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Lower Jurassic Navajo-Aztec-Equivalent Sandstones in Southern Arizona and Their Paleogeographic Significance[1]

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ABSTRACT

Thick sequences of Lower Jurassic rhyolitic and andesitic volcanic rocks in several mountain ranges of southern Arizona contain interbedded quartzarenites. Locally up to 250 m thick, these sandstone lenses, composed of well-sorted and well-rounded quartz grains, commonly contain large-scale cross-stratification and are considered to be eolian sand deposits. The eolian sands were blown up against the continental side of the Early Jurassic volcanic arc that trended northwest-southeast across the southwestern margin of the North American continent and/or plate at that time. Paleocurrent data suggest southerly eolian transport of the sands from the Colorado Plateau area. Correlation of these sandstones with the Lower Jurassic Navajo and Aztec Sandstones is indicated by the paleocurrent data as well as radiometric dating of the interbedded volcanics. Eolian sand transport southward across central Arizona in the Early Jurassic indicates that the Mogollon highlands either did not then exist, or were merely low, discontinuous inselbergs on a broad back-arc ramp, more appropriately called the Mogollon slope.

INTRODUCTION

The Early Jurassic paleogeography of southern Arizona was dominated by a northwest-southeast-trending continental margin magmatic arc of "Andean" type (Figure 1). This magmatic arc extended northwestward into California, southward into Mexico, and was directly related to eastward subduction of an oceanic plate beneath the southwestern edge of North America (Coney, 1978; Dickinson, 1981). The Lower Jurassic volcanic, plutonic, and associated sedimentary rocks of the arc terrane are widely scattered in the isolated mountain ranges of the southern Basin and Range province of southeastern California (Armstrong and Suppe, 1973; Marzolf, 1980), southern Arizona (Hayes et al, 1965; Hayes and Drewes, 1978; Haxel et al, 1980b, 1984), and northern Mexico (Anderson and Silver, 1978; Rangin, 1978). The arc terrane was separated from thick Triassic-Jurassic nonmarine sedimentary sequences to the northeast on the Colorado Plateau (Harshbarger et al, 1957) by a northwest-trending belt about 250 km wide, where virtually no rocks of comparable age are known. This belt, which trends across central Arizona and New Mexico, lies just south of the southern margin of the Colorado Plateau or Mogollon Rim and contains Precambrian basement exposed over a large area. This belt occupied a position of great paleotectonic and paleogeographic significance through geologic time, and has been given several different names: Texas lineament (Albritton and Smith, 1956; Moody and Hill, 1956), Deming axis (Turner, 1962), and Mogollon highlands (Harshbarger et al, 1957; Cooley and Davidson, 1963; Stewart, 1969; Stewart et al, 1972).

The relationship of the Lower Jurassic clastic sedimentary strata of the Colorado Plateau to the very different rocks of the volcanic-arc terrane to the southwest, across this belt of Precambrian exposure, is of significant paleogeographic importance. Coney (1978) suggested that the ancestral Mogollon highlands stood as a topographic barrier between the alluvial systems of the Colorado Plateau region and the arc terrane to the southwest. Most workers dealing with the Triassic-Jurassic strata of the Colorado Plateau consider the ancestral Mogollon highlands to have been the source area for the sediments (Harshbarger et al, 1957; Cooley and Davidson, 1963; Stewart, 1969; Stewart et al, 1972; Blakey and Gubitosa, 1984). The presence of eolian Navajo-Aztec-equivalent sandstones intercalated with Lower Jurassic arc volcanics along the rear or continent side of the arc and definitely south of the inferred northwest-trending ancestral Mogollon highlands in central Arizona suggests that a modification of prior paleogeographic reconstructions is needed (Bilodeau and Keith, 1979, 1984; Bilodeau, 1985).

Thick sequences of mature quartz sandstones intercalated with rhyolitic to andesitic volcanics of Early Jurassic age are located in several southern Arizona mountain ranges. Based on similarities in age, lithology, petrography, and paleowind directions deduced from the orientation of large-scale cross-stratification, we correlated these rocks with the Aztec Sandstone exposed 600 km to the northwest in the Mojave Desert (Miller and Carr, 1978; Marzolf, 1980, 1982), and the Navajo Sandstone 400 km to the north on the Colorado Plateau (Peterson and Pipiringos, 1979). The widespread southern Arizona quartzarenites of Early Jurassic age are best exposed in five widely separated southern Arizona localities: (1) within the Mount Wrightson For-

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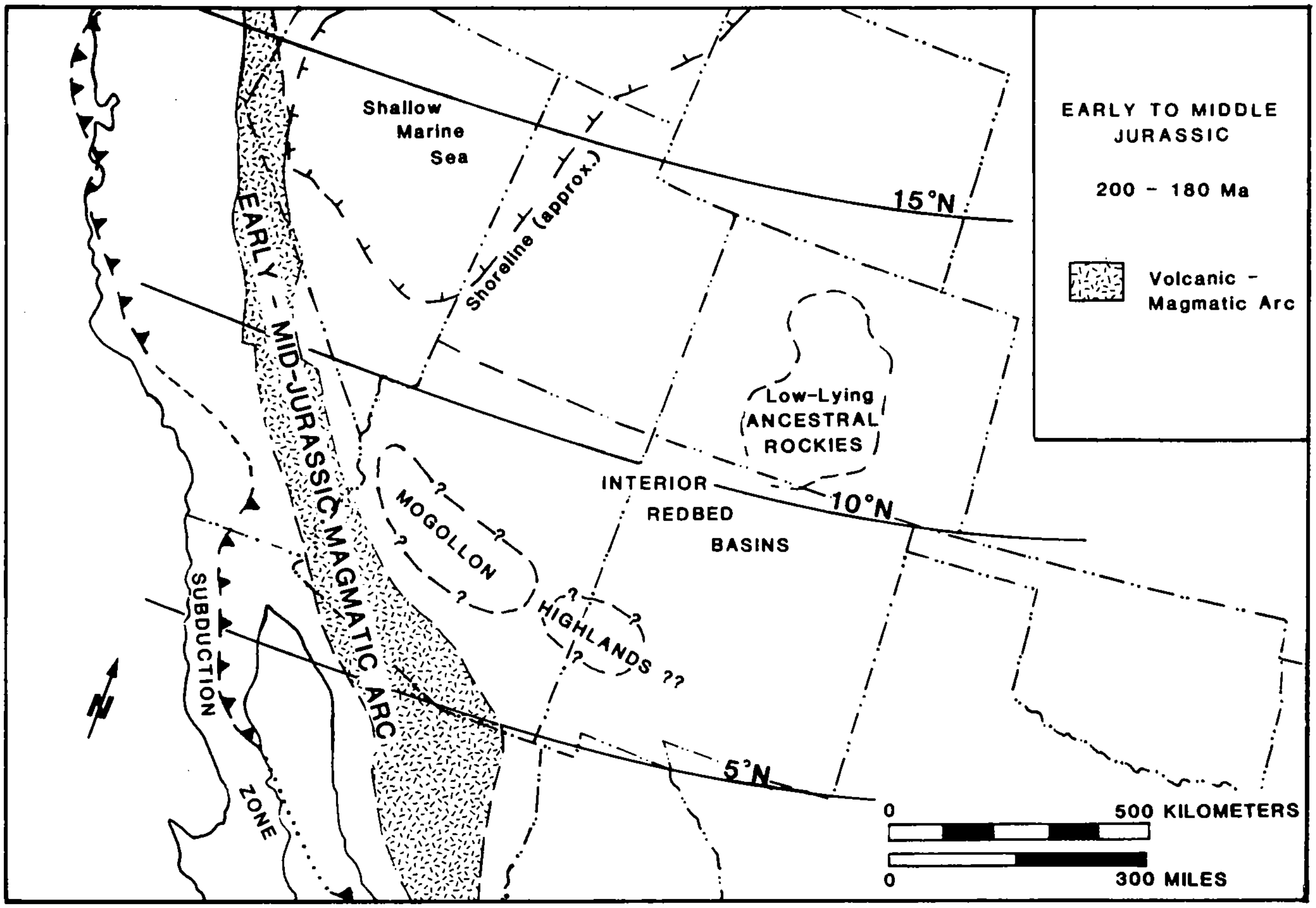

Figure 1—Regional paleogeographic setting of southwestern United States during Early to Middle Jurassic.

mation in the Santa Rita Mountains, (2) within the Ox Frame Volcanics of the Sierrita Mountains, (3) within the Ali Molina Formation in the Baboquivari Mountains, (4) within the Sil Nakya Formation of the Sil Nakya Hills, and (5) within the Cobre Ridge tuff and other unnamed volcanic units in the small mountain ranges around Arivaca, northwest of Nogales (Figure 2).

LOWER JURASSIC SANDSTONE UNITS

Mount Wrightson Formation

In the north-central Santa Rita Mountains (Figure 3), located south-southeast of Tucson, a minimum of 2,800 m of volcanic and sedimentary rocks of Triassic(?)-Jurassic age are widely exposed. These strata, named the Mount Wrightson Formation by Drewes (1971a), contain the thickest and best preserved quartzarenite units in the region. The Mount Wrightson Formation is exposed in a homoclinal north-northwest-trending outcrop belt that dips moderately to the east and forms the backbone, as well as the highest peaks, of the Santa Rita Mountains. The base of the formation is everywhere an intrusive contact. Several intrusive bodies of younger Jurassic to Late Cretaceous age form a distinct northwest-trending plutonic belt along the west and southwest margins of the Mount Wrightson Formation. To the north and northeast, the Mount Wrightson Formation is truncated by a major, northwest-trending complex fault zone (the Sawmill Canyon fault zone), and is unconformably overlain by Cretaceous volcanic and sedimentary rocks to the east.

The Mount Wrightson Formation was informally divided by Drewes (1971a) into three members. The lower is at least 457 m thick, composed mostly of dacitic to andesitic volcanics with lenses of quartzose sandstone and quartzite (near the basal intrusive contact), that are typically up to 6 m thick and a few hundred meters long. At one locality, several lenses converge to form a single body of quartzite over 100 m thick (Drewes, 1971a). Because the sandstones within the lower member have been metamorphosed, most vestiges of original texture and mineralogy have been obscured.

The middle member is approximately 1,524 m thick and contains mostly rhyolitic to latitic flows, flow breccias, and tuffs, with about 5% dacitic volcanics and 1% sedimentary rocks (Drewes, 1971a). Most of the sedimentary strata are lenses of sandstone and quartzite similar to those in the lower member, and characteristically contain large-scale cross-stratification. Some of the sandstone lenses are distinctly tuffaceous (Drewes, 1971a), but most commonly they are well-sorted quartzarenites (quartz > 90%) with subrounded to rounded grains 0.2-0.5 mm in diameter. The

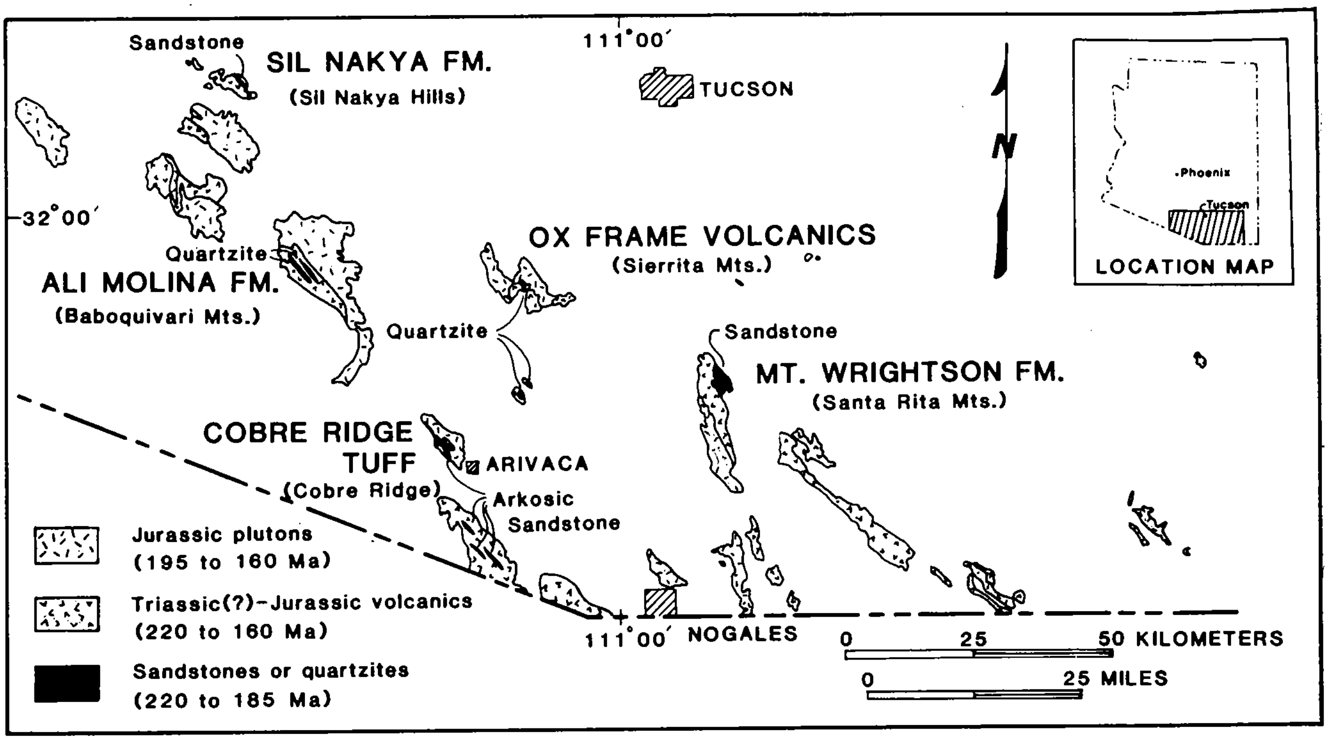

Figure 2—Location map for Jurassic rocks in southern Arizona showing the five principal localities and formations of concern in this paper.

sandstone lenses in the upper part of the middle member are almost unaffected by metamorphism, and contributed both petrographic and paleocurrent (cross-bed) data.

The upper member contains the most significant amount of quartzarenite within the Mount Wrightson Formation and in the entire region. This member is about 610 m thick, 50% of which is quartzarenite, 40% dacitic and andesitic volcanics, and 10% rhyodacite (Drewes, 1971a). Locally, the quartzarenite attains a thickness of 244 m, with large-scale trough or wedge-planar cross-stratification (1 to 3-m thick sets) present throughout the section. Petrographically, the sandstone is fine grained and well sorted, and contains subrounded to rounded, commonly frosted grains, of which over 90% are monocrystalline quartz similar to grains in the quartzarenites of the middle member (Figure 4). The texture and sedimentary structures strongly suggest an eolian origin for the quartzarenite lenses. The sandstone becomes increasingly indurated with quartz overgrowths and sutured grain boundaries as the Sawmill Canyon fault zone is approached (Figure 3). Along the fault zone, which forms the northeast boundary of the formation's outcrop, the sedimentary lenses are massive quartzite.

Paleocurrent directions from 49 large-scale cross-beds measured in the thickest lens of quartzarenite in the upper member of the Mount Wrightson Formation are plotted on a rose diagram (Figure 5a). Some of the data were obtained from R. F. Wilson (1978, written communication). The diagram implies southerly paleowind directions roughly oblique to the trend of the Early Jurassic magmatic arc in southern Arizona. The vector mean for the data set is S15°W.

The age of the Mount Wrightson Formation is here considered to be Early Jurassic. The basal contact of the Mount Wrightson is intruded by the Piper Gulch Monzonite, dated at 184 ± 20 Ma (lead-alpha method), and a date of 220 ± 30 Ma (lead-alpha method) was obtained on a welded tuff from the middle member (Drewes, 1971a). Also, Drewes (1971a) noted that detritus from the Mount Wrightson Formation is contained in the Gardner Canyon Formation, a red-bed unit found within the Sawmill Canyon fault zone. Volcanics interbedded with the mudstone member yielded a zircon concentrate with a 192 ± 20 Ma (lead-alpha method) apparent age. The lead-alpha method is imprecise, and we consider the ages to be somewhat old for the true age of the Mount Wrightson Formation (see age discussions for the Ali Molina and Sil Nakya Formations).

Ox Frame Volcanics

In the central Sierrita Mountains (Figure 6), the next mountain range to the northwest of the Santa Rita Mountains (Figure 2), at least 1,500 m of rhyolitic to andesitic flows and tuffs containing lenticular beds of sandstone, quartzite, and conglomerate is exposed (Cooper, 1971). These rocks have been named the Ox Frame Volcanics by Cooper (1971), and have been correlated with the Mount Wrightson Formation in the Santa Rita Mountains by Cooper (1971) and Hayes and Drewes (1978).

The Ox Frame Volcanics, in their type locality, are divided into three members: (1) a lower silicic member, composed of massive rhyolite flows, rhyodacite, and rhyolite tuffs; (2) a middle andesitic member, with flows of dark

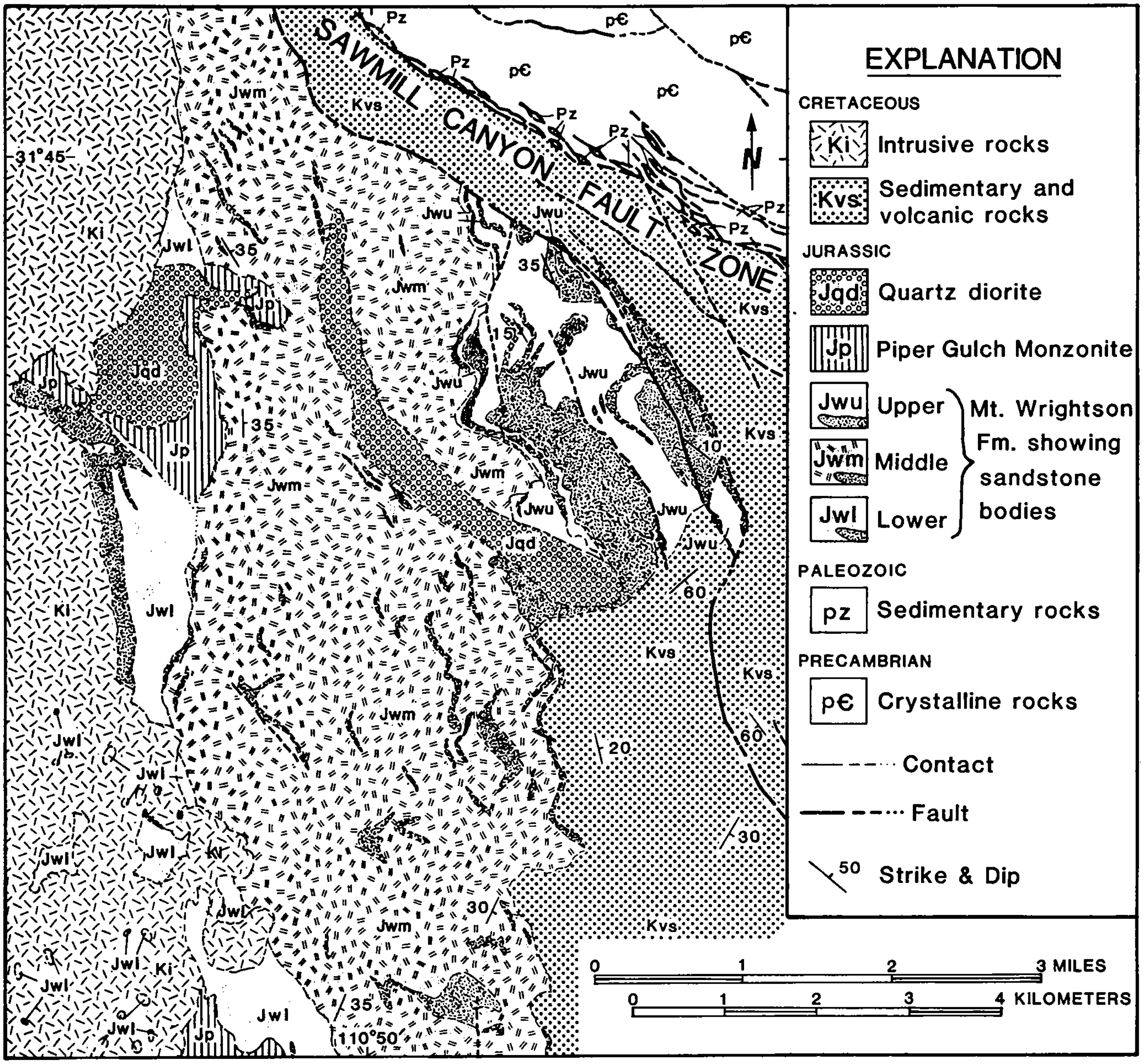

Figure 3—Simplified geologic map of part of Santa Rita Mountains. Quartzarenite lenses within Mount Wrightson Formation are stippled. (Modified from Drewes, 1971b, 1971c.)

porphyritic andesite and dacite; and (3) an upper silicic member, consisting primarily of rhyolitic welded tuffs and flows with intercalated volcanic sandstone and conglomerate and thick lenses of quartzite (Cooper, 1971). As in the Mount Wrightson Formation, the quartzite beds are most abundant toward the top of the formation, typically occurring as scattered lenses a few meters to a few hundred meters thick and a few tens of meters to over 1,000 m long. Petrographically, the quartzite is fine to medium grained (0.2-0.3 mm), and contains generally subrounded, moderately sorted, closely packed grains that are over 90% quartz (Figure 4). The rocks are cemented by silica in the form of quartz overgrowths, and by sericitic material (clay and chlorite) from altered feldspar or volcanic grains. The exposures of the quartzite are typically light or dark gray and have been moderately metamorphosed, as most of the quartzite lenses are located within 0.5 km of the intrusive contact with the Harris Ranch quartz monzonite. Quartzite lenses locally show relict sandstone textures and rare small to medium-scale (5 to 20 cm thick) cross-bedding. No large-scale eolian cross-stratification was observed. Locally, the quartzite lenses are distinctively spotted and mottled.

Paleocurrent directions from only six cross-bed orientations obtained from the quartzite lenses of the Ox Frame Volcanics show northerly trends (Figure 5b). Half the readings exhibit a west-northwest direction and the other half an east-northeast direction with a vector mean of N9°E. Inasmuch as all of the cross-strata were small to medium scale

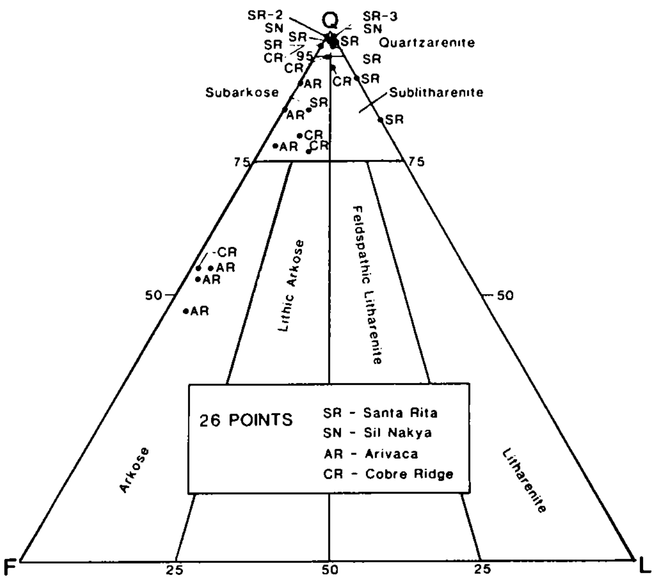

Figure 4—Standard triangular diagram showing modal percentages of quartz (Q), feldspar (F), and lithics (L) for 26 samples from four sites. Arivaca samples are from exposures near town of Arivaca and are considered to be northwest extensions of Cobre Ridge tuff (classification after Folk et al, 1970).

and came from two different lenses, either the paleoslope was highly variable or unrecognized local structural rotations have affected one or both of the localities. We feel that the former possibility is the likeliest, because both trends were also found in the Ali Molina Formation quartzites in the Baboquivari Mountains. The presence of such clean quartzarenite intercalated within a thick pile of volcanic rocks lacking other associated sedimentary strata, when coupled with the scale of the cross-bedding and the paleocurrent directions, suggests that these rocks were fluvially reworked from eolian sand deposits. It is also possible that they are just poorly preserved eolian deposits. The small number of paleocurrent readings from moderately metamorphosed quartzite may not be a significant data set, though we consider it to be one.

The age of the Ox Frame Volcanics is considered to be Early Jurassic. The Ox Frame Volcanics are intruded by the Harris Ranch quartz monzonite (190 ± 20 Ma, lead-alpha method, zircons), which is in turn intruded by the Sierrita Granite (150 ± 20 Ma, lead-alpha method, zircons; 140 ± 14 Ma, rubidium-strontium, whole rock) (Cooper, 1971). The similarity of lithology and contact relationships support the correlation of the Ox Frame Volcanics with the Mount Wrightson Formation of the Santa Rita Mountains,

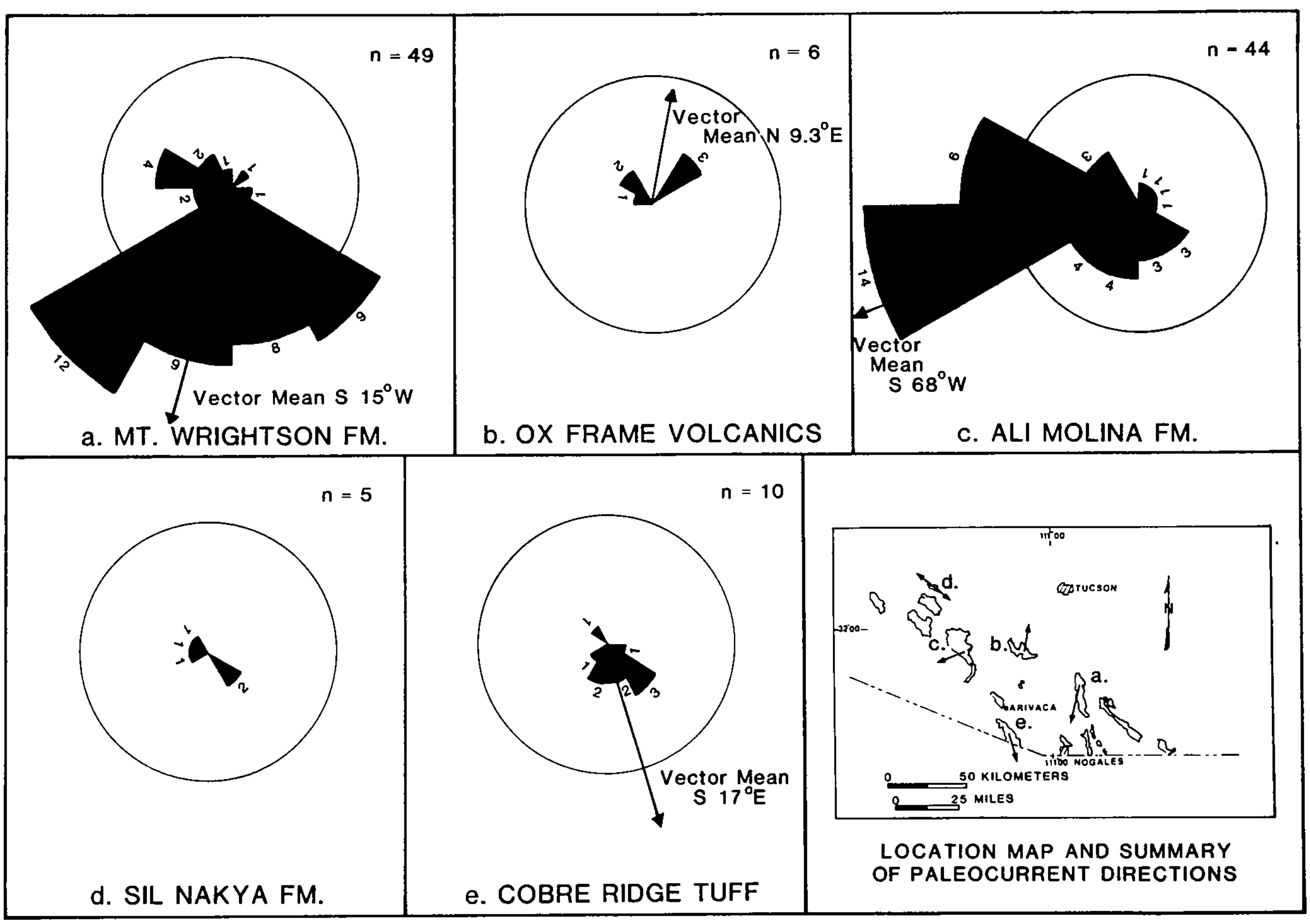

Figure 5—Rose diagrams of foreset paleocurrent data from each locality. All data have been structurally corrected by doing only a single rotation around a horizontal axis. n = number of samples.

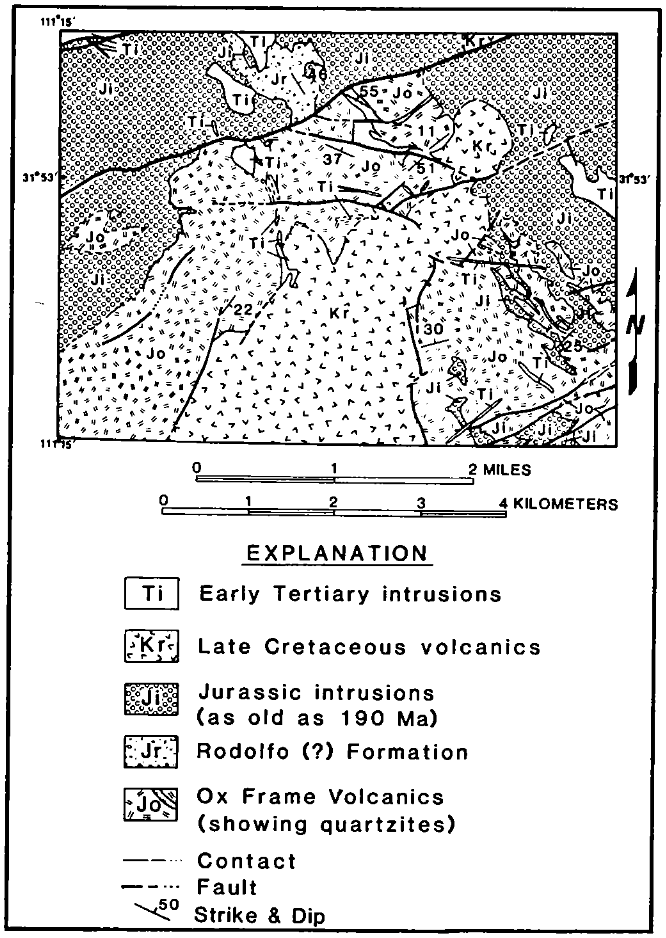

Figure 6—Simplified geologic map of part of Sierrita Mountains. Quartzite lenses within Ox Frame Volcanics are stippled. (Modified from Cooper, 1973.)

and the radiometric-age dates provide a minimum age of approximately 190 Ma for both.

Ali Molina Formation

Several substantial quartzite lenses intercalated with rhyodacitic volcanics of Early Jurassic age are exposed in the west-central Baboquivari Mountains, due west of the Sierrita Mountains (Figure 2). These rocks are part of a thick section of mildly to moderately metamorphosed sedimentary and silicic volcanic rocks that were originally defined and named the Ali Molina Metamorphic Complex by Heindl and Fair (1965). Haxel et al (1980a, b) delineated several thick quartzite lenses within their redefined Ali Molina Formation (Figure 7).

The quartzite lenses range from gray arkosic sandstone with coarse (0.7-0.8 mm) K-feldspar grains to white quartzarenite (Figure 4), and from 30 to more than 150 m in thickness. The lowermost lenses are distinctly less arkosic than the uppermost lenses. Several thin sections from each unit were cut, but the degree of metamorphism present made the point counts ambiguous; therefore, they are not included in Figure 4. The degree of metamorphism and the pervasive jointing also make identification of primary sedimentary structures difficult but not impossible. Most of the cross-bedding recognized in the quartzite lenses was small to medium scale. However, some large-scale cross-beds were identified in the lower quartzarenite lenses, and their orientations were measured (Figure 5c). The diagram shows a dominant west-southwest paleocurrent trend with subsidiary west-northwest and southwest trends. The vector mean for the data is S68° W. A large proportion of the cross-beds from the clean quartzarenite lenses have paleocurrent trends to the west-southwest, whereas most of the northeast and southeast directions are from the arkosic lenses. The small-scale cross-strata in the arkosic lenses are most likely alluvial in origin and thus show local variability in paleoslope. The arkosic character of the lenses indicates that they are probably reworked from the rhyodacitic volcanics with some eolian sand input. In contrast, the large-scale cross-bedding, clean character, and consistent southwestward paleocurrent indicators for the lower quartzitic lenses suggest a primarily eolian origin.

The age of the Ali Molina Formation has been determined by Wright et al (1981) as Early Jurassic. Isotopic ages were resolved for two size fractions of zircons from a quartz porphyry in the Ali Molina and yield a mean lead-lead method age of 191 Ma.

Sil Nakya Formation

In the Sil Nakya Hills, 80 km west of Tucson (Figure 2), more than 2,500 m of Mesozoic rhyolite to rhyodacitic volcanic flows and tuffs, sedimentary red beds, and quartzarenite are exposed (Figure 8) (Haxel et al, 1978). These rocks were originally described by Heindl (1965) and named the Sil Nakya Formation. The silicic volcanics make up over 75% of the section, with quartzose sandstone comprising most of the remainder.

The quartzarenite is poorly exposed, 100-200 m thick, white to tan in color, well sorted, and fine to medium grained, with over 95% subrounded to well-rounded quartz grains (Figure 4). The matrix is comprised of secondary quartz overgrowths (most abundant), clay, and carbonate cement (least abundant). In a few places, thin mudstone beds are intercalated with the sandstone, and in one locality, maroon rhyolite porphyry has intruded it, recrystallizing the sandstone to a ridge-forming quartzite. Where well exposed, the unit is typically thin bedded (2-10 cm), with rare small to medium-scale cross-stratification. Large-scale cross-bedding was observed in only one locality, and only five cross-bed orientation determinations were recorded. The paleocurrent data show no unique trends (Figure 5d). The predominant small scale of the cross-beds, lack of any unique paleocurrent trend, clean character, and thin bedding of the strata suggest that the Sil Nakya sandstones are a mixture of eolian dune and interdune deposits and fluvial sands reworked from former eolian deposits.

The Sil Nakya Formation has been isotopically dated by Wright et al (1981) as Early Jurassic. Zircons from welded

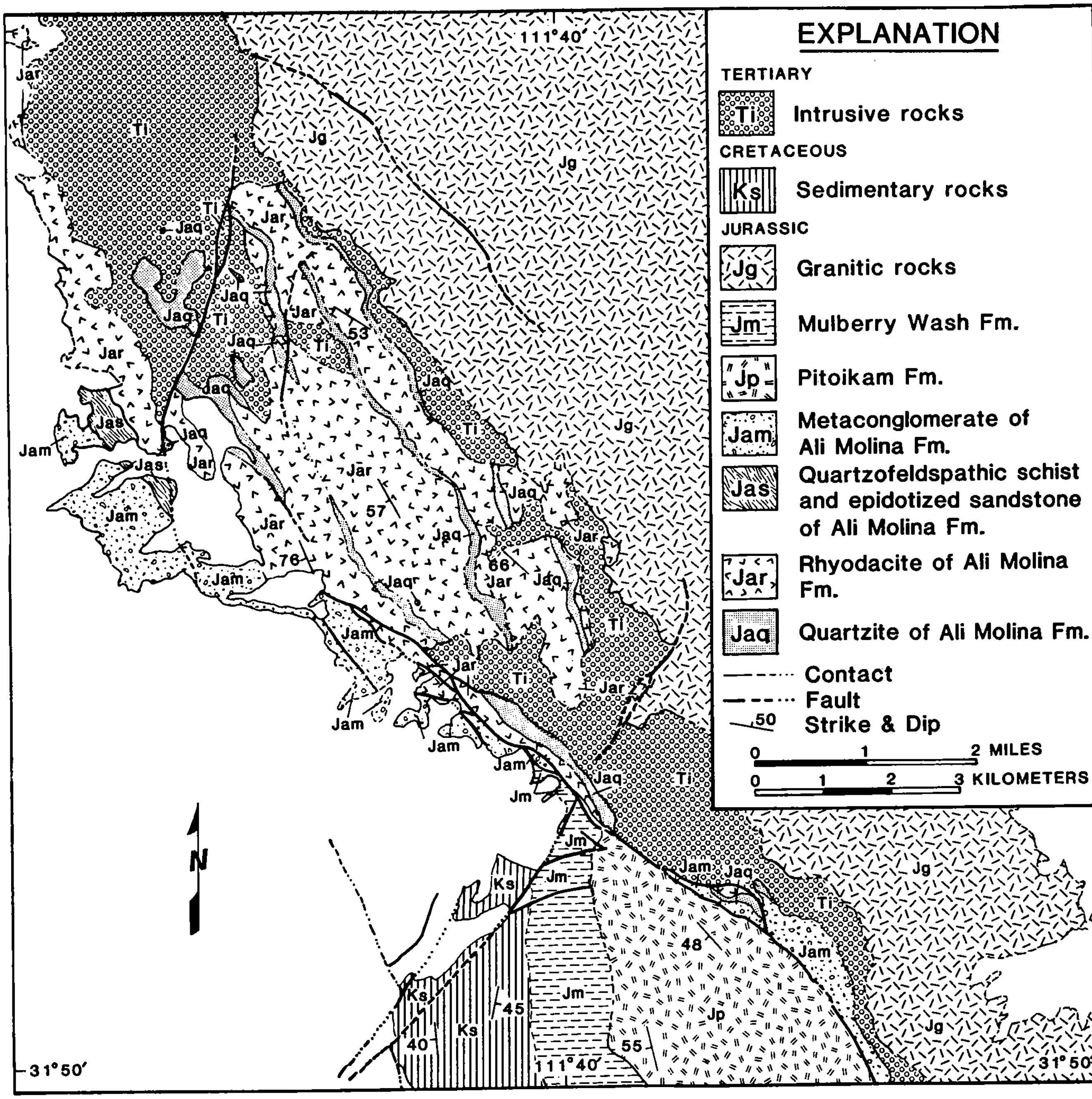

Figure 7—Simplified geologic map of part of Baboquivari Mountains. Quartzite lenses within Ali Molina Formation are stippled. (Modified from Haxel et al, 1980a.)

tuff in the Sil Nakya give a lead-lead method age of 188 Ma. This age is considered by Wright et al (1981) to be indistinguishable, within analytical error, from the isotopic age of the Ali Molina Formation in the Baboquivari Mountains to the south.

Cobre Ridge Tuff and Unnamed Units

In the Arivaca area, 30-35 km south of the Sierrita Mountains (Figure 2), undated Mesozoic volcanic and sedimentary rocks, including quartzarenites, have been mapped (Knight, 1970; Keith and Theodore, 1975). In the Oro Blanco area, southeast of Arivaca, Knight (1970) described over 3,700 m of ignimbritic rhyodacitic to rhyolitic tuffs containing intercalated arkosic quartzites (Figure 9). This sequence was named the Cobre Ridge tuff by Knight (1970) and divided into three members: (1) the lower rhyolite member; (2) the middle welded tuff member; and (3) the upper arkose member. The principal sandstones of interest here occur as lenses in the welded tuff member. The Cobre Ridge tuff is intruded by an undated monzonite pluton (Jurassic Warsaw quartz monzonite of Knight, 1970) and several

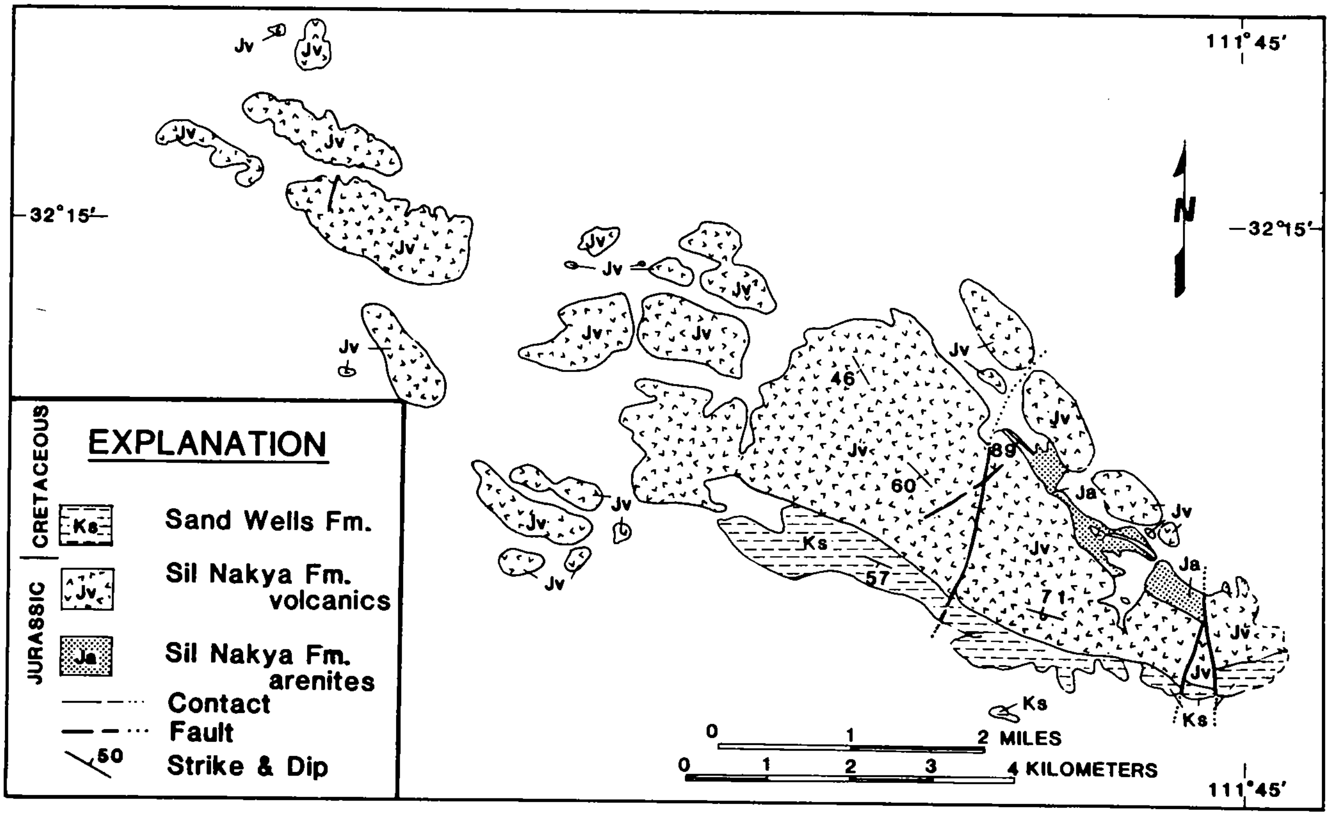

Figure 8—Simplified geologic map of Sil Nakya Hills. Quartzarenite lenses within Sil Nakya Formation are stippled. (Modified from Haxel et al, 1978; Bergquist et al, 1978.)

Upper Cretaceous and lower Tertiary plutons, dikes, and sills. The entire package is, in turn, unconformably overlain by clastic sedimentary rocks of the Oro Blanco formation, strata correlative to Lower Cretaceous rocks to the east. Because of its lithologic similarity and analogous stratigraphic position, we believe that the Cobre Ridge tuff can be correlated with the other Lower Jurassic eolian and volcanic sequences of the region.

The sandstones in the welded tuff member of the Cobre Ridge tuff occur in lenses of two main types: (1) poorly sorted, medium to coarse-grained subarkose with subangular to subrounded grains of quartz, K-feldspar, plagioclase, and volcanic rock fragments; and (2) moderately to well-sorted, medium to fine-grained quartzarenite with subrounded to well-rounded grains of quartz and minor K-feldspar (Figure 4). Locally, the subarkose lenses also contain volcanic conglomerate zones and small to medium-scale cross-bedding. The quartzarenite lenses are massive to medium bedded, and commonly contain large-scale cross-stratification. Paleocurrent directions from 10 large-scale cross-beds are plotted on Figure 5e. The diagram shows a dominant south-southeast trend with a vector mean of S17°E. These clean quartzarenites are interpreted as eolian deposits, whereas the coarser arkoses are of probable fluvial origin, much the same as the sandstones interbedded in the thick silicic volcanics of Early Jurassic age in the region.

The other localities around Arivaca that contain thick silicic volcanic sections with intercalated quartzose sandstones have similar lithologies, though the sandstones commonly occur near intrusive contacts and are moderately metamorphosed to quartzite. No large-scale eolian cross-stratification was observed in these outcrops, though small to medium-scale cross-bedding was observed. Petrographically, they are all medium to coarse-grained, poorly to moderately sorted arkoses and subarkoses (Figure 4) of probable fluvial origin.

In the Pajarito Mountains, between the Oro Blanco area and Nogales, Riggs (1985) described a 3,000-m thick section of Lower or Middle Jurassic(?) rhyolite to rhyodacite flows containing intercalated arkosic sandstone lenses, which she correlated with the Cobre Ridge tuff. These rocks were previously mapped by Drewes (1981) as Upper Cretaceous Salero Formation volcanics and Cretaceous rhyodacite porphyry. Detailed analysis of the intercalated sedimentary rocks has yet to be made.

SEDIMENTOLOGICAL IMPLICATIONS

Mature quartzarenites interbedded with very thick sequences of rhyolitic to andesitic volcanics are an unusual association, especially if the quartzarenites are hundreds of meters thick and are the dominant sedimentary rock type in the section, with only minor sedimentary red beds and volcanogenic sediments. For an adequate explanation, the provenance of the sandstones must be unrelated to the vol-

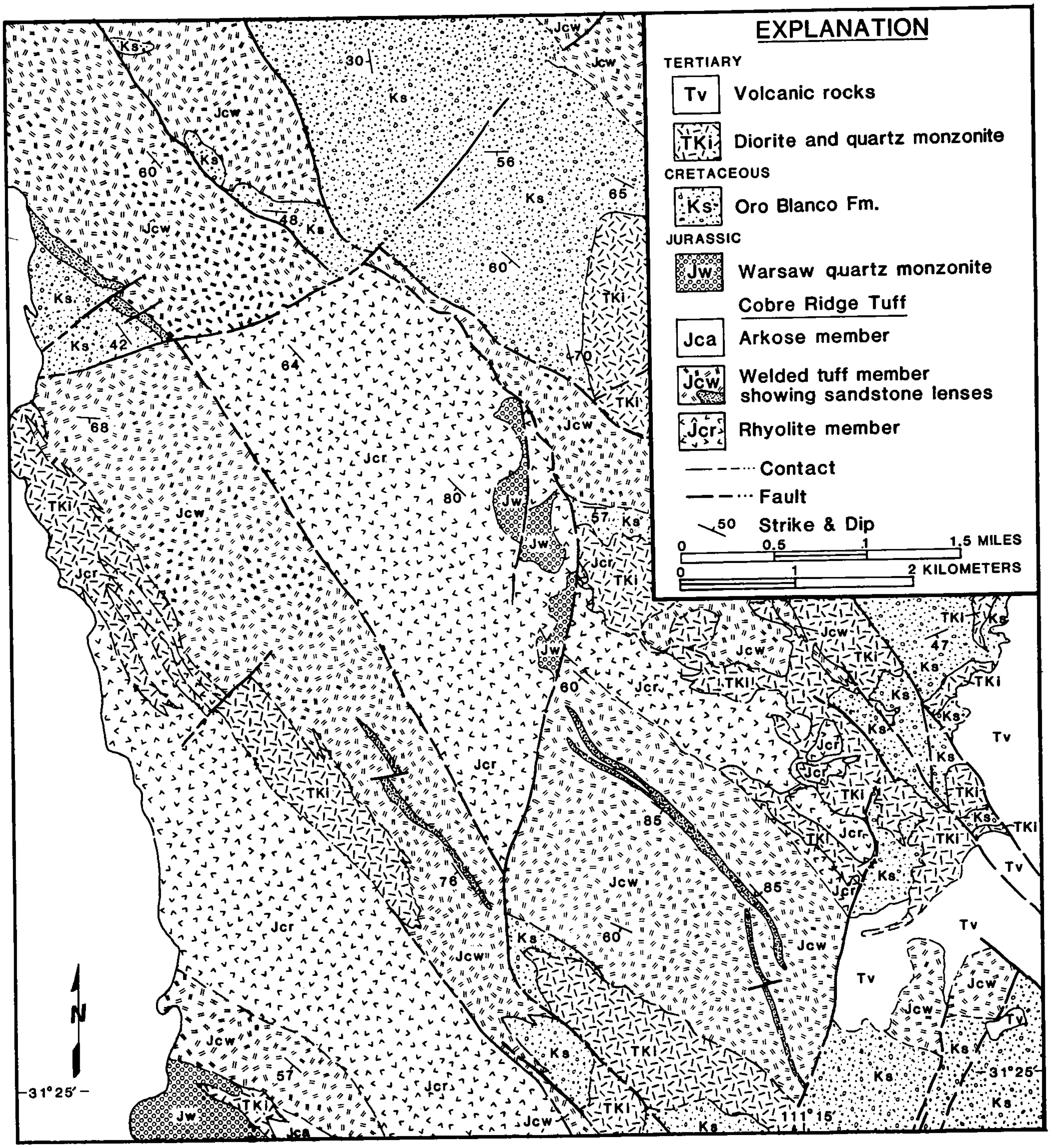

Figure 9—Simplified geologic map of Cobre Ridge area, west of Nogales, Arizona. Sandstone lenses within Cobre Ridge tuff are stippled. (Modified from Knight, 1970.)

canic arc, and the depositional mechanism must produce a well-sorted, mature quartzarenite.

The large-scale cross-bedding, so common in the Mount Wrightson Formation and less common in the other units, provides evidence for eolian transport and deposition of sands from the north and northeast (Figure 5). Fluvial reworking of the quartzarenites (small to medium-scale cross-bedding) and deviation from prevailing wind directions owing to local topography in the back-arc area are two possible explanations for the various subordinate paleocurrent trends shown on the rose diagrams of Figure 5.

REGIONAL CORRELATIONS

The Lower Jurassic mature quartzarenites in southeastern Arizona are here specifically correlated with Aztec

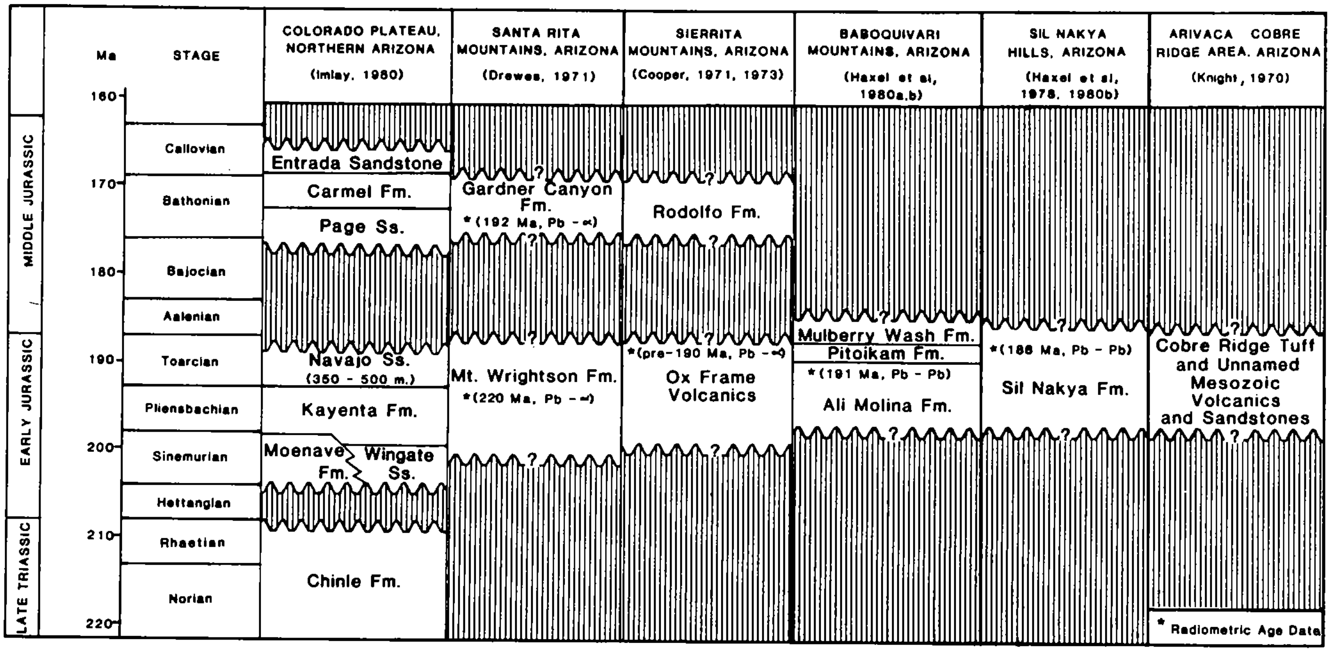

Figure 10—Stratigraphic correlation chart comparing Lower Jurassic rocks from the five southern Arizona localities to Colorado Plateau formations of similar age. Time scale from Palmer (1983); age ranges of Colorado Plateau Jurassic units after Imlay (1980).

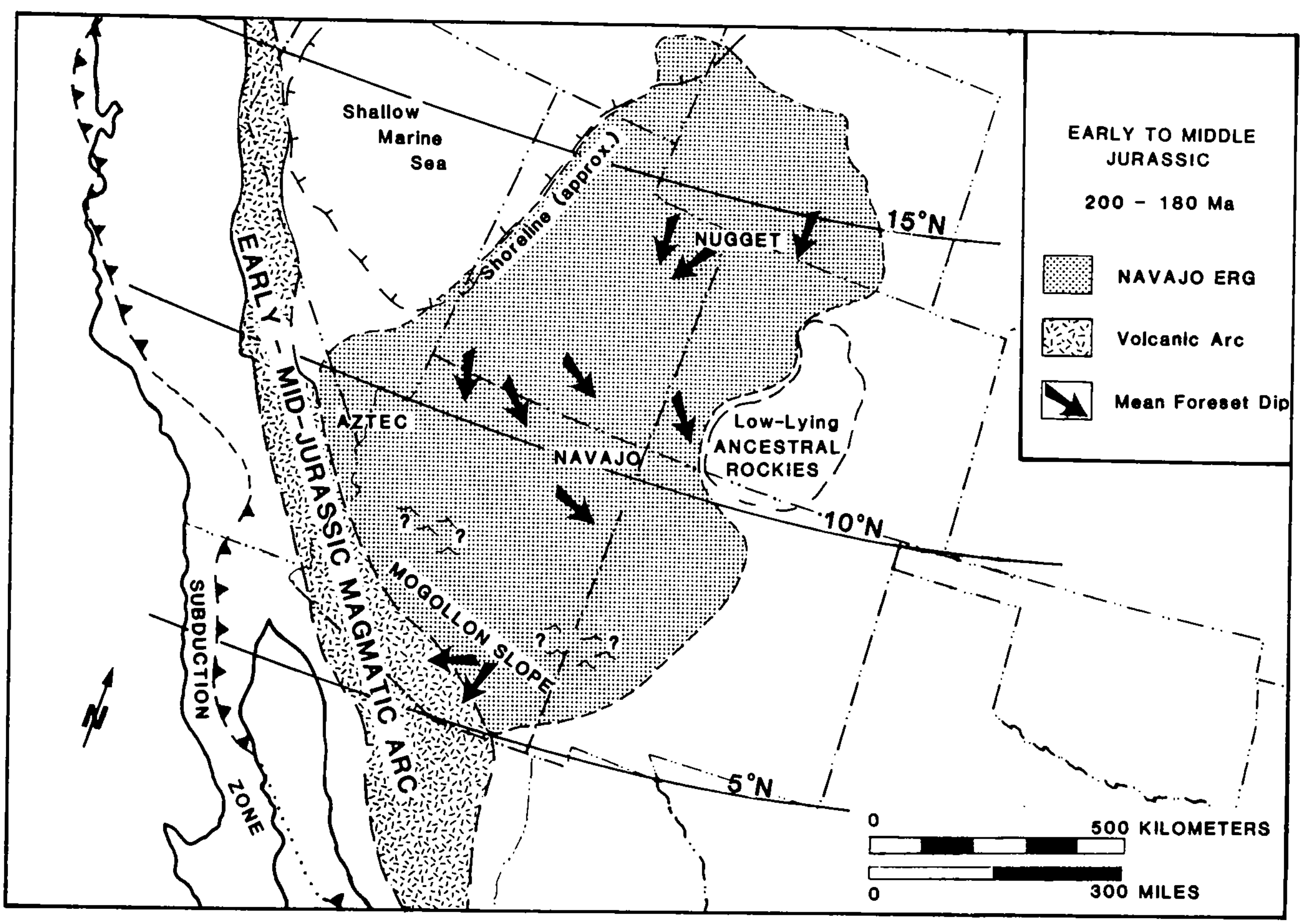

Figure 11—Regional paleogeographic map of southwestern United States in Early to Middle Jurassic showing extent of Nugget-Navajo-Aztec erg.

Sandstone 600 km to the northwest, in the Mojave Desert and southern Nevada, and to the Navajo Sandstone 400 km to the north, on the Colorado Plateau (Figure 10). Of the five southern Arizona localities of these sandstones, the Mount Wrightson Formation in the Santa Rita Mountains is the best exposed, least metamorphosed, and contains ubiquitous large-scale sweeping cross-beds of eolian origin. The southwest to southeast paleowind directions (Figure 5) correlate well with the directions reported for the Aztec Sandstone (Poole, 1962; Marzolf, 1982) and for the Navajo Sandstone (Poole, 1962).

The age of the Navajo and Aztec Sandstones is still somewhat controversial, as the age assignments are based on data mainly from the rock units above and below the formations, and from widely separated localities. Marzolf (1982) summarized most of the known relationships, and stressed that the Navajo and Aztec Sandstones are time-transgressive units not everywhere of the same age. He suggested wide age limits of Late Triassic (Rhaetian) to Middle Jurassic (Bajocian) as maximum and minimum ages. The latest geologic time scale, compiled by Palmer (1983) for the Decade of North American Geology would date this age range as approximately 212-180 Ma. Most workers now agree that these formations are probably entirely of Early Jurassic age in most if not all localities (Peterson and Pipiringos, 1979; Imlay, 1980). The age data for the southeastern Arizona sandstones are consistent with these age ranges. The 190 Ma isotopic age determined by Wright et al (1981) for the Ali Molina and Sil Nakya Formations makes them Pliensbachian to Toarcian, consistent with the age assignment of Imlay (1980) for the Navajo Sandstone (Figure 10). Freeman (1976) suggested that parts of the Chinle, Moenave, Wingate, Kayenta, and Navajo formations are all lateral facies of one another and, thus, that parts of each unit may have regional age equivalence.

PALEOGEOGRAPHIC IMPLICATIONS

The Lower Jurassic sandstone sequences in southern Arizona provide important details for defining the northwest-southeast trend of the Early Jurassic continental margin magmatic arc as well as the northeastern or continentward edge of the arc (Figure 10). Quartzite and quartzarenite interbedded with volcanogenic sediments in the Mojave Desert region have been correlated previously with the Aztec Sandstone in southern Nevada (Miller and Carr, 1978; Marzolf, 1980, 1982). These Aztec-equivalent or Navajo-equivalent sandstones suggest that clean quartz sands were blown up against the rear or continental side of the Early Jurassic magmatic arc in southern California. Our studies suggest that this was also the case in southern Arizona (Bilodeau and Keith, 1979, 1984).

In Arizona, isotopic dating of the interbedded volcanics of arc affinity, and the recorded paleowind directions from cross-bed orientations present stronger evidence that eolian sands were blown into the region of the magmatic arc than do the Mojave strata. Based on regional studies of the entire western United States, Kocurek and Dott (1983) agreed with our correlations and developed an integrated paleogeographic and paleoclimatic picture for the Early Jurassic.

The effect of our correlations on reconstructions of Early Jurassic paleogeography in central and southern Arizona are significant. The presence of north-derived eolian sandstone intercalated with arc volcanics in southern Arizona places important restrictions on the location, elevation, and duration of the Mogollon highlands from the Late Triassic, when they are inferred by some to have been the source area for various members of the Chinle Formation (Stewart, 1969; Stewart et al, 1972; Blakey and Gubitosa, 1983, 1984), to the Late Jurassic, when they are thought to have been the source for the Morrison Formation (Cooley and Davidson, 1963). Most paleogeographic reconstructions consider the Mogollon highlands as a structurally uplifted region trending northwestward across central Arizona in the area of the present Mogollon Rim. Our data suggest that during the Early Jurassic, the Mogollon highlands either (1) did not exist in central Arizona, or (2) existed as a discontinuous series of low uplifts or inselbergs separated by wide lowlands or passes, and thus were not able to block southward transport of eolian sands across central Arizona and up the rear flank of the Early Jurassic magmatic arc (Figure 11).

The eolian sands were blown from a large interior desert or erg at the south end of a shallow back-arc sea (Stanley et al, 1971; Kocurek and Dott, 1983), across a gently sloping plain we call the "Mogollon slope," and up against the magmatic arc where the quartz sands interfingered with the arc volcanics. The term "Mogollon slope" has been used previously as the present-day northward sloping region of the Colorado Plateau between the Mogollon Rim and the Little Colorado River (Lance and Wilson, 1960; Wilson, 1962), and as the paleogeographic area between the Late Triassic Mogollon highlands and the Chinle depositional basin to the north (Cooley and Davidson, 1963). The latter usage is extended here to include the area of central Arizona throughout the Triassic and Jurassic (Bilodeau, in press).

Local topographic features on the "Mogollon slope" and in the foothills of the northeastern flank of the volcanic arc may have caused fluctuations in Early Jurassic paleowind directions. Fluvial reworking and local lacustrine conditions commonly destroyed the eolian sedimentary structures and produced a variety of secondary paleocurrent directions directed parallel to and away from the volcanic arc. The source for various members of the Upper Triassic Chinle Formation was probably the magmatic arc itself rather than the Mogollon highlands, although Triassic igneous rocks have yet to be found in southern Arizona and northern Mexico (Anderson et al, 1984).

REFERENCES CITED

Albritton, C. C., Jr., and J. F. Smith, 1956, The Texas lineament: 20th International Geological Congress, Mexico D. F. [Trabajos], Section 5, p. 501-518.

Anderson, T. H., and L. T. Silver, 1978, Jurassic magmatism in Sonora, Mexico (abs.): GSA Abstracts with Programs, v. 10, p. 359.

——— G. B. Haxel, L. T. Silver, J. H. Stewart, and J. E. Wright, 1984, Late Triassic paleogeography of the southern Cordillera—the problem of a source for voluminous volcanic detritus in the Chinle Formation of the Colorado Plateau region (abs.): GSA Abstracts with Programs, v. 16, p. 430.

Armstrong, R. L., and J. Suppe, 1973, Potassium-argon geochronometry of Mesozoic igneous rocks in Nevada, Utah and southern California: GSA Bulletin, v. 84, p. 1375-1392.

Bergquist, J. R., P. M. Blacet, and S. T. Miller, 1978, Reconnaissance geologic map of the Santa Rosa Mountains Quadrangle, Pima County, Arizona: USGS Miscellaneous Field Studies Map MF-935.

Bilodeau, W. L., 1985, The Mogollon highlands: a Jurassic arc and/or an early to mid-Cretaceous rift-flanking uplift (abs.): GSA Abstracts with Programs, v. 17, p. 209.

——— in press, The Mesozoic Mogollon highlands, Arizona: an Early Cretaceous rift shoulder: Journal of Geology.

——— and S. B. Keith, 1979, Intercalated volcanics and eolian "Aztec-Navajo-like" sandstones in southeast Arizona; another clue to the Jurassic-Triassic paleo-tectonic puzzle of the southwestern U.S. (abs.): GSA Abstracts with Programs, v. 11, p. 70.

——— ——— 1984, Early Jurassic eolian "Navajo-Aztec-like" sandstones in SE Arizona and their paleogeographic significance (abs.): GSA Abstracts with Programs, v. 16, p. 215.

Blakey, R. C., and R. Gubitosa, 1983, Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona, *in* M. W. Reynolds, and E. D. Dolly, eds., Mesozoic paleogeography of west-central United States, Rocky Mountain Paleogeography Symposium 2: Rocky Mountain Section, SEPM, p. 57-76.

——— ——— 1984, Controls of sandstone body geometry and architecture in the Chinle Formation (Upper Triassic), Colorado Plateau: Sedimentary Geology, v. 38, p. 51-86.

Coney, P. J., 1978, The plate tectonic setting of southeastern Arizona, *in* J. F. Callender, ed., Land of Cochise: New Mexico Geological Society 29th Field Conference Guidebook, p. 285-290.

Cooley, M. E., and E. S. Davidson, 1963, The Mogollon highlands—their influence on Mesozoic and Cenozoic erosion and sedimentation: Arizona Geological Society Digest, v. 6, p. 7-35.

Cooper, J. R., 1971, Mesozoic stratigraphy of the Sierrita Mountains, Pima County, Arizona: USGS Professional Paper 658-D, 42 p.

——— 1973, Geologic map of the Twin Buttes Quadrangle, southwest of Pima County, Arizona: USGS Miscellaneous Geologic Investigations Map I-745.

Dickinson, W. R., 1981, Plate tectonic evolution of the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 113-135.

Drewes, H., 1971a, Mesozoic stratigraphy of the Santa Rita Mountains, southeast of Tucson, Arizona: USGS Professional Paper 658-C, 81 p.

——— 1971b, Geologic map of the Sahuarita Quadrangle, southeast of Tucson, Pima County, Arizona: USGS Miscellaneous Geological Investigations Map I-613.

——— 1971c, Geologic map of the Mt. Wrightson Quadrangle, southeast of Tucson, Santa Cruz and Pima Counties, Arizona: USGS Miscellaneous Geological Investigations Map I-614.

——— 1981, Tectonics of southeastern Arizona: USGS Professional Paper 1144, 96 p.

Folk, R. L., P. Andrews, and D. W. Lewis, 1970, Detrital sedimentary rock classification and nomenclature for use in New Zealand: New Zealand Journal of Geology and Geophysics, v. 13, p. 937-968.

Freeman, W. E., 1976, Regional stratigraphy and depositional environments of the Glen Canyon Group and Carmel Formation (San Rafael Group), *in* J. G. Hill, ed., Geology of the Cordilleran hingeline: Rocky Mountain Association of Geologists Guidebook, p. 247-259.

Harshbarger, J. W., C. A. Repenning, and J. H. Irwin, 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country: USGS Professional Paper 291, 74 p.

Haxel, G., D. J. May, J. E. Wright, and R. M. Tosdal, 1980a, Reconnaissance geologic map of the Baboquivari Peak Quadrangle, Arizona: USGS Miscellaneous Field Studies Map MF-1251.

——— J. E. Wright, D. J. May, and R. M. Tosdal, 1980b, Reconnaissance geology of the Mesozoic and lower Cenozoic rocks of the southern Papago Indian Reservation, Arizona: Arizona Geological Society Digest, v. 12, p. 17-27.

——— R. M. Tosdal, D. J. May, and J. E. Wright, 1984, Latest Cretaceous and early Tertiary orogenesis in south-central Arizona—thrust faulting, regional metamorphism and granitic plutonism: GSA Bulletin, v. 95, p. 631-653.

——— J. A. Briskey, J. J. Rytuba, J. R. Bergquist, P. M. Blacet and S. T. Miller, 1978, Reconnaissance geologic map of the Comobabi Quadrangle, Pima County, Arizona: USGS Miscellaneous Field Studies Map MF-964.

Hayes, P. T., and H. Drewes, 1978, Mesozoic depositional history of southeastern Arizona, *in* J. F. Callender, ed., Land of Cochise: New Mexico Geological Society 29th Field Conference Guidebook, p. 201-207.

——— F. S. Simons, and R. B. Raup, 1965, Lower Mesozoic extrusive rocks in southeastern Arizona—the Canelo Hills Volcanics: USGS Bulletin 1194-M, 9 p.

Heindl, L. A., 1965, Mesozoic formations in the Comobabi and Roskruge Mountains, Papago Indian Reservation, Arizona: USGS Bulletin 1194-H, 15 p.

——— and C. L. Fair, 1965, Mesozoic(?) rocks in the Baboquivari Mountains, Papago Indian Reservation, Arizona: USGS Bulletin 1194-I, 15 p.

Imlay, R. W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: USGS Professional Paper 1062, 134 p.

Keith, W. J., and T. G. Theodore, 1975, Reconnaissance geologic map of the Arivaca Quadrangle, Arizona: USGS Miscellaneous Field Studies Map MF-678.

Knight, L. H., Jr., 1970, Structure and mineralization of the Oro Blanco mining district, Santa Cruz County, Arizona: PhD dissertation, University of Arizona, Tucson, Arizona, 172 p.

Kocurek, G., and R. H. Dott, Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountains region, *in* M. W. Reynolds and E. D. Dolly, eds., Mesozoic paleogeography of the west-central United States, Rocky Mountain Paleogeography Symposium 2: Rocky Mountain Section, SEPM, p. 101-116.

Lance, J. F., and E. D. Wilson, 1960, Geology, *in* Arizona, its people and resources: Tucson, University of Arizona Press, p. 84-98.

Marzolf, J. E., 1980, The Aztec Sandstone and stratigraphically related rocks in the Mojave Desert, *in* D. L. Fife and A. R. Brown, eds., Geology and mineral wealth of the California desert: Santa Ana, California, South Coast Geological Society, p. 215-220.

——— 1982, Paleogeographic implications of the Early Jurassic(?) Navajo and Aztec Sandstones, *in* E. G. Frost and D. L. Martin, eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, California, Cordilleran Publishers, p. 493-501.

Miller, E. L., and M. D. Carr, 1978, Recognition of possible Aztec-equivalent sandstones and associated Mesozoic metasedimentary deposits within the Mesozoic magmatic arc in the southwestern Mojave Desert, California, *in* D. G. Howell and K. A. McDougall, eds., Mesozoic paleogeography of the western United States, Pacific Coast Paleogeography Symposium 2: Pacific Section, SEPM, p. 283-289.

Moody, J. D., and M. J. Hill, 1956, Wrench-fault tectonics: GSA Bulletin, v. 67, p. 1207-1246.

Palmer, A. R., 1983, The Decade of North American Geology, 1983 Geologic Time Scale: Geology, v. 11, p. 503-504.

Peterson, F., and G. N. Pipiringos, 1979, Stratigraphic relations of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona: USGS Professional Paper 1035-B, 43 p.

Poole, F. G., 1963, Wind directions in late Paleozoic to middle Mesozoic time on the Colorado Plateau: USGS Professional Paper 450-D, p. 147-151.

Rangin, C., 1978, Speculative model of Mesozoic geodynamics, central Baja California to northeastern Sonora (Mexico), *in* D. G. Howell and K. A. McDougall, eds., Mesozoic paleogeography of the western United States, Pacific Coast Paleogeography Symposium 2: Pacific Section, SEPM, p. 85-106.

Riggs, N., 1985, Stratigraphy, structure, and mineralization of the Pajarito Mountains, Santa Cruz County, Arizona: Master's thesis, University of Arizona, Tucson, Arizona, 102 p.

Stanley, K. O., W. M. Jordan, and R. H. Dott, Jr., 1971, New hypothesis of Early Jurassic paleogeography, and sediment dispersal for western United States: AAPG Bulletin, v. 55, p. 10-20.

Stewart, J. H., 1969, Major Upper Triassic lithogenetic sequences in Colorado Plateau region: AAPG Bulletin, v. 53, p. 1866-1879.

——— F. G. Poole, and R. F. Wilson, 1972, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region: USGS Professional Paper 690, 336 p.

Turner, G. L., 1963, The Deming axis, southeastern Arizona, New Mexico and Trans-Pecos, Texas: New Mexico Geological Society 13th Field Conference Guidebook, p. 59-71.

Wilson, E. D., 1963, A resumé of the geology of Arizona: Arizona Bureau of Mines Bulletin 171, 140 p.

Wright, J. E., G. Haxel, and D. J. May, 1981, Early Jurassic uranium-lead isotopic ages for Mesozoic supracrustal sequences, Papago Indian Reservation, southern Arizona (abs.): GSA Abstracts with Programs, v. 13, p. 115.

DAVID BLOOM

Associated rhyo-andesite volcanics } unusual
Intercalated w/ qtz arenites

qtz arenite 100s m thick - dominant
minor: sed red beds, volcanogenic sed

SS from different provenance from volcanics

eolian transport from N & NE

40000
Mt Wrightson Fm - X-beds large (eg eolian)
(Navajo - Aztec Fms: time transgressive entirely Early J 212-180 Ma)

Define NW-SE · E. Jur cont. margin volcanic arc

IN E. Jurassic Mogollon Highlands did not exist
· (didn't restrict wind-blown ~~sediment~~ sand)

Are Large X-beds eolian?
Is Volcanic + qtz arenite unusual? eg RG Rift
What is an erg?