizona. Shaded dashed line separates dominantly marine from dominantly nonmarine paleoenvironments. B. Lithostratigraphic map of southern Arizona showing Mesozoic arc volcanic and plutonic rocks discussed in text. Diagrams modified from Reynolds (1988), Tosdal and others (1989), Busby-Spera and others (1990), and Riggs and Busby-Spera (1991).

for eolian sequences between the magmatic arc and units of the Colorado Plateau. Volcanic rocks were dated from two disparate volcanic settings: the Mount Wrightson Formation in the Santa Rita Mountains (Drewes, 1968, 1971a, 1971b, 1971c; Riggs and Busby-Spera, 1990) and the informally named strata of Cobre Ridge (Riggs and Busby-Spera, 1991) in the Pajarito Mountains and Cobre Ridge area (Figs. 1, 2, and 3). New data presented here suggest that eolian sands gained access to the continental volcanic arc in southern Arizona during a 35-m.y. interval in Early and Middle Jurassic time.

The long-term access of craton-derived sediments has important implications for the paleogeographic and tectonic setting of the northeastern part of the magmatic arc. In contrast to high-standing "Andean" magmatic arcs such as the Andes Mountains or the Cascade Range, which are topographic barriers to the migration of sediments, the Mesozoic magmatic arc in southern Arizona apparently remained low standing. The arc was characterized by depositional basins that were the result of tectonic and/or volcanic subsidence (Riggs and Busby-Spera, 1991), and mature quartz sand transported by wind from the north gained access to and was trapped by these basins during Early and Middle Jurassic time.

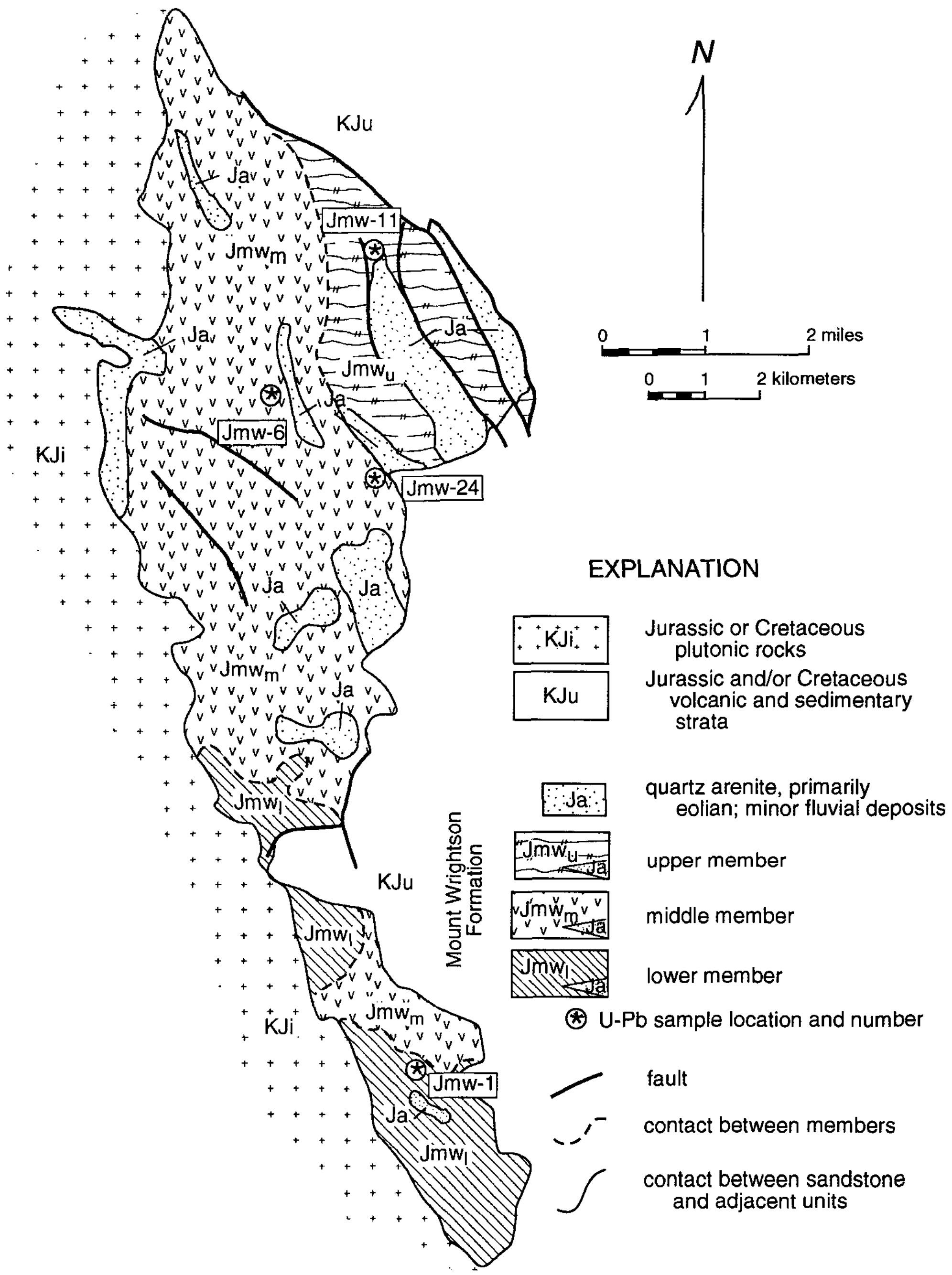

Figure 2. Generalized geologic map of the Mount Wrightson Formation, Santa Rita Mountains, showing distribution of quartzarenite horizons (simplified from Riggs and Busby-Spera, 1990).

GEOLOGIC SETTING OF JURASSIC VOLCANIC ROCKS IN SOUTHERN ARIZONA

The Mesozoic Cordilleran magmatic arc in southern Arizona was built on a basement of Proterozoic (1.8–1.4 Ga) metamorphic and plutonic rocks (Anderson and Silver, 1978; Silver, 1978) overlain by Paleozoic shelf and stable platform sedimentary rocks. Proterozoic units exposed in the Santa Rita Mountains to the north of the Mount Wrightson Formation include the Pinal Schist, an assemblage of ≈1700 Ma biotite gneiss and schist, and the ≈1400 Ma Continental Granodiorite (Drewes, 1968, 1981). The Cobre Ridge area, however, is part of a large area within southern Arizona in which rocks older than Jurassic arc-related strata are not exposed, or, where exposed, are allochthonous (Haxel and others, 1988; Riggs and Haxel, 1990). Isotopic evidence suggests that the crust below this area is also Proterozoic in age (Wright and Haxel, 1982; Farmer and DePaolo, 1984).

Although Lower Jurassic volcanic rocks of the Mount Wrightson Formation, reported on herein and by Asmerom and others (1990), and coeval strata in the Baboquivari Mountains (Wright and others, 1981) are the oldest confidently dated strata related to the Jurassic

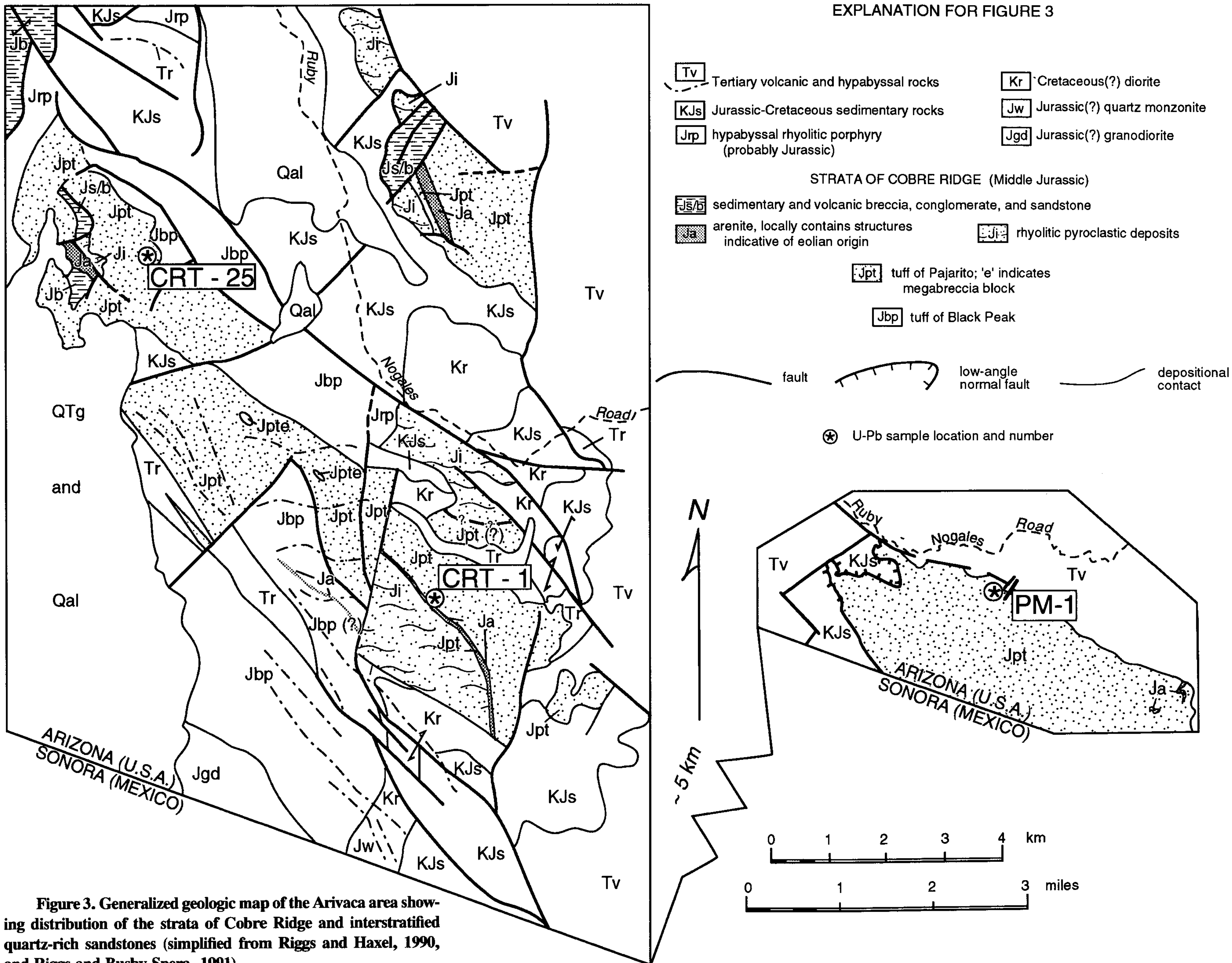

Figure 3. Generalized geologic map of the Arivaca area showing distribution of the strata of Cobre Ridge and interstratified quartz-rich sandstones (simplified from Riggs and Haxel, 1990, and Riggs and Busby-Spera, 1991).

magmatic arc, it is not certain that they represent the inception of magmatism in southern Arizona. The presence of an epiclastic volcanic breccia at the base of the Mount Wrightson Formation indicates a previous episode of volcanism (Riggs and Busby-Spera, 1990). Additionally, magmatic rocks as old as Late Permian have been documented from eastern California (Miller, 1978; Cox and Morton, 1980; Walker, 1988), and plutonic or volcanic rocks of similar and slightly older ages than those given here are reported from western Arizona, eastern California, and the Sierra Nevada (Chen and Moore, 1982; Barth and others, 1990; Tosdal and others, 1989; Saleeby and Busby-Spera, 1992). Volcanic clasts in the Late Triassic Chinle Formation on the Colorado Plateau are proposed to have been derived from the south, suggesting that an as yet unidentified volcanic terrain older than the Mount Wrightson Formation existed in southern Arizona or Sonora (Stewart and others, 1986).

STRATIGRAPHY AND PALEOENVIRONMENTAL SETTING OF EOLIAN QUARTZOSE SANDSTONES AND VOLCANIC ROCKS

Mount Wrightson Formation

The Mount Wrightson Formation was named and mapped by Drewes (1968, 1971a, 1971b, 1971c), who divided the formation into three members (Fig. 2). Riggs and Busby-Spera (1990) identified nine volcanic and sedimentary lithofacies within these three members and proposed that the formation records the evolution of a multiple-vent complex that was active within a subsiding intra-arc basin. The base of the formation is everywhere intruded by Jurassic plutonic rocks (Drewes, 1971b, 1971c), and Drewes (1971c) correlated the formation in the Santa Rita Mountains with strata in the Patagonia Mountains (Fig. 1) that overlie fossiliferous Permian strata.

Mature, quartz-rich sandstone occurs in all three members of the Mount Wrightson Formation but is most common in the middle and upper members (Fig. 2). In many sandstones, wind-ripple laminations and grainflow cross stratification indicate that sands accumulated on eolian dunes as much as 20 m in height. Other sandstone horizons contain channels, graded bedding, and intercalated pebble conglomerates and are red in color, indicating deposition in small fluvial channels. Sedimentary structures are not preserved in some sandstone beds, primarily due to alteration (Riggs and Busby-Spera, 1990).

The lower member of the Mount Wrightson Formation comprises a pyroclastic and epiclastic unit overlain by interstratified dacite and andesite lava flows and flow breccias. Quartz-rich sandstone beds within the lower member are rare and thin but are petrographically identical to those in the middle and upper members (Riggs and Busby-Spera, 1990). Sample Jmw-1 (Tables 1, 2, and 3; Fig. 2) was collected from a dacite lava flow ≈150 m below the top of the member and ≈500 m above the thickest quartz-rich sandstone horizon in the lower member. The age of this sample (183.8 ± 8.5 Ma) documents the approximate time of early incursion of sand into the Mount Wrightson Formation depocenter.

The middle and upper members of the Mount Wrightson Formation are virtually indistinguishable, with the exception of a higher percentage of eolian quartzarenite relative to volcanic rocks in the upper member (Drewes, 1971b, 1971c; Riggs and Busby-Spera, 1990).

TABLE 1. U-Pb ISOTOPIC DATA FOR ZIRCONS FROM THE MOUNT WRIGHTSON FORMATION, SANTA RITA MOUNTAINS, SOUTHERN ARIZONA

Sample no.	Fraction (mesh size)	Concentrations[#]		Pb isotopic compositions[†]			Ages, in Ma[§]		
		$^{206}Pb^*$	^{238}U	208/206	207/206	204/206	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$
Lower member									
Jmw-1-1	$-320 + 260^{a,d}$	2.56	93.32	0.2056	0.0570	0.0000433	201.2	223.4	466 ± 2
-2	$-320 + 260^{a,c}$	7.77	275.7	0.2057	0.0595	0.0000831	206.5	236.2	541 ± 3
-3	$-320 + 206^{a}$	6.68	198.3	0.3405	0.1246	0.0039684	247.1	319.1	893 ± 55
-4	$<206^{a,c}$	2.67	93.55	0.2175	0.0654	0.0004424	209.1	244	595 ± 15
Middle member									
Jmw-6-1	$-320 + 206^{b}$	8.02	346.5	0.3855	0.0647	0.000981	170	172.9	212 ± 15
-2	$-206 + 151^{b}$	5.69	241.2	0.3591	0.0676	0.001190	173.3	175.3	202 ± 20
-3	$bulk^{b,g}$	11.38	499.1	0.4359	0.0629	0.000868	167.5	169.8	203 ± 11
-4	$-206 + 100^{a,e}$	5.653	232.2	0.2938	0.0541	0.0002602	177.9	180.0	206 ± 7
-5	$-206 + 100^{a,i}$	2.79	116.6	0.2784	0.0510	0.0000907	175.8	176.1	180 ± 2
-6	$>206^{a}$	4.38	177.9	0.3341	0.0521	0.0000530	180.5	185.5	254 ± 2
Middle member									
Jmw-24-1	$>320^{a}$	4.02	166.4	0.2202	0.0534	0.0002521	176.8	177.5	181 ± 5
-2	$-320 + 206^{a,c}$	4.50	194.1	0.2148	0.0502	0.0000285	170	171.5	185 ± 2
-3	$-320 + 206^{a,d}$	4.00	168.5	0.2152	0.0502	0.0000291	174.2	174.5	183 ± 2
-4	$-320 + 206^{a}$	1.66	67.63	0.2194	0.0523	0.0001896	180.2	179.2	164 ± 20
-5	$-206 + 151^{b,c,f}$	1.56	63.00	0.2569	0.0591	0.0004611	181.5	183.6	211 ± 14
-6	$-206 + 151^{a,d,i}$	8.40	338.8	0.2423	0.0517	0.0001360	182	181.9	180 ± 4
-7	$-206 + 151^{a,d}$	2.28	91.92	0.3456	0.0977	0.0032408	182.8	183.5	209 ± 33
-8	$-206 + 151^{a,c}$	6.18	253.0	0.2466	0.0530	0.0002130	179.3	180	189 ± 7
Upper member									
Jmw-11-1	$-320 + 206^{b}$	5.32	221.4	0.4315	0.0835	0.002048	176.4	189.5	356 ± 33
-2	$-320 + 206^{b,d}$	7.84	329.9	0.3748	0.07234	0.001371	174.5	183.4	299 ± 17
-3	$-320 + 206^{b,c}$	3.26	130.5	0.4726	0.0993	0.003011	183.4	202.6	432 ± 54
-4	$-320 + 206^{a,g}$	2.91	93.55	0.3697	0.0825	0.001487	227.4	268.2	640 ± 152
-5	$-206 + 151^{b}$	3.57	142.2	0.4678	0.0996	0.003168	183.7	205.7	466 ± 35
-6	$-206 + 151^{a,g}$	4.80	178.7	0.3254	0.0589	0.000327	196.7	211.2	376 ± 57
Jmw-11-7	$-206 + 151^{a,d}$	5.03	207.2	0.3230	0.05329	0.0001276	178	183.7	259 ± 3
-8	$>206^{b,h}$	17.84	139.65	0.2990	0.16486	0.0051350	887	1091.4	1526 ± 34
-9	$bulk^{b,e}$	6.47	285.9	0.4245	0.0736	0.001409	166.2	177.5	331 ± 14

Note: all samples nonmagnetic at 0.5° side tilt, 15° forward tilt on Frantz isodynamic magnetic separator except as noted. a = residue of stepwise dissolution; b = total dissolution; c = coarse tap; d = fine tap; e = 1° side tilt nonmagnetic; f = air abraded; g = 0° side tilt nonmagnetic; h = rounded, pitted, apparently detrital zircons; i = broken crystals.

[#]Concentrations in ppm. Total dissolution procedure after Krogh (1973); stepwise dissolution procedure described in Riggs (1991), after Krogh and Davis (1975) and Mattinson (1984, and unpub. data). * = radiogenic lead, corrected for common lead using 208:207:206:204 of 38.5:15.6:18.4:1 (after Stacey and Kramers, 1975).

[†]Isotopic compositions corrected for 0.125% per mass unit fractionation based on numerous replicate analyses of NBS Pb and U standards. Uncertainties in 208/206 and 207/206 are <0.09%; uncertainties in 204/206 vary from 0.3% to 6%.

[§]Decay constants used: $^{235}U = 9.8485 \times 10^{-10}$; $^{238}U = 1.55125 \times 10^{-10}$; $^{238}U/^{235}U = 137.88$. Combined sources of error on $^{206}Pb^*/^{238}U$ age include error propagated in measurements of individual isotope and assessment of error on initial $^{206}Pb/^{204}Pb$. $^{206}Pb^*/^{238}U$ ages estimated to have ±1% error (≈±2 Ma). Uncertainty in $^{207}Pb^*/^{206}Pb^*$ ages is based on error in measured $^{206}Pb/^{204}Pb$ and on initial $^{207}Pb/^{204}Pb$ values. See Mattinson (1987) for rigorous evaluation of error analysis in zircon geochronology, and Riggs (1991) for detailed error analysis in this study.

TABLE 2. LOCATIONS OF GEOCHRONOLOGY SAMPLES

Sample	Latitude	Longitude
Mount Wrightson Formation		
Jmw-1	31°36′57″	110°47′39″
Jmw-6	31°43′30″	110°50′13″
Jmw-24	31°29′37″	110°48′56″
Jmw-11	31°34′12″	110°48′48″
Strata of Cobre Ridge		
PM-1	31°38′01″	111°6′25″
CRT-1	31°26′10″	111°15′41″
CRT-25	31°29′48″	111°19′33″

Both members comprise tuff, eolian quartzarenite, and intermediate to silicic hypabyssal intrusions, with less abundant debris-flow deposits and intermediate lava flows. Eolian sandstone horizons are as much as 300 m thick, with thicker units containing high-angle cross-stratification as much as 10 m in thickness. The sandstones are petrographically quartzarenite, sublitharenite, and subarkose, and may contain a maximum of 11% volcanic rock fragments and/or volcanic crystals. Pyrogenic quartz crystals are rare to absent, indicating that quartz grains within the sandstone were not locally derived, and that relief and weathering of the volcanic rocks occurred slowly (Riggs and Busby-Spera, 1990).

Two samples of the middle member were collected: a hypabyssal intrusion from the middle of the member (Jmw-6; Tables 1, 2, and 3; Fig. 2) and a densely welded ignimbrite from the top of the member (Jmw-24; Tables 1, 2, and 3; Fig. 2). An ignimbrite from the upper member (Jmw-11; Tables 1, 2, and 3; Fig. 2) that depositionally overlies a quartzarenite was also analyzed. These three samples provide information on the span of volcanism, and therefore the length of time in which craton-derived sand gained access to the volcanic complex.

Strata of Cobre Ridge

The strata of Cobre Ridge (Figs. 1 and 3) are exposed in a dominantly southwestward-dipping homocline and comprise ignimbrite with lesser fallout tuff, surge deposits, eolian and fluvial sandstone, and debris-flow deposits. These strata represent a caldera complex (Riggs and Busby-Spera, 1991) and are dominated by the tuff of Pajarito, a crystal-rich rhyodacite as much as 3,000 m thick.

Sandstone units within the strata of Cobre Ridge are everywhere less than ≈50 m thick, are characterized by wind-ripple lamination or plane-lamination continuous over tens of meters, and probably accumulated on sand sheets rather than on dunes characteristic of the Mount Wrightson Formation (Riggs and Busby-Spera, 1991). Petrographically, these sandstones are much richer in volcanic detritus than those of the Mount Wrightson Formation, resulting from deposition on, and mixing with, unconsolidated and nonwelded pyroclastic flows. Most quartz grains are rounded to ellipsoidal with undulose extinction, indicating a nonvolcanic derivation (Riggs and Busby-Spera, 1991). The thickest sandstone horizons are interstratified near the top of the tuff of Pajarito, in the northwest part of the caldera complex, where only ≈750 m of the tuff accumulated. Sandstone occurs in thinner sheets elsewhere throughout the strata of Cobre Ridge. At the southeast edge of the complex, thin sandstone near the base of the tuff of Pajarito (Fig. 3) may have been incorporated into the tuff as megabreccia blocks.

The tuff of Pajarito was sampled in three locations over ~125 km^2 (Tables 2 and 4; Fig. 3), including ≈10 m below one of the sandstone horizons near the top of the tuff (CRT-1), ≈2,000 m above the base of the ignimbrite (PM-1), and close to the base of the tuff adjacent to a megabreccia block (CRT-25; Fig. 3). These three samples insure complete geographic and stratigraphic coverage of the unit.

U-Pb ZIRCON GEOCHRONOLOGY

Methods and Analytical Procedures

Uranium-Lead Dating System. Mesozoic volcanic rocks in southern Arizona in general consist of intermediate to silicic pyroclastic deposits and lava flows, and related deposits. They are in general chemically amenable to K/Ar or Rb/Sr methods of dating, and these techniques have been employed in the past (Cooper, 1971; Marvin and others, 1973, 1978; Kluth and others, 1982; May and others, 1986). Alkali-element exchange, however, has been documented in Mesozoic volcanic rocks in ranges throughout southern Arizona (Drewes, 1971c; Riggs, 1985, 1987; Krebs and Ruiz, 1987), causing uncertainty in interpreting the results of these studies. Because the uranium-lead dating method utilizes two independent U-Pb decay systems, results obtained may give a more accurate assessment of disturbances that affected the isotopic system.

Analytical Methods. Methods of sample preparation and U-Pb mass spectrometry used in this study are reported by Riggs (1991). Work in the early phases of this study was done by conventional methods (modified from Krogh [1973]), but $^{206}Pb/^{204}Pb$ values were commonly quite low, resulting in high errors on $^{207}Pb^*/^{206}Pb^*$ ages. Moreover, it was apparent that both lead-loss and inheritance had occurred in many zircon samples, complicating age interpretation. In order to reduce the levels of common Pb and to help resolve the

TABLE 3. U-Pb ISOTOPIC DATA FOR LEACHATES OF STEPWISE DISSOLUTION AND COMBINED LEACHATES AND STEPWISE DISSOLUTION RESIDUES†

Sample no.	Concentrations		Ages, in Ma		
	$^{206}Pb^*$	^{238}U	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$
#Jmw-1-1	0.653	22.13	216.0	251.2	563.1 ± 17.2
-3	0.928	31.04	218.8	255.9	611.2 ± 13.1
-4	0.555	20.67	196.7	233.1	617.5 ± 100.6
#Jmw-6-5	0.471	19.98	173.1	168.9	109.8 ± 79
#Jmw-24-2	0.902	38.2	173.5	174.4	185.7 ± 9.2
-3	0.781	32.4	176.8	177.9	192.6 ± 27
-4	0.298	12.4	177.1	182.8	257.0 ± 110
-6	0.53	25.7	151.1	182.9	617.0 ± 349
#Jmw-11-7	2.706	111.98	177.5	184.4	274.1 ± 10.6
#PM-1-1	2.122	91.78	169.9	172.5	207.9 ± 45
-7	0.41	16.1	132.9	155.7	518.7 ± 355
-9	0.248	12.35	147.7	162.4	381.8 ± 250
#CRT-1-1	1.862	80.33	170.3	171.6	188.6 ± 58.6
-6	1.94	80.74	176.8	182.3	254.6 ± 10
#CRT-25-1	0.535	24.58	160.1	163.7	215.3 ± 40.5
-2	1.492	66.54	165.6	164.6	149.3 ± 20.7
-3	1.234	53.35	169.9	168.3	145.4 ± 22.5
®Jmw-1-1	3.21	115.5	203.9	228.8	492.6
-3	7.61	229.3	242.5	311.4	861
-4	3.22	114.2	206.8	239.7	574.8
®Jmw-6-5	3.26	136.6	175.4	175.0	170.1
®Jmw-24-2	4.6	497.9	170.6	171.6	185.2
-3	4.08	171.7	174.4	175.1	183.7
-4	1.80	68.87	180.7	180.2	174.4
-6	8.46	341.4	181.3	181.9	183.1
®Jmw-11-7	7.74	319.1	178.0	184.2	378.1
®PM-1-1	3.48	147.5	173.5	174.3	186.1
-7	4.1	175.0	172.0	173.9	199.6
-9	8.15	341.9	175.1	178.5	224.9
®CRT-1-1	4.48	192.6	170.9	172.4	192.2
-6	13.5	559.5	177.1	184.0	279.6
®CRT-25-1	4.63	206.4	164.8	465.7	178.6
-2	10.28	458.9	164.7	165.3	173.9
-3	13.0	648.4	147.5	153.85	252.0

Note: #, leachate of stepwise dissolution; ®, combined residue and leachate.

†From the Mount Wrightson Formation, Santa Rita Mountains, and the tuff of Pajarito, southern Arizona.

TABLE 4. U-Pb ISOTOPIC DATA FOR ZIRCONS FROM THE TUFF OF PAJARITO, COBRE RIDGE AND PAJARITO MOUNTAINS, SOUTHERN ARIZONA

Sample no.	Fraction (mesh size)	Concentrations[#]		Pb isotopic compositions[†]			Ages, in Ma[§]		
		$^{206}Pb^*$	^{238}U	208/206	207/206	204/206	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$
PM-1-1	>320[a]	1.36	55.7	0.2478	0.0708	0.0014769	174.6	173.5	154 ± 30
-2	−320 + 206[b,d]	17.04	779.6	0.3657	0.1160	0.0044546	160.7	165.1	228 ± 23
-3	−320 + 206[b,c]	16.51	717.3	0.3493	0.1097	0.0040182	169.1	173.7	237 ± 21
-4	−206 + 151[b,d]	15.30	675.2	0.3647	0.1175	0.0045479	166.5	171.3	239 ± 24
-5	−206 + 151[b,c]	15.89	698.6	0.3915	0.1291	0.0053063	167.1	173.6	264 ± 29
-6	−206 + 151[a]	10.61	445.8	0.2634	0.0781	0.0018493	175	179.7	243 ± 14
-7	−206 + 151[a]	4.05	158.7	0.3096	0.0963	0.003189	176.1	175.8	171 ± 44
-8	−151 + 100[a]	7.90	329.5	0.2257	0.0612	0.0007273	176	179	219 ± 8
-9	−151 + 100[a]	4.92	207.9	0.2241	0.0584	0.0006745	174	171.6	140 ± 21
CRT-1-1	>206[a,d]	2.62	112.26	0.2608	0.0551	0.0003441	171.2	172.8	195 ± 14
-2	−320 + 206[b,d]	18.35	801.7	0.3350	0.0738	0.0015992	168.2	171.1	212 ± 11
-3	−320 + 206[a,c]	13.30	561.2	0.2914	0.0615	0.0007604	174.1	176.7	212 ± 7
-4	−206 + 151[b,c]	14.52	609.5	0.3958	0.0915	0.0027448	174.9	180.8	258 ± 14
-5	−206 + 151[a,d]	14.09	597.3	0.2711	0.0528	0.0001859	173.2	174.8	197 ± 4
-6	<151[a,f]	11.54	478.8	0.2717	0.0517	0.0000454	177.2	183.9	242 ± 2
CRT-25-1	−206 + ~175[a]	4.01	179.1	0.1740	0.0521	0.0001735	167.8	168.2	172 ± 4
-2	−206 + 151[a,d,f]	8.77	392.4	0.1852	0.0505	0.0000571	164.4	167.8	178 ± 2
-3	<151[a,f]	11.75	503.2	0.1753	0.0506	0.0000465	171.6	175.6	193 ± 4

Note: all samples nonmagnetic at 0.5° side tilt; 15° forward tilt on Frantz isodynamic magnetic separator except as noted. a = residue of stepwise dissolution; b = total dissolution; c = coarse tap; d = fine tap; e = 1° side tilt nonmagnetic; f = air abraded; g = 0° side tilt nonmagnetic; h = rounded, pitted, apparently detrital zircons.
[#,†,§] See footnotes in Table 1 for explanations.

problems of combined inheritance and recent Pb loss, we applied stepwise partial dissolution techniques following Mattinson (1984). Our earlier successful applications of these methods (for example, Mattinson, 1990; Lahren and others, 1990; Busby-Spera and others, 1990; Kimbrough and others, 1992) have clearly demonstrated the validity of this technique in removing most of the common Pb in the zircons and preferentially dissolving zircon domains most strongly affected by recent Pb loss. These studies also demonstrate the absence of significant laboratory-induced U/Pb fractionation effects, especially for the final "residues" (see especially Mattinson, 1990, fig. 5, and Kimbrough and others, 1992, figs. 9 and 10). Error analysis used in this study follows that of Mattinson (1987) and is described in detail by Riggs (1991). In this study, the combined effects of measurement error, estimation of initial lead error, decay constant error, etc., indicate a minimum error on ages of ±2 m.y. on the $^{207}Pb^*/^{206}Pb^*$ ratio and the $^{238}U/^{206}Pb^*$ ratio.

Limitations on U-Pb Zircon Geochronology

The data presented herein, combined with those of Wright and others (1981) and Asmerom and others (1988, 1990), provide the most accurate assessment of crystallization ages of Mesozoic volcanic rocks in southern Arizona. Although published errors on Rb-Sr and K-Ar data from elsewhere in southern Arizona are smaller than those given here, postcrystallization fluid migration has apparently influenced chemistry of Mesozoic volcanic rocks and has probably caused open-system exchange, and these methods probably do not produce reliable ages in this case. The U-Pb method, in contrast, allows use of the concordia intercept, which aids in interpreting the effects of open-system behavior. In zircons from southern Arizona samples, U-Pb systematics suggest possible complex inheritance as well as multistage lead loss histories. Thus, the U-Pb zircon data given here, and those reported by others, are subject to geological as well as analytical uncertainties and should be interpreted conservatively.

Mount Wrightson Formation

The minimum age of the lower member of the Mount Wrightson Formation is constrained by the intrusion of the Piper Gulch granodiorite, for which Asmerom and others (1988, 1990) published a concordant age of 188 ± 2 Ma. U-Pb dating of volcanic rocks of the Mount Wrightson Formation by Riggs and others (1986) and Asmerom and others (1988, 1990) provided preliminary age assignments of <220 Ma for the lower member and 206 ± 5 Ma to 181 ± 9 Ma for the middle and upper members. Inheritance of older material and superposed lead loss were recognized by Riggs and others (1986) and by Asmerom and others (1988, 1990) in most samples, complicating the interpretation of the age of volcanic rocks.

Lower Member. Asmerom and others (1988, 1990) assigned an age of ≈220 Ma to the lower member of the Mount Wrightson Formation, based on analysis of five fractions. These fractions were not encompassed by a single discordia trajectory, and Asmerom and others (1990) argued that the $^{207}Pb/^{206}Pb$ ratio of the smallest size fraction corresponded to the most nearly accurate age assignment, while demonstrating that smaller size fractions also showed the greatest lead loss. The sample analyzed by Asmerom and others (1988, 1990) was obtained from the andesite/dacite flow sequence in the lower member and is in approximately the same stratigraphic position as our sample. Our work with stepwise strong-acid washing indicates that many of the effects of lead loss can be lessened, and our analysis of the lower member of the Mount Wrightson Formation supports this conclusion.

Four strong-acid–washed zircon fractions from the lower member of the Mount Wrightson Formation are discordant (Jmw-1, Table 1, Fig. 4) but define a single discordia trajectory with intercepts at 183.8 ± 8.5 Ma and 1,966 ± 390 Ma based on a Ludwig (1982) regression program (all uncertainties are stated at the 2σ level). The 184 ± 8 Ma lower intercept is inferred to define the maximum age of the Mount Wrightson Formation; this age overlaps with the age assigned by Asmerom and others (1988, 1990) to the Piper Gulch pluton, which intrudes the lower member.

Middle and Upper Members. Our analysis of a total of six fractions from Jmw-6 includes three fractions analyzed by conventional total dissolution and three fractions analyzed by stepwise dissolution methods. The three fractions analyzed by total dissolution early in the study (Jmw-6-1, Jmw-6-2, and Jmw-6-3, Table 1) are similar in that their $^{207}Pb^*/^{206}Pb^*$ ages lie between 202 Ma and 212 Ma. Errors on these three fractions, however, are relatively high (11–15 m.y.). Riggs and others (1986) previously interpreted the mean weighted average

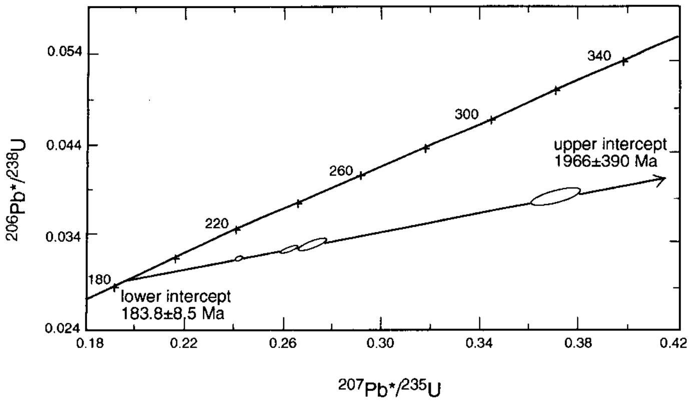

Figure 4. Wetherill concordia diagram of zircons from a dacite lava flow (Jmw-1) from the lower member of the Mount Wrightson Formation. Errors are using York (1969) regression analysis, with emphasis on accuracy of fractions near the lower intercept. All uncertainties are stated at the 2σ level.

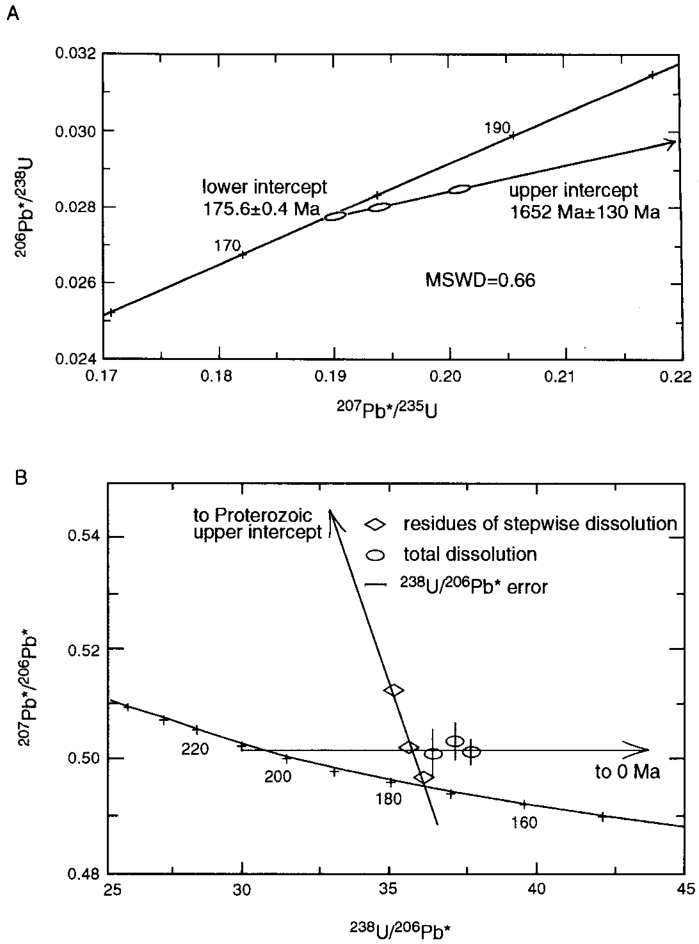

Figure 5. Concordia diagram of zircons from a hypabyssal intrusion (Jmw-6) from the middle member of the Mount Wrightson Formation. (A) Wetherill concordia; (B) Tera-Wasserburg plot. Solid bars through circles show errors; errors on residues are encompassed by diamonds.

of these $^{207}Pb^*/^{206}Pb^*$ ages (206 ± 9 Ma) as representing the age of crystallization of the zircons, assuming a recent lead loss and no inheritance. Our more recent stepwise dissolution analyses, however, clearly demonstrate that this earlier interpretation was oversimplified. The Jmw-6 zircons do contain inherited material, thus the $^{207}Pb^*/^{206}Pb^*$ ages by themselves have no geologic meaning. A York fit (York, 1969) through the three residues of stepwise dissolution gives a lower intercept of 175.6 ± 0.4 Ma and a geologically reasonable upper intercept of 1652 ± 130 Ma (Fig. 5). Errors on the $^{207}Pb^*/^{206}Pb^*$ ages of these fractions range from 2–7 m.y. One of the residue fractions (Jmw-6-5, Table 1) is very nearly concordant at ~176 Ma, and additionally, its combined residue plus stepwise dissolved material is also nearly concordant at ≈175 Ma (Table 3). Oddly, this fraction was slightly more magnetic than most of the fractions (nonmagnetic at 1° side tilt, as opposed to 0.5° side tilt), comprised broken and cracked crystals, but contained much less of both U and Pb than other fractions from the sample. The near concordance of both the residue and the combined residue and the stepwise dissolved material for Jmw-6-5, together with the very small error on the discordia trajectory for the three residues (Fig. 5A), strongly indicates an igneous crystallization age of this middle-member hypabyssal intrusion of 175 ± 2 Ma.

The differences between analyses of fractions that underwent stepwise dissolution and those that did not are made clear in a graphic representation on the Tera-Wasserburg diagram (Tera and Wasserburg, 1972; Fig. 5B). The three residues lie on a chord that intercepts concordia at ≈175 Ma, and the three nontreated fractions form a small cluster well off of this chord, in the direction of recent lead loss.

The age of 175 Ma obtained for this hypabyssal intrusion provides a minimum age for middle-member volcanism. The intrusion is not widespread, but lies stratigraphically below Jmw-24, which it postdates. Geochronologic constraints (see below) suggest that the intrusion is related to upper member volcanic activity.

We analyzed seven fractions of a densely welded ignimbrite from the middle member (Jmw-24) by stepwise dissolution and one fraction (Jmw-24-5) by air-abrasion and total-dissolution methods. Points cluster at concordia on a Wetherill concordia diagram, but on the Tera-Wasserburg plot (Fig. 6), the expanded $^{207}Pb^*/^{206}Pb^*$ scale shows small but important differences between the points. The five fractions (Jmw-24-1, -2, -3, -6, and -8) with the most precisely determined $^{207}Pb^*/^{206}Pb^*$ ages (2σ errors ranging from 2 to 7 Ma) define a very tight grouping with $^{206}Pb^*/^{238}U$ ages ranging from 170 to 182 Ma. The $^{207}Pb^*/^{206}Pb^*$ ages for these fractions all agree within errors, with a weighted mean of 183 Ma. These data are suggestive of simple, minor, recent Pb loss and the absence of inheritance. Two of the fractions (1 and 6) are "technically" concordant within errors. Overall, the data strongly indicate a crystallization age of about 183 ± 2 Ma, based on the pooled $^{207}Pb^*/^{206}Pb^*$ ages.

One fraction (Jmw-24-5) was air abraded and has a slightly older $^{207}Pb^*/^{206}Pb^*$ age, outside of analytical errors. Thus it plots slightly above the grouping for the five fractions discussed above. This is suggestive of a very minor inherited component. A reference discordia trajectory drawn through fraction 5 to a Proterozoic upper intercept that is reasonable, based on our other samples for which the inherited component is better defined, yields a lower intercept of about 181 Ma. This is consistent with the 183 ± 2 Ma age that is based on the other five fractions. The indication of a minor inherited component in this abraded fraction raises the possibility of a very minor inherited contribution in the other five fractions. Such a contribution

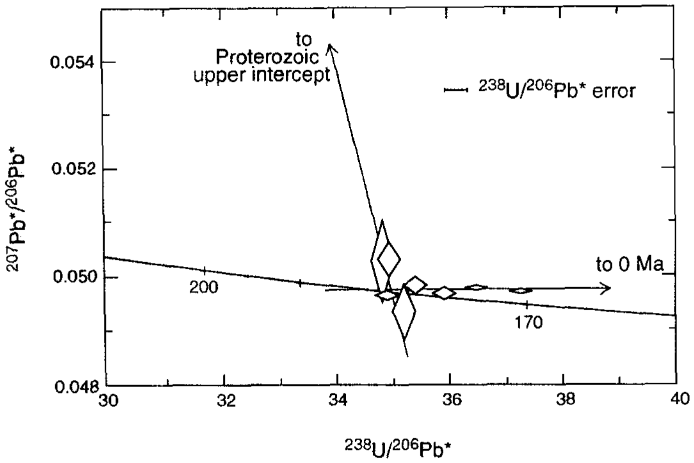

Figure 6. Tera-Wasserburg concordia diagram of zircons from a rhyolitic ignimbrite (Jmw-24) from the middle member of the Mount Wrightson Formation. Size of diamond represents error.

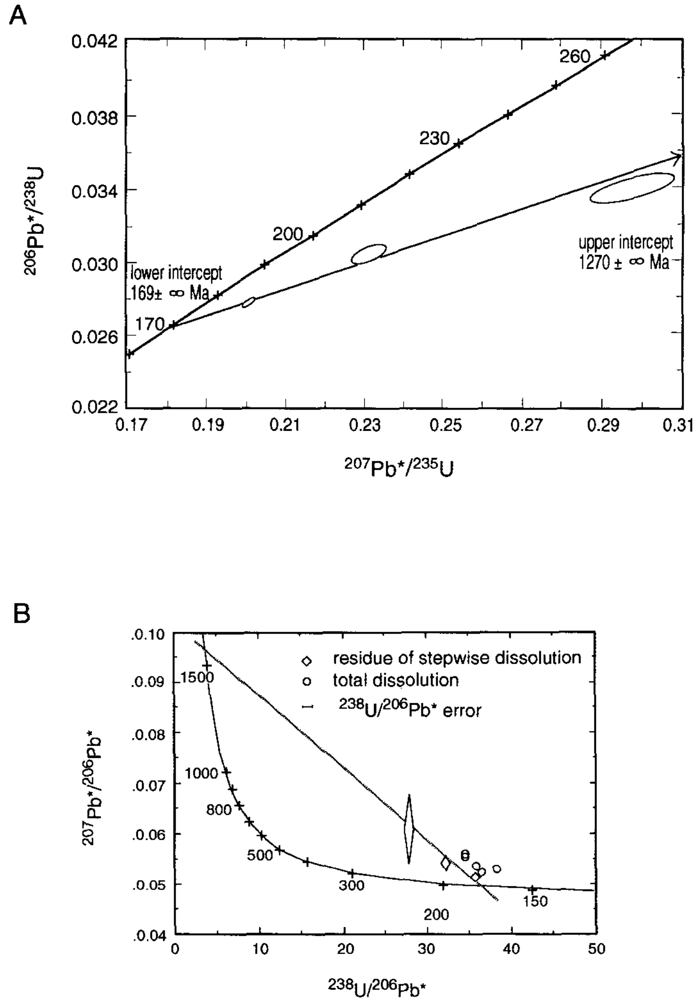

Figure 7. Concordia diagram of zircons from a rhyolitic ignimbrite (Jmw-11) from the upper member of the Mount Wrightson Formation. (A) Wetherill concordia. Unrealistically large error on lower intercept may be due to poor fit on three-point line. (B) Tera-Wasserburg plot. Shaded reference line is drawn through geologically reasonable upper intercept and visually estimated best fit of residue fractions.

would make the 183 Ma pooled $^{207}Pb^*/^{206}Pb^*$ age too high. The near concordance of the five unabraded fractions, however, and the model lower intercept age for Jmw-24-5 (based on the most conservative assumption of no later Pb loss for this fraction) preclude the presence of a significant inherited component in the unabraded fractions. The 183 ± 2 Ma age, based on the best $^{207}Pb^*/^{206}Pb^*$ data, remains our preferred age for the upper middle member.

The two other fractions (Jmw-24-4 and -7) have less well determined $^{207}Pb^*/^{206}Pb^*$ ages. They are consistent with the above interpretation but do not help refine it.

The upper member ignimbrite, Jmw-11, comprises nine fractions. Early in the study, we analyzed five fractions digested by total dissolution methods (Jmw-11-1, Jmw-11-2, Jmw-11-3, Jmw-11-5, and Jmw-11-9; Table 1). Three of the remaining fractions were digested by stepwise dissolution (Jmw-4, Jmw-6, Jmw-7), and one fraction (Jmw-8) consisted of frosted, rounded or oblong grains that yielded strongly discordant ages with a Precambrian $^{207}Pb^*/^{206}Pb^*$ age (Jmw-11-8, Table 1). It is not clear whether these apparently detrital grains were inherited at depth or were entrained into the ash flow as it moved across unconsolidated sand, although frosting and pitting of the grains suggest the latter.

All fractions of Jmw-11 are strongly discordant. In addition, low $^{206}Pb/^{204}Pb$ ratios (commonly <1,000) of most of the fractions yield high errors on the $^{207}Pb^*/^{206}Pb^*$ ages (Table 1). Although we infer that the effects of lead loss are removed by stepwise dissolution, a standard Ludwig regression (Ludwig, 1982) of residues of stepwise dissolution produces unrealistically large error margins on the lower intercept of 169 Ma, owing to the scatter in the data (Figs. 7A and 7B).

In order to obtain a more precise crystallization age, we did York regressions (York, 1969) based on assigned possible upper intercepts (1400 Ma, 1600 Ma, and 1700 Ma, based on geologically reasonable ages of Proterozoic crust contributing zircon) and the fraction with the smallest error, Jmw-11-7. Assumptions that must be made in this model are that (1) the assumed Proterozoic sources of inheritance have not undergone major lead loss between the time of crystallization and the time of incorporation into the magma and (2) any effects of postcrystallization lead loss have been removed from the residues by the early dissolution steps. For Jmw-11-7, for assumed upper intercepts between 1400 and 1700 Ma, the lower intercepts were in the range of 171 ± 2 Ma. Because this age is model dependent, a rigorous error analysis is not possible. On the basis of these data, however, we infer that the upper member of the Mount Wrightson Formation was emplaced at approximately 170–175 Ma.

Discussion. Deposition of the Mount Wrightson Formation spanned 15–20 m.y., from ≈189 to ≈170 Ma. Our data suggest that intrusion and crystallization of the Piper Gulch granodiorite, dated at 188 ± 2 Ma by Asmerom and others (1990), began very shortly after the eruption of the lower member. Drewes (1971b) mapped an intrusive contact between the Piper Gulch pluton and the middle member of the Mount Wrightson Formation, indicating that the pluton is younger than the lowest middle member; but Asmerom and others (1990) reported ambiguous field relations between the pluton and the middle member. Riggs and Busby-Spera (1990) reported that the part of the Mount Wrightson Formation apparently intruded by the Piper Gulch granodiorite (mapped as middle member by Drewes, 1971b) is very dissimilar in appearance, environment of deposition, and min-

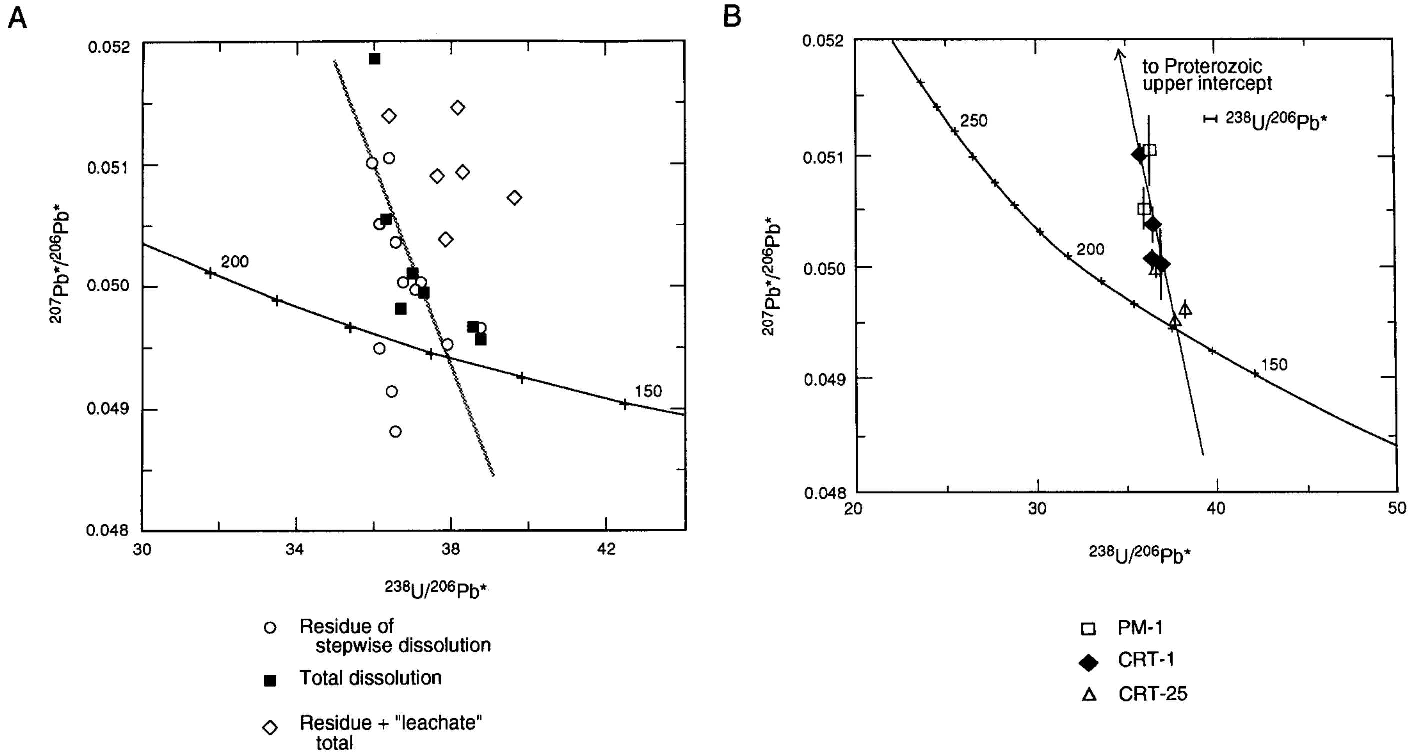

Figure 8. Concordia diagram of zircons from the tuff of Pajarito. (A) Tera-Wasserburg plot. Shaded line is modeled with Proterozoic upper intercepts; points to the right of line have had recent lead loss. See text for discussion. (B) Residues of stepwise dissolution. Errors not shown in A.

eralogy from the rest of the formation, and they hypothesized that these rocks may be a different formation. It is also possible that the contact, which is very poorly exposed, is not intrusive, or that Asmerom and others (1990) did not recognize conditions of disturbance within the zircon fractions analyzed. The contact between the lower member and rocks that are confidently assigned to the middle member is characterized by a valley-fill sequence of conglomerate and fluvial sandstone (Riggs and Busby-Spera, 1990), and this sequence may represent the ≤6-m.y. gap between the lower and middle members suggested by our geochronologic and stratigraphic data. The style of volcanism in this time changed dramatically from effusive to dominantly explosive, also supporting the idea of a time gap between the two members. It must be noted, however, that the ≈1.5-km thickness of the middle member between the lower member and the stratigraphic horizon of the sample site may encompass several million years, and thus the time interval between the end of lower-member deposition and the beginning of middle-member deposition may have been brief.

Middle- and upper-member volcanism apparently lasted for 5–15 m.y. (probably ≈10 m.y.), based on the new ages obtained and geologic considerations. The presence of several ignimbrites between the middle-member and upper-member ignimbrite samples may support the proposed 10-m.y. time span. By analogy, eruptions in the San Juan volcanic field (Steven and Lipman, 1976), the Yellowstone area (Christiansen, 1984), and the Jemez volcanic field (Gardner and others, 1976; Self and others, 1986) are separated by 0.3–2 million years. In contrast, Wilson and others (1984) documented numerous eruptions within 1 m.y. in the Taupo Volcanic Zone. Upper-member deposition was characterized dominantly by eolian-sand deposition and represents sedimentation during waning volcanism. It is thus reasonable to infer that the age of the upper member sample, 175–170 Ma, approximates the end of Mount Wrightson Formation volcanism.

Strata of Cobre Ridge

The maximum age limit for the strata of Cobre Ridge is inferred by the presence of probable Mount Wrightson–equivalent strata that underlie the strata of Cobre Ridge in northern Sonora, Mexico. The minimum age limit is based on the correlation of sedimentary rocks that overlie the strata of Cobre Ridge with fossiliferous Cretaceous strata of the Bisbee Group elsewhere in southern Arizona (Drewes, 1981; Riggs, 1987).

Data from the tuff of Pajarito, the widespread, caldera-forming unit that dominates the strata of Cobre Ridge, proved the most difficult of all results in this study to interpret. On a concordia diagram, fractions cluster around concordia between 165 and 180 Ma, without any clear trend. Residues of step-wise dissolution, total dissolution-method fractions, and combined residue-leachate totals plot as a cluster on a Tera-Wasserburg plot as well (Fig. 8A). Fractions digested by total dissolution methods early in the study plot in a scatter (solid squares, Fig. 8A). Ages of the residues of stepwise dissolution plot more linearly, giving a probably more accurate estimate of the minimum age of crystallization (Fig. 8B). In light of the better resolution of stepwise dissolved samples from the Mount Wrightson Formation, the following discussion is based only on analyses of stepwise dissolution residues.

The four residue fractions of CRT-1 (Figs. 8B and 9; Tables 2 and 4) are too scattered to define precise intercepts on concordia. We

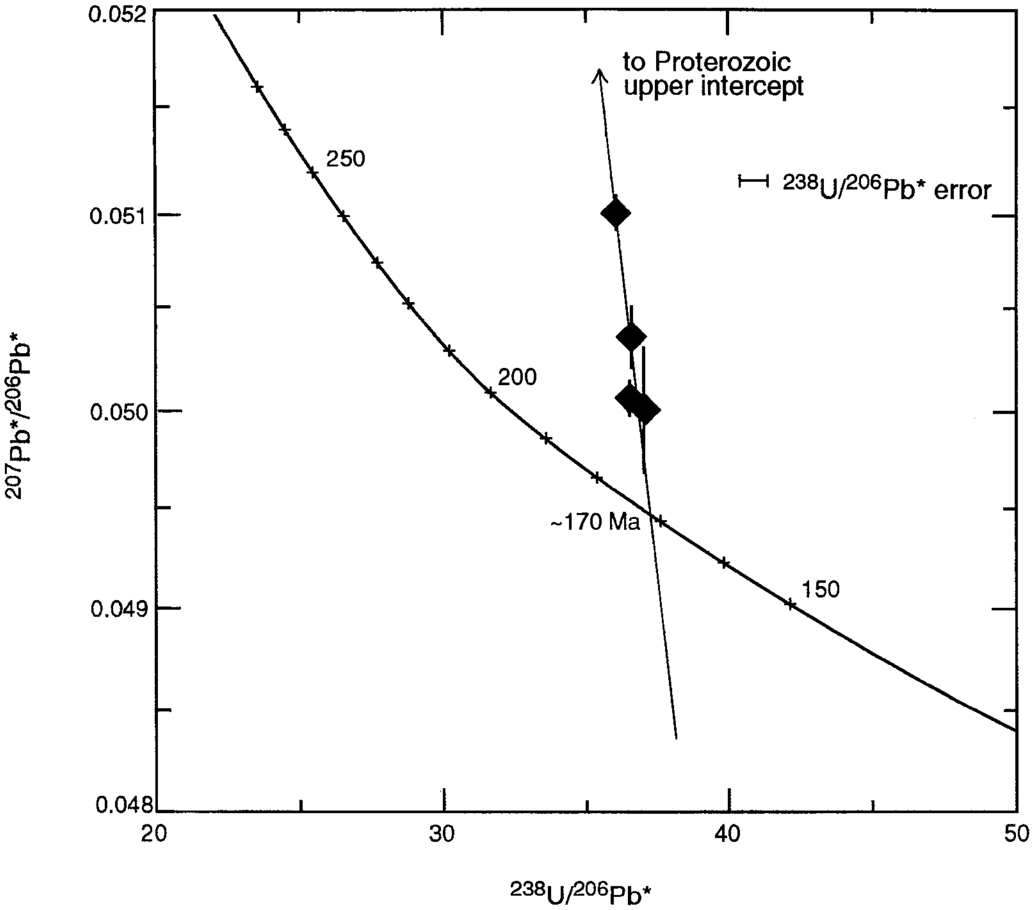

Figure 9. Tera-Wasserburg plot of the tuff of Pajarito from Cobre Ridge (CRT-1). Solid vertical lines are error on $^{207}Pb^*/^{206}Pb^*$ ratio; error of $^{238}U/^{206}Pb^*$ ratio is within the diamond.

have assigned model upper intercepts of 1400 Ma, 1600 Ma, and 1700 Ma on the basis of evidence for the age of Proterozoic crust underlying this part of southern Arizona provided by isotopic studies of Farmer and DePaolo (1984). Trajectories through these fractions yield lower intercepts of 170 ± 3 Ma. Errors are small to moderate on all four of the fractions ($^{207}Pb^*/^{206}Pb^*$ age errors = 2 to 14 m.y., Table 2).

The three CRT-25 fractions (Figs. 8B and 10, all residues; Tables 2 and 4) similarly cluster near concordia but do not define a linear trend on either the concordia diagram or the Tera-Wasserburg plot. One of these fractions (CRT-25-1) is concordant within errors at ≈169 Ma. The lower intercepts of discordia trajectories through CRT-25-3, again using upper intercepts of 1400 Ma, 1600 Ma, and 1700 Ma, are 167 ± 1 Ma. Trajectories of the third fraction, CRT-25-2, with the same upper intercepts, give a lower intercept of 160 ± 2 Ma.

Discordia trajectories were projected through the two measured PM-1 zircon fractions that have the smallest error bars (PM-1-6, error ±14 Ma; PM-1-8, error ±8 Ma). For both samples, lower intercepts were within 171 ± 4 Ma, within the error margins of the CRT-1 and CRT-25 fractions. The other three Pajarito tuff residues (PM-1-1, -7, and -9) have relatively low $^{206}Pb/^{204}Pb$ values, and hence very large uncertainties in their $^{207}Pb^*/^{206}Pb^*$ dates. The residues plot below concordia (open circles, Fig. 8A), and two overlap concordia within analytical uncertainties. We place little significance on these results. The uncertainties are large, and the results suggest that we may not have used appropriate values in correcting for common Pb in the PM samples.

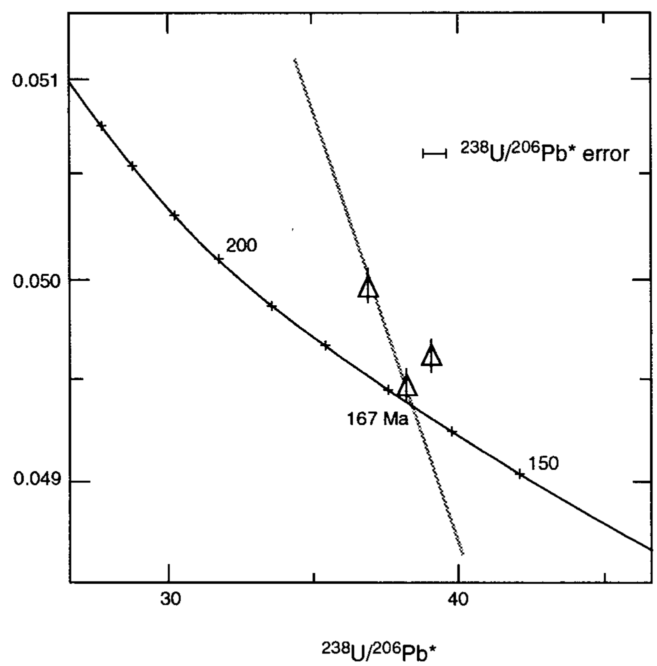

Figure 10. Tera-Wasserburg plot of the tuff of Pajarito from Cobre Ridge (CRT-25). Solid vertical lines are error on $^{207}Pb^*/^{206}Pb^*$ ratio; error of $^{238}U/^{206}Pb^*$ ratio is within the triangle. Best-fit (visual inspection) line through points shown.

The scatter of all fractions of the tuff of Pajarito does not allow a statistically meaningful line to be drawn through the points. Nearly all the fractions, which cluster near to concordia, however, yield similar lower intercepts when geologically reasonable upper intercepts are assumed. In this case, the lower intercept or age of crystallization of 170 ± 5 Ma assumes little or no subsequent lead loss. Fractions that lie to the right of the reference chord (Fig. 8B) through 170 ± 5 Ma and 1550 ± 150 Ma (for example, CRT-25-2, total dissolution-method fractions) may reflect more recent lead loss.

The final interpreted age of the tuff of Pajarito, 170 ± 5 Ma, is a model age. The apparently concordant fraction (CRT-25-1) has small errors, but the possibility of multiple disturbances cannot be discounted for the majority of fractions from the tuff of Pajarito. The overall clustered nature of the distribution of points is suggestive of multiple disturbances (Gebauer and Grünenfelder, 1979), as is the noncorrespondence of grain size and U or Pb content. Although the combined data are somewhat linear on a Tera-Wasserburg plot, this linearity may be an externally imposed function of numerous episodes of open-system lead loss.

REGIONAL CORRELATION WITH MESOZOIC ARC AND BACK-ARC STRATA

Correlations with Dated Deposits within the Cordilleran Arc

U-Pb geochronologic data on Jurassic volcanic rocks from southern Arizona are confined to this study, that of Asmerom and others (1988, 1990), and work of Wright and others (1981) on the Fresnal Canyon sequence in the Baboquivari Mountains (Fig. 1). Asmerom and others' (1988, 1990) suggested age of ≈220 Ma for the lower member of the Mount Wrightson Formation is reinterpreted in the light of new data presented here; the lower member is assigned an age of 189 ± 3 Ma. Ages suggested by Asmerom and others (1988, 1990) for the middle member of the Mount Wrightson Formation are more similar to those obtained in our study.

Wright and others (1981) reported the age of the Fresnal Canyon sequence as ~190–195 Ma, using analysis of eight fractions from volcanic rocks in three formations. The age assignment was based on a clustering of the $^{207}Pb^*/^{206}Pb^*$ ages in all eight fractions between 187.5 and 191.9 Ma, and the observation that despite the disparity of the three formations in stratigraphic position, location, and metamorphic grade, all eight analyzed fractions lie on a single discordia trajectory. This age assignment requires the assumption that no inheritance of older material has occurred. The Fresnal Canyon sequence contains quartzarenite lenses, some several tens of meters in thickness and containing high-angle large-scale cross-stratification, within its lower third (Ali Molina Formation [Haxel and others, 1980a, 1980b, 1981]). Haxel (1989, 1990, personal commun.; and in Riggs and Haxel, 1990) has supported a correlation of the strata of Cobre Ridge and overlying strata to the west of Cobre Ridge with the lower part of the Fresnal Canyon sequence based on stratigraphic and lithologic similarities. Both units contain widespread silicic, locally quartz-phyric volcanic sequences with intercalated quartz-rich horizons, both are overlain by clastic sequences, and both are intruded by probably coeval granite porphyry and hypabyssal rhyodacite. Within errors estimated by Wright and others (1981) and by us, however, the two units are apparently not coeval. Because the Fresnal Canyon sequence was dated prior to use of air abrasion and stepwise dissolution techniques, however, we suggest that analysis of fractions of the Fresnal Canyon sequence subjected to abrasion and stepwise dissolution might yield different constraints on the age of that unit, perhaps by revealing the presence of a minor inherited component. It is equally possible that the Fresnal Canyon sequence is older than other volcanic strata in southern Arizona or is perhaps coeval with the lower member of the Mount Wrightson Formation.

Eolian or quartz-rich sandstones are interstratified with remnants of the magmatic arc throughout western Arizona and southeastern and eastern California. Busby-Spera and Saleeby (1987) reported an age of ≈190 Ma for arc-volcanic rocks that overlie quartz-rich sandstones in the Mineral King pendant of the Sierra Nevada and suggested that these sandstones are marine equivalents of the Navajo Sandstone. Quartzose sandstones of Early-Middle Jurassic age and similar depositional environment are present in smaller pendants near Lake Tahoe (Fisher, 1990; Fig. 1); these deposits represent distal, marine equivalents of eolian sedimentation seen in the lower and middle members of the Mount Wrightson Formation. In southeastern California and western Arizona, arc-related strata are ≈165–175 Ma in age (Tosdal and others, 1989; Busby-Spera and others, 1990), and the intercalated sandstones are probably correlative with the Temple Cap Sandstone. These deposits are coeval with the upper member of the Mount Wrightson Formation and with the strata of Cobre Ridge.

Correlation with Mesozoic Back-Arc Strata

Eolian sedimentation occurred in the region of the Colorado Plateau at intervals between Middle Pennsylvanian and Late Jurassic time (Blakey and others, 1988; Fig. 11); of importance to this study are deposits of Early and Middle Jurassic age. The time scale used herein is that of Harland and others (1990), but the ages associated with stage boundaries are in nearly all cases imprecisely known. The Pleinsbachian to Toarcian Navajo Sandstone of the Glen Canyon Group is the most widespread of the eolian units. Eolian sedimentation also occurred in the area of north-central and northeastern Arizona and southernmost Utah during Sinemurian time (Lukachukai Member of the Wingate Sandstone, Glen Canyon Group), Aalenian time (Temple Cap Sandstone, San Raphael Group), Bajocian time (Page Sandstone, San Raphael Group), and Callovian time (Entrada Sandstone, San Raphael Group), and these units all record southward-directed paleowind directions (R. C. Blakey, 1991, personal commun.). Major unconformities between these units indicate fluctuations in tectonic subsidence and/or eustatic sea level (Riggs and Blakey, in press).

Our data, together with those of Wright and others (1981), suggest that eolian sedimentary rocks correlative with several Mesozoic units on the Colorado Plateau are present within magmatic-arc strata in southern Arizona (Fig. 11). The lower member of the Mount Wrightson Formation and of (?) the Fresnal Canyon sequence in the Baboquivari Mountains, which contain quartz-rich sandstone interbeds, are ≈190–195 Ma, suggesting correlation of these units with the Navajo Sandstone. The middle member of the Mount Wrightson Formation (≈183 Ma) is only slightly younger than the Navajo Sandstone on the Colorado Plateau (Fig. 11).

The ages of the upper member of the Mount Wrightson Formation and the strata of Cobre Ridge are approximately equal at 170 ± 5 Ma (Fig. 11). These ages correspond most closely with the Temple Cap Sandstone and, at the lower error margin, with the Page Sandstone. The age of the Page Sandstone is well constrained by $^{40}Ar/^{39}Ar$ dating by Everett and others (1989), but other units are dated only by stratigraphy and fossil evidence. Sandstone horizons in the Mount Wrightson Formation are the largest and thickest Mesozoic eolian units in southern Arizona. Riggs and Busby-Spera (1990) have inter-

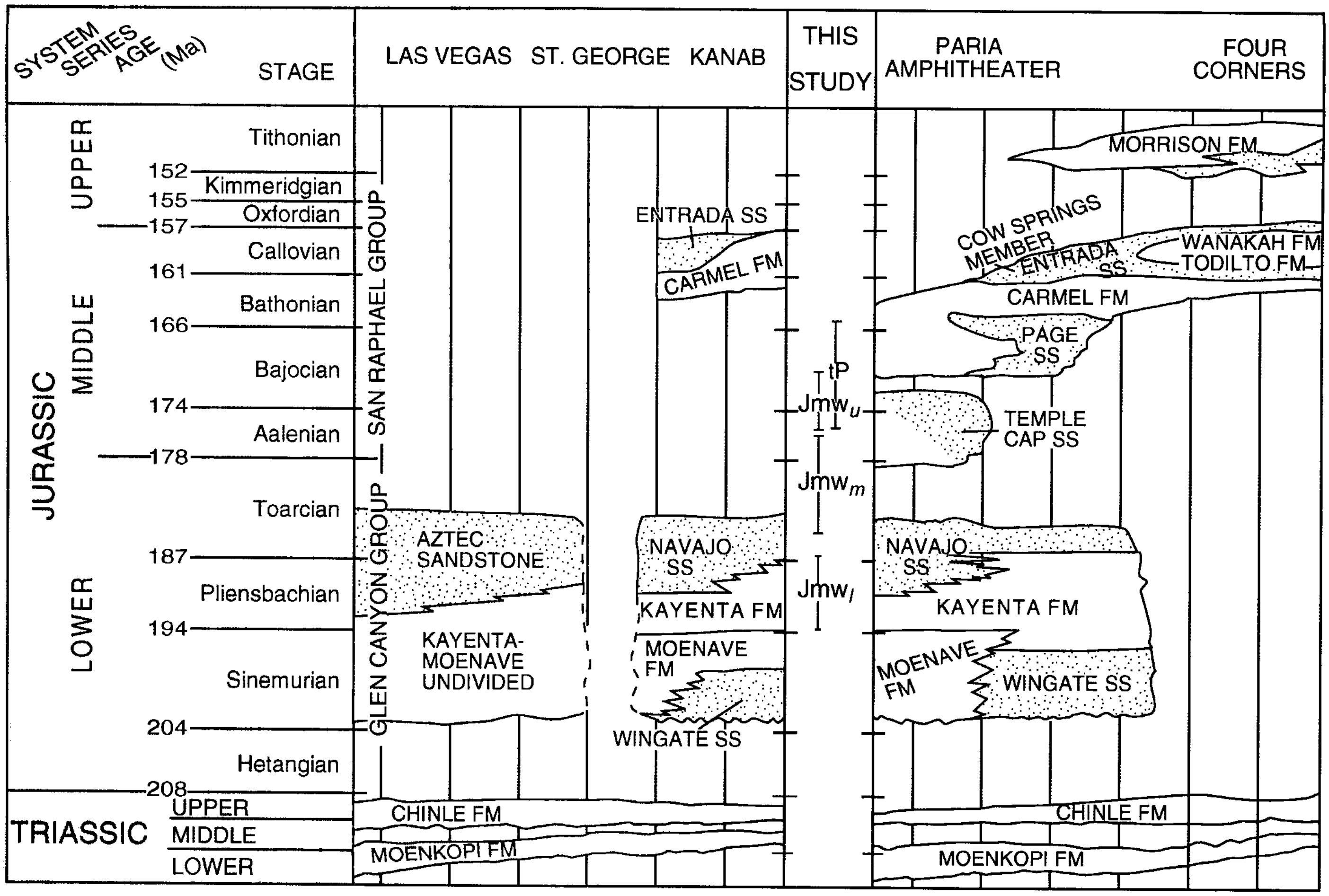

Figure 11. Generalized composite stratigraphic chart of Triassic and Jurassic strata in southwestern Nevada, northern Arizona, and southern Utah, modified from Blakey and others (1988), showing ages obtained in this study. Ages of stages are from Harland and others (1990).

preted the abundance of eolian sandstone in the upper member of the Mount Wrightson Formation as indicative of waning volcanism, thus allowing nonvolcanic units to accumulate. The amount of time necessary to accumulate the thickness of sandstone observed (≤300 m) can be estimated by inferring wind sediment saturation values, deceleration in wind velocity across the complex, and modern rates of deposition (Fryberger and others, 1984; Illenberger and Rust, 1988; Havholm and Kocurek, 1991; K. A. Havholm, 1991, personal commun.). These estimations suggest that abundant sand was available for between 200 ky and 1.5 m.y.

CONCLUSIONS

Several conclusions may be drawn regarding the age and duration of volcanism and eolian sedimentation in southern Arizona. The Piper Gulch pluton, which intrudes the lower member, is dated by Asmerom and others (1990) as 188 ± 2 Ma, providing a minimum age for the lower member. Our dating of the lower member of the Mount Wrightson Formation yields an age of 184 ± 8 Ma. Combining errors on Asmerom and others' data (1990) and on our data suggests that the age of the member is between 186–192.5 Ma. It is possible that andesite and dacite of the lower member of the Mount Wrightson Formation are the volcanic derivative of the monzonite-monzogabbro-composition Piper Gulch pluton, and this possible equivalence supports the hypothesis of an age similarity between the two. The age of the lower member is therefore concluded to be 189 ± 3 Ma, suggesting an early incursion of mature quartz sand into the arc equivalent either to Wingate Sandstone or to early phases of the Navajo Sandstone (Fig. 11).

Discussion of the age of the middle and upper member of the Mount Wrightson Formation is made more difficult by the possible intrusion of the Piper Gulch pluton into volcanic rocks that are lithologically dissimilar to the middle member and that may not be part of the formation (Riggs and Busby-Spera, 1990). All samples reported on herein are confidently part of the Mount Wrightson Formation, and nowhere is either the middle or upper member known to be intruded by the Piper Gulch pluton.

The range of highly probable ages for the middle and upper members of the Mount Wrightson Formation is 183 ± 2 to ≈170 Ma. We are confident that stepwise dissolution removes the majority of domains in a zircon that experienced open-system lead loss, but it remains possible that multiple lead-loss episodes may have affected the three middle- and upper-member samples and that they may be older. During this time, morphology of the Mount Wrightson depocenter remained characteristically low, allowing continuous accumulation of eolian sands probably coeval with the Navajo and Temple Cap ergs (Fig. 11).

The tuff of Pajarito is only given a model age, owing to the cluster of points on a Wetherill concordia diagram, to the fact that on a Tera-Wasserburg concordia diagram the points are only approximately linear, and to the large errors on some of the fractions. By assigning reasonable Proterozoic inheritance ages as upper intercepts to several individual fractions, the age of the tuff of Pajarito is modeled as 170 ± 5 Ma. If eolian sandstones within the strata of Cobre Ridge represent new incursions of sand derived from the Colorado Plateau, they probably correlate with the Temple Cap and Page Sandstones (Fig. 11). Within the range of errors assigned to both the strata of Cobre Ridge and the upper member of the Mount Wrightson Formation, however, it is possible that quartz sand in eolian sediments within the strata of Cobre Ridge were derived from emergent, unlithified or only partially lithified sand dunes of the uppermost Mount Wrightson Formation.

Although the errors on the ages of the tuff of Pajarito and the middle and upper members of the Mount Wrightson Formation overlap, we consider it unlikely that the two units are coeval. A sequence of undated ignimbrites identical to the middle member of the Mount Wrightson Formation underlies the tuff of Pajarito in northern Sonora, Mexico (Riggs and Busby-Spera, 1991), and we infer that at least the middle member of the Mount Wrightson Formation is older than the tuff of Pajarito. In addition, facies analysis of the Mount Wrightson Formation (Riggs and Busby-Spera, 1990) indicates that the formation represents a multiple-vent center active within a basin that was subsiding during emplacement of the volcanic and volcaniclastic strata. The tuff of Pajarito, in contrast, was probably deposited by a large-volume caldera-forming eruption (caldera size is ≈1,500 km^2; Riggs and Busby-Spera, 1991), and although outflow from this caldera has not yet been recognized, an eruption of this magnitude may have produced a large outflow sheet. The implication of these differences in volcanic and depositional settings is that if deposition of the Mount Wrightson Formation and the eruption of the tuff of Pajarito were simultaneous, outflow of the ignimbrite might have gained access to the Mount Wrightson depocenter about 25 km away. It remains possible, though unlikely, however, that a topographic barrier was created between the two areas after eruption of the middle member of the Mount Wrightson Formation and prior to eruption of the tuff of Pajarito, and that the two sequences are coeval.

IMPLICATIONS FOR PALEOGEOGRAPHY OF THE JURASSIC MAGMATIC ARC

The presence of mature, craton-derived quartzarenite interbedded in volcanic strata ranging in age from ≈190 Ma to ≈170 Ma has important implications for the paleogeographic and paleotectonic setting of the Mesozoic magmatic arc in southern Arizona. Although eolian sedimentation is presently occurring in the high Andes of South America, these deposits are apparently derived exclusively from erosion of nearby volcanic rocks, and they have a low preservation potential. The association of volcanic and compositionally mature eolian sedimentary rocks is rare in the geologic record. This association, coupled with the apparent morphology of volcanoes indicated by facies analysis of volcaniclastic rocks (Riggs and Busby-Spera, 1990, 1991), suggests that the northeastern margin of the Cordilleran Jurassic magmatic arc was not a high-standing topographic barrier that impeded the migration of sediments derived from the back arc. Our data indicate that for at least 20 m.y., and possibly as much as 35 m.y., during Early and Middle Jurassic time, these mature sediments gained access to, and were preserved in, vent-proximal regions of the magmatic arc in southern Arizona.

The Upper Triassic Chinle Formation on the Colorado Plateau contains abundant south-derived volcanic detritus, ranging in size from ash to cobbles (Stewart and others, 1972; Blakey and Gubitosa, 1983; Ash, 1992). The source of the detritus is controversial, due to the apparent lack of preserved suitable-aged volcanic material to the south of exposures of the Chinle Formation (Stewart and others, 1986). Asmerom and others (1990) suggested that the Mount Wrightson Formation may be a source for volcanic detritus in the Chinle Formation, based on their age of ≈220 Ma for the lower member of the Mount Wrightson Formation and the presence of andesitic cobbles dated at 196–222 Ma (K-Ar, Peirce and others, 1985) in the Chinle Formation. Our data, including a four-point discordia trajectory, indicate that the Mount Wrightson Formation is younger than the youngest of these cobbles. Additionally, work by Abbott and Peterson (1978) suggests that mafic to intermediate volcanic rocks are unlikely to withstand fluvial transportation of 150–200 km. Although our data do not shed any new light on the problem of a source terrane for the Chinle volcanic cobbles, we disagree with the suggestion that the Mount Wrightson Formation may have been that source.

Geochronologic data and facies distributions allow the possibility that eolian and other quartz-rich sands within the strata of Cobre Ridge were redistributed from the upper member of the Mount Wrightson Formation, and that only one major incursion of sand into the arc occurred. Evidence that sand reached the arc in at least two pulses includes the immense quantity of sand in the upper member of the Mount Wrightson Formation, making a simple reworking of older sand unlikely, and the fact that sandstone of equivalent age is common throughout magmatic arc deposits in western Arizona and eastern California. We propose that sand related to the Navajo erg and to the Temple Cap and/or Page Sandstone ergs independently gained access to the magmatic arc. We suggest that ongoing subsidence within the magmatic arc terrane may have allowed a more continuous preservation of rocks characterized by unconformities on the Colorado Plateau (Fig. 11).

Our geochronologic data, together with those of Wright and others (1981), indicate that Mesozoic magmatism in southern Arizona began at, or was developed by, ≈190 Ma and continued to at least ≈170 Ma, with little or no interruption. The presence of craton-derived eolian quartzarenite throughout this ≥20-m.y. section indicates that the magmatic arc was low lying and characterized by basins and topographic lows (including calderas), in which far-traveled, wind-blown sand could accumulate and be preserved. The earliest of these ages, those that indicate magmatism at ≈190 Ma, are from the oldest subaerial Mesozoic volcanic rocks in the Cordillera with which mature quartz sandstone are interstratified. An extensional or transtensional environment in the arc is indicated by facies analysis of some of these strata (Riggs and Busby-Spera, 1990; Riggs and others, 1990) and corresponds in age with a similar tectonic setting in the Sierra Nevada of California, where volcanism and sedimentation of quartz-rich sands were occurring in the marine realm (Busby-Spera and Saleeby, 1987). Eolian sedimentary rocks are interstratified with magmatic arc rocks dated from ≈175 Ma to ≈165 Ma (Busby-Spera and others, 1990) throughout southern and western Arizona and eastern California, and their presence supports a continued low-lying arc.

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