Petrology and Tectonic Setting of the Livingston Hills Formation, Yuma County, Arizona

by

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Abstract

The Livingston Hills Formation is part of an undated 6-km-thick Mesozoic sedimentary terrane exposed over a 16,000 km^2 area of southeastern California (McCoy Mountains Formation) and southwestern Arizona (Livingston Hills Formation and continental red-bed deposits). The terrane is very different from the well-known Mesozoic sedimentary rocks of the Colorado Plateau and has never been included in a regional tectonic synthesis of southwestern North America.

Exposed in both the southern Plomosa Mountains (2,000 m thick) and the Livingston Hills (3,600 m thick), the Livingston Hills Formation consists of conglomerate, sandstone, and siltstone. It was deposited in subaerial and shallow-water environments as a series of debris-flow, tidal-flat, and lacustrine sediments. In the Livingston Hills conglomerate clast lithology changes abruptly from supracrustal to igneous. Sediment-transport directions obtained from the Plomosa Mountains exposure of the Livingston Hills Formation are northeast and west-southwest. Twenty-two petrographic point counts from the two sections of Livingston Hills Formation suggest nonidentical, mixed plutonic-volcanic provenances.

The Livingston Hills Formation is part of a stratigraphically correlative depositional terrane exposed in the Livingston Hills and Plomosa and Dome Rock Mountains, Arizona, and the Palen, McCoy, and Mule Mountains, California. The sedimentary terrane is in depositional contact above Paleozoic carbonate rocks and probably Jurassic volcanic rocks. It is regionally deformed and locally highly metamorphosed and is intruded by undeformed latest Cretaceous plutons. Preliminary fossil evidence suggested that the terrane was Cretaceous or Paleocene. A preliminary paleomagnetic pole obtained from sites near the base of the McCoy Mountains Formation is at 64°N., 103°E. (D=344°, I=24°, α_{95}=5.2°), if no correction for structural tilting is made. This pole lies very near the pole from the Upper Jurassic Summerville Formation on the Colorado Plateau. If a structural correction is made, the result yields a pole at 23°N., 194°E., near no part of the known polar wander path for North America. Therefore the data suggest that the age of tilting and metamorphism of the McCoy Mountains Formation may be no younger than Late Jurassic and that the protolith is older. Besides placing an age constraint on the McCoy Mountains Formation, and by stratigraphic extension, on the entire Mesozoic sedimentary terrane, the paleomagnetic evidence implies that the terrane was part of cratonic North America by Late Jurassic time and that much of the metamorphism and deformation in southwestern Arizona and southeastern California may be Jurassic.

Introduction

Throughout southwestern and south-central Arizona and southeastern California, there are extremely thick sequences of Mesozoic sedimentary and volcanic rocks exposed in isolated mountain ranges. These rocks are found stratigraphically above Paleozoic rocks and below mid-Tertiary volcanic rocks. Sparse fossil and radiometric evidence from California and Arizona suggests that the age could range from Permian through Paleocene. The sedimentary rocks, being monotonous in lithology, unfossiliferous, and exceedingly thick, are very different from the classic Mesozoic sequence exposed on the Colorado Plateau. Lithologies include conglomerate, sandstone, siltstone, and minor carbonaceous limestone and pyroclastic and volcanic rocks. Thick-

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nesses range from several hundred meters to 6 km. All sequences show effects of metamorphism, varying from minor mineralogic changes in matrix to complete recrystallization into high-grade gneisses. Perhaps most indicative of the enigmatic nature of these sedimentary rocks is the fact that they have not been included in any paleotectonic reconstructions of the Mesozoic in southwestern North America.

In an attempt to answer questions about the age, depositional environment, and tectonic setting of these Mesozoic sedimentary rocks, the Livingston Hills Formation, which is exposed in the Plomosa Mountains and Livingston Hills, Yuma County, Arizona, was chosen for detailed study (Fig. 1).

Geologic Setting of the Livingston Hills Formation

The Livingston Hills Formation is exposed in highly complex structural relationships with a variety of rocks. These rocks include fossiliferous Paleozoic rocks, probably Jurassic metavolcanic rocks, other Mesozoic sedimentary rocks, Tertiary volcanic rocks, and plutonic rocks of unknown age. Low-angle faults are common, as are other types of faults. Many rock sequences are completely fault bounded. The following discussion of the geologic setting of the Livingston Hills Formation is largely based on the geologic map of the Quartzsite quadrangle by Miller (1970) and reconnaissance mapping and observations by the author.

Three separate sections of fossiliferous Paleozoic sedimentary rocks are exposed in the Plomosa Mountains. All are cratonic sequences of mixed southeastern Arizona–Grand Canyon affinity. Formations present include the Bolsa Quartzite, the Abrigo and Martin Formations, the Escabrosa Limestone, the Supai Group, the Coconino Sandstone, and the Kaibab Formation. Thickness of the Paleozoic section totals 857 m. Paleozoic rocks are in depositional contact with 1.7-b.y.-old quartz monzonite. In addition to the more complete sections, low-angle, fault-bounded "slices" of metamorphosed Paleozoic sedimentary rocks are exposed throughout the southern Plomosa Mountains. The Plomosa Mountains section of the Livingston Hills formation is in depositional contact with one of these "slices."

Thick (3,300 m) volcanic and volcaniclastic sequences are exposed in the western Plomosa Mountains. The volcanic sequences consist of flows, tuffs, and agglomerates ranging from basaltic to rhyolitic. They are homoclinally dipping, penetratively foliated, and locally metamorphosed. Miller (1966, 1970) assigned a Jurassic or Precambrian age to the thick metavolcanic sequences of the western Plomosa Mountains. The possibly

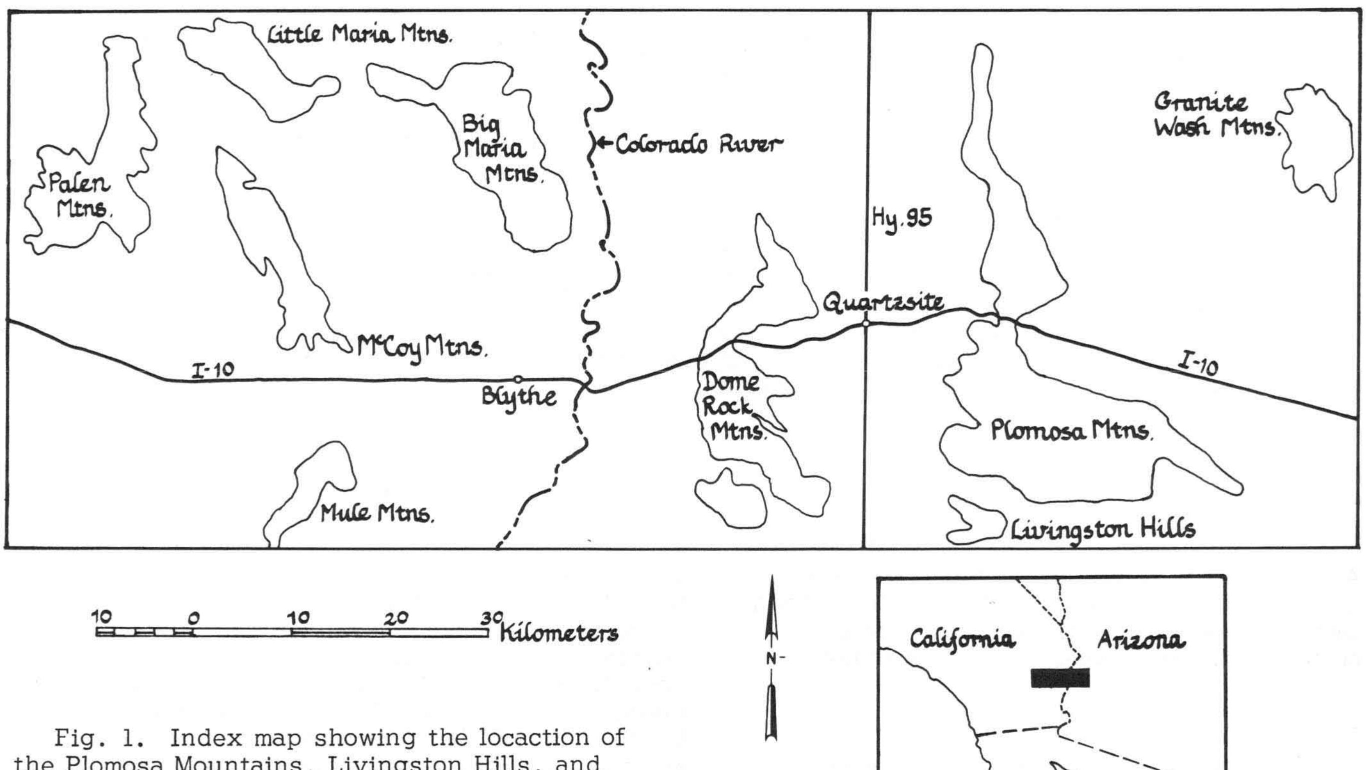

Fig. 1. Index map showing the locaction of the Plomosa Mountains, Livingston Hills, and other places mentioned in the text

Precambrian age assignment was based on lithologic similarity of the metavolcanic rocks with the Yavapai Series of known Precambrian age exposed south of the Mogollon Rim. A Jurassic age was based on lithologic similarity to rocks exposed in the Dome Rock Mountains 16 km to the west dated by Leon T. Silver (cited in Miller, 1970). Due to the proximity, thickness, and lithologic similarity between the sections in the Dome Rock Mountains and the western Plomosa Mountains a correlation between the sections should be considered. An additional age complication may be indicated by a metavolcaniclastic boulder found bearing a Permian sponge, *Actinocoelia*, in the Copper Bottom Pass area of the central Dome Rock Mountains. Although the significance of the find is still uncertain, Precambrian, Permian, and Jurassic ages can be considered for the volcanic sequences.

Exposed in the southernmost Plomosa Mountains in fault-bounded blocks and isolated hills is a sequence of interbedded maroon siltstone, quartzite, sandstone, and conglomerate that Miller (1970) called continental red-bed deposits. Structural complications have made it difficult to establish the stratigraphic sequence and thickness of this unit, but it is at least 305 m thick. In the western Plomosa Mountains the continental red-bed deposits rest on a quartz porphyry. As will be discussed later, the continental red-bed deposits are probably stratigraphically equivalent to the Livingston Hills Formation (Harding, 1978; Robison, 1979, this volume).

A quartz porphyry unit crops out in several places in the central Plomosa Mountains. It locally intrudes Paleozoic carbonate rocks and is interstratified with the overlying Livingston Hills Formation. Lithologically similar quartz porphyry is exposed in the western Plomosa Mountains with continental red-bed deposits interbedded with it and resting above it. At least three separate undated quartz monzonite intrusions are mapped in the southern Plomosa Mountains. They have been assigned a Mesozoic or early Tertiary age because they intrude Paleozoic carbonates.

The Livingston Hills Formation, as exposed in the central Plomosa Mountains, is a homoclinal sequence 2,000 m thick deposited on Paleozoic carbonate rocks and the intrusive–extrusive quartz porphyry unit. The top of the sequence is truncated by a low-angle fault. In the Livingston Hills, the Livingston Hills Formation is in high-angle fault contact at its base with continental red-bed deposits. The top of the sequence is not exposed. The Livingston Hills section is 3,600 m thick and dips homoclinally. Subhorizontal rhyolites and andesites capped in some places by basalts make up the section of mid-Tertiary volcanic rocks that overlies the Livingston Hills Formation with pronounced angular unconformity in the Plomosa Mountains and Livingston Hills (Miller and McKee, 1971).

The Livingston Hills Formation

The most complete exposures of the Livingstone Hills Formation are in the south-central Plomosa Mountains and in the Livingston Hills (Fig. 1). In both places the Livingston Hills Formation consists of conglomerate, sandstone, and siltstone. The superficial lithologic similarity of these exposures led Miller (1966) to suggest that they were correlative, although they differ in thickness, petrology, outcrop characteristics, and contact relationships. Data from the two exposures are presented separately in the following sections.

Livingston Hills Section

The thickest section of the Livingston Hills Formation is exposed in the Livingston Hills as a 3,600-m-thick homoclinal sequence dipping 30°–45° S. The base of the sequence is in high-angle fault contact with continental red-bed deposits. The upper contact is nowhere exposed. Volcanic rocks of mid-Tertiary age overlie parts of the section with pronounced angular unconformity. Although not conclusive, rare facing indicators (channels and ripple marks) imply that the entire section is right side up.

Conglomerate interbedded with sandstone forms the lowermost third of the Livingston Hills section of the Livingston Hills Formation. Thickness of the conglomerate is about 1,375 m. The lower 730 m of the section is typically a light blue gray, poorly sorted feldspathic (terminology from Crook, 1960) matrix-supported conglomerate interbedded with fine- to coarse-grained, poorly sorted feldspathic sandstone (5% of the section) showing a well-developed near-horizontal cleavage of unknown significance. In the upper 645 m of the section the conglomerate contains more matrix (as much as 80% locally), is medium gray, and shows only local cleavage development. It contains interbeds of feldspathic sandstone, pyroclastic sandstone, and rare tuff. Beds in the conglomerate range from 10 cm to 10 m thick and are continuous along strike for at least 1 km. All strata vary slightly in thickness along strike, suggesting wedge-shaped depositional units. Clasts in the conglomerate are subangular to subrounded and are up to 1 mm in diameter. All conglomerate beds are heterogeneous, containing clasts of many different lithologies. In the basal beds of the conglomerate member chips of maroon siltstone are found that are lithologically similar to the maroon siltstone in Miller's continental red-bed deposits.

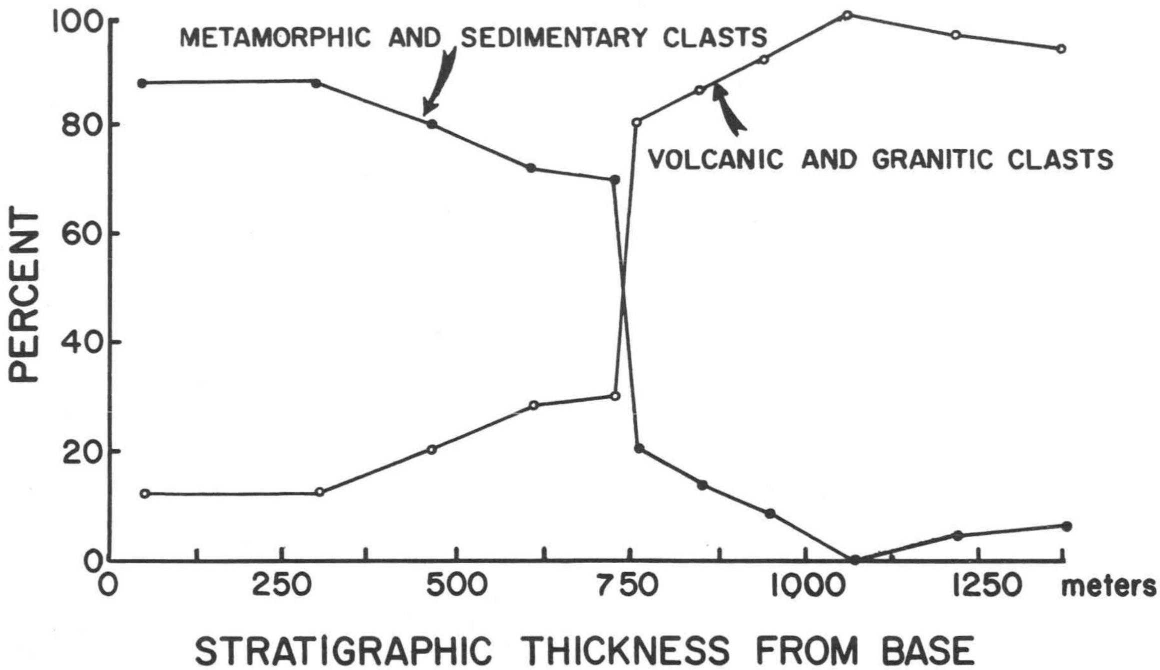

Fig. 2. Change in clast lithology, conglomerate member, Livingston Hills

An analysis of clast lithologies in the conglomerate exposed in the type section in the Livingston Hills (Fig. 2) shows that in the lower 730 m of the section quartzite and carbonate clasts predominate, although a minor igneous component (usually granitic) is always present. In this part of the section the largest clasts are granitic boulders up to 1 m in diameter. At 730 m above the base of the section, clast lithology suddenly changes. Volcanic and granitic clasts (roughly half and half) become the dominant clast lithologies with a minor but stable quartzite component remaining. Size of clasts slowly diminishes upward through this part of the section from about 35 cm in diameter down to a few centimeters. Beds of matrix-supported conglomerate occur throughout the Livingston Hills Formation but are concentrated in the lower third of the section. The thickness of these beds is generally less than 1 m.

The conglomerate is overlain by 915 m of sandstone, which forms the middle third of the Livingston Hills Formation. Outcrops vary from massive (no visible bedding) to thinly bedded. All outcrops are heavily coated with desert varnish and commonly show a shallow-dipping cleavage. The sandstone is heavily fractured and sheared. Fractures and shears are generally nearly vertical. Where marker beds are available, displacement along shear zones is less than 2 m.

The sandstone interval consists of extremely monotonous, medium- to dark-gray, fine- to coarse-grained feldspathic sandstone. Interbeds less than 30 cm thick of multicolored siltstone and carbonaceous recrystallized limestone make up a small proportion of the section. Beds of matrix-supported conglomerate 10 to 30 cm thick are more common. Clasts in the conglomerate are granitic, silicic volcanic, and quartzite and are commonly well rounded. Bedding thickness in the sandstone ranges from 10 cm to 10 m and is both massive and graded.

Siliceous siltstone makes up the upper third of the Livingston Hills Formation and is beautifully exposed in the highest peaks of the southern Livingston Hills. Total thickness is about 1,285 m. Locally, feldspathic and pyroclastic sandstone constitutes between 10 and 50 percent of the siltstone. Near the top of the siltstone interval, the section contains roughly equal amounts of sandstone and siltstone. The sandy siltstone section contains numerous shear zones, variable south-dipping cleavage, and very poorly exposed bedding.

The siltstone is medium to light gray, siliceous, and quite resistant in outcrop. Interlamination of silt and sand on a very fine scale is common, as are massive beds of pure silt. Beds range from 2 cm to 8 m in thickness. Bedding-plane surfaces are commonly covered with slightly asymmetric transverse ripples. Fossil branchiopods found in a less resistant siltstone horizon about 7 m thick were too poorly preserved for identification of genus or age but possibly indicate a lacustrine environment (N. J. Silberling, written comm., 1978). Paleocurrent directions measured at 82 different outcrop localities on transverse ripple orientations within the siltstone section in the Livingstone Hills (Fig. 3) show a maximum current direction to the south (55% of data) and a submaximum direction to the north with almost no data indicating east- or west-directed currents. Thus, dominant direction of sediment transport was to the south.

Plomosa Mountains Section

The Plomosa Mountains section of the Livingston Hills formation is exposed in a 15-km^2 area around Apache Wash in the south-central Plomosa Mountains and in a restricted area in the southern Plomosa Mountains. Conglomerate similar to conglomerate from the Plomosa Mountains section is exposed in low hills near Crystal Hill in the southernmost Plomosa Mountains. Siltstone similar to siltstone from the Plomosa Mountains section crops out in the west-central Plomosa Mountains. Isolated patches of conglomerate and siltstone from the Livingston Hills Formation have been mapped throughout the Quartzsite quadrangle (Miller, 1970), but lithologies vary from one outcrop to the next. Some outcrops have an affinity with the Livingston Hills section, some with the Plomosa Mountains section, and others look quite different from either section.

In the Apache Wash region of the Plomosa Mountains the Livingston Hills Formation is exposed as a generally east-dipping, locally overturned, homoclinal sequence that rests on cliff-forming Paleozoic marbles. The top of the section is truncated by low-angle faults. The overturned part of the sequence can be traced both up and down section into the right-side-up beds. Facing indicators—ripple marks, flute casts, and cross-bedding—indicate that the section is otherwise right side up.

Exposed along the basal contact of the Livingston Hills Formation in the Plomosa Mountains is a unit that Miller (1970) called both an intrusive and extrusive quartz porphyry. The quartz porphyry was mapped by Miller as intruding the basal contact of the Livingston Hills Formation. Further mapping by the author confirmed that the quartz porphyry is in intrusive and extrusive contact with the Paleozoic marbles and that it is interstratified with the lower 10 m of the Livingston Hills Formation. In the western Plomosa Mountains, mapping by the author suggests that the quartz porphyry is overlain by continental red-bed deposits in depositional contact. This relationship with the quartz porphyry, along with

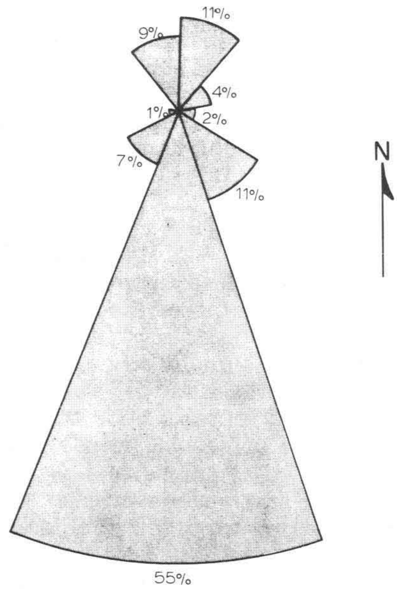

Fig. 3. Paleocurrent directions, siltstone member, Livingston Hills. —Eighty-two points were used.

lithologic similarities between the continental red-bed deposits and the conglomerate of the Livingston Hills Formation exposed in Apache Wash, suggests a possible correlation between the continental red-bed deposits and the conglomerate of the Livingston Hills Formation as exposed in Apache Wash.

Conglomerate forming the basal section of the Livingston Hills Formation exposed in Apache Wash is about 372 m thick. Much of it is overturned and dips 50°-85° W. It is composed of light-pink to orange-red, medium- to coarse-grained, lithofeldspathic, interbedded sandstone and conglomerate. Lithic grains in the conglomerate interval are predominantly of clastic origin. In addition to the interbeds of quartz porphyry exposed in the lower 10 m of the conglomerate, arenaceous carbonate lenses 10-50 m long and 30 cm to 5 m thick are exposed in the same interval. Two types of stromatolites, neither of which is age specific (Miller, 1966), and oncolites suggestive of hot spring origin (N. J. Silberling, written comm., 1978) are plentiful throughout the carbonate lenses. Monolithologic conglomerate horizons of limestone, granite, and quartzite clasts are common. Clast size is generally between 1 and 15 cm in diameter, but granitic clasts are as large as 60 cm in diameter. Groove marks indicating southwest or northeast transport are found in several horizons in sandstone interbeds in the conglomerate. Fine-grained sandstone beds and laminated siltstone beds within the conglomerate contain load casts and evidence of soft sediment deformation. One example of small-scale, fluvial-type cross-bedding indicating sediment transport to the west was also found. Unlike the extremely steep nobby slopes and ridges formed by conglomerate in the Livingston Hills, conglomerate in the Plomosa Mountains is only moderately resistant.

Sandstone makes up 625 m of the Plomosa Mountains section of the Livingston Hills Formation and overlies the conglomeratic interval. In contrast to the conglomerate the sandstone is medium gray, massive, and feldspathic or lithofeldspathic, with bedding only locally exposed and of variable attitude. Shear zones are common with no marker beds available to indicate amount of offset. The section is further complicated by numerous feeder dikes to probably mid-Tertiary basaltic extrusives. Horizons of matrix-supported conglomerate and graded sandstone beds are common. In outcrop, the section looks quite similar to the more massive exposures of sandstone in the Livingston Hills.

In the southern Plomosa Mountains, siltstone of the Livingston Hills Formation is exposed on the east side of Apache Wash. The section is complicated by small-scale folding and faulting and contains rare graded sandstone beds. Bedding thickness ranges from 1 to 6 cm. The siltstone is light to medium gray, intensely fractured, and commonly laminated. Thickness of the section is about 900 m. Silty calcareous oval-shaped concretions as large as 1 m in diameter occur throughout the middle third of the siltstone. Lunate and transverse ripples occur in several localities. Figure 4 shows all current indicator data from the Livingston Hills Formation exposed in Apache Wash. The data suggest currents flowing both to the southwest and northeast as well as considerable variability in direction of flow. Bits of

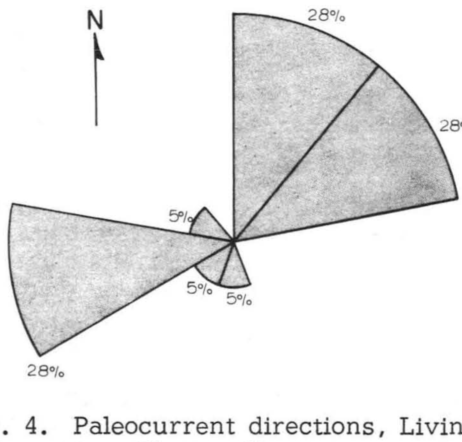

Fig. 4. Paleocurrent directions, Livingston Hills Formation, Plomosa Mountains. — Eighteen data points were used.

angiosperm(?) fossil wood, mostly plant stems, were found in siltstone exposed in Apache Wash. In contrast to siltstone in the Livingston Hills that is siliceous and forms high peaks, siltstone in the Plomosa Mountains is nonresistant and forms low rounded hills.

Depositional Environment of the Livingston Hills Formation

The conglomerate of the Livingston Hills Formation (both exposures) exhibits extreme variation in sorting of clasts and matrix, grain size or matrix, and bedding thickness from bed to bed. Commonly, the conglomerate is matrix supported and clasts are not imbricated or found in preferred orientations. Beds thicken and thin along strike, suggesting wedge-shaped depositional units, and can be continuous in outcrop over at least 1 km. Bedding in the conglomerate ranges from 10 cm to 10 m in thickness. The feldspathic sandstone interbeds within the conglomerate commonly show graded bedding and are between 1 cm and 1 m thick. The conglomerate exposed in Apache Wash and near Crystal Hill in the Plomosa Mountains is orange red to pink and contains large amounts of iron oxide as interstitial material. The conglomerate exposed in the Livingston Hills is blue gray to gray; calcite and sericite predominate as interstitial material. Limestone lenses containing oncolites and stromatolites and one example of fluvial cross-bedding suggest a shallow-water and subaerial environment for the Plomosa Mountains section conglomerate. In thin section all samples from the conglomerate contain large volumes of secondary micas, which may be alteration products of an originally clay rich matrix.

Criteria diagnostic of alluvial fan deposits described by Bull (1972) and seen in the conglomerate of the Livingston Hills Formation include matrix-supported conglomerate, the oxidized nature of the sedimentary rocks in the Plomosa Mountains section, the variability of thickness, particle size, and sorting between beds, and the presence of clay matrix. This evidence suggests that the conglomerate of the Livingston Hills Formation was deposited as a series of debris flows and mudflows in a subaerial or shallow-water fan-type environment.

Characteristics of subaerial fan deposits found in the sandstone sections of the Livingston Hills Formation include variability of grain size, sorting, and bedding thickness; presence of clasts and mud chips floating in a sand matrix; graded beds; lack of fossils; and continuous bedding over long distances (>1 km). The presence of these characteristics suggests that the sandstones may also have been deposited as a series of mudflows and debris flows. As with the conglomerate, no criteria are available to distinguish between subaerial and shallow-water (lacustrine or marine) deposition.

Tidal-flat environments are characterized by fine-grained sediment deposition, interlamination of sand and silt, both massive and laminated beds, asymmetric oscillation ripples, and bidirectional current indicators (Reineck, 1972). Siltstone of the Livingston Hills Formation from the Livingston Hills contains interlaminated sand and silt, massive sand and silt and laminated silt beds, and slightly asymmetric transverse ripples that indicate bidirectional current flow. Evidence that the siltstone of the Livingston Hills Formation was deposited in a tidal-flat environment includes similarity to characteristics listed by Reineck and the bidirectional current rose pattern diagnostic of tidal-flat environments (Potter and Pettijohn, 1977).

In Apache Wash, siltstone of the Livingston Hills Formation is typified by laminated silt beds, 1-6 cm thick, interbedded with graded sandstone beds less than 4 cm thick. Lunate and transverse ripples occur on bedding-plane surfaces but do not indicated highly preferred directions of sediment transport (Fig. 4). Fossil wood was found at one locality. Siltstone in Apache Wash contains a high percentage of sericitized clays and sericite, indicating an originally clay rich matrix. Environment of deposition could be tidal flat, as for the Livingston Hills section siltstone, or lacustrine, as suggested by the locally graded sandstone interbeds. Although sparsely distributed throughout both Livingston Hills section exposures, all facing indicators (ripples, flute casts, cross-bedding, etc.) suggest that the sequences are right side up.

Petrography of the Livingston Hills Formation

The petrography of the Livingston Hills Formation was studied in detail with the hope that it would provide information about provenance and either confirm or invalidate the correlation between the exposures in the south-central Plomosa Mountains and Livingston Hills.

In Q–F–L plots (e.g., Dickinson, 1970) all quartz is assigned to the Q pole. Monocrystalline quartz from igneous terranes is therefore included with polycrystalline quartz (chert, quartzite, and metaquartzite) from sedimentary and metamorphic terranes. Thus, emphasis is on the textural maturity of the rock rather than on provenance. Because valuable information comes from textural maturity and provenance data, Graham, Ingersoll, and Dickinson (1976) suggested a way to do both. They defined Q as being Qm (monocrystalline quartz) plus Qp (polycrystalline quartz) and Lt as including L (volcanic-metavolcanic fragments, Lv, and sedimentary-metasedimentary fragments, Ls) plus Qp. Then data can be plotted in three ways: a Q–F–L plot emphasizing textural maturity, a Qm–F–Lt plot emphasizing provenance, and a Qp-Lv-Ls plot comparing lithic fragments. A Qm-F-Lt plot is especially useful if the rocks being compared differ in textural maturity but not in source area.

From more than 200 hand samples, 80 of which were thin sectioned, 22 were chosen for analysis of detrital modes. Twelve samples were from the Livingston Hills Formation in the Plomosa Mountains, and 10 were from the Livingston Hills. Three hundred counts were made per slide. Modes counted included monocrystalline quartz, polycrystalline quartz (chert and quartzite differentiated), potassium feldspar, plagioclase feldspar, lithic fragments, interstitial material, and detrital mica. Types of lithic fragments counted included felsitic, microlitic, and lath-work as defined by Dickinson (1970, p. 701), sedimentary-metasedimentary, chert, quartz-foliate metaquartzite, and indeterminate.

Figures 5, 6, and 7 show graphic results of these point counts. Points from the Plomosa Mountains and Livingston Hills are loosely grouped into two large fields. The Q–F–L plot (Fig. 5) shows that the Plomosa Mountains section is more quartz rich than the Livingston Hills section. The Qm–F–Lt plot (Fig. 6) is only slightly different from the Q–F–L plot due to the small amount of polycrystalline quartz in

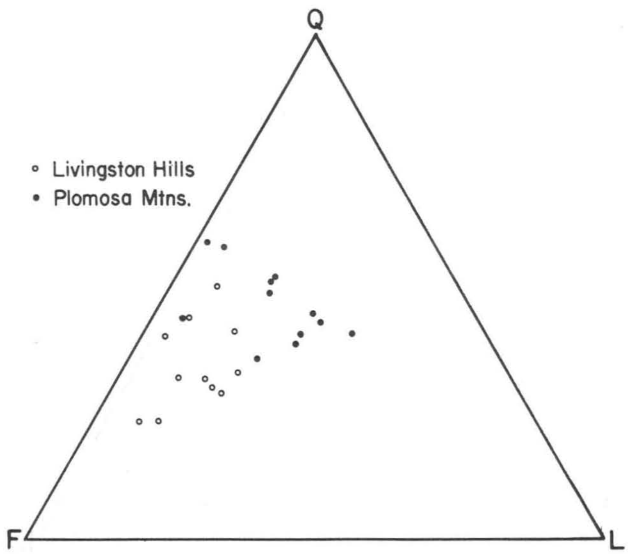

Fig. 5. Q-F-L plot

the samples. A difference in provenance is suggested by the Qp–Lv–Ls plot (Fig. 7), with the Livingston Hills section containing more volcanic lithic fragments than the Plomosa Mountains section.

Results obtained from detrital mode determinations suggest nonidentical mixed plutonic-volcanic provenances for the Plomosa Mountains and Livingston Hills sections of the Livingston Hills Formation. However, the results stop short of implying mutally exclusive provenances for the sections either in time or in space. A mixed volcanic-plutonic source is suggested by conglomerate clast lithologies as well. A complete petrographic analysis, including calculation of parameters helpful in determining provenance, was discussed by Harding (1978).

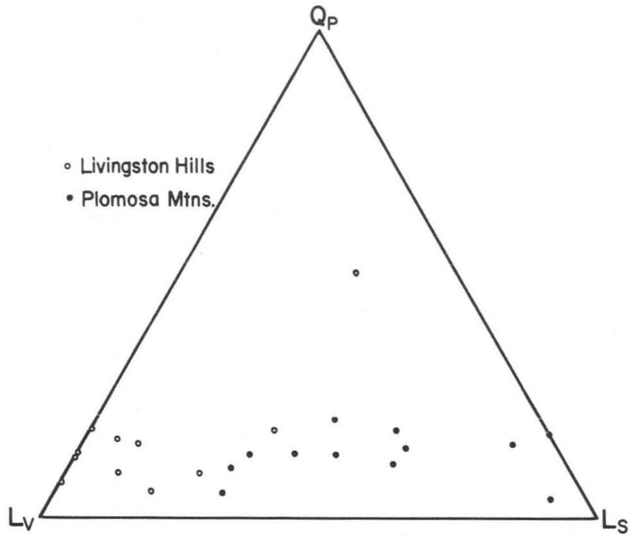

Fig. 7. Q_p-L_v-L_s plot

Stratigraphic Correlation and Age Constraints for the Livingston Hills Formation

The Livingston Hills Formation is part of an undated Mesozoic terrane of unknown tectonic significance exposed in isolated mountain ranges from southeastern California to south-central Arizona over an area of 16,000 km². The terrane contains volcanic, plutonic, and sedimentary rocks of different ages and from different tectonic settings. Lithologically similar to the Livingston Hills Formation are the McCoy Mountains Formation, exposed in the McCoy and Palen Mountains, California, and unnamed sedimentary sequences exposed in the Dome Rock and Granite Wash Mountains, Arizona, and in the Mule and Maria Mountains, California. Mesozoic sedimentary rocks of the Papago Reservation described by Haxel and others (this volume) may be in part equivalent to the Mesozoic sedimentary terrane of southwestern Arizona and southeastern California. Thickness of sequences ranges between 2 and 6 km. Lithologies include quartzites, lithic and feldspathic sandstones, siltstones, conglomerates, ash-fall tuffs, and minor evaporites and carbonaceous limestones. The Mesozoic terrane is in depositional contact with Paleozoic carbonate rocks in the Plomosa and Maria Mountains (Hamilton, 1971) and on probably Jurassic volcanic rocks in the Palen, McCoy, Dome Rock, and Mule Mountains. Upper contacts of the terrane are faulted or covered by Tertiary volcanic rocks and Holocene alluvium. The sedimentary sequences are metamorphosed, varying from minor mineralogic changes in matrix to recrystallization into high-grade gneisses. Sequences are commonly homoclinally exposed and dip south and southeast.

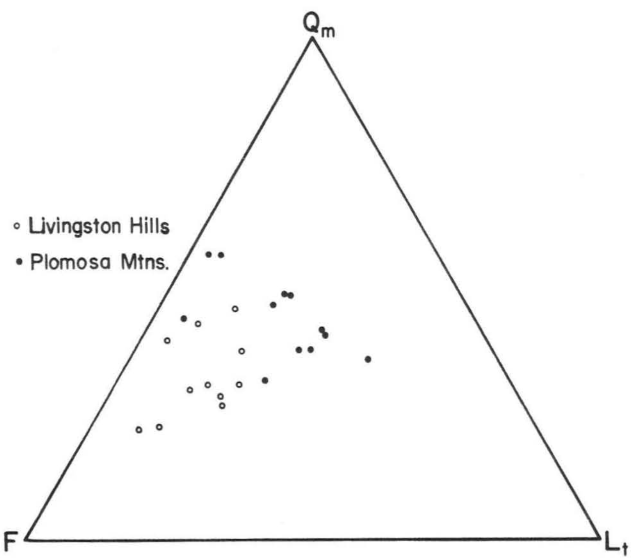

Fig. 6. Q_m-F-L_t plot

The most complete and unbroken Mesozoic clastic sequence yet found is the McCoy Mountains Formation, described by Pelka (1973). The McCoy Mountains Formation is exposed in both the McCoy and Palen Mountains, northwest of Blythe, California, where its thickness exceeds 6 km. At its base the McCoy Mountains Formation is interstratified with a rhyodacite porphyry. The rhyodacite porphyry is lithologically similar to Miller's (1970) quartz porphyry exposed in the Plomosa Mountains. The basal part of the McCoy Mountains Formation consists of purple and green mudstone interbedded with sandstone, quartzite, and rare conglomerate. Lithologies become increasingly feldspathic upsection. Mudstones and sandstones from the basal part of the McCoy Mountains Formation are lithologically similar to

Miller's continental red-bed deposits. Pink-orange, matrix-supported conglomerates similar to conglomerates from the Plomosa Mountains section of the Livingston Hills Formation area also present in the basal part of the McCoy Mountains Formation. The blue-gray feldspathic conglomerates and sandstones from the Livingston Hills section of the Livingston Hills Formation have lithologic counterparts in the upper two-thirds of the McCoy Mountains Formation as well, although their exact stratigraphic position is not known. A sequence stratigraphically similar to that found in the McCoy Mountains Formation, consisting of probably Jurassic volcanic rocks overlain by mudstones and quartz-rich clastics and grading upsection into feldspathic sandstone, is found in the central Dome Rock Mountains (Marshak, 1979). The Dome Rock Mountains are located geographically between the McCoy Mountains and the Plomosa Mountains–Livingston Hills area. It therefore appears that similar, possibly correlative stratigraphics exist continuously from the McCoy Mountains through the Dome Rock Mountains to the Plomosa Mountains–Livingston Hills area.

Data previously presented illustrate the differences in thickness, lithology, outcrop characteristics, and contact relationships between the Plomosa Mountains and Livingston Hills sections of the Livingston Hills Formation. The differences between the two sections admit the possibility that the two sections of Livingston Hills Formation are not correlative (Harding, 1978). Similarity between the sections may be due instead to repeated stratigraphy. In addition, similar basal contact relationships of the continental red-bed deposits and Plomosa Mountains section of the Livingston Hills Formation (both are interstratified at their bases with an intrusive-extrusive quartz porphyry) suggest that they are correlative. Robison (1979; this volume) was able to laterally trace continental red-bed deposits into the Plomosa Mountains section of the Livingston Hills Formation.

The most complete Mesozoic sequence, the McCoy Mountains Formation, may be able to serve as a model for the relative positioning of the incomplete Mesozoic sequences exposed in the Livingston Hills and Plomosa Mountains as the Livingston Hills Formation and continental red-bed deposits. It is suggested that the continental red-bed deposits and the Plomosa Mountains section of the Livingston Hills Formation are correlative with the basal part of the McCoy Mountains Formation; the Livingston Hills section of the Livingston Hills Formation is correlative with the upper part of the McCoy Mountains Formation and is therefore stratigraphically above the Plomosa Mountains section of the Livingston Hills Formation; and the intrusive-extrusive quartz porphyry of the Plomosa Mountains is correlative with the rhyodacite porphyry of the McCoy Mountains.

The rhyodacite porphyry on which the McCoy Mountains Formation is deposited yielded a 176-m.y. (K-Ar, plag.) apparent age in the McCoy Mountains (Pelka, 1973). In the Palen Mountains the McCoy Mountains Formation is intruded by latest Cretaceous plutons (Pelka, 1973). A metasedimentary sequence, which may be correlative with the Livingston Hills Formation and McCoy Mountains Formation, is exposed in the Granite Wash Mountains, Arizona, where it is intruded by undeformed latest Cretaceous plutons (Reynolds, this volume).

Fossil wood tentatively identified as belonging to the angiosperm class and fossil pollen (type unavailable) were found in the McCoy Mountains Formation (Pelka, 1973). Both suggest a Late Cretaceous or younger age for the McCoy Mountains Formation. Fossil pollen collected by the author from the siltstone of the Livingston Hills Formation was identified as Tertiary contamination (R. Tschudy, written comm., 1978). Ostracods and branchiopods as well have been collected from the Livingston Hills Formation, but neither has yet proved to be age specific. Stratigraphy and isotopic dating have constrained this Mesozoic terrane to be younger than the Paleozoic carbonate and probably Jurassic volcanic rocks on which it was deposited and older than the latest Cretaceous plutons that intrude it.

Preliminary paleomagnetic evidence obtained from six sites near the base of the McCoy Mountains Formation in the McCoy Mountains suggests that the Mesozoic terrane is pre-Late Jurassic. Thirty-eight oriented cores drilled from purple-brown mudstones similar to Miller's continental red-bed deposits give a preliminary paleomagnetic pole position at 64°N., 103° E. ($D=344°$, $I=24°$, $\alpha_{95}=5.2°$), if no correction for structural tilting is made. This pole position lies very close to the pole position of the Callovian Summerville Formation on the Colorado Plateau as determined by Steiner (1978). If a structural correction is made, the paleomagnetic pole position moves to 23°N., 194°E., which is near no part of the established polar wander path for North America (Butler and Taylor, 1978). Several factors suggest that the paleomagnetic evidence records a metamorphic and tilting age for the Mesozoic sedimentary terrane:

1. Cores from all sites collected showed normal polarity—no reversed intervals were found.
2. Grouping of pole position for specimens at each site and the grouping for all sites were extremely tight.
3. The magnetic recorder is hematite, which exists as matrix for the mudstones rath-

er than as detrital grains.

4. The sites, if uncorrected for structural tilting, yield a paleomagnetic pole extremely close to a previously determined paleomagnetic pole for the Summerville Formation. Allowing for major errors in dip measurement of the attitude of the McCoy Mountains Formation still does not yield a paleomagnetic pole position near the known polar wander path.

The paleomagnetic data therefore suggest that the age of metamorphism and tilting of the McCoy Mountains Formation is no younger than Late Jurassic and that the protolith is older. Besides placing an important age constraint on the McCoy Mountains Formation and, by stratigraphic and lithologic extension, on the entire Mesozoic sedimentary terrane, the paleomagnetic evidence implies that the terrane was part of cratonic North America by Late Jurassic time and that much of the metamorphism and deformation in southwestern Arizona and southeastern California may be Jurassic.

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