CORRELATION OF SOME MID-MESOZOIC REDBEDS
AND QUARTZ SANDSTONES IN THE SANTA RITA MOUNTAINS,
MUSTANG MOUNTAINS, AND CANELO HILLS, SOUTHEASTERN ARIZONA

by

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Figure 1. Generalized location map of exposures of mid-Mesozoic redbeds (triangles) and quartz sandstones (circles) in southeastern Arizona.
Correlation of Some Mid-Mesozoic Redbeds
and Quartz Sandstones in the Santa Rita Mountains,
Mustang Mountains, and Canelo Hills, Southeastern Arizona

Abstract

Mid-Mesozoic redbeds in the Santa Rita Mountains, Mustang Mountains, and Canelo Hills are lithologically and petrographically correlative. Quartz sandstone overlying the redbeds in the Mustang Mountains and Canelo Hills is also lithologically and petrographically correlative. The sediments were deposited during one or more breaks in volcanism associated with a continental magmatic arc that was active in southern Arizona during Triassic (?) and Jurassic time. The exact timing of sedimentation cannot be determined without more accurate dating of volcanics associated with the redbed strata.

Redbeds of the Gardner Canyon Formation in the Santa Rita Mountains were probably deposited during and after eruption of the Mount Wrightson volcanics, the lower member of which is presently dated at 210 ±3 Ma. The Monkey Canyon redbeds and the Dark Canyon sandstone in the Canelo Hills and identical rocks in the Mustang Mountains are probably equivalent and were deposited between or during one or more hiatuses in two volcanic episodes presently dated at 165-185 Ma and 150-155 Ma, or before the 165-185 Ma volcanism and possibly as early as the period when the Gardner Canyon Formation was deposited.

The Gardner Canyon Formation and Monkey Canyon redbeds are sequences of interbedded mudstone, siltstone, fine- to coarse-grained
volcaniclastic sandstone, and volcanic conglomerate. They are interpreted as the product of meandering fluvial systems developed in close proximity to local volcanic sources, probably in distal alluvial fan or floodplain environments. The Dark Canyon and upper member Mount Wrightson quartz sandstones are bimodal, fine- and medium-grained, and average 93 percent monocrystalline quartz. They were probably deposited by both fluvial processes in stream channels and as windblown sand.

**Introduction**

Redbeds of probable early to mid-Mesozoic age are exposed in several mountain ranges of southeastern Arizona (Fig. 1). Previous workers have noted similarities in the redbed sequences between the different localities but have made no attempt to correlate them lithologically or petrographically. Quartz sandstone of mid-Mesozoic age is associated with the redbeds at some localities (Fig. 1). The sandstone lies stratigraphically above the redbeds and locally interfingers with the redbeds.

The purpose of this study is to describe the sedimentology, petrography, and contact relationships of the lower to mid-Mesozoic redbed and quartz sandstone units in the Santa Rita Mountains, Mustang Mountains, and Canelo Hills and to discuss the basis for lithologic, stratigraphic, and geochronologic correlation. Understanding how these rock units are related to each other is significant for understanding the Mesozoic paleogeography of the region.

Geotectonic evolution in the southern Cordillera during Mesozoic time involved a complex interplay between the compressional forces and arc magmatism associated with subduction along the Pacific margin of the North American continent to the west and extensional forces associated
with intracontinental rifting during the opening of the Gulf of Mexico to the southeast (Dickinson, 1981, Coney, 1978). Rock assemblages and tectonic elements related to both of these systems are present in southern Arizona.

In southeastern Arizona, lithologic assemblages associated with the magmatic arc that swept eastward during Late (?) Triassic to mid-Jurassic time include granitic plutons, hypabyssal intrusions, intermediate to felsic volcanics, and volcaniclastic sediments. Specific rock units referred to in this paper include: (1) Mount Wrightson Formation silicic volcanics and eolian sandstones, (2) Gardner Canyon Formation red beds (Drewes, 1968), (3) Canelo Hills Volcanics silicic volcanics (Hayes and others, 1965), (4) three members of the Mt. Hughes formation (Kluth, 1982): Monkey Canyon member red beds, Dark Canyon member sandstone, and Canelo Ridge member silicic volcanics, and (5) unnamed volcanics and sediments of the Mustang Mountains (Hayes and Raup, 1968).

Overlying or interfingering with these rocks are upper Mesozoic sequences associated with Gulf of Mexico extensional tectonics. They include terrestrial and marine epiclastic strata and lacustrine deposits of the Bisbee Group and related formations. Volcanic or volcaniclastic rocks are locally interbedded with these assemblages. Most of these sediments were deposited in the Bisbee Basin, which connected to the Chihuahua trough to the southeast.

The arc magmatism and associated sediments are thought to predate the trough sedimentation in the Bisbee Basin. In some localities, however, including the Santa Rita and Mustang Mountains and the Canelo Hills, the age relationships between the two are unclear (Dickinson, 1981). This study shows that the lower to mid-Mesozoic red beds in these
ranges were derived from arc volcanics rather than rift-related assemblages.

**Nomenclature**

Different names are used for the various potentially correlative mid-Mesozoic volcanic and sedimentary units in southeastern Arizona. Figure 2 shows the history of stratigraphic nomenclature for units discussed in this paper. The Gardner Canyon and Mount Wrightson Formations are accepted names in the Santa Rita Mountains for the lower to middle Mesozoic redbeds and silicic volcanics, respectively (Drewes, 1968).

In the Canelo Hills, Kluth (1982) named the mid-Mesozoic sedimentary rocks and certain silicic volcanic units the Mt. Hughes formation, composed of four distinct members: from oldest to youngest, the Monkey Canyon mudstone and sandstone, Dark Canyon sandstone, Canelo Ridge silicic volcanic, and Canelo Pass conglomerate members. Vedder (1984) reassigned the upper three members of the Mt. Hughes formation to the Glance Conglomerate. However, as this research indicates, the lower two members should each be considered separate stratigraphic units, distinct from the Glance Conglomerate, whose lithologic correlative is the Canelo Pass member only.

The volcanic and sedimentary units in the Mustang Mountains have not been formally named. Hayes and Raup (1968) referred to these rocks as the "volcanic and sedimentary rocks of the Mustang Mountains." As discussed later in this paper, the redbeds and quartz sandstone in the Mustang Mountains are identical to the Monkey Canyon member redbeds and the Dark Canyon member quartz sandstone in the Canelo Hills. Therefore, it is recommended that those names be applied to the strata in the Mustang Mountains (Fig. 2).
Figure 2. History of Mesozoic stratigraphic nomenclature in the Santa Rita Mountains, Canelo Hills, and Mustang Mountains.
Study Sites

The Mesozoic sedimentary sequences were studied in the Santa Rita and Mustang Mountains and the Canelo Hills (Fig. 3). Sites where it was possible to determine the stratigraphic sequence of the redbeds were selected for detailed lithologic and petrographic study. Redbed facies composed of mudstone, siltstone, fine- to coarse-grained sandstone, and conglomerate were studied in each mountain range, as were quartzarenite facies. Exposures of both lithofacies are partially or completely fault-bounded in all areas and are rarely more than 1.5 km² in extent.

Santa Rita Mountains

The Santa Rita Mountains consist of complexly deformed sedimentary, intrusive, and extrusive rocks of Precambrian to Cenozoic ages. The oldest strata within the study area, Late Triassic (?) to Early Jurassic in age, consist of volcanics and eolian sandstones of the Mount Wrightson Formation and redbeds of the Gardner Canyon Formation redbeds (Drewes, 1971b, 1971c).

The Gardner Canyon-Sawmill Canyon area in the central part of the range offers the best exposure of the redbeds and lies within the Sawmill Canyon Fault zone (Figs. 3 and 4). This complex structural zone contains steeply dipping northwest trending faults and has a Triassic to Paleocene movement history (Drewes, 1972). Repeated movements in more than one direction occurred along the zone throughout Mesozoic time. Folds, thrust faults, and tear faults formed as a result of Late Cretaceous compression oriented northeast-southwest are interpreted as Paleocene in age (Drewes, 1972).
Figure 3. Location map of major study sites in the Santa Rita Mountains, Mustang Mountains, and Canelo Hills: Gardner/Sawmill Canyon, Fish Creek, Cow Tank, Tufa Hill, and Mustang Mountains (adapted from May, 1985).

Explanation

JKb - Bisbee Group sediments
JKg - Glance Conglomerate
Jcr - Canelo Ridge member volcanics
Jrb - redbeds
Jv - volcanics
Jcv - Canelo Hills Volcanics
TrJwv - Mount Wrightson Formation volcanics
P1 - undifferentiated limestone

normal faults, dashed where approximate
thrust fault, teeth on upper plate
anticlinal axis, arrow in direction of plunge
Figure 4. Generalized geologic map of the Gardner-Sawmill Canyon and Fish Creek study sites (adapted from Drewes, 1971, 1972).

Explanation

Ks - sediments
JKg - Glance Conglomerate
Jg - Gardner Canyon Formation redbeds
   u - upper member
   l - lower member
   d - dacite
   c - conglomerate
TrJw - Mount Wrightson Formation volcanics
Pl - undifferentiated limestones
pCc - Continental Granodiorite

▲ major sample sites
|| measured sections
\- normal fault, dashed where approximate
\- thrust fault, teeth on upper plate
\- anticlinal axis, arrow in direction of plunge
\- synclinal axis, arrow in direction of plunge
Canelo Hills

The Canelo Hills, which lie to the southeast of the Santa Rita Mountains, are bounded on the northeast by the Sawmill Canyon Fault Zone and on the southwest by the Lampshire Canyon Fault (Fig. 5). Steeply dipping northwest-trending faults associated with the Sawmill Canyon Fault zone and a large-scale, northwest-plunging anticlinal flexure are the dominant structural features in the northern Canelo Hills (Davis and others, 1979; Kluth, 1982). Movement on these faults paralleled movement along the Sawmill Canyon Fault zone (Davis, 1979; Davis and others, 1979, Kluth, 1982). Northeast-trending high-angle faults also cut the range. At least some of these faults were active during Triassic (?)–Jurassic time (Davis and others, 1979).

The Monkey Canyon red beds are exposed mainly in the northern Canelo Hills and thin rapidly to the southeast. They occur most commonly as relatively small outcrops (less than 1 km²), in either fault or unconformable contact with exotic blocks of Paleozoic limestone and with mid-Mesozoic Canelo Ridge member volcanics (Fig. 5). The exotic limestone blocks are interpreted as slide blocks that were derived from fault scarps in the Sawmill Canyon Fault zone to the northeast during Triassic (?)–Jurassic time and slid to the southwest into fault troughs filled with mud and volcanic debris (Simons and others, 1966; Davis and others, 1979). In the center of this part of the range, autochthonous Paleozoic limestone was uplifted during Triassic (?)–Jurassic time and underwent faulting throughout Mesozoic and Tertiary time (Davis and others, 1979; Kluth, 1982). Some exposures of red beds lie unconformably on Paleozoic limestone units.
Figure 5. Generalized geologic map of the northern Canelo Hills, showing major study sites Cow Tank and Tufa Hill (modified from Kluth, 1982 and Vedder, 1984).

Explanation

Kfc - Fort Crittenden sediments
Kb - Bisbee Group sediments
JKg - Glance Conglomerate
Jcr - Canelo Ridge member volcanics

Jdc - Dark Canyon sandstones
Jmc - Monkey Canyon redbeds
Jcv - Canelo Hills Volcanics
Pl - undifferentiated limestones

▲ sample site
├── measured section
├── normal fault
├── anticlinal axis, arrow in direction of plunge
Mustang Mountains

The Mustang Mountains are a small range that lies north of the Sawmill Canyon Fault zone and south of the Whetstone Mountains (Fig. 6). Faults trending northwest-southeast, parallel to those in the Sawmill Canyon Fault zone, are projected through this area (Hayes and Raup, 1968). Faults trending northeast-southwest also cut across the range. The history of movement on these faults is probably similar to that in the northern Canelo Hills.

The Mustang Mountains are composed of Paleozoic limestone and quartzose sandstone and Mesozoic sedimentary and volcanic rocks. Quartz sandstone, the major Mesozoic sedimentary lithology, is either faulted against or unconformably overlies the Paleozoic limestones, and is unconformably overlain by felsic volcanics. In a few places the sandstone is interbedded with the volcanics (Hayes and Raup, 1968). Redbeds are locally poorly exposed either below the quartz sandstone or separately, with neither base nor top exposed.

Sedimentology and Depositional Environments

Redbeds

The Gardner Canyon and Monkey Canyon redbeds are both composed of interbedded mudstone, siltstone, sandstone, and conglomerate (Fig. 7). Typical exposures of mudstone and siltstone range from 5 to 60 m thick (Figs. 8 and 9). The total thickness of the redbeds is difficult to estimate in both the Santa Rita Mountains and the Canelo Hills because all exposures are either partially or completely fault-bounded. Hayes and Drewes (1979) estimated the thickness of the Gardner Canyon Formation at 600 m, and Kluth (1982) estimated the thickness of the Monkey Canyon redbeds at 200 m. Calcareous nodules are common and
Figure 6. Generalized geologic map of the Mustang Mountains (adapted from Hayes and Raup, 1968). (A) indicates the location of the quartzite and fossiliferous limestone conglomerate horizon discussed in the text.

Explanation

Jv - silicic volcanics

Js - Dark Canyon sandstone and Monkey Canyon redbeds
Ps - Scherrer Formation quartzose sandstone
P1 - undifferentiated limestones

sample site

normal fault, dashed where approximate

thrust fault, teeth on upper plate
Figure 7. Measured sections from study sites in the Canelo Hills and the Santa Rita Mountains.

Explanation

- Mudstone and siltstone
- Sandstone
- Conglomerate
- Limestone
- Ash fall tuff

- Mudchips
- Calcareous nodules
- Fault
- Folds
Figure 8. Type section of upper and lower members of the Gardner Canyon Formation composed of mudstone, siltstone, and sandstone in Gardner Canyon in the Santa Rita Mountains.
Figure 9. Typical sequence of lenses of mudstone, siltstone, and sandstone in the Monkey Canyon redbeds. Photograph taken at Cow Tank in the Canelo Hills. Note the large volcanic clast (probably dacite) at the top of the hammer.
occur either in small pockets or in laterally continuous horizons up to 1 m thick. The nodules typically range from 5 mm to 5 cm in diameter.

The sandstone occurs as both laterally continuous beds and as lenses 1 to 35 m thick and is composed of very fine- to coarse-grained lithic sandstone that is moderately to poorly sorted and has a silty mud matrix (Fig. 10). In the Gardner Canyon Formation, most of the sandstone is bimodal, with grain populations of both fine and medium sand. Many lenses of fine- to medium-grained sandstone are thinly laminated and locally include cross-laminations 1 to 3 cm in scale. Fining-upward cycles are typically 1-3 m thick and are locally stacked to create sandstone packages up to 50 m thick. Mud chips are common (Fig. 11). On a larger scale, fining-upward cycles from sandstone to mudstone are repeated throughout each section in all four study sites, with the mudstone and siltstone becoming more abundant toward the top of each section (Fig. 7).

Lenses of conglomerate 1-6 m thick consist of rounded to well-rounded pebbles and cobbles set in a muddy siltstone to silty sandstone matrix. Though not matrix-supported, the conglomerates are matrix-rich. They are massive, showing no imbrication, and occur as lenses either at the base of or interbedded with sandstone beds.

Measured Sections

Three stratigraphic sections were measured in the upper member of the Gardner Canyon Formation: two in the central part of the range in Sawmill Canyon (Fig. 4) and one at Fig Tree Springs, 15 km north of Sawmill Canyon on the east flank of the range (T18S, R16E, E1/2 sec.19), (Drewes, 1971a, 1971b; Finnell, 1970a, 1970b). In the Canelo Hills, one section was measured in the Monkey Canyon redbeds at Cow Tank (Fig. 5).
Figure 10. Thinly laminated crossbedded sandstone of the upper member of the Gardner Canyon Formation, Sawmill Canyon.
Figure 11. Sandy pebble conglomerate with mud chips near the base, grading to a very coarse sandstone near the top, located in the Monkey Canyon redbeds, Cow Tank, Canelo Hills. Lower left foreground is the top of a layer of mudstone. 1.5-meter stick for scale.
Drewes (1971) recognized two units in the Gardner Canyon Formation: a lower member composed of coarse-grained siltstone, and an upper member composed of mudstone, siltstone, arkosic to lithic sandstone, and volcanic conglomerate.

It was not possible at any of the localities to measure a complete section from Paleozoic limestone at the base to mid-Mesozoic volcanics at the top. At Cow Tank the upper part of the section could be measured to the contact with the overlying volcanics, but several faults occur near the middle of the section. The continuous representative section from Cow Tank (Fig. 7) was taken from stratigraphically below the faults. It is uncertain where the measured sections at Sawmill Canyon and Fig Tree Springs lie stratigraphically within the Gardner Canyon Formation.

Each measured section shows repetitive fining-upward sequences from conglomerate to mudstone (Fig. 7). A layer of white volcanic ash 1 m thick is found in the measured sections at Cow Tank (Fig. 12a) and Fig Tree Springs. A similar white ash layer is exposed in an area adjacent to Fish Creek in the Santa Rita Mountains (Fig. 12b). These ash layers are petrographically similar.

**Depositional Environment**

The depositional environment of the redbeds in both ranges is interpreted as a meandering fluvial system developed in close proximity to local volcanic sources, probably in distal fan and floodplain environments (Kluth, 1982; Nilsen, 1982; Drewes, 1971c). The mudstone and siltstone, and fine sandstone sequences represent overbank deposits and crevasse splays, whereas the medium- to coarse-grained sandstone and conglomerate units represent channel fill and basal lag deposits (Miall,
Figure 12. (a) Volcanic ash layers found in the Monkey Canyon redbeds at Cow Tank in the Canelo Hills (upper) and (b) in the Gardner Canyon Formation at Sawmill Canyon in the Santa Rita Mountains (lower).
1978, 1981). The thicker sequences of mudstone and siltstone, particularly those with calcareous nodules present, probably represent sediments deposited in shallow lakes or ponded streams.

**Quartz Sandstone**

Quartz sandstone from the Mustang Mountains and Canelo Hills was studied lithologically and petrographically. Everywhere it is exposed as plane-laminated beds of orange color (Fig. 13 and 14). Kluth (1982) estimated the maximum thickness of the Dark Canyon sandstone at 85 to 100 m. In the Mustang Mountains it is approximately 50 m thick (calculated from map by Hayes and Raup 1968).

**Santa Rita Mountains**

One sample of quartz sandstone from the upper member of the Mount Wrightson Formation in the Santa Rita Mountains (number 1, Santa Rita Mountains, Table 2) was collected for petrographic comparison with the Canelo Hills and Mustang Mountains sandstone. The sandstone in the Mount Wrightson formation occurs in lenses up to 245 m thick and locally displays large sweeping crossbeds.

**Mustang Mountains**

The sandstone in the Mustang Mountains lies unconformably between Paleozoic limestone and the Mustang Mountains volcanics and is locally interbedded with the volcanics (Fig. 6) (Hayes and Raup, 1968). In a few places the sandstone lies on top of redbeds similar in outcrop appearance to the Gardner Canyon Formation and Monkey Canyon redbeds.

The sandstone is commonly bimodal, composed of fine and medium sand grains with local horizons of very fine sand. The grains are subangular to subrounded, moderately well compacted, and mostly cemented by silica.
Figure 13. Thinly laminated and cross-bedded quartz sandstone in the Mustang Mountains.
Figure 14. Example of thinly laminated bedding in the Dark Canyon sandstone in the Canelo Hills.
A minor amount of mica-rich matrix (probably sericite or illite) occurs between many grains. The rocks are thinly laminated and horizontally bedded with local planar-tabular crossbeds up to 20 cm thick (Fig. 13). In one locality, small longitudinal ripples with both wavelength and amplitude approximately 0.5 cm are exposed (Fig. 15). At every locality the rock grades from quartzite, near the contact with the overlying volcanics, to well-compacted sandstone downsection. A 1 to 3 m thick conglomeratic horizon of subrounded to rounded pebbles and cobbles of pink, tan, and gray quartzite clasts and gray fossiliferous limestone clasts occurs near the top of the section at one exposure in the southern end of the Mustang Mountains (Fig. 6).

Sandstone samples were collected from six locations along the east flank of the western Mustang mountains (Fig. 6).

_Canelo Hills_

Outcrops of the Dark Canyon member sandstone of the Mt. Hughes formation in the Canelo Hills are mapped as either fault-bounded slivers surrounded by the younger Canelo Ridge member volcanics, stringers interbedded with the Canelo Ridge member volcanics, or lenses resting unconformably on Paleozoic limestone or conformably on top of Monkey Canyon member redbeds (Kluth, 1982).

Though less well compacted, the sandstone is similar to the Mustang Mountains sandstone. The sandstone is composed of subangular to rounded fine-grained clasts set in a minor amount of sericite- or illite-rich matrix. Silica cement is virtually absent. Some strata are bimodal, with fine and medium sand grains. The sandstone is thinly and horizontally laminated with local planar-tabular crossbeds up to 20 cm thick (Fig. 14).
Figure 15. Small longitudinal ripples in the Dark Canyon sandstone in the Mustang Mountains.
Sandstone samples were collected from two sites: Tufa Hill and a major exposure 1 km north of Tufa Hill (T20S, R16E, Sec.3) (Fig. 5).

**Depositional Environment**

The depositional environment of the sandstone is uncertain. The predominance of horizontal stratification rather than large-scale, high-angle cross-bedding indicative of eolian dunes suggests that the sand was probably deposited by fluvial rather than eolian processes. However, the well-sorted and rounded grains common in the sandstone suggest that eolian processes may have affected the sands. Eolian processes probably transported the sand into the area and left some primarily eolian deposits. Most of the sand was then reworked by fluvial processes.

**Petrography**

Detrital modes of sandstones from both the redbed and the quartz sandstone sequences were determined to compare their respective provenances. Redbed sandstone samples were collected from two sites in the Gardner Canyon Formation and two sites in the Monkey Canyon member. Quartz sandstone samples were collected from one site in the Mount Wrightson Formation, two sites in the sedimentary rocks of the Mustang Mountains, and two sites in the Dark Canyon member.

Detrital modes were determined by point-counting a minimum of 400 grains in each sample. Thin sections were stained for both potassium and calcium feldspars. Detrital modes of framework grains were calculated and plotted on ternary diagrams according to the methods described by Dickinson (1970, 1985), Dickinson and Suczek (1979, and Dickinson and others (1979, 1983) (Fig. 16). Percentages of all framework grains for each sample and means and standard deviations for
Figure 16. Ternary diagrams comparing detrital modes of (1) Gardner Canyon Formation and Monkey Canyon member redbeds, and (2) upper member Mount Wrightson Formation, Dark Canyon member, and Mustang Mountains quartz sandstones. Classification of framework grains is described in Table 1. Diagrams indicating provenance from Dickinson and others (1983).
PROVENANCE CATEGORIES

- CRATON INTERIOR
- TRANSITIONAL CONTINENTAL
- BASEMENT UPLIFT
- DISSECTED ARC
- TRANSITIONAL ARC
- UNDISSECTED ARC

QUARTZOSE
- RECYCLED
- MIXED
- TRANSITIONAL RECYCLED
- LITHIC RECYCLED

F ~------------------------------------------------~Lt

redbeds
- Gardner Canyon Fm.
- Monkey Canyon mbr.

quartz sandstone
- Dark Canyon mbr.
- Mustang Mtn.
- Mount Wrightson
each area are listed in Table 1 for the redbeds and in Table 2 for the quartz sandstones. Categories for grouping framework grains of quartz (Qt), feldspar (F), and lithic fragments (Lt) are listed in Table 1.

Redbeds

Both the Monkey Canyon and Gardner Canyon Formation redbeds are composed primarily of lithic fragments (mean Lt = 51 percent), with lesser amounts of feldspar and monocrystalline quartz. Total lithic fragments (Lt) represent a slightly higher amount (55 percent) of total framework grains in the Monkey Canyon redbeds than in the Gardner Canyon Formation (45 percent) (Table 1). Polycrystalline quartz grains (Qp) account for approximately 20 percent of the Lt population in each unit and 11 percent of the total framework grain population.

Volcanic lithic fragments (Lv) range from 63 to 100 percent of lithic fragments (L), excluding polycrystalline quartz, in both units, and they average 86 percent. Sedimentary rock fragments (Ls) are more abundant in the Gardner Canyon Formation redbeds than in the Monkey Canyon redbeds, but represent only a minor part (mean of 6 percent) of the total lithic fragment content.

The volcanic lithic fragments are felsitic to microlitic and hold a plagioclase stain. Many grains display felty fabrics of lath-shaped microlites (probably plagioclase) in a cryptocrystalline groundmass. Grains with hyalopilitic textures, where relict glass (recrystallized as silica) occur interstitially between the feldspar microlites, are present in a few samples. Other rock fragments have phenocrysts of quartz and feldspar randomly oriented in a microcrystalline groundmass of the same. All of these textures and compositions suggest that the volcanic lithic fragments are derived from both siliceous volcanics,
Table 1. Percentages of sandstone framework grains for all redbed samples plotted on ternary diagrams in Figure 16. Mean percentages and standard deviation are given for each area and for the total facies.

Classification of sandstone grains:

\[ \text{Qt} = \text{Qm} + \text{Qp} \]
\[ \text{Qt} = \text{total quartzose grains} \]
\[ \text{Qm} = \text{monocrystalline quartz} \]
\[ \text{Qp} = \text{polycrystalline quartz, including chert (Ch)} \]

\[ \text{F} = \text{P} + \text{K} \]
\[ \text{F} = \text{total feldspar grains} \]
\[ \text{P} = \text{plagioclase feldspar} \]
\[ \text{K} = \text{potassium feldspar} \]

\[ \text{Lt} = \text{L} + \text{Qp} \]
\[ \text{Lt} = \text{total aphanitic lithic fragments} \]
\[ \text{L} = \text{Lv} + \text{Ls} \]
\[ \text{Lv} = \text{volcanic lithic fragments} \]
\[ \text{Ls} = \text{sedimentary and metasedimentary lithic fragments} \]
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Table 2. Percentages of sandstone framework grains for all quartz sandstone samples plotted on ternary diagrams in Figure 16. Classification of framework grains is listed in Table 1.
## Quartz Sandstones

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<th>Qp</th>
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such as rhyolites and dacites, and intermediate volcanics, typically of an andesitic nature.

Most of the sedimentary rock fragments are rounded grains of argillite or siltstone, commonly heavily stained with hematite. Metamorphic fragments of quartz-sericite schist, microgranular quartz aggregates, and some foliated grains are present but rare.

Feldspar grains (F) are more abundant in the Gardner Canyon Formation (mean = 40 percent) than in the Monkey Canyon redbeds (mean = 25 percent), and for both units they average 30 percent of all framework grains (Table 1). Potassium feldspar accounts for only 2 percent of total framework grains in only one sample. In many samples the plagioclase grains are in various stages of replacement by calcite or show plagioclase overgrowths. Albite twinning is abundant, and myrmekite is locally common.

Monocrystalline quartz (Qm) occurs in subequal amounts in both rocks, averaging 18 percent of all framework grains (Table 1). It is also twice as common as polycrystalline quartz in both units, averaging 63 percent of total quartz grains (Qt). Silica overgrowths are common in several samples from both units. The monocrystalline quartz is interpreted as volcanic, based on the presence of straight extinction, euhedral to subhedral crystal form, embayed edges, and a general lack of inclusions (Pettijohn and others, 1972; Dickinson and Rich, 1972; Folk, 1980). Chert (Ch) is present in most samples and averages 7 percent of all framework grains (Table 1). Chalcedony occurring as radiating, fibrous grains is locally present in half of the samples.

Individual samples in both units show a wide variation in the ratio of Qt:L with a mean ratio of 29:41 (Table 1). However, there is no
correlation between stratigraphic position and Qt:L ratio.

The matrix in both units is commonly composed of muddy quartz siltstone rich in a micaceous mineral, probably sericite, and averages 10 percent of all points counted. Calcite cement is common in a few samples from each unit and accounts for 14 percent of one sample where calcite replacement of plagioclase grains is also pervasive. A zeolite mineral, possibly laumontite, is a dominant part of the matrix in one sample from the Monkey Canyon redbeds.

Most of the sandstones from both redbed units plot in the fields indicative of sands derived from a transitional arc environment on the ternary diagrams of Dickinson and others (1983) (Fig. 16). The spread in composition from feldspar-rich to lithic-rich probably reflects progressive winnowing and washing of the sands to cause the less stable lithic fragments to disintegrate. The sandstones show no correlation between provenance, as inferred in the ternary diagrams, and stratigraphic position.

Quartz Sandstone

The Dark Canyon sandstone in the Canelo Hills and the Mustang Mountains and the sandstone in the upper unit of the Mount Wrightson Formation are all composed primarily of monocrystalline quartz, which averages 93 percent of all framework grains. Lithic fragments are the next most common grain type, followed by subequal amounts of plagioclase and potassium feldspar grains.

The samples listed in Table 2 included 6 samples from the above-mentioned units, 2 samples from the Gardner Canyon Formation redbeds (samples 2 and 3, Santa Rita Mountains), and 1 sample from the Monkey Canyon redbeds (sample 4, Canelo Hills). Two of the three samples from
the redbed units have significantly higher percentages of lithic fragments and feldspar grains than do the samples from the quartz sandstone units. One sample in the Santa Rita Mountains (number 3) is from a lens of white quartz-rich sandstone found in the redbeds at Fish Creek (Fig. 4).

In all of the samples the majority of quartz grains are rounded to subrounded and show some degree of undulose extinction, ranging from very slight to 10 degrees. Vacuoles and microlites are locally present. These characteristics suggest a plutonic source for the quartz (Folk, 1980; Pettijohn and others, 1972). However, postdepositional strain is evident in the Mustang Mountains sandstone samples where "healed" deformation cracks are common in the quartz, indicating possible postdepositional extensional deformation followed by compaction. Also, some quartz grains appear to have negative crystals, and others show remnant embayments, both characteristics attributed to volcanic quartz (Pettijohn and others, 1972; Folk, 1980). It is probable that mixing of sand from plutonic and volcanic sources occurred prior to deposition of the quartz sand.

Plagioclase and potassium feldspar occur in subequal amounts in all three units, averaging 3 percent of all framework grains (Table 2). Where plagioclase is interpreted as present, it occurs as fine to very fine highly altered grains. Potassium feldspar grains are fine to very fine, subangular, heavily fractured, and abraded fragments.

Lithic fragments average 11 percent of total framework grains for all samples and range from 0.6 to 17 percent of the total grain population in individual samples (Table 2). Subequal amounts of volcanic and sedimentary fragments are present. The lithic fragments are texturally identical to the lithic fragments of silicic volcanics.
found in the sandstones in the redbed formations. The significantly higher percentage of lithic fragments in samples 2 and 4 mentioned above probably reflects their location interbedded with lithic-rich redbed sandstones in each area.

The sandstone in the upper member of the Mount Wrightson Formation (Table 2, Santa Rita Mountains, sample 1) is similar in nearly all respects to both the Mustang Mountains and Dark Canyon sandstones. It is composed of 96 percent monocrystalline quartz, 3 percent potassium feldspar, and a trace of plagioclase feldspar and volcanic lithic fragments. It is thinly laminated and bimodal, with medium- and fine-grained populations. Most grains exhibit slight undulatory extinction, and grains with negative crystals are locally present.

Samples from all quartz sandstones plot in the upper field of the ternary diagrams (Fig. 16), suggesting a cratonic source for the sandstones. The three samples that plot in the quartzose recycled field of the diagram are the quartz-rich sandstones from the redbed formations. This suggests that mixing probably occurred between the quartz-rich and lithic-rich sandstones in the region. Evidence of this is observed in the field in the Canelo Hills at Tufa Hill, where the Monkey Canyon redbeds grade vertically upward into the Dark Canyon sandstone. Petrographic analysis of three samples in this area, selected progressively upsection from the Monkey Canyon member to the Dark Canyon member, plot in each of the three fields: transitional arc, quartzose recycled, and craton interior, respectively.

Conglomerates

Clast counts of the conglomerate facies in the Gardner Canyon Formation at Fish Creek and in the Monkey Canyon member at Tufa Hill
indicate that porphyritic purple volcanic clasts and microcrystalline tan, pink, and purple volcanic clasts are dominant (Fig. 17). Chert and red mudstone "rip-up" clasts are common. Granitic clasts were not found.

**Age Relationships**

The redbeds and quartz sandstone discussed in this study are interpreted as Middle Triassic to mid-Late Jurassic in age (Hayes and others, 1965; Hayes and Drewes, 1968; Hayes and Raup, 1968; Drewes, 1968, 1971c; Asmerom, 1987). However, the exact ages of the sedimentary rocks remain uncertain. Determining whether the underlying and overlying volcanics in each area are geochronologically correlative may provide the constraints necessary to determine whether the sedimentary rocks from each are the same age.

The Mount Wrightson Formation silicic volcanics, Gardner Canyon Formation dacites, Canelo Ridge member and Canelo Hills Volcanics silicic volcanics, and the silicic volcanics of the Mustang Mountains have been dated isotopically, but uncertainties remain concerning the accuracy of the dates. Radiometric dating in progress by other workers in these areas and other parts of southeastern Arizona may provide the dates necessary to clarify the stratigraphy of the region. Various published and unpublished dates for the volcanics in the areas studied for this report are discussed here.

**Canelo Hills**

Kluth (1982) interpreted the four members of the Mt. Hughes formation as overlying the Canelo Hills Volcanics, which are dated at 169 _+6 Ma (K-Ar) in the northern Hauchuca Mountains and 177 _+8 Ma (K-Ar) in the southern Canelo Hills (Marvin and others, 1978), based on a Rb-Sr date for the Canelo Pass member of 151 _+2 Ma. Vedder (1984)
Figure 17. Tan cobble conglomerate in the Gardner Canyon Formation at Fish Creek, Santa Rita Mountains, showing pink, purple, tan, and gray volcanic clasts set in a silty sandstone matrix.
reinterpreted the upper three units of the Mt. Hughes formation as Glance Conglomerate, based, in part, on the similarity in ages of the Canelo Pass member volcanics and the volcanics interbedded with the Glance Conglomerate in the Huachuca Mountains to the southeast, dated at 147 $^{+6}_{\text{Ma}}$ (K-Ar, biotite) and 149 $^{+11}_{\text{Ma}}$ (Rb-Sr) (Marvin and others, 1978). Paleomagnetic analysis also supports a 150 Ma age for the Canelo Pass member volcanics (Kluth and others, 1982).

Geochemical data indicate that the Canelo Ridge member volcanics are identical to the Canelo Hills Volcanics (Krebs and others, 1986). This evidence and poorly understood stratigraphic relationships suggest that, until the history of the Canelo Ridge member volcanics is better understood, this volcanic package should be treated as a unit separate from the Glance Conglomerate (Fig. 18).

Mustang Mountains

The volcanics in the Mustang Mountains were mapped as Triassic-Jurassic in age by Hayes and Raup (1968). It is still not certain whether they represent Middle or Late Jurassic volcanism. An unpublished Rb-Sr date of 150 $^{+2}_{\text{Ma}}$ obtained by May in 1984 (written comm., 1987) suggests that they represent Late Jurassic volcanism similar to the Canelo Pass member volcanics. Correlation of the volcanics would also infer correlation of the underlying sandstones and redbeds in both ranges (Fig. 18, alternative A). Lithologically, the Mustang Mountains volcanics are also similar to the Canelo Ridge member volcanics. In both ranges they occur as red, pink, purple, gray, and brownish ash flows and welded tuffs.

A second interpretation suggests that the Mustang Moutains volcanics are correlative with the Canelo Hills Volcanics dated at
Figure 18. Correlation models for middle to upper Mesozoic stratigraphic units in the Santa Rita Mountains, Mustang Mountains, and Canelo Hills. Alternative (A) suggests the sediments in the Canelo Hills and Mustang Mountains are correlative if the overlying volcanics in both ranges are approximately 150 Ma. Under this alternative the Gardner Canyon Formation redbeds, which are older, would not be correlative with the Monkey Canyon sediments. Alternative (B) suggests the redbeds in the Canelo Hills and the Mustang Mountains are correlative with the Gardner Canyon Formation redbeds if the overlying volcanics in the Canelo Hills (Canelo Ridge member volcanics and Canelo Hills Volcanics) and in the Mustang Mountains are dated at approximately 165-185 Ma. In both alternatives the Gardner Canyon Formation in the Santa Rita Mountains is shown as syndepositional with or younger than the Mount Wrightson Formation. (Note: the thickness of units is not drawn to scale.)
165-185 Ma. Peter W. Lipman (Personal comm., 1987) suggests that the Mustang Mountains volcanics are distal equivalents of the Canelo Hills Volcanics. Unpublished preliminary paleomagnetic results, obtained by May in 1984, (written comm., 1987) are inconclusive, but similarities with paleomagnetic data obtained for the Canelo Hills Volcanics (May, 1985) and lithologic similarities between these two volcanic packages also suggest that the Mustang Mountains volcanics may be correlative with the Canelo Hills Volcanics (Fig. 18, alternative B). Accurate dating of the Mustang Mountains volcanics and more complete paleomagnetic analysis are needed to resolve this question.

Santa Rita Mountains

Preliminary U-Pb dates for the middle member of the Mount Wrightson indicate it is between 185 and 200 Ma (Asmerom, personal comm., 1987). U-Th-Pb dates also obtained by Asmerom (in progress) confirm that the lower member of the Mount Wrightson Formation is older (210 +3 Ma, U-Pb) than a dacite (200 Ma U-Th-Pb), that is interbedded with the Gardner Canyon redbeds. Previous workers obtained Pb-alpha dates of 220 +30 Ma for the middle member of the Mount Wrightson Formation and 190 +20 Ma for the dacite interbedded with the Gardner Canyon Formation (Drewes, 1968).

The new dates support the idea that all or part of the Gardner Canyon Formation redbeds were deposited in Late Triassic time and are syndepositional with or younger than the Mount Wrightson Formation. However, geologic mapping by Drewes (1971a, 1971b) never shows the Mount Wrightson and Gardner Canyon Formation in either depositional or fault contact with each other; therefore their stratigraphic relationship is uncertain.

The dacite of the Gardner Canyon Formation is everywhere interbedded with the lower member of the formation, and therefore it is
probable that the 200 Ma date for the dacite closely approximates the lower age limit of sediment deposition. However, the upper age limit is presently not constrained, because everywhere the redbeds are either eroded or faulted away at the top.

Discussion and Conclusions

Based on the data presented in this report, both the Mesozoic redbeds in the Santa Rita and Mustang Mountains and the Canelo Hills, and the quartz sandstones in the Canelo Hills and Mustang Mountains are interpreted as lithologically and petrographically correlative. Geochronologic data does not constrain the exact time of deposition of the sediments, but it does suggest that the sediments in all three mountain ranges were deposited between Middle Triassic and mid-Late Jurassic time. Figure 18 suggests possible scenarios for deposition of the redbeds and quartz sandstones.

Canelo Hills and Mustang Mountains

Lithologically and petrographically, the redbeds and quartz sandstone are identical in the two mountain ranges. The stratigraphic sequence of the redbeds and quartz sandstones in the Mustang Mountains and the Canelo Hills is also the same. In both ranges the redbeds lie unconformably on Paleozoic limestone and are conformably or unconformably overlain by the quartz sandstone or felsic volcanics. Where the redbeds are not present, the quartz sandstone lies unconformably on Paleozoic limestone and is everywhere unconformably overlain by felsic volcanics (Hayes and Raup, 1968; Kluth, 1982). In at least two localities in the Canelo Hills, the quartz sandstone is interbedded with the redbeds.
The conformable nature of the Monkey Canyon redbeds and Dark Canyon sandstone suggests one of two modifications to Vedder's 1984 stratigraphic interpretation of the Mt. Hughes Formation and Glance Conglomerate in the Canelo Hills (Fig. 18). One alternative is to include the Monkey Canyon member as the basal unit of the Glance Conglomerate, thus reassigning the entire Mt. Hughes formation to the Glance Conglomerate instead of only the upper three members. This interpretation is inconsistent with what is presently known about the Glance Conglomerate throughout southeastern Arizona. Redbeds of this magnitude are not associated with the Glance Conglomerate in any other locality.

A second interpretation is to consider both the Monkey Canyon redbeds and the Dark Canyon sandstone as distinct from the Glance Conglomerate, thus representing an earlier Mesozoic depositional sequence. This interpretation is supported not only by the fact that the two units are interbedded but also by the interpretation that the Canelo Ridge member volcanics, which overlie the sediments in the Canelo Hills, form a unit distinct from the Glance Conglomerate (Fig. 18, alternative A). The Canelo Ridge member volcanics were not necessarily associated with the same tectonic regime or depositional environment as the Glance Conglomerate. Furthermore, geochemical evidence suggests that the Canelo Ridge member volcanics may be similar to the Canelo Hills Volcanics (Fig. 18, alternative B). The interpretation that the Canelo Ridge member volcanics are a unit distinct from the Glance Conglomerate supports a corresponding separation of the underlying Dark Canyon and Monkey Canyon members from the Glance Conglomerate.

This interpretation does not, however, constrain the exact time of deposition of the sediments. The 150–155 Ma age suggested for the
Canelo Pass member volcanics and the volcanics of the Mustang Mountains is the upper age limit for sediment deposition. The lower limit could be constrained by the age of the Canelo Hills Volcanics, presently dated at 165–185 Ma. However, nowhere are the Canelo Hills Volcanics in depositional contact with the sediments; thus their relationship to the sediments is uncertain. And if the sediments were deposited before the Canelo Hills Volcanics (which is possible if the Canelo Ridge member and Mustang Mountain volcanics are the same age as the Canelo Hills Volcanics), then the lower limit could be any time after the onset of early Mesozoic volcanism. These parameters bracket approximately 90 million years (240 to 150 Ma) during which sedimentation could have taken place in one or several hiatuses in volcanism. The stratigraphic, lithologic, and petrologic similarities suggest that they were probably deposited at the same time.

Given the similarities between the redbeds and sandstone in both mountain ranges, it is recommended that the informal name "sediments of the Mustang Mountains" (Hayes and Raup 1968) be abandoned in favor of the names Monkey Canyon redbeds and Dark Canyon sandstone, as designated by Kluth (1982) for the sediments in the Canelo Hills. The term "member" should also be dropped from the Monkey Canyon and Dark Canyon names, because the Mt. Hughes formation as a four-member unit no longer exists. Using this nomenclature will emphasize the similarity of the two units in view of the broader Mesozoic depositional environments in southeastern Arizona.

Santa Rita Mountains

The Gardner Canyon Formation redbeds are lithologically and petrographically identical to the Monkey Canyon redbeds. They are
stratigraphically similar to the extent that both units lie unconformably on Paleozoic limestones; however, the top of the Gardner Canyon Formation is everywhere either eroded away or faulted off. Thus the upper age limit for the formation of this unit is still unknown, but the lower limit is Late Triassic based on the 200 Ma date for the Gardner Canyon Formation dacite. The lower member of the Mount Wrightson Formation volcanics is dated at 210 ±3 Ma and the middle member between 185 and 200 Ma; therefore, the Gardner Canyon Formation was deposited syndepositionally with and possibly later than these volcanics.

These age constraints overlap with the possible ages of the Monkey Canyon redbeds as discussed above. Thus the Gardner Canyon Formation and Monkey Canyon redbeds could be geochronologically correlative, both having been deposited as early as approximately 200 Ma ago and continuing intermittently with the volcanism through the mid-Late Jurassic (Fig. 18, alternative B). Accurate dating of all the volcanics will help determine the most probable scenario for geochronologic correlation.
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One of the author's field vehicles after its "death" in the Canelo Hills. The Santa Rita Mountains are in the background.