Stratigraphy and Structure of Paleozoic Outer Continental-Margin Rocks in Pilot Knob Valley, North-Central Mojave Desert, California

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By MICHAEL D. CARR, ANITA G. HARRIS,
FORREST G. POOLE, and ROBERT J. FLECK

Stratigraphic interpretation of one of the few exposures of Paleozoic outer continental-margin rocks in the Cordillera of the southwestern United States

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Stratigraphy and Structure of Paleozoic Outer Continental-Margin Rocks in Pilot Knob Valley, North-Central Mojave Desert, California

By Michael D. Carr, Anita G. Harris, Forrest G. Poole, *and* Robert J. Fleck

Abstract

Paleozoic metasedimentary strata, originally deposited along the outer continental margin of western North America, form an enclave of discontinuous, small exposures surrounded by Cenozoic volcanic and sedimentary deposits in Pilot Knob Valley, several kilometers south of the left-lateral Garlock fault in the north-central Mojave Desert. The metasedimentary sequence includes rocks assigned to the Ordovician through the Lower Mississippian on the basis of their conodont faunas and lithofacies. The Ordovician rocks consist of meta-argillite, cherty meta-argillite, and argillaceous metachert, with sparse but conspicuous intervals wholly or partly containing beds of dolomitic and (or) calcitic marble. The Silurian and (or) Lower Devonian rocks consist of turbiditic beds. These turbiditic strata are overlain by meta-argillite and metachert with sparse marble-bearing intervals lithologically similar to the Ordovician rocks, and these are, in turn, overlain by a distinctive Middle Devonian interval of sandy marble and limy quartzite. Greenstone occurring in the northernmost of the Pilot Knob Valley exposures is inferred to be of Late Devonian(?) age. A Lower Mississippian sequence of distinctive argillite-pebble metaconglomerate and meta-argillite rests unconformably on the older rocks and is interpreted as a synorogenic deposit related to the Antler orogeny. The age of a sequence containing the orthoquartzite, orthoquartzite-cobble metaconglomerate, phyllite, argillaceous quartzite, and calcsilicate rocks that crop out in the southernmost of the Pilot Knob Valley exposures remains uncertain. These rocks could be the upper Proterozoic and (or) lower Paleozoic substratum of the outer continental-margin sequence.

The outer continental-margin sequence in Pilot Knob Valley is metamorphosed to upper greenschist and (or) lower amphibolite facies. The rocks are structurally interleaved by tight, westward-vergent folds and faults that are nearly parallel to layering. Postkinematic granodiorite and hornblende diorite plutons intrude the deformed metamorphic rocks. These plutons yield conventional potassium-argon biotite and hornblende ages ranging from 79.4 to 77.5 Ma, indicating a minimum age of Late Cretaceous for the intrusions and for the deformation and metamorphism of the country rock. Although effects of the Late Devonian to Early Mississippian Antler orogeny may be manifested in the stratigraphy of the outer continental-margin rocks of Pilot Knob Valley, there are no demonstrable Antler-age structures in the area. Regional metamorphism and the deformation accompanying it are inferred to be Late Permian in age on the basis of correlation with similarly deformed outer continental-margin metasedimentary rocks in the El Paso Mountains, 50 km to the west and on the north side of the Garlock fault.

The outer continental-margin rocks in Pilot Knob Valley generally correlate with Ordovician through Lower Mississippian outer continental-margin rocks forming the western part of the Garlock assemblage in the El Paso Mountains. The rocks in Pilot Knob Valley are coeval with some Paleozoic units in the Goldstone area, 40 km to the southeast, and a few units known or presumed to be Middle or Late Devonian in age are lithologically similar. However, Ordovician rocks in Pilot Knob Valley represent a deeper water facies than those in the Goldstone area. The Ordovician rocks at Goldstone correlate better with rocks of similar age in the eastern El Paso Mountains, which are interpreted as transitional between outer and inner continental-margin facies.

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INTRODUCTION

Exposures of upper Proterozoic and Paleozoic sedimentary rocks are sparse in the Mojave Desert (fig. 1). Most of the pre-Mesozoic sedimentary terrane in the Mojave Desert was obliterated by intrusion of Mesozoic granitoid rocks of the Cordilleran magmatic arc or is covered by volcanic rocks and nonmarine sedimentary deposits that accumulated during Cenozoic extension of the Basin and Range province. Most of the upper Proterozoic and Paleozoic rocks in the Mojave Desert are inner continental-margin rocks deposited on the continental shelf along the western margin of ancient North America or cratonic-platform rocks similar to those exposed in the Grand Canyon (Miller and Cameron, 1982; Stone and others, 1983; Poole and others, in press). Isolated exposures of Paleozoic outer continental-margin rocks deposited on the continental-slope, -rise, and (or) ocean floor adjacent to ancient North

America crop out in the north-central Mojave Desert, the southwesternmost Great Basin, and in some roof pendants of the southern Sierra Nevada (see Miller and Sutter, 1982; Carr and others, 1984; Geraci and others, 1987; Dunne and others, 1988; Poole and others, in press). The term "inner continental-margin" is used here as a general adjective to describe assemblages mostly of limestone and dolostone with minor amounts of shale and quartzite, lithologically similar to rock assemblages in north-central Nevada that historically were described as "miogeosynclinal" or "eastern" assemblage by Roberts and others (1958). The term "outer continental-margin" is used here to describe assemblages consisting predominantly of fine-grained siliceous clastic rocks and chert with intercalated volcanic and pyroclastic rocks and is synonymous with the "eugeosynclinal" or "western" assemblage as used by Roberts and others (1958). Strata not clearly belonging to either the outer and inner continental-margin assemblages and probably deposited either on the outer continental shelf or upper continental slope also are present locally in southern California. Lithologically similar rocks in north-central Nevada were relegated to a "transitional" assemblage by Roberts and others (1958) and also are described as "transitional" here. The historical terminology is modified here to avoid ties to geosyncline theory or any provincialism implied by the historical terms.

Geologists attempting to understand the paleogeography of the ancient continental margin of western North America and the tectonic evolution of the Cordilleran orogen have attached significance to the distribution of outer continental-margin and transitional facies rocks in the Mojave Desert and southwestern Great Basin. Many authors have emphasized that outer continental-margin rocks of known and inferred Paleozoic age (especially Cambrian through Devonian) in the El Paso Mountains and north-central Mojave Desert lie spatially on trend with apparent

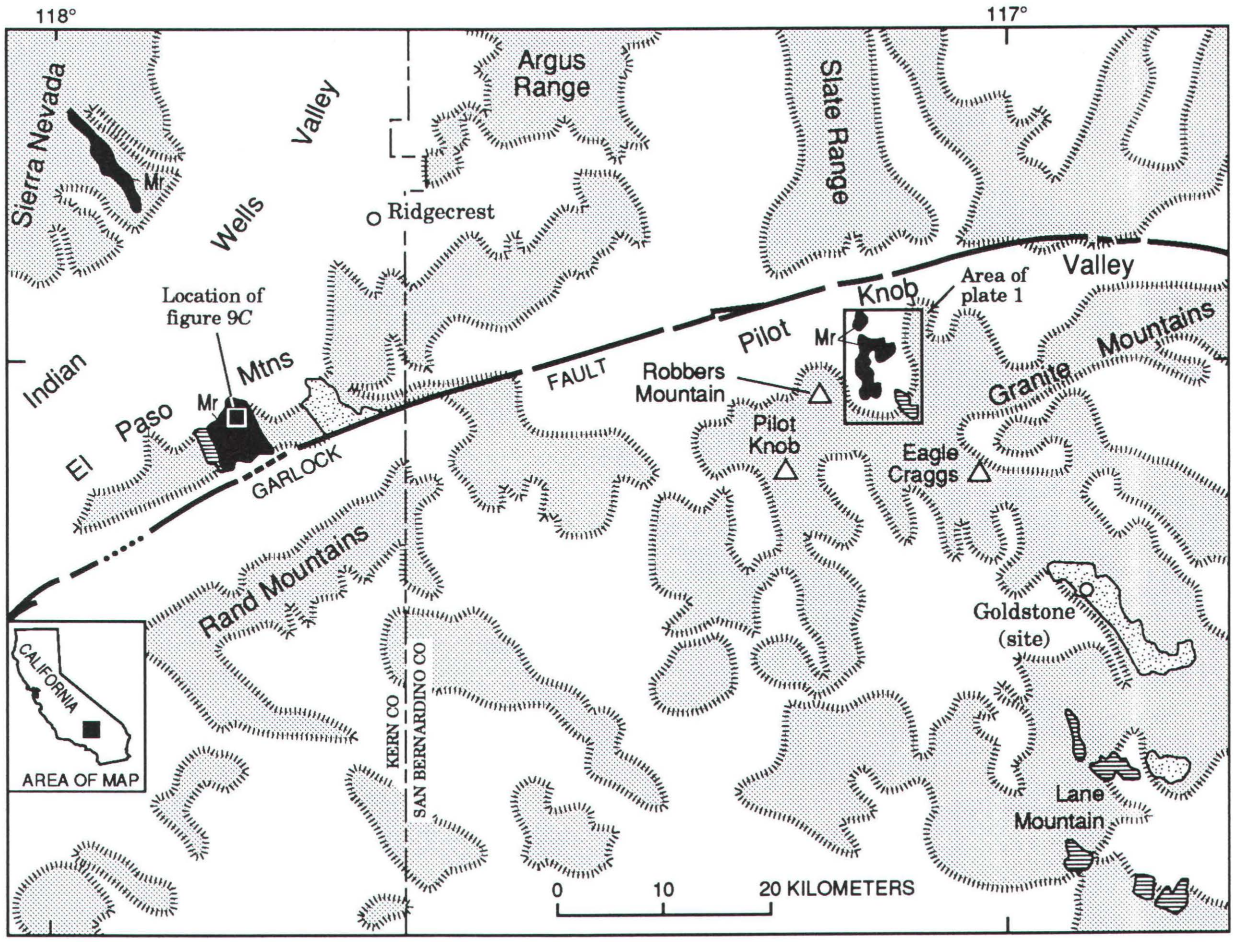

Figure 1. Generalized geologic map showing exposures of lower and middle Paleozoic metasedimentary rocks in north-central Mojave Desert and southwestern Great Basin. Explanation of patterns and symbols: black, Ordovician to Devonian outer continental-margin rocks (**Mr**, denotes areas where Lower Mississippian Robbers Mountain Formation or correlative rocks are present in addition to Ordovician to Devonian outer continental-margin rocks); stippled, Ordovician to Devonian rocks of a facies transitional between outer and inner continental-margin rocks; horizontal rules, metamorphic rocks of uncertain age that might correlate with quartzite of Moonshine Spring; shaded, highland (bedrock) areas. Modified from Jennings (1977). Garlock fault dashed where approximately located; dotted where concealed.

southwest-striking facies belts of coeval inner continental-margin rocks projecting from the Great Basin (see Davis and others, 1978; Burchfiel and Davis, 1981; Dickinson, 1981; Schweikert, 1981). This apparent geographic discordance has given rise to the hypothesis that the Pacific margin of North America was truncated during Permian or Triassic time, preceding the establishment of a subduction-related magmatic arc that characterized this margin during most of the Mesozoic (see Hamilton and Myers, 1966; Hamilton, 1969; Burchfiel and Davis, 1972, 1975). Because the preserved stratigraphic record of Paleozoic time is sparse in southern California, and few detailed stratigraphic studies have been reported, each exposure of Paleozoic rocks has magnified importance for establishing a stratigraphic framework and testing whether tectonic models are compatible with the geologic record.

This report describes a small enclave of metasedimentary rocks exposed in Pilot Knob Valley, just south of the left-lateral Garlock fault in the north-central Mojave Desert (figs. 1 and 2; pl. 1). The metasedimentary rocks in

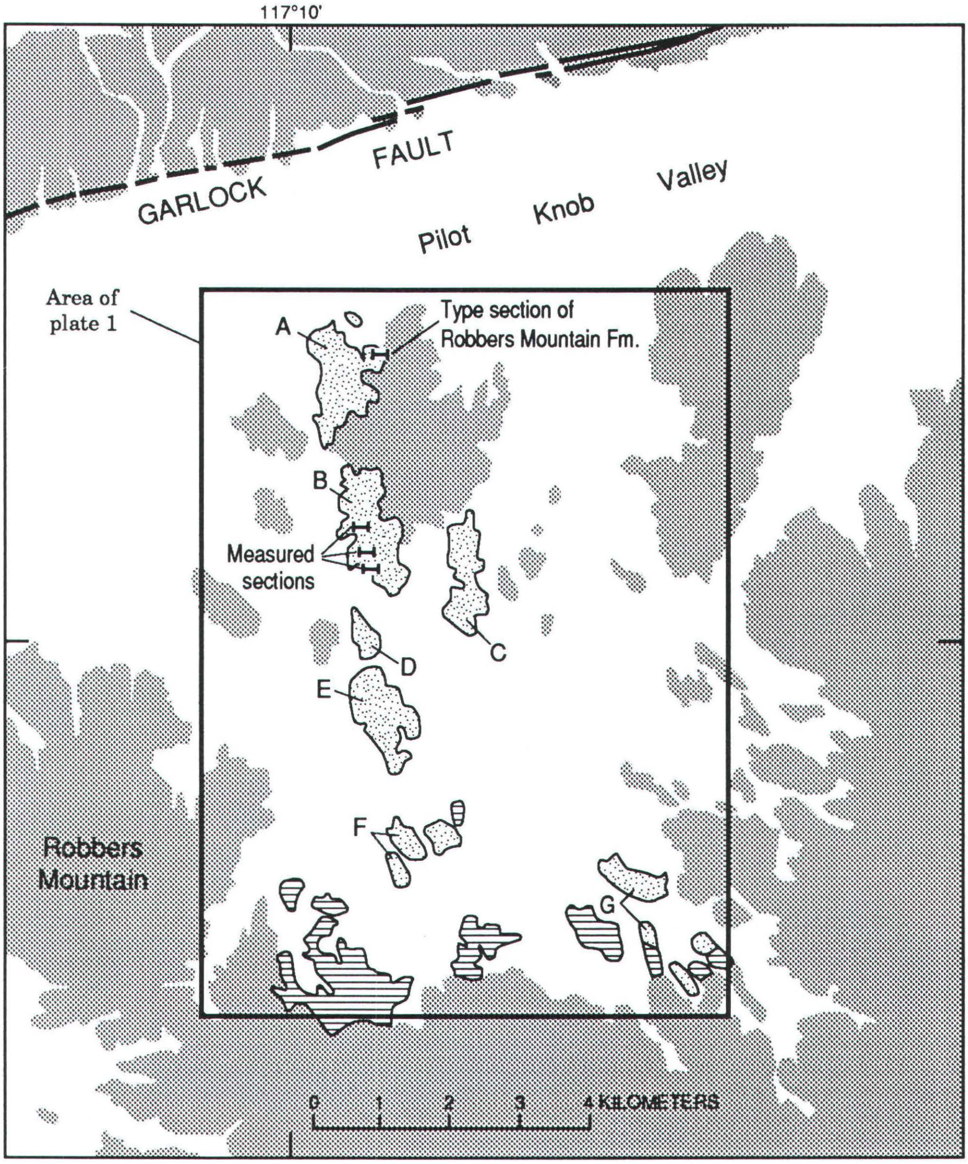

Figure 2. Generalized geologic map of Pilot Knob Valley study area. Shows lines of measured sections of Ordovician through Devonian rocks in area B (see fig. 5) and line of type section for Robbers Mountain Formation (see fig. 8). Explanation of patterns: stippled, Paleozoic metasedimentary rocks; horizontal rules, Mesozoic intrusive rocks; shaded, Tertiary volcanic and sedimentary rocks; unpatterned, Quaternary surficial deposits. Letters A to G designate outcrop areas shown on plate 1 and discussed in text; letter designations correspond to those used by Smith and Ketner (1970) to identify their measured sections. Modified from Smith and Ketner (1970).

Pilot Knob Valley were correlated with a more extensive section of Paleozoic outer continental-margin rocks in the El Paso Mountains, 50 km to the west on the north side of the Garlock fault by Smith and Ketner (1970). As an adjunct to our study of the structure and Paleozoic stratigraphy of the El Paso Mountains (Carr and others, 1984), here we reexamine the Pilot Knob Valley exposures. On the basis of physical stratigraphy and conodont biostratigraphy, we define an Ordovician through Lower Mississippian stratigraphy for the outer continental-margin rocks in Pilot Knob Valley, which also is applicable to most of the laterally equivalent lower Paleozoic outer continental-margin rocks in the El Paso Mountains. A distinctive metaconglomerate, assigned herein to a newly proposed Lower Mississippian unit named the Robbers Mountain Formation, rests unconformably on the Ordovician through Devonian section in Pilot Knob Valley. Lithologically similar Lower Mississippian rocks exposed in the El Paso Mountains (Carr and others, 1984) are equivalent to parts of the Robbers Mountain Formation in Pilot Knob Valley as defined herein. Recognition of a more strongly metamorphosed section of the distinctive metaconglomerate in the southern Sierra Nevada (Geraci and others, 1987; Dunne and others, 1988) provides a tentative basis for extending at least part of the Paleozoic outer continental-margin stratigraphy discussed in this report into some of the metamorphic roof pendants of the southern Sierra Nevada (Geraci and others, 1987; Dunne and others, 1988; Poole and others, in press).

Paleozoic rocks in Pilot Knob Valley are metamorphosed to at least the greenschist facies and are tightly folded at both outcrop and map scales. Layering generally strikes northward and dips near vertical. Contacts between lithologic units commonly are faulted along surfaces nearly parallel to layering; thus, it is difficult to demonstrate stratigraphic continuity.

The Paleozoic rocks crop out in several low hills south of the axis of Pilot Knob Valley, 3 to 8 km east and northeast of Robbers Mountain (figs. 2 and 3; pl. 1). None of the exposures is larger than 1 km^2. Pilot Knob Valley is an asymmetric alluvial basin paralleling the left-lateral Garlock fault. The steep alluvial fans that form the narrow northern slope of the valley are fed from the Slate Range across the Garlock fault (fig. 1). The Paleozoic rocks form inselbergs among the broad coalescing alluvial fans that form the southern slope of the valley and merge southward with an upland of Tertiary volcanic and sedimentary rocks.

The Wingate Pass and Pilot Knob 15-minute quadrangles contain the study area. Access to the area is from the west along the Randsburg Road. Several unmaintained dirt tracks reach the southernmost exposures of Paleozoic rocks between Lead Pipe Spring and Moonshine Spring

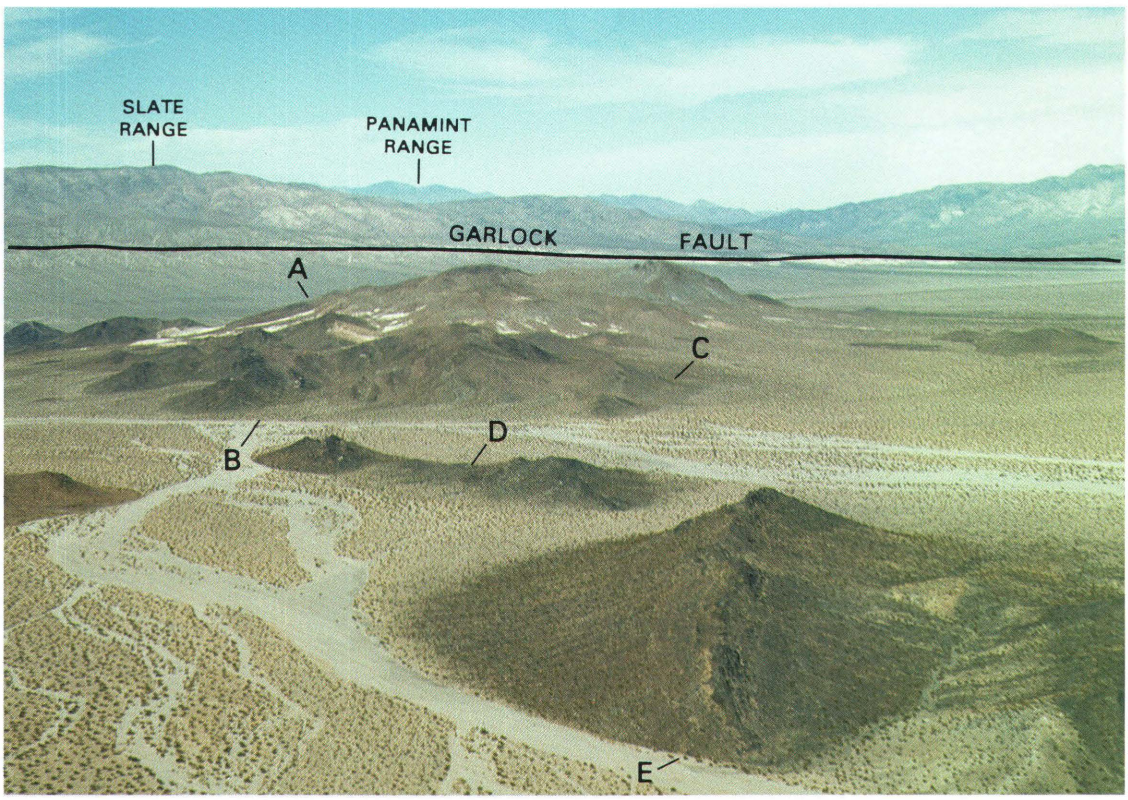

Figure 3. Oblique aerial view northward showing exposures of Paleozoic metasedimentary rocks in areas A through E (pl. 1) in Pilot Knob Valley. Garlock fault is along south flank of hills (southernmost Slate Range) forming near horizon. Distance from foreground to Garlock fault approximately 12 km.

(pl. 1). Pilot Knob Valley is part of the U.S. Naval Weapons Center at China Lake and access is restricted.

Previous Work

Spurr (1903, p. 205) noted the outcrops of deformed metasedimentary rocks in the (Pilot Knob) valley 8 miles (13 km)[1] northeast of Pilot Knob (fig. 1). Smith and others (1968) mapped and described these rocks in that part of Pilot Knob Valley within the Wingate Pass 15-minute quadrangle. They considered the metasedimentary rocks to be Paleozoic in age.

Smith and Ketner (1970) described the meta-sedimentary rocks of Pilot Knob Valley in more detail and interpreted them as a distinctly eugeosynclinal meta-sedimentary sequence, generally correlative with the now-abandoned Garlock Formation (Dibblee, 1967; Carr and others, 1984) in the El Paso Mountains, approximately 50 km to the west on the north side of the Garlock fault (fig. 1). They used this correlation as a partial basis for estimating 30 to 40 miles (48 to 64 km) of left-lateral displacement on the Garlock fault. Smith and Ketner (1970) outlined all of the major outcrops of Paleozoic rocks in Pilot Knob Valley at a scale of 1:62,500 and described intrusive relations in the southernmost part of the area (fig. 2; pl. 1, area G). Devonian fossils from the northernmost Paleozoic outcrops in Pilot Knob Valley (pl. 1, area A) were reported by Carr and others (1981), providing biostratigraphic evidence to strengthen Smith and Ketner's correlation with the metasedimentary rocks of the El Paso Mountains.

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We wish to thank the personnel of the U.S. Naval Weapons Center at China Lake for their extraordinary cooperation and support, without which this project would not have been possible. We are especially grateful to Carolyn Shepherd, Tilly Barling, Glenn Roquemore, Tom McGill, and Pierre St. Armand for their kindness and assistance. We thank the U.S. Navy for permission to enter the restricted test range in Pilot Knob Valley. George Smith provided unpublished notes from his previous investigations in the area.

PRE-CENOZOIC STRATIGRAPHY

The pre-Cenozoic rocks in Pilot Knob Valley are divisible into three stratigraphic sequences: (1) Ordovician through Devonian outer continental-margin rocks; (2) Lower Mississippian syntectonic deposits, consisting of metaconglomerate and fine-grained siliciclastic rocks; and (3) metasedimentary rocks of uncertain age, mostly consisting of quartzite, metaconglomerate, phyllite, and quartz-silt meta-argillite (fig. 4). The Ordovician through Devonian outer continental-margin rocks are lithologically similar to rocks of the same age in Nevada that were grouped as the shale and chert province by Stewart and Poole (1974), Poole and others (1977), and Stewart (1980). The Lower Mississippian rocks in Pilot Knob Valley are lithologically similar to some siliceous Mississippian rocks in Nevada, which Stewart (1980) grouped as "deposits within the Antler highland terrace." The clastic sequence of uncertain age, mostly exposed in area G (pl. 1), also is of uncertain paleogeographic association. These clastic rocks could be (1) Late Proterozoic or Early Cambrian in age and part of the North American continental-shelf sequence, (2) Carboniferous deposits of the Antler foreland basin, or (3) part of an unknown Mesozoic marine sequence. Both the Ordovician through Devonian and the Lower Mississippian successions can be correlated more specifically with outer continental-margin rocks in the central El Paso Mountains (fig. 1), which were included in the Garlock Formation by Dibblee (1952, 1967; Dibblee's units 1 through 9).

Ordovician Through Devonian Outer Continental-Margin Rocks

Most of the metasedimentary rocks in Pilot Knob Valley are known or presumed to be Ordovician through Devonian in age. Conodont age determinations support this assignment (fig. 4; appendix 1). The Ordovician through Devonian rocks are divisible into four principal lithostratigraphic units informally designated herein as the (1) lower meta-argillite unit, (2) quartzite and meta-argillite unit, (3) upper meta-argillite unit, and (4) sandy marble unit (fig. 5; pl. 1). An additional unit, composed mostly of greenstone, also may belong in the Ordovician through Devonian succession, but neither the age of the greenstone nor its stratigraphic position are conclusively established. The units are repeated by tight folds and faults at small angles to layering. Nowhere is there a complete stratigraphic section, and the stratigraphy was defined largely on a composite of partial sections exposed in area B (fig. 5).

Lower Meta-Argillite Unit

Meta-argillite is the predominant Paleozoic rock type in Pilot Knob Valley. Meta-argillite forms two of the principal lithostratigraphic units in a composite stratigraphic section for area B, which contains the most complete Ordovician through Devonian sections in Pilot

[1] Approximate metric-English equivalents given only for those measurements that were converted from data originally published or measured in English units.

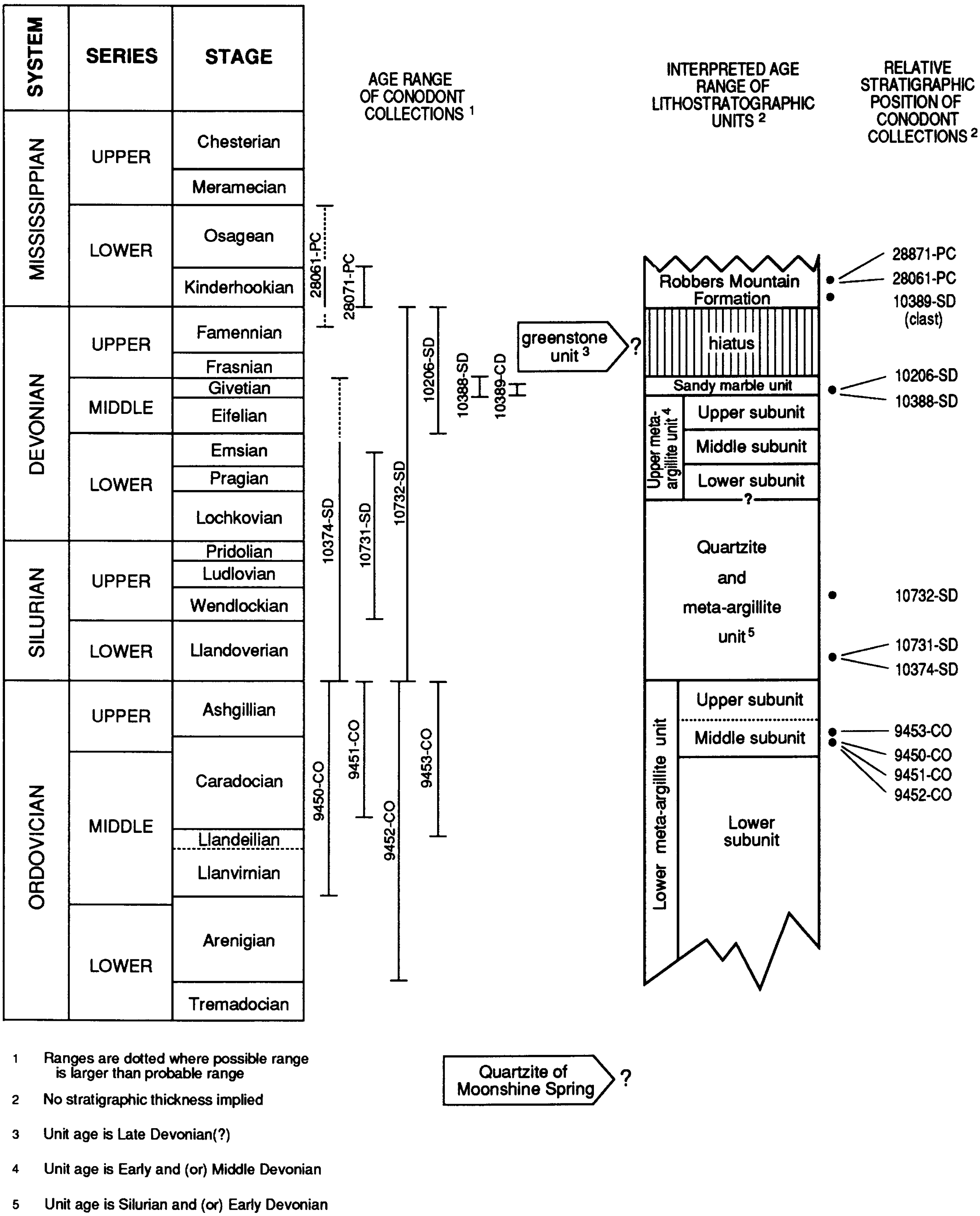
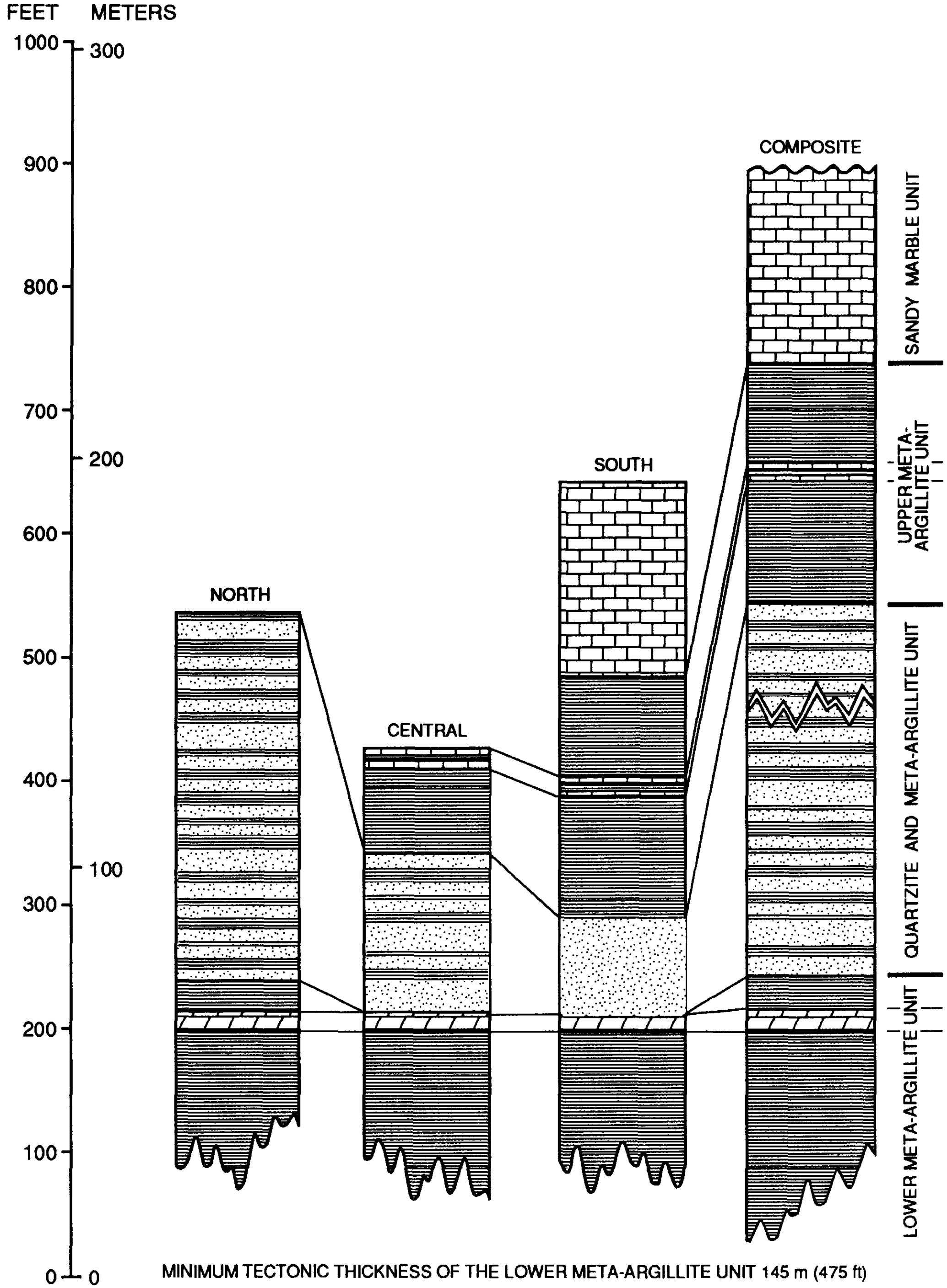


Figure 4. Stratigraphic summary for metamorphic rocks of Pilot Knob Valley. See text for detailed discussion. Relative duration of Ordovician series is from Barnes and others (1981); relative duration of Silurian through Mississippian series and stages is modified from Harland and others (1982). Stage boundary dotted where relative duration uncertain. See plate 1 for localities of conodont collections.



SANDY MARBLE UNIT

Sandy marble; medium gray, weathers pale to dark yellowish orange and dusky yellowish to light brown; poorly to moderately well bedded in beds as thick as 2 m; marble beds variously are massive, laminate, or cross laminated; marble is mostly calcitic, fine to medium crystalline, and contains silt- and sand-sized grains of frosted quartz; varies from matrix to grain supported; locally, altered to dolomitic marble

UPPER META-ARGILLITE UNIT

Upper subunit: Meta-argillite; light greenish, bluish, and olive gray to olive black, weathers pale to moderate yellowish brown; commonly is uniformly color banded over intervals of several tens of centimeters; uniformly very fine grained; moderately well layered; layers range from 1 to 20 cm, but layers generally are of uniform thickness over intervals of several meters; layer partings are layer-parallel spaced cleavage not coincident with any readily apparent lithologic variation

Meta-argillite interval above middle subunit locally divisible into: lower part, 9 m (30 ft) thick, which is strongly silicified, and generally contains layers 10 to 20 cm thick; and upper part, 15 m (50 ft) thick, which is less well silicified, thinner layered (less than 5 cm), and less resistant than lower part; uppermost 3 m of interval grades from less resistant than lower part; uppermost 3 m of interval grades from meta-argillite through light-brown calcareous siltite to sandy marble

Middle subunit: Meta-argillite and calcitic marble, distinctive marker unit approximately 4.6 m (15 ft) of meta-argillite (like that in enclosing intervals) interlayered with beds of medium-light-gray calcitic marble as thick as 10 cm; calcitic marble is fine grained and laminated, locally altered to moderate-brown dolomitic marble; carbonate rocks form 25 to 50 percent of total rock volume throughout marker interval; base of marker unit 20 to 30 m (70 to 100 ft) above base of upper meta-argillite

Lower subunit: Meta-argillite; predominate rock type same as upper subunit; lower subunit contains several beds of massive, fine-grained, moderate-brown dolomitic marble15 to 20 cm thick near middle of interval in some sections

QUARTZITE AND META-ARGILLITE UNIT

Interbedded quartzite and meta-argillite; pale-reddish-brown to moderate-reddish-orange quartzite beds intercalated with light-greenish, yellowish, and light-olive-gray meta-argillite; quartzite is fine grained and forms beds 1 to 20 cm thick; quartzite beds variously are massive, laminated, cross laminated, and graded; relative abundance of quartzite and argillite varies, but quartzite generally forms at least 50 percent of total rock volume; unit locally contains sparse beds of massive, fine-grained, moderate-brown dolomitic marble as thick as 10 cm

LOWER META-ARGILLITE UNIT

Upper subunit: Meta-argillite and recrystallized silty chert; light-olive-gray to olive-black, weathers in hues of light gray and moderate brown to dark reddish brown; uniformly very fine grained; moderately well layered; layers range from 1 to 50 cm thick but generally are of uniform thickness over intervals of several meters. Locally contains sparse layers of moderate-brown fine-grained dolomitic marble as thick as 0.3 m; unit is a moderate ridge former; strongly silicified intervals forming ribs of outcrop on otherwise rubbly slopes

Middle subunit: Moderate brown; fine- to medium-grained; nonbedded to moderately well bedded dolomitic marble; beds are massive or finely laminated; unit is 3 to 5 m (10 to 15 ft) thick; base of unit is 14 m (45 ft) below top of lower meta-argillite; both base and top of unit are gradational into meta-argillite over 1 to 2 m interval

Lower subunit: Same rock types as upper subunit.

Figure 5. Partial and composite measured sections of Ordovician through Devonian metasedimentary rocks in area B (fig. 2) in Pilot Knob Valley.

Knob Valley (fig. 5). The two meta-argillite units in area B are informally designated as the lower and upper meta-argillite units. On the basis of its position in area B sections, the lower meta-argillite unit is interpreted as the oldest unit in the Ordovician through Devonian outer continental-margin sequence. The lower meta-argillite unit consists of three subunits: (1) a lower subunit predominantly composed of meta-argillite, (2) a middle subunit composed of dolomitic marble, and (3) a thin upper subunit also predominantly composed of meta-argillite (fig. 5). The two meta-argillite intervals are indistinguishable in the absence of the intervening dolomitic marble interval.

Lower Subunit

The lower subunit consists of meta-argillite and recrystallized argillaceous metachert (fig. 6*A*). The subunit is a moderately resistant ridge former with thick-bedded, strongly silicified intervals forming resistant ribs of outcrop along otherwise rubbly slopes. Fresh rock ranges from light olive gray to olive black, and weathered surfaces range in hues of light gray and moderate brown to dark reddish brown. The rocks are uniformly very fine grained and moderately well layered. Layers are separated by evenly spaced partings that parallel bedding where it is distinguished by contrasting rock types. Generally, partings do not coincide with any readily apparent lithologic contrasts. Locally, layers are distinguished by color contrast. Layering generally is uniform in thickness over stratigraphic intervals of a few meters, but layer thicknesses range from 1 to 50 cm throughout the subunit. Sparse beds of fine-grained, moderate-brown dolomitic marble less than 1 m thick are interlayered locally with meta-argillite. These beds commonly are tectonically flattened and discontinuous.

Thin sections reveal that the lithology of the lower subunit is variable. Much of the subunit is quartz silt-bearing meta-argillite, or recrystallized micaceous chert, composed predominantly of cryptocrystalline quartz, muscovite, and opaque oxide minerals. Other rocks are nearly pure recrystallized chert, containing less than 10 percent mica or carbonate minerals. Some rocks that are predominantly cryptocrystalline also contain angular, silt-size grains of quartz. Several samples contain recrystallized radiolarians, which are taxonomically unidentifiable.

The base of the lower subunit is not exposed. Its minimum thickness is estimated as 145 m (475 ft)[2], but the unit could be significantly thicker.

[2]Paleozoic units in Pilot Knob Valley commonly are tightly folded on a mesoscopic scale; therefore, the reported unit thicknesses are structural rather than stratigraphic.

Middle Subunit

A conspicuous dolomitic marble interval conformably overlies the lower subunit in both areas A and B (fig. 6*B*). The lower contact of the dolomitic marble is gradational over a 1-m-thick interval that contains beds of thinly layered meta-argillite intercalated with dolomitic marble beds.

The middle subunit consists of moderate-brown-weathering, fine-grained dolomitic marble, which in most areas is poorly bedded and massive. Locally, the dolomitic marble is moderately well bedded, beds are 2 to 20 cm thick, and some finely laminated beds are preserved. Most of the rock is cryptocrystalline dolomite, but it also contains very sparse, angular, silt-size grains of quartz (less than 1 percent).

The middle subunit is 3 to 5 m (10 to 15 ft) thick in the measured sections from area B (fig. 5), but elsewhere it is as thick as 18 m (60 ft). The thickness of the subunit ranges laterally, at least in part, because of tectonic flattening and necking of the dolomitic marble into discontinuous lenses. A string of dolomitic marble lenses occupies a consistent stratigraphic position above the lower subunit throughout areas A and B.

Upper Subunit

An upper subunit of meta-argillite rests conformably on the middle subunit in the northernmost measured section of area B. In sections farther south, this upper subunit is faulted out (figs. 5 and 6*C*). The basal contact of the upper subunit is gradational. The lower 2 m of the subunit consist of interbedded dolomitic marble and meta-argillite. The remainder of the upper subunit is meta-argillite lithologically similar to the lower subunit. The upper subunit reaches a maximum thickness of approximately 10 m in the vicinity of the measured sections (fig. 5).

Age and Correlation

The middle subunit yielded the only fossils recovered from the lower meta-argillite unit. Of the four Ordovician conodont faunas from the middle subunit, two indicate a Caradocian through Ashgillian age (fig. 4; appendix 1), restricting the middle subunit to the middle Middle through Late Ordovician. Furthermore, these faunas restrict the age of the lower subunit of the lower meta-argillite unit to no younger than Late Ordovician, and the upper subunit to no older than middle Middle Ordovician.

Neither the lower nor upper age limit for the lower meta-argillite unit as a whole is tightly constrained. Lithologically similar rock sequences in the El Paso Mountains yielded conodont and graptolite faunas as old as Early Ordovician and possibly latest Cambrian (Carr and others, 1984). The lower meta-argillite unit is overlain conformably by a sequence of quartzite and meta-argillite beds that yielded Silurian to Early Devonian conodonts;

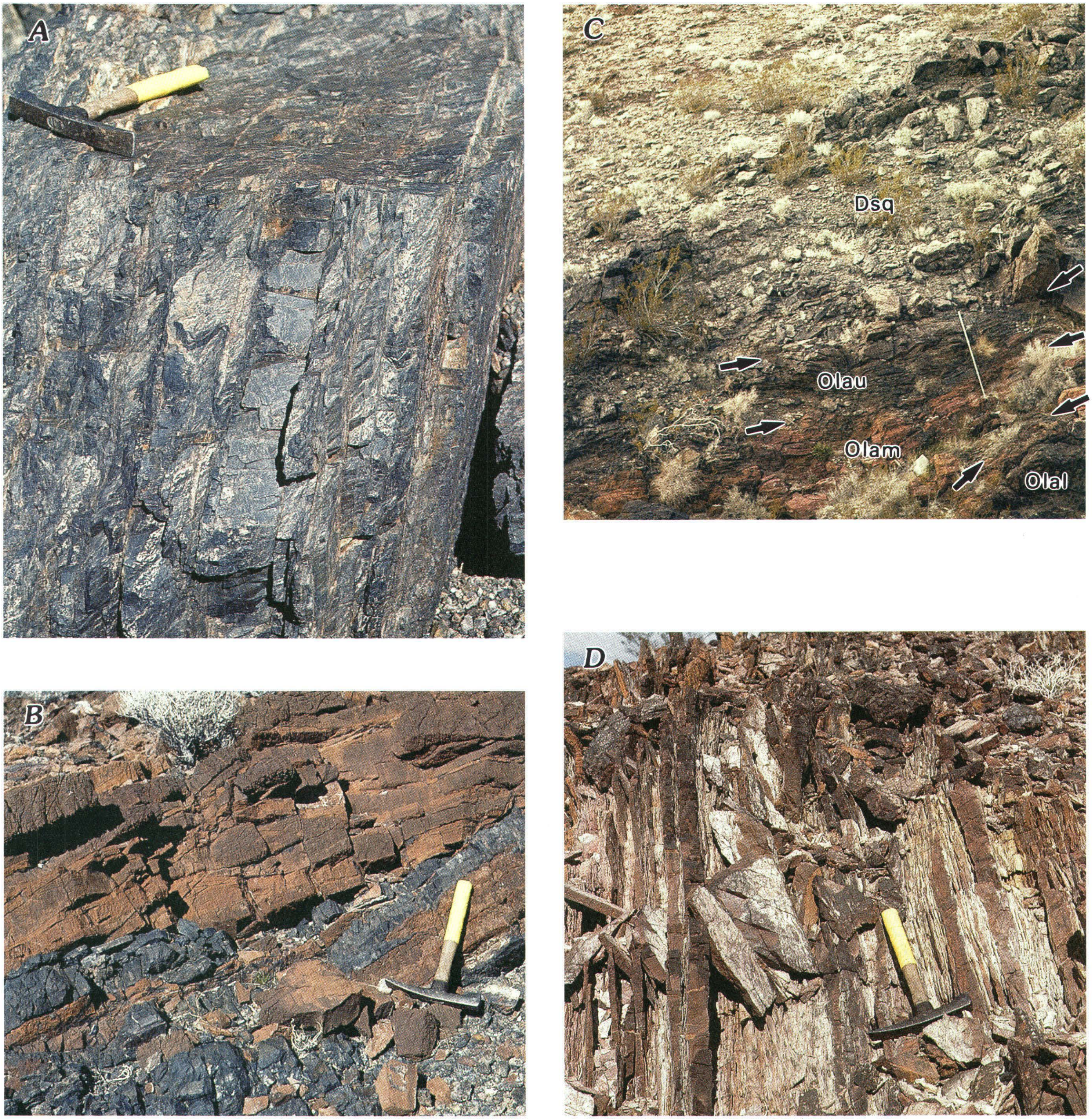


Figure 6. Ordovician through Devonian outer continental-margin rocks from area B in Pilot Knob Valley. *A*, Ordovician lower meta-argillite unit—lower subunit—consisting of meta-argillite. Bedding is nearly vertical. *B*, Ordovician lower meta-argillite unit—gradational lower contact of middle subunit. *C*, View of northernmost measured section showing Ordovician lower meta-argillite unit—upper part of lower subunit (**Olal**), middle subunit (**Olam**), and upper subunit (**Olau**)—overlain by lower part of the Silurian and (or) Lower Devonian quartzite and meta-argillite unit (**DSq**). Measuring staff opened to 5 ft (1.5 m). Contacts are between arrows. Top of staff at lower contact of Silurian and (or) Lower Devonian quartzite and meta-argillite unit; base of staff on upper part of middle subunit (of lower meta-argillite unit). *D* and *E*, Silurian and (or) Lower Devonian quartzite and meta-argillite unit—thin to medium-bedded quartzite (turbidite or contourite flows) interlayered with meta-argillite (hemipelagic deposits). *F*, Lower and (or) Middle Devonian upper meta-argillite unit—lower subunit consisting of meta-argillite. Layers are near vertical. *G*, Lower and (or) Middle Devonian upper meta-argillite unit—middle subunit consisting of thinly interbedded meta-argillite and calcitic marble. *H*, Middle Devonian sandy marble unit. Measuring staff opened to 5 ft (1.5 m) and placed perpendicular to bedding. *I*, Closeup view of laminated and crosslaminated sandy marble beds in the Middle Devonian sandy marble unit.

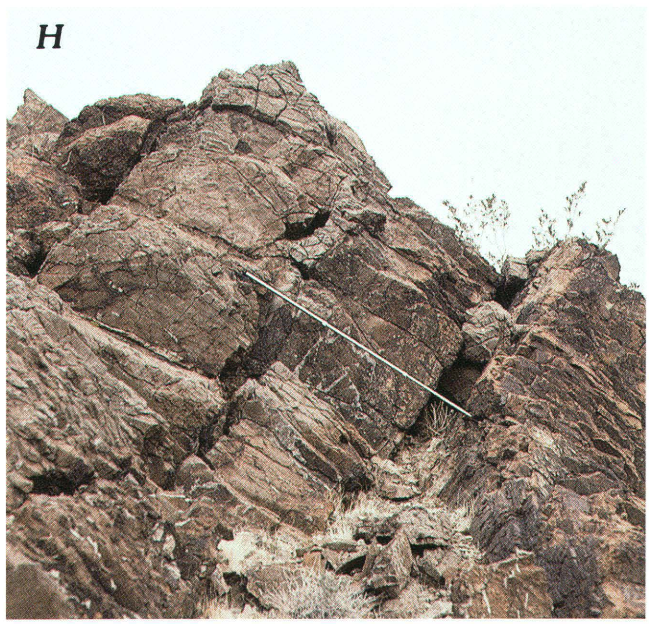


Figure 6. Continued.

consequently, the uppermost part of the lower meta-argillite unit is no younger than Early Devonian. The upper subunit is only a few meters thick, however, and rests conformably on the middle Middle through Upper Ordovician middle subunit. Therefore, we tentatively assign the entire unit to the Ordovician. We acknowledge, however, that the unit possibly could include some Cambrian, Silurian, or even Lower Devonian rocks.

The Ordovician rocks in Pilot Knob Valley are lithologically similar to pelitic Ordovician rocks forming part of the metasedimentary sequence in the El Paso Mountains (unit 9 of the Garlock Formation of Dibblee, 1967; eugeoclinal facies Ordovician rocks of Carr and others, 1984). The metasedimentary sequence in the Goldstone area (25 km southeast of Pilot Knob Valley, fig. 1) also contains basinal Ordovician rocks (Miller and Sutter, 1982), however, the Goldstone section contains significantly more interbedded carbonate rocks, as well as distinctive intervals of orthoquartzite and graptolitic shale (schist). The Goldstone rocks lithologically are more like Ordovician rocks in the eastern El Paso Mountains (upper half of unit 18 through unit 22 of the Garlock Formation of Dibblee, 1967; transitional facies Ordovician rocks of Carr and others, 1984) than they are like the Ordovician rocks in Pilot Knob Valley or the western part of the metasedimentary sequence in the El Paso Mountains. The rocks at Goldstone and those in the eastern El Paso Mountains probably represent a transitional facies between the outer continental-margin rocks of Pilot Knob Valley, the El Paso Mountains, Sierra Nevada, and western Great Basin and the inner continental-margin rocks of the central and eastern Great Basin and much of the Mojave Desert.

Quartzite and Meta-Argillite Unit

Interbedded quartzite and meta-argillite conformably overlie the lower meta-argillite unit in the northernmost measured section of area B (fig. 5). The lower contact of the quartzite and meta-argillite unit is placed at the base of the stratigraphically lowest quartzite bed overlying the meta-argillite interval above the middle subunit (of the lower meta-argillite unit) (fig. 6*C*). The top of the quartzite and meta-argillite unit is faulted in this section, but in the southern two sections of area B, the top of the unit is conformable and placed at the highest occurrence of quartzite in the section. The base of the unit is faulted in the southern two sections.

The quartzite and meta-argillite unit consists of pale-reddish-brown to moderate-reddish-orange quartzite beds 5 to 30 cm thick intercalated with moderate-light-olive-gray, platy meta-argillite (figs. 6*D* and *E*). The quartzite is fine to medium grained. Quartzite beds variously are massive, thinly laminated, cross laminated, or graded. Sedimentary structures in the quartzite beds suggest that they were deposited either as turbidites or contourites. The relative proportion of quartzite to meta-argillite beds varies without any demonstrated trend through the stratigraphic section. Locally, sparse, thin (less than 10 cm) beds of massive moderate-brown dolomitic marble are interbedded with the quartzite and meta-argillite. The quartzite beds consist of fine- to medium-grained, angular to subangular quartz sand set in a matrix of cryptocrystalline quartz, opaque oxide minerals, and muscovite.

The structural thickness of the quartzite and meta-argillite unit is at least 91 m (300 ft) in the northern section of area B (fig. 5).

Age and Correlation

The quartzite and meta-argillite unit yielded conodonts from both areas A and B (fig. 4; appendix 1). The two faunas from area A indicate a Silurian to late Early Devonian age, but the meager fauna from area B merely indicates a Silurian or Devonian age. Specimens from area B were collected approximately 25 to 30 m above the base of the northern measured section, whereas the stratigraphy of the unit in area A is poorly constrained. The age of the quartzite and meta-argillite unit is limited below by the middle Middle through Late Ordovician fossils in the middle subunit of the lower meta-argillite unit. The age is limited above by late Middle Devonian fossils in the sandy marble unit. The quartzite and meta-argillite unit is inferred to be Silurian and (or) Early Devonian in age, considering the absence of Ordovician conodonts in the collection from within 30 m of the base of the unit in area B and the presence of an intervening unit, approximately 60 m thick, between the quartzite and meta-argillite unit and the upper Middle Devonian sandy marble unit in area B (fig. 5).

Upper Meta-Argillite Unit

A second unit composed predominantly of meta-argillite rests conformably on the quartzite and meta-argillite unit in area B (fig. 5). Where defined in the southernmost measured section of area B, the upper meta-argillite unit is divisible into lower and upper subunits composed of meta-argillite separated by a middle subunit containing interbedded meta-argillite and metalimestone. The lower and upper subunits are similar lithologically to the lower and upper subunits of the lower meta-argillite unit, and these subunits are indistinguishable where observed out of stratigraphic context.

Lower Subunit

The lower subunit consists of 21 to 30 m (70 to 100 ft) of meta-argillite in the southern two measured sections of area B (fig. 5). The meta-argillite, which is olive gray to olive black, is uniformly fine grained and occurs in layers 1 to 20 cm thick (fig. 6*F*). Several beds of moderate-brown dolomitic marble, 15 to 20 cm thick, occur in the middle part of the lower subunit. Like the lower meta-argillite unit, a variety of lithologies ranging from nearly pure recrystallized chert to micaceous and (or) calcareous quartz-silt meta-argillite also are recognized in thin sections of this subunit.

Middle Subunit

Five meters (15 ft) of interbedded meta-argillite and calcitic marble form a distinctive marker layer conformably above the lower subunit (fig. 5). The middle subunit contains beds composed of medium-gray, fine-grained, laminated, calcitic marble from 5 to 10 cm thick intercalated with layers of meta-argillite lithologically similar to the meta-argillite of the lower subunit (fig. 6*G*). The calcitic marble beds locally are altered to moderate-brown dolomite. The carbonate rocks form 25 to 50 percent of the total rock volume. The calcitic marble layers consist predominantly of cryptocrystalline calcite, but sparse, angular grains of quartz silt compose as much as 5 percent of most layers. In some layers, quartz silt composes as much as 50 percent of the rock.

Nothing is known about the lateral stratigraphic continuity of the middle subunit because its exposures are limited to the southernmost part of area B.

Upper Subunit

In the southernmost measured section of area B, the middle subunit is conformably overlain by 24 m (80 ft) of meta-argillite (fig. 5). This upper subunit is similar lithologically to the meta-argillite forming most of the lower subunit of the upper meta-argillite unit. The upper subunit is gradational upward into a distinctive sandy marble unit. The uppermost 3 m of the upper meta-argillite unit contain calcareous silty meta-argillite and an increasing number of metalimestone beds.

Age and Correlation

No fossils were recovered from the upper meta-argillite unit. The unit can be no older than Silurian on the basis of conodonts from the underlying quartzite and meta-argillite unit, and no younger than Middle Devonian on the basis of conodonts from the overlying upper Middle Devonian sandy marble unit (fig. 4). Consequently, the upper meta-argillite unit is tentatively assigned an Early and (or) Middle Devonian age.

Sandy Marble Unit

A distinctive unit of moderately well bedded sandy calcitic marble rests conformably on the upper meta-argillite unit in area B (fig. 5). Sandy calcitic marble is also recognized in many of the other outcrop areas in Pilot Knob Valley (pl. 1). The lower contact of the unit in area B is gradational with the upper meta-argillite unit through an interval of approximately 3 m, but nowhere in Pilot Knob Valley has the upper stratigraphic contact of the unit been definitely recognized. In most places, both the upper and lower contacts of the sandy marble unit are faults.

The sandy calcitic marble is medium gray and weathers to hues of yellowish orange and light brown (fig. 6*H*). Beds are as much as 2 m thick, and the unit ranges from poorly bedded to well bedded. Beds are internally massive or laminated, and some beds are crosslaminated (fig. 6*I*). The unit variously contains sandy to silty calcitic marble, calcareous quartzite, and quartzite. The relative proportions of quartz sand to calcite matrix varies both vertically and laterally with no apparent trend. In the extreme case, a bed or several beds may grade laterally from sandy marble to quartzite as the amount of calcareous matrix decreases, the quartz sand becomes grain supported, and the calcareous matrix is replaced by secondary interstitial silica and (or) silica overgrowths on quartz grains.

Thin sections of the unit reveal that the detrital quartz grains are angular to well rounded with the large grains tending to be better rounded than small grains. The detrital grains have a bimodal size distribution with estimated peaks at about 0.2 mm and 0.5 mm. In samples where quartz grains form the bulk of the rock, many grains contain silica overgrowths that are optically continuous with the core grain. Quartz grains are distinctly frosted in hand specimens. The sand-grain population also includes as much as 1 percent of moderately well rounded, detrital orthoclase grains approximately 0.5 mm in diameter. The matrix consists of recrystallized calcite forming irregular interstitial masses where the rock is grain supported, and mosaics of crystals flattened in the foliation plane where the matrix supports the detrital quartz grains. Sparse secondary crystals of an unidentified opaque oxide mineral generally occur in the matrix.

Age and Correlation

The sandy marble unit is late Middle Devonian in age. Rocks assigned to the sandy marble unit yielded Devonian conodonts at two localities in area A (fig. 4; appendix 1); one of these collections is restricted to the late Middle Devonian (Givetian). A clast of sandy marble incorporated into metaconglomerate of the overlying Robbers Mountain Formation also yielded late Middle Devonian conodonts.

Sandy limestone units lithologically similar to the sandy marble in Pilot Knob Valley also occur in the outer continental-margin succession in the El Paso Mountains (Dibblee, 1952, 1967; Christiansen, 1961) and are structurally interleaved with outer continental-margin and (or) transitional facies Ordovician rocks in the Miller Mountain area of west-central Nevada (Stanley and others, 1977; Stewart, 1984). Devonian conodonts have been recovered from the sandy limestone at both localities (Stanley and others, 1977; Carr and others, 1984).

Greenstone Unit

Vesicular greenstone crops out only in small drainages at the southwest edge of area A (fig. 7; pl. 1), but dark-green phyllitic greenstone float is present on the low knolls adjacent to these drainages. Fragments of pillow structures occur among the greenstone debris, and some outcrops of greenstone contain lenses of light-gray calcitic marble. The greenstone unit is in fault contact with other metamorphic rocks to the east.

The greenstone has a fine-grained, felty groundmass composed predominantly of calcite, biotite, and chlorite. Albite(?), epidote, sphene, and opaque iron oxide minerals also occur in the groundmass, and epidote occurs in veins, as well. Calcite-filled amygdules form as much as 50 percent of the rock volume. The amygdules are flattened approximately 4:1 in thin section. The marble lenses consist of a mosaic of twinned calcite crystals elongate parallel to foliation. Sparse 1-mm-diameter quartz grains occur in laminae of fine-grained sandy marble within the calcitic marble lenses.

The occurrence of pillow fragments in the greenstone unit suggests that the greenstone is a metamorphosed submarine basaltic lava flow. The presence of sandy laminae in the marble suggests a sedimentary origin for the calcitic marble, and the marble lenses are interpreted to represent accumulations of calcareous mud and fine sandy calcareous mud deposited between basalt flows on the seafloor.

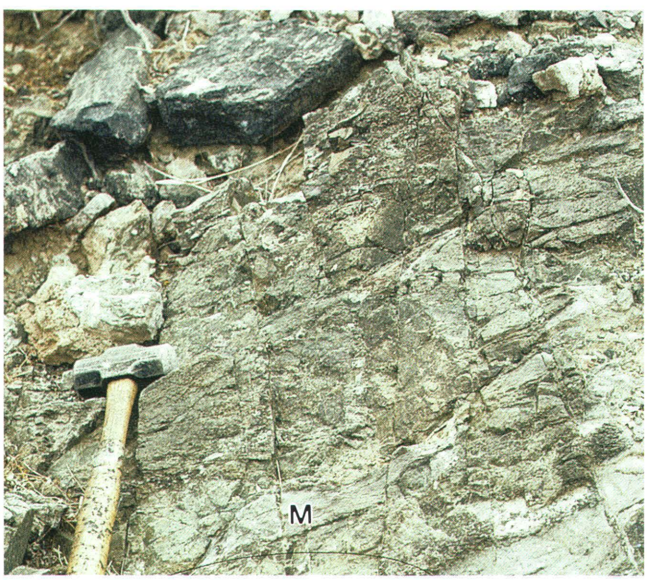


Figure 7. Greenstone unit (Upper Devonian?) cropping out along western edge of area A in Pilot Knob Valley. Note vesicular texture to immediate right of hammer head. Lens of medium-gray, calcitic marble (M) interlayered with greenstone in lower middle part of photograph.

Age and Correlation

Greenstone lithologically similar to that in Pilot Knob Valley occurs as part of the outer continental-margin sequence within the Garlock assemblage (Carr and others, 1984) in the El Paso Mountains (see also, Dibblee, 1952, 1967; Christiansen, 1961). The greenstone in the El Paso Mountains, inferred to be early Middle Devonian or older by Carr and others (1984), could be a stratigraphic equivalent of the greenstone unit in Pilot Knob Valley, but the actual age and correlation of the greenstone units remain a problem. Greenstone of unknown age also is structurally interleaved with Ordovician outer continental-margin or transitional facies rocks in the Goldstone area (Miller and Sutter, 1982).

Deposition of the Ordovician lower meta-argillite unit through the Middle Devonian sandy marble unit apparently was continuous, judging from the stratigraphic sequence of area B in Pilot Knob Valley. This interpretation implies that the greenstone unit in Pilot Knob Valley is either older than the Ordovician lower meta-argillite unit or younger than the Middle Devonian sandy marble unit. Clasts of Middle Devonian sandy calcitic marble occur in the lowermost Mississippian rocks assigned to the Robbers Mountain Formation (defined below) in area A of Pilot Knob Valley. The Middle Devonian sandy marble unit lies unconformably below the Robbers Mountain Formation in Pilot Knob Valley. In the El Paso Mountains, Middle to Upper Devonian meta-argillite lying stratigraphically above Middle Devonian sandy calcitic marble occurs immediately below the unconformity at the base of the Robbers Mountain Formation. Clasts of greenstone and Devonian sandy calcitic marble occur together in the Robbers Mountain Formation in the El Paso Mountains, suggesting that the greenstone unit is older than Mississippian. No units older than the sandy marble unit are known to have been eroded prior to the deposition of the Robbers Mountain Formation either in the El Paso Mountains or Pilot Knob Valley. If the composite stratigraphic section in outcrop area B represents a continuous rock succession, then it appears more likely that the greenstone unit is an Upper Devonian unit lying stratigraphically above the sandy marble unit, rather than an Ordovician unit lying stratigraphically below the Ordovician lower meta-argillite unit. It remains possible, however, that the composite stratigraphic sequence in area B is not continuous. If so, then the greenstone unit in Pilot Knob Valley could be Middle Devonian or older as inferred on the basis of structural position of greenstone in the El Paso Mountains. The possibility also remains that the greenstone unit is older than the Ordovician lower meta-argillite unit in Pilot Knob Valley, but we here propose a tentative age of Late Devonian(?) for the greenstone unit.

Mississippian Syntectonic Deposits

A Lower Mississippian silicified metaconglomerate and meta-argillite unit that rests unconformably on older Paleozoic outer continental-margin rocks has been mapped in both Pilot Knob Valley and the El Paso Mountains. The name "Robbers Mountain Formation" is proposed for this unit. These rocks are interpreted to represent early synorogenic deposits related to the Antler orogeny (Carr and others, 1984), which affected the western margin of Paleozoic North America during the Late Devonian and Early Mississippian.

Robbers Mountain Formation

The name "Robbers Mountain Formation" is here applied to Lower Mississippian meta-argillite, silty meta-argillite, and argillite-pebble metaconglomerate that rests unconformably on older Paleozoic outer continental-margin rocks in Pilot Knob Valley and in the El Paso Mountains. The Robbers Mountain Formation in Pilot Knob Valley crops out on an isolated hill in the northeastern part of area A and in the west-central part of area B. The type section (unsurveyed area, SE¼SW¼ Wingate Pass 15-minute quadrangle) was measured and described at the area A outcrop, where the most complete biostratigraphic information was obtained (fig. 8; pl. 1). The type section begins at lat 35°32'14" N., long 117°09'04" W. and follows a bearing of 280° (fig. 2). Because of restricted access to Pilot Knob Valley, reference sections (T. 29 S., R. 39 E., Garlock 7.5-minute quadrangle) were measured and described in the El Paso Mountains (fig. 9). The reference sections begin 1.7 km east of Gerbracht Camp at lat 35°26'53" N., long 117°49'05" W. and initially follow a bearing of 260° (fig. 9*C*). The formation is named for Robbers Mountain, a prominent peak located in the Pilot Knob 15-minute quadrangle, approximately 8 km southwest of the type section in area A (fig. 2).

The Robbers Mountain Formation consists of two informal members—a lower metaconglomerate member and an upper meta-argillite member. In the type section, the metaconglomerate member is approximately 80 m thick, and an incomplete section of the meta-argillite member is approximately 30 m thick (fig. 8). The rocks of area A are complexly deformed, and thickness measurements represent structural rather than stratigraphic thicknesses.

The metaconglomerate member rests unconformably on the distinctive Middle Devonian sandy marble unit in the type section in Pilot Knob Valley and on a Devonian meta-argillite unit that conformably overlies the sandy marble unit in the reference section in the El Paso Mountains (figs. 10*A* and *B*). The basal contact of the Robbers Mountain Formation is interpreted as either a slight angular unconformity or a major disconformity regionally having significant erosional relief, because the formation rests on different Devonian units in the El Paso Mountains than it does in Pilot Knob Valley.

Metaconglomerate Member

The basal contact of the Robbers Mountain Formation is sharp. The basal few meters of the formation above the contact contain pebbles and cobbles of subjacent Devonian rocks, such as sandy calcitic marble in the type section and meta-argillite in the reference section. Several beds of orange silty dolomitic marble as much as 10 cm thick and grayish-pink platy meta-argillite as much as 1 m thick are intercalated with metaconglomerate beds in the basal 10 m of the type section.

The metaconglomerate member consists mainly of pale-pink to pale-red-purple metaconglomerate, which weathers grayish red to grayish red purple (figs. 8 and 10*C*). The matrix of this clast-supported metaconglomerate is meta-argillite, which contains scattered quartz grains. The metaconglomerate is predominantly composed of flattened, angular meta-argillite, silty meta-argillite, and chert clasts, which mostly are pebble size, but cobble-size clasts are common in some intervals (fig. 10*C*). The metaconglomerate also contains sparse clasts of sandy calcitic marble. An interval several meters thick containing common cobbles and boulders of sandy calcitic marble occurs in the middle part of the metaconglomerate member in the type section. In the El Paso Mountains, there are local intervals containing sparse clasts of vesicular greenstone as large as small boulders as well as clasts of sandy calcitic marble.

Meta-Argillite Member

The metaconglomerate member is conformably overlain by the meta-argillite member. The basal contact of the meta-argillite member is abruptly gradational. Platy laminated meta-argillite and silty meta-argillite are the predominant rock types. The color of weathered outcrop ranges between pale red to pinkish gray and pale yellow brown to light gray. Fresh surfaces exhibit these same colors but commonly are stained by red and brown iron oxide. Minor quartzite, gritty quartzite, and pebble-conglomerate layers as much as 2 cm thick occur throughout the meta-argillite member. These coarser layers contain detrital conodonts. The thin quartzite and gritty quartzite layers are internally massive. The thin metaconglomerate layers consist of the same rock type that forms most of the metaconglomerate member. Overall, the meta-argillite member is a slope former.

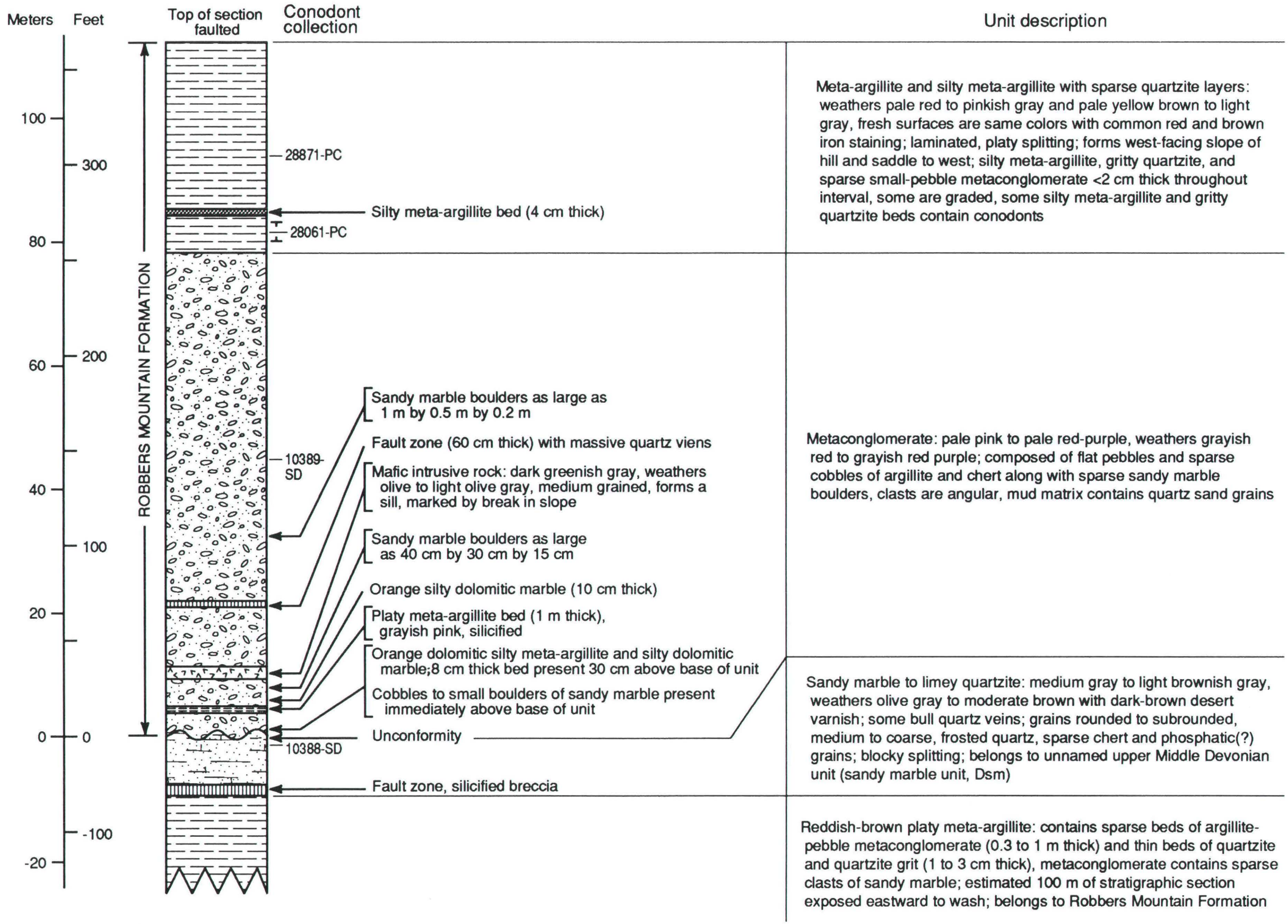


Figure 8. Type section of Lower Mississippian Robbers Mountain Formation measured in northeastern part of area A in Pilot Knob Valley. See figure 2 for location of measured section; see plate 1 for location of conodont collections and location of area A.

Age and Correlation

The age of the Robbers Mountain Formation has been determined by conodont biostratigraphy that is summarized in figure 8 and appendix 1. The formation is post-late Middle Devonian (Givetian), on the basis of the age of the subjacent sandy marble unit and on the clasts of sandy calcitic marble within the metaconglomerate member in the type section. Late Devonian conodonts were collected in meta-argillite from 15 to 25 m stratigraphically below the Robbers Mountain Formation in the El Paso Mountains (USGS colln. 10733-SD; lat 35°26'09" N., long 117°49'11" W.), further restricting the lower age limit of the Robbers Mountain Formation. Conodonts of Early Mississippian (Kinderhookian) age occur in the lower part of the meta-argillite member in the type section (appendix 1; colln. 28871-PC). The upper part of the meta-argillite member is faulted or removed by erosion in all known sections of the Robbers Mountain Formation. The Robbers Mountain Formation may possibly range in age from latest Devonian through Early Mississippian; however, it is tentatively interpreted here as Early Mississippian (Kinderhookian).

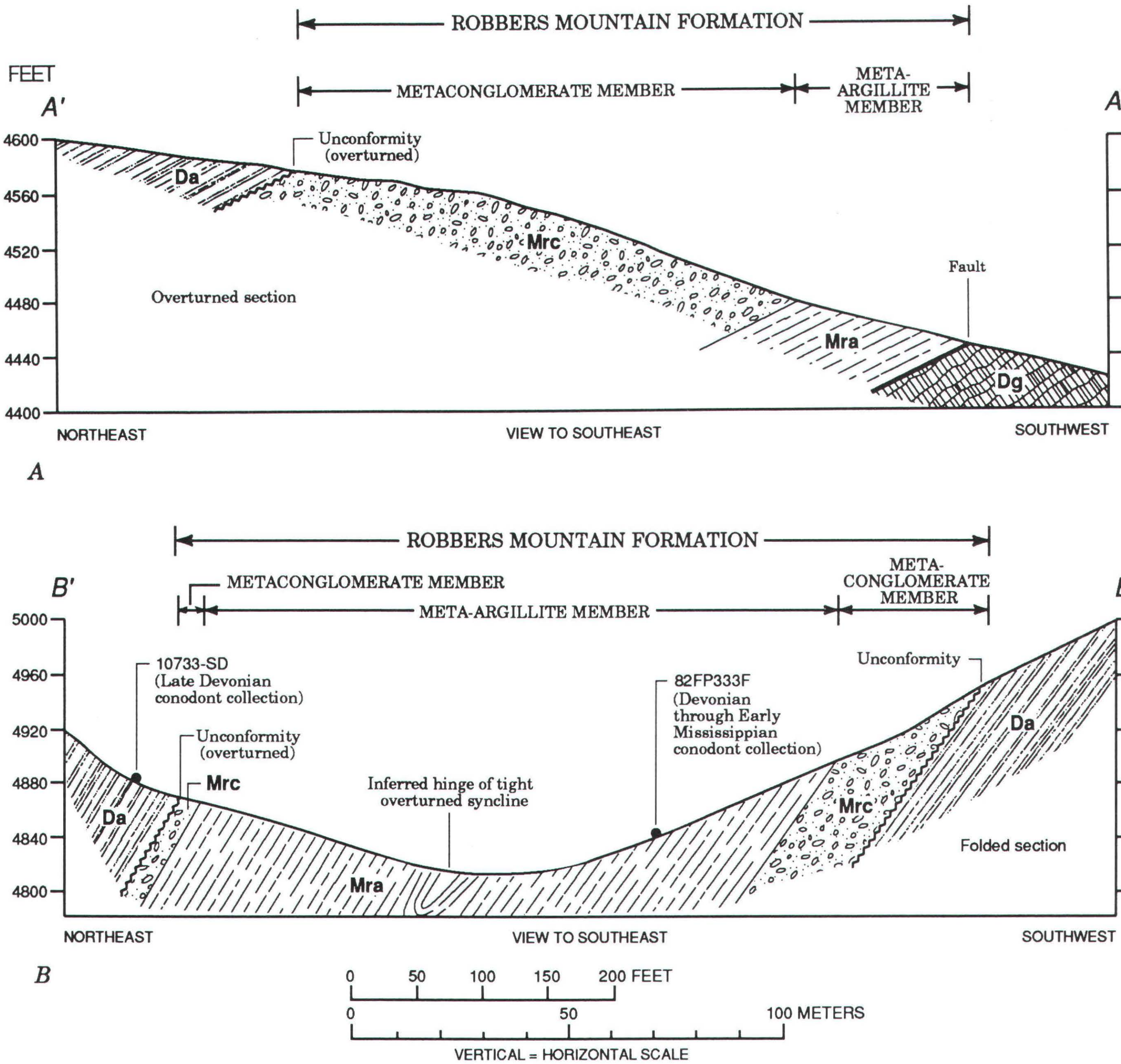


Figure 9. Reference sections for Lower Mississippian Robbers Mountain Formation in El Paso Mountains. Sections measured by F.G. Poole, 1974-75. Sections *A'-A* (*A*) and *B'-B* (*B*) are not to scale of geologic map (*C*) of Gerbracht Camp area (based on mapping by R.L. Christiansen, 1959-60 and M.D. Carr, 1980-81). Base from U.S. Geological Survey Garlock 7.5-minute quadrangle, California (1967); contour interval 40 feet. Note: Sections are views from north.

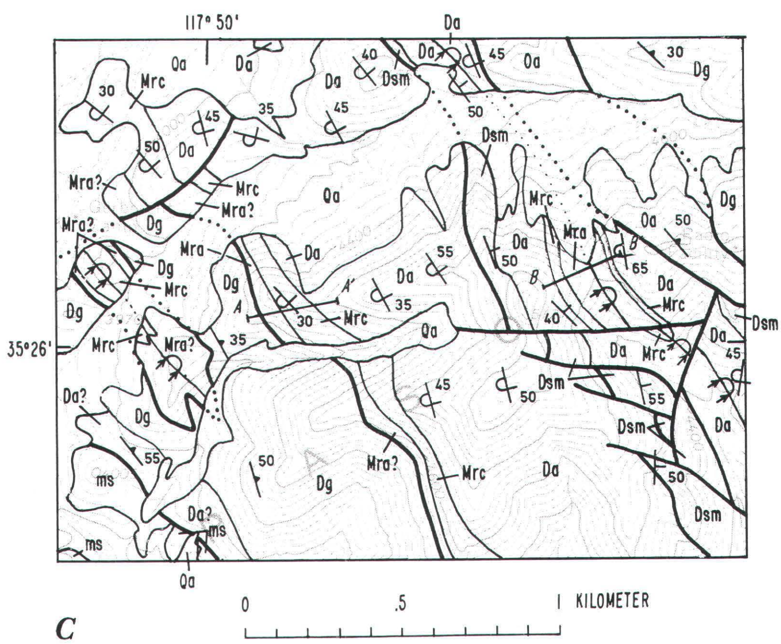
Rocks assigned to the Robbers Mountain Formation in the El Paso Mountains are correlated with the type section on the basis of their similar stratigraphic position, lithostratigraphy, and biostratigraphy. No other units correlative with the Robbers Mountain are known in the southwestern Great Basin-Mojave Desert region except for a lithologically similar metaconglomerate unit within a roof pendant south of Indian Wells Canyon in the southern Sierra Nevada (Geraci and others, 1987). Although it is composed primarily of argillite pebbles, the metaconglomerate in the Indian Wells Canyon pendant also contains distinctive clasts of sandy calcitic marble lithologically similar to those in the metaconglomerate member of the Robbers Mountain Formation, and it contains clasts of amphibolite that probably are recrystallized greenstone clasts similar those in the Robbers Mountain Formation in the El Paso Mountains.

The Lower Mississippian Webb Formation (as restricted by Ketner and Smith, 1982) in northeastern Nevada also is correlative, in a broad sense, to the Robbers Mountain Formation. Both formations consist, to a large extent, of rocks composed of clastic debris derived from erosion of the lower(?) and middle Paleozoic outer continental-margin section. This erosion of the outer continental-margin section might have been in response to the Antler orogeny. As is the case with the Webb Formation (Ketner and Smith, 1982), however, it remains unclear whether the Robbers Mountain Formation is an overlap assemblage that was deposited after Antler deformation, or an early synorogenic deposit of the Antler orogeny that subsequently was carried as part of the allochthonous outer continental-margin terrane during continued Antler deformation or younger orogenesis.

Metasedimentary Rocks of Uncertain Age

A sequence of coarse- to fine-grained quartzite and subordinate phyllite, metaconglomerate, and sparse calcitic marble makes up the low hills west and southwest of Moonshine Spring in the southeastern part of the map area (pl. 1, area G). The informal name "quartzite of Moonshine Spring" is proposed here for these rocks of uncertain age and correlation.

The sequence is divided into four mappable units on the basis of rock type. These units, in sequence from west to east, are the (1) orthoquartzite and metaconglomerate unit, (2) phyllite unit, (3) quartzite and micaceous quartzite unit, and (4) calcsilicate rock unit. It is not known whether this succession represents a stratigraphic or tectonic sequence. Most of the unit contacts are poorly exposed, but some appear to be gradational. No fossils have been found in any of the Moonshine Spring rocks. Intrusive relations, however, restrict their age to the pre-Late Cretaceous. The sequence is intruded on the southwest by Cretaceous granodiorite and is faulted against hornblende diorite on the ridge south of Moonshine Spring. An unqualified age assignment for these rocks must wait until correlations can be made with comparable stratigraphic sequences in the surrounding region.



C

EXPLANATION

- Qa — Alluvial deposits (Quaternary)
- Robbers Mountain Formation (Lower Mississippian)—Divided into:
  - Mra — Meta-argillite member
  - Mrc — Metaconglomerate member
- Da — Meta-argillite (Devonian)
- Dg — Greenstone (Upper or Middle Devonian)
- Dsm — Sandy marble unit (Middle Devonian)
- Oa — Meta-argillite (Ordovician)
- ms — Marble and schist (age uncertain)
- Contact
- Fault—Dotted where concealed
- 50 Bedding—Inclined
- 45 Bedding—Inclined, overturned
- 30 Foliation—Inclined
- Syncline—Overturned; dotted where concealed

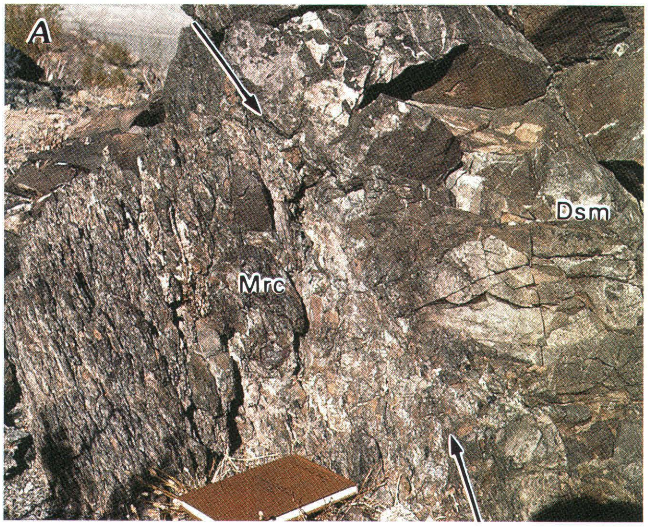
(Note: Units designated Qa, Da, Dg, and Oa on figure 9C are lithologically similar to units defined for Pilot Knob Valley area (pl. 1), but stratigraphic ranges may not be entirely equivalent. Members of Robbers Mountain Formation and sandy marble unit correlate directly with corresponding units in Pilot Knob Valley area.)

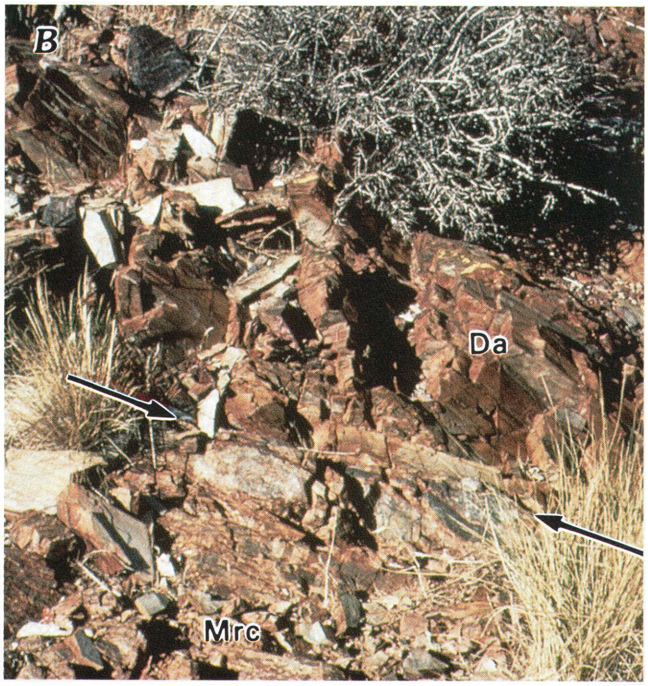
Figure 9. Continued.

Orthoquartzite and Metaconglomerate Unit

Massive, fine-grained orthoquartzite and quartzite-pebble metaconglomerate crop out at the western end of the ridge west of Moonshine Spring and on the hill farther south where the intrusive contact of the Cretaceous granodiorite is exposed. The orthoquartzite and metaconglomerate unit is the structurally lowest unit of the quartzite of Moonshine Spring. These siliciclastic rocks range from pale yellowish brown to dusky yellowish brown. They generally are nonbedded, but faintly bedded intervals within the unit are recognized locally. The orthoquartzites commonly are color banded or laminated.

The lower (westernmost) part of the unit, adjacent to the contact with the granodiorite, is predominantly quartzite-pebble to -cobble metaconglomerate (fig. 11*A*). Clasts are moderately well rounded and are flattened 4:1 in a nearly vertical, north-striking foliation that approximately parallels layering. Long axes of the clasts measure 1 to 5 cm. Sparse, weak lineations have a nearly vertical plunge. The metaconglomerate mostly is matrix-supported with





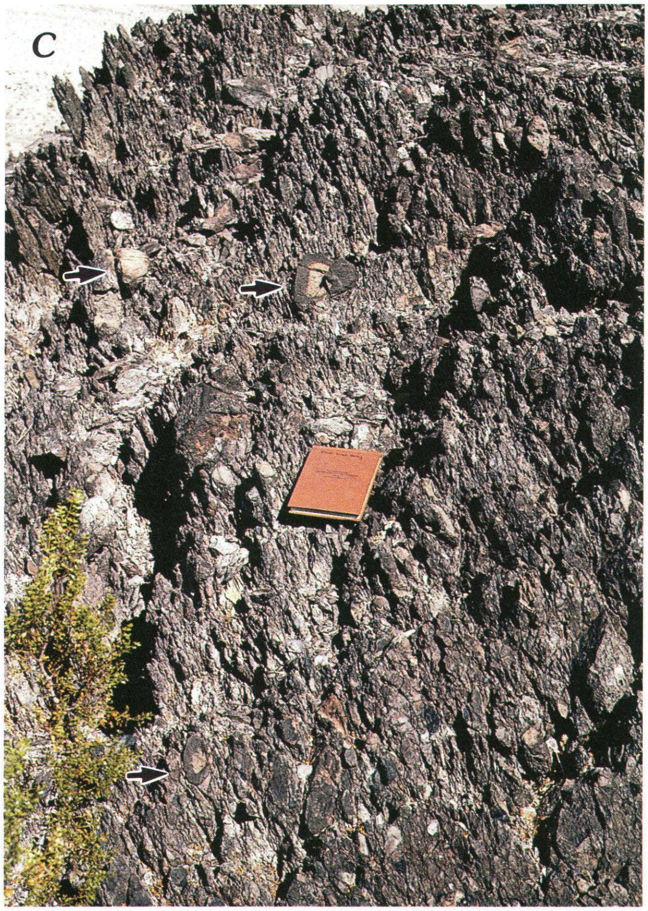


Figure 10. Lower Mississippian Robbers Mountain Formation. *A*, Lower contact of Robbers Mountain Formation in area A in Pilot Knob Valley. Metaconglomerate member (**Mrc**) resting unconformably on Middle Devonian sandy marble unit (**Dsm**). Contact (between arrows) is overturned and dipping to right (east). *B*, Lower contact of Robbers Mountain Formation in El Paso Mountains. Metaconglomerate member (**Mrc**) resting unconformably on Upper Devonian meta-argillite (**Da**). Contact (between arrows) is overturned and dipping to right (east). Note flattened, cobble-size clasts of meta-argillite in lowermost part of metaconglomerate member of Robbers Mountain Formation. These clasts were derived from underlying Upper Devonian meta-argillite. *C*, Typical outcrop of tectonically flattened metaconglomerate in metaconglomerate member of Robbers Mountain Formation in Pilot Knob Valley. Arrows point to examples of cobble- to boulder-size clasts derived from Middle Devonian sandy marble unit. Foliation (and overturned layering) dip steeply to right (east). Width of notebook 13.5 cm.

some clast-supported intervals. The matrix of the metaconglomerate is orthoquartzite. The metaconglomerate locally contains interbeds of quartzite and phyllite.

The conglomeratic interval grades into fine-grained orthoquartzite approximately 40 m east of its contact with the granodiorite; orthoquartzite predominates to the eastern edge of the outcrop belt. Locally, the orthoquartzite is distinctively coarse grained; elsewhere, there are intervals of micaceous quartzite and (or) meta-argillite. The orthoquartzite also contains sparse beds of pebble and small cobble conglomeratic quartzite that range from a few

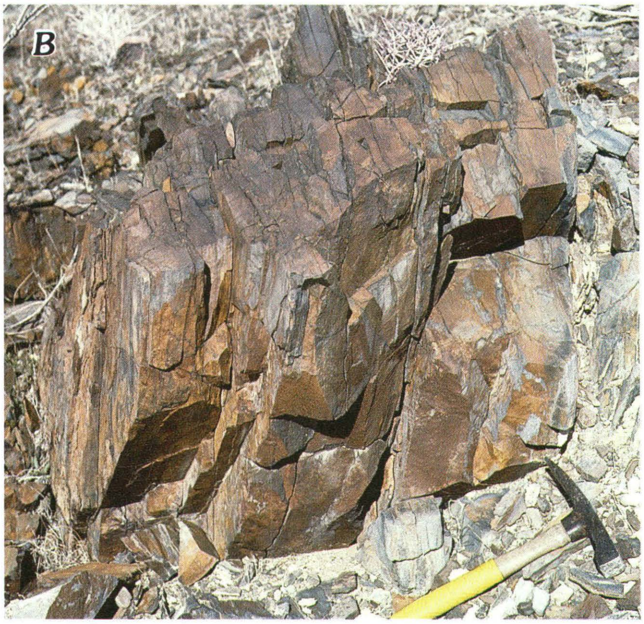


Figure 11. Quartzite of Moonshine Spring in area G in Pilot Knob Valley. *A*, Flattened orthoquartzite-clast metaconglomerate from the orthoquartzite and metaconglomerate unit. Foliation is nearly vertical. *B*, Phyllite unit. Foliation is nearly vertical. *C*, Quartzite and micaceous quartzite unit. Measuring staff is 60 cm. *D*, Calcsilicate rock unit.

centimeters to 0.5 m in thickness. Two such beds suggest eastward grading, but are not definitive. At one locality in the northernmost part of the outcrop belt, thin layers of marble (2 to 5 cm thick) are intercalated with orthoquartzite through an interval approximately 1 m thick.

Thin sections reveal that most of the unit is an orthoquartzite or orthoquartz metaconglomerate. The orthoquartzite is totally recrystallized, and most rocks exhibit granoblastic-polygonal textures, but in some samples, quartz grain boundaries are sutured, indicating slight deformation after recrystallization (Spry, 1969). Metaconglomerate clasts predominantly are polycrystalline fine-grained quartzite, but some samples also contain clasts consisting of single crystals. Muscovite is present in many samples, and occurs generally as sparse (1 to 2 percent) individual grains interstital to quartz, although some beds contain distinct screens of muscovite that separate individual quartzite laminae and compose as much as 10 percent of the rock. Some samples contain a few percent to as much as 25 percent recrystallized matrix consisting entirely of diopside. One diopside-bearing sample also contained sparse tremolite. Many samples contain sparse crystals of opaque oxide minerals.

Phyllite Unit

The orthoquartzite and metaconglomerate unit is succeeded to the east by the phyllite unit. The contact is not well exposed, but the orthoquartzite and metaconglomerate unit gradually becomes argillaceous toward its easternmost exposures suggesting the possibility of a primary gradational contact. Fresh phyllite is greenish gray to moderate bluish gray, but weathered phyllite is light to moderate brown. The phyllite is nonbedded with flaggy splitting along the foliation (fig. 11*B*). The foliation strikes north-northwest and dips nearly vertical; plunge of the lineation also is steep. The phyllite locally contains porphyroblasts of andalusite. In some areas, thinly laminated, fine-grained, micaceous quartzite is intercalated with the phyllite.

Thin sections reveal that most of the phyllite is composed of 50 to 75 percent quartz with a granoblastic texture and 25 to 50 percent micaceous minerals, mostly sericite or muscovite with lesser amounts of biotite and possibly some chlorite. Most samples contain crystals of opaque oxide minerals. In addition to quartz, muscovite, and chlorite, a sample of the porphyroblastic phyllite contained andalusite porphyroblasts. Most porphyroblasts have been recrystallized to sericite. This rock also contains traces of apatite and tourmaline.

Quartzite and Micaceous Quartzite Unit

The contact of the quartzite and micaceous quartzite unit with the phyllite unit is abrupt, but generally not well exposed. Quartzite occurring immediately above the phyllite unit is pale to moderate yellowish brown. Many intervals are distinctly banded in light- and moderate-hued bands, 1 to 5 m thick. The quartzite is fine grained and nonbedded (fig. 11*C*). The quartzite and micaceous quartzite unit contains intervals of meta-argillite, as well as intervals of pale-brown orthoquartzite. Locally, the rock exhibits a spaced cleavage (spacing 1 to 2 cm). Outcrop-scale folding occurs throughout the unit, and larger-scale repetitions of rock types within the unit also could be the result of folding. This unit is a moderately resistant ridge former.

Similar to the orthoquartzite and metaconglomerate unit to the west, the quartzite and micaceous quartzite unit is mostly orthoquartzite; it is composed primarily of quartz with a granoblastic-polygonal texture or, in some cases, sutured grain boundaries. Some orthoquartzites exhibit a distinct bimodal size distribution of the quartz grains. Muscovite and lesser amounts of biotite occur as interstitial crystals. In some of the more pelitic rock types, micaceous minerals form as much as 50 percent of the rock.

Calcsilicate Rock Unit

The quartzite and micaceous quartzite unit is overlain eastward by a unit of calcsilicate rock along a gradational basal contact. Freshly broken rock is greenish gray, whereas weathered rock is light brown. The rocks generally have an irregularly layered or mottled appearance (fig. 11*D*). Sparse beds of both calcitic and dolomitic marble as much as 3 m thick are present within the calcsilicate rock unit. Slopes underlain by this unit are lighter in color than those underlain by adjacent quartzite. Thin sections reveal that most of the calcsilicate rock unit is formed by rocks composed of quartz and diopside having a granoblastic-polygonal texture. In addition to quartz and diopside, these rocks contain fine crystals of tremolite and sparse calcite. No primary structures or textures were observed.

Age and Correlation

No definitive age assignment or correlations can be made presently for the quartzite of Moonshine Spring. The salient features of the Moonshine Spring section important to any correlation are the (1) predominance of orthoquartzite, micaceous quartzite, and metaconglomerate composed entirely of orthoquartzite clasts in an orthoquartzite matrix, (2) subordinative pelitic rocks, (3) sparse carbonate and calcsilicate rocks, and (4) absence of volcanic rocks.

The Moonshine Spring rocks differ from Paleozoic outer continental-margin sections in the region. The Ordovician through Devonian outer continental-margin sections forming most of the outcrops in Pilot Knob Valley and much of the Paleozoic sequence in the El Paso Mountains contain mostly pelitic rocks. Ordovician through Devonian sections in the El Paso Mountains and Goldstone area (fig. 1) that are transitional between outer and inner continental-margin facies contain far more pelitic and carbonate rocks than the Moonshine Spring section, and only sparse quartzite. The Pennsylvanian and Permian marine sections in the El Paso Mountains (see Dibblee, 1952, 1967; Carr and others, 1984) also differ from the Moonshine Spring rocks in that they contain mainly pelitic rocks, some carbonate rocks, and only sparse quartzite occurring as turbidite beds. The Upper Permian section in the El Paso Mountains contains abundant intermediate volcanic and volcaniclastic rocks.

The Paleozoic inner continental-margin sections of the Mojave Desert are predominantly continental-shelf carbonate rocks, and the quartzite of Moonshine Spring cannot be correlated with any of them. However, a general lithologic equivalence between the quartzite of Moonshine Spring and upper Proterozoic inner continental-margin rocks in the Mojave Desert remains possible. Upper Proterozoic units in continuity with Paleozoic inner continental-shelf sections show significant variation from the Great Basin across the Mojave Desert to the Transverse Ranges in southern California (Cameron, 1982; Miller and Cameron, 1982), but the sparse upper Proterozoic sections in southern California do contain thick successions of orthoquartzite, argillaceous quartzite, and meta-argillite, in varying proportions, with subordinate, but conspicuous, beds of carbonate rocks and conglomerate intervals almost exclusively containing well-rounded clasts of orthoquartzite.

The now-abandoned Mesquite Schist (Dibblee, 1952; Carr and others, 1984) exposed in the El Paso Mountains consists, in part, of a succession of micaceous quartzite and schist. These rocks are in contact with a sequence of interlayered calcitic marble and schist that forms the remainder of the Mesquite Schist. The marble and schist were interpreted as a metamorphosed succession of Ordovician transitional facies rocks similar to a less altered, fossiliferous section exposed farther east in the El Paso Mountains (Carr and others, 1984). One possible stratigraphic interpretation of the Mesquite Schist is that it consists of a lower part of upper Proterozoic and (or) Lower Cambrian fine-grained micaceous quartzite and schist and an upper part of metamorphosed Cambrian through Ordovician carbonate and pelitic strata that were deposited in a transitional setting between the outer and inner continental margin west of ancient North America. Similarly, the quartzite of Moonshine Spring might be upper Proterozoic and (or) Lower Cambrian clastic rocks in stratigraphic succession below the Ordovician to Devonian outer continental-margin rocks exposed in Pilot Knob Valley. In area F of Pilot Knob Valley, rocks of the outer continental-margin sequence are in contact with rocks tentatively assigned to the quartzite of Moonshine Spring, but the contacts are faulted and stratigraphic relations between the two sequences remain unknown.

Aside from the upper Proterozoic and Lower Cambrian continental-shelf clastic wedge, only a few other stratigraphic sequences in the southern Cordillera contain successions of quartz-rich clastic rocks that are even vaguely similar lithologically to the quartzite of Moonshine Spring. These include rocks interpreted as Mississippian foreland-basin deposits of the Antler orogenic belt and upper Paleozoic to lower Mesozoic rocks of a marine province known mainly from the Mojave Desert (Walker, 1988), where marine sedimentary deposits are interlayered with rocks erupted from isolated volcanic centers representing the incipient Cordilleran magmatic arc. The quartzite of Moonshine Spring in Pilot Knob Valley and the rocks interpreted as Mississippian Antler foreland-basin deposits (Poole, 1974) in the El Paso Mountains both contain sequences of metaconglomerate, orthoquartzite, micaceous quartzite, and meta-argillite. However, the rocks in the El Paso Mountains are predominantly argillite and contain distinct intervals with turbiditic sandstone, siltstone, and conglomerate beds, whereas the quartzite of Moonshine Spring typically is nonbedded and lacks diagnostic sedimentary structures. Furthermore, the inferred Mississippian foreland-basin deposits in the El Paso Mountains do not contain any calcsilicate or carbonate rocks lithologically similar to those in the Moonshine Spring section. Conglomerate in the inferred Mississippian section of the El Paso Mountains contains quartzite and metachert clasts, whereas the metaconglomerate in the Moonshine Spring section contains only orthoquartzite clasts.

Lower Mesozoic sections containing thick quartzite and metaconglomerate units have been described in the Mojave Desert (Walker, 1988). Most of these Mesozoic sections contain rocks of volcanic origin in addition to sedimentary rocks. Conglomerate clasts in these sections generally are mixed rock types, although quartzite clasts may predominate. The quartzite of Moonshine Spring, because it does not contain any volcanogenic rocks or polymictic conglomerate, probably is not a Mesozoic sequence.

The quartzite of Moonshine Spring is more similar lithologically, in our estimation, to sequences of upper Proterozoic and Lower Cambrian clastic rocks than to any other sequences of clastic rocks in the region. Originally such upper Proterozoic and Lower Cambrian rocks were part of a clastic wedge deposited along the western margin of North America. The Moonshine Spring section might have been deposited on the continental shelf in stratigraphic succession below Paleozoic continental-shelf carbonate rocks lithologically similar to those exposed in the Mojave Desert and Great Basin, or it might have been deposited west of the continental-shelf edge, forming a stratigraphic substrate for Paleozoic outer continental-margin and transitional facies rocks, such as those now exposed in Pilot Knob Valley or the El Paso Mountains.

MESOZOIC INTRUSIVE ROCKS

Cretaceous Plutonic Rocks

Granodiorite

The foothills between Moonshine Spring and Lead Pipe Spring expose parts of a granodiorite pluton that intrudes the quartzite of Moonshine Spring near the southeast corner of the map area (pl. 1). Dikes and small irregularly shaped bodies of the granodiorite intrude the metasedimentary units in many of the exposures west of Moonshine Spring. The granodiorite is medium grained and equigranular (fig. 12*A*). The rock is medium gray and peppered with dark biotite grains on fresh surfaces and yellow brown on weathered surfaces.

The granodiorite consists of approximately 60 percent plagioclase, 20 percent quartz, 10 percent alkali feldspar, 5 percent biotite, and 3 percent hornblende. Sphene is a common accessory mineral (approximately 2 percent), and apatite and zircon are present in trace amounts. Plagioclase occurs as subhedral laths, which rarely exhibit myrmekitic texture.

The tectonic foliation of the metamorphic rocks is cut by the intrusive granodiorite (fig. 12*B*). The pluton itself is unfoliated except within a few centimeters of its intrusive contact with the metasedimentary rocks. At such contacts, the foliation in the intrusive rocks parallels the contact, whereas the contact cuts the tectonic foliation of the metasedimentary units. The granodiorite intruded after the metasedimentary sequence was deformed and metamorphosed.

The granodiorite is cut by two strong sets of vertical joints that are approximately orthogonal, generally trending N. 60° E. and N. 35° W. Coarsely crystalline pegmatite dikes, 10 to 20 m wide and parallel to the northeast-trending joint set, intrude the granodiorite at the southern end of the spur that trends north-northwestward from the 3790-ft peak (SE. corner of pl. 1). Massive quartz veins are common with the pegmatite dikes. These dikes and veins are less resistant to erosion than the granodiorite and underlie saddles along the resistant granodiorite ridges. The dikes are present throughout the granodiorite terrane but are most abundant near its contact with the Cenozoic volcanic sequence.

Hornblende Diorite

Hornblende diorite crops out directly east of the metasedimentary rocks in the southernmost part of area G and on a small isolated knoll in the northeastern part of area F, where a weathered exposure is surrounded by alluvial deposits (pl. 1). The contact between the hornblende diorite and the metasedimentary rocks in area G is abrupt and subparallel to foliation in the metasedimentary rocks. A 3- to 4-m-wide zone of altered rocks occurs along the contact, and a 10-m-wide border zone within the igneous body is foliated parallel to the contact. Although the contact is interpreted as intrusive, it has been faulted. The hornblende diorite is separated from Tertiary volcanic rocks on the east by a mafic Tertiary dike (too narrow to map at 1:24,000 scale). The dike appears to be intruded along a normal fault but is sheared along its contact with the hornblende diorite. Contacts between the hornblende diorite and the granodiorite are not exposed.

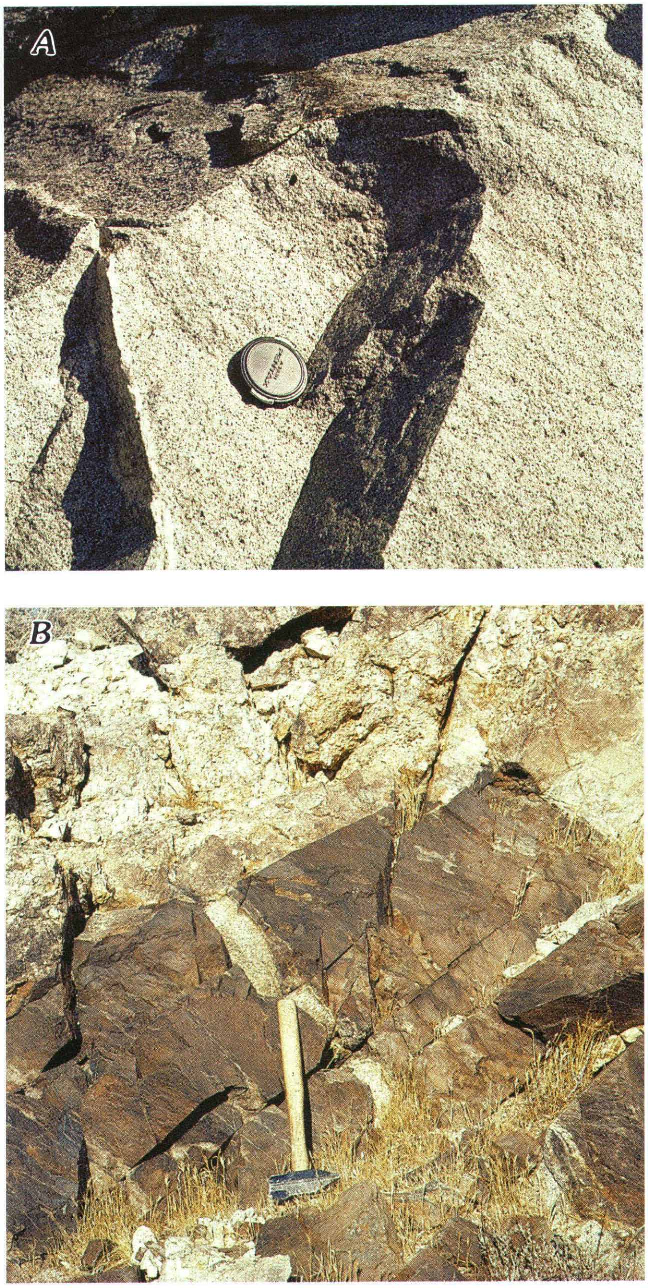


Figure 12. Cretaceous granodiorite in area G in Pilot Knob Valley. *A*, Typical rock type. *B*, Granodiorite intruding metamorphic country rock (quartzite of Moonshine Spring).

The hornblende diorite is dark gray, medium to fine grained, and nearly equigranular. In area G, the hornblende diorite consists of 60 to 65 percent plagioclase, 20 to 25 percent hornblende, 10 to 12 percent biotite, 0 to 2 percent potassium feldspar, and 1 to 2 percent opaque minerals. Commonly, the rock is altered and irregularly veined. Chlorite and calcite occur locally as alteration products and as vein minerals. In area F, the weakly foliated hornblende diorite contains more than 80 percent hornblende, approximately 15 percent plagioclase, and 5 percent opaque minerals.

Isotopic Ages and Correlation of Plutonic Rocks

Conventional potassium-argon ages were determined for biotite and hornblende from both the granodiorite and the hornblende diorite (table 1). Biotite from the granodiorite yielded an age of 79.3 Ma, while hornblende yielded an age of 77.8 Ma (sample C80PK-39). Biotite from the hornblende diorite in the Moonshine Spring area yielded an age of 79.4 Ma, while hornblende yielded an age of 77.5 Ma (C80PK-46). Hornblende from the hornblende diorite exposed northeast of area F yielded an age of 56.4 Ma (C80PK-57). The approximate concordance of the paired mineral ages for both the granodiorite and the hornblende diorite near Moonshine Spring suggests that the isotopic ages of both plutons represent their cooling ages. Although we interpret the intrusion of both the granodiorite and the hornblende diorite to be Late Cretaceous in age, the possibility exists that the plutons are older and that the isotopic systems of both mineral pairs were reset by some younger thermal event.

Granitoid plutons that intrude Paleozoic metasedimentary rocks in the vicinity of Goldstone, California (site), approximately 35 km to the southeast, have been interpreted as belonging to two episodes of plutonism (Miller and Sutter, 1982). The older episode is considered to be Late Jurassic in age (~148 Ma) and the younger episode Late Cretaceous (90 to 85 Ma). The cooling age of the younger plutons was interpreted by Miller and Sutter (1982) to be about 78.4 Ma. The inferred cooling ages for the granodiorite and the hornblende diorite exposed in southern Pilot Knob Valley are consistent with the younger episode of plutonism recognized by Miller and Sutter. It is noted, however, that the younger pluton in the Goldstone area is a biotite granite, and all of the hornblende-bearing plutonic rocks in that area were interpreted by Miller and Sutter as belonging to the Late Jurassic plutonic episode.

The 56.4-Ma potassium-argon age for hornblende from the hornblende diorite northeast of area F is interpreted as partial resetting of the isotopic system. Whether this mineral age reflects regional uplift, activity in some local (hydro)thermal system, or argon loss through weathering has not been determined. The fact that neither biotite nor hornblende from samples collected less than 4 km away shows any evidence of a thermal event younger than about 77.5 Ma suggests that some local process was responsible for the argon loss in the area F hornblende sample. On the other hand, Miller and Sutter (1982) postulated cooling through regional uplift as the mechanism for fixing the isotopic systems at about 45 Ma. Their hypothesis was based on apparent ages of 41.5 to 46.3 Ma for the first few percent of argon released in $^{40}Ar/^{39}Ar$ incremental heating experiments on three biotite samples from the inferred Late Jurassic plutons in the Goldstone area.

Hypabyssal Andesitic Dikes

Sparse porphyritic dikes of intermediate composition intrude the metasedimentary rocks in most of the outcrop areas. Most of these dikes are too small to show at a scale of 1:24,000. The dikes range from less than a meter to approximately 10 m in width, and some of the widest dikes can be traced continuously for more than 1 km. Mine shafts in areas B and C, where the dikes are most abundant, explore mineralization along the dikes. The dikes typically intrude parallel to the foliation of the metasedimentary rocks, but locally they cut across the structural grain of the older rocks. Some dikes are faulted along their contacts, and some are weakly foliated parallel to their contacts.

The porphyry dikes are altered, and weather yellow brown to red brown; no fresh rock was discovered. The phenocrysts are sericite pseudomorphs after euhedral to subhedral plagioclase laths as large as 2 mm in length. Relic zoning or twinning rarely are preserved. Phenocryst content ranges from 50 to 80 percent of the rock volume. The fine-grained matrix consists mostly of secondary sericite and opaque minerals but also contains a few percent quartz and trace amounts of carbonate minerals. Some dikes also contain secondary chlorite in the matrix. The rock generally is stained by iron oxide.

Age and Correlation

No isotopic ages were determined for the altered and deeply weathered hypabyssal andesitic dikes in Pilot Knob Valley. The only indication of their age is based on a tentative correlation of the dikes in Pilot Knob Valley with petrographically similar dikes intruding the Paleozoic metasedimentary rocks of the Garlock assemblage in the El Paso Mountains. The dikes of both areas are similar in appearance, have similar intrusive and structural relations with the country rock, and have similar mineralization associated with them. Therefore, the dikes in Pilot Knob Valley and the El Paso Mountains are tentatively interpreted as having been intruded during the same intrusive event. This event postdated deformation of the Paleozoic country rocks. Deformation of the Paleozoic rocks has

Table 1. Potassium-argon age data for granitoid rocks west of Moonshine Spring

[Isotopic abundances and decay constants used in this study are those recommended by the IUGS Stratigraphic Comission, Subcomission on Geochronology (Steiger and Jager, 1977). Argon measurements and age calculation by Elliot Kollman, U.S. Geological Survey, Menlo Park, Calif. Potassium measurements by Paul Klock, U.S. Geological Survey, Menlo Park, Calif. Sample locations shown on pl. 1, Pilot Knob, California, 15-minute quadrangle: C80PK-39 (granodiorite)—lat 35°27'20" N., long 117°06'22" W.; C80PK-46 (hornblende diorite)—lat 35°27'26" N., long 117°06'06" W.; C80PK-57 (hornblende diorite)—lat 35°28'05" N., long 117°08'18" W.]

Sample Number	Mineral	Percent K_20	$^{40}Ar_{rad}$ (moles/g)	$\frac{^{40}Ar_{rad}}{^{40}Ar\ total}$	Calculated age (Ma)
C80PK-39	Biotite	9.12 = 9.115 9.11	1.064×10^{-9}	0.86	79.3 ± 1.6
	Hornblende	0.733 = 0.7375 0.742	8.446×10^{-11}	0.67	77.8 ± 1.6
C80PK-46	Biotite	9.26 = 9.255 9.25	1.082×10^{-9}	0.89	79.4 ± 1.6
	Hornblende	0.805 = 0.0825 0.800	9.147×10^{-11}	0.72	77.5 ± 1.6
C80PK-57	Hornblende	0.476 = 0.475 0.474	3.920×10^{-11}	0.38	56.4 ±1.1

been dated as latest Permian in the El Paso Mountains (Carr and others, 1984). The event predated major displacement along the Garlock fault if the dikes are correctly correlated between the El Paso Mountains and Pilot Knob Valley. In the El Paso Mountains, the porphyry dikes are separated by a major unconformity from the overlying Goler Formation, which was reported as Paleocene in age by Dibblee (1952), McKenna (1960), West (1970), and Cox (1982). Cox and Diggles (1986) summarized evidence for a Paleocene and Eocene age for the Goler Formation but could not rule out the possibility of a latest Cretaceous age for its lowermost part. Zircons from one such dike northwest of Holland Camp in the El Paso Mountains yielded a fission track date of 99.5±8.8 Ma, indicating that the dike was not subjected to temperatures greater than about 175 to 225 °C since the Early Cretaceous (table 2). In the absence of more definitive age determinations, the minimum age for this dike and its associated mineralization is interpreted as Early Cretaceous(?), but it might be as old as Triassic.

CENOZOIC ROCKS

Tertiary Volcanic and Sedimentary Rocks

The Paleozoic metasedimentary and Mesozoic plutonic rocks in Pilot Knob Valley are unconformably overlain by a sequence of Tertiary volcanic and sedimentary rocks. The Tertiary rocks make up Robbers Mountain, the high ridges south of Pilot Knob Valley, and the ridges and low hills east of the Paleozoic rock exposures. The Tertiary sequence is predominantly ash-flow and ash-fall(?) tuff ranging from thinly layered, nonwelded, pyroclastic deposits to thick, welded, ash-flow cooling units. Fluvial deposits form a subordinate constituent of the Tertiary section. The Tertiary deposits locally are intruded by a set of northwest-trending vertical dikes, which range from 1 to 30 m in width. The widest dikes of this set are from 0.5 to 1.5 km long. The dikes are most abundant along the ridge south of Pilot Knob Valley between Lead Pipe Spring and Moonshine Spring and in the hills north of Moonshine Spring. The dike rocks are fine grained and weather to pale yellow brown. Some of the narrower dikes have black, glassy, chilled margins. The Tertiary rocks were not studied and were not subdivided for mapping in this report.

Quaternary Deposits

A system of coalescing alluvial fans originating from the volcanic upland south of Pilot Knob Valley surrounds most of the exposures of Paleozoic rocks in the map area. The alluvial-fan deposits consist of unconsolidated silt, sand, and gravel. The most recent deposits form broad, braided washes. Older fan deposits, while maintaining their fan morphology, are sharply incised by younger drainages, especially in the upper fan areas. The oldest of

Table 2. Fission-track data for zircon from hypabyssal andesitic dike near Holland Camp in the El Paso Mountains

[Sample location: Garlock, California, 7.5-minute quadrangle; lat 35°28'16" N., long 117°48'31" W. Decay constant (λ_f)=7.03×10^{-17}yr^{-1}.]

Sample number	Analysis[1] number	Mineral	Spontaneous-track density[2] (ρ_s) (10^6 tracks/cm^2)	Induced-track density[2] (ρ_i) (10^6 tracks/cm^2)	Neutron flux (ϕ) (10^{15} n/cm^2)	Fission-track age (Ma±2σ)	Number of grains	Correlation coefficient (r)	Uranium content (ppm)
C82EP-91	DF-4449	zircon	10.16 (1317)	5.23 (339)	0.862	99.5±8.8	6	0.74	190

[1] Analysis by C.W. Naeser, U.S. Geological Survey, Denver, Colorado.
[2] Numbers in parentheses indicate total number of tracks counted in each determination.

the alluvial deposits are preserved as east-northeast-trending lines of small hills near the axis of Pilot Knob Valley (Smith and others, 1968). According to Smith and others (1968), these so-called old gravels are younger than the Pleistocene Christmas Canyon Formation, and all of the alluvial-fan deposits within the map area are presumed to be of Quaternary age. Uplift and erosion of the old gravel deposits near the axis of Pilot Knob Valley apparently are in response to deformation along the Garlock fault (Clark, 1973). The Quaternary deposits were not studied and were not subdivided for mapping in this report.

METAMORPHISM

Mineral associations diagnostic of metamorphic grade are sparse in the quartz-rich metasedimentary rocks of Pilot Knob Valley. Most of the pelitic or silty rocks consist predominantly of quartz+muscovite±calcite. In addition to muscovite, some rocks contain biotite and a few contain chlorite. A conspicuous porphyritic layer within the phyllite unit of the quartzite of Moonshine Spring contains the assemblage quartz+muscovite+andalusite+chlorite. Opaque oxide minerals also are common in this rock. Tourmaline and apatite occur as accessory minerals. Sericite forms pseudomorphs after andalusite porphyroblasts. Similar sericite-filled pseudomorphs were described by Smith and Ketner (1970) in rocks from area E and probably are pseudomorphs after andalusite, one of several alternative explanations offered for their origin by Smith and Ketner. Sericite pseudomorphs after andalusite also occur in some of the highest grade metasedimentary rocks in the El Paso Mountains (Christiansen, 1961), such as the rocks assigned to the Mesquite Schist by Dibblee (1952); pseudomorphs after andalusite occur locally in Ordovician schist in the Goldstone area, as well.

The calcsilicate rocks from the Moonshine Spring section contain the assemblage quartz+diopside+tremolite+calcite. The greenstone unit contains chlorite+biotite+calcite+albite+epidote+sphene+opaque oxide minerals.

All of the conodonts recovered from the metasedimentary rocks in Pilot Knob Valley have conodont color alteration indices (Epstein and others, 1977) of 5, which suggests that the maximum temperature reached during metamorphism of these rocks was in the range 300 to 480 °C (Rejebian and others, 1987).

The metamorphic mineral assemblages and conodont-based temperature determinations described in general above, coupled with the common presence of foliations defined by preferred orientations of metamorphic mineral growth, indicate that the Paleozoic rocks in Pilot Knob Valley underwent regional low- to medium-grade metamorphism, which was accompanied, at least in part, by deformation. The presence of andalusite indicates pressure of less than 3.86 kb (Spear and Cheney, 1989). Replacement of most of the andalusite porphyroblasts by sericite suggests subsequent retrograde metamorphism. The equilibrium paragenesis diopside-tremolite-calcite-quartz indicates temperature in excess of about 500 °C but not more than about 600 °C for pressures of 2 to 4 kb, except in cases where the fluid concentration of carbon dioxide (X_{CO_2}) is less than about 0.1 (Eggert and Kerrick, 1981). The temperatures indicated by the metamorphic mineral assemblages for the calcsilicate rocks from area G are higher than those indicated by the conodont alteration indices for rocks from the northern outcrop areas, suggesting either that the rocks in the south experienced higher temperatures or that one or both of the experimentally calibrated geothermometers is inaccurate.

STRUCTURAL GEOLOGY

Layering and foliation in the metasedimentary rocks of areas A through E strike northward and dip steeply either to the east or west (pl. 1). In areas F and G, layering and foliation strike northwest and generally dip steeply northeast. In nearly all areas, layering is folded on outcrop and more rarely on map scale. Where stratigraphy is best defined in areas A and B, units are repeated by both mapscale folds and faults nearly parallel to layering. Local overturning of stratigraphic sequences so that they young westward and dip eastward, as well as an apparent west-vergent asymmetry of several mapscale folds suggest an overall top-to-the-west tectonic transport with respect to the present structural orientations. That significant ductile flattening accompanied deformation is indicated by flattened clasts, which have long to short axis ratios of three or four to one measured in the plane of foliation in metaconglomerates of both the quartzite of Moonshine Spring and the Robbers Mountain Formation.

Most of the contacts between the metasedimentary rock units are faults. Generally these faults are steep, and the fault planes are oriented at a small angle to layering. Near the middle of area B, one of the faults follows the core of a syncline. Reversal of stratigraphic facing across this and other faults in the area suggests that many of the structural contacts formed as faulted tight or isoclinal folds and that both the folding and faulting are consequences of a single deformational event. There is at least one case in the northwestern part of area A where a faulted contact between the Middle Devonian sandy marble unit and the adjacent Ordovician lower meta-argillite unit apparently is folded. However, all of the observed relations between folds and faults in the area can be explained in the context of a single progressive deformation. The faults and attendant folding have structurally interleaved the stratigraphic sequence so that units are omitted at some fault contacts, and at other contacts, units are repeated.

In the few cases where striae were observed on the northward-striking fault surfaces in areas A through E, they were near horizontal indicating that the youngest movement was predominantly strike slip. It is assumed in these cases that the striae were formed during the Cenozoic in the context of motion on the left-lateral Garlock fault zone. As such, the movement indicated by the striae is unrelated to the structural framework in which these faults formed. Where the northward-striking fault through the middle of area B intersects the westward-flowing drainage system that cuts across the north end of area B, a fault surface striking N. 40° W. and dipping 65° SW. displaces Quaternary alluvial deposits in a small drainage along the trend of the bedrock fault. (The thin Quaternary deposits along the narrow channel are not shown on pl. 1.) On aerial photographs, two tributaries of this drainage system appear to deflect in a right-lateral sense where they cross the fault trend. (We were unable to return to the field to verify these relations.) Right-lateral movement on north- to northwest-striking faults would be consistent with a stress orientation conducive to left-lateral movement on the Garlock fault. Sparse striae and offset layering on the northward-dipping faults that cut through areas F and G indicate down-to-the-north dip slip and left-lateral strike slip components of movement. Such movement also is consistent with displacements related to the Garlock fault system. It is not known whether the northward-dipping faults formed during the Cenozoic as part of the Garlock system, or whether they are a reactivated element of an older fault system.

Although folds are common at outcrop scale, there was insufficient time available for a systematic study of fold geometries. The predominant outcrop-scale folds have northward-striking and steeply dipping axial planes. Attitudes of fold axes vary but most tend to fall into two groups, plunging either near vertical or near horizontal. Map-scale folds, such as those in the northernmost part of area A, are gently plunging and westward vergent with upright to steeply eastward-dipping axial planes. No consistent sense of asymmetry was determined for the outcrop-scale folds. Folds generally are close to tight, having sharp hinges and straight limbs. Thickening occurs in the hinge areas of the more tightly appressed folds, indicating ductile behavior. Locally, spaced axial-plane cleavage surfaces are developed in hinge areas. In at least two cases, isoclinal folds having moderately well developed axial-plane foliation are refolded by open, upright folds. The second generation folds are concentric and have striae developed perpendicular to the hingelines on the folded layers, indicating flexural slip. Fold styles and conditions of folding appear similar to those reported for the El Paso Mountains (Christiansen, 1961) and Goldstone area (Miller and Sutter, 1982).

The age of the folding, faulting, and metamorphism could not be meaningfully restricted solely on the basis of information from Pilot Knob Valley. This deformation postdated deposition of the Lower Mississippian Robbers Mountain Formation and predated the intrusion of the Cretaceous granodiorite west of Moonshine Spring, as indicated by crosscutting intrusive relations along the western contact of the metasedimentary rocks in area G (fig. 12*B*). In the easternmost part of area B, hypabyssal andesitic dikes intrude parallel to foliation in the country rock. Several of the dikes in area B are very weakly foliated parallel to their contacts, but most of the andesitic dikes in the Pilot Knob Valley area are unfoliated; intrusion of the whole set of dikes is interpreted as postkinematic. The deformation and metamorphism of the metamorphic rocks in Pilot Knob Valley are similar to that affecting the Garlock assemblage in the El Paso Mountains. The age of deformation and metamorphism in the El Paso Mountains has been restricted to the Late Permian (Carr and others, 1984), and we infer a Late Permian age for the deformation and metamorphism of the correlative rocks in Pilot Knob Valley. Miller and Sutter (1982) similarly inferred a Permian age for the deformation and metamorphism of the metamorphic rocks of the Goldstone area, which also correlate with parts of the Garlock assemblage.

There is no direct structural evidence that the Late Devonian and (or) Early Mississippian Antler orogeny affected the metasedimentary rocks in Pilot Knob Valley. However, the age of the unconformity at the base of the Robbers Mountain Formation falls within the age limits traditionally assigned to the Antler orogeny (Poole, 1974). The metaconglomerate forming the lower member of the Robbers Mountains Formation represents an abrupt change in sedimentation from the predominantly fine grained Devonian rocks. The presence in the metaconglomerate member of the Robbers Mountain Formation of clasts derived from Devonian units indicate substantial erosion. The changes in the sedimentation recorded by the stratigraphy of the metamorphic rocks in Pilot Knob Valley could have been a local consequence of the Antler orogeny. Alternatively, other causes, such as a lowering of sea level, could have triggered erosion in submarine canyons and the deposition of conglomeratic debris flows lower on the continental slope or continental rise. A substantial glacioeustatic event does mark the Devonian-Carboniferous boundary (Flajs and others, 1988).

DISCUSSION AND CONCLUSIONS

The metamorphic rocks of Pilot Knob Valley represent a basinal marine depositional sequence consisting chiefly of Ordovician through Devonian meta-argillite with subordinate quartzite, carbonate rocks, and greenstone. The Ordovician meta-argillite units appear to represent a hemipelagic, starved-basin accumulation of very fine grained detrital sediments and some radiolarian ooze. The rain of very fine grained sediment was interrupted in the Silurian and (or) Early Devonian by an influx of turbidite or contourite flows composed predominantly of fine to medium quartz sand. A resumption of sediment-starved basin conditions during the Early Devonian is recorded by a succession of meta-argillite and thinly interbedded meta-argillite and fine-grained calcite marble. An influx of Middle Devonian debris flows composed of quartz sand and carbonate detritus once again interrupted the hemipelagic sedimentation. Eruptions of submarine basalt recorded by the occurrence of greenstone may have occurred in the Late Devonian, but the age is uncertain.

Ordovician through Devonian metasedimentary rocks in Pilot Knob Valley compose a suite of rock types and sedimentary structures that are broadly indicative of deposition in an outer continental-margin setting (continental-slope, continental-rise, and near-margin ocean basin). The quartz-rich Silurian and (or) Lower Devonian turbidites (or contourites) and the quartz sand and carbonate detritus of the upper Middle Devonian sandy marble unit suggest proximity to a mature sediment source probably on an adjacent continental shelf or cratonic platform. Furthermore, conodont fragments reworked into the sandy marble unit include robust forms indicative of high-energy continental-shelf or -platform biofacies (appendix 1).

This Ordovician to Devonian outer continental-margin succession is overlain disconformably or with angular unconformity by Lower Mississippian metaconglomerate that grades abruptly upward into meta-argillite. The sudden influx of coarse debris flows was accompanied by erosion of the underlying outer continental-margin section, possibly in submarine canyons higher on the continental slope. The abrupt change in sedimentation falls within the broad age limits for the Antler orogeny, and the Robbers Mountain Formation may represent a local stratigraphic manifestation of that orogenic event. However, there are no direct structural indications of the Antler orogeny in the outer continental-margin terrane of the Mojave Desert or southwesternmost Great Basin, and the stratigraphic relations between the Robbers Mountain Formation and older Paleozoic units alternatively could have resulted from a glacioeustatic event that marks the Devonian-Carboniferous boundary, or an inferred period of Late Devonian to Early Mississippian extension along the western continental margin of North America hypothesized by Turner and others (1989).

The southernmost metasedimentary sequence in Pilot Knob Valley, the quartzite of Moonshine Spring, consists of micaceous quartzite with subordinate orthoquartzite, orthoquartzite-cobble metaconglomerate, phyllite, calcsilicate rocks, and sparse marble. These rocks are of uncertain age and may belong stratigraphically below the Ordovician to Devonian outer continental-margin rocks. The quartzite of Moonshine Spring appears to represent a shallower water marine facies than the Ordovician through Devonian outer continental-margin succession and is in some respects lithologically similar to rocks of the upper Proterozoic and (or) Lower Cambrian wedge of continental-shelf clastic rocks characteristic of the Great Basin and Mojave Desert.

The fragmental history for the early and middle Paleozoic suggested here on the basis of rocks in Pilot Knob Valley broadly mimics a general history presented by Turner and others (1989) for the extensive terranes of outer continental-margin rocks in the Roberts Mountains allochthon and northern Canadian Cordillera. Notably, Turner and others emphasized starved, deep-water basin conditions during the Middle and Late Ordovician, an influx of clastic debris during the Silurian, a return to starved-basin conditions during the Early and Middle Devonian, and a period of tectonism accompanied by a renewed influx of clastic debris during the Late Devonian and (or) Early Mississippian. Turner and others cited intertonguing stratigraphic sequences from the Canadian Cordillera that tie Paleozoic outer continental-margin strata there to North America inner continental-margin sequences. The chemistry of greenstones from the Roberts Mountains allochthon indicates alkalic compositions, regardless of their age, suggesting an intraplate origin consistent with a rifted outer continental-margin setting (Madrid, 1987; Turner and others, 1989). On the basis of stratigraphic and structural similarities, Turner and others proposed that the tie to North America extended from the outer continental-margin strata of the northern Canadian Cordillera to strata of the Roberts Mountains allochthon. Similarly, we propose that the Paleozoic metasedimentary rocks of Pilot Knob Valley belong to the outer continental-margin terrane of western North America, extending that terrane southward as far as the north-central Mojave Desert. It remains unknown whether the outer continental-margin rocks in the Mojave Desert originally formed at their present latitude, whether they are part of an allochthon of the Antler orogeny, and (or) whether they were translated into their present position during some later orogenic event or continental truncation.

The marine sequence exposed in Pilot Knob Valley was deformed and weakly to moderately metamorphosed, possibly in the Late Permian. The complex style of tectonic interleaving, which was accomplished through tight westward-vergent folding and (thrust?) faulting at small angles to layering, is similar to that of other outer continental-margin rock sequences in the north-central Mojave Desert and southwestern Great Basin, notably the outer continental-margin sequences in the El Paso Mountains (Christiansen, 1961) and Goldstone area (Miller and Sutter, 1982). The Cretaceous granitic rocks and hypabyssal andesitic dikes that intrude the metamorphic rocks postdate the deformation and metamorphism.

The stratigraphic section in Pilot Knob Valley correlates generally with the western part of the Garlock assemblage in the El Paso Mountains (units 1 to 9 of the Garlock Formation of Dibblee, 1967; lower and middle Paleozoic eugeoclinal rocks of Carr and others, 1984). Correlations for several especially distinctive units, such as the Middle Devonian sandy marble unit and the Lower Mississippian Robbers Mountain Formation, are particularly strong and are supported by both biostratigraphic and rock-stratigraphic similarities. These correlations reinforce the conclusion of Smith and Ketner (1970) that the metamorphic rocks in Pilot Knob Valley are a continuation of the Garlock assemblage, offset from the El Paso Mountains by left-lateral displacement along the Garlock fault.

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APPENDIX 1

APPENDIX 1.—LIST OF CONODONT COLLECTIONS FROM PILOT KNOB VALLEY

[Collections are identified by USGS collection numbers; geologist's field collection numbers follow in parentheses. Collections are cataloged by USGS collection numbers and redeposited in the conodont laboratory of the U.S. Geological Survey, Reston, Virginia. CAI = Conodont color alteration index (Epstein and others, 1977). All collections were analyzed by Anita G. Harris.]

ORDOVICIAN

9450-CO (C80PK-105C)
Lat 35°31'55" N., long 117°09'21" W.
Middle subunit of the lower meta-argillite unit
Area A
1 Sc element of either *Baltoniodus* sp. indet. or *Amorphognathus* sp. indet.
1 *Panderodus* sp. indet. fragment
2 indet. bar fragments
Age: Middle to Late Ordovician
CAI = 5 (host rock reached at least 300 °C)

9451-CO (C80PK-115C)
Lat 35°31'49" N., long 117°09'29" W.
Middle subunit of the lower meta-argillite unit
Area A
1 Pb element of *Amorphognathus* sp. indet.
2 *Dapsilodus*? *similaris* (Rhodes) elements
2 *Drepanoistodus suberectus* (Branson & Mehl) elements
4 *Protopanderodus* aff. *P. liripipus* Kennedy, Barnes & Uyeno elements
28 indet. chiefly coniform fragments
Age: middle Middle Ordovician through Late Ordovician (*Baltoniodus gerdae* Subzone through *Amorphognathus ordovicicus* Zone)
Biofacies: cool-water cosmopolites
CAI = 5 (host rock reached at least 300 °C)

9452-CO (C80PK-117C)
Lat 35°31'52" N., long 117°09'14" W.
Middle subunit of the lower meta-argillite unit
Area A
1 *Protopanderodus* sp. indet. fragment
1 acodontiform element
1 oistodontiform element
Age: middle Early through Late Ordovician
CAI = 5 (host rock reached at least 300 °C)

9453-CO (C80PK-142C)
Lat 35°30'47" N., long 117°09'09" W.
Middle subunit of the lower meta-argillite unit
Area B
1 *Dapsilodus*? *similaris* (Rhodes) element
2 *Protopanderodus* sp. indet. fragments
4 indet. coniform fragments
Age: middle Middle Ordovician through Late Ordovician
CAI = 5 (host rock reached at least 300 °C)

SILURIAN TO DEVONIAN

10374-SD (C80PK-116C)
Lat 35°31'51" N., long 117°09'20" W.
Quartzite and meta-argillite unit
Area A
All conodonts embedded in rock matrix
2 *Panderodus* sp. elements
Unassigned elements:
2 P (ozarkodiniform)
1 M
1 Sa
8 Sc
50+ indet. bar, blade and coniform fragments
Age: Silurian through Middle Devonian (probably Silurian through Early Devonian). The presence of *Panderodus* together with post-Ordovician Sc elements restrict the age of this collection to Silurian through Middle Devonian. The collection is probably Silurian through Early Devonian because there are many ramiform elements and no readily apparent platform elements. During this time interval, many ozarkodinid apparatuses contain bladelike platform elements that would be difficult to identify as such when embedded in matrix.
CAI = 5 (host rock reached at least 300 °C)

10731-SD (82FP-330F)
Lat 35°31'51" N., long 117°09'20" W.
Quartzite and meta-argillite unit
Area A
All conodonts embedded in rock matrix
Ozarkodina excavata excvata (Branson & Mehl)
1 Pa element
3 Pb elements
1 M element
2 Sc elements
2 unassigned Sc elements
14 indet. bar and blade fragments
Age: Late Silurian (Wenlockian) to late Early Devonian (early Emsian)
CAI = 5 (host rock reached at least 300 °C)
Note: *Ozarkodina excavata excavata* is the dominant conodont in continental-margin and deeper water deposits of Late Silurian to late Early Devonian age.

10732-SD (82FP-331F)
Lat 35°30'55" N., long 117°09'09" W.
Quartzite and meta-argillite unit
Area B
All conodonts embedded in rock matrix
1 *Belodella* sp. element
1 Sb element of post-Ordovician morphotype
7 indet. bar and blade fragments
Age: Silurian through Devonian
CAI = 5 (host rock reached at least 300 °C)

DEVONIAN

10206-SD (NWC-12)
Lat 35°31'59" N., long 117°09'30" W.
Sandy marble unit
Area A
9 I element fragments of *Icriodus* sp. indet. (short-platform morphotype without processes)
18 Pa element fragments of *Polygnathus* spp. indet.
51 indet. bar, blade, and platform fragments
Age: Middle to Late Devonian
Biofacies: platformal or shelfal, normal marine
CAI = 5 (host rock reached at least 300 °C)

10388-SD (C80PK-144C)
Lat 35°32'14" N., long 117°09'04" W.
Sandy marble unit
Area A

1 I element fragment of *Icriodus* sp. indet.
5 Pa elements (mostly incomplete) of *Polygnathus ansatus* Ziegler & Klapper of *P. timorensis* Klapper, Philip & Jackson
4 Pa elements of *Polygnathus linguiformis linguiformis* Hinde
1 Pa element of *Polygnathus* aff. *P. varcus* Stauffer
24 Pa element fragments of *Polygnathus* spp. indet.
1 unassigned M element
111 indet. bar, blade, and platform fragments

Age: late Middle Devonian (Givetian) and possibly Middle *varcus* Subzone. This chiefly polygnathid assemblage is characteristic of the *varcus* Zone and, if some of these specimens are truly *P. ansatus*, then the collection is restricted to the Middle *varcus* Subzone.
Biofacies: polygnathid biofacies; the robust, chiefly broken specimens suggest these forms originated in a relatively high energy shelf or platform environment.
CAI = 5 (host rock reached at least 300 °C)

10389-SD (C80PK-145C)
Lat 35°32'14" N., long. 117°09'06" W.
Clast of the sandy marble unit in the metaconglomerate member of the Robbers Mountain Formation
Area A

Icriodus sp. indet.
2 I element fragments
1 S element
2 Pa elements of *Polynathus linguiformis* Hinde
1 Pa element of *Polygnathus* aff. *P. timorensis* Klapper, Philip & Jackson
10 Pa element fragments of *Polygnathus* spp. indet.
Unassigned elements:
1 M
1 Sc
67 indet. bar, blade, and platform fragments

Age: late Middle Devonian (Givetian; *varcus* Zone into the *hermannicristatus* Zone
CAI = 5 (host rock reached at least 300 °C)

MISSISSIPPIAN

28061-PC (C80PK-118C)
Lat 35°32'15" N., long 117°09'07" W.
Meta-argillite member of the Robbers Mountain Formation
Area A

All conodonts embedded in rock matrix
1 Pa element of *Polygnathus* aff. *P. communis* Branson & Mehl (lower view)
1 Pa element of *Siphonodella*? sp. indet. (lower view)
5 unassigned P element fragments (lower views)
1 unassigned Pb element
20+ indet. bar and blade fragments

Age: latest Devonian through Early Mississippian (middle Famennian through Osagean); probably earliest Mississippian (Kinderhookian). *P. communis* restricts the age of this collection to middle Famennian through Osagean. One of the platform elements might be a *Siphonodella*, but the preservation is not good enough to be certain. The age of the collection is restricted to the earliest Mississippian (Kinderhookian) if the platform element truly is a *Siphonodella.*
CAI = 5 (host rock reached at least 300 °C)

28871-PCC (82FP-329F)
Lat 35°32'15" N., long 117°09'07" W.
Meta-argillite member of the Robbers Mountain Formation
Area A

All conodonts embedded in rock matrix
1 Pa element of *Siphonodella* sp. indet.
4 Pa elements of *Siphonodella* or *Polygnathus*
20 indet. bar and blade fragments

Age: early Early Mississippian (Kinderhookian)
CAI = 5 (host rock reached at least 300 °C)

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