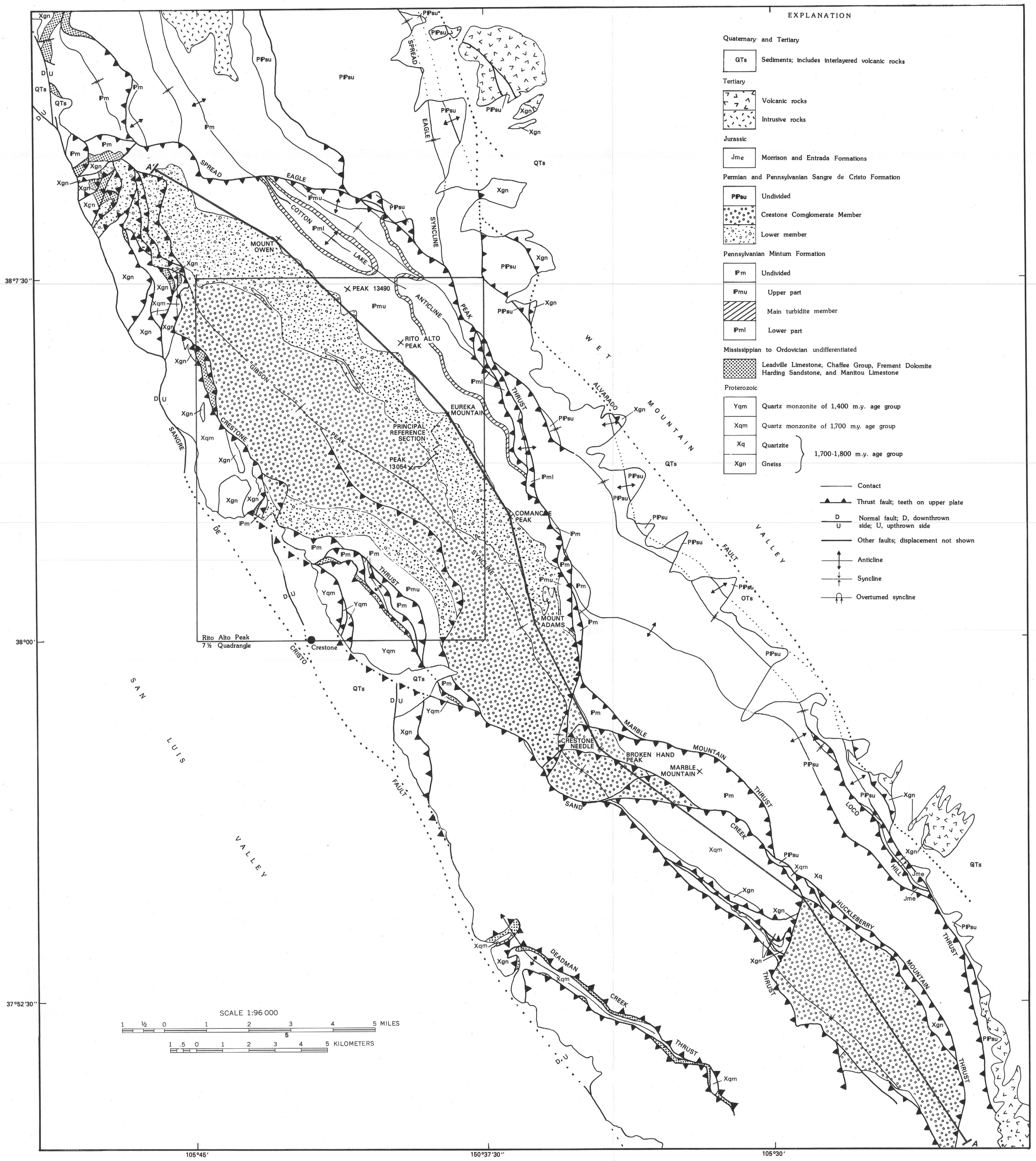

Figure 1.--Geologic map showing part of the northern Sangre de Cristo Range, and the location of the principal reference section, south-central Colorado (from Lindsey and others, 1983).

PRINCIPAL REFERENCE SECTION FOR THE SANGRE DE CRISTO FORMATION (PENNSYLVANIAN AND PERMIAN), NORTHERN SANGRE DE CRISTO RANGE, SAGUACHE COUNTY, COLORADO

By

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INTRODUCTION

The name "Sangre de Cristo Formation" has been applied to red beds of Pennsylvanian and Permian age in the Sangre de Cristo Range since 1899 (Hills, 1899; 1900), but use and definition of the name has varied because no type section has been designated and described. Bolyard (1959) designated a "type locality" in the range east of the village of Crestone (fig. 1), but described the formation only in general terms. This report presents a detailed measured section within Bolyard's (1959) type locality of the Sangre de Cristo Formation and its Crestone Conglomerate Member, and designates this section as the principal reference section of the Sangre de Cristo Formation. The principal reference section is in a region of abrupt facies changes and therefore should be used in conjunction with other sections, such as those to the north and south described by Brill (1952). The Crestone Conglomerate Member is adopted in this report.

The principal reference section was measured by tape and compass in the summers of 1979 and 1980; observations were recorded on a micro-cassette tape recorder in the field and transcribed in the office. This method permitted rapid acquisition of data on thickness, nature of contacts, color, grain size, and sedimentary features; for each described rock unit, these data are shown on the graphic section. Rock units having common attributes or a readily identified sequence of attributes that define depositional cycles are grouped together for description and for interpretation of their genetic significance.

C. A. Brannon and R. F. Clark assisted in the field in 1979 and 1980, respectively; S. J. Soulliere assisted in compilation.

LOCATION AND GEOLOGIC SETTING

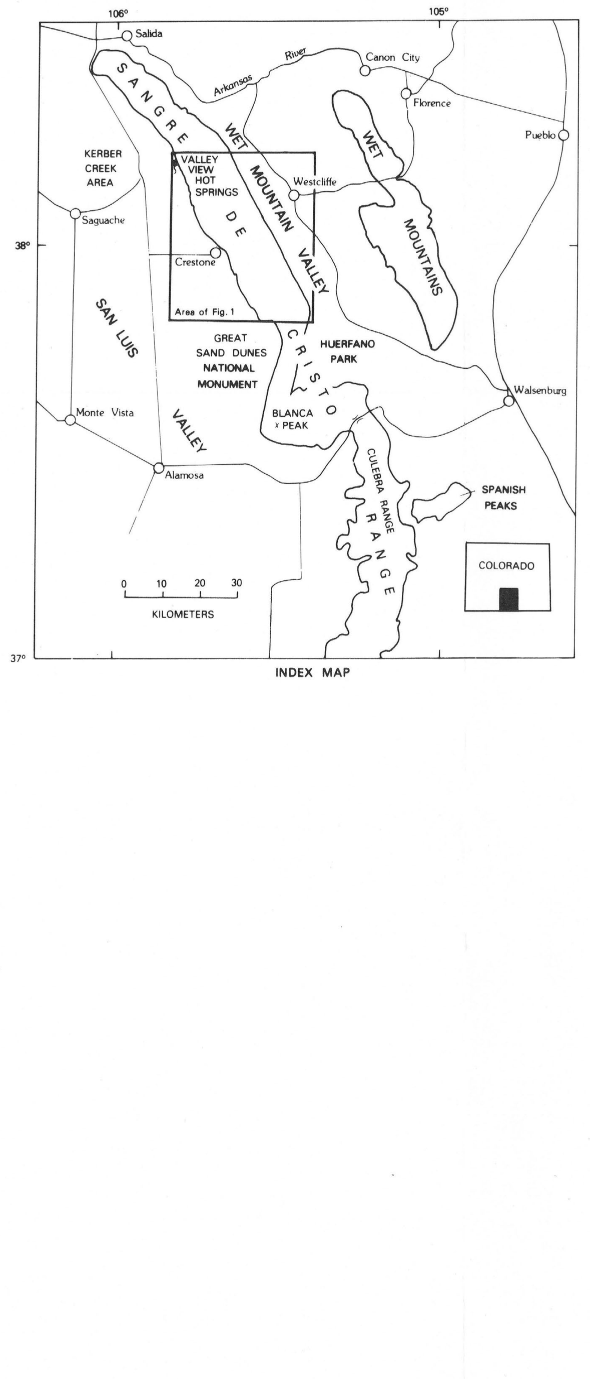
The principal reference section is located west of the crest of the Sangre de Cristo Range in the Rito Alto Peak 7 1/2′ quadrangle, Saguache County, south-central Colorado (fig. 1). The section extends from the base of the Sangre de Cristo Formation, where it overlies the Middle Pennsylvanian Minturn Formation at the summit of Eureka Mountain, southwest to the summit of peak 13054 (fig. 2). A continuous, almost totally exposed section was obtained by offsetting south at the Rito Alto trail and on the high ridge overlooking Groundhog Basin to the west. The error in thickness, introduced mainly by the uncertainity of tracing bedding along the two offsets, is estimated at 30 m or less. The top of the Sangre de Cristo Formation is not exposed, so the section was terminated at the end of good exposures on peak 13054. An additional 120 m of poorly exposed conglomerate and sandstone, located above the described section but not studied, is southwest of peak 13054, toward the axis of the Gibson Peak syncline. No major faults cut the section, and the west-dipping (40-50^{o}) beds provide excellent exposures on ridges and east-facing slopes.

The section is located in the Spread Eagle Peak thrust plate, one of the largest thrust plates identified in the northern Sangre de Cristo Range (fig. 1) (Lindsey and others, 1983). The upper Paleozoic strata of individual thrust plates share general stratigraphic similarities but contain distinctive features peculiar to each plate. The Sangre de Cristo Formation of the Spread Eagle Peak plate is composed of two members: an unnamed lower member of sandstone and an upper member of conglomerate (Crestone Conglomerate Member). The lower member disappears to the south and west, where the Crestone Conglomerate Member rests directly on older rocks. In the Marble Mountain and Huckleberry Mountain thrust plates, the Sangre de Cristo Formation is composed entirely of the Crestone Conglomerate Member (fig. 1). The Crestone Conglomerate Member thins as it intertongues with the lower member of sandstone in the northern part of the Spread Eagle Peak plate. The Sangre de Cristo Formation of the autochthonous terrane east of the Spread Eagle Peak thrust is composed entirely of sandstone.

PREVIOUS WORK

The names "Sangre de Cristo conglomerate" and "Sangre de Cristo formation" were first applied by Hills (1899; 1900) to the entire section of coarse clastic rocks of Upper Carboniferous (sic) age in the Sangre de Cristo Range and vicinity, replacing Endlich's (1874, p. 326-329) name "Arkansas sandstone," which had fallen into disuse (Burbank and Goddard, 1937, p. 939-940). Melton (1925, p. 811-812) divided the formation into the "Upper Sangre de Cristo conglomerate," consisting of 5,500 ft (1,676 m) of coarse red conglomerate, and the "Lower Sangre de Cristo conglomerate," consisting of 7,500 ft (2,286 m) of conglomerate and arkose which are finer grained and darker than those in the upper part. Melton (1925, p. 812) recognized an extremely coarse local facies of the "Upper Sangre de Cristo conglomerate," which he named the "Crestone conglomerate phase". Some of these early descriptions are difficult to reconcile with later subdivision of the section, probably in part because the faulted structure of the range was not recognized until the work of Johnson (1929, p. 12-13). He (1929, p. 5-6) used the name "Sangre de Cristo formation" in its presently accepted form, but assigned most of the section to the upper part of the Sangre de Cristo Formation.

The basis for the presently accepted division of the section into the Pennsylvanian Minturn Formation (equivalent to the Pennsylvanian Madera Formation along the east side of the Sangre de Cristo Range from Crestone Needle southward, according to Bolyard (1959)) and the Pennsylvanian and Permian Sangre de Cristo Formation is the work of Brill (1952), who studied and correlated upper Paleozoic strata throughout central and southern Colorado. He measured and described in detail sections on the Arkansas River Valley and at Whiskey Creek Pass, north and south of the principal reference section of the Sangre de Cristo Formation. Bolyard (1959) followed Brill's (1952) terminology and studied stratigraphic relationships in the Sangre de Cristo Range between Brill's sections; Bolyard (1959, p. 1923) designated a "type locality" east of the village of Crestone, between Crestone Needle and Eureka Mountain, and gave member status to Melton's (1925) "Crestone conglomerate phase."



THICKNESS AND DEFINITION OF CONTACTS

The principal reference section is about 1,740 m thick, including approximately 120 m of undescribed strata at the top. It rests conformably upon the Minturn Formation and has an eroded top in the Gibson Peak syncline. The members designated by Bolyard (1959) are recognized here: the lower member (unnamed), 607 m thick, and the Crestone Conglomerate Member, 1,132 m thick. The lower member consists of interbedded red to maroon conglomerate, sandstone, siltstone, and minor shale and limestone, arranged in fining-upward cycles. The Crestone Conglomerate Member consists mostly of coarse-grained red conglomerate and sandstone; it occurs in the Spread Eagle Peak thrust plate, the Marble Mountain thrust plate, the Huckleberry Mountain thrust plate, and as remnants overlying Precambrian rocks in thrust plates to the west of these (fig. 1). The Sangre de Cristo Formation east of the Spread Eagle Peak thrust (fig. 1) consists entirely of red sandstone, siltstone, and minor conglomerate, shale, and limestone; it has not been divided into members there, but is considered to be the facies equivalent of the lower member.

The stratigraphic relationships between the two members of the Sangre de Cristo Formation and the Minturn Formation have been established by detailed (1:24,000 scale) field mapping and are shown schematically in figure 3. The lower member interfingers with and passes abruptly into the Crestone Conglomerate Member at Mt. Adams, 8 km southeast of the principal reference section. The Crestone Conglomerate Member thins abruptly as it interfingers with the lower member northwest of Mt. Owen, 9 km northwest of the principal reference section. A subtle angular discordance between the two members, observed by Peel (DeVoto and Peel, 1972, p. 306) on aerial photographs of Groundhog Basin and areas to the north, is not an erosional unconformity but probably a reflection of the northerly rise of the level at which conglomerate interfingers with the lower member. The base of the Crestone Conglomerate Member is defined as the lowest level of numerous thick conglomerate beds. Placing the contact at the lowest level where 50 percent of the strata are composed of conglomerate (Munger, 1959, p. 42) yields about the same mappable contact. Any definition is somewhat arbitrary because of the interfingering nature of the contact.

The Sangre de Cristo Formation conformably overlies the Minturn Formation at the principal reference section (fig. 3). The base of the Sangre de Cristo Formation is placed at the bottom of the first cycle of red to maroon conglomerate, sandstone, siltstone, and shale that overlies interbedded gray and red sandstone, siltstone, shale, and limestone containing scattered marine fossils. At the principal reference section and nearby, the upper part of the Minturn is composed of an easily recognized interval of beds that consists of 1-2 m of silty marine limestone (unit 2, designated the "marker limestone") overlain by 42-76 m of gray to pink crossbedded sandstone and siltstone (unit 3). The lower part of the marker limestone is generally dark gray, silty, carbonaceous, pyritic, and anomalously radioactive; the upper part is medium gray and contains stromatolites, brachiopods, crinoid columnals, and other marine fossils. The sandstone beds of unit 3 are conglomeratic and contain distinctive, large (to 1 m) festoon to planar crossbeds and lenses of dark-gray radioactive siltstone containing plant debris and marine fossils. These marker beds have been traced along strike 9 km northwest almost to Mt. Owen and 5 km southeast to Comanche Peak (fig. 3); their consistency in thickness and distance below the cycles of red conglomerate, sandstone, siltstone, and shale of the lower member of the Sangre de Cristo Formation is good evidence that the base of the formation is conformable with the Minturn Formation.

The nature of the base of the Sangre de Cristo Formation changes along strike from the principal reference section (fig. 3). South of Mt. Adams, in the Marble Mountain thrust plate, the Crestone Conglomerate Member lies unconformably on the Minturn Formation, and the contact bevels about 120 m of Minturn strata from the north side of Crestone Needle southeast to the head of Sand Creek (a distance of 4,000 m), where all strata of Paleozoic age are truncated by a major fault. The unconformity is clearly visible in cliffs on the east side of Broken Hand Peak, where the amount of beveling was estimated by measuring the thickness of conglomerate below a distinctive marker bed of diamictite, shown in figure 3. West of Mt. Owen, 9 km northwest of the principal reference section, the lower part of the Sangre de Cristo Formation conformably overlies marine strata of the Minturn Formation.

Other features may serve as useful guides to the location of the base of the Sangre de Cristo Formation but do not have general application in view of the complexities described here. Color (Bolyard, 1959, p. 1923; DeVoto and Peel, 1972, p. 284, 306) is a useful guide at the principal reference section inasmuch as the contact is marked by an abrupt change from interbedded gray and red strata of the Minturn Formation to red strata of the Sangre de Cristo Formation. The usefulness of red color as a guide to the base of the Sangre de Cristo Formation is limited, however, by its obvious diagenetic origin. Intervals of red strata occur within the Minturn Formation at Eureka Mountain; north of the principal reference section, the main color boundary varies with respect to the position of limestones (Nolting, 1970, p. 48); such relationships are expected inasmuch as the red color is of diagenetic origin.

Previously, the base of the Sangre de Cristo Formation had been placed at the top of the highest fossiliferous marine limestone (Scott and Taylor, 1974). This placement is unsatisfactory because lenticular beds of marine limestone occur in the upper parts of fining-upward clastic cycles at various stratigraphic levels in the lower part of the Sangre de Cristo Formation, both north and south of the principal reference section; such lenticular beds of marine limestone are common in the lower member west of peak 13490 and Mt. Owen. If the base was picked at the highest marine limestone, the lenticular and sporadic nature of the limestone beds would result in a contact that varied in stratigraphic position by hundreds of meters. In this study a single marker bed of fossiliferous marine limestone in the upper part of the Minturn Formation was traced in the field; it serves as a reference horizon located just below the base of the Sangre de Cristo Formation.

AGE

Previously, ages have been assigned to the Sangre de Cristo Formation from fossils collected at both ends of the Sangre de Cristo Range. In the Arkansas River Valley at the north end of the range, a vertebrate fauna from the lower part of the Sangre de Cristo Formation has been interpreted as Missourian (Late Pennsylvanian) in age (Vaughn, 1972). In the southern part of the Sangre de Cristo Mountains of New Mexico, the Sangre de Cristo Formation overlies strata of Wolfcampian (Early Permian) age as determined from fusulinids (Baltz and O'Neill, 1980).

There is new evidence that the age of the lower member of the Sangre de Cristo Formation at the principal reference section is at least in part Middle Pennsylvanian. Limestones in the lower 300 m of the lower member west of Mt. Owen, north of the principal reference section, contain conodonts of Atokan or Desmoinesian (Middle Pennsylvanian) age (B. R. Wardlaw, written commun., 1982); fossils of marine invertebrates from these limestones were previously assigned a Desmoinesian age (Nolting, 1970, p. 33) but their stratigraphic position in the Sangre de Cristo Formation was not recognized. The uppermost limestone beds of the Minturn Formation on the east spurs of Comanche Peak and Mt. Adams contain fusulinids of Beedeina sp. of Desmoinesian age (R. C. Douglass, written communication, 1981); these strata are conformable with those of the overlying principal reference section of the Sangre de Cristo Formation.

Considering the conformable nature of the Minturn-Sangre de Cristo contact and the intertonguing relationship between the lower member and the Crestone Conglomerate Member at the principal reference section, a case can be made for rapid deposition of the entire Sangre de Cristo Formation during Middle Pennsylvanian time. The range in age of the principal reference section is limited also by removal of the top of the Sangre de Cristo Formation by erosion. Evidence for a Wolfcampian (Early Permian) age for the formation is from distant localities in New Mexico (Baltz and O'Neill, 1980); correlation of these localities with the reference section cannot be made with available data. In conclusion, the age of the lower part of the Sangre de Cristo Formation at the principal reference section is considered to be Desmoinesian (Middle Pennsylvanian), but the age of the upper part of the formation may range from Desmoinesian to as young as Wolfcampian (Early Permian).

LOWER MEMBER

The principal reference section of the lower member of the Sangre de Cristo Formation consists mostly of cycles, 2-37 m thick, of red conglomerate, sandstone, siltstone, and minor shale. These cycles were called "piedmont cyclothems" by Brill (1952, p. 821) and Bolyard (1959, p. 1925); they closely resemble the cycles in vertical-profile models of braided-stream deposits (Miall, 1978). Conglomerate and conglomeratic sandstone typically fill small channels and scours at the base of the cycles and pass gradually upward into sandstone and siltstone of decreasing bed thickness. Sandstone ranges from crossbedded (both trough and tabular types) to horizontally laminated; crossbedding inclined at very low (<5^{o}) angles to bedding is common in the upper part of the lower member. Thin-bedded sandstone and siltstone commonly contain ripple cross-lamination and current ripple marks. Mudcracks are rare, but red shale chips are present locally. The uppermost shaley part of a thin cycle in unit 5 contains calcareous nodules interpreted as paleocaliche. Fragmentary plant fossils are rare; no other fossils were observed in the principal reference section, but fossils of marine invertebrates occur in lenticular limestone beds north of the section. Where present, these limestones are near the tops of cycles.

The upper 185 m of the lower member contains coarse conglomerate beds, 0.3-3 m thick, interbedded with the strata of the red clastic cycles. These conglomerates are disorganized clast- and matrix-supported units interpreted as debris-flow and mudflow deposits, respectively. They contain clasts of igneous and metamorphic rocks as large as boulders. Some of the debris-flow conglomerates occur at the base of fining-upward cycles; they generally have sharp and in some cases, eroded bases. Some of the conglomerates are compound in nature, being composed of two or more beds deposited by debris flows and mudflows (units 34 and 42).

CRESTONE CONGLOMERATE MEMBER

The Crestone Conglomerate Member is composed of coarse conglomerate, conglomeratic sandstone, sandstone, and minor siltstone and shale. The conglomerate beds, deposited mostly by debris flows according to the criteria of Middleton and Hampton (1975, p. 209-212), range to 55 m in thickness and consist of unsorted, chaotically-packed, angular to subround clasts ranging up to boulder size. Clasts are mostly distinctive red syenite and pink-to-red porphyritic felsite, granite, and gneiss of various types, gray quartzite, and minor amounts of other igneous and metamorphic rocks. The thickest beds of debris-flow conglomerate are sheet-like bodies that extend more than a kilometer along strike. They generally have sharp contacts; a few have eroded basal contacts. As seen from the ridge ascending peak 13054, one debris-flow conglomerate (unit 96) fills a broad channel tens of meters thick and hundreds of meters wide in the cirque headwall of Groundhog Basin. Most of the conglomerates are massive to faintly stratified and tend to become increasingly stratified and sorted toward the top; stratification is most commonly defined by thin (<0.3 m) sand lenses. Matrix-supported conglomerates as much as 10 m thick, interpreted as mudflow deposits, underlie and are interbedded with some debris-flow conglomerates.

Sequences of stratified conglomerate and sandstone as much as 50 m thick, interpreted as streamflow and sheetflow deposits, alternate with debris-flow conglomerates. The stratified rocks are typically horizontally laminated (lamination not shown on the section) and contain low-angle (<5^{o}) crossbedding; the laminae in these structures are defined by black sand composed of iron oxide minerals. Outsize clasts are common in horizontally stratified sandstone.

Fining-upward cycles of clastic rocks are not common in the Crestone Conglomerate Member because of the flood of conglomeratic debris, but they are prominent about 235 m stratigraphically below peak 13054. Units 91-94 comprise four fining-upward cycles having an aggregate thickness of about 40 m. They contain the sequence of grain sizes and sedimentary structures described as typical for the lower member and representative of deposition by braided streams. The upper part of the lowermost cycle contains a well-developed, zoned interval of calcareous beds interpreted as a paleocaliche horizon. The interval has zones from bottom to top of calcite-cemented sandstone, limestone nodules in siltstone, and laterally extensive thin (1-5 cm) lenses and beds of unfossiliferous silty limestone; such zoning has been cited as diagnostic of paleocaliche (Steel, 1974).

DEPOSITIONAL ENVIRONMENTS

The principal reference section of the Sangre de Cristo Formation contains a continuous sequence of coarse clastic red beds deposited on an alluvial fan that extended into the sea. From bottom to top, the sequence of environments and deposits is: (1) lower fan braided-stream deposits (lower member) and (2) upper fan debris-flow and braided-stream deposits (Crestone Conglomerate Member).

The lower member consists mainly of fining-upward cycles that closely resemble those of distal braided rivers (Rust, 1978, p. 617-619) and the Donjek braided-stream model (Miall, 1978), named for the middle reaches of the Donjek River in Yukon Territory, Canada, which contains well-developed cycles of mostly gravelly sediments. In the Sangre de Cristo Formation, strata in fining-upward cycles were deposited by braided streams on the lower part of an alluvial fan. The presence of marine strata below the lower member, and interbedded with the lower member along strike from the principal reference section, indicates that the braided streams flowed to the sea.

The lower member interfingers upward with the Crestone Conglomerate Member, which consists mostly of debris-flow and coarse alluvial sediments characteristic of alluvial fans (Bull, 1972). The many thick debris-flow conglomerate beds in the middle and upper parts of the Crestone were probably deposited in the upper part of the fan. The broad channel filled by debris flows in the upper part of the Crestone is evidence for dissection of the head of an alluvial fan. The upper part of the fan prograded over the braided-stream plain of the lower part of the fan.

Other features of the Sangre de Cristo Formation, although not diagnostic of alluvial-fan sedimentation, are compatible with that interpretation. Abundant horizontal lamination and stratification in conglomerate and conglomeratic sandstone of both members is in accord with the structure of these deposits in alluvial-fan deposits (Bull, 1972) and in small natural and man-made fans observed in a gravel pit (Rachocki, 1981 p. 29, 62, 106). Low-angle crossbedding has been reported from braided alluvial deposits (Miall, 1978) that might form on fans. Abundant black sand laminae in the Sangre de Cristo Formation are similar to those observed in flash-flood deposits in arid regions (Luchitta and Suneson, 1981). The occurrence of paleocaliche at a few diverse levels in the Sangre de Cristo Formation is in accord with a subaerial fan environment (Bull, 1972) and, together with the occurrence of abundant debris-flow deposits, suggests an arid climate (Steel, 1974).

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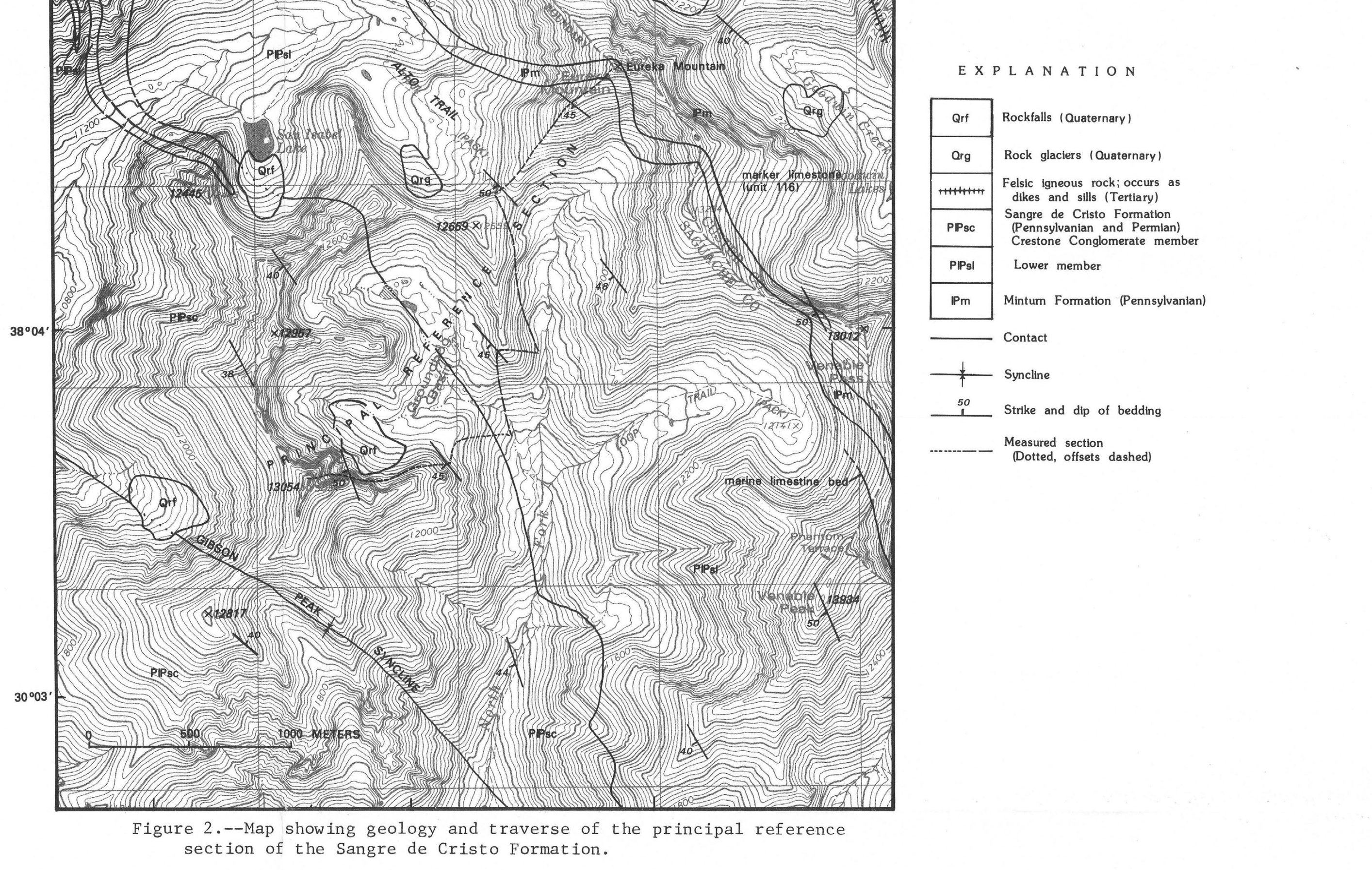

Figure 2.--Map showing geology and traverse of the principal reference section of the Sangre de Cristo Formation.

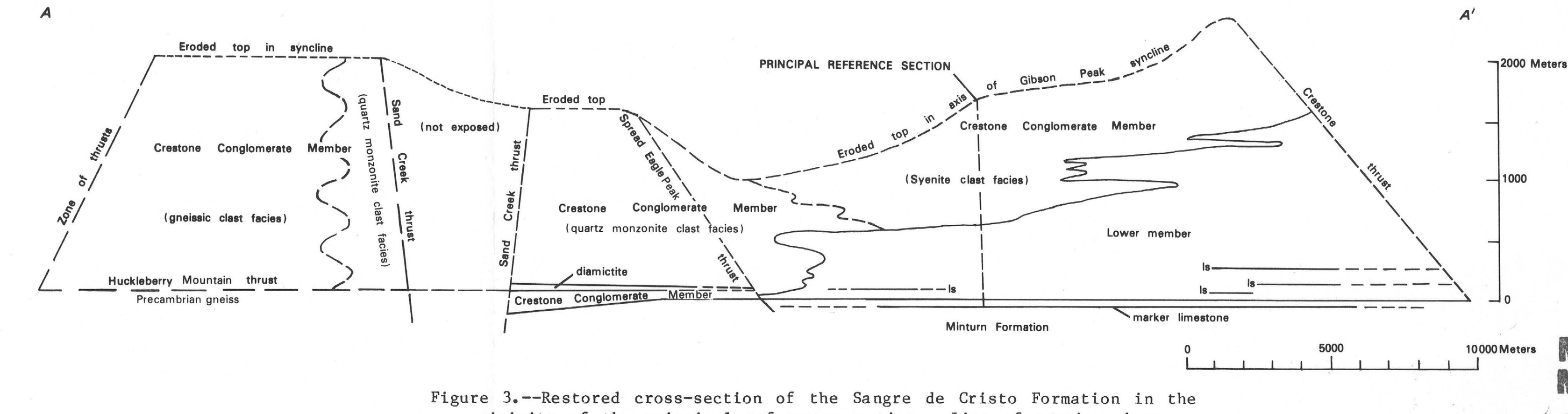

Figure 3.--Restored cross-section of the Sangre de Cristo Formation in the vicinity of the principal reference section. Line of section shown on Figure 1; drawn from southeast to northwest, as viewed from the east side of the Sangre de Cristo Range; relative easterly displacement of thrust plates not taken into account. ls = limestone.

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