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The Pennsylvanian System in New Mexico—overview with suggestions for revision of stratigraphic nomenclature

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Abstract

Understanding of Pennsylvanian lithostratigraphy in New Mexico has developed at an uneven pace, and the nomenclature currently applied to Pennsylvanian strata is in some cases antiquated, inconsistent, redundant, or inappropriate. The main Pennsylvanian rock sequences in New Mexico are reviewed, and several recommendations for revision of the lithostratigraphic nomenclature are proposed. In some cases these recommendations build upon or broaden changes that have been implemented by other workers in restricted areas. These recommendations include: 1) abandon use of Magdalena Group in New Mexico; 2) raise Madera Formation to Group rank; 3) treat previously used members within the Madera as formations, including the widely exposed and recognizable units still called "lower gray limestone" and "upper arkosic limestone" members; 4) apply the earliest valid formal names for the latter two units (Gray Mesa and Atrasado, originally defined in the Lucero uplift) widely throughout the Madera Group outcrop area; in some cases replace other formation names that have been proposed, and recognize that locally a third upper Madera unit (Bursum Formation and equivalents) may also be present; 5) recognize Madera Group strata and terminology more widely (e.g., into the Caballo and Robledo Mountains), yet retain current non-Madera terminology where appropriate, especially for sequences associated with rapidly subsiding basins (e.g., San Andres Mountains, Sacramento Mountains, Sangre de Cristo Mountains); 6) reevaluate the lithostratigraphic (formation and group) names of Thompson (1942), which remain valid and of potential use as members of more broadly defined Pennsylvanian formations; and 7) use New Mexico lithostratigraphic names for subsurface Pennsylvanian strata within the state, rather than names applied to Pennsylvanian rocks in central Texas.

Introduction

Pennsylvanian strata were among the first to be observed in detail by geologists entering New Mexico during and immediately after the American occupation, and Pennsylvanian fossils were among the first to be described from New Mexico Territory

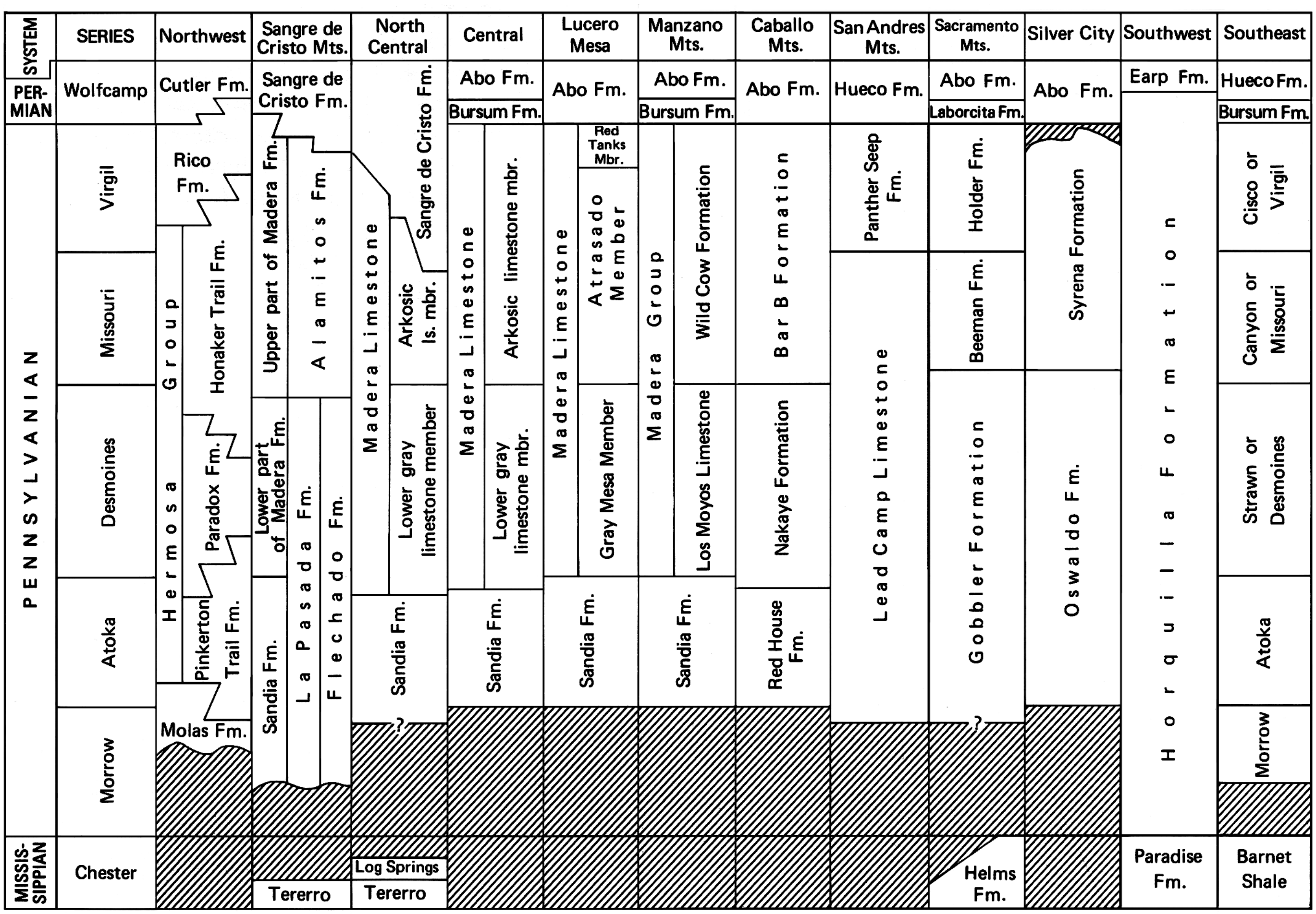


FIGURE 1—Currently used Pennsylvanian stratigraphic nomenclature in New Mexico (reproduced from Armstrong et al., 1979). The only significant addition since 1979 has been establishment of the Porvenir Formation for the lower part of the Madera in the southeastern Sangre de Cristo Mountains, with the upper part recognized as the Alamitos Formation and Madera raised to Group rank (Baltz and Myers, 1984, 1999).

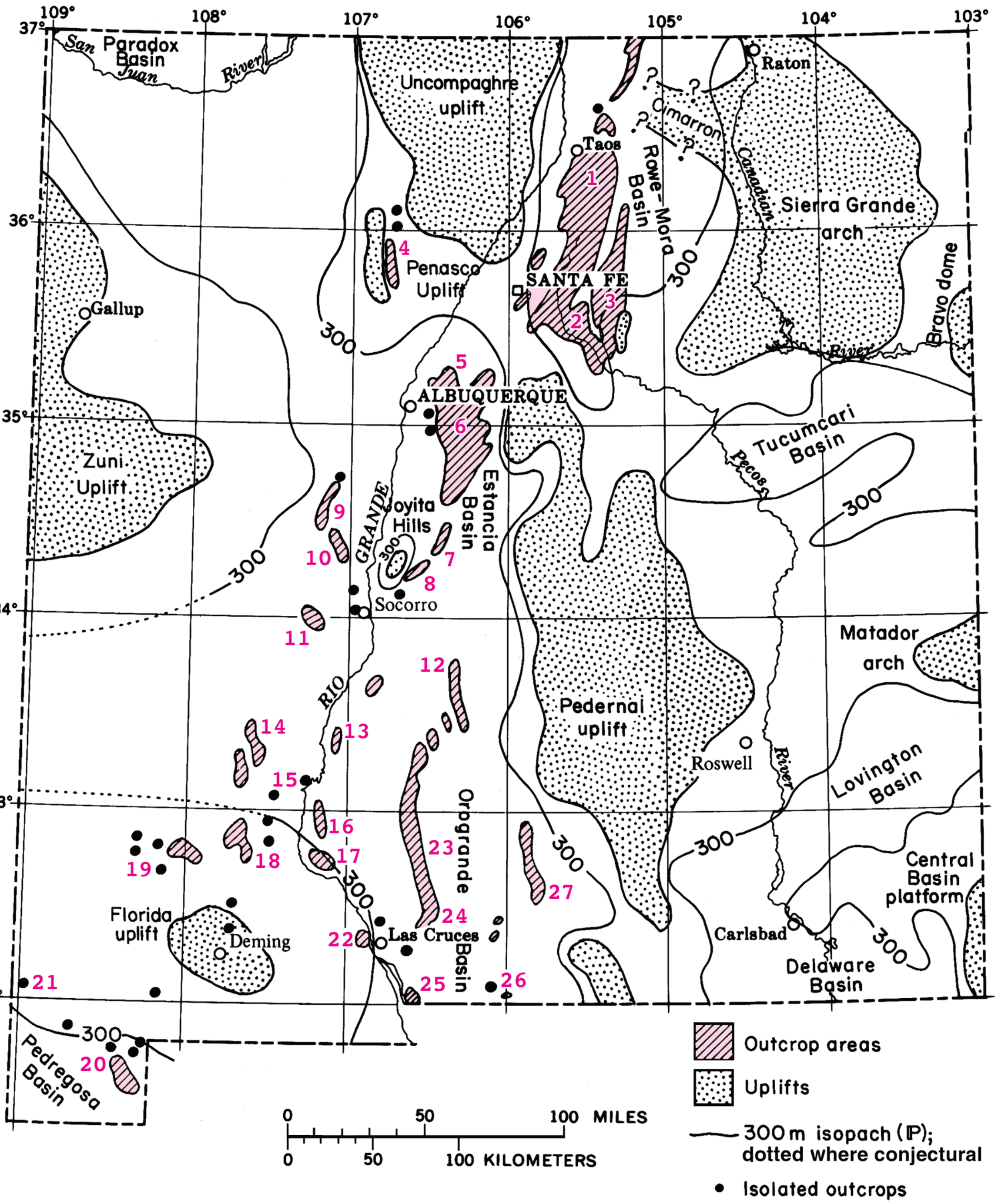


FIGURE 2—Main exposures of Pennsylvanian strata discussed in text (reproduced from Armstrong et al., 1979). Numbers refer to mountain ranges and other locations as follows: 1) northern Sangre de Cristo Mountains; 2) southern Sangre de Cristo Mountains; 3) southeastern Sangre de Cristo Mountains; 4) Nacimiento and Jemez Mountains; 5) Sandia Mountains; 6) Manzanita–Manzano Mountains; 7) Los Pinos Mountains; 8) Socorro area; 9) Lucero uplift; 10) Sierra Ladrones; 11) Magdalena Mountains; 12) Sierra Oscura; 13) Fra Cristobal Range; 14) Sierra Cuchillo area; 15) Mud Springs Mountains; 16) Caballo Mountains; 17) Derry Hills area; 18) Kingston area; 19) Santa Rita–Silver City area; 20) Big Hatchet Mountains; 21) Peloncillo Mountains; 22) Robledo Mountains; 23) San Andres Mountains; 24) northern Organ Mountains; 25) northern Franklin Mountains and Bishop Cap Hills; 26) northern Hueco Mountains; 27) Sacramento Mountains.

(e.g., Hall, 1856; Marcou, 1858). Later 19th century geologists (e.g., Stevenson, 1881) added information on Pennsylvanian stratigraphy of the territory, but subdivision and naming of Pennsylvanian strata began in the early 1900s (e.g., Herrick, 1900; Gordon, 1907) and has continued ever since. Thompson (1942) made the first real attempt to recognize, correlate, and name lithostratigraphic units throughout New Mexico; Kottlowski (1960a) summarized in detail Pennsylvanian stratigraphic sequences and nomenclature for much of the state; and Armstrong et al. (1979) provided a general summary of New Mexico Pennsylvanian strata (Fig. 1).

Although Pennsylvanian strata are not as widely exposed in New Mexico as Permian, Triassic, Cretaceous, and Paleogene strata, they include a greater diversity of depositional environments and a greater variety of reported fossil species (more than 1,250) than any system except the Cretaceous (Kues, 1982, table 2). Thick

(500+ m [1,640+ ft]) Pennsylvanian sections are exposed in many parts of northern and southern New Mexico (Fig. 2) chiefly in fault-block mountain ranges along the Rio Grande rift and adjacent regions, and Pennsylvanian strata are widely present in the subsurface in most parts of the state, where some units are reservoirs for oil and gas (e.g., Broadhead, 1999), and others are hydrogeologic aquifers producing water.

Development of our understanding of Pennsylvanian stratigraphy in New Mexico has proceeded at an uneven pace. Pennsylvanian sequences in a few areas have been intensively studied, whereas, more commonly, sequences in other areas have been examined in only moderate detail, typically in the context of structural/stratigraphic studies of individual mountain ranges. The Pennsylvanian of some ranges is known only at the level of reconnaissance mapping done several decades ago. Similarly, the stratigraphic nomenclature applied to Pennsylvanian sequences in New Mexico has developed in a piecemeal fashion, producing a large number of currently used group, formation, and member names, some of which are inappropriate, redundant, informal, or applied only to unnecessarily restricted areas, and some of which have been widely used for decades without designation of type sections or adequate formal definition.

Lateral facies changes may frustrate recognition of stratigraphic units very far from their type sections. This has contributed, on the one hand, to the establishment of unique successions of formation names in individual, closely spaced mountain ranges, and, on the other hand, to approaches that deemphasize the lithostratigraphic subdivision of thick Pennsylvanian sequences in favor of relying on fusulinid biostratigraphy to recognize chronostratigraphic units, such as the five Pennsylvanian series—Morrowan, Atokan, Desmoinesian, Missourian, and Virgilian—as the only subdivisions of the Pennsylvanian (Kottlowski, 1960a). In addition, in many parts of the state, Upper Pennsylvanian strata grade upward through a transitional sequence with progressively less marine influence, into nonmarine, clastic, red-bed units near the Pennsylvanian–Permian boundary. The position of this boundary within some of these transitional sequences and the terminology for them deserve more study.

A century after the first Pennsylvanian formation was named in New Mexico (Sandia Formation, Herrick, 1900), this paper 1) provides an overview of Pennsylvanian stratigraphy around the state, 2) reviews current lithostratigraphic nomenclature, 3) proposes some revisions of this nomenclature in some areas, and 4) indicates locations where additional study of the Pennsylvanian would be useful. A brief summary of the major recommendations was presented earlier (Kues, 2000). A correlation chart of major exposed Pennsylvanian sequences in New Mexico incorporates proposed revisions in lithostratigraphic nomenclature that are discussed in this paper (Fig. 3).

In proposing revisions of currently used stratigraphic nomenclature, the desirability of maintaining stability of nomenclature by preserving familiar and long-used names is recognized, even if in retrospect they may not have been the most logical or appropriate names to apply to a particular stratigraphic unit. Separate formation names are appropriate for distinctive lithological units that are mappable at a scale of 1:24,000; however, the same lithostratigraphic names should be used for similar lithologic units that may be exposed widely in a region, cropping out, for example, in several isolated mountain ranges. New and existing names should reflect significant lithological differences from equivalent units in a region, but not be established simply as a convenient way to designate local successions of strata with little reference to equivalent successions elsewhere in the region. In this paper, little attention is devoted to the nomenclature of the transitional Pennsylvanian–Permian units noted above. Recent proposals to raise the Pennsylvanian–Permian boundary to a position within the Wolfcampian stage in North America (e.g., Baars et al., 1994; Lucas et al., 2000) are likewise not addressed. These are the focus of ongoing studies by the author and others, and conclusions will be presented in a future paper. Although the focus here is on exposed parts of the Pennsylvanian sequence, some observations are included on terminology of subsurface units as well.

Nomenclature of Thompson (1942)

Thompson (1942), in a publication titled *Pennsylvanian System in New Mexico*, sought to classify the strata of the entire Pennsylvanian using eight group names, two each for the "Derryan" (Atokan), Desmoinesian, Missourian, and Virgilian Series; 15 formation names; and one member name, all of which were new. His names were not used by the U.S. Geological Survey in its large-scale reconnaissance mapping projects in the 1940s, and ultimately none of Thompson's names were used by other workers in later stratigraphic studies in New Mexico, although Kottlowski (1960a) continued to apply Thompson's Missourian and Virgilian unit names in the Sierra Oscura.

Thompson's nomenclature was rejected by later workers for essentially three reasons. First, he initially divided the Pennsylvanian using fusulinid biostratigraphy into the four series (chronostratigraphic units) noted above, and then fit the lithostratigraphic units he defined to the chronostratigraphic units, particularly with respect to their boundaries, rather than defining groups and formations entirely on a lithologic basis, as is required by the North American Code of Stratigraphic Nomenclature. It is a misconception, however, that Thompson's lithostratigraphic units were nothing more than faunal zones, as claimed by some workers (e.g., Kelley and Silver, 1952, p. 89). His lithostratigraphic units were defined precisely, described in detail, and type sections for each of them were designated.

A second difficulty with Thompson's units, however, was that they were based almost entirely on the stratigraphy of two restricted areas. His Atokan and Desmoinesian units were based on exposures in the Derry Hills–Mud Springs Mountains area, and his Missourian and Virgilian units were based on strata in the northern Sierra Oscura, with the exception of one group having a type section in the northern Sacramento Mountains. Although Thompson stated that many of his units could be recognized in areas far distant from their type sections, he provided little information to aid such correlations. Later field geologists found that many of his units could not be recognized easily very far from their type areas.

Thirdly, Thompson's groups and formations largely represented restricted stratigraphic intervals that in some cases were not easily distinguishable lithologically from underlying or overlying units, and in many cases were not mappable at the scales required by the present Code of Stratigraphic Nomenclature.

Thompson's work is noted here in part because the rejection of his stratigraphic terminology was premature and done with little discussion of its merits. While it is true that Thompson's unit names generally cannot be applied very widely, some units can be recognized more than 160 km (100 mi) away from their type localities (e.g., Kottlowski, 1960a, p. 21). Other units, such as Thompson's Bruton Formation, were well defined lithologically and recognizable regionally, to the extent that U.S. Geological Survey geologists adopted and mapped it, although renaming it the Bursum Formation (see Wilpolt and Wanek, 1951). Thompson's Armendaris and Bolander Groups (Desmoinesian) are together lithologically similar to the widespread "lower gray limestone" member of the Madera of many previous workers, a unit now considered a formation with formal names in some areas of the state. Thompson's group and formation names in the Mud Springs Mountains, Derry Hills, and Sierra Oscura areas remain available (most appropriately as member names, because the current Code of Stratigraphic Nomenclature [NACSN, 1983, p. 858] does not require that members be mappable) for units in those areas, should future workers studying the

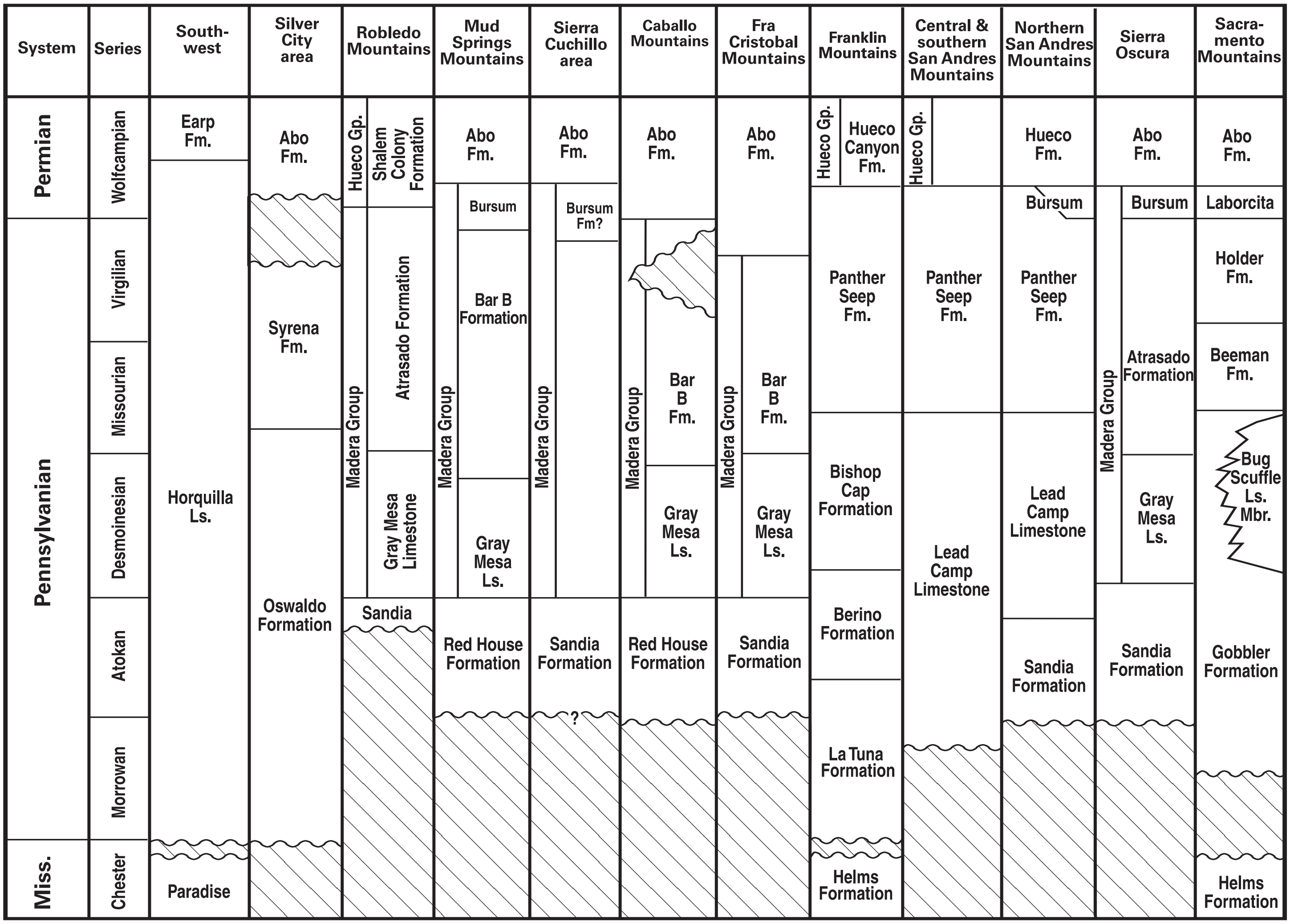


FIGURE 3—Stratigraphic nomenclature for major Pennsylvanian exposures in New Mexico, as proposed in this paper. Note that in some areas, formation-rank units within the Madera Group have yet to be established.

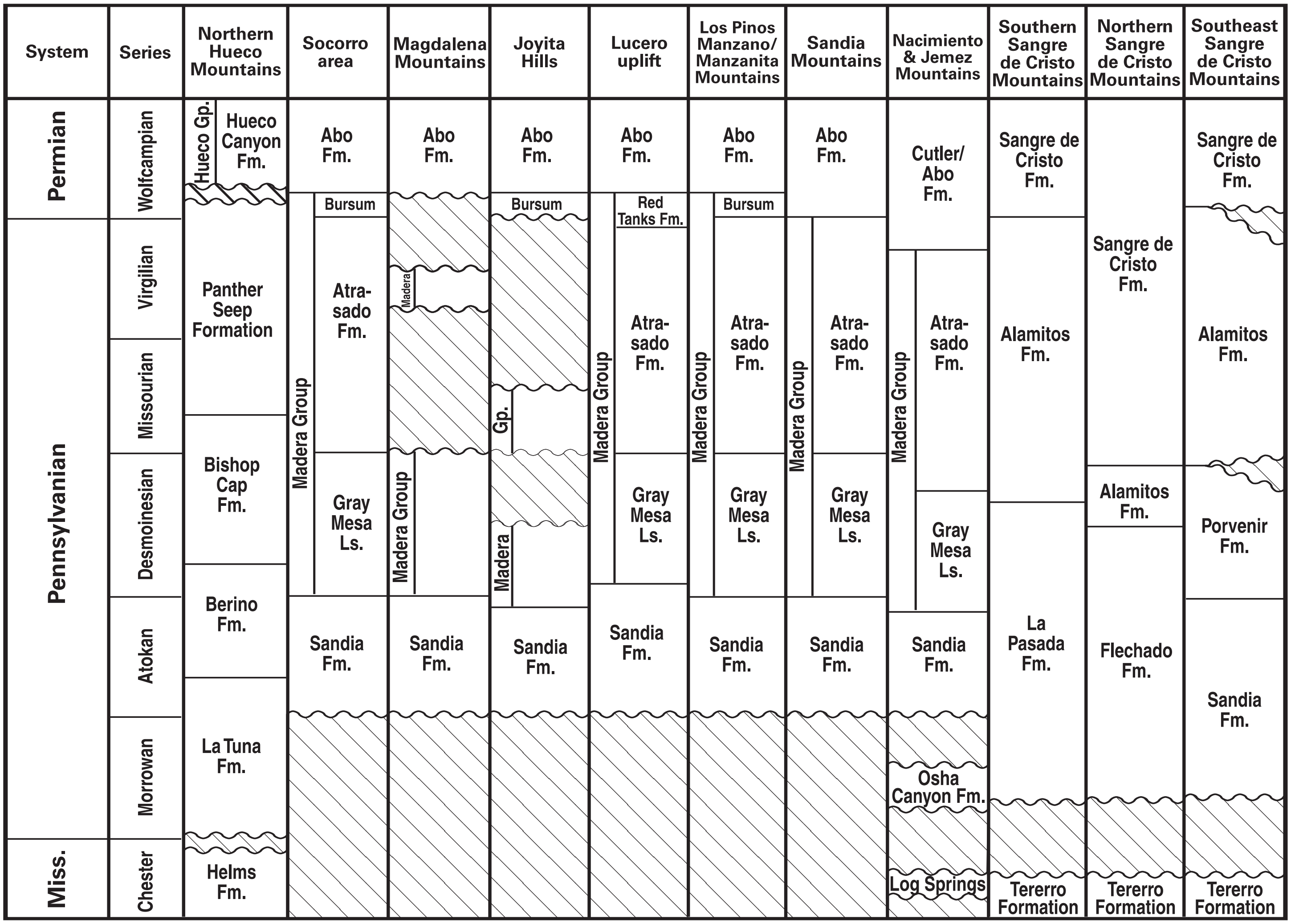
Pennsylvanian stratigraphy in detail require member names.

In his 1942 study, Thompson (p. 26) proposed the term Derry Series for "all rocks in the central to the extreme south central areas of New Mexico between the base of the Pennsylvanian system and the basal part of the…Des Moines series," and this name has persisted in the more recent literature as a New Mexico equivalent to the Atoka Series of the midcontinent. It is now known that Thompson's type Derry section (Derry Hills, south of Truth or Consequences) includes strata of late Morrowan and Atokan age (e.g., Clopine et al., 1991), and that thick sequences of Morrowan strata occur at the base of the Pennsylvanian in both northern and southern New Mexico. Recognition of the Morrowan and Atokan Series in New Mexico is straightforward, and it is therefore preferable to use these series names (which are used widely across much of the U.S.) rather than the superfluous and local term Derry Series.

Magdalena Group

Gordon (1907) proposed the name Magdalena Group to include the Sandia Formation (of Herrick, 1900; Herrick and Bendrat, 1900) and overlying Madera Limestone (of Keyes, 1903). The name was taken from the Magdalena Mountains west of Socorro, and the group was recognized by Gordon in Socorro, Bernalillo, and Sierra Counties, although he noted that it could not be subdivided in Sierra County. When proposed, the Magdalena Group was believed to represent the lower part of the Pennsylvanian, the upper part being represented by the Manzano Group (of Herrick, 1900) and consisting of the Abo, Yeso, and San Andres Formations (Lee and Girty, 1909). The Permian age of the formations of the Manzano Group was soon recognized (e.g., Lee, 1917, 1921), and the term Manzano Group passed out of usage in the 1930s, leaving the Magdalena Group essentially synonymous with the Pennsylvanian System. Indeed, Darton (1928) and Needham (1940) applied the term Magdalena Group or Formation to essentially all Pennsylvanian sequences in New Mexico, and in later decades the U.S. Geological Survey and others continued to use the term Magdalena throughout the state, from the Sangre de Cristo to Franklin Mountains. Rock units of Late Mississippian age (e.g., the "lower limestone member" of the Sandia Formation of Wood and Northrop, 1946, now the Arroyo Peñasco Group) and of Early Permian age (e.g., Bursum Formation, Wilpolt et al., 1946) were also included in the Magdalena Group. P. B. King (1942, pp. 675–677) believed that the upper part of the Magdalena Group in New Mexico included much Wolfcampian strata and could be traced southward into the Early Permian Hueco Limestone.

Objections to use of the term Magdalena Group, registered in the literature for more than 50 yrs, fall generally into three categories. First, as commonly used in most regions, the name is synonymous with Pennsylvanian System and thus is superfluous. Second, over the years, the name Magdalena Group has been applied in so many different ways and to such different



successions of formations that it is essentially meaningless in any precise stratigraphic sense. Third, the highly faulted, intruded, metamorphosed, and incomplete Pennsylvanian section in the Magdalena Mountains makes this area unsuitable for a type section, as Kottlowski (1959, p. 59) aptly noted: "Even with deliberate care a more unsuitable type section probably could not be found." In reality, no type section for the Magdalena Group has ever been established, nor could an adequate type section be established in the future because of the anomalous nature of the Pennsylvanian section in the Magdalena Mountains, including the absence of Upper Pennsylvanian beds owing to faulting or erosion, and the lack of a stratigraphic contact with the overlying Abo Formation (Kottlowski, 1960a).

As early as 1942, Thompson (p. 22) abandoned use of the term Magdalena Group as a stratigraphic unit in New Mexico, stating that the term "Magdalena…seems to be essentially synonymous with the systemic term Pennsylvanian…" and "…it seems inadvisable to attempt to preserve this…term by merely restricting the name in any sense to a small portion of the Pennsylvanian in New Mexico." R. E. King (1945, p. 21) echoed Thompson's recommendation and added his own: "…the unfortunate name Magdalena has become more deeply entrenched in recent geologic literature published by the U.S. Geological Survey…and it is recommended that the term Magdalena, a relic of an antiquated type of stratigraphic nomenclature, be permanently abandoned." Pray (1961, p. 72), in rejecting use of Magdalena Group in the Sacramento Mountains, stated that the "term is so broad…and the sections to which it has been applied are so varied in New Mexico, that it serves little practical purpose." Kottlowski (1960a, p. 21) speculated that the main reason for continuing to use Magdalena Group rather than simply Pennsylvanian might be to "indicate inclusion of more than only Pennsylvanian strata within the group," and noted (Kottlowski, 1962, p. 343) that "if pre and post-Pennsylvanian units were eliminated from the Magdalena Group…the remainder is the equivalent of the Pennsylvanian System, of which the term Magdalena is a somewhat unnecessary duplication." Inclusion of Mississippian strata is no longer an issue, as these have been separated out and named (e.g., Kelly Limestone, Arroyo Peñasco Group). And, as Kottlowski undoubtedly realized, if use of the name Magdalena Group is an unnecessary duplication of "Pennsylvanian," it is even more nebulous a term when applied to Pennsylvanian plus Lower Permian strata.

In recent decades, use of the term Magdalena Group has been discontinued in many areas of New Mexico where it formerly had been applied. These areas include the San Andres Mountains (Kottlowski et al., 1956), Sacramento Mountains (Pray, 1961), Sangre de Cristo Mountains (Sutherland, 1963; Baltz and Myers, 1984, 1999), northern San Andres and Oscura Mountains (Bachman, 1968; Bachman and Harbour, 1970), Joyita Hills (Kottlowski and Stewart, 1970), Manzano and Manzanita Mountains (Myers, 1973), Los Pinos Mountains (Myers et al., 1986), Nacimiento Mountains (Woodward, 1987), and generally in central and south-central New Mexico (Bachman and Myers, 1975). The term Magdalena Group does not appear anywhere in the statewide Pennsylvanian stratigraphic correlation chart of Armstrong et al. (1979, fig. 8).

There is clearly an ongoing, progressive recognition that application of the name Magdalena Group or Formation serves no useful purpose. Further use of the name should cease in all parts of New Mexico where it is currently still used. These areas include the Hueco Mountains (e.g., Williams, 1963; Stoklosa et al., 1998); Franklin Mountains (e.g., Harbour, 1972; LeMone, 1982, 1992; Kelley and Matheny, 1983); Bishop Cap Hills (Seager, 1973); Silver City–Santa Rita area (e.g., Jones et al., 1967, 1970; Pratt, 1967); Caballo Mountains and Derry Hills (e.g., Kelley and Silver, 1952; Seager and Mack, 1991, 1998; Mack et al., 1998); Mud Springs Mountains (Maxwell and Oakman, 1990); Fra Cristobal Mountains (Nelson, 1986); Socorro County (e.g., Siemers, 1983; McLemore and Bowie, 1987); Lucero uplift (Kelley and Wood, 1946); and Sandia Mountains (Kelley and Northrop, 1975, although Lucas et al., 1999a, b, extended into the Sandias Myers' [1973] terminology for the Manzano–Manzanita Mountains, which specifically rejects usage of the term Magdalena Group). The most recent North American Code of Stratigraphic Nomenclature (NACSN, 1983, p. 855) states that "…the lack of need or useful purpose for a unit, may be a basis for abandonment; so, too, may widespread misuse in diverse ways which compound confusion." Both are true of the Magdalena Group. Perhaps the most obvious misuse of the name occurs in the Franklin Mountains, where a sequence of three Morrowan to Desmoinesian formations, composed of massive limestone at the base, and becoming increasingly shaly upsection, are included in the Magdalena Group, in complete contrast to the Magdalena as used in central New Mexico, which is primarily clastics at the base and massive limestones in the Desmoinesian portion. Discontinuing use of the name Magdalena Group will not adversely affect stratigraphic understanding of the Pennsylvanian sequences anywhere in New Mexico.

Madera Formation/Group

The name Madera Formation was first applied to Upper Carboniferous blue to gray beds, "the superior part of the great limestone formation" in the Sandia Mountains by Keyes (1903). Herrick (1900) had recognized this interval between his "Sandia series" and "Manzano series" but applied no name to it. Gordon (1907) adopted the name Madera Limestone for "the great limestone plate along the back slope of the Sandia Mountains," named for the former village of La Madera, and he recognized the formation as the upper part of his Magdalena Group in Bernalillo and Socorro Counties. No formal type section for the Madera has ever been established, but a reasonable reference section was presented by Kelley and Northrop (1975, p. 125) at Montezuma Ridge, east of Placitas and a few kilometers north of the site of La Madera village.

Although Thompson (1942) argued against using the name Madera because Keyes' (1903) definition was so poor and he was inconsistent in his usage, the term has proven useful for the thick, predominantly limestone unit between the Sandia Formation and the Wolfcampian Abo red beds. By 1950 the Madera Formation was recognized in the Sandia, Manzano, Nacimiento, Sangre de Cristo, Los Pinos, Oscura, and Magdalena ranges, the Lucero uplift, the Joyita Hills, and elsewhere in Socorro County. Detailed stratigraphic sections were published for the Madera in many of these areas, leaving no doubt as to its lithologic composition and stratigraphic position. In the 1940s (see Read and Wood, 1947) the U.S. Geological Survey (USGS) adopted the convention in reconnaissance mapping of recognizing informally a lower "gray limestone member" of Desmoinesian age and an upper "arkosic limestone member," typically of Missourian and Virgilian age. An exception was in the Lucero uplift area (see below), where Kelley and Wood (1946) applied formal names to these subdivisions of the Madera. In central New Mexico, from the south end of the Manzano Mountains southward, a separate Bursum Formation was also recognized, incorporating Early Permian beds transitional between the mainly marine sediments of the Madera Formation and the nonmarine red-bed clastics of the Abo Formation. In southern New Mexico, Madera terminology generally has not been used. Strata correlative with the Madera have received local formation names, resulting in separate stratigraphic nomenclatures applied to the Pennsylvanian sequences in the Caballo, San Andres, Sacramento, and Franklin Mountains, and in the Silver City–Santa Rita area.

As studies progressed, the Madera Formation in two areas was raised to group status, its members raised to formations, formal formation names given to the lower "gray limestone" and upper "arkosic limestone" members, and formal member names given to subdivisions of these units. For example, in the Manzano and Manzanita Mountains (see below) the lower member was named the Los Moyos Limestone and the upper member the Wild Cow Formation by Myers (1973), within a Madera Group that also included the Bursum Formation. Similarly, in the southeastern Sangre de Cristo Mountains (see below), Baltz and Myers (1984, 1999) raised the Madera to group rank and recognized the Porvenir and Alamitos Formations, in place of the lower "gray limestone" and upper "arkosic limestone" members, respectively. These revisions of Madera terminology reflect more detailed stratigraphic study and illustrate approaches that are applicable to other ranges as well. These approaches, which are used below, include: 1) raising the Madera Formation to Group, a more appropriate rank, given its great thickness (typically 300–700+ m [1,000–2,300 ft]), widespread distribution, and long duration (Desmoinesian to Virgilian or early Wolfcampian); 2) formally naming formations to replace informal subdivisions such as lower "gray limestone" and upper "arkosic limestone" members; and 3) where appropriate, formally naming members to designate localized but distinctive lithologic units within formations. The Madera Group encompasses two or three formation-rank units that are readily mappable at a scale of 1:24,000.

The Madera Group generally reflects two major depositional sequences. During Desmoinesian time marine deposition across widespread carbonate shelf environments (e.g., Ye et al., 1996) produced massive, gray, cliff-forming limestone units, typically cherty, with little interbedded clastic sediments. This was followed by marine environments that were increasingly, although not everywhere evenly, affected by influx of siliciclastic sediments derived from increased tectonic activity in (principally) the Uncompahgre, Pedernal, and Zuni land masses associated with Ancestral Rocky Mountains tectonism during Missourian, Virgilian, and locally into Wolfcampian time. Expansion of continental, transitional (e.g., delta, lagoon), coastline, and marine, clastic shelf environments at the expense of carbonate shelf environments occurred during this time (Ye et al., 1996). In the upper part of the Madera Group, marine limestones typically still predominate, but generally in thinner beds and with little to no chert. Interbedded shales and siltstones approach (in the Missourian and Virgilian) or may locally surpass (in the Virgilian and early Wolfcampian) the thickness of the limestones. Siliciclastic beds in the upper Madera Group are generally gray or brown low in the upper unit, but become gradually more colorful upsection, with the addition of red, maroon, purple, and green lithologies, which ultimately dominate the uppermost part of the Madera sequence. Finally, marine deposition and limestone lithologies cease, and continental nonmarine red-bed clastics of the Abo Formation prevail.

The term Madera Group appropriately encompasses this broad depositional pattern, which can be recognized across much of New Mexico. Units of formation rank, as characterized in the present Code of Stratigraphic Nomenclature (NACSN, 1983, p. 858), are suitable for the main lithologic units, including the lower cherty limestone sequence and the upper interbedded limestone/siliciclastics sequence. As previous workers have done in some areas, this upper sequence can be divided into two formation-rank units, the lower of which is dominated by marine limestone with no or few red, maroon, or green beds, and the upper of which is typically thinner and dominated by colored clastic beds, typically of nonmarine origin, with subsidiary marine limestones.

The Madera Group reflects deposition on shelf and basin margin, and in slowly subsiding basin conditions that were dominated by marine environments until nearly the end of Madera deposition. Sequences of similar age deposited in rapidly subsiding basins (e.g., Orogrande Basin, Taos trough) are lithologically considerably different and generally much thicker than Madera Group sequences. Thus, although Baltz and Myers (1984, 1999) included the Porvenir and Alamitos Formations within the Madera Group in north-central New Mexico, these Taos trough formations differ so greatly from typical Madera lithologies that application of the term Madera Group to them is not recommended. The Desmoinesian Porvenir Formation (see below) consists of dominantly clastic facies (even in the most carbonate-rich sections, limestones—generally noncherty—are less than 50% of the total thickness), in contrast to the uniform, massive, cherty limestone beds of the lower part of the Madera Group. The late Desmoinesian to Virgilian Alamitos Formation consists predominantly of nonmarine arkosic sandstones and conglomerates, shale, and minor marine limestones, quite different from the alternating marine limestones and shales, with minimal coarse clastics, that characterize the upper part of typical Madera sequences. Similarly, rapid subsidence and filling of the central Orogrande Basin in the Missourian and Virgilian produced an abnormally thick (1,000 m; 3,280 ft) Panther Seep sequence that consists mainly (74%) of coarse to fine siliciclastics (Schoderbek, 1994) with minor marine limestone and some evaporite beds that reflect mainly nonmarine deposition—again, so different in lithology and thickness from typical upper Madera units that Madera Group terminology is clearly inappropriate.

Within the general succession of typical Madera strata defined above, lateral variations in deposition reflect different environments, distance from land masses, and short-term transgressive and regressive sequences owing to fluctuations in tectonic and eustatic activity. Where warranted by considerable differences in lithology, these units may also be recognized as local formations, but normally recognition as members of more broadly defined formations is recommended. Member-level lithostratigraphic units in the Madera Group typically reflect local, gradational lateral or vertical facies changes, and therefore are restricted in extent, perhaps limited to individual mountain ranges. Fine-scale sequence-stratigraphic studies, such as have been undertaken in restricted parts of the Madera Group in the Sandia Mountains (e.g., Wiberg and Smith, 1993; Smith, 1999), will help to refine understanding of the cyclic sedimentary processes responsible for Madera lithologic units and ultimately, the nomenclature that is applied to them.

Recommendations for revision of stratigraphic nomenclature for units within the Madera Group follow the philosophy discussed above. The earliest formal names applied to the lower "gray limestone" and upper "arkosic limestone" members of the Madera Formation were established by Kelley and Wood (1946) in the Lucero uplift–Sierra Ladrones region of western Valencia and northwestern Socorro Counties (see below). These members, Gray Mesa and Atrasado, respectively, in this paper are considered formations within the Madera Group, and are recognized widely in central New Mexico, from the Nacimiento and Jemez Mountains on the north, to the Caballo and Robledo Mountains on the south, along the western platform margin of the Orogrande Basin. The transitional Pennsylvanian–Permian strata at the top of the Madera Group, including the Bursum Formation and Bursum-equivalent strata, whether named or not, are not covered in detail here; a future paper will describe and correlate these strata and consider their nomenclature.

Lucero uplift–Sierra Ladrones

Kelley and Wood (1946) recognized the Sandia and Madera Formations within the Magdalena Group in the Lucero uplift–Sierra Ladrones region and named (in ascending order) the Gray Mesa, Atrasado, and Red Tanks Members within the Madera. Thickness of the Madera ranges from approximately 525 m to 700 m (1,725–2,300 ft) from north to south along the Lucero uplift to the Sierra Ladrones, and each member is lithologically distinctive, more than 100 m (325 ft) thick, and can be mapped at a scale of 1:63,000 (Kelley and Wood, 1946). These members meet all the requirements of formation-rank units. The term Magdalena Group is herein abandoned in the Lucero uplift area, for reasons noted above, and the Madera is raised to group status, with its constituent members as formations, as has been done in the neighboring Manzano–Manzanita and Los Pinos Mountains (Myers, 1973; Myers et al., 1986).

The formations of the Madera Group in the Lucero uplift area are important, as they are each well exposed and their names were the first formal names to be applied to the three subdivisions of the Madera that can be recognized widely in central and south-central New Mexico. Kelley and Wood's descriptions of the three formations, though brief, adequately characterize them, and subsequent workers (Martin, 1971, for the Gray Mesa and Atrasado, and Kues and Kietzke, 1976, for the Red Tanks) have studied the stratigraphy of these units in detail, providing the basis for comparing them with equivalent units elsewhere in New Mexico.

As defined by Kelley and Wood (1946), the Gray Mesa Limestone consists of predominantly massive, gray, markedly cherty, cliff-forming limestones, as well as minor amounts of gray shale and sandstone, and a conspicuous tan-weathering limestone at the top. Thin-bedded and locally noncherty limestones are also present, though not abundant. Martin (1971), on the basis of stratigraphic sections measured on Gray Mesa (= Mesa Aparejo on USGS topographic maps) and Carrizo Mesa, Monte de Belen (= Mesa Sarca), and in the northern and southern Sierra Ladrones, determined the thickness of the Gray Mesa Limestone to range from approximately 215 m to 250 m (700–820 ft), and its composition to be between 70% and 88% marine limestones, 4–23% shale/siltstone, and 4–7% sandstone/conglomerate. The highest proportion of fine to coarse siliciclastics (30%) is in the southernmost section (southern Sierra Ladrones). The age of the Gray Mesa Limestone, based on detailed fusulinid biostratigraphy (Martin, 1971), ranges from at or just above the Atokan–Desmoinesian boundary to the end of the Desmoinesian. The Desmoinesian–Missourian boundary corresponds in all sections to an abrupt change in lithology from massive limestone beds to a thick shale sequence at the base of the overlying Atrasado Formation.

Kelley and Wood (1946) characterized the Atrasado Formation as consisting of thin- to thick-bedded, gray limestone, gray and reddish shales, and red to light reddish-brown and gray conglomeratic sandstone. The limestones in the Atrasado have far less chert than those of the Gray Mesa Limestone. Martin's (1971) study indicated thicknesses ranging from approximately 225 m (740 ft) on the north to possibly as much as 450 m (1,475 ft) in the southern Sierra Ladrones. Martin (1971), using series divisions within the Madera, did not indicate the division between the Atrasado and Red Tanks Formations in his stratigraphic analysis, and in the southern Sierra Ladrones the boundary is not clear. Kottlowski (1960a) reported a similar thickness of approximately 420 m (1,375 ft) for the Atrasado-equivalent (Missourian–Virgilian) sequence, and Siemers (1983) reported 455 m (approximately 1,500 ft) for this sequence in the Sierra Ladrones. The Atrasado consists of a cyclic sequence of from 15 to more than 20 thin-to-thick limestone units separated by shale intervals of equal or greater thickness. Age ranges from earliest Missourian to well into, and possibly near the end of, the Virgilian (Martin, 1971). The northernmost section of the Atrasado (Mesa Aparejo–Mesa Carrizo) includes approximately 63% of fine- to coarse-grained siliciclastic beds and approximately 37% limestones; the proportion of limestone increases to nearly 50% to the south, in the Sierra Ladrones. Sandstone and conglomerate beds are very minor (typically approximately 2–3% in all sections), and shale units, mostly gray to greenish gray in the Missourian part of the formation, display more varied coloration (yellow, purple, red) in the Virgilian portion.

The Red Tanks Formation, as thick as approximately 135 m (440 ft; Kues and Kietzke, 1976) consists mainly of green, red, reddish-brown, and gray shales (the latter locally carbonaceous with a thin coal seam), and subordinate gray marine limestone beds and sandstones, both essentially restricted to the lower 60% of the formation. Kelley and Wood (1946) and Armstrong et al. (1979) believed the Red Tanks to be of Late Pennsylvanian age, but later work on its prolific and varied fauna and flora (e.g., Tidwell et al., 1999, and references therein) suggest that most of the formation is Wolfcampian. The Red Tanks is therefore coeval with, although lithologically distinct from, the upper unit of the Madera Group (Bursum Formation) to the east.

Kelley and Wood (1946) did not designate type sections for the three members of the Madera they defined, and the names Gray Mesa and Atrasado (from Atrasado Arroyo) were based on geographic features indicated on their map, which were later replaced by the names Mesa Aparejo and Arroyo Alamitos on U.S. Geological Survey topographic maps. A name change, or even the disappearance of a geographic feature, is not a basis for abandoning a lithostratigraphic name that was based on the feature (see NACSN, 1983, pp. 852–853), so Gray Mesa and Atrasado, which have been used in the Lucero uplift area for more than a half century, are considered valid names. Later workers (e.g., Bates, 1947; Jicha and Lochman-Balk, 1958) indicated Gray Mesa (Mesa Aparejo) as the type section for the Gray Mesa Member, indicated tributaries of Red Tanks Arroyo as the type locality for the Red Tanks Member, and stated that no type section for the Atrasado had been designated. However, this information was apparently based on the assumption that type sections must be at the localities that were the sources of the names for particular units, which, of course, is not necessarily true. Here, the type section for the Gray Mesa Limestone and Atrasado Formations is considered to be the sequence exposed along the east slope of Gray (= Aparejo) and Carrizo Mesas, as measured by Martin (1971) in sec. 14 T5N R3W and sec. 7 T6N R2W southwestward to sec. 35 T6N R3W. The type section for the Red Tanks Formation is the locality where Kelley and Wood (1946) indicated the most complete section of this unit is exposed, and where Kues and Kietzke (1976) measured a complete stratigraphic section, along Carrizo Arroyo near the northeast end of Mesa Carrizo (= South Mesa of Kelley and Wood), around the center of SW¼ sec. 6 T6N R2W. All of these localities are in Valencia County.

To complete this summary of Pennsylvanian strata in the Lucero uplift area, the Sandia Formation is conformably present below the Madera Group, resting unconformably on Mississippian limestones. It is composed of mainly shale and sandstone, and thickens southward from approximately 46 m (150 ft) at Mesa Aparejo to approximately 150 m (500 ft) in the southern Sierra Ladrones. Sandstones and conglomerate, primarily quartz arenites, represent approximately 72% of the total Sandia Formation to the north but dwindle to 12% in the south. In contrast, dark, often carbonaceous shales represent 11% of the total thickness to the north but increase to 83% in the south. Marine limestones are limited to between one and a few thin beds and total no more than 17% of the formation thickness at any locality. Fusulinid biostratigraphy (Martin, 1971) indicates an Atokan to earliest Desmoinesian age for the Sandia Formation at most localities in the Lucero uplift area.

Sandia Mountains

The first two formation names (Sandia, Madera) in current usage that were applied to Pennsylvanian strata in New Mexico were based on rocks in the Sandia Mountains. Herrick (1900) and Herrick and Bendrat (1900) established the "Sandia series" for a 46-m-thick (250-ft-thick) sequence of shales, sandstones, and conglomerate above Proterozoic granite in the Sandia Mountains, and Gordon (1907) adopted Herrick's name for the lower part of his Magdalena Group. Kelley and Northrop (1975) summarized the subsequent development of the concept of the Sandia Formation in the Sandia and neighboring ranges, including eventual recognition of a basal, intermittent, thin lower carbonate sequence as Mississippian in age. In the Sandia Mountains, the Sandia Formation consists of (in order of abundance) sandstone, shale, limestone, conglomerate, and siltstone. Although lateral facies changes are pronounced, clastics always dominate, and in some sections limestone beds are very sparse. The shale is black, gray, or olive and has local coal seams and plant fossils. Contact with the overlying Madera is gradational, but in most places the top of the Sandia Formation is easily placed at the base of the first massive limestone of the lower Madera. In the Sandia Mountains, the thickness of the Sandia Formation ranges from approximately 15 m (50 ft) to possibly as much as 90 m (300 ft), and its age, though poorly constrained, is Atokan to possibly early Desmoinesian (Kelley and Northrop, 1975). The Sandia Formation has been recognized widely in central New Mexico, from the southeastern Sangre de Cristo Mountains (Baltz and Myers, 1984, 1999) on the north to the Mud Springs Mountains (Maxwell and Oakman, 1986) on the south.

In the Sandia Mountains, Kelley and Northrop (1975) treated the Madera, which is 400+ m (1,300+ ft) thick, as a formation in the Magdalena Group, using the informal lower "gray limestone" and upper "arkosic limestone" member names. Lucas et al. (1999a, b) provisionally extended the names Los Moyos Limestone and Wild Cow Formation from the Manzano Mountains into the Sandias, implicitly abandoning the Magdalena Group and raising Madera to group rank. As suggested elsewhere in this paper, the Lucero uplift names Gray Mesa, instead of Los Moyos, and Atrasado, instead of Wild Cow, may be more appropriate names for these units, based on similarity of lithology and priority, in the Manzano as well as the Sandia Mountains. A retreat to the old informal members of a Madera Formation in recent mapping in the Sandia and Manzano Mountains (e.g., Ferguson et al., 1996; Read et al., 1998, 1999) is based apparently on the perception that formal lithostratigraphic units cannot be recognized if the boundaries between them are gradational, and that the named lithostratigraphic units in the Manzano Mountains are based on fusulinid biostratigraphy. Both are erroneous misconceptions, and the informal Pennsylvanian stratigraphic divisions of these workers are rejected.

Further work is needed in order to establish the boundaries between the Los Moyos (or Gray Mesa) and Wild Cow (or Atrasado) Formations in the Sandia Mountains. Read et al. (1944) for example, assigned only the lower 39% and 34% of two measured Madera sections (Monte Largo and Tejano Canyon) to the lower "gray limestone" member, whereas Kelley and Northrop (1975, p. 125), in their Montezuma Ridge reference section, included 239 m (783 ft) of the total 386 m (1,267 ft; = 62%) thickness of the Madera in the lower member, despite their assertion (p. 34) that the lower member constitutes only 40–45% of the total Madera thickness. In addition, their probable boundary between the lower and upper members was placed at the base of a 38-m-thick (126-ft-thick) sequence of blue-gray, cherty limestones, which would appear lithologically to be better placed in the lower member. Such great variation in the thickness of the two Madera units is less likely a result of lateral depositional variation over short distances than due to inconsistent definition of the two units. The Red Tanks and Bursum Formations have not been recognized in the Sandia Mountains, but a transitional sequence of predominantly nonmarine siliciclastic sediments (noted by Kelley and Northrop, 1975, p. 30), of varying thickness, is present at the top of the Madera Group, immediately below the Abo Formation. This transitional sequence is thin in the Placitas area (Lucas et al., 1999b) but is much thicker to the southeast, where it is currently under study.

The member names of the Wild Cow Formation established by Myers (1973) in the Manzano and Manzanita Mountains are explicitly not extended to the Sandias at the present time, as more detailed stratigraphic study is required to evaluate their presence or absence there.

Manzano–Manzanita Mountains

Read and Wood (1947) continued Gordon's (1907) division of the Pennsylvanian in the Manzano Mountains into the Sandia and Madera Formations of the Magdalena Group, and they divided the Madera into lower "gray limestone" and upper "arkosic limestone" members. Myers (1973), based on extensive mapping in the range, raised the Madera to group rank, named the lower member the Los Moyos Limestone, and named the upper member the Wild Cow Formation, and he included the Bursum Formation as the upper unit of the Madera Group. Three named members of the Wild Cow Formation, in ascending order, Sol se Mete, Pine Shadow, and La Casa Members, were also established and mapped. The ages of all of these units are well constrained by fusulinid biostratigraphy (Myers, 1988a, b).

In the Manzanos, the Sandia Formation ranges from 15 m to 92 m (50–300 ft) in thickness; is Atokan in age; and consists of a basal conglomeratic sandstone overlain by gray to brown sandstones, dark-gray to brownish-gray, locally carbonaceous and plant-bearing shales, and thin, gray marine limestones, which are more common near the top (Myers, 1982). Within the Madera Group, the Los Moyos Limestone is 180 m (approximately 600 ft) thick; is early Desmoinesian to earliest Missourian in age; gradationally overlies the Sandia Formation; and is predominantly gray, highly cherty limestone, calcarenitic in parts of the sequence, with much thinner interbeds of sandstone, siltstone, shale, and conglomerate. The overlying Wild Cow Formation is 225–275 m (approximately 750–900 ft) thick; is early Missourian to earliest Wolfcampian in age; and "consists of alternating sequences of arkosic sandstone, sandstone, conglomerate, gray to yellow siltstone and shale, gray to black calcareous shale, and thin- to thick-bedded calcarenite that is locally cherty" (Myers, 1982, p. 236). The three members of the Wild Cow defined by Myers (1973) are of similar thickness, and each includes sandstone, conglomerate, shale, and limestone beds that vary laterally lithologically from north to south to a considerable degree. There do not appear to be any consistent lithologic characteristics of any of these members that distinguish them from each other. In the Manzanita Mountains, the Pine Shadow Member includes a deltaic sequence, exposed in Kinney quarry, which contains a remarkable mainly nonmarine fauna and flora that is documented in a book-length volume (Zidek, 1992).

The Madera section in the Manzano–Manzanita Mountains is quite similar to that in the Lucero uplift, only 60–70 km (37–43 mi) to the west, and it is unfortunate that Myers coined new names for the formation-rank units in the Manzanos without detailed comparison with the previously named equivalent units in the Lucero uplift. With little doubt, the Los Moyos Limestone in the Manzano Mountains is the same formation as the Gray Mesa in the Lucero uplift. The descriptions of the overlying Missourian–Virgilian Atrasado Formation provided by Kelley and Wood (1946) and Martin (1971) suggest that it is the same unit described by Myers (1973) as the Wild Cow Formation in the Manzano–Manzanita Mountains. Detailed comparison between the Atrasado and Wild Cow Formations, in terms of fine-scale vertical and lateral distribution of lithologies and facies, would be worthwhile. It is clear that the Wild Cow Formation is characterized by significant lithologic heterogeneity as a sequence of interbedded limestone, sandstone, siltstone, shale, and conglomerate, the relative proportions of these lithologies varying laterally and vertically. The Atrasado Formation has a similar heterogeneous lithology, although local facies differences are present. Both formations occupy the same position in the Pennsylvanian stratigraphic succession, both are of Missourian–Virgilian age, are geographically closely spaced, and possess extreme lithologic heterogeneity of the same general kind, "which in itself may constitute a form of unity when compared to the adjacent rock units" (North American Code of Stratigraphic Nomenclature, 1983, p. 858). The latter point is emphasized by the code as one of the bases on which formations may be recognized. It is difficult to escape the conclusion that strata very similar to the unit named the Atrasado Formation in the Lucero uplift are present in the Manzano Mountains (where they have been called the Wild Cow Formation), as well as in the Sandia Mountains, the uplifts of Socorro County, and elsewhere where they have been recognized informally as the "upper arkosic limestone member" of the Madera Formation.

The relationship between the late Virgilian–early Wolfcampian La Casa Member of the Wild Cow Formation plus Bursum Formation in the Manzano Mountains and the Red Tanks Formation in the Lucero uplift is less certain and currently under study.

Socorro County

Siemers (1983) studied the Pennsylvanian strata of uplifts in Socorro County, including the Magdalena, Lemitar, southeast San Mateo, and northern Oscura Mountains, Sierra Ladrones, Joyita Hills, Little San Pasqual Mountain, and the Cerros de Amado. He used the lithostratigraphic units of earlier workers—Sandia Formation and Madera Limestone within the Magdalena Group, with lower "gray limestone" and upper "arkosic limestone" members in the Madera—but analyzed characteristics of the strata for the Atokan through Virgilian Series within the Pennsylvanian sequence.

In this region, the Sandia Formation (Atokan) is predominantly gray, green, and brown, fine-grained, terrigenous sediments. Sandstones increase in amount to the east, and carbonates increase to the south. The Sandia attains a greater thickness in this area than elsewhere, typically more than 100 m (325 ft) and as much as 211 m (692 ft) in the Cerros de Amado, east of Socorro.

The lower "gray limestone" member of the Madera is Desmoinesian in age, although beginning in the late Atokan and extending into the earliest Missourian in some places; thickness ranges from approximately 115 m to 250 m (approximately 375–825 ft). The upper "arkosic limestone" member, essentially the Missourian–Virgilian part of the Madera, is typically approximately 180 m (600 ft) or less in thickness but reaches 455 m (1,500 ft) in the Sierra Ladrones. As is the case in other regions, Desmoinesian strata are predominantly gray, thick-bedded, cherty limestone units. Missourian and Virgilian strata are also chiefly limestones (averaging 59% and 67% of total thickness, respectively; Siemers, 1983, table 2). They become progressively more thinly bedded upsection, and the proportion of shale and sandstone beds in the upper Madera is about twice that in the Desmoinesian sequence. Siemers (1983) noted that in the Missourian–Virgilian, limestones increase in abundance and terrigenous grains become finer from east to west across the Socorro area, indicating derivation of siliciclastic material mainly from the Pedernal uplift, the local Joyita uplift being a minor source of sediments.

The Pennsylvanian strata of Socorro County fit into the revised lithostratigraphic nomenclature advocated in this paper—Sandia Formation overlain by the Madera, raised to group rank, and the Magdalena Group abandoned. Kelley and Wood (1946) mapped their Gray Mesa and Atrasado Members into the Sierra Ladrones of north-central Socorro County, and their names, as formations within the Madera Group, are appropriate for the lower "gray limestone" and upper "arkosic limestone" members used by Siemers (1983) and earlier workers.

Tidwell et al. (2000) and Lucas and Estep (2000) have extended Gray Mesa–Atrasado terminology eastward across the Rio Grande into the Cerros de Amado area. It is also of interest that Rejas (1965) used Thompson's (1942) stratigraphic terminology in the Cerros de Amado area, and Kottlowski (written comm., 2000) noted that Thompson's Missourian and Virgilian formations are traceable from the Sierra Oscura to the Cerros de Amado, Sierra Ladrones, and Mesa Sarca. Thompson's formation names might well be used in these areas as members of the Atrasado Formation. Although not discussed by Siemers (1983), the type section of the early Wolfcampian Bursum Formation is also in Socorro County (Lucas et al., 2000), and here it is considered the uppermost formation of the Madera Group in areas where it can be differentiated from the Red Tanks Formation of the Lucero uplift region.

Nacimiento and Jemez Mountains

Wood and Northrop (1946), who mapped this area, recognized the Sandia Formation, consisting of a "lower limestone" and "upper clastic" members, and the Madera Formation, composed of lower "gray limestone" and upper "arkosic limestone" members within the Magdalena Group. Subsequent work revealed the "lower limestone" member of the Sandia Formation to be Mississippian (it is now the Arroyo Peñasco Group, e.g., Armstrong and Mamet, 1974). The lower part of the "upper clastic" member was separated as the 20-m-thick (66-ft-thick) Osha Canyon Formation (DuChene et al., 1977), which consists of bioclastic limestones and gray to tan shales of Morrowan age, and may be an erosional western remnant of the La Pasada Formation of the southwestern Sangre de Cristo Mountains. The remaining upper strata of the Sandia Formation are Atokan in age, as much as 70 m (230 ft) thick, and consist mainly of a basal, brown quartz sandstone unit, overlain by slope-forming, green, gray, and yellow shales and sandstones, and ledges of subordinate gray marine limestones (Woodward, 1987).

Woodward (1987) used the terminology of Wood and Northrop (1946) in describing the Madera in the Nacimiento Mountains. Although widely exposed in the Nacimiento and Jemez Mountains, the thickness of the Madera varies considerably because of faulting and locally differing onlap relationships upon earlier sedimentary and Precambrian rocks. The most complete and well-exposed Madera section in the Nacimiento Mountains is in Guadalupe Box, where it totals 232 m (760 ft) in thickness (DuChene, 1974; Woodward, 1987). Here, as in other sections, the lower "gray limestone" member is much thinner (38 m [125 ft]) than the upper "arkosic limestone" member. Ages of the two Madera units are not well constrained, but the lower member appears to be late Atokan to middle Desmoinesian (Read and Wood, 1947), and the upper member middle Desmoinesian to middle Virgilian (Woodward, 1987).

The lithology of the lower member of the Madera is predominantly dense, gray, cherty limestones intercalated with thinner intervals of arkosic sandstone and gray shale, although in some localities (Wood and Northrop, 1946) chert is nearly absent. The upper "arkosic limestone" member is a cyclic sequence (Yancey et al., 1991; Swenson, 1996) of arkosic limestone, arkose, and shale, with siliciclastics becoming more abundant and variably colored, and limestones less abundant near the top (Woodward, 1987).

Sutherland and Harlow (1967) defined in San Diego Canyon a thin (9–12 m [30–40 ft]), red shale unit near the top of the Madera as the Jemez Springs Shale Member, although not including in it an overlying marine limestone (1–2 m [3–7 ft] thick) at the top of the Madera sequence in this area. The interval called the Jemez Springs Shale is part of a Missourian–Virgilian sequence at least 80 m (260 ft) thick (Kues, 1996), in which marine limestones predominate over marine shales in the Missourian part but nonmarine to marine, gray, red, brown, and purple shales are collectively thicker than marine limestone ledges in the Virgilian. Good fusulinid and macroinvertebrate data place the age of the top of the Madera as middle Virgilian, with Abo red beds conformably overlying the Madera. Although the Madera is relatively thin in the Nacimiento and Jemez Mountains compared with other areas, Woodward (1987, fig. 5) noted thicknesses as great as 540 m (1,775 ft) along the north side of San Pedro Mountain, just north of the Nacimientos.

In the Nacimiento–Jemez Mountains area, the term Magdalena Group is abandoned here, and the Madera is considered a group consisting of two formations. Madera sedimentation and lithologies were influenced by local uplift of the Peñasco axis, an elongate island that existed during the Pennsylvanian at the approximate location of the present Nacimiento Mountains (Woodward, 1987). Lithologies, thickness, and durations of the two Madera formations therefore differ to a modest degree from that of the Madera Group to the south, but overall their general features broadly resemble the Gray Mesa and Atrasado Formations, and those names are here extended to the Madera sequence in the Nacimiento/Jemez Mountains. Equivalence of the uppermost part of the Madera Group in this area to the transitional Madera/Abo formations recognized farther south (Red Tanks and Bursum Formations) remains to be demonstrated; if present, this interval is both thinner and older (middle Virgilian) than is the case with these units farther south, closer to their type areas.

Sangre de Cristo Mountains

The Pennsylvanian of the Sangre de Cristo Mountains was observed and described by early workers on New Mexico geology (e.g., Marcou, 1858; Stevenson, 1881). Reconnaissance mapping (e.g., Read et al., 1944; Northrop et al., 1946) led to extension of the Sandia and Madera Formation names (and Magdalena Group), and of the "lower gray limestone" and "upper arkosic limestone" members of the Madera (Read and Wood, 1947; Brill, 1952) into the Sangre de Cristos. Sutherland (1963), however, did not recognize a distinct lithologic break between rocks equivalent to the Sandia and Madera Formations along the west side of the range; instead, the only major lithologic break he observed was between the "lower" and "upper" members of the Madera. Accordingly, the terms Magdalena, Sandia, and Madera were not used by Sutherland in this area. He named a Morrowan–Desmoinesian unit (La Pasada Formation, type section at Dalton Bluff, north of Pecos) that is equivalent to the strata of the Sandia and "lower gray limestone" member of the Madera of previous workers, and he named the "upper arkosic limestone" member the Alamitos Formation (type section north of Pecos).

The La Pasada Formation (297 m [973 ft] thick at its type section) is primarily clastic in its lower (Morrowan) part (limestone = 27%, shale/siltstone = 50%, sandstone/conglomerate = 23%), but carbonates increase upsection, so that in the Desmoinesian part, the (upper 178 m [584 ft] of the La Pasada), the ratio of major rock types is: limestone = 67%, shale/siltstone = 24%, sandstone/conglomerate = 9%. Very little chert is present in the limestones, which thus differ from Desmoinesian limestone units farther south. The late Desmoinesian–Virgilian Alamitos Formation, approximately 390 m (1,275 ft) thick at its type locality, is a heterogeneous assemblage of complexly interbedded fine to coarse clastics with subsidiary limestones.

Northward from the type section, the La Pasada thickens and changes laterally into an almost entirely marine and nonmarine clastics-dominated unit, which Sutherland named the Flechado Formation (type locality northwest of Tres Ritos; thickness 762 m [2,500 ft]). The Alamitos also thickens to the north of its type locality, to 1,220 m

(4,000 ft), but its age is constricted to the middle–late Desmoinesian, owing to earlier onset of influx of red continental clastics of the Sangre de Cristo Formation from the nearby Uncompahgre uplift as the Taos trough became filled with sediments.

In the southeastern part of the Sangre de Cristos, detailed mapping and stratigraphic work by Baltz and Myers (1984, 1999) led to a different classification of the Pennsylvanian sequence. They recognized a clastic-dominated Sandia Formation that spanned Morrowan and Atokan time and thickened northward from approximately 10 m (33 ft) near Bernal to more than 1,525 m (5,000 ft) east of Mora, paralleling the northward thickening of the Morrowan–Atokan lower part of the La Pasada/Flechado Formations to the west, but containing fewer carbonates than the equivalent part of the La Pasada Formation. The Madera, above the Sandia Formation, was raised to group status, containing the Porvenir Formation, a new name for strata formerly mapped as "lower gray limestone" member, overlain by the Alamitos Formation. The Porvenir Formation (Desmoinesian) is 325 m (1,065 ft) thick at its type locality west of Gallinas and increases in thickness northward to a maximum of almost 500 m (1,640 ft). It is represented by a carbonate facies (with significant shale) through most of its distribution in the southeastern Sangre de Cristos, by a sandstone-shale-limestone facies to the north, and by a shaly facies to the northwest (Baltz and Myers, 1999). All three facies contain considerable shale, sandstone, and conglomerate beds; limestone represents less than 50% of the total Porvenir stratigraphic thickness even in the carbonate facies of the type section. The carbonate facies of the Porvenir is laterally equivalent to the carbonate-rich Desmoinesian upper part of the La Pasada Formation to the west, and the shaly facies of the Porvenir in the northwest part of its outcrop belt grades westward into the upper part of Sutherland's Flechado Formation.

The Alamitos Formation in the southeastern Sangre de Cristos is similar in its lithologic heterogeneity and dominance of clastic strata to the formation in the western Sangre de Cristos; in both areas are fossiliferous limestones near the top and bottom that allow accurate dating of its upper and lower boundaries. To the west, the Alamitos ranges from late Desmoinesian to Virgilian in the southern part of its outcrop, but is restricted to middle and late Desmoinesian to the north (Sutherland 1963; Sutherland and Harlow, 1973). In the southeastern Sangre de Cristos, the formation ranges from late Desmoinesian to earliest Wolfcampian, based on fusulinids (Baltz and Myers, 1999). In both areas, red, green, and purple clastic units and thin marine limestones are present within a transition zone into the basal nonmarine Sangre de Cristo Formation, and Baltz and Myers (1999, p. 96) noted some marine limestones a little above the top of the Alamitos as defined by Sutherland (1963) in its type area.

Although there might be a tendency to expect a unified nomenclature for Pennsylvanian strata in the Sangre de Cristos, the nomenclatures of both Sutherland (1963) and Baltz and Myers (1984, 1999) are based on detailed stratigraphic studies, and each set of formational stratigraphic names is appropriate to studies of the lithologic sequences in the areas in which they have been applied. As noted earlier, it is recommended that the term Madera Group not be used in the Sangre de Cristo Mountains. The nature of the Pennsylvanian sequence in the Sangre de Cristos, strongly influenced as it is by proximity to the Uncompahgre land mass and rapidly subsiding Taos trough and other local basins, is unlike that of any other part of New Mexico, and the formational nomenclature, with the exception of use of the Sandia Formation, is likewise restricted to this part of north-central New Mexico. Even the Sandia Formation, recognized by Baltz and Myers (1984, 1999) in the southeastern Sangre de Cristos on lithologic grounds, differs from Sandia deposits to the south in attaining a much greater thickness and spanning Morrowan and Atokan time. The study by Baltz and Myers (1999) represents the most detailed and comprehensive examination and synthesis of Pennsylvanian stratigraphy yet completed in any part of New Mexico, and stands as a model for future studies in other parts of the state.

Caballo Mountains

Current nomenclature for the Pennsylvanian of the Caballo Mountains and neighboring small uplifts such as the Derry Hills is that of Kelley and Silver (1952). They assigned the Pennsylvanian section to the Magdalena Group, divided into, in ascending order: the Red House (110 m [362 ft] thick at the type section), Nakaye (128 m [419 ft] thick), and Bar B (103 m [339 ft] thick) Formations. Although no age data were provided for these formations, Kelley and Silver (1952, fig. 11) correlated the Red House with the Sandia and lower part of the "lower gray limestone" member of the Madera in central New Mexico; the Nakaye with most of the "lower gray limestone" member and basal "arkosic limestone" member; and the Bar B with most of the "arkosic limestone" member and the Bursum Formation. Later studies of these units in the Derry Hills, including data based on fusulinids, conodonts, and brachiopods (Clopine, 1991, 1992; Clopine et al., 1991; Sutherland, 1991; Kaiser and Manger, 1991), indicate that the base of the Red House Formation (and the base of Thompson's, 1942, "Derryan Series") is of latest Morrowan age; that the Red House extends through the Atokan; that the Nakaye is of early to late Desmoinesian age; and that the Bar B is of late Desmoinesian, Missourian, and possibly earliest Wolfcampian age, with the Virgilian missing because of an unconformity (Seager and Mack, 1991; Mack et al., 1998).

Lithologically, the Red House consists predominantly of thin-bedded, gray limestone beds (64% of total thickness in the Derry Hills; Seager and Mack, 1991), interbedded with thin, gray shale units and brown to green siltstone. The Nakaye is mainly thick, massive, gray, cherty limestone, becoming somewhat thinner bedded toward the top, and having minor amounts of gray shale. The Bar B consists chiefly of thin-bedded limestone separated by thicker intervals of gray shale (shale is approximately 80% of the total thickness). The uppermost 15 m (50 ft) of the Bar B is composed of reddish-brown siltstone, limestone conglomerate, and sandstone beds beneath the overlying Abo red beds, and appears to be Bursum-equivalent strata. Curiously, although Kelley and Silver (1952, p. 89) strongly criticized Thompson's (1942) units in this area as being, among other things, "scarcely mappable," they did not map the three formations they recognized either; nor did Seager and Mack (1991, 1998) in the Derry Hills and Nakaye and Red House Mountain areas. Doubt has been expressed as to the validity of Kelley and Silver's formations as cartographic units (Gehrig, 1958, p. 6; Bachman and Myers, 1975, p. 108).

The Red House Formation, although temporally closely correlative with the Sandia Formation, is lithologically distinct in its high abundance of limestone beds. The Nakaye Formation is not significantly different lithologically from the widespread, massive, cherty, cliff-forming limestone unit of Desmoinesian age that crops out throughout central New Mexico, and which should be designated with a single name, which here is recommended to be Gray Mesa Limestone. Although proposed by the same worker (V. C. Kelley) who coined the name Gray Mesa in the Lucero uplift, Nakaye Formation is a good example of a redundant, unnecessary stratigraphic name.

The Bar B Formation generally resembles that unit earlier called "arkosic limestone" member of the Madera in central New Mexico, albeit with more shale and a smaller proportion of limestone than typically is present in that unit in some other areas. Tentatively, the name Bar B is retained, but further work may demonstrate that Atrasado and Bursum are more appropriate terms for this unit. Use of the term Magdalena Group is unnecessary for this sequence of Pennsylvanian strata in the Caballo Mountains. The upper two of Kelley and Silver's (1952) formations accord well with the concept of the Madera

Group farther north, and it is recommended that this term be applied in the Caballos. As noted below, Madera terminology has been employed in the Cuchillo and Mud Springs Mountains a short distance to the northwest.

Mud Springs Mountains

Kelley and Silver (1952) simply mapped the Pennsylvanian of the southern Mud Springs Mountains as Magdalena Group, and Kottlowski (1960a) gave brief lithologic and thickness information for the Atokan through Virgilian divisions of the sequence. Earlier (see above), Thompson (1942) used the excellent section in Whiskey Canyon as type and reference sections for his Atokan and Desmoinesian groups and formations, and Gehrig (1958) provided a detailed stratigraphic section of Thompson's Desmoinesian units (Armendaris and overlying Bolander Groups, with included formations), totaling 216 m (709 ft) in Whiskey Canyon. Strata of Missourian and Virgilian age in the Mud Springs Mountains attain thicknesses of 98 m (320 ft) and 140 m (460 ft), respectively (Kottlowski 1960a), and these are overlain by approximately 19 m (62 ft) of possibly Wolfcampian Bursum-equivalent beds.

Maxwell and Oakman (1986), in a preliminary map of the Mud Springs Mountains, recognized a thin Sandia Formation (46 m [150 ft] thick) only in the southern part of the range, overlain by a thick Madera Formation (457 m [1,500 ft]), consisting of three units: 1) a lower part consisting of thin-bedded, locally cherty limestones and considerable gray to green shale beds; 2) a middle part of mainly massive cherty limestone; and 3) an upper part of thin-bedded limestones alternating with gray shale and greenish to reddish shale and siltstone. The upper part of the Madera was said to grade into the overlying, 50-m-thick (160-ft-thick) Bursum Formation, composed mainly of red, green, and purple shales and minor sandstone and limestone.

In the final version of their map (Maxwell and Oakman, 1990), the term Madera was not used, the Pennsylvanian units were assigned names derived from the Caballo Mountains, and these units, together with the overlying Bursum Formation, were included in the Magdalena Group. Specifically, the middle part of the Madera of the earlier map was termed Nakaye Formation, the upper Madera was called Bar B (although the uppermost part of this unit was included in the Bursum Formation on the later map, as the thickness of the Bursum increased from 50 to 90 m [160 to 300 ft] from the earlier to later map), and the Sandia Formation (plus apparently the lower part of the Madera) of the earlier map was included in the Red House Formation on the final map. A note on the preliminary map (Maxwell and Oakman, 1986) stating that it had not been reviewed for conformity with U.S. Geological Survey stratigraphic nomenclature perhaps explains the changes in nomenclature introduced on the final map.

The contrasting nomenclature used by Maxwell and Oakman (1986, 1990) illustrates the similarities of the central New Mexico Madera sequence to that of the Caballos, with its local stratigraphic terminology, and the application of different nomenclatural philosophies to the Mud Springs Mountains Pennsylvanian sequence. As in the Caballo Mountains, it seems clear to me that the unit called Nakaye is the Gray Mesa, and that the Gray Mesa–Bar B–Bursum sequence of the Mud Springs Mountains represents the Madera Group. Similarly, use of the term Magdalena Group should be discontinued in this range, as Maxwell and Oakman (1986) implicitly suggested. Possibly some of Thompson's (1942) lithostratigraphic names might be useful as member names in the Mud Springs Mountains.

Cuchillo Mountains

In the Cuchillo Mountains of northwestern Sierra County, the Pennsylvanian sequence is relatively poorly exposed and has been little studied. It was divided into the Sandia and Madera Formations (of the Magdalena Group) and as much as 67 m (220 ft) of "Magdalena transition beds" below the overlying Abo Formation by Jahns (1955) and Jahns et al. (1978). The Sandia Formation, as much as 53 m (173 ft) thick, consists principally of shale and greenish-gray to red-brown siltstones and sandstones interbedded with gray, locally cherty, limestone ledges. Strata assigned to the Madera Limestone attain a thickness of 275–300 m (900–985 ft) and are predominantly gray, thin-bedded to massive, often cherty limestones separated by minor beds of shale and sandstone. Stratigraphic information is currently insufficient to allow subdivision of the Madera or to compare it in detail with Madera sections elsewhere. The "transition beds" are greenish, brown, or maroon clastics, interbedded with limestone beds and some sandstone, limestone, and quartzose conglomerates, similar to the uppermost Madera regionally and probably in part equivalent to the lower Bursum Formation to the northeast.

More detailed information on this Pennsylvanian sequence would be desirable. For now, the term Magdalena Group should be abandoned, and Madera should be raised to group rank, though with formations yet to be defined.

Fra Cristobal Range

The most recent geological study of the Fra Cristobal Range (Nelson, 1986) uses the Pennsylvanian terminology introduced by Kelley and Silver (1952) in the Caballo Mountains to the south, recognizing the Red House, Nakaye, and Bar B Formations within the Magdalena Group, which encompasses the entire Pennsylvanian section. Unfortunately, too little detailed stratigraphic information on these units is provided to allow comparison with other Pennsylvanian sequences in the region. An earlier study (Cserna, 1956), summarized by Kottlowski (1960a), described three Pennsylvanian units: 1) a lower shaly member (81 m [266 ft] thick), 2) a medial cherty limestone member (331 m [1,087 ft] thick), and 3) an upper shaly member (81 m [266 ft] thick) having a thin (6-m [20-ft]) transition zone of purplish limestone and shale grading into the overlying Abo Formation. The lithology of these units suggests the presence of the Sandia Formation at the base, overlain by the "lower gray limestone" (= Gray Mesa Limestone) and "upper arkosic limestone" (probably the Atrasado Formation) of the Madera Group.

Fusulinid biostratigraphy (Verville et al., 1986) in a section south of Cserna's more complete section records only 10 m (33 ft) of Atokan strata; 260 m (853 ft) of Desmoinesian strata, equivalent to Cserna's medial cherty limestone unit; 60 m (197 ft) of Missourian strata, mainly gray, medium- to thick-bedded limestones with less chert than the Desmoinesian limestones; and 50 m (164 ft) of Virgilian strata that grade upward into the red beds of the Abo. The stratigraphically highest fusulinids, a few meters below the base of the Abo, are no younger than middle Virgilian.

Robledo Mountains

The Pennsylvanian sequence exposed in the Robledo Mountains was deposited on the Robledo shelf along the west side of the Orogrande Basin. It is unusually thin, especially compared with the basinal sequences to the east, and unusually rich in carbonates. Not much clastic material reached the Robledos during the Pennsylvanian from the Pedernal and Florida land masses (Kottlowski, 1960b). Kottlowski (1960a, b) published a relatively detailed stratigraphic section of Pennsylvanian and early Wolfcampian strata that included Atokan (30 m [100 ft] thick), Desmoinesian (69 m [225 ft]), Missourian (52 m [170 ft]), and Virgilian (73 m [240 ft]) strata totaling approximately 225 m (735 ft) thick (Kottlowski and Seager, 1998), overlain by a 55-m-thick (180-ft-thick) Bursum interval. Atokan strata, thinned by partial assimilation in an Oligocene sill, consist of blackish, silty limestone and greenish-gray shale; the Desmoinesian predominantly of massive, cherty limestones interbedded with minor limy shale and calcareous sandstone; the Missourian of slope-forming limestones and limy shales with several ledge-forming limestones; and the

Virgilian chiefly of several thick, noncherty limestone cliffs interbedded with thin-bedded limestone and shale. The interval containing early Wolfcampian "Bursum" fusulinids (Thompson, 1954) is predominantly limestone and is not similar to the lithostratigraphic unit called Bursum Formation to the north; Jordan (1975) did not recognize the Bursum Formation in the Robledos, nor have more recent workers such as Krainer et al. (2000) and Wahlman and King (in press).

To date there has been little published detailed information on the Pennsylvanian in the Robledo Mountains, and no lithostratigraphic names have been applied to this sequence. The Atokan section lithologically resembles the Sandia Formation, and the Desmoinesian interval is closely comparable in lithology, if not in thickness, to the lower Madera Group formation farther north for which the name Gray Mesa Limestone is recommended. The Missourian and Virgilian units are tentatively regarded as a southern, thinner expression of the Atrasado Formation, although with a higher proportion of carbonates in the Virgilian part.

Silver City, Santa Rita, and Kingston areas

The incomplete, faulted, and generally poorly exposed Pennsylvanian sequence in the Silver City–Santa Rita area was initially included with Mississippian and Permian strata within the Fierro Formation (Paige, 1916). Spencer and Paige (1935) discarded the term Fierro and divided the Pennsylvanian section into the lower Oswaldo Formation (130 m [425 ft] thick) and overlying Syrena Formation (120 m [395 ft] thick) of the Magdalena Group, because the sequence appeared lithologically different from the Sandia and Madera Formations used elsewhere. These formations were summarized by Kottlowski (1960a) and discussed by Jones et al. (1967, 1970), Pratt (1967), and LeMone et al. (1974), among others. The Oswaldo Formation consists almost entirely of limestone, locally cherty, with shale interbeds near the top and locally a shale unit at its base. The Syrena Formation includes a basal, thick (as much as 40 m [131 ft]), dark shale or limestone unit and an upper sequence of interbedded gray limestones and nodular limestones and brown, yellow, and red shale.

LeMone et al. (1974) reported a Morrowan–earliest Missourian age for the Oswaldo, an early Missourian to Virgilian age for the Syrena, and suggested that these strata were deposited on open-marine shelf environments between those of extreme southwestern New Mexico and the Robledo shelf to the east. Lithologically the Oswaldo Formation reflects the prevailingly carbonate character of Lower and Middle Pennsylvanian strata in southern New Mexico (e.g., Lead Camp Limestone of the San Andres Mountains), and the Syrena reflects increased siliciclastics in the Upper Pennsylvanian, comparable to the Atrasado and equivalent units to the north and east. The unneeded term Magdalena Group is abandoned here, but the names Oswaldo and Syrena are retained as useful local divisions of an incomplete Pennsylvanian sequence.

To the east, near Kingston, Kuellmer (1954) described in detail three incomplete sections of Pennsylvanian strata, indicating a composite thickness of approximately 200 m (655 ft) or more, assigned to the Magdalena Limestone but not further subdivided. Faulting and quartz monzonite intrusions complicate interpretation of these outcrops. In two sections, 15–23 m (50–75 ft) of basal, Sandia Formation-like, dark shales and sandstones rest unconformably on Mississippian limestone, and are overlain by as much as 20 m (65 ft) of massive, cherty limestones similar to Desmoinesian units deposited widely across the state. The thickest section (III, of Kuellmer, 1954) rests on a quartz monzonite intrusion and consists mainly of massive, gray, cherty limestones (130 m [425 ft]) overlain by approximately 60 m (200 ft) of gray and brown shaly limestone, yellow shale, thin-bedded and nodular limestone, and limestone-pebble conglomerate. At the base is approximately 10 m (33 ft) of interbedded dark shale and limestone. The isolation of these sections from others and the fact that fusulinid ages of these strata have not been reported complicate correlation, but the thickest section, although thinner than is typical of the Madera, lithologically resembles the Madera Group in its lower cherty limestone formation and upper interbedded limestone and siliciclastic formation. More detailed study and comparison with the nearest Pennsylvanian sequences to the east (Caballo Mountains), north (Cuchillo Mountains), and west (Santa Rita–Silver City area) would increase our understanding of all of these sequences.

Southwestern New Mexico

Pennsylvanian strata in southwestern New Mexico, best exposed in the Big Hatchet Mountains, are assigned to the Horquilla Formation, which also includes units of Wolfcampian age (Zeller, 1965; Ross, 1979; Thompson and Jacka, 1981; Drewes, 1991). The time represented by Horquilla deposition has been reliably determined by fusulinid biostratigraphy as Morrowan to Wolfcampian, with the following series thicknesses reported by Thompson and Jacka (1981) for the Big Hatchet Peak section: Morrowan, 75 m (247 ft); Atokan, 115 m (378 ft); Desmoinesian, 305 m (1,001 ft); Missourian, 142 m (466 ft); Virgilian, 128 m (419 ft); and Wolfcampian, 219 m (719 ft). The total thickness of the Horquilla is approximately 1,000 m (3,280 ft), of which approximately 765 m (2,500 ft) is of Pennsylvanian age. Zeller (1965) and Thompson and Jacka (1981) informally divided the Horquilla into lower (420 m [1,380 ft] thick; Morrowan to upper Desmoinesian) and upper (570 m [1,870 ft] thick; upper Desmoinesian to Wolfcampian) members. The lower member is 90+% gray limestones with moderate chert beds, and the upper member is 70% limestone and 30% dolostone with little chert.

In the Big Hatchet Mountains, these carbonates were deposited primarily in shallow marine shelf environments. The shallow carbonates of the upper member change laterally to the southwest into basinal deposits of dark mudstones and limestones, reflecting onset of subsidence of the Pedregosa (or Alamo Hueco) Basin at a faster rate than deposition occurred (e.g., Greenwood et al., 1977; Thompson and Jacka, 1981; Wilson, 1989). Large, mainly Late Pennsylvanian and Wolfcampian phylloid algal bioherms are conspicuous on outcrop and mark the shelf margins adjacent to the subsiding basin (e.g., Zeller, 1965). Deposition of the Horquilla Formation was very cyclic, and its cyclic stratigraphy can be correlated with midcontinent Pennsylvanian cyclothems (Connolly and Stanton, 1992).

Deposition and thickness of the Horquilla were strongly influenced by subsidence of the Pedregosa (or Alamo Hueco) Basin and represent an unusually long span of nearly completely carbonate deposition that is unlike that of the Pennsylvanian–Early Permian of any other part of the state. It is a well-defined, lithologically homogeneous, lithostratigraphic unit, appropriately considered to be of formation rank. The Horquilla has been traced northward in New Mexico to the Peloncillo Mountains, where a highly faulted and intruded section approximately 450 m (1,475 ft) thick apparently extends from Atokan to Wolfcampian time (Gillerman, 1958; Kottlowski, 1960a). Deposition of carbonate shelf sediments extended continuously northeastward from the area of the Pedregosa Basin to the Silver City and perhaps Robledo shelf areas, but in those regions the Pennsylvanian sequence is both much thinner and contains considerably more siliciclastic beds than the Horquilla.

San Andres Mountains

The San Andres Mountains extend for nearly 140 km (85 mi) from near the Sierra Oscura on the north to the Organ Mountains on the south. Pennsylvanian strata crop out along the entire length of the range but are most accessible in a series of canyons, which from north to south are: Mockingbird Gap, separating the San Andres from the Oscura range, and

Rhodes, Hembrillo, San Andres, Ash, and Bear Canyons. The San Andres Mountains also occupy the western side of the Pennsylvanian–Early Permian Orogrande Basin, resulting in a thick Pennsylvanian sequence that differs markedly, especially in the Missourian and Virgilian, from that of the broad, stable Robledo shelf to the west (Robledo, Caballo, Mud Springs Mountains and Sierra Cuchillo), and from the Pennsylvanian sequence deposited along the steep, fault-bounded eastern margin of the basin in the Sacramento Mountains.

The definitive work on the stratigraphy of the San Andres Mountains is by Kottlowski et al. (1956), with subsequent summaries and updates by Kottlowski (1960a, 1975) and Kottlowski and LeMone (1994), among others. As described by these authors, Atokan strata (34–105 m [107–345 ft] thick) are mainly siliciclastic to the north and carbonates to the south; Desmoinesian beds (56–190 m [183–622 ft] thinning to the south) are chiefly massive to medium-bedded cherty limestones with some clastic and calcarenitic units; and Missourian strata (44–83 m [145–271 ft] thinning to the south) consist of interbedded argillaceous limestone and calcareous shale, with local massive cherty limestones. Bachman and Myers (1969, 1975) combined this predominantly carbonate sequence into the Lead Camp Limestone, which is 262 m (861 ft) thick at the type locality in San Andres Canyon in the southern part of the range. They recognized possible Morrowan fusulinids at the base and early Missourian fusulinids at the top. The lower, mainly siliciclastic beds in the Atokan part of the section to the north were assigned to the Sandia Formation, which thus grade southward into the mostly cherty limestones of the lower Lead Camp Limestone. The upper part of the Lead Camp Limestone is lithologically similar to units named Gray Mesa and Los Moyos Formations to the west and north.

Above the Lead Camp Limestone is an abnormally thick sequence, named the Panther Seep Formation by Kottlowski et al. (1956), which thickens progressively southward from approximately 250 m (820 ft) near Mockingbird Gap (Kottlowski et al., 1956) to 865 m (2,885 ft) in the Ash Canyon area and 975+ m (3,200 ft) in the subsurface of the central Orogrande Basin (Schoderbek, 1994). The Panther Seep consists of cyclic (Schoderbek, 1994; Soreghan, 1994), brackish-water, deltaic, stream channel and marginal marine, brown to dark-gray carbonaceous shales and coarse to fine-grained sandstones, argillaceous and calcarenitic limestones, calcareous sandstones, phylloid algal bioherms (near Rhodes and Hembrillo Canyons, see Toomey, 1991; Soreghan and Giles, 1999a, b), and several gypsum beds near the top near Ash Canyon and southward. Terrigenous clastics represent about 74% of total Panther Seep thickness (Schoderbek, 1994, p. 92). The age of the Panther Seep ranges from middle or late Missourian to early Wolfcampian (Bachman and Myers, 1969, 1975), and its lithology is quite different from that of any other Late Pennsylvanian sequence in the state. Rapid subsidence of the Orogrande Basin during this time was matched by enormous amounts of sediment shed from the Pedernal land mass, keeping the basin filled nearly to or above sea level, while glacioeustatic fluctuations of sea level imprinted cyclicity on the depositional sequences (Schoderbek, 1994).

Kottlowski et al. (1956) recognized from 23 m (76 ft) of Bursum Formation in Hembrillo Canyon to 81 m (287 ft) of Bursum in Rhodes Canyon unconformably overlying the Panther Seep and underlying the Hueco Formation in the north part of the range. Bachman and Harbour (1970) apparently included both Bursum and Hueco strata in the upper part of the Panther Seep north of Rhodes Canyon. Similarly, Kottlowski et al. (1956) reported the Panther Seep in Mockingbird Gap, but Bachman (1968) referred these strata to the upper member of the Madera Formation. Although Madera Group terminology is not appropriate for the Lead Camp and Panther Seep Formations through most of the San Andres Mountains, these formations, and the Sandia Formation below the Lead Camp in the northern part of the range, grade laterally into the familiar Sandia/Madera Group units to the north and west, where deposition occurred on the more stable shelf areas along the margins of the Orogrande Basin. Similarly, the units of the predominantly basinal Pennsylvanian sequence exposed in the San Andres Mountains can be traced in detail through individual cycles within facies and thickness changes to the narrow, tectonically active shelf to the east, in the Sacramento Mountains (e.g., Wilson, 1967; Algeo et al., 1991).

Organ Mountains

In the northern Organ Mountains, immediately south of the San Andres range, the Lead Camp Limestone (200–265 m [650–870 ft] thick) intertongues with the overlying Panther Seep Formation (approximately 600 m [1,970 ft] thick). The lithologies of the two formations in the Organ Mountains are not greatly different from their lithologies in the San Andres Mountains, except for several thick gypsum beds near the base and near the top of the Panther Seep (Seager, 1981). The upper 120 m (400 ft) of the Panther Seep is transitional into the overlying lower unit of the Early Permian Hueco Formation.

Franklin Mountains, New Mexico–west Texas

The Pennsylvanian sequence in the Franklin Mountains was first studied in detail by Nelson (1940), who assigned it to the Magdalena Formation and divided it into (in ascending order) the La Tuna, Berino, and Bishop Cap Members. Harbour (1972), in mapping the range, added an unnamed upper member between the Bishop Cap and the overlying Permian Hueco Limestone, which was later found to be the Panther Seep Formation, described initially (Kottlowski et al., 1956) in the San Andres Mountains. Current nomenclature (LeMone, 1982, 1992) recognizes the Magdalena Group as comprising the La Tuna (as much as 156 m [511 ft] thick), Berino (as much as 157 m [514 ft] thick), and Bishop Cap (180 m [590 ft] thick) Formations, overlain by the Panther Seep Formation (213 to possibly 376 m [700–1,235 ft] thick). These formations have been accurately dated using fusulinids and conodonts (e.g., Wilson, 1989; Clopine et al., 1991; Clopine, 1992).

The La Tuna Formation (Morrowan–early Atokan) is predominantly cliff-forming, gray, cherty limestones with algal mounds and thin lenses of shale near the top. The Berino (middle Atokan–middle Desmoinesian) consists of alternating gray cherty limestone and gray shale beds in about a 70:30 ratio. The Bishop Cap Formation (middle Desmoinesian–early Missourian) comprises mainly gray to brown shale (65–75%) alternating with thin ledges of gray limestone. As noted previously, this sequence differs greatly in its lithology from the sequences in central New Mexico to which the term Magdalena Group was first applied, and therefore use of the name Magdalena is both confusing and inappropriate; I strongly recommend that this group name be abandoned in the Franklin Mountains.

The Panther Seep Formation in the Franklin Mountains is a poorly fossiliferous yellow-gray shale and siltstone sequence, with minor carbonates, several gypsum beds near the top, and a basal, 6-m-thick (20-ft-thick), chert-pebble conglomerate, marking an unconformable contact with the underlying Bishop Cap Formation (LeMone, 1982). Its age is middle Missourian to possibly earliest Wolfcampian, as it conformably underlies the basal limestones of the Hueco Group, which are known to be of early (but not earliest) Wolfcampian age (Williams, 1966).

In the Bishop Cap Hills, approximately 10 km (6 mi) north of the Franklin Mountains, only the La Tuna and Berino Formations are exposed (Harbour, 1972), with thicknesses of approximately 80 m (260 ft) and 150 m (500 ft), respectively (Seager, 1973, 1981).

Hueco Mountains, New Mexico and Texas

Beede (1920) first assigned the Pennsylvanian sequence in the Hueco Mountains to the Magdalena Group, and King et al. (1945) divided what they called the Magdalena Limestone into three informal divisions—lower, middle, and upper. This nomenclature has persisted to the present (e.g., Williams, 1963; Seewald, 1968; Stoklosa et al., 1998). The upper part of the Magdalena sequence of these authors is bounded by an unconformity at the base of the Lower Permian unit (Powwow Conglomerate) of the overlying Hueco Group, which rests on progressively older beds from the north (Wolfcampian) to the south (Atokan in Powwow Canyon). Thompson (1954) recognized a thin (6 m [20 ft]) "Bursum" unit based on fusulinids at the top of the Magdalena and below the unconformity, and Williams (1963) described an additional 60-m (200-ft) of Wolfcampian ("*Pseudoschwagerina* beds of the Magdalena Limestone") along the west side of the northern part of the range. Cys (1975), however, interpreted these beds as being part of the lower Hueco Group, with the Powwow Conglomerate being below, rather than above them.

In the central and southern Hueco Mountains, according to Seewald (1968), the "lower division" of the Magdalena (162 m [530 ft] thick; Morrowan–early Atokan in age) is composed mainly of massive, gray, very cherty limestones, with abundant oosparites (see also Connolly and Stanton, 1983). The "middle division" (90 m [300 ft] thick; middle Atokan–middle Desmoinesian) is poorly exposed shale and thin limestone beds with lithology and fauna "strikingly similar" to that of the Berino Formation in the Franklin Mountains. The "upper division" (145 m [480 ft] thick; late Desmoinesian–early Wolfcampian) is lithologically heterogeneous and characterized by cyclic sedimentation, large algal mounds (Toomey, 1991), and a chiefly carbonate environment, interrupted by thin shales and conglomerates. Hardie (1958) pointed out that the lithology of the upper 365 m (1,200 ft) of the Magdalena in the northern (New Mexico) part of the Hueco Mountains is considerably different from that in the southern part of the range, consisting mainly of gray to grayish-red shale (50+%), massive gray limestone (35–40%), especially in the upper part, and lesser proportions of limestone-pebble conglomerates, and one gypsum bed as much as 23 m (75 ft) thick near the top. Although precise ages for the northern sequence were not available, Hardie believed most of the sequence to be of Virgilian and early Wolfcampian age, and Kottlowski (1960a) interpreted the sequence as "Panther Seep formation" types of sediments.

Developing a formal, reasonable, lithostratigraphic nomenclature for the Pennsylvanian of the Hueco Mountains could be done with detailed stratigraphic study, dating, and correlation of units in the northern and southern parts of the range, and then correlation with Pennsylvanian sequences elsewhere in the region, especially in the Franklin Mountains, approximately 40 km (25 mi) to the west. Probably the Hueco Mountains section could be accommodated by the formations defined in the Franklin Mountains, as Wilson (1989, p. 9, fig. 2B) suggested for the Morrowan–Desmoinesian part of the sequence, and Kottlowski (1960a) for the upper ("Panther Seep") portion of the Pennsylvanian–early Wolfcampian sequence in the northern part of the range. Applying the name Magdalena Limestone or Group to this sequence in the Hueco Mountains is inappropriate for the same reasons as in the Franklin Mountains, and the name should be abandoned in future work.

Sacramento Mountains

The Pennsylvanian sequence of the Sacramento Mountains was divided into (in ascending order) the Gobbler, Beeman, and Holder Formations by Pray (1959, 1961), all based on a continuous type section near Long Ridge and Mule Canyon southeast of Alamogordo. There, the Gobbler Formation (?Morrowan or early Atokan–late Desmoinesian in age; Bachman and Myers, 1975; Wilson, 1989) is approximately 400 m (1,300 ft) thick, and the Beeman (Missourian–possibly early Virgilian in age; Bachman and Myers, 1975; Raatz and Simo, 1998) is 120 m (400 ft) thick. The Holder Formation (early–late Virgilian) attains a maximum thickness of approximately 275 m (900 ft) north of the type section.

The basal 60–150 m (200–500 ft) of the Gobbler Formation consists of slope-forming quartz sandstone, gray to black shale, and ledges of dark, cherty limestone. Above this clastic interval, two facies of the Gobbler are recognized: 1) a northern detrital facies composed almost entirely of nonmarine to nearshore marine quartz sandstone and shales with minor limestone and 2) a cliff-forming, massive, locally cherty marine limestone facies, named by Pray (1961) the Bug Scuffle Limestone Member, which is present in the northern Sacramentos, dominates the central and southern parts of the range, and interfingers with and grades into the detrital facies. The Bug Scuffle Limestone represents carbonate deposition widely across the narrow Sacramento shelf and adjacent slope along the east side of the Orogrande Basin. The detrital facies should be named formally as a member of the Gobbler by those actively engaged in studying the formation. It represents a wedge of terrigenous clastic sediments derived from the Pedernal land mass immediately to the east and deposited within an intrashelf graben, the Alamo trough of Algeo et al. (1991), which divided the Sacramento shelf into two independent tectonic blocks. The Gobbler sequence is very cyclic, and the 20–25 independent cycles can be traced laterally from shelf to slope to basinal facies (Algeo et al., 1991; Algeo, 1996).

The Beeman Formation consists mainly of interbedded calcareous shale and thin-bedded, locally argillaceous limestone. The lower third of the formation contains significant sandstone bodies (Pray, 1961) that represent cyclically deposited shelf to basinal environments (see Raatz and Simo, 1998, for detailed facies and sequence stratigraphic analysis). Basinal sequences within the Beeman are considerably thicker and have many more parasequences than the shelf sequences.

The Holder Formation consists of a wide variety of sedimentary strata, primarily marine but increasingly brackish to nonmarine toward the top. Holder strata are very cyclic, and the cycles can be traced westward into the thicker basinal sequence (Panther Seep Formation) of the Orogrande Basin (Cline, 1959; Wilson, 1967). The basal Holder is characterized by large phylloid-algal bioherms as much as 23 m (75 ft) high (e.g., Toomey et al., 1977; Toomey, 1991), which grew along the shelf margin. Overlying the Holder conformably in the northern part of the Sacramentos is the 150-m-thick (500-ft-thick) Laborcita Formation, initially considered latest Virgilian to early Wolfcampian in age (Otte, 1959) but later determined on the basis of fusulinid biostratigraphy to be entirely Wolfcampian (Steiner and Williams, 1968). To the south, red beds of the Abo Formation unconformably overlie each of the three Pennsylvanian formations at various localities (Pray, 1961, fig. 26).

Clearly, local paleogeography and the tectonic processes operating on it have greatly influenced Pennsylvanian sedimentary deposition in the Sacramento Mountains, resulting in a distinctive Pennsylvanian sedimentary sequence that has appropriately received unique formation and member names. These units have become a focus for sequence stratigraphic studies in the past decade, with the result that some of the cyclic sequences recognized here can be traced not only to the west, into the axis of the Orogrande Basin, but also eastward to the midcontinent area (e.g., Raatz and Simo, 1998).

Subsurface stratigraphy

Although the emphasis in this paper is on exposed Pennsylvanian rocks, one comment on subsurface stratigraphic nomenclature in New Mexico is needed. Most reports have assigned intervals of the Pennsylvanian petroleum-bearing strata in eastern New Mexico to divisions such as the Strawn, Canyon, and Cisco Series (e.g., Broadhead and King, 1988). These units are actually lithostratigraphic units (groups) composed of many formations with their type sections in north-central Texas and should not be used as chronostratigraphic units (series). According to Kier et al. (1979, p. S5) there was an attempt in the 1940s to redefine these groups as series to facilitate subsurface correlation between basins, but "…several attempts have been made to apply [this] classification in the field" and "…such applications have proven difficult, if not entirely inappropriate." Present usage of the Strawn, Canyon, and Cisco names in Texas is as groups (e.g., Kier et al., 1979; the Geologic Atlas of Texas maps), the standard U.S. series names (e.g., Desmoinesian, Missourian, Virgilian) as the major chronostratigraphic units. If these names are not used as series names in Texas, there is no justification for using these names as series names in the subsurface of New Mexico. Nor is there any justification for using them as group terms in New Mexico as these units do not extend laterally from north-central Texas into New Mexico, and the lithologies of these groups in north-central Texas do not resemble the lithologies of the subsurface units in New Mexico to which these names have been applied. For example, the Strawn Group in Texas "consists predominantly of cyclic terrigenous clastic facies deposited by…fluvial-deltaic systems" (Kier et al., 1979, p. S13), whereas Desmoinesian strata in most of New Mexico are massive, cherty, marine limestones. Use of these names in the New Mexico subsurface should be abandoned, and lithostratigraphic terms based on exposed New Mexico strata (or if this is not possible, the standard series names) should be used for subsurface Pennsylvanian stratigraphy. Permian lithostratigraphic units established on the basis of outcrops in and near New Mexico, such as Hueco, Abo, Yeso, and San Andres Formations, are routinely used as Permian subsurface stratigraphic units in the state, and there is no reason why the same cannot be done with Pennsylvanian units.

Summary and conclusions

This review of Pennsylvanian stratigraphy in New Mexico is not intended to be comprehensive, but rather to provide a broad overview of the major Pennsylvanian sequences across the state and the nomenclature that has been applied to them. The revisions suggested herein are designed to adapt the lithostratigraphic nomenclature to more appropriately and accurately reflect the major features of the varied Pennsylvanian successions exposed, and to provide an integrated nomenclatural framework that can be consistently applied as studies of Pennsylvanian stratigraphy around the state proceed. The correlation chart (Fig. 3) indicates the lithostratigraphic terminology of New Mexico Pennsylvanian strata advocated in this paper. In some areas, detailed studies of the Pennsylvanian sequences are needed to test the validity of the proposed nomenclature.

The paleogeography and tectonic history of New Mexico during the Pennsylvanian Period were complex. Although deposition was mainly in shallow marine environments across much of the state during all but the earliest (Morrowan) part of the period, stable shelf environments were interrupted, to varying degrees at different times, by four major subsiding basins: Taos trough and Orogrande, Delaware, and Pedregosa Basins. These basins accumulated unusually great thicknesses of sediment, although generally in shallow rather than deeper marine environments, from four large (Uncompahgre, Sierra Grande, Zuni, and Pedernal) and several smaller island uplifts that provided fluctuating volumes of siliciclastic sediments to marine and coastal environments (Fig. 2). The interplay between paleogeography, tectonic activity, eustatic sea level changes, and climate through the Pennsylvanian produced depositional sequences of significant lithologic variability. Most Pennsylvanian sequences accessible for detailed study are within relatively recently (Cenozoic) uplifted, isolated, fault-block mountain ranges, which have tended to emphasize apparent differences between local sequences, rather than the broader depositional patterns that tie them together. However, it is these broad patterns that are used here as the basis for lithostratigraphic units such as formation and groups, with the view that for nomenclatural purposes, most local lithologic variability is properly accommodated within local member-rank units of rather broadly defined and geographically extensive formations. This approach is not new; it was foreshadowed, albeit somewhat irregularly and informally, by the extensive reconnaissance mapping and stratigraphic studies undertaken by U.S. Geological Survey geologists in the 1940s to 1960s.

The main recommendations for revision of current Pennsylvanian lithostratigraphic nomenclature are as follows:

1) Use of the term Magdalena Group in those parts of the state (mainly southern New Mexico) where it is still being employed should be abandoned. This term, a relic of the earliest attempts to subdivide the Pennsylvanian in New Mexico, has been applied in so many confusing and contradictory ways as to render it meaningless, and nearly a century of subsequent, more detailed stratigraphic work has deprived it of any utility it might once have possessed.

2) The Madera Formation is most appropriately regarded as a Group wherever it occurs in the state, an assessment already implemented by some workers in areas such as the Manzanita, Manzano, and Los Pinos Mountains.

3) Units previously regarded as members within the Madera Formation should be treated as formations, as they have all of the attributes of formations as outlined in the present Code of Stratigraphic Nomenclature. This especially applies to the informal "lower gray limestone" and "upper arkosic limestone" member names widely used beginning in the 1940s and continuing today in many parts of central New Mexico. These two units represent two very different, widespread, easily recognized sedimentary sequences; the lower, an essentially Desmoinesian sequence of cherty, massive, cliff-forming, carbonate-shelf marine limestones and the upper, a cyclic Missourian–Virgilian sequence of alternating, generally thinner and chertless marine limestones and siliciclastic units. Locally, a third unit at the top of the Madera may be recognized (e.g., Bursum and Red Tanks Formations), composed primarily of variably colored, nonmarine siliciclastic beds with subordinate marine limestones, reflecting final regression of the Madera sea and replacement of marine strata with continental red beds near the beginning of Permian time.

4) Formal formation names should be applied to the "lower gray limestone" and "upper arkosic limestone" members. The earliest valid, adequately defined, formal names given to these widely distributed and easily distinguished units within the Madera are Gray Mesa Limestone and Atrasado Formation, respectively, in the Lucero uplift area (Kelley and Wood, 1946). These formations can be recognized widely in central New Mexico, and they, as well as the Madera Group, are here extended southward into the Caballo and Robledo Mountains area. The Madera sequence in the Lucero uplift area is an important reference section for these lithostratigraphic units. Only in cases where the lithostratigraphy departs considerably from that of the type Gray Mesa and Atrasado Formations need different formation names be considered.

5) Madera Group terminology reflects sedimentary sequences deposited on stable platforms or along the margins of subsiding basins, as is the case with the Lucero uplift sequence. Broadly similar Madera sequences, though variable locally, can be recognized along the western and northern margins of the Orogrande Basin, and northward to the Peñasco uplift area. Pennsylvanian sequences deposited more centrally in subsiding basins, such as in the San Andres Mountains or the Sangre de Cristo Mountains, or within unique tectonic regimes, as along the eastern side of the Orogrande Basin in close proximity to the Pedernal uplift (Sacramento Mountains) display strata that differ markedly from typical Madera Group sequences, and dif-

ferent sets of lithostratigraphic names, some including Morrowan and Atokan strata not normally present in the Madera Group, have appropriately been applied by previous workers.

6) Pre-Madera (generally pre-Desmoinesian) strata are heterogeneous and have received distinct formational names (e.g., Sandia and Red House Formations), or are included in formations (such as the Lead Camp Limestone in the southern San Andres Mountains) that show no significant breaks in sedimentation from Early to Middle or even into Late Pennsylvanian time. The Atokan, predominantly clastic Sandia Formation is widely present beneath the Madera Group, but it becomes gradationally more carbonate-rich to the south, where other names have been appropriately used for this interval.

7) The lithostratigraphic formation and group names proposed by Thompson (1942), which were never widely used and are all but forgotten today, should be reevaluated. They designate legitimate, well-defined lithostratigraphic units, and some of them may be appropriate as member names locally within the more broadly conceived formations discussed above. They also have priority over most other lithostratigraphic names used for parts of the Pennsylvanian sequence in New Mexico.

8) Lithostratigraphic names used for Pennsylvanian strata in the subsurface of New Mexico should, as far as possible, be the same as those defined from exposed strata in the state, rather than names based on surficial units in central Texas, which have no apparent relationships with New Mexico strata.

Acknowledgments. I thank Frank Kottlowski, New Mexico Bureau of Mines and Mineral Resources, Spencer Lucas, New Mexico Museum of Natural History and Science, and Elmer Baltz for reviewing an earlier version of this paper and offering suggestions that improved it. Thanks also to Mabel Chavez for word processing the manuscript. This paper is dedicated to Frank Kottlowski in recognition of 50 yrs of contributions to our knowledge and understanding of New Mexico Pennsylvanian stratigraphy and to many other aspects of New Mexico's geological record.

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On October 15, 2001, the University of New Mexico Printing Services closed its doors after nearly 70 years of service. New Mexico Bureau of Geology and Mineral Resources was among many state-affiliated entities that regularly did business with UNM Printing Services. They printed every issue of *New Mexico Geology* since its inception in February 1979. However, this association between the two organizations goes back much farther. This long partnership owed its success to the dozens of dedicated and skilled employees who worked alongside bureau editors to make beautiful and accurate geologic publications and maps. We wish all of those employees well in their new endeavors.