Pennsylvanian and Permian stratigraphy, tectonism, and history, northern Sangre de Cristo Range, Colorado

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PENNSYLVANIAN AND PERMIAN STRATIGRAPHY, TECTONISM, AND HISTORY, NORTHERN SANGRE DE CRISTO RANGE, COLORADO

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INTRODUCTION

In portions of the northern Sangre de Cristo Range the Pennsylvanian and Permian sedimentary rocks are at least 18,000 feet thick (figs. 1 and 2). Folding and faulting have disrupted the rocks so that complete stratigraphic sections are almost nonexistent. The structural complexity and the abrupt facies changes that occur within this stratigraphic sequence have led to major difficulties in subdividing the section into distinct mappable units. This paper presents the results of detailed mapping of lithologic units within the thick Pennsylvanian and Permian sequence in the Arkansas River Valley (Pierce, 1969) (fig. 2) and the same lithologic units throughout the northern Sangre de Cristo Range by means of field work, and the use of high-altitude color and color infrared air photographs (Peel, 1971) (see plate 1, back pocket). The stratigraphic mapping and sedimentologic observations have permitted significant conclusions concerning sedimentation patterns and tectonism in this area during the Pennsylvanian and Permian.

STRATIGRAPHY

Pierce (1969) subdivided the Pennsylvanian and Permian sedimentary rocks that are exposed along the Arkansas River Valley southwest of Salida into seven major mappable units which he labeled, from oldest to youngest, Unit I through Unit VII. Based primarily on color, these divisions make excellent bases for subdividing and mapping the Pennsylvanian and Permian sedimentary rocks throughout the northern Sangre de Cristo Range as shown in Figure 3. The units, with only minor changes, may also be adjusted to the existing nomenclature as follows:

Pierce (1969)	This paper
Units VI & VII	—Upper Member—Sangre de Cristo Formation (including Crestone Conglomerate)
Units IV & V	—Lower Member—Sangre de Cristo Formation
Unit III	—Madera Formation
Unit II	—Sharpsdale Formation
Unit I	—Kerber Formation

Table 1 shows the historical development of the stratigraphic nomenclature of the Pennsylvanian and Permian rocks in the area. Table 2 graphically depicts the relationship of these formations from one locality to the next throughout the northern Sangre de Cristo Range.

KERBER FORMATION

Type Locality

The Kerber Formation contains the oldest Pennsylvanian sedimentary rocks in south-central Colorado. It was first described and named by Burbank (1933, p. 13) in the vicinity of Kerber Creek (T. 46 N., R. 9 E.) a few miles west of the hamlet of Villa Grove (see fig. 2). Burbank described the formation as a 200-foot sequence of carbonaceous shales, coarse-grained sandstones and "grits," occasionally interbedded with thin coals. At the type section, the Kerber formation rests unconformably on the Leadville Limestone (Mississippian) and conformably beneath the Sharpsdale Formation.

Lithology

Throughout south-central Colorado the sandstones of the Kerber Formation are typically quartzose, light gray, and tan to buff; the quartz grains tend to be subrounded to rounded. White kaolinite in many cases is a common matrix constituent. The kaolinite matrix, the quartzose mineralogy, and light gray to buff colors distinguish the Kerber Formation from the overlying red feldspathic rocks of the Sharpsdale Formation. Sandstones of the Kerber are, in some localities, conglomeratic, with pebbles averaging between ¼ to ½ inch in diameter. The shales are buff

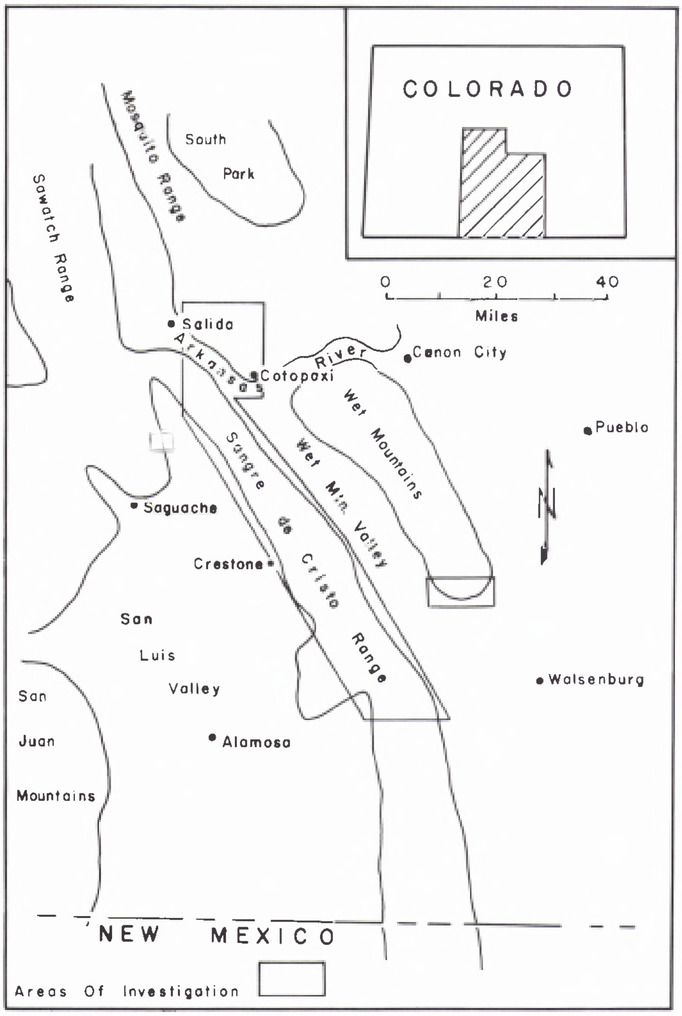

FIGURE 1.

Index map.

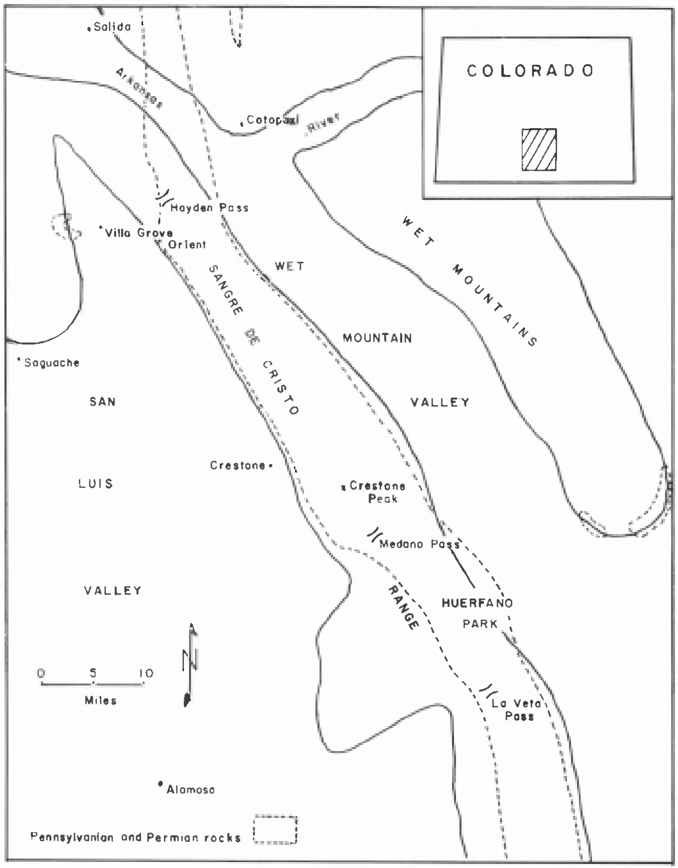

FIGURE 2.

Map of Pennsylvanian and Permian outcrops, south-central Colorado.

to dark brownish gray and are thinly laminated with an abundance of carbonaceous plant debris. Thin, fossiliferous, marine limestones and coal beds are present at a few localities within the formation.

The Kerber Formation is relatively nonresistant to weathering and, as a result, outcrops are sparse and poorly exposed. The formation is poorly stratified and sandstones pinch out laterally within short distances (500 to 800 feet). Some outcrops exhibit crude cyclic and graded bedding with coarse-grained, conglomeratic sandstones grading upward into siltstones and shales at the top of each cycle. The more coarse-grained sandstone beds exhibit some cross stratification or horizontal bedding. In some exposure cut-and-fill structures or scour features are present at the base of some of the sandstones and some of these contain lithoclasts of the underlying siltstones and shales.

The gray to buff quartzose sandstones, shales, and a few thin coal and limestone beds of the Kerber Formation occur ubiquitously at the depositional contact of the Pennsylvanian rocks with the underlying Paleozoic rocks and in some places with Precambrian rocks throughout south-central Colorado (figs. 4, 5, and 6). Along the Arkansas River Valley the Kerber Formation contains 300 to 400 feet of gray to buff, medium- to coarse-grained, quartzose sandstones and buff to tan, siltstones interbedded with a few thin, black carbonaceous shales. At least 3 brachiopod-bearing limestones are interbedded with the shales near the top of the formation.

At the north end of the Cotopaxi inlier, 8 miles north of the town of Cotopaxi, approximately 90 feet of gray to light gray, kaolinitic, quartzose sandstones interbedded with slightly carbonaceous shales are present at the base of the Pennsylvanian section. These beds, previously mapped as part of the Minturn Formation (Vargus, 1961) have the typical lithologic characteristics of the Kerber Formation and should be mapped as such (see plate 1, back pocket).

Kerber lithologies can be traced from known outcrops, with the aid of high-altitude color and color-infrared air photographs, south from the Arkansas River Valley over Hayden Pass along the western flank of the Sangre de Cristo Range to Major Creek (see Plate 1, back pocket). South of Major Creek the Kerber Formation is complexly faulted and the more continuous outcrop pattern that is found to the north ceases to exist. Despite the complex structure, Kerber lithologies are present in the North

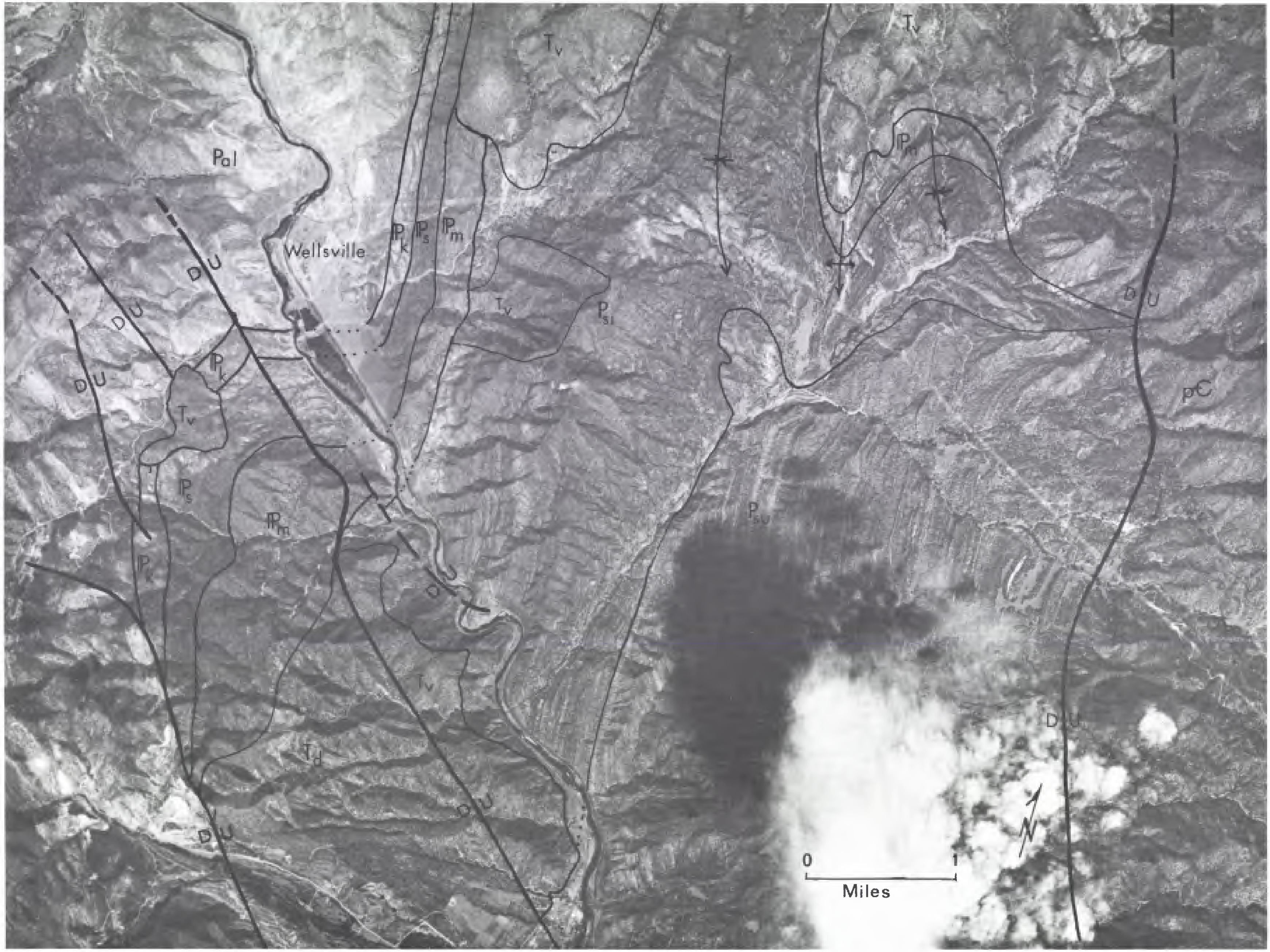

FIGURE 3.

High altitude air photograph of the Arkansas River Valley showing subdivisions of Pennsylvanian and Permian strata. Kerber (P_k), Sharpsdale (P_s), Madera (P_m), Sangre de Cristo Fm., Lower Member (P_{sl}), Upper Member (P_{su}).

TABLE 1.
History of the Pennsylvanian and Permian nomenclature, south-central Colorado.

BURBANK & GODDARD 1937	BRILL 1952 Arkansas River	BRILL 1952 Huerfano Park	BOLYARD 1959 Northern Sangre de Cristo Range	PIERCE 1969 Howard Area	THIS PAPER Northern Sangre de Cristo Range
Sangre de Cristo Formation: Crestone Congl. Phase	Sangre de Cristo Formation	Badito Formation	Sangre de Cristo Formation: Crestone Congl. Member	Unit VII	Sangre de Cristo Formation: upper member
		Sangre de Cristo Formation: Crestone Phase		Unit VI	Sangre de Cristo Formation: Crestone Congl. Member
Sangre de Cristo Formation: Congl. Red Beds	Jacque Mtn. Ls.	Sangre de Cristo Formation	Sangre de Cristo Formation: Lower Member	Unit V	Sangre de Cristo Formation: lower member
	Minturn Formation			Unit IV	
Rico Fm.		Madera Formation: Whiskey Cr. Pass Ls.	Madera Formation: Whiskey Cr. Pass Ls.	Unit III	Madera Formation: Whiskey Cr. Pass Ls.
Hermosa Formation		Madera Formation: Arkosic Member Gray Ls. Member	Madera Formation		Madera Formation
		Sandia Formation	Deer Creek Formation	Unit II	Sharpsdale Formation
Kerber Formation	Kerber Formation	Kerber Formation	Kerber Formation	Unit I	Kerber Formation

TABLE 2.

Correlation chart of Pennsylvanian and Permian rocks in south-central Colorado. For locations see Figure 2.

		Arkansas River	Orient	Crestone	Huerfano Park
JURASSIC		? ?	? ?	? ?	Entrada Ss.
PERMIAN		upper mem.	upper mem.	upper mem. / ? Crestone Conglomerate	upper mem. / ? Crestone Conglomerate (Sangre de Cristo Fm.)
PERMIAN		lower mem.	lower mem.	lower mem.	lower mem. (Sangre de Cristo Fm.)
PENN	?	? Whiskey Cr. Pass Ls.	? Whiskey Cr. Pass Ls.	? Whiskey Cr. Pass Ls.	? Whiskey Cr. Pass Ls.
PENN	Des Moinesian	Madera Fm.	Madera Fm.	Madera Fm.	Madera Fm.
PENN	Atokan	Sharpsdale Fm.	Sharpsdale Fm.	Sharpsdale Fm.	Sharpsdale Fm.
PENN	Morrowan	Kerber Fm.	Kerber Fm.	Kerber Fm.	Kerber Fm.
PRE-PENN		Leadville Ls.	Leadville Ls.	Leadville Ls.	Precambrian

Crestone Creek area (T. 44 N., R. 12 E.) along Burnt Gulch (T. 44 N., R. 12 E.) and along Deer Creek (T. 27 S., R. 72 W.) at the type section of the Sharpsdale Formation.

Although Burbank and Goddard (1937) recognized and described Kerber lithologies at Grayback Mountain, west of Huerfano Park, recent investigators have tended to ignore this and have placed these beds within the Sharpsdale Formation. Along Deer Creek (T. 27 S., R. 72 W.), at the type section of the Sharpsdale Formation, Bolyard (1959, p. 1908) described 104 feet of light gray to grayish yellow, quartzose sandstones and conglomerates resting unconformably on Precambrian crystalline rocks. Upon examination of this section the authors believe that these rocks, because of their lithology and stratigraphic position beneath the Sharpsdale Formation, should be mapped as the Kerber Formation (fig. 7). Because the lithologic changes are gradational, the Kerber-Sharpsdale contact is arbitrarily placed at the position in the section where the lithologies change vertically to predominently arkosic sandstones and overall deep red color. This places the top of the Kerber between Bolyard's intervals 11 and 12 of the type measured section of the Sharpsdale.

Contrary to Bolyard's belief (1961, p. 22) that sporadic occurrence of the Kerber Formation suggests erosion of much of the formation in south-central Colorado, the authors found Kerber lithologies everywhere the Sharpsdale occurs, except where they have been faulted out. Although the Kerber thins to the south of Crestone, it was probably deposited over the whole of the area. The gradational contact with the overlying Sharpsdale indicates that no post-Kerber, pre-Sharpsdale erosion has taken place in the northern Sangre de Cristo Range.

The rocks in the upper one-third of the Kerber are finer-grained and the percentage of limestones, shales, and siltstones increases with respect to the rocks of the lower part of the Kerber, except at Kerber Creek and Deer Creek. At Kerber Creek and Deer Creek, however, sandstones and conglomerates predominate and are evenly distributed throughout the section.

FORMATION BOUNDARIES

Throughout south-central Colorado the Kerber Formation generally rests disconformably on the Leadville Limestone (Mississippian) (fig. 4). A longer period of pre-Kerber erosion occurred near the margins of the Central Colorado trough, a narrow north-northwest-trending Pennsylvanian and Permian basin which existed between the Uncompahgre Highland on the southwest and the Wet Mountain (Apishapa) Highland on the east (fig. 5). The

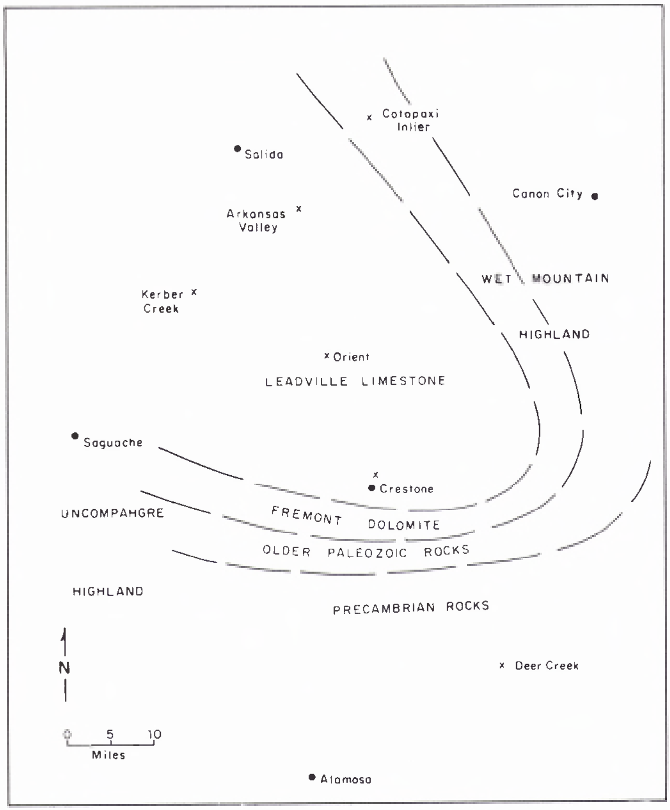

FIGURE 4.

Restored paleogeologic map of the rocks subcropping beneath the Kerber Formation.

incipient basin development and greater erosion in the areas of the adjacent highlands caused the Kerber to overlap the Middle and Lower Paleozoic rocks onto Precambrian rocks, as shown on Figure 4. Hence, the Kerber rests on the Fremont Dolomite (Late Ordovician) in the Cotopasic inlier (T. 49 N., R. 12 E.). A gradual thinning of the Leadville Limestone, the unit directly beneath the Kerber, occurs along the western flank of the Sangre de Cristo Range between Major Creek (T. 45 N., R. 11 E.) and Willow Creek (T. 43 N., R. 12 E.), so that further south Kerber lithologies lie directly on Precambrian crystalline rocks at Deer Creek (Sec. 23, T. 27 S., R. 72 W.) in Huerfano Park (fig. 4).

Although Bolyard (1961, p. 22) postulated an erosional contact at the top of the Kerber Formation, the authors have found Kerber lithologies to grade upward into Sharpsdale lithologies. Burbank (1933, p. 14) originally placed the top of the Kerber Formation at the base of the lowest stratigraphic position of micaceous shale occurring in the Pennsylvanian section. This criterion can only be used in the area of the type section. Therefore in this study the contact is arbitrarily placed at the stratigraphic position where the gray, light gray, and buff, quartzose sandstones of the Kerber change to the overlying arkosic, deep-red, Sharpsdale lithologies. This basis for mapping the contact between the Kerber and Sharpsdale can be used effectively throughout south-central Colorado.

DEPOSITIONAL ENVIRONMENT AND AGE

The abundant plant material, coal beds, and lenticular channel sandstones in the Kerber indicate that most of the Kerber section was deposited in nonmarine coastal plain and low-lying swamps and mudflat environments. The lithofacies and isopach map of the Kerber (fig. 4) reflects deposition in a narrow north-northwest-trending trough, the center of which roughly parallels the eastern edge of the present Sangre de Cristo Range. The Kerber thins and becomes more coarse grained toward the edges of the trough. The rough coincidence of the coarse-grained facies in the Kerber (fig. 4) with the deep pre-Kerber erosion into the Paleozoic and Precambrian section (fig. 3) suggests that incipient uplift of the adjacent highland areas occurred prior to the deposition of the Kerber and that a longer period of pre-Pennsylvanian erosion prevailed along the edge of the depositional trough, followed by eventual onlap of the Kerber Formation. The coarse-grained rocks along the edge of the trough were deposited in fluvial, coastal-plain environments, while the finer-grained facies with coals and carbonaceous shales were accumulating in the center of the basin.

Regional correlations show that the Kerber lithologies change facies to marine black shales and limestones of the Beldon Formation to the north of the Arkansas River Valley (Brill, 1952, p. 814; De Voto, 1965). An increase in the number of limestones in the upper part of the Kerber Formation at the Arkansas River Valley suggests that this area was influenced by more marine conditions toward the later stages of deposition.

No diagnostic fossils have been found in the Kerber. Fossils found in the overlying Sharpsdale Formation and the facies relationships of the Kerber with the fossiliferous Beldon suggest that the Kerber was deposited during the Morrowan and possibly Early Atokan.

SHARPSDALE FORMATION

TYPE LOCALITY

Bolyard (1956, p. 116-125) described a section of interbedded, deep-red arkosic sandstones, siltstones and shales lying unconformably on Precambrian crystalline rocks along Deer Creek (Sec. 23 and 24, T. 27 S., R. 72 W.) which he named the Deer Creek Formation. Chronic (1958, p. 61) later stated that the term Deer Creek had been pre-empted and consequently substituted the term "Sharpsdale" after the nearest settlement, the only one in the township. Bolyard (1961, p. 123) rejected the Sharpsdale name because it was derived from a "one-room log schoolhouse" no longer standing. Workers from Michigan State University (Rhodes, 1964, p. 18; Volkman, 1965, p. 33 and others) have introduced the term "Red Wing Formation" for the same sequence of rocks.

The authors propose that the term "Sharpsdale" be accepted for the typically deep-red, arkosic sandstones and shales which occur stratigraphically above the Kerber Formation and below the Madera Formation and that all others be dropped. The Code of Stratigraphic Nomenclature (1961, p. 652) clearly states that "Names derived

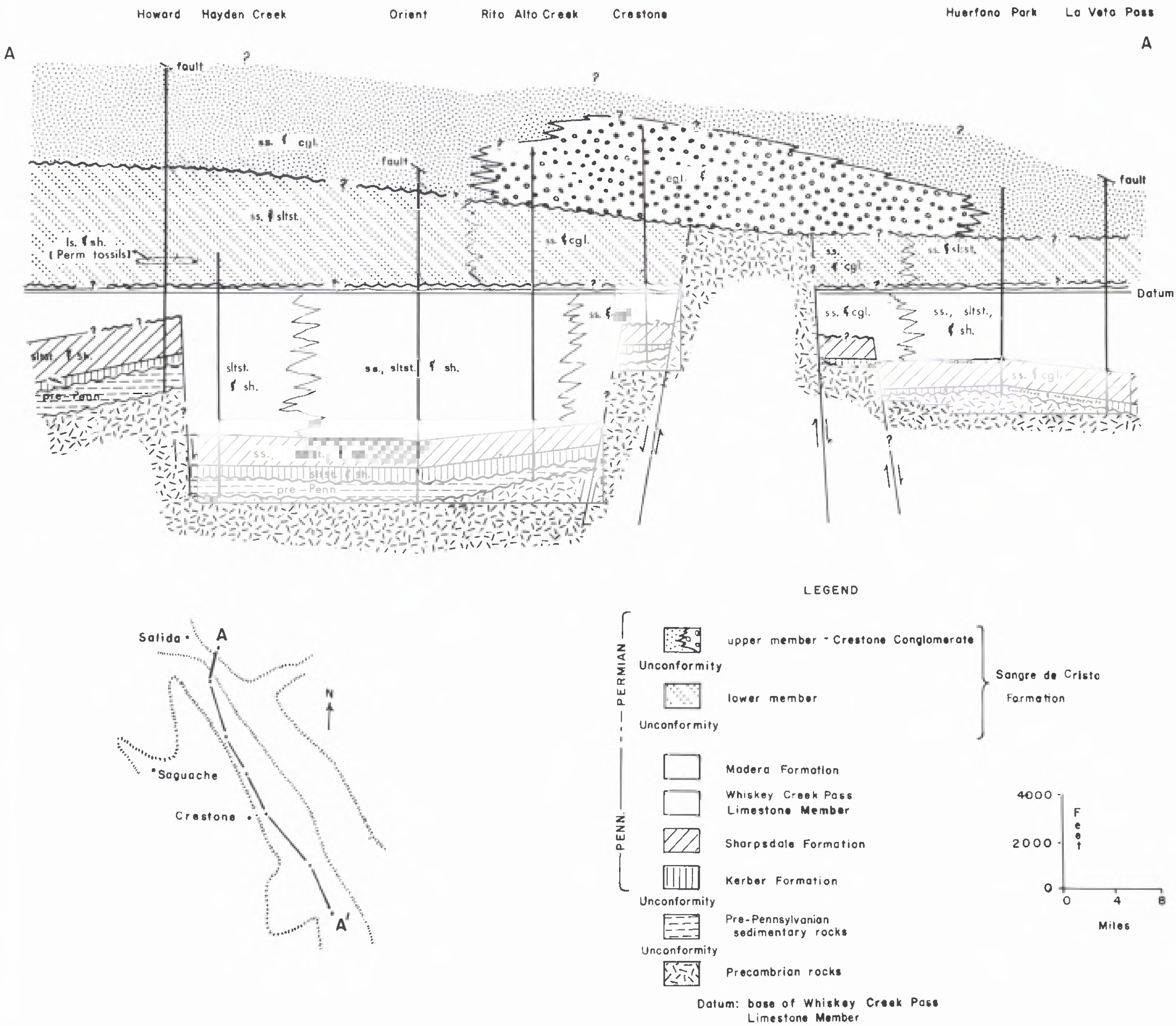

FIGURE 5.

Restored north-south stratigraphic section.

from changeable sources as the names of farms or ranches, churches, schools, and small communities are not entirely satisfactory but are acceptable if no others are available." Since the term "Deer Creek" has been pre-empted and the term "Red Wing" has not formally appeared in the literature, the term "Sharpsdale" is, in this case, the most satisfactory.

The basal 104 feet of Bolyard's type section of the Sharpsdale Formation at Deer Creek contains Kerber Lithologies. The lower boundary of the Sharpsdale Formation at the type section is, therefore, placed between intervals 11 and 12 of Bolyard's measured section. By redefinition of its lower boundary, the Sharpsdale Formation is restricted to the predominantly reddish-brown arkosic sandstones and deep-red shales, making the formation a more easily recognizable and mappable unit.

Lithology

The Sharpsdale Formation consists predominantly of red to deep red, fine- to coarse-grained, angular to subangular, micaceous, feldspathic to arkosic sandstones interbedded with deep-red shales and siltstones. Conglomeratic sandstones and conglomerates are not uncommon, and several beds of thin gray limestones, ranging to as much as 30 feet thick, are present throughout the section.

The conglomerates contain quartz, granite and gneiss pebbles and boulders as large as 8 inches in diameter. The matrix is generally fine-grained, argillaceous, feldspathic, sandstone. Most beds are lenticular, poorly sorted and extremely variable in thickness.

The limestones contain brachiopods and ostrocodes, but many contain as much as 40 percent clay, siltstone and/or sandstone. They commonly grade both laterally and vertically into sandstones and shales.

The sandstones, siltstones and shales generally are poorly sorted, containing varying amounts of clay, sand, and silt. Cross bedding and cut-and-fill stratification are common. Clasts of deep-red shale are common near the base of the sandstones that exhibit the cut-and-fill stratification. Although red and deep-red beds predominate, a few greenish-red and gray beds are present; dark gray to black beds are almost nonexistent.

Contrary to Bolyard's (1956) belief that the Huerfano River marked the northern extent of the Sharpsdale Formation, Karig (1964, p. 25) recognized 1,000 feet of the Sharpsdale along North Crestone Creek and Peel (1971) has traced the Sharpsdale north along the west flank of the Sangre de Cristo Range into the Arkansas River Valley (see plate 1, back pocket). Here the formation is 1,800 feet thick and corresponds exceptionally well with Pierce's Unit II (1969). The Sharpsdale is also present within the Cotopaxi inlier (see plate 1, back pocket) and at Kerber Creek.

Along the Arkansas River Valley the lower 400 feet is predominantly deep-red, micaceous siltstones and shales with thin brachiopod-bearing limestones. The upper 1,400 feet contains no limestones and is comprised of deep-red shales and siltstones interbedded with lenticular, red, arkosic sandstones. Although sandstones, siltstones and shales are equally distributed throughout the Sharpsdale at Kerber Creek, the brachiopod-bearing limestones are concentrated in the lower portion of the section.

As in the Arkansas River Valley section, gray shales and siltstones predominate the lower 300 to 400 feet of the Sharpsdale at Orient and North Crestone Creek. Thin arkosic sandstones are interbedded with the shales and siltstones but no limestones are present. The upper 500 to 600 feet at these localities are predominantly arkosic sandstones.

Sandstones comprise the major portion of the Sharpsdale at Deer Creek. Shales, siltstones and limestones are evenly distributed throughout. In this section the limestones are thicker and more common than elsewhere in the northern Sangre de Cristo Range.

Formation Boundaries

The contact between the Sharpsdale and Kerber Formations is gradational and the base of the Sharpsdale is placed at the change from predominantly gray to buff, quartzose sandstones of the Kerber to the red, arkosic sandstones and deep red shales of the Sharpsdale. In many outcrops throughout Huerfano Park, as well as farther south, the Sharpsdale is in fault contact with Precambrian rocks. As much as 600 feet of the lower portion of the formation may be missing as a result of faulting. An excellent example of this relationship can be observed at La Veta Pass, 1.1 miles east of the Russell Post Office, where the fault contact is well exposed in an old prospect pit.

Throughout much of south-central Colorado, at Kerber Creek, Hayden Creek, Orient, Rito Alto Creek, Huerfano Park, and La Veta Pass (figs. 5 and 6), the upper contact of the Sharpsdale is gradational with the overlying Madera Formation and the red sandstones of the Sharpsdale intertongue with the gray-green sandstones and black shales of the overlying Madera Formation. In the Arkansas River Valley, however, this contact is relatively sharp and no intertonguing occurs. The regional stratigraphic relationships, as displayed in Figures 5 and 6, suggest that erosion or nondeposition occurred at the contact between the Sharpsdale and Madera Formations at Howard and Cotopaxi, north of the Arkansas River (fig. 6), and in the area between Crestone and Huerfano Park (fig. 5) on upthrown fault blocks.

Depositional Environments and Age

As suggested by the isopach and lithofacies map (fig. 8) the Sharpsdale Formation was deposited in the same narrow north-northwest-trending basin as was the Kerber Formation. The coincidence of occurrence of red colors, angular pebbles of Precambrian rocks, abundant feldspar grains in the sandstones in the Sharpsdale beds in striking contrast with the gray to buff colors of the quartzose sandstones and shales of the Kerber suggests that the environment of deposition of the Sharpsdale was markedly different from that of the Kerber. The red colors of the Sharpsdale beds indicate that the interstitial ground waters soon after deposition were oxidizing and alkaline, probably fresh ground water in an arid, nonmarine environment. The red colors are due to hematite which is derived from iron-bearing minerals in these conditions. Hence, the change from coals, carbonaceous shales, and gray colors of the Kerber to the red colors and absence of preserved plant debris of the Sharpsdale indicates that the climate became more arid, producing the Sharpsdale lithologies.

The presence of abundant iron-bearing minerals, feldspar, and granite pebbles in the Sharpsdale beds indicates that the Paleozoic rocks had been stripped from the erosional areas in the adjacent highlands and that detritus from Precambrian rocks was being transported into the basin during the deposition of the Sharpsdale. Block faulting at the margins of the basin and highlands could have produced a climate change to an arid climate and erosion of Precambrian detritus in the highland areas. The block faults interpreted from the restored sections (figs. 5 and 6) to have been active subsequent to the deposition of the Sharpsdale and prior to the deposition of the Madera may have also been active in the creation of uplift blocks during the time of Sharpsdale deposition.

The coarse-grained facies and the current transport directions obtained by cross-strata measurements of the Sharpsdale, shown on fig. 8, suggest that streams flowed off the uplift blocks, depositing the coarsest material close to the source areas. Thus, the conglomerates and sandstones in the Sharpsdale in the Deer Creek and La Veta Pass areas were derived by southward transport from an uplift block to the north (figs. 5 and 8). The conglomerates and sandstones of the Cotopaxi inlier probably were derived

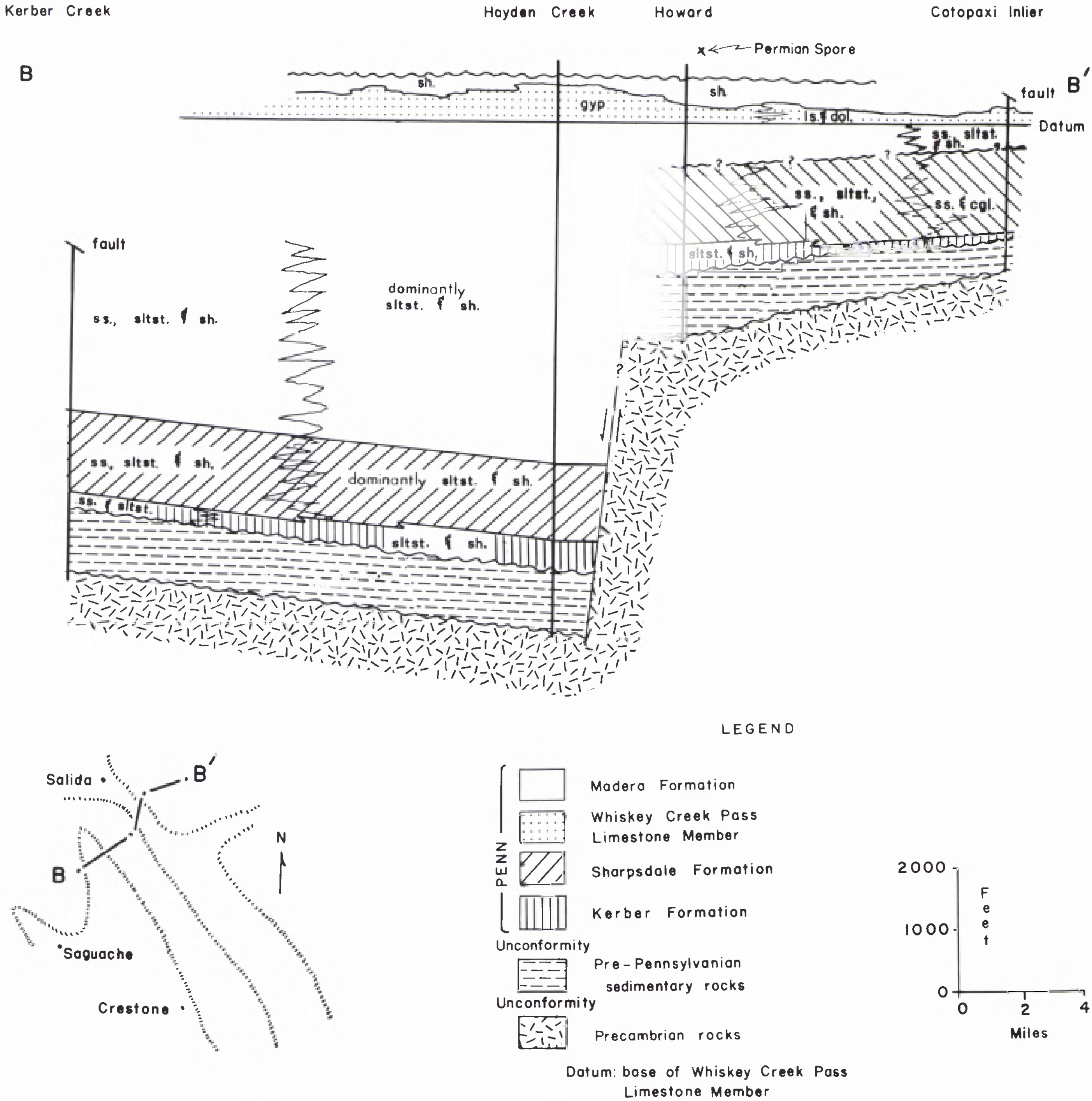

FIGURE 6.

Restored east-west stratigraphic section.

from an uplift block to the south (fig. 8) or immediately to the west. The Sharpsdale at Kerber Creek and the Arkansas Valley sections are comprised of finer detritus derived by northeast transport from the Uncompahgre Highland to the southwest.

These facies patterns and the presence of marine limestones within the Sharpsdale indicate that the structural activity was sporadic and recurrent during the deposition of the Sharpsdale. The presence of marine carbonates in the Sharpsdale at the Arkansas River Valley section and at Deer Creek and their absence in the northern Sangre de Cristo Range suggest that marine waters invaded the Central Colorado trough along its axis both from the north and south, probably due to structural movements of the

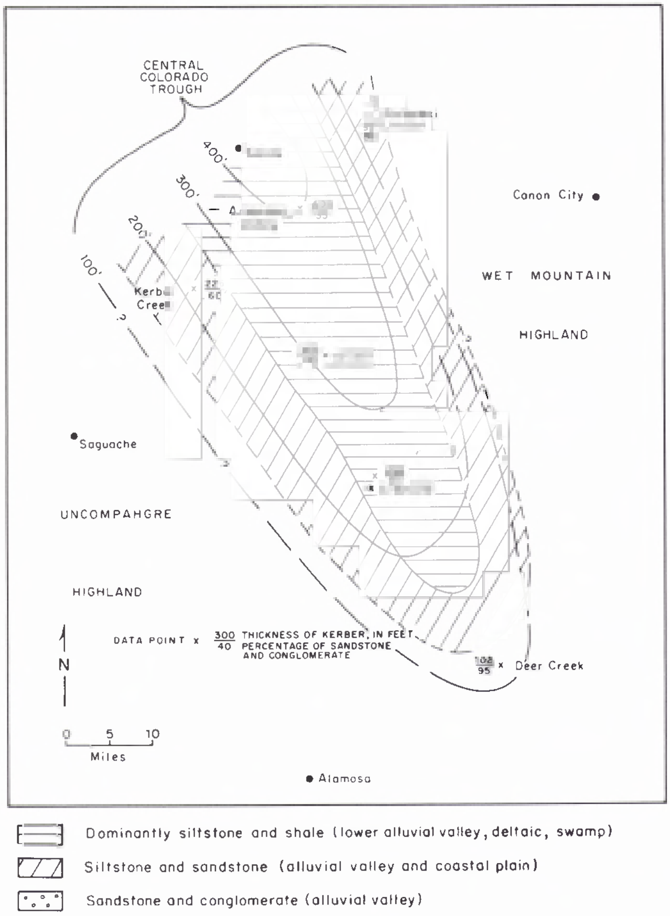

FIGURE 7.

Isopach and lithofacies map of the Kerber Formation in the Sangre de Cristo Range, Colorado.

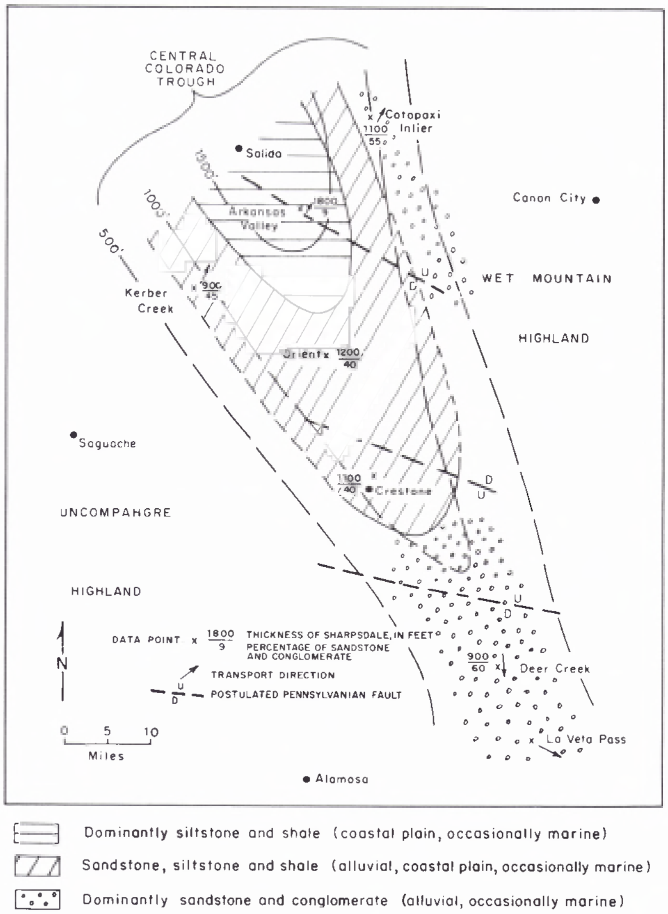

FIGURE 8.

Isopach and lithofacies map of the Sharpsdale Formation in the Sangre de Cristo Range, Colorado.

area. The uplift block between Crestone and Huerfano Park may have acted as a barrier to marine transgression during the times of the invasion of marine waters into the trough.

Thus, the Sharpsdale strata were deposited on alluvial fans and alluvial plains adjacent to actively rising uplift blocks in an arid climate. Marine transgressions occurred occasionally along the basin axis from the north and south.

Fossils found in the Sharpsdale (*Fusulinella devexa* in Huerfano Park and ostracodes in the Arkansas River section) (Brill, 1952, p. 830) and regional stratigraphic relationships (De Voto, 1965) indicate that the Sharpsdale was deposited in the Atokan and possibly the Early Desmoinesian.

MADERA FORMATION

LITHOLOGY

Brill (1952, p. 818) traced the Madera Formation into the south-central Colorado from its type locality in New Mexico and correlated it with the Minturn Formation of central Colorado. The formation grades laterally from a predominantly carbonate type section in New Mexico to a predominantly clastic section in south-central Colorado.

White to light-gray and greenish-gray sandstones and conglomerates, micaceous siltstones, and black shales comprise the bulk of the Madera Formation. The formation, deposited in the Desmoinesian, rests stratigraphically on the red sandstones and siltstones of the Sharpsdale and underlies the red sandstones and conglomerates of the Lower Member of the Sangre de Cristo Formation.

The Madera Formation is present throughout the northern Sangre de Cristo Range (see plate 1, back pocket) but complete sections are uncommon due to faulting and erosion. The formation reaches a maximum thickness of 5,500 feet near Orient, but thins markedly to the north and to the south (fig. 5), so that it is about 1,200 feet thick north of the Arkansas River and 1,000 feet thick near Crestone. South of Medano Pass (T. 24 S., R. 72 W.) the formation thickens more gradually. Along the Arkansas River Valley the Madera consists of green, pale gray-green, and brown, feldspathic sandstones and interbedded dark-gray to black shale. The sandstones are poorly sorted, but may exhibit trough cross stratification and scour features. Black micaceous shale, thin dolomite, lime-

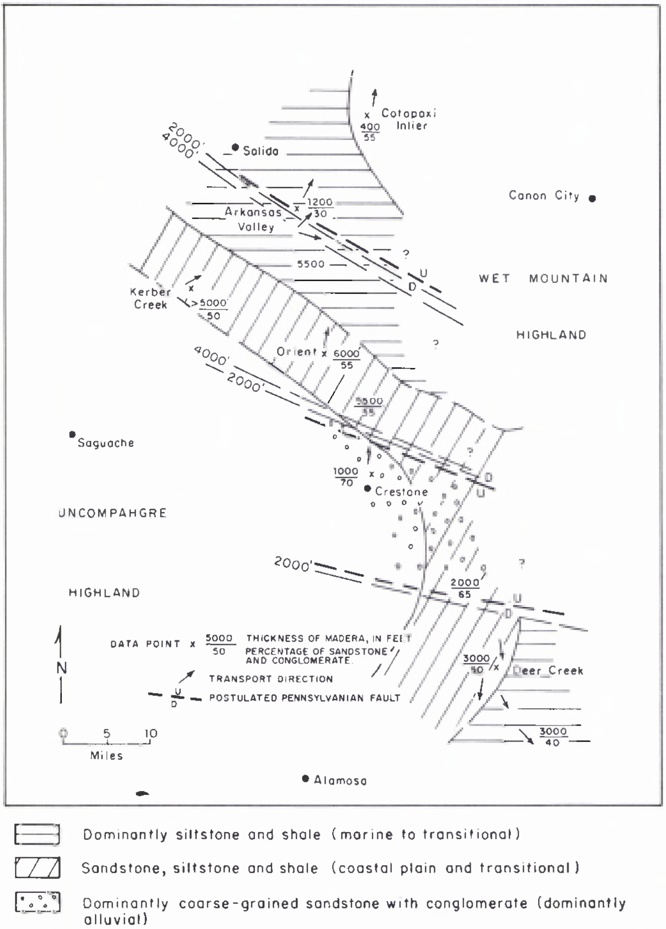

FIGURE 9.

Isopach and lithofacies map of the Madera Formation (excluding the Whiskey Creek Pass Limestone Member) Sangre de Cristo Range, Colorado.

stone and gypsum beds dominate the upper 150 feet of the section. In this upper zone sandstones are lighter hued and more mineralogically mature than those stratigraphically lower in the Madera.

A similar thickness and lithology were noted in the Cotopaxi inlier. Sandstones, however, are thicker, more coarse-grained and more prominent throughout the section than at the Arkansas Valley section (fig. 9). Gypsum beds are not present at the top of the formation, but two bioherms (fig. 10), which occupy approximately the same stratigraphic horizon as the gypsum beds at the Arkansas Valley section, develop to the maximum thickness of 200 feet and length of 2,000 feet. Their bases grade laterally into sandstone and siltstone; the upper half grades into black marine shale (fig. 10).

South of Orient the Madera Formation gradually becomes coarser-grained and includes a greater percentage of sandstones and conglomerates (fig. 9). In the vicinity of North Crestone Creek the conglomeratic material ranges from a few inches to three feet in diameter. Pebbles and boulders are chiefly comprised of quartz, feldspar, and granite, although some mica schist and gneiss pebbles are present. The most coarsely grained material is present between Rito Alto Creek (T. 45 N., R. 11 E.) and Arena Creek (T. 27 S., R. 22 W.) (see plate 1, back pocket). Along Middle Taylor Creek (T. 45 N., R. 12 E.) the conglomerate clasts increase in size stratigraphically upward to a position 2,500 feet below the top of the formation. Above this horizon the rocks are composed chiefly of pebbles and coarse-grained sandstone. Dark gray and black shales and siltstones are interstratified throughout the section with the sandstones and conglomerates but comprise only a small percentage of the total thickness. These shales and siltstones are thin but usually can be traced in the outcrop for several thousands of feet.

South of Arena Creek the formation again grades laterally into fine-grained lithologies, and limestones are present throughout the section. At La Veta Pass the sedimentation has been cyclic, with fine-grained sandstones grading upward into siltstones, shales and limestones.

The Whiskey Creek Pass Limestone Member, at the top of the Madera Formation, consists of 150 to 300 feet of interbedded gray limestone, black shale and siltstone, and greenish-gray sandstone. Limestones are more abundant near the base of the member and thin and thicken from locality to locality. At La Veta Pass the Whiskey Creek Pass Limestone Member is 160 feet thick (Brill, 1952, p. 829) and contains thin-bedded to massive gray oolitic limestones. Most limestones in this area contain a high percentage of sand and silt particles. Brill (1952, p. 818) reported gastropods and pectinoid pelecypods within the limestones.

Although a continuous outcrop does not exist, Bolyard (1959, p. 1915) has indicated that the Whiskey Creek Pass Limestone Member correlates with a similar zone at Marble Mountain (T. 24 S., R. 73 W.) and at South Colony Creek (T. 24 S., R. 73 W.). Two thick biohermal mounds are developed at Marble Mountain and have been described in detail by Berg (1967). Bolyard was able to trace this zone from South Colony Creek north to Rito Alto Creek and Munger (1959) was able to trace it, in almost continuous outcrop, to the Cotton Creek area (T. 45 N., R. 12 E.) where, he states, it appears to be Litsey's (1958) "D" zone. This zone can then be traced in outcrop to Big Cottonwood Creek (T. 47 N., R. 11 E.).

The authors believe that these zones are stratigraphic equivalents and may be correlated with the Whiskey Creek Pass Limestone Member because: (1) they are all stratigraphically located at the top of the Madera Formation and directly beneath the red, coarse-grained, arkosic lithologies distinctive of the overlying Sangre de Cristo Formation, and (2) although the zone varies in thickness throughout the northern Sangre de Cristo Range, the black shales, siltstones and gray fossiliferous limestones are everywhere similar. Fossil assemblages collected from this zone from different localities vary considerably, but crinoid columnals, gastropods, and pelecypods are common almost everywhere. With the exception of fossils dated as Late Cherokeean by Berg (1967, p. 10) most fossils from this zone have long ranges and can only be dated as Desmoinesian.

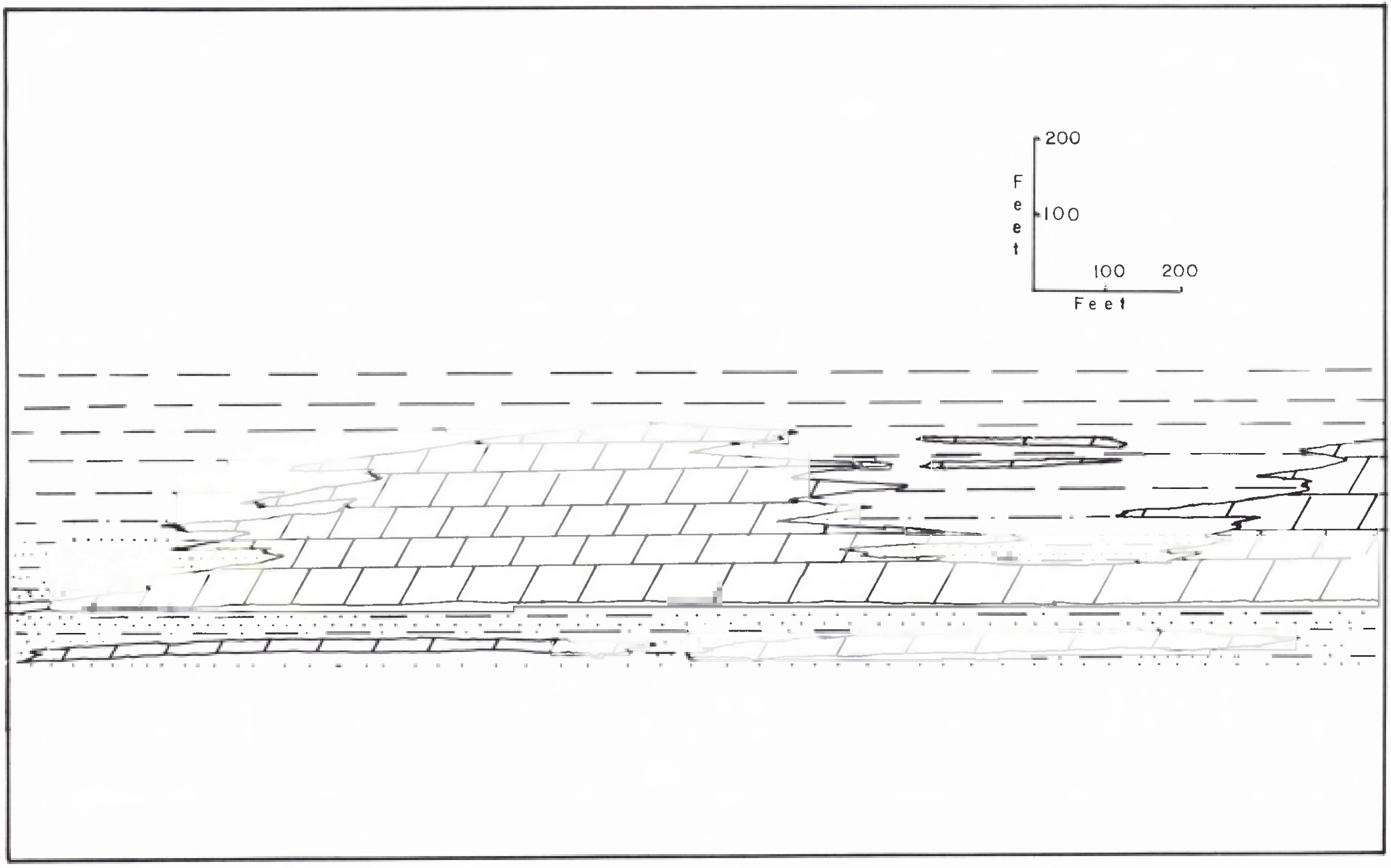

FIGURE 10.

Field sketch of bioherm in the Madera Formation at Cotopaxi inlier (Sec. 7, T. 49 N., R. 11 E.) showing lateral facies relationships.

FORMATION BOUNDARIES

As previously discussed, the contact between the Sharpsdale and Madera Formation is in places gradational and marked by the intervening of different lithologies. When intertonging occurs, the contact is placed at the change from predominantly red arkosic Sharpsdale lithologies to the green, feldspathic Madera strata. As interpreted, in other places the contact between the Madera and Sharpsdale is sharp and erosional (figs. 5 and 6).

The top of the Madera Formation is placed at the first occurrence of red arkosic sandstones, siltstones and shales characteristic of the Sangre de Cristo Formation. Throughout the northern Sangre de Cristo Range this change to redbeds is closely parallelled by the Whiskey Creek Pass Limestone Member, a 150- to 300-foot zone of gray marine limestones, black shales and siltstones, which occur directly beneath the contact in the uppermost part of the Madera.

In the Arkansas River Valley Brill (1952, p. 832) chose to place the top of the Madera Formation at the top of the highest marine limestone in the Pennsylvanian and Permian section. This falls at the top of a 200-foot sequence of gypsum, limestone, dolomite, and black shale. He believed that this sequence was correlative with the Whiskey Creek Pass Limestone Member of the Madera Formation and the Jacque Mountain Limestone Member of the Minturn Formation of north-central Colorado. However, below this sequence of limestone and shale is 1,850 feet of red, arkosic sandstones typical of the Sangre de Cristo Formation (figs. 5 and 6). Paleontologic data of Scott (1967) and White (1912) suggest that this uppermost marine sequence is of Permian rather than Desmoinesian age. White (1912) collected a number of fossil plants from this sequence where it crops out at the D & R G railroad tunnel in Sec. 28, T. 49 N., R. 10 E., which he considered as definitely Permian. Scott (1967) identified *Bisaccate gymnospermous* pollen collected along U.S. Highway 50, SE¼ SE¼ Sec. 18, T. 48 N., R. 11 E., which suggests a Permian age. The pollen was collected from beds near the base of what the authors consider typical Sangre de Cristo lithologies, stratigraphically below the uppermost marine limestones. If these sedimentary rocks are Permian, as indicated by fossil data, the uppermost marine limestones and shales cannot correlate with the Whiskey Creek Pass Limestone or Jacque Mountain Limestone as believed by Brill. Therefore, the sequence of limestone, gypsum, siltstone and shale previously mentioned to occur at the top of the gray-green feldspathic sandstones and siltstones more logically correlates with the

Whiskey Creek Pass Limestone and subsequently the top of the Madera should be placed at the top of this sequence (figs. 5 and 6).

Brill (1952, p. 811) assumed that the absence of datable Missourian and Virgilian beds was evidence of an unconformity at the base of the Sangre de Cristo Formation. Pierce (1963, p. 29) also suggests the possibility of an unconformity between his Unit III and Unit IV. The age of the Whiskey Creek Pass Limestone, on the basis of fossil data, is Desmoinesian and pollen found in the lower beds of the Sangre de Cristo Formation, approximately is dated as Permian. This indicates a break in the record with Missourian and Virgilian strata missing between the Madera and Sangre de Cristo Formation. The contact between these two formations in Big Cottonwood Creek when viewed from Nipple Mountain (T. 46 N., R. 11 E.) displays a slight angular discordance (fig. 11). Thus, the contact between the Madera and Sangre de Cristo Formations is probably unconformable throughout the northern Sangre de Cristo Range.

FIGURE 11.

Angular unconformity between the Madera Formation (P_m) and Lower Member of the Sangre de Cristo Formation (P_{sl}) at the head of Big Cottonwood Creek (Sec. 11, T. 47 N., R. 11 E.). Looking southeast from Nipple Mountain.

Depositional Environment

The distinct color change from the redbeds of the Sharpsdale to the green, gray, and black beds of Madera suggest that the Madera deposits accumulated in environments with different ground-water chemistry, i.e., in coastal plains and mudflats and/or marine conditions where the ground water table was shallow, allowing the preservation of organic debris and a reducing environment. The Whiskey Creek Pass Limestone Member accumulated in marine water with a diminished supply of terrigenous sediment. Bedded gypsum developed locally due to restricted bodies of marine water.

The configuration of the basin during the deposition of the Madera was markedly different from its configuration earlier in the Pennsylvanian. Block faulting that influenced the Sharpsdale deposition and the locally developed erosion surface on the top of the Sharpsdale significantly affected the facies patterns, thickness variations, and transport directions of the Madera beds (fig. 9). The highland uplift block between Crestone and Huerfano Park shed coarse-grained detritus to the north and south. Cross-stratification, current-transport directions (fig. 9) suggest that this east-southeast-trending horst block is probably an eastward extension of the Uncompahgre Highland. Finer-grained sediment shed from the Uncompahgre was transported to the northeast to the area of the Arkansas River Valley. On the downthrown side of the postulated fault in the Arkansas River Valley, two dominant transport directions were obtained from the Madera strata: (1) S. 50 E. from the lower 4,500 feet and (2) N. 55 E. from the upper 1,200 feet. This data suggests that the fault in the Arkansas River Valley may have diverted the drainage to the southeast during the deposition of the lower Madera beds and that the fault may have been overlapped by the upper beds of the Madera with renewed north and northeast transport (figs. 5, 6, and 9). The coarser grained sediment of the Cotopaxi inlier may have been derived from a northern projection of the Wet Mountain Highland.

Environmental conditions varied periodically throughout the deposition of the Madera, as both marine and nonmarine rocks occur in most sections. The area north of Orient was dominated by marine, coastal mudflat and deltaic conditions, with minor periods of alluvial deposition. Poorly sorted sandstones, some exhibiting ripple marks along bedding planes, intertongue with black marine shales and are probably marine and transitional in origin. Other coarser grained, trough, cross-bedded sandstones, which show cut-and-fill features, were probably deposited in fluvial environments.

In the Cotopaxi inlier, at Deer Creek and Kerber Creek fluvial sandstones comprise a greater percentage of the strata. Fine-grained littoral sandstones and a few black marine shales are present but in less abundance. At these localities the environment was probably a coastal plain with alternating periods of emergence and submergence.

On the horst block at Crestone the sandstones are coarse-grained and conglomerates are not uncommon. Some near-shore marine strata are interbedded with cross-bedded fluvial sandstones, suggesting that this area was dominantly alluvial plain subject to occasional periods of submergence.

The strata of the Whiskey Creek Pass Limestone Member are predominantly marine and the cross-bedded fluvial sandstones are confined to the lower ⅓ to ½ of the section. Gypsum beds in the Arkansas River Valley section within this stratigraphic horizon indicate periods when portions of the trough were restricted, probably by carbonate reef developments.

SANGRE DE CRISTO FORMATION

The name "Sangre de Cristo Conglomerate" was first used by Hills (1899, 1900, 1901) and later by Melton (1925a, 1925b) for the entire Pennsylvanian and Permian sequence of strata in the Sangre de Cristo Range. Brill (1952, p. 821) redefined the Sangre de Cristo Formation to include only those beds above the Madera Formation.

Bolyard (1959, p. 1923) subdivided the Sangre de Cristo Formation into the Lower Member and the overlying Crestone Conglomerate Member in the Crestone area. Inasmuch as no type area had been chosen for the Sangre de Cristo Formation, he proposed the area between Crestone Needle (T. 24 S., R. 73 W.) and Eureka Mountain (T. 44 N., R. 12 E.) as the type locality for the formation. Although both members are present and well exposed in this area, a continuous section could not be designated because of complex faulting, rugged topography, and inaccessibility.

In the Arkansas River Valley Pierce (1969) recognized and mapped four Permian units above the Madera Formation. He termed these subdivisions, Unit IV through Unit VII. Although his individual units can not be mapped throughout the northern Sangre de Cristo Range, Units IV and V, when combined, are equivalent to Bolyard's Lower Member, and Units VI and VII are a lateral facies of the Crestone Conglomerate (table 1, fig. 5).

Pierce discovered and mapped an angular unconformity between Unit V and Unit VI. This unconformity represents a major period of tectonism and erosion during the Permian in the Arkansas River Valley area (Pierce, 1969).

The authors prefer to retain the established Sangre de Cristo nomenclature with the addition of the term "Upper Member" of the Sangre de Cristo Formation. The "Upper Member" is herein defined as the finer grained, lateral equivalent of the Crestone Conglomerate and includes all Permian strata above the unconformity which forms the contact between it and the underlying Lower Member. Table 2 graphically depicts this interpretation.

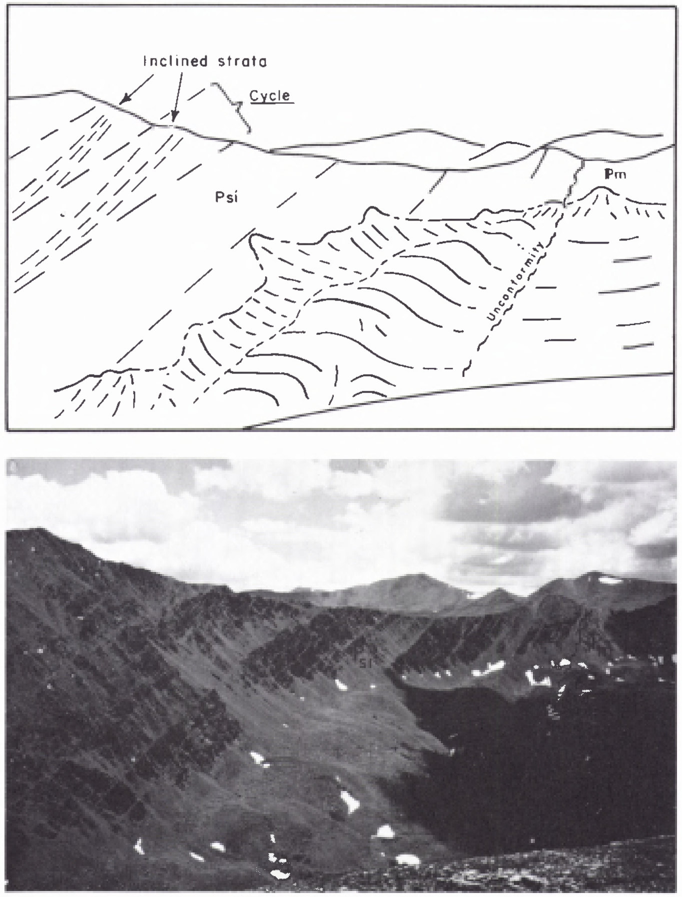

FIGURE 12.

Cycles within the Lower Member of the Sangre de Cristo Formation (P_{sl}). Looking southeast at the head of Cloverdale Basin, Sec. 24, T. 46 N., R. 11 E. Large scale inclined strata within several cycles suggest alluvial-fan deposition from the west to the east.

LOWER MEMBER

Lithology—The type section near Eureka Mountain consists mainly of red, grayish-red, maroon and grayish-green, arkosic sandstone and conglomerate, interbedded with red siltstone, light gray mudstone, and limestone. The section is comprised of cyclic deposits each cycle grading upward from conglomerates and conglomeratic sandstone to highly indurated, fine-grained sandstones, siltstones and shales. Limestone is present in several localities near the top of some of the cyclic units. Figure 12 is a photograph and field sketch, looking south from the head of Cloverdale Basin (T. 46 N., R. 11 E.), which shows the cyclic nature of the bedding. The coarser rocks at the base of each cycle tend to be less resistant to weathering than the finer grained material at the top. Each cycle averages between 500 and 700 feet in thickness. Large-scale inclined strata within several cycles suggest alluvial fan deposition from the west (fig. 12).

UPPER MEMBER

Lithology—The most complete section of the Upper Member is present in the Arkansas River Valley and has been measured and described in detail by Brill (1952, p. 865). The Upper Member is included in his intervals 331 through 471. The section consists of red to brown, coarse-grained, arkosic sandstones interbedded with red, micaceous shales and siltstones.

The coarse-grained, arkosic sandstones are commonly thick bedded and poorly sorted but grade upward into medium-grained sandstones. Trough cross bedding and scour features are common. In some localities cobbles, as much as 3 feet in diameter, are present in the coarser grained sandstones and generally are composed of granite and gneiss.

The red, micaceous siltstones and shales are thin bedded to finely laminated and exhibit ripple marks and mud cracks. These shales in places are carbonaceous and black.

One of the most striking characteristics of the Upper Member is the occurrence of cobble conglomerates comprised of flat limestone cobbles in a coarse-grained, arkosic matrix.

The Upper Member exhibits a cyclic nature similar to the Lower Member except that the cycles are thinner. Each cycle is coarser grained at the base and grades upward into finer grained sandstones, siltstones and shales.

The member as a whole shows a general upward gradation to finer grained rocks.

The Upper Member crops out north of the Arkansas River, in the Rito Alto Creek to Medano Pass area (see plate 1, back pocket) at Huerfano Park and possibly La Veta Pass, but faulting and erosion have removed much of the section and a complete section is nonexistent. The most complete section of the Upper Member of the Sangre de Cristo Formation occurs in the Arkansas River Valley where Pierce (1969) measured 8,500 feet to 9,000 feet.

Bolyard (1959) described a thick section of coarse-grained, boulder conglomerates with some thin beds of arkosic sandstone in the area of Crestone Peak. He designated this unit, which lies above the Lower Member, as the Crestone Conglomerate Member of the Sangre de Cristo Formation. On a regional scale, the Crestone Conglomerate is a lens (or lentil) within the Upper Member and it disappears through facies changes both north and south of the type area (fig. 5).

The Crestone Conglomerate consists of sub-rounded boulders, as large as 20 feet in diameter, of granite and gneiss, with some mica schist and other rock types. These are generally found in a matrix of fine- to coarse-grained, arkosic sandstone and siltstone. Although the boulder beds appear to be massive, when viewed at a distance under proper lighting conditions they do exhibit a faint horizontal stratification. Sandstones and siltstones are poorly sorted and show some trough cross stratification.

Exposures of the Crestone Conglomerate are confined to the area between Rito Alto Creek and Medano Pass (see plate 1, back pocket). A short distance to the north of Rito Alto Creek and south of Medano Pass the conglomerates decrease in coarseness and the sandstones increase in number and thickness (fig. 5).

Peel (1971) has recognized a subtle angular discordance between the Lower Member and the Crestone Conglomerate on high-altitude color air photographs in the vicinity of San Isabell Lake and Groundhog Basin in T. 44 N., R. 12 E. (see plate 1, back pocket). The unconformity reported by Pierce in the Arkansas River Valley and the one in the San Isabell—Groundhog Basin area occur at approximately the same stratigraphic position.

The Lower Member is distinguished from the overlying sedimentary rocks by its finer grain size and higher percentage of red shales and siltstones. The red color of the Upper Member is also more drab than that of the Lower Member.

Depositional Environment—Trough cross-bedding, scour features, very poor sorting and large-scale inclined bedding in the sandstones and conglomerates and desiccation cracks in the siltstones and mudstones indicate that the Lower Member was deposited on an aggrading alluvial plain under predominantly fluvial conditions. The abundant cycles in the section suggest recurrent structural activity or climatic cycles in or adjacent to the depositional basin. The overall gradual upward coarsening of grain size in the section suggests progressive uplift of the adjacent highland blocks. The isopach and lithofacies map (fig. 13) indicates

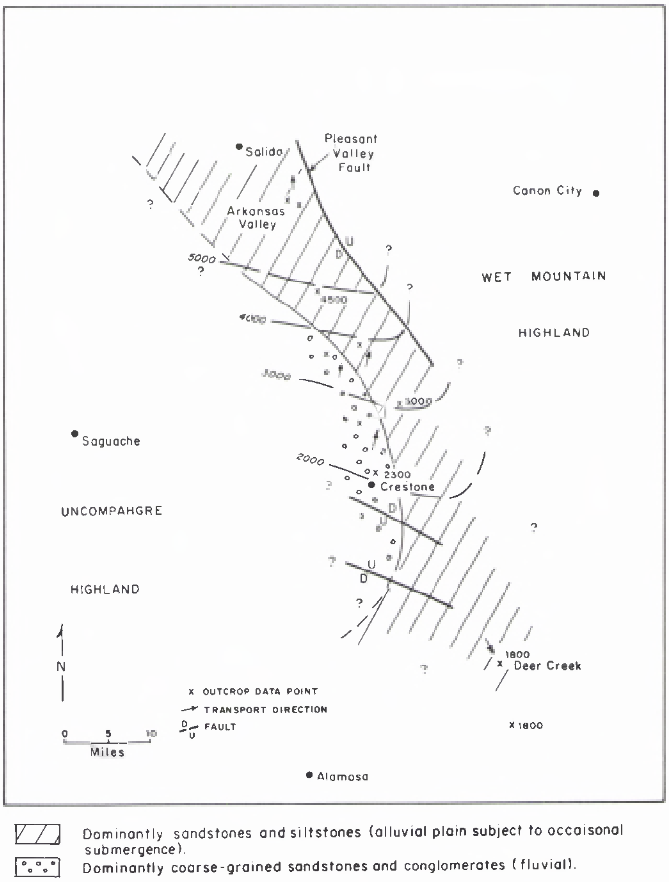

FIGURE 13.

Isopach and lithofacies map of the Lower Member, Sangre de Cristo Formation, south-central Colorado.

that the detritus was probably dominantly shed from an eastward projection of the Uncompahgre Highland, which may have been recurrent movement on the horst block in the Crestone area previously discussed (fig. 9). The occurrence of marine limestone interbedded with sandstones and siltstones suggests that parts of the trough were submergent for short periods of time.

The conglomerates and conglomeratic sandstones are composed of well rounded pebbles, cobbles, and, in some localities, boulders which reach a diameter of 1 foot. The stream-rounded pebbles and cobbles consist of granite, gneiss, and mica schist, with some sandstone and siltstone derived from the Lower Member itself. Arkosic sandstone generally composes the matrix of the conglomerates.

The arkosic sandstones are poorly sorted, fine- to coarse-grained and commonly are very micaceous and argillaceous. They are thin to thick bedded and contain trough cross stratification and cut-and-fill features throughout.

Although no fossils have been found, the thin gray limestones which are rarely more than 3 feet thick, are considered marine in origin. Some of the limestones exhibit stromatolitic banding and are cherty. Black shales occur only sparsely throughout the Lower Member.

The Lower Member gradually thickens from 2,300 feet at Crestone Peak to 4,500 feet at Orient and 6,000 feet in the Arkansas River Valley.

Figure 13, a lithofacies map of the Lower Member, shows the lateral facies changes within this member throughout the northern Sangre de Cristo Range. Fine-grained sandstones and siltstones dominate the section on the Arkansas River Valley and along the eastern flank of the Sangre de Cristo Range in Huerfano Park and La Veta Pass. These sedimentary rocks grade laterally to dominantly medium- to coarse-grained sandstones and conglomerates at Orient, Crestone and the northern end of Huerfano Park. Most sections show a gradual coarsening of the conglomerates toward the top of the member.

Member Boundaries—The contact between the Lower Member of the Sangre de Cristo Formation and the underlying Madera Formation is probably an unconformity, as discussed previously. The contact is easily recognized by a change from gray-green, feldspathic sandstones, siltstones and black shales of the Madera Formation to the predominantly maroon to red arkosic sandstones and red shales of the Lower Member.

The contact between the Lower Member and the overlying Upper Member is unconformable in many places also. Pierce (1969) discovered an angular discordance between his Units V and VI which is the contact between the Lower Member and the Upper Member in the Arkansas River Valley (table 1). Erosion at the unconformity truncates 6,000 feet of underlying Pennsylvanian and Permian strata in a distance of 3 miles as the Pleasant Valley fault is approached (figs. 14 and 15). Anticlinal and synclinal folding developed in the beds underlying the unconformity before the overlying beds were deposited.

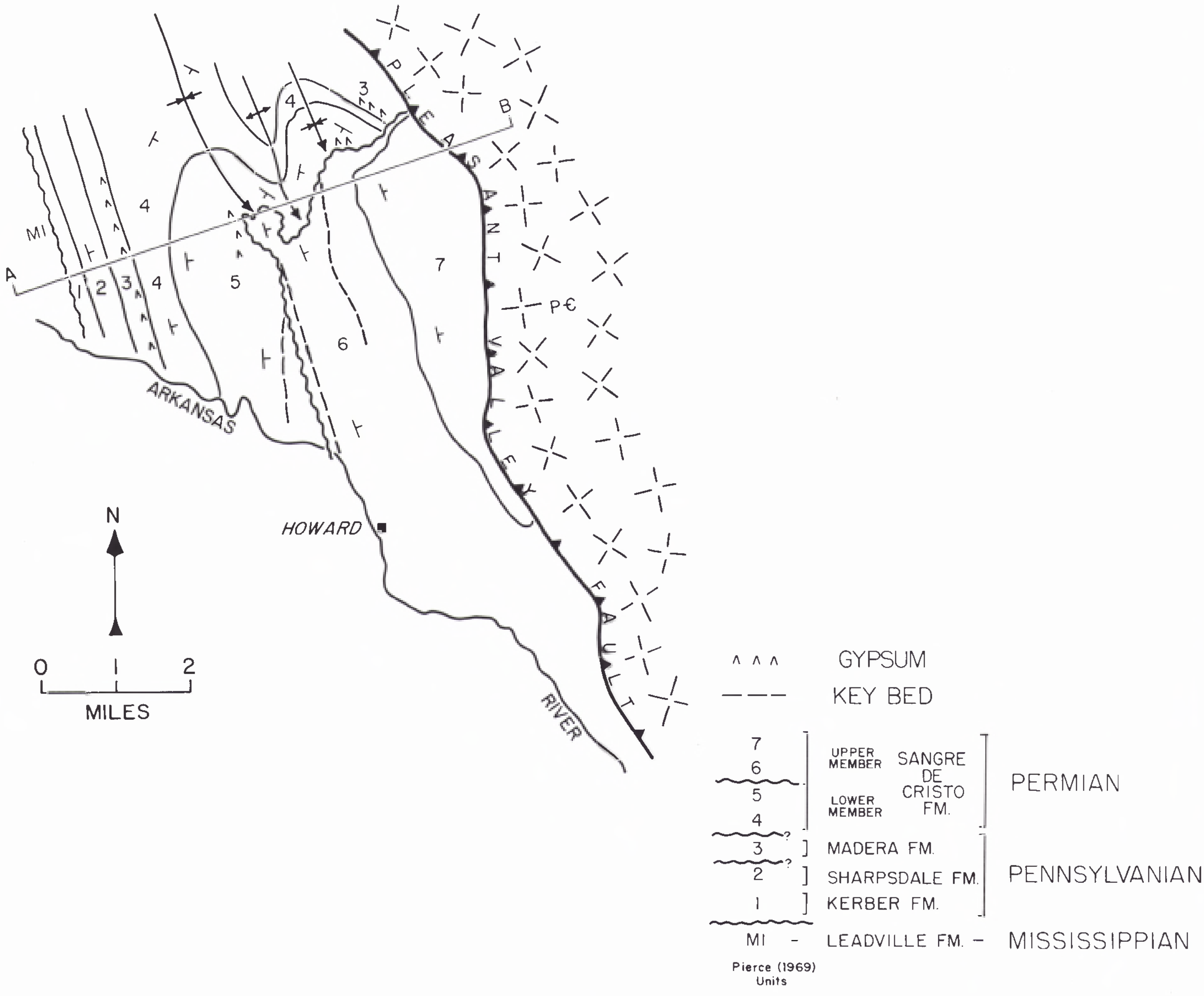

FIGURE 14.

Pennsylvanian and Permian mappable units, Arkansas River Valley, Colorado.

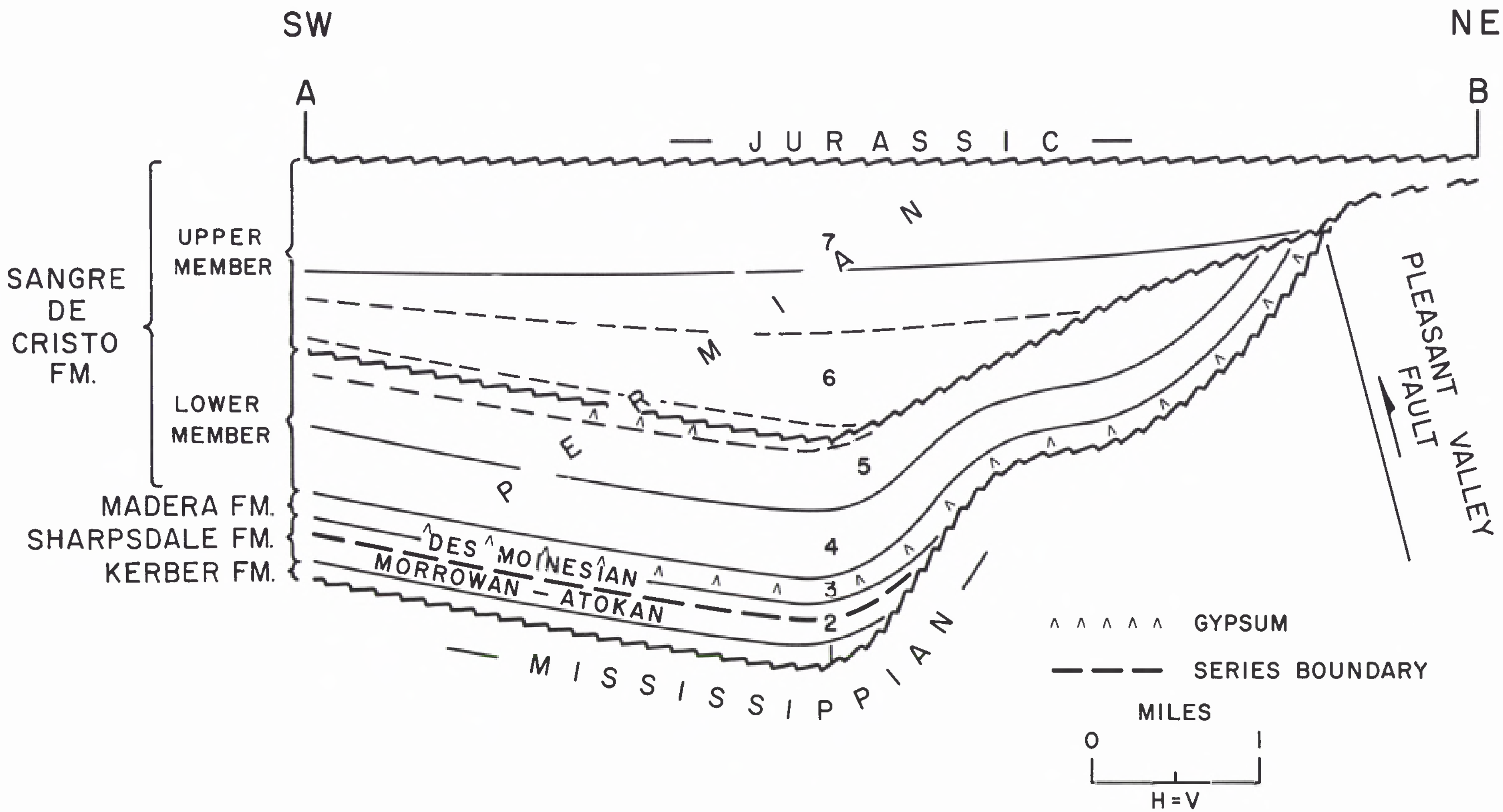

FIGURE 15.

Restored section, Pennsylvanian and Permian rocks, Arkansas River Valley, Colorado (after Pierce, 1969). Line of section shown on Figure 14.

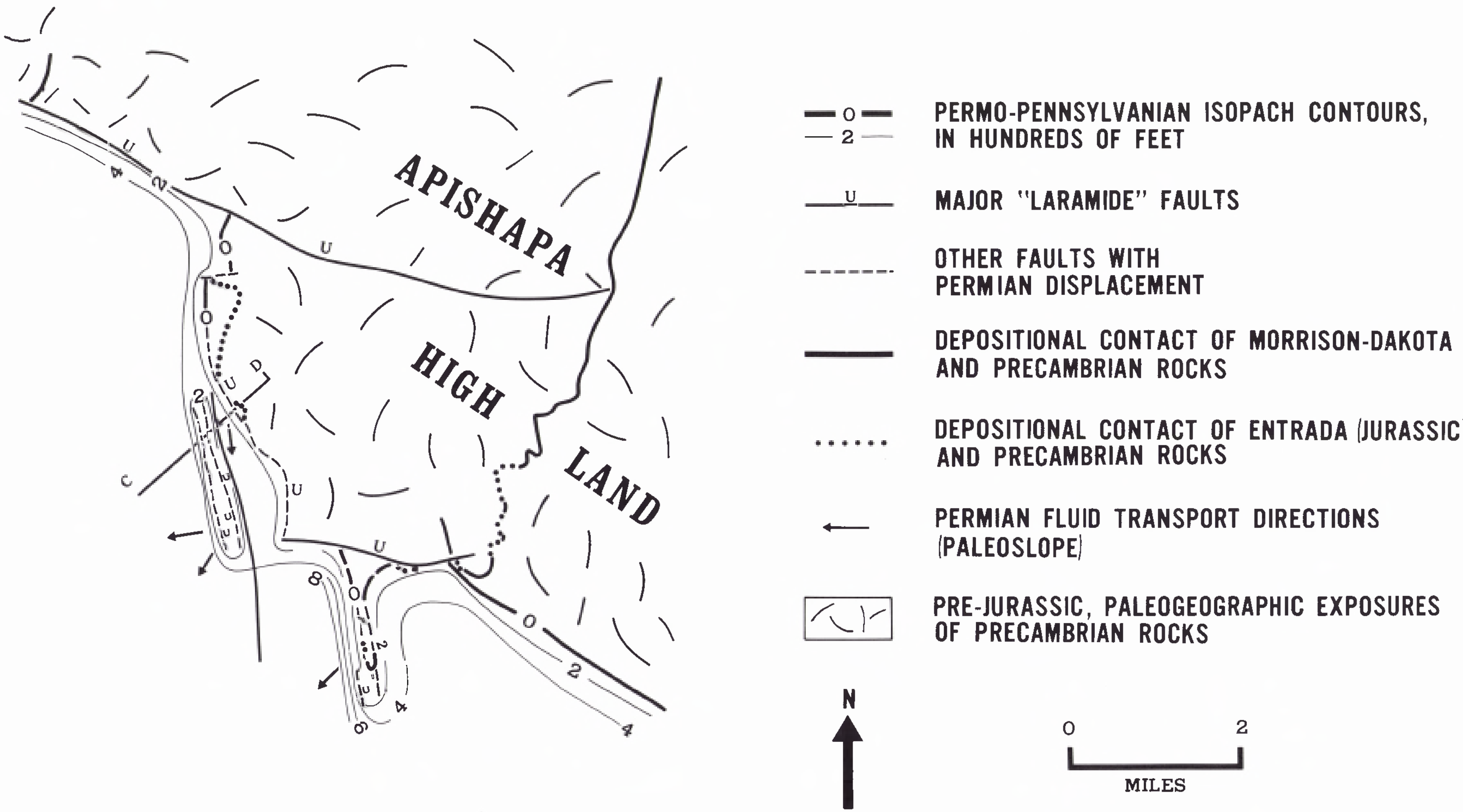

FIGURE 16.
Restored geographic and isopach map showing Permian faulting, southern Wet Mountains, Colorado.

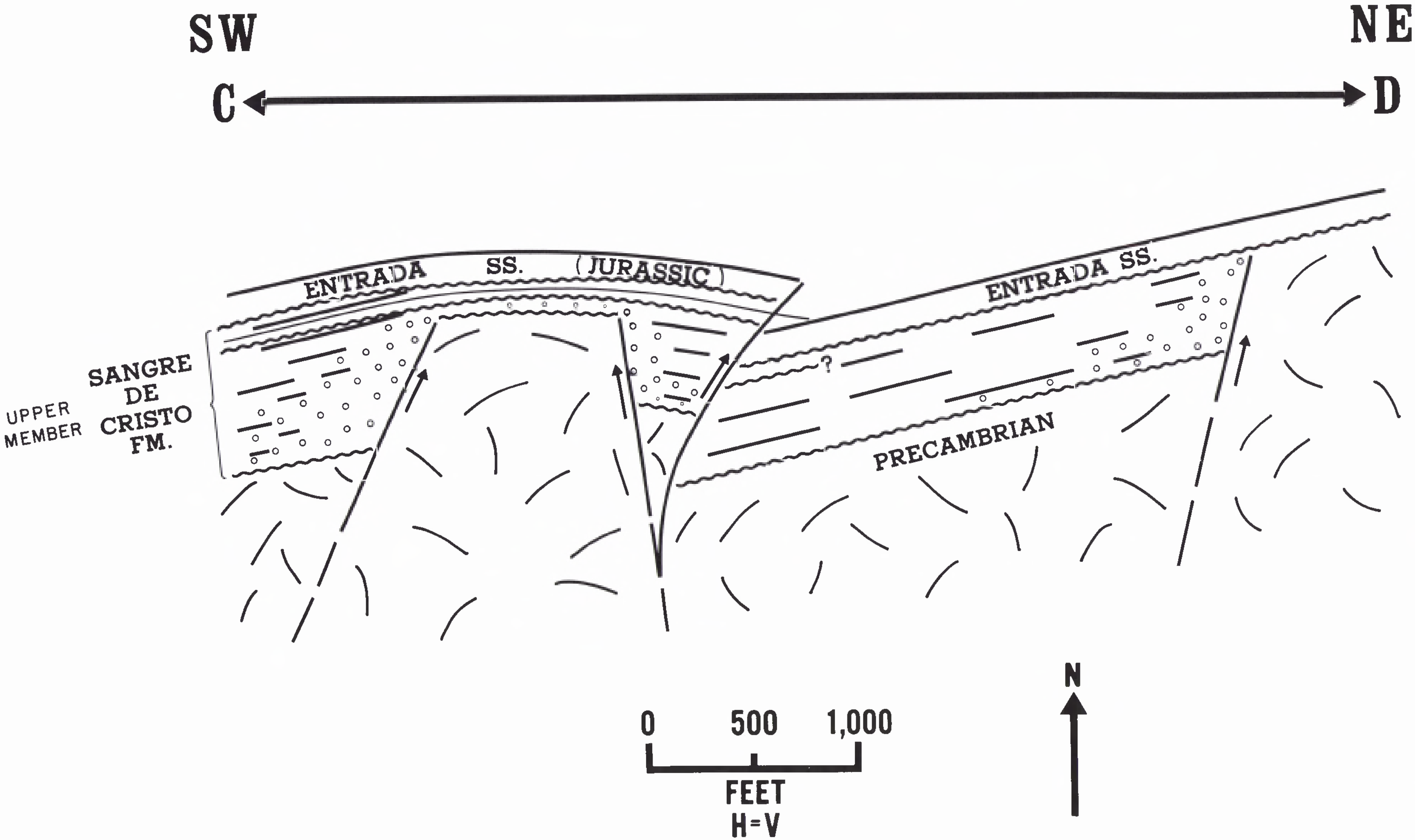

FIGURE 17.
Geologic cross section, Red Canyon, southern Wet Mountains, Colorado.

More than 5,000 feet of the Upper Member of the Sangre de Cristo Formation onlap the unconformity in the Arkansas River Valley area. The amount of truncation of underlying strata, the angular discordance at the unconformity and the onlapping relationships increase as the Pleasant Valley fault is approached. Thus, the unconformity between the Upper and Lower Members of the Sangre de Cristo Formation in the Arkansas River Valley area is related to Permian structural movements on the Pleasant Valley fault. The section is not complete, but Bolyard (1959) has estimated the Crestone Conglomerate to be 6,000 feet thick in the Crestone Peak area.

Member Boundaries—The Upper Member of the Sangre de Cristo Formation generally lies unconformably on the Lower Member. However, in the Medano Creek area (see plate 1, back pocket) and at the southern end of the Wet Mountains (figs. 16 and 17) it overlaps the Lower Member and rests unconformably on Precambrian rocks. The contact of the Upper Member of the Sangre de Cristo Formation with the overlying Jurassic Entrada Sandstone is unconformable.

Depositional Environment—Continental, primarily fluvial, deposits comprise the bulk of the Upper Member. The great thickness, extreme coarseness, poor sorting, poor bedding and interbeds of thin sandstone and siltstone suggest a sequence of coalescing alluvial fans formed at the base of a rising highland. South of Music Mountain near Medano Pass (see plate 1, back pocket) the Crestone Conglomerate lies directly on Precambrian rocks suggesting that some of the faults in this area were active well into Permian time. The facies change, north and south of the Crestone area, to finer-grained conglomerates and sandstones (fig. 18) suggests that these areas were farther from the source area and that there was a decrease in stream gradient, with stream-transport directions of the uplift block in the Crestone area to the north and south.

The pronounced angular unconformity between the Upper and Lower Members, the increased grain size of the detritus in the Upper Member, the onlapping relationships of the beds of the Upper Member onto the uplift block, and the discordance of structures beneath and above the unconformity indicate that the Pleasant Valley fault was active during the Permian and significantly influenced sedimentation. Doubtlessly detritus was shed from the up-

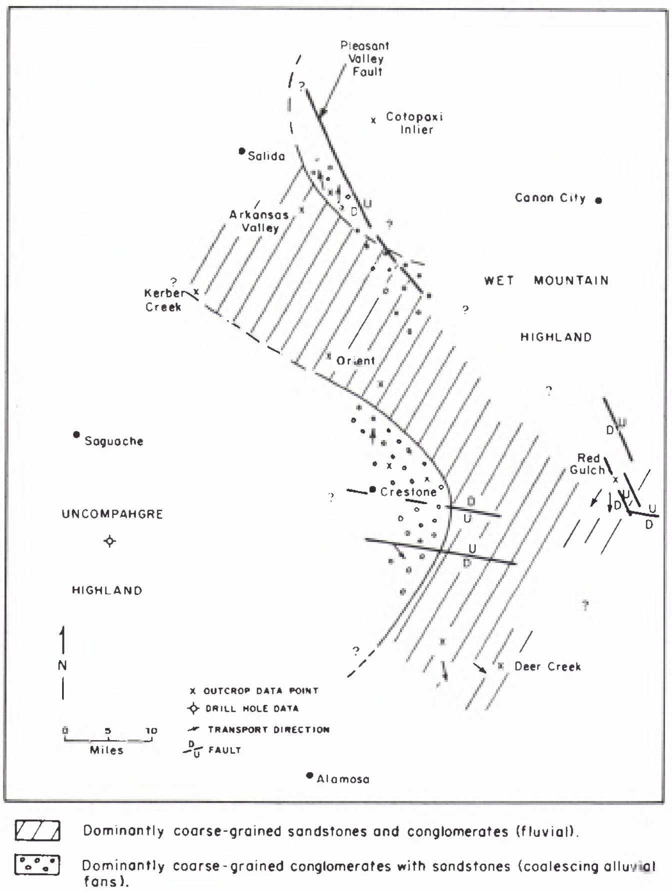

FIGURE 18.

Lithofacies map of the Upper Member, Sangre de Cristo Formation, south-central Colorado.

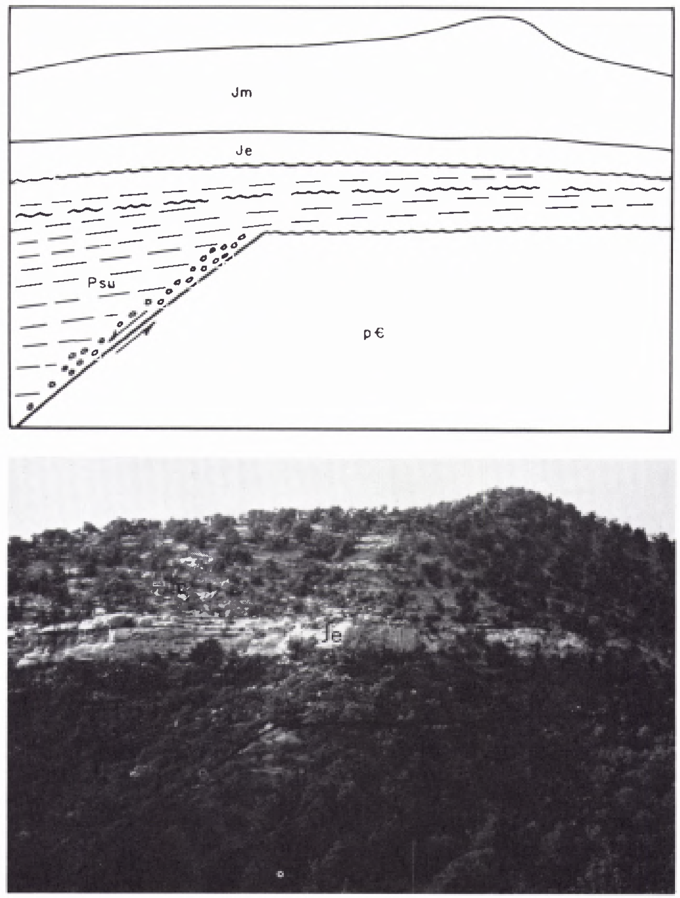

FIGURE 19.

Permian fault contact between Permian sedimentary rocks (P_{su}) and Precambrian crystalline rocks (P€). Photograph looking toward the north wall of Red Canyon located at the southern end of the Wet Mountains in sec. 7, T. 26 S., R. 68 W. The Entrada (Je) and Morrison (Jm) formations overlie the Permian strata.

lift block into the asymmetric basin, the axis of which developed close to the downdropped west side of the fault.

Field studies along the southern end of the Wet Mountains indicate Permian fault relationships between Permian sedimentary rocks and Precambrian crystalline rocks (figs. 16 and 17). Figure 19 is a photograph and field sketch of one such outcrop in Red Canyon in Sec. 7, T. 26 S., R. 68 W. (fig. 17) which illustrates the following observed relationships:

1. Bedding trends into and is truncated at or near the contact between the Upper Member of the Sangre de Cristo Formation and Precambrian rocks.
2. The Permian rocks are unbedded near the contact.
3. For a distance of 5 to 20 feet from the contact the Permian rocks are conglomeritic and very poorly sorted.
4. The Permian rocks decrease in grain size away from the contact.
5. The uppermost Permian sedimentary rock beds of the Upper Member of the Sangre de Cristo Formation overlap the fault and are folded slightly with the fold axis positioned directly over the fault.
6. An angular unconformity is present within the upper part of the Upper Member of the Sangre de Cristo Formation.

The above evidence indicates that a Permian normal fault was active during the deposition of the beds of the Upper Member of the Sangre de Cristo Formation. At least several hundred feet of relief resulted from the faulting. Near the end of Permian deposition, the fault became inactive and was then overlapped by the upper beds. Later, slight reactivation of the fault caused minor folding or draping of the overlapping sediments, without rupture. Similar fault relationships were observed in Secs. 6, 21, and 28, T. 26 S., R. 68 W. (see fig. 16). At these locations the Permian rocks end abruptly at the fault contacts with Precambrian rocks but the faults are overlapped by the Jurassic Entrada Formation. On the downthrown block the Entrada lies unconformably above the Permian strata, while on the upthrown block it rests unconformably on Precambrian rocks. Thus, several east-west and north-northwest-trending faults at the south end of the Wet Mountains suffered recurrent displacements during the deposition of the Upper Member of the Sangre de Cristo Formation. Detritus was shed from the uplift blocks to the south and southwest (figs. 16, 17, and 18).

AGE

Due to the lack of marine fossils, the age of the Sangre de Cristo Formation is uncertain. Brill (1952) suggested two possibilities: (1) the Lower Member of the Sangre de Cristo Formation in southern Colorado is the nonmarine equivalent of the Upper Pennsylvanian marine rocks found in New Mexico, or; (2) Wolfcampian erosion truncated Upper Pennsylvanian strata and, therefore, they wedge out in northern New Mexico. Scott (1967) identified *Bisaccate gymnospermous* pollen, collected from beds the authors have interpreted as being the lower part of the Lower Member (SE¼ SE¼, Sec. 18, T. 48 N., R. 11 E.), and suggested a Permian age. White (1912) collected the following fossils, near the south portal of the Denver and Rio Grande Tunnel (Sec. 28, T. 49 N., R. 10 E.) from strata believed to be approximately 1,300 feet above the base of the lower member:

**Callipteris* sp.
**Psygmophyllum* cf. *cuneifolium*
Odontopteris subcrenulata Rost?
Macrostachya? sp.
**Sigillariostrobus nastatus*
Walchia cf. *piniformis*
Walchia cf. *imbricata*
Rhabdocarpos dyadicus Geinitz?

White believed those with the asterisk to be definitely Permian. *Calamities* sp. are common throughout the Upper Member. On the basis of the above fossil data, the authors tentatively conclude that Missourian and Virgilian probably are not present in the northern Sangre de Cristo Range. Vaughn (1969, p. 26), however, on the basis of preliminary studies of vertebrate fossils (diadectes) he collected from Brill's measured inverval 300 (Lower Member), believes that they are actually Upper Pennsylvanian *Desmatodon* remains.

PENNSYLVANIAN AND PERMIAN HISTORY

Prior to deposition in the Morrowan, portions of south-central Colorado were uplifted to cause erosion of the widespread marine rocks that had been deposited earlier in the Paleozoic. Thus an east-west trending structural element became active south of Crestone, causing erosion of the Middle and Lower Paleozoic rocks (fig. 4). Similarly a north-south structural element developed to the east of the Arkansas River Valley section in the Late Mississippian and early in the Pennsylvanian.

Subsequent to and possibly during the erosion of the Lower and Middle Paleozoic rocks from the adjacent highland areas, the marine shales and limestones of the Beldon Formation were deposited to the north while the quartzose sandstones, shales, and coal beds of the Kerber Formation accumulated to the south in nonmarine coastal-plain and low-lying swamp and mudflat environments in the incipient Central Colorado trough (fig. 7). The sea invaded further into the trough from the north as the Morrowan progressed, as evinced by the fossilferous marine limestones in the upper part of the Kerber. The facies relations and isopach data of the Kerber beds indicate that the adjacent highland areas shed sediment into the narrow subsiding, north-northwest-trending trough.

Block faulting at the basin margins during the Atokon probably produced the changes in climatic conditions and depth of erosion which resulted in the deposition of the red, hematite-stained, arkosic sandstones, siltstones, and shales of the Sharpsdale Formation. This block faulting probably created the topographic relief and stream gradients which caused coarse-grained sediments to be deposited in the Cotopaxi inlier and Deer Creek areas. Recurrent movements along these same faults could have produced the erosional unconformity at the top of the Sharpsdale locally in south-central Colorado (figs. 5, 6, and 8). The facies patterns and the presence of marine limestones within the Sharpsdale indicate that the structural activity was sporadic and recurrent during the deposition of the Sharpsdale. The uplift block between Crestone and Huerfano Park may have acted as a barrier to marine transgression during the times of invasion of marine waters into the trough from the north and south.

The Sharpsdale was deposited dominantly on alluvial fans and alluvial plains adjacent to actively rising uplift blocks in an arid climate. Marine transgressions occurred occasionally during this Atokan deposition.

A thick sequence of greenish-gray sandstones, siltstones, and black shales, with an upper zone of limestones and marine shales, accumulated in the Central Colorado trough during the Desmoinesian and comprise the Madera Formation. The distinct color-changes from the redbeds of the Sharpsdale to the green, gray, and black beds of Madera suggests that the Madera accumulated on low-lying coastal plains and mudflats and/or conditions where the groundwater table was shallow.

The facies patterns abrupt thickness variations, and current transport directions in the Madera indicate that the basin configuration was markedly different during Madera deposition (figs. 5, 6, and 9). The northwest-trending block uplift between Crestone and Huerfano Park shed coarse-grained detritus to the north and south. The coarser grained beds of the Cotopaxi inlier probably were shed northward from the Wet Mountain Highland. The abrupt thickness variations indicate onlap of the Madera onto the upthrown side of the fault blocks, as shown on figs. 5 and 6.

Environmental conditions varied throughout the deposition of the Madera from marine to coastal mudflat and deltaic conditions. The limestone beds of the upper Whiskey Creek Pass Limestone Member connote occasional widespread marine inundation of the Central Colorado trough.

The apparent absence of Missourian and Virgilian strata in the Central Colorado trough suggests that erosion occurred subsequent to Madera deposition and prior to deposition of the Sangre de Cristo beds in the Permian.

Red arkosic sandstones, conglomerates, siltstones and mudstones of the Lower Member of the Sangre de Cristo Formation were deposited in the Permian on an aggrading alluvial plain under predominantly fluvial conditions. Abundant cycles of grain-size variations (fig. 12) suggest recurrent structural activity. The lithofacies map (fig. 13) indicates that the detritus was probably dominantly shed from the eastward projection of the Uncompahgre Highland.

Subsequent to the deposition of the Lower Member of the Sangre de Cristo Formation in the Permian, major tectonic activity occurred throughout south-central Colorado, in many cases along faults which were also active later in the Laramide. In the Arkansas River Valley area, the Pleasant Valley fault suffered more than 11,000 feet of Permian displacement and the nearby Pennsylvanian and Permian rocks were complexly folded as well (see figs. 14 and 15). A major uplift block in the Medano Creek area caused the beds of the Upper Member of the Sangre de Cristo Formation to be very coarsely conglomeratic (fig. 18) and to lap onto Precambrian rocks (see plate 1, back pocket). Several east-west and north-northwest-trending faults at the south end of the Wet Mountains suffered recurrent displacements during the deposition of the Upper Member of the Sangre de Cristo Formation (and later in the Laramide) and detritus was shed off these uplift blocks to the southwest (see figs. 16, 17 and 18). Thus, angular discordance at the base of the Upper Member and coarse-grained facies lapping onto the unconformity at several localities indicate that the Permian tectonic activity along east-west and north-northwest-trending structures significantly affected sedimentation patterns.

The coarse-grained redbeds of the Upper Member and its Crestone Conglomerate facies of the Sangre de Cristo were shed from the uplift blocks onto alluvial fans and plains in the block-fault basins. The basins filled with detritus so that the deposits encroached upon the adjacent uplift areas, onlapping them and reducing the topographic relief of the terrain in the Permian.

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