The Pennsylvanian System, Socorro region, New Mexico--Stratigraphy, petrology, depositional environments

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THE PENNSYLVANIAN SYSTEM SOCORRO REGION NEW MEXICO STRATIGRAPHY, PETROLOGY DEPOSITIONAL ENVIRONMENTS

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INTRODUCTION

Socorro, the principal settlement in west-central New Mexico, is located about 120 km south of Albuquerque. Pennsylvanian rocks in this area crop out in widely separated, isolated, fault-block mountains within and along the Rio Grande rift. Studies of Pennsylvanian rocks in west-central New Mexico have been chiefly reconnaissance efforts that have produced a general model of Pennsylvanian stratigraphy and sedimentation (reviewed in Kottlowski, 1960). More recent studies (Martin, 1971; Myers, 1973; Siemers, 1978) have focused on stratigraphic interpretations, petrography, and depositional systems of the Pennsylvanian deposits. Regional and local aspects of the Pennsylvanian rocks, including: (1) stratigraphy, biostratigraphy, and nomenclature; (2) thickness estimates; (3) petrography; and (4) depositional framework, are reviewed here.

PALEOGEOGRAPHIC FRAMEWORK

Several land masses, collectively referred to as the Ancestral Rocky Mountains, developed in the southern Rocky Mountain region during the late Paleozoic. During Mississippian time, northern New Mexico was part of the Penasco dome, a low-relief structural highland that existed throughout the early and middle Paleozoic (Armstrong, 1962). In the early Pennsylvanian, the Colorado Plateau was subjected to tectonic forces which caused the breakup of the Penasco uplift, and its associated shelf area to the south, into a number of distinct tectonic elements (fig. 1). These defined a north-northwest-trending seaway in west-central New Mexico (Kottlowski, 1960), which was bounded on the west by the Zuni-Defiance uplift and on the east by the Uncompahgre and Pedernal highlands. Depocenters included the Paradox basin (northwestern New Mexico and southwestern Colorado), the Estancia, Lucero, and San Mateo basins (central New Mexico), and the Orogrande, Pedregosa, and Delaware basins (southern New Mexico). Local source areas included the Joyita and Florida highlands.

Fault-block uplifts and basins that are late Cenozoic in age dominate present structural elements of the region. Most of these, however, reflect the influence of older structure (Chapin and Seager, 1975). Rio Grande rift structures, for example, were superimposed during late Cenozoic time upon a north-trending tectonic belt that was strongly deformed during the late Paleozoic and again during the Laramide Orogeny.

STRATIGRAPHY

Stratigraphic classifications of Pennsylvanian beds in west-central New Mexico (Gordon, 1907; Kelley and Wood, 1946; Loughlin and Koschmann, 1942; Myers, 1973; Read and Wood, 1947; Thompson 1942; Wilpolt and Wanek, 1951) are based on both rock- and time-stratigraphic units. Most are generally patterned after Gordon (1907), but many authors have changed the rank of his terms and named various members within his basic framework. Consequently, the Pennsylvanian nomenclature of west-central New Mexico has become complicated by a myriad of names converging from all directions.

The most practical stratigraphic approach has been to establish easily recognizable rock-stratigraphic units and then tie these to a biostratigraphic framework based on fusulinid faunal zones. The only easily recognizable lithologic breaks (fig. 2) that occur with some consistency throughout the region are between: (1) a lower terrigenous unit, (2) a medial limestone unit, and (3) an uppermost mixed limestone-terrigenous sequence. Gordon (1907) referred to all Pennsylvanian-age rocks as the Magdalena Group. He called the lower terrigenous sequence the Sandia Formation and the upper two units the Madera Limestone. Read and Wood (1947) subsequently subdivided the Madera Limestone into a lower gray limestone member and an upper arkosic limestone member. Such a classification (fig. 2) breaks the Pennsylvanian System into easily recognizable and useful units that are mappable throughout west-central New Mexico.

The Sandia Formation is a transgressive suite consisting mainly of terrigenous elastic sediments of early Pennsylvanian age. The lower boundary of the Sandia coincides with the base of the Magdalena Group and is placed at the top of rocks interpreted to be Mississippian or older in age. The contact between the terrigenous Sandia Formation and the

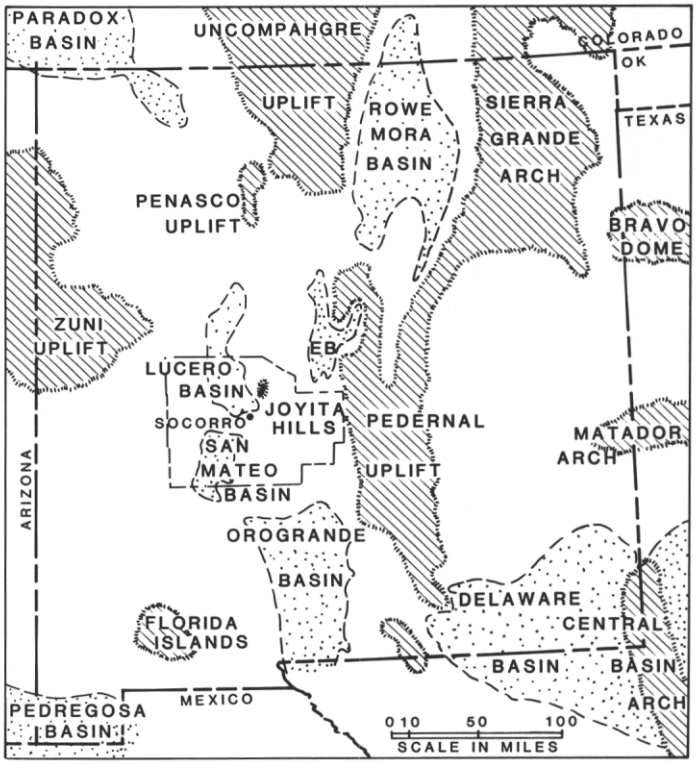

Figure 1. Map showing location of the Socorro region and major Pennsylvanian tectonic elements (modified from Kottlowski and Stewart, 1970).

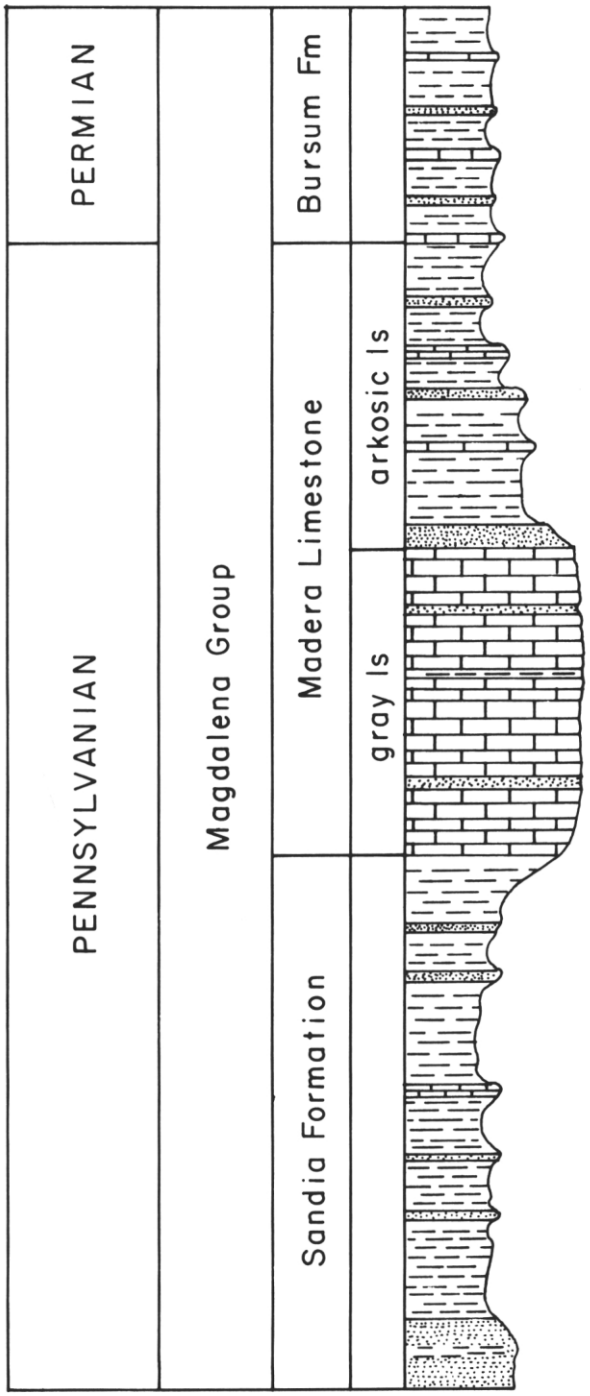

Figure 2. Generalized stratigraphic section and classification of Pennsylvanian rocks in west-central New Mexico.

overlying Madera Limestone is gradational, with the position of the boundary being somewhat arbitrary. The boundary is commonly placed at the top of a prominent sandstone unit, below which ten-igenous lastics predominate and above which carbonates are dominant.

The Madera Limestone is overlain by either the Bursum Formation Dr the Abo Formation, both of which are Wolfcampian (Lower Permian) in age. The Bursum Formation is a transitional unit consisting of al- ternating limestones and reddish-brown sandstones and shales that grade upward into the predominantly continental red beds of the overlying Abo Formation. The Magdalena Group comprises the Pennsylvanian and, locally, Permian beds which represent a complete transgressive- regressive cycle beneath the Abo red beds.

AGE AND CORRELATION

In the absence of adequate published and unpublished faunal data, time-stratigraphic units, although based on fusulinid faunal zones, are actually chosen (as described by Adams, 1962) to coincide with the limits of a lithologic entity. Though inexact, this method is useful in the absence of precise fusulinid determinations, and boundaries are probably as accurately determined as those recognized elsewhere over equally extensive areas with such widely spaced control.

Morrowan faunas have not been reported from Pennsylvanian beds in west-central New Mexico. Although areas to the south were undergoing limestone deposition (Kottlowski, 1960), most of west-central New Mexico apparently lay just above sea level during Morrowan time.

In most Pennsylvanian sections of west-central New Mexico (fig. 3), the top of the Atokan coincides closely with the top of the Sandia Formation (Cheetham, 1950; Geddes, 1963; Kottlowslci, 1960 and 1963; Martin, 1971). In the southern Manzano Mountains, near Abo Pass, Sandia strata bear Atokan faunas (Myers, 1973), but the uppermost beds have been removed by faulting. No faunal studies have been made of Pennsylvanian rocks in the Lemitar Mountains; nevertheless, about 8 km to the south on Socorro Peak, Kottlowski (1960) reported an Atokan age for the Sandia section. Disagreement exists as to the age of Sandia beds in the southeastern San Mateo Mountains where faunas have been interpreted by G. L. Wilde (Kottlowski, 1960) to be Atokan, and by W. J. Stewart (personal commun., 1977) to be Desmoinesian in age.

Lowermost Madera Limestone beds in west-central New Mexico are Desmoinesian in age except in the Joyita Hills and northern Oscura Mountains, where lowermost Madera limestones are Atokan in age (fig. 3). The top of the Desmoinesian occurs at or near the top of the gray limestone member, except in the Joyita Hills, the Cerros de Amado, and the San Mateo and northern Oscura Mountains where the very uppermost gray limestone member is Missourian in age (fig. 3). The arkosic member of the Madera Limestone, throughout the region, is Missourian and Virgilian in age (fig. 3).

Although conceptually distinct, Pennsylvanian chronostratigraphic and lithostratigraphic boundaries are nearly coincident within the Socorro region. With minor exception, Sandia beds are Atokan in age, the Madera gray limestone member is Desmoinesian in age, and the Madera arkosic limestone member is Missourian-Virgilian in age.

DESCRIPTIVE PETROLOGY

Sandia Formation

Basal relationships and thickness

In the Socorro region, Sandia beds rest with erosional unconformity on Precambrian granite and metamorphic rocks or on Osagian (Lower Mississippian) or Ordovician limestones that survived episodes of erosion during the Devonian, Mississippian, and Early Pennsylvanian. In the Magdalena Mountains, southern Lemitar Mountains, and northern Ladron Mountains, the Sandia rests unconformably above 3 to 30 m of Kelly Limestone (Osagian). In the area east of Socorro, and locally in the Ladron and southern Lemitar Mountains, where late Mississippian/early Pennsylvanian erosion removed the Kelly Limestone, the Sandia rests on Precambrian granite. In the southeastern San Mateo Mountains, where Sandia beds unconformably overlie the Upham Dolomite (Ordovician), a 60-m-thick Cambro-Ordovician section separates Pennsylvanian rocks from Precambrian quartzite (Kelley and Furlow, 1965; Kottlowski, 1963). Because of faulting, original basal relationships cannot be determined at Little San Pasqual Mountain or Abo Pass. In the nearby Manzano and Los Pinos Mountains, north and south of Abo Pass, respectively, Sandia beds overlie Precambrian rocks.

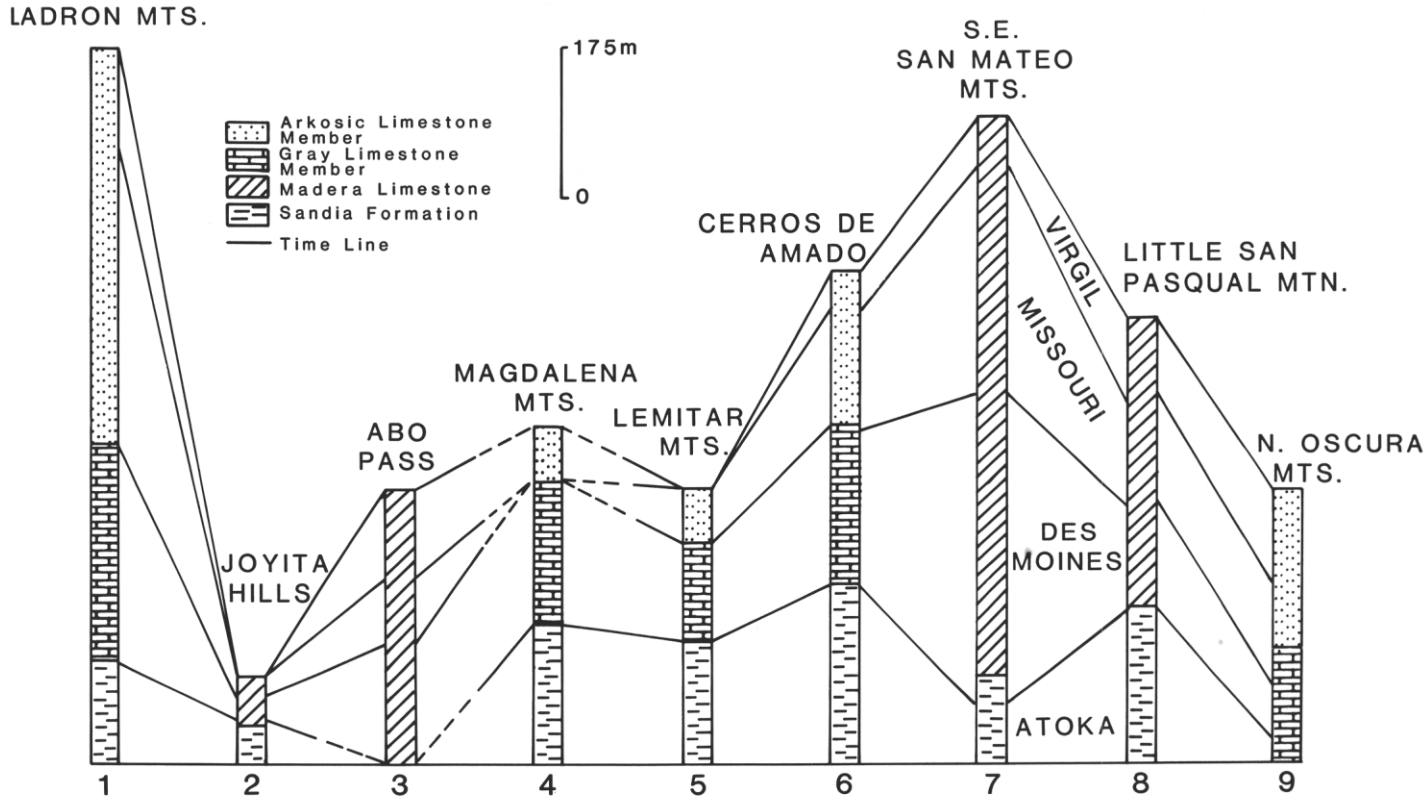

Figure 3. Correlation chart showing the relationship between rock- and time-stratigraphic units within the Pennsylvanian System of the Socorro region.

The thickness of the Sandia Formation (Table 1) within the Socorro region ranges from 10 to 211 m and averages about 116 m (Siemers, 1978). The thickest sections lie along a north- to northwest-trending axis through the central part of the region. Local, rapid thickness changes associated with penecontemporaneous faulting are common at some localities. Regional thinning and eventual wedging out of the Sandia occurs against the Pedernal and Zuni uplifts. Some thinning also occurs against the Pennsylvanian Joyita uplift.

At localities where the base of the section is exposed, a basal sandstone ranging from 1 to 20 m in thickness is observed. Where this sandstone overlies Precambrian rocks it is typically a white to light-gray, siliceous, quartzose sandstone characterized by a basal pebbly zone. At localities where this lower sandy unit rests on the Kelly Limestone, its composition, texture, and color are quite variable.

In the southernmost part of the region, the character of these basal beds is less uniform. The poorly exposed, lowermost beds in the southeastern San Mateo Mountains are terrigenous mudrocks and limestones. In the northern Oscura Mountains, slope debris covers the base of the Sandia Formation. In the southern part of the range, however, Kottlowski (1960) noted that black shales, sandstones, and conglomerates of the Sandia rest unconformably on Precambrian granite.

Table 1. Summary of thickness and lithology for the Sandia Formation. Sandstone (Ss), Mudrock (Mr), Limestone (Ls), Clastic/Carbonate Ratio (CR), Sandstone/Mudrock Ratio (SMR).

NAME	THICKNESS (meters)				LITHOLOGY				
	Ss	Mr	Ls	Total	Ss%	Mr%	Ls%	CR	SMR
Ladron Mts.	21.2	95.9	6	123.1	17	78	5	19.5	0.22
Joyita Hills	9.8	38.2	0	48	20	80	0	–	0.26
Abo Pass	–	–	–	60	–	–	–	–	–
Magdalena Mts.	26.2	135.9	4.8	166.9	16	81	3	33.8	0.19
Lemitar Mts.	37.3	90.8	17	145.1	26	62	12	7.5	0.41
Cerros de Amado	63.7	96.6	50.4	210.7	30	46	24	3.2	0.66
S.E. San Mateo Mts.	0	85	17.6	102.6	0	83	17	4.8	0
L. San Pasqual Mtn.	19.8	115.1	46.5	181.4	11	63	26	2.9	0.17
N. Oscura Mts.	–	–	–	10	–	–	–	–	–

Lithology and petrography

The Sandia Formation consists of diverse terrigenous and carbonate lithologies. Clastic/carbonate ratios that average 12.0 (Table 1) and sandstone/mudrock ratios averaging 0.27 testify to the terrigenous nature of the formation and to the preponderance of terrigenous mudstone, accounting for the slope-forming character of the unit. Higher clastic/carbonate and sandstone/mudrock ratios in the western part of the region suggest an increase in the abundance of terrigenous mudrock toward the west. Lower clastic/carbonate ratios south of Socorro signify the growing importance of carbonate toward the south. Throughout the Socorro region, the sandstone content is highest in the lower part of the Sandia section and its abundance decreases upward.

Fine-grained terrigenous lithologies constitute about 67 percent of the Sandia Formation, but exposures are limited due to their slope-forming nature and cover by talus, soil, and vegetation. Individual units range in thickness from less than one meter to more than 65 m, with the thicker intervals most commonly occurring in the middle and upper part of the unit. Thin, shaley intervals and partings also occur between beds within limestone and sandstone intervals. Mudrock color is variable, including various shades of gray, green, and brown, with gray being most common.

Thin-section analysis has shown that, with grain-to-mud ratios of less than one to three, most Sandia mudrocks are clay-shales consisting of subangular, coarse, silt-size grains of quartz and muscovite floating in a recrystallized groundmass of carbonate, cherty silica, and phyllosilicate material. Porosity, which occurs as microscopic fractures, channels, and vugs, is negligible.

Bedding within claystone intervals ranges from thin to very thick and is uneven and irregular. Claystones frequently display discontinuous to continuous, parallel to nonparallel, wavy and planar lamination and less frequently thin, low-angle, small-scale cross-lamination. These are sometimes disturbed by small-scale, soft-sediment deformation and minor burrowing.

Terrigenous beds composed of more than 25 percent sand and gravel constitute about 18 percent of the Sandia Formation. Such lithologies are nearly absent at some localities in the southern part of the region (southeastern San Mateo Mountains). Individual sandstone units range from less than one meter to as much as 20 m in thickness and crop out as low ledges, breaking the monotony of the covered, shaley Sandia slopes. Although poorly exposed, basal contacts are apparently sharp, with little evidence of erosion or channeling.

The Sandia contains many diverse terrigenous elastic lithologies, including, in decreasing order of abundance, quartz sandstones, arkoses and subarkoses, sublithic and lithic sandstones, and sedlithic conglomerates. Feldspathic sandstones are quite abundant in the Joyita Hills, whereas conglomerates are common in the basal Sandia section in the Lemitar Mountains. Most sandstones are light- to medium-gray in color.

Most Sandia sandstones are grain-supported arenites composed primarily of detrital quartz and feldspar and less than 10 percent interstitial material. The detrital fraction is most commonly low-sphericity, angular to subangular, poorly sorted, coarse- to very coarse grained sand. In the southern part of the region, sandstones are finer grained and better sorted.

Fossil debris, consisting mainly of crinoid columnals and gastropod material, is a primary component of lowermost Sandia sandstone in the Joyita Hills. Sandia sections in the Joyita Hills and Lemitar and Ladron Mountains also contain woody plant impressions as much as 10 cm wide and 50 cm long.

Matrix material typically consists of detrital silt and cloudy, recrystallized phyllosilicate minerals. Silica, the most common cementing agent, occurs as quartz overgrowths on detrital grains, or simple pore-fillings of quartz or cherty quartz. Calcite, occurring as finely crystalline pore-fillings and as large poikilotopic patches that may enclose many detrital grains, is also a common cementing agent. Cementation of the sandstone is fairly complete, resulting in well-indurated beds with negligible interparticle porosity.

Sandstone bedding is quite variable within the Sandia; it ranges from thin to very thick and exhibits little vertical consistency. Most sandstones, however, occur in the medium- to thick-bedded range. Frequently, sandstone units comprise only one isolated bed within a shale interval. Lateral continuity of the sandstones is difficult to determine because of slope cover.

Most sandstones appear to be massive, but this may result from weathering and varnishing in the semiarid New Mexico climate. The Suite of sedimentary structures that were observed includes: (1) very thin to thin, subparallel, relatively continuous planar and wavy lamination; (2) solitary, concordant and discordant, small- to medium-scale, low-angle, tabular- and wedge-shaped, planar cross-lamination, and (3) load structures. Sparse data regarding cross-lamination orientations suggest that sediment transport was primarily toward the southwest.

Carbonate lithologies constitute 3 to 26 percent of the Sandia section; they are most common in the Cerros de Amado–Little San Pasqual Mountain areas. Medium-gray to black mudstones, wackestones, and packstones crop out as low ledges among the slope-forming shales. Except in the Magdalena Mountains where mudstones are quite common, wackestones (biomicrites and biomicrudites) are the predominant carbonate lithology.

Most limestones are composed of skeletal debris and small percentages of terrigenous and carbonate grains floating in a recrystallized micritic groundmass. Crinoid and brachiopod pieces constitute the bulk of the skeletal material. Other taxa present include bryozoans, calcareous algae, solitary and colonial corals, mollusks, and foraminifera—mostly fusulinids. Fossil debris tends to be poorly sorted, although its distribution within most beds is fairly uniform, with the more linear pieces oriented with their long axes subparallel to bedding surfaces. Silicification of fossil material within Sandia carbonates is unusual.

Terrigenous grains typically make up less than one percent of the Sandia limestones and are represented by angular grains of monocrystalline quartz and traces of muscovite and feldspar all in the silt to fine-sand range. Carbonate grains occur very rarely in the Sandia and in abundance of less than five percent.

The chief component of these limestones is a rather uniform, brownish, subtranslucent groundmass of subequant calcite crystals less than 30 p.m in diameter. The original carbonate mud converted to microspar by aggrading neomorphism. Porphyroid textures, resulting from continued local aggradational neomorphism to coarsely crystalline pseudospar, are also common. Precipitation of finely to coarsely crystalline sparry calcite has reduced porosity to no more than a trace. Any porosity that occurs is either microporosity or is related to secondary dissolution and fracturing.

Limestone bedding ranges from thin to very thick and is laterally continuous with parallel, planar surfaces. Bedding tends to thicken and become more even in the southern part of the Socorro region. Limestones are typically massive, but may exhibit zones of thin, subparallel to nonparallel, continuous to discontinuous, planar and wavy lamination that are enhanced by weathering to a brownish-orange color. The laminated zones commonly contain somewhat higher concentrations of terrigenous material.

Madera Limestone

Basal relationships and thickness

At some localities, the change from the more terrigenous Sandia Formation to thick, massive-looking, gray limestones of the lower Madera Limestone is rapid and the boundary between the two units is easy to pick. In many sections, however, the gradational nature of the contact makes the selection of a boundary more difficult and quite arbitrary. Under such circumstances, a widely used, practical solution (Loughlin and Koschmann, 1942) is to place the boundary at the top of a prominent sandstone, above which limestones are predominant and below which terrigenous strata dominate.

The basal Desmoinesian beds of the Madera are generally parallel to those of the underlying Atokan beds. Geddes (1963), however, described a slight Atokan-Desmoinesian angular unconformity at Little San Pasqual Mountain. The unconformity is apparently restricted to the southern part of the small uplift, for it has not been traced into or found in the northern part of the range. Thompson (1942) likewise noted, on the basis of faunal evidence, a discontinuity between the two series throughout central and southern New Mexico. Although a small Atokan-Desmoinesian hiatus probably occurs within the Socorro region, it is difficult to recognize and any interruption in sedimentation involved a relatively short time interval with only minor, possibly local diastrophism.

Missourian beds are essentially parallel to those of the underlying Desmoinesian, although Thompson's (1942) faunal studies demonstrated a disconformity of some magnitude at this boundary. Basal Missourian terrigenous beds also contain reworked Desmoinesian fusulinids . A disconformable relationship is likewise illustrated by conglomeratic sandstones and local channeling that mark the base of the Missourian.

Thompson's (1942) faunal studies and the occurrence of basal conglomerates also suggest a disconformity at the base of the Virgilian.

Furthermore, Myers (1973) described a basal Virgilian arkosic conglomerate containing poorly sorted metamorphic clasts and fossilized wood fragments in the southern Manzano Mountains. Within most of the Socorro region, however, basal Virgilian beds are siltstones and shales, or less commonly, fine-grained sandstones.

The Pennsylvanian-Permian contact is disconformable over much of central New Mexico. Uppermost Virgilian beds in central New Mexico and Kansas are time-equivalent, whereas lowermost Permian beds that overlie the Virgilian beds in Kansas are somewhat older than the basal Permian beds in central New Mexico (Thompson, 1942). Furthermore, although lowermost Permian beds in central and southern New Mexico are time equivalent, uppermost Virgilian strata in central New Mexico are considerably older than uppermost Virgilian beds in southern New Mexico. Therefore, parts of the lower Permian and upper Virgilian sections are missing in central New Mexico.

Madera thicknesses range from 64 to 716 m in the Socorro region (Table 2), with the thickest section occurring along a north-trending axis through the southern Ladron, Magdalena, and southeastern San Mateo Mountains. The section thins toward the east and west and eventually wedges out against the Pedernal and Zuni highlands (Kottlowski, 1960; Siemers, 1978). The Madera is only 232 m thick in the Magdalena Mountains, where normal faulting has cut out the Missourian and parts of the Virgilian section. Well data (Krewedl, 1974) and stratigraphic reconstructions (Siemers, 1975), however, demonstrate that the original thickness of that section was probably 500 to 550 m.

Thinning of Desmoinesian and Missourian intervals and Wolfcampian erosion of Virgilian strata (Kottlowski and Stewart, 1970) have reduced the thickness of the Madera to only 64 m in the Joyita Hills. In the Lemitar Range, gravelly Wolfcampian red beds superpose late Missourian strata, documenting the thinning of that section by erosion that probably also occurred during Wolfcampian time.

Table 2. Summary of thickness and lithology for Atokan, Desmoinesian, Missourian, and Virgilian beds within the Madera Limestone. Sandstone (Ss), Mudrock (Mr), Limestone (Ls), Clastic/Carbonate Ratio (CR), Sandstone/Mudrock Ratio (SMR).

	NAME	THICKNESS (meters)				LITHOLOGY				
		Ss	Mr	Ls	Total	Ss%	Mr%	Ls%	CR	SMR
VIRGILIAN	Ladron Mts.	0	41.5	58.1	99.6	0	42	58	0.71	0
	Joyita Hills	0	0	0	0	–	–	–	–	–
	Abo Pass	4.6	59.4	48.4	112.4	4	53	43	1.3	0.07
	Magdalena Mts.	0	20.0	40.7	60.7	0	33	67	0.49	0
	Lemitar Mts.	0	0	0	0	–	–	–	–	–
	Cerros de Amado	0.9	9.1	20.1	30.1	3	30	67	0.50	0.10
	S.E. San Mateo Mts.	3.0	19.0	55.9	55.9	0	0	100	0	–
	L. San Pasqual Mtn.	7.6	24.1	62.8	94.5	8	26	66	0.50	.32
	N. Oscura Mts.	18.3	24.3	78.4	121.0	15	20	65	0.54	0.75
MISSOURIAN	Ladron Mts.	23.4	123.2	214.3	360.9	7	34	59	0.68	0.19
	Joyita Hills	0	8.3	22.8	31.1	0	27	73	0.36	0
	Abo Pass	16.7	48.8	9.7	75.2	22	65	13	6.8	0.34
	Magdalena Mts.	–	–	–	–	–	–	–	–	–
	Lemitar Mts.	0	29.5	39.5	69.0	0	43	57	0.75	0
	Cerros de Amado	8.2	70.7	69.2	148.1	6	48	46	1.1	0.11
	S.E. San Mateo Mts.	0	64.9	202.5	267.4	0	24	76	0.32	0
	L. San Pasqual Mtn.	0	41.8	71.8	113.6	0	37	63	0.58	0
	N. Oscura Mts.	4.6	15.0	88.9	108.5	4	14	82	0.22	0.31
DESMOINESIAN	Ladron Mts.	4.6	13.7	237.4	255.7	2	5	93	0.08	0.34
	Joyita Hills	0	3.6	18.3	21.9	0	16	84	0.20	0
	Abo Pass	0	64.6	79.9	144.5	0	45	55	0.81	0
	Magdalena Mts.	11.2	34.7	125.7	171.6	7	20	73	0.37	0.32
	Lemitar Mts.	0	0	115.7	115.7	0	0	100	0	–
	Cerros de Amado	10.4	81.6	97.4	189.4	6	43	51	0.94	0.13
	S.E. San Mateo Mts.	17.1	89.5	233.6	340.2	5	26	69	0.47	0.19
	L. San Pasqual Mtn.	3.0	13.7	119.6	136.3	2	10	88	0.14	0.22
	N. Oscura Mts.	0	1.8	65.0	66.8	0	3	97	0.03	0
ATOKAN	Ladron Mts.	0	0	0	0	–	–	–	–	–
	Joyita Hills	0	0	11.0	11.0	0	0	100	0	–
	Abo Pass	0	0	0	0	–	–	–	–	–
	Magdalena Mts.	0	0	0	0	–	–	–	–	–
	Lemitar Mts.	0	0	0	0	–	–	–	–	–
	Cerros de Amado	0	0	0	0	–	–	–	–	–
	S.E. San Mateo Mts.	0	0	0	0	–	–	–	–	–
	L. San Pasqual Mtn.	0	0	0	0	–	–	–	–	–
	N. Oscura Mts.	0	8.6	24.9	33.5	0	26	74	0.34	0

Lithology and petrography

Within the Socorro region, the Madera Limestone comprises diverse carbonate and terrigenous rock types. An average elastic/carbonate ratio of 0.45 (Table 2), indicates that the formation is dominated by limestone. Low sandstone/mudrock ratios (mean of 0.16) testify to the fine-grained character of terrigenous strata within the unit; sandstones, in fact, rarely compose more than about 5 percent of the Madera section. The Desmoinesian section (elastic/carbonate ratio = 0.34) is completely dominated by limestone. The resistant nature of the thickly bedded Desmoinesian carbonates in the semiarid New Mexico climate makes the lower limestone member of the Madera a prominent ridge-former throughout the region.

Missourian elastic/carbonate ratios, discounting the extremely terrigenous Abo Pass section where sandstones and shales constitute 87 percent of the Missourian section, average 0.58. Virgilian clastic/carbonate ratios generally range between 0.5 and 0.7. No terrigenous rocks occur among Virgilian strata in the southeastern San Mateo Mountains and the only occurrences of Virgilian sandstones are restricted to the eastern part of the region.

Clastic/carbonate and sandstone/mudrock ratios, therefore, indicate variability in the quantity and nature of sediments, both geographically and stratigraphically, within the Madera Limestone. Terrigenous material is significantly more abundant in the section at Abo Pass and in the Cerros de Amado. In most sections, the terrigenous content increases upward within the Madera.

Limestone composes about 70 percent of the Madera Limestone within the Socorro region. At some localities, where their abundance appears to exceed 80 percent of the section (Lemitar Mountains, Joyita Hills, Little San Pasqual Mountain), carbonate values are probably inflated. The parts of the section that are commonly more terrigenous are missing because of erosion and faulting (Siemers, 1978).

The thickness of carbonate intervals within the Madera commonly ranges between 5 and 15 m. Some Desmoinesian limestone units, particularly in the Ladron and Lemitar Mountains and at Abo Pass, are as much as 140 m thick and are virtually uninterrupted except for infrequent, very thin calcareous shales.

The majority of the Madera limestones are mudstones and wackestones (biomicrites and biomicrudites). A few dolostone beds occur at Abo Pass and in the southeastern San Mateo Mountains. Limestone colors are commonly some shade of gray, with the darker hues predominating. Uppermost Virgilian beds are sometimes brownish-gray to grayish-red in color. Dolostones tend to weather yellowish- to orangish-brown.

The framework component of the limestones comprises skeletal debris (5 to 15 percent) and some terrigenous detritus. The bulk of the skeletal material is crinoidal and bryozoan debris. Less-abundant taxa include fusulinids, calcareous algae, corals, gastropods, and pelecypods. Fossil material within the Madera limestones is occasionally silicified.

Occurrences of terrigenous detritus within Madera limestones are rare, but abundances of such material are as much as 5 to 10 percent in some carbonates. Grains in the silt and fine-sand sizes are mostly restricted to angular, monocrystalline quartz and muscovite. Allochemical grains attain local significance within isolated beds, but in general, such grains constitute less than three percent of the rock.

Brownish, subtranslucent micrite and microspar constitute 75 to more than 90 percent of most limestone beds within the Madera. Coarsely

crystalline calcite is also quite common; most of it, on the basis of its distribution and textural traits, is thought to be neomorphic in character. Sparry calcite most commonly occurs as polycrystalline and monocrystalline overgrowths on skeletal grains, particularly crinoid fragments.

The thickly bedded, dark-gray Desmoinesian limestones are frequently fairly siliceous. The silica occurs as isolated microscopic patches of chalcedony and as nodules and lens-shaped pods of cherty quartz. The chert ranges from light-gray to black in color and usually weathers light- to medium-brown. The size and shape of the chert structures are extremely variable. Inclusion of bioclastic material within chert nodules suggests they are secondary replacement features.

Bedding thicknesses of limestones within the Madera range from thin to very thick. Desmoinesian limestones are generally more thickly bedded than are limestones higher in the Madera. The beds are laterally continuous with subparallel, planar to wavy bedding surfaces. More thinly bedded limestones occasionally exhibit thin, sub- to non-parallel, continuous and discontinuous, wavy and planar lamination. More thickly bedded limestones are usually massive.

Terrigenous mudrocks and sandstones constitute about 25 and 7 percent of the Madera section, respectively, with the terrigenous content of the upper Madera (Missourian-Virgilian) being about twice that of the Desmoinesian section. Mudrocks occur mostly as light- to dark-gray, slope-forming mud-shales and siltstones. Silt-size material comprises angular grains of quartz and muscovite floating in a calcareous phyllosilicate matrix. Claystones are commonly burrowed and carbonaceous plant impressions are common along the parting planes of many shales.

Madera sandstones are as much as 14 m thick, although most are no more than 5 m thick. Basal Missourian and Virgilian sandstones frequently lie on surfaces cut into underlying beds, particularly in the northeastern part of the Socorro region. Nonerosional bases characterize Desmoinesian sandstones.

The sandstone suite is quite variable, including quartz sandstones, subarkoses, and sublithic sandstones; subarkoses are most common, except in the Magdalena Mountains where quartz sandstones are predominant. Sedlithic conglomerates occur within the Missourian section at Little San Pasqual Mountain. Quartz-pebble conglomerates occur near the top of the Madera section in the Magdalena Mountains near the ghost town of Kelly (Blakestad, 1978).

Framework material includes poorly sorted, fine to very coarse sand-size grains of quartz, feldspar, chert, lithic fragments, and mica. Lithic fragments are generally restricted to chert grains. In the Cerros de Amado, however, uppermost sandstones contain carbonte mudstone intraclasts, and at Little San Pasqual Mountain, gravel-conglomerates contain limestone, chert, and siltstone rock fragments. Woody plant debris commonly occurs within sandstone units at Abo Pass, the Ladron Mountains, and the Cerros de Amado. Myers (1973) reported that basal Missourian sandstones in the Manzano Mountains, north of Abo Pass, locally contain petrified logs as long as 2.5 m.

Interstitial material seldom composes more than 5 to 10 percent of these sandstones. Matrix material is limited to silt-size quartz and muscovite and cloudy, recrystallized, clay-size phyllosilicates. Calcite and silica are the primary cementing agents. Cementation is complete, resulting in well-indurated sandstones with negligible porosities.

Bed thickness decreases upward from the base of the Madera, from thick-bedded Desmoinesian through medium-bedded Missourian to thin-bedded Virgilian sandstones. Within a sandstone unit, beds tend to show vertical variability and lateral irregularity in their thickness; the lateral continuity of the beds is somewhat better, however, among Desmoinesian sandstones.

Many sandstones appear to be massive; again, this may be because of weathering and varnishing in New Mexico's semiarid climate. Some sandstones, however, exhibit continuous and discontinuous, subparallel, wavy and planar lamination. Others contain solitary, concordant and discordant, small- to medium-scale, tabular- and wedge-planar cross-lamination. Cross-lamination orientations suggest the direction of transport was generally toward the south (Siemers, 1978). Other sedimentary structures include loadcasts, minor burrowing, and very small-scale penecontemporaneous deformation features. Asymmetrical lunate ripples with amplitudes less than 5 cm and wavelengths between 10 and 25 cm characterize the bedding surfaces of some Virgilian sandstones in the Abo Pass section.

SYNTHESIS AND INTERPRETATION

Tectonic Framework

Others (reviewed in Kottlowski, 1960, and Siemers, 1978) have shown that Pennsylvanian rocks in west-central New Mexico were deposited on the southwestern flank of the North American craton in a shallow marine seaway, bounded and interrupted by several long, narrow uplifts (fig. 1). Before Pennsylvanian time, northern and central New Mexico were part of the Penasco dome, a structural highland which, although having been a major terrigenous source during the late Cambrian, remained barely awash throughout the early and middle Paleozoic (Kelley and Silver, 1952; Kottlowski and others, 1956; Armstrong, 1958 and 1962). By early Mississippian time, the region was a beveled surface cut on Precambrian metamorphic and igneous rocks with a shallow marine shelf to the south. Inundation of the region began during Kinderhookian time by an eastward transgression from the Cordilleran miogeosyncline and by transgression of a shallow sea from the south; this resulted in a division of the Penasco dome into the Zuni-Defiance highlands to the west and the Pedernal highlands to the east. By Keokuk time, the Zuni-Defiance highlands had been reduced to a low island, probably awash in shallow seas, and the weakly developed Transcontinental Arch was completely covered by the shallow marine seaway.

This early and middle Paleozoic tectonic framework did not, however, persist into the Pennsylvanian, which was dominated by more northerly structural trends (Kottlowski and Stewart, 1970). lsopach maps of the late Mississippian (Armstrong, 1962) clearly document the onset of the new tectonic elements that were to control Pennsylvanian sedimentation. The Zuni uplift began to develop as a low-relief feature with the retreat of the late Mississippian sea; the restriction of Mississippian strata to the San Mateo—Magdalena sag (Armstrong, 1962) marks the beginning of differential subsidence along an axis of sedimentation passing through the Socorro region (fig. 4).

The Pedernal and Zuni uplifts were the major sources of Pennsylvanian sediment to all of west-central New Mexico (figs. 1, 2). Though variously interpreted (Wengerd, 1959; Kottlowski, 1960; Hambleton, 1962), the Joyita uplift probably comprised only a small submarine platform or group of islands and littoral areas barely awash in shallow seas and of no more than local influence during most of the Pennsylvanian (Kottlowski, 1963; Kottlowski and Stewart, 1970; Martin, 1971). A small hiatus within upper Desmoinesian strata suggests that the Joyita uplift was above sea level sometime during the late Desmoinesian. The absence of Virgilian strata beneath Wolfcampian red beds in the Joyita Hills section indicates uplift and either nondeposition during Virgilian time or erosion during the early Wolfcampian.

The Pennsylvanian Zuni uplift has long been known from outcrops in the Zuni Mountains where Permian strata overlie Precambrian rocks. Following the Mississippian inundation, the Zuni region underwent epeirogenic upwarping and subsequent erosion, followed by a period of domal uplift which caused it to become a sediment source during

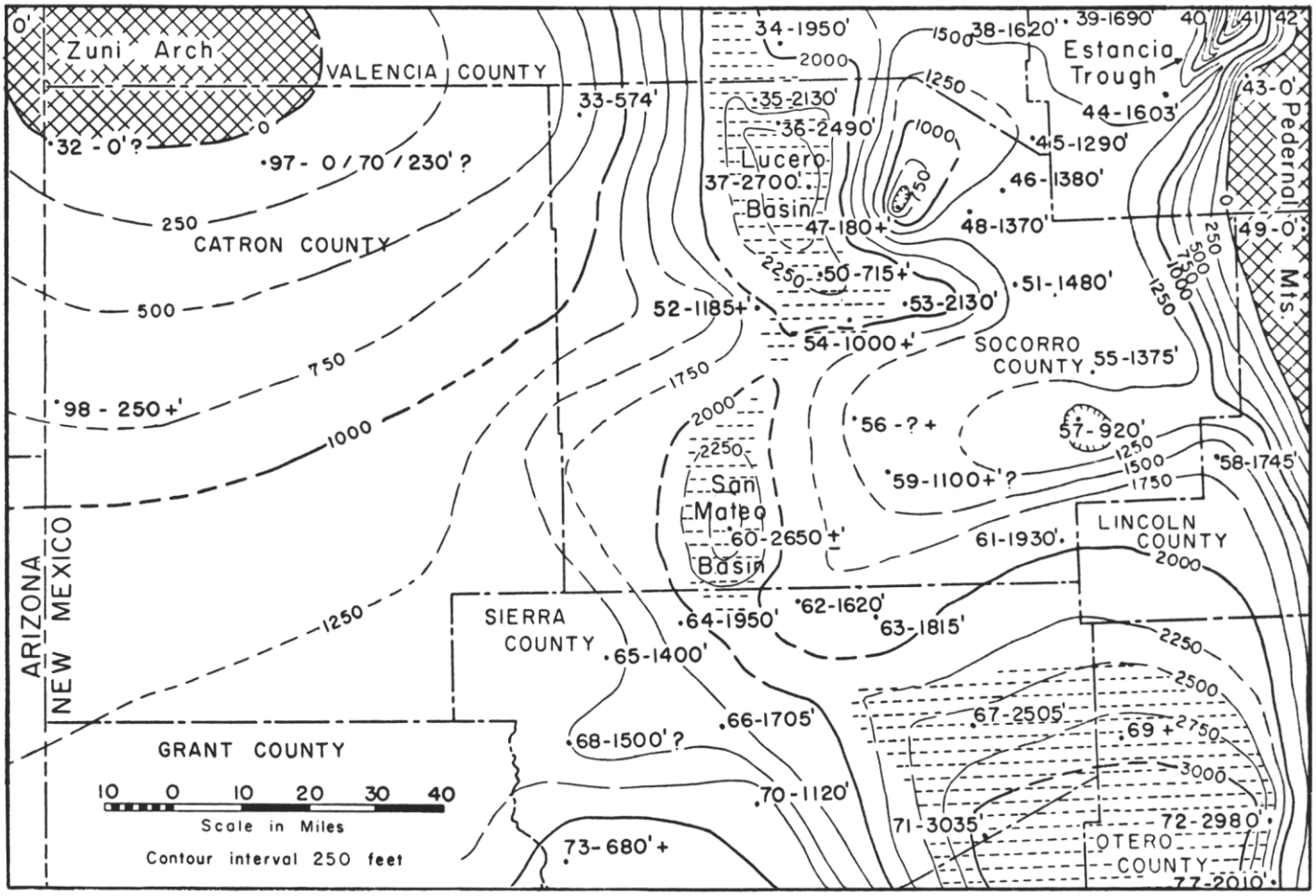

Figure 4. Isopach map showing area of maximum sedimentation along the axis of the Magdalena prong of the Orogrande Basin. Revised estimates of thicknesses in the Magdalena Mountains (section 52) suggest original thicknesses of the Pennsylvanian section west of Socorro were similar to those in the San Mateo and Lucero basins. This indicates that these basins were less distinct than shown here and that the Magdalena prong was a fairly continuous axis of sedimentation along which 800 to 850 m of Pennsylvanian sediment were deposited. From Kottlowski (1960).

Desmoinesian time (Kelley, 1967). Martin (1971) noted that the uppermost strata of each succeeding Pennsylvanian series extend farther onto the flanks of the Zuni uplift than did the strata of the preceding series. The Zuni highlands, therefore, were evidently onlapped and buried following broad regional subsidence during the remainder of the Pennsylvanian.

The Pedernal uplift, as defined by Thompson (1942), refers to a region that extends from the eastern flank of the Sacramento Mountains to northern Torrance County, where Permian red beds rest directly on Precambrian rocks. The Precambrian masses represent buried remnants of the Ancestral Rocky Mountains, which extended almost unbroken from Colorado across central New Mexico to near the state's southern border. The truncation of pre-Wolfcampian strata along the flanks of the uplift and the occurrence of thick Virgilian-Wolfcampian terrigenous deposits in the Orogrande and Estancia basins to the west indicate maximum uplift of the Pedernal region occurred during the late Pennsylvanian and early Permian. The low clastic/carbonate and sandstone/mudrock ratios of the Atokan and Desmoinesian sections within the Socorro region suggest the Pedernal landmass was fairly low-lying.

Kottlowski's (1960) isopach map (fig. 4) of Pennsylvanian rocks in west-central New Mexico clearly illustrates that the Socorro region was part of a broad depocenter between the Zuni and Pedemal highlands. The documentation of original thicknesses of as much as 715 m in the Magdalena Mountains (Siemers, 1975; Krewedl, 1974) provides evidence that the San Mateo—Lucero downwarp was one continuous north-trending axis of sedimentation, called the Magdalena prong of the Orogrande basin by Siemers (1978).

Paleoenvironmental Framework

Within the tectonic framework described above, more than 900 m of Pennsylvanian sediment accumulated in the Orogrande basin and nearly 850 m of Pennsylvanian sediment was deposited along the axis of its north-trending Magdalena prong. To either side of this axis of sedimentation, thinner sequences of sediment were deposited in diverse, sometimes rapidly changing, sedimentary environments that characterized the broad shelf between the Zuni and Pedernal uplands.

Morrowan sedimentation

Morrowan sediments, although deposited in the Orogrande basin (Pray, 1961) to the south and in other New Mexico basins (Myers, 1973; Miller and others, 1963; Wengerd, 1962; Zeller, 1965), are absent in the Socorro region. Much of central New Mexico was an exposed low-lying upland during Morrowan time (Kottlowski and Stewart, 1970).

Atokan sedimentation

Late Mississippian—Early Pennsylvanian erosion stripped early and middle Paleozoic sediments from much of the Socorro region; nevertheless, as much as 40 m of Mississippian strata are preserved in the

San Mateo–Lucero downwarp. In the southwestern part of the Socorro region, this erosion surface was carved on the Montoya Group (Ordovician). Atokan deposits spread across this surface are more than 200 m thick in the central part of the Socorro region; they thin and eventually pinch out against the Pedernal and Zuni uplifts.

The high elastic/carbonate ratios and low sandstone/mudrock ratios of Atokan strata are indicative of nearshore and inner-shelf conditions. The quartz sandstones within the lower sandy interval of the Atokan carry a marine fauna. Their clean, massive to laminated or cross-laminated, thickly bedded, coarse-grained character suggests they are nearshore bar or beach deposits. The basal quartz pebble conglomerates that occur in local shallow depressions or channels are most likely reworked Mississippian and Precambrian detritus on the Mississippian-Pennsylvanian erosion surface. Interbedded shales and limestones also carry a marine fauna and represent more quiet-water, nearshore, tidal-mudflat and lagoonal deposition.

Shale and limestone dominate the middle and upper Atokan. The carbonate wackestones carry a diverse marine fauna suggestive of normal, open-marine conditions. The laminated, continuous bedding and parallel bedding surfaces suggest shallow, quiet, well-circulated, inner-shelf conditions. Dark-gray to black, carbonaceous shales in the Joyita Hills that contain gypsum and bone coal are more indicative of restricted, possibly euxinic, nearshore lagoonal sedimentation.

The absence of limestone and the abundance of coarse-grained, sometimes pebbly, cross-laminated sandstone and calcareous, carbonaceous mud-shale in the Cerros de Amado indicates a steady influx of terrigenous material into the area throughout the Atokan. The Cerros de Amado are only 24 km south of the Joyita Hills, where nearshore conditions prevailed. Paleocurrent data suggest source areas were to the north and east. It is likely, therefore, that the terrigenous beds of the Cerros de Amado represent elastic debris deposited along the western flanks of the Pedernal uplift by small deltaic complexes.

Desmoinesian sedimentation

Following a brief interruption in sedimentation, Desmoinesian sediments, dominated by gray carbonate mudstones and wackestones, were deposited across the Socorro region, with maximum accumulation (about 340 m) occurring along the axis of the Magdalena prong of the Orogrande Basin. The thick to very thick and regular bedding, abundant chert, diverse marine fauna, and mud-supported textures are indicative of outer marine-shelf deposition. Wilson (1975) noted that in the outer marine-shelf environment, dark- to light-colored carbonate mudstones typically occur landward of more offshore cherty, bioclastic wackestones. Interbedding of these lithologies within the Desmoinesian probably represents laterally changing outer-shelf conditions owing to minor fluctuations in water depth.

Coarse-grained sandstones interbedded with the outer-shelf limestones are an enigma. Such occurrences are well-documented in the literature (Pettijohn and others, 1972), but little is known of the processes that concentrate mud-free sandstones on carbonte shelves. Whether the sandstones are related to persistent longshore or tidal currents, occasional intense storms, or grain flows is uncertain.

Most of the terrigenous material within the Desmoinesian rocks is clay- and silt-sized material, suggesting distant source areas. The fine-grained nature of terrigenous deposits near the Joyita uplift attests to its weakly positive nature. The distant Zuni landmass may also have contributed some detritus to the region. Most of the terrigenous material, however, occurs in the eastern sections and limited paleocurrent data suggest that much of the detritus was coming from the east—the Pedernal highlands. The small Penasco uplift may have been a local source of detritus for the Lucero area (Martin, 1971).

Late Pennsylvanian sedimentation

More than 450 m of Late Pennsylvanian sediment were deposited above the disconformity at the base of the Missourian, with maximum accumulation occurring along the axis of the Magdalena prong of the Orogrande basin. Limestones increase in abundance and terrigenous rocks become finer grained from east to west across the Socorro region. In the eastern area, coarse-grained, cross-bedded, immature arkosic sandstones, often containing petrified logs, reflect nearshore, possibly deltaic, environments. To the west, medium- to thick-bedded, cherty carbonate mudstones and gray terrigenous mud-shales were deposited under open, marine-shelf conditions.

Hambleton (1962) believed much of the Late Pennsylvanian detritus was derived from the Joyita uplift. Kottlowski (1963) and Siemers (1978) argued that the large amounts of terrigenous material in the Late Pennsylvanian were supplied from the larger Pedernal and Zuni landmasses, rather than the small Joyita uplift. Higher elastic ratios and the coarse, feldspathic character of sandstones in the eastern areas, along with southwesterly transport directions, indicate that most of the late Pennsylvanian detritus was supplied by the Pedernal uplift. Some of the fine-grained terrigenous material in the western part of the region may have come from the distant Zuni landmass. The Joyita uplift probably never gained more than local importance in the northeastern part of the Socorro region.

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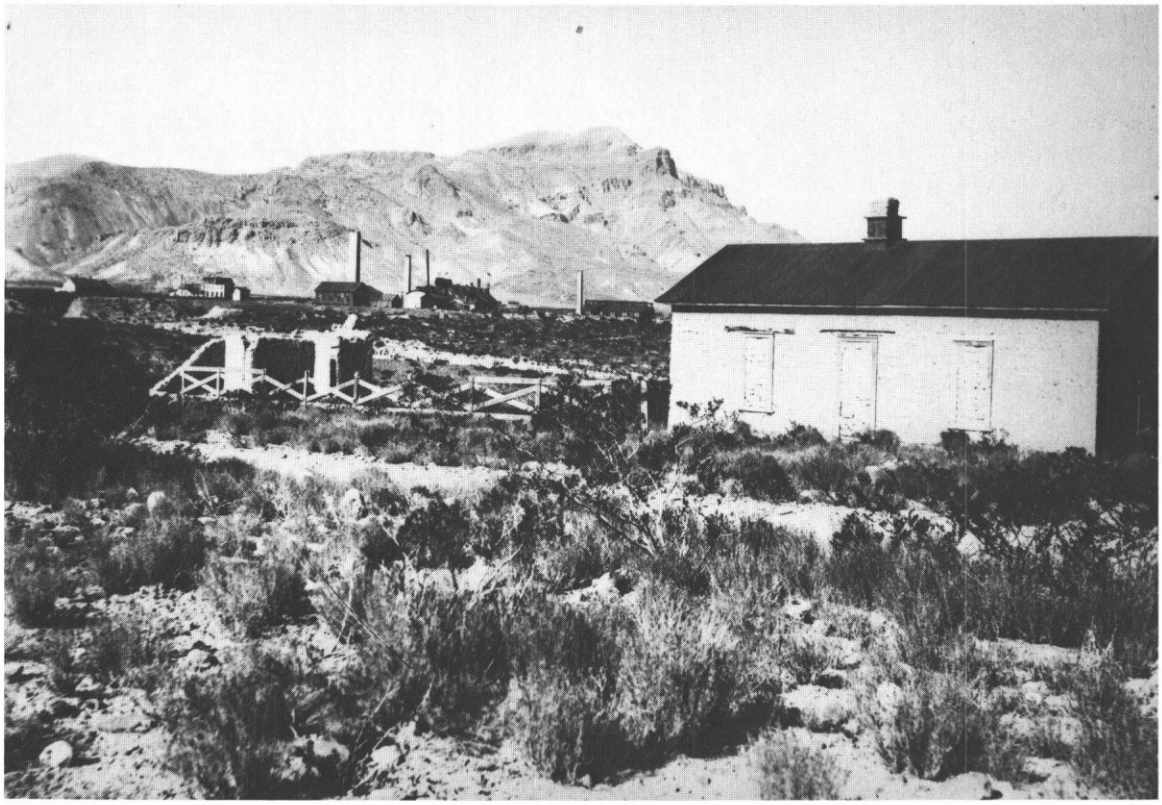
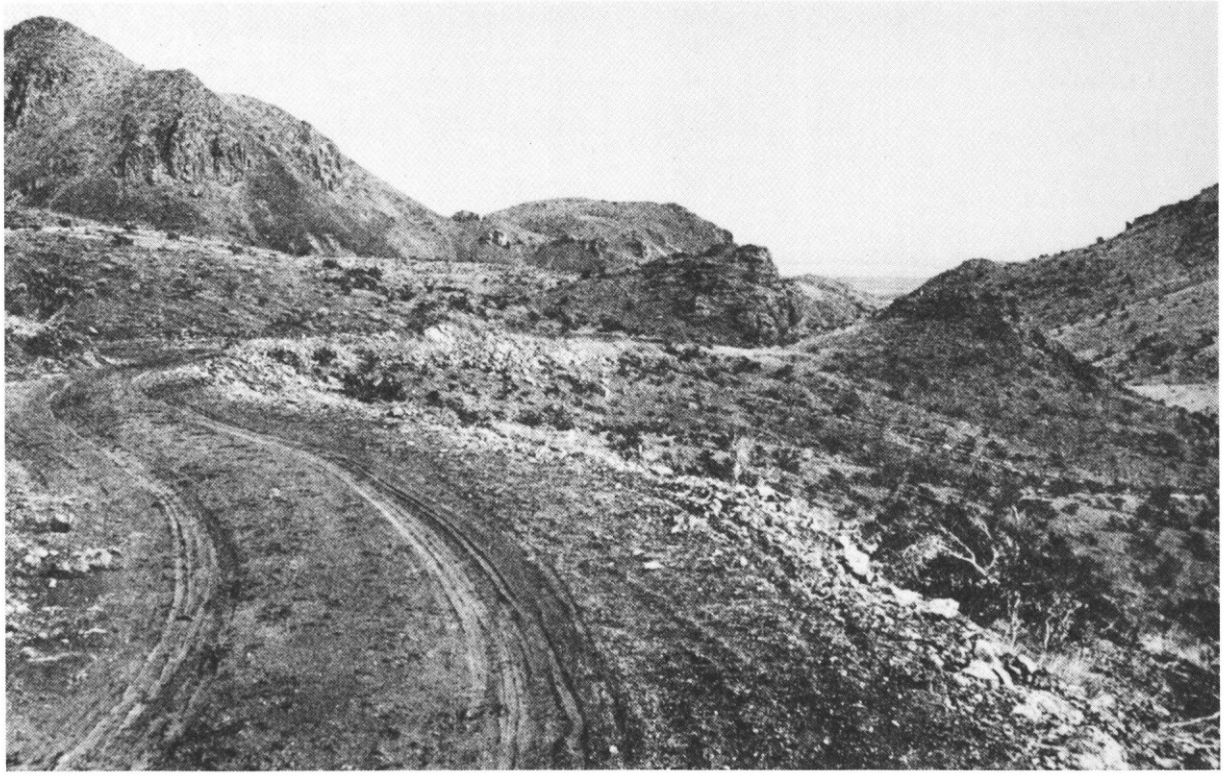
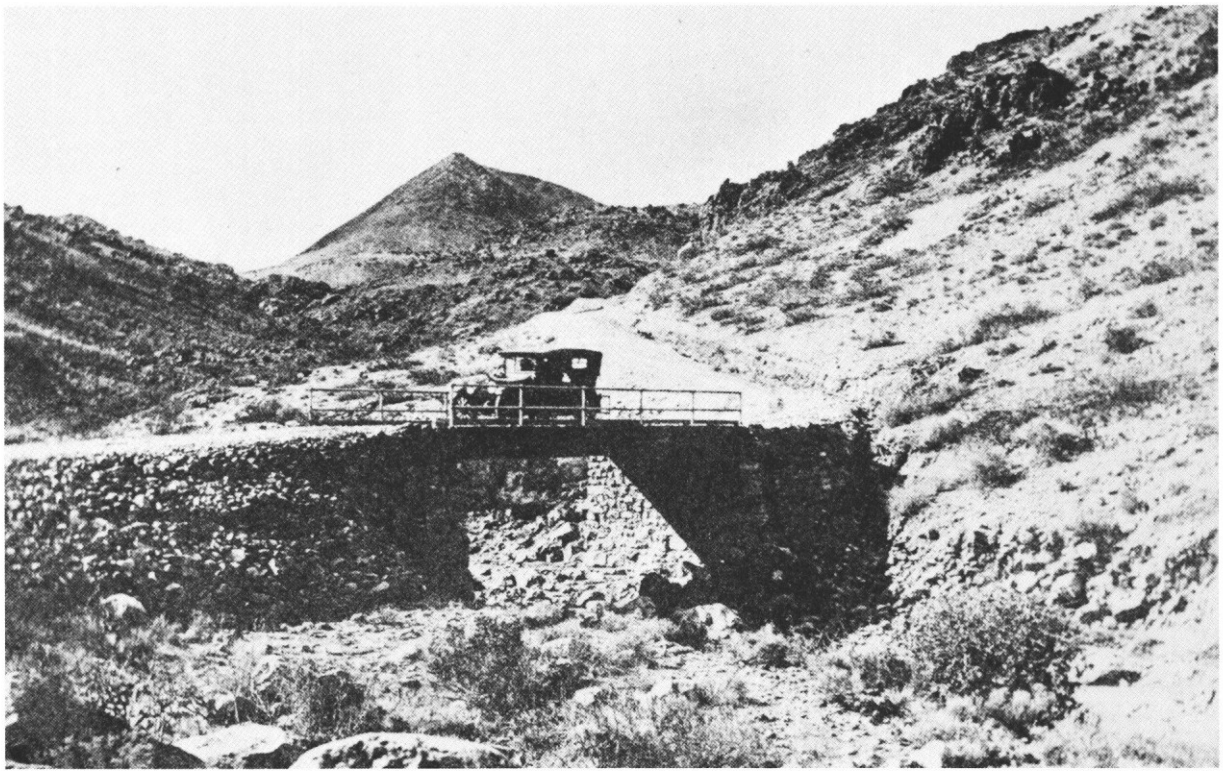


Abandoned Rio Grande (Billing) smelter at Park City, southwest of Socorro, ca. 1895. Gustav A. Billing's smelter, the very first large-scale industrial enterprise in New Mexico, was a tremendous success for the ten year period beginning September 1883, producing between $15 and $20 million in base bullion (lead bars containing gold and silver). Billing's honesty and business expertise enabled hundreds of precious metal mines in New Mexico, Arizona, and southern Colorado to flourish for over a decade—truly a golden age of mining in the southwest. Many years would pass before production of gold and silver would again match that prior to the silver crash of 1893 which forced this great enterprise and many others like it to close throughout the western United States. Joseph E. Smith photo, courtesy Ed Smith; New Mexico Bureau of Mines and Mineral Resources collection.



The Ocean-to-Ocean Highway through Blue Canyon in the Socorro Peak area, ca. 1915. From collections in the Museum of New Mexico.



Blue Canyon bridge on the Ocean-to-Ocean Highway west of Socorro, ca. 1915. From collections in the Museum of New Mexico.