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NOTES ON THE GEOLOGY OF THE SOUTHEASTERN SANGRE DE CRISTO MOUNTAINS, NEW MEXICO *

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INTRODUCTION

Physiography

The Sangre de Cristo Mountains of northeastern New Mexico and southeastern Colorado are a generally north-trending chain of structurally complex mountains between the Rio Grande Basin on the west, and the High Plains on the east. The southeastern spur of the mountains in western San Miguel and Mora Counties, New Mexico, is divided physiographically into two north-trending ranges separated by hilly uplands (Fig. 1). The southern part of the higher range at the west is known locally as Barillas Ridge. Farther north the highest part of this range is the Elk Mountain-Mora Range. An eastward salient of the range is Hermit's Peak, a well-known landmark of the region. The lower hills and hogback ridges along the east edge of the mountains are known locally as the Creston Range, or, more simply, the Crestons. The mountains north of Mora are the Rincon Range. The broad, rolling Las Vegas Plateau lies east of the Sangre de Cristo Mountains.

The Las Vegas Plateau ranges in altitude from 6,500 feet to more than 7,500 feet. The Creston Range attains an altitude of more than 8,000 feet in places. Barillas Ridge rises northward from about 7,000 feet to more than 11,000 feet at Elk Mountain. Northward the crest of the Mora Range is nearly 12,000 feet in altitude.

Previous work

The southernmost part of the Sangre de Cristo Mountains was mapped by Read and others (1944) as part of a regional map in north-central New Mexico. The hogback area of the Creston Range south of Sapello, and the plains to the east were mapped and described by Northrop and others (1946). The Ocate area was mapped and described by Bachman (1953). A general resume of some of the structural features of the southeastern part of the Sangre de Cristo Mountains was given by Baltz (1954).

STRATIGRAPHY

Precambrian rocks

Precambrian rocks are exposed on Barillas Ridge, along the scarp on the east side of the Elk Mountain-Mora Range, and on Hermit's Peak. Precambrian rocks underlie the broad valley north of Rociada and are well exposed south of Mora and in the eastern part of the Rincon Range. In the southern part of the Creston Range Precambrian rocks are exposed in small patches west of Kearny's Gap, and in Gallinas and Bonito Canyons and the area between these canyons.

The oldest Precambrian rocks are mainly metasediments but some metavolcanic rocks are present. These rocks may be grouped generally into three series. The oldest series is composed of schist, gneiss, and quartzite. Above this is a thick series composed dominantly of quartzite. At the top is another series of schist, gneiss, and quartzite. The thickness of these rocks is unknown but they may aggregate more than 10,000 feet.

The youngest Precambrian rocks are pink, medium- to coarse-grained granite intruded into the metasedimentary rocks. The granite occurs as sills, dikes, stock-like masses, and as alaskitic pegmatite bodies ranging in size from stringers less than one inch thick to dikes and sills several tens of feet thick. At most places the metasedimentary rocks contain conspicuous amounts of pegmatite. Large bodies of granite are exposed at places in the southern part of the Elk Mountain-Mora Range and in the canyon of the Gallinas River. At many places in this region the metasedimentary rocks have been intruded by granite in lit-par-lit fashion forming great thicknesses of migmatite. North of the latitude of Sapello no large bodies of granite are exposed although the metasedimentary rocks contain much pegmatite.

It is possible that the granitic rocks of the region are of more than one generation. Much of the granite is well foliated and this foliation follows the general trend of lineation in the metasedimentary rocks. However, some of the larger granite bodies and pegmatite show no evidence of foliation and are discordant with the metasediments and foliated granite.

Devonian (?), Mississippian, and Pennsylvanian rocks

The Pennsylvanian system is represented in part in the southeastern Sangre de Cristo Mountains by the Magdalena group. The Magdalena group in this region is composed of the Sandia formation overlain conformably by the Madera limestone. Rocks of the Sandia and

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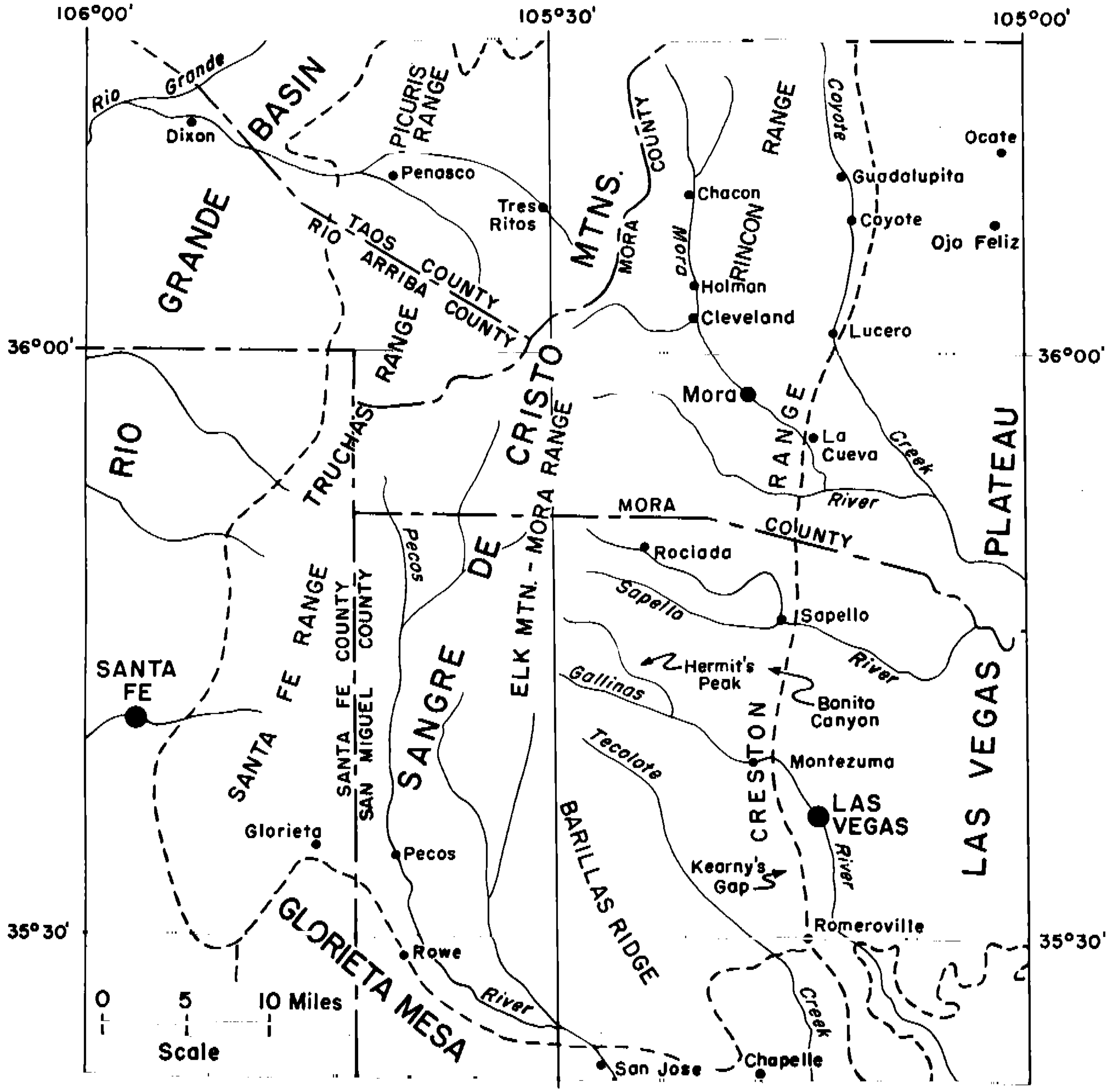


FIG. I. GEOGRAPHIC AND PHYSIOGRAPHIC FEATURES OF THE SOUTHERN SANGRE DE CRISTO MOUNTAINS, N.M.

Madera formations are at the surface in the Creston Range; in most of the mountainous upland between the Creston Range and the Elk Mountain-Mora Range; and on the west side of the Rincon Range.

Sediments of the Magdalena group were deposited in the Rowe-Mora basin, a Pennsylvanian and early Permian geosyncline that occupied the area which is now the central part of the Sangre de Cristo Mountains.

During much of the Pennsylvanian time the Pedernal uplift, a narrow highland, separated the Rowe-Mora basin from the subsidiary Las Vegas basin to the east. The Pedernal uplift occupied the position of the southern part of the present Creston Range but farther north the positive feature may lie to the east of the present mountain front. Relationships of Paleozoic rocks are shown diagramatically in Fig. 2.

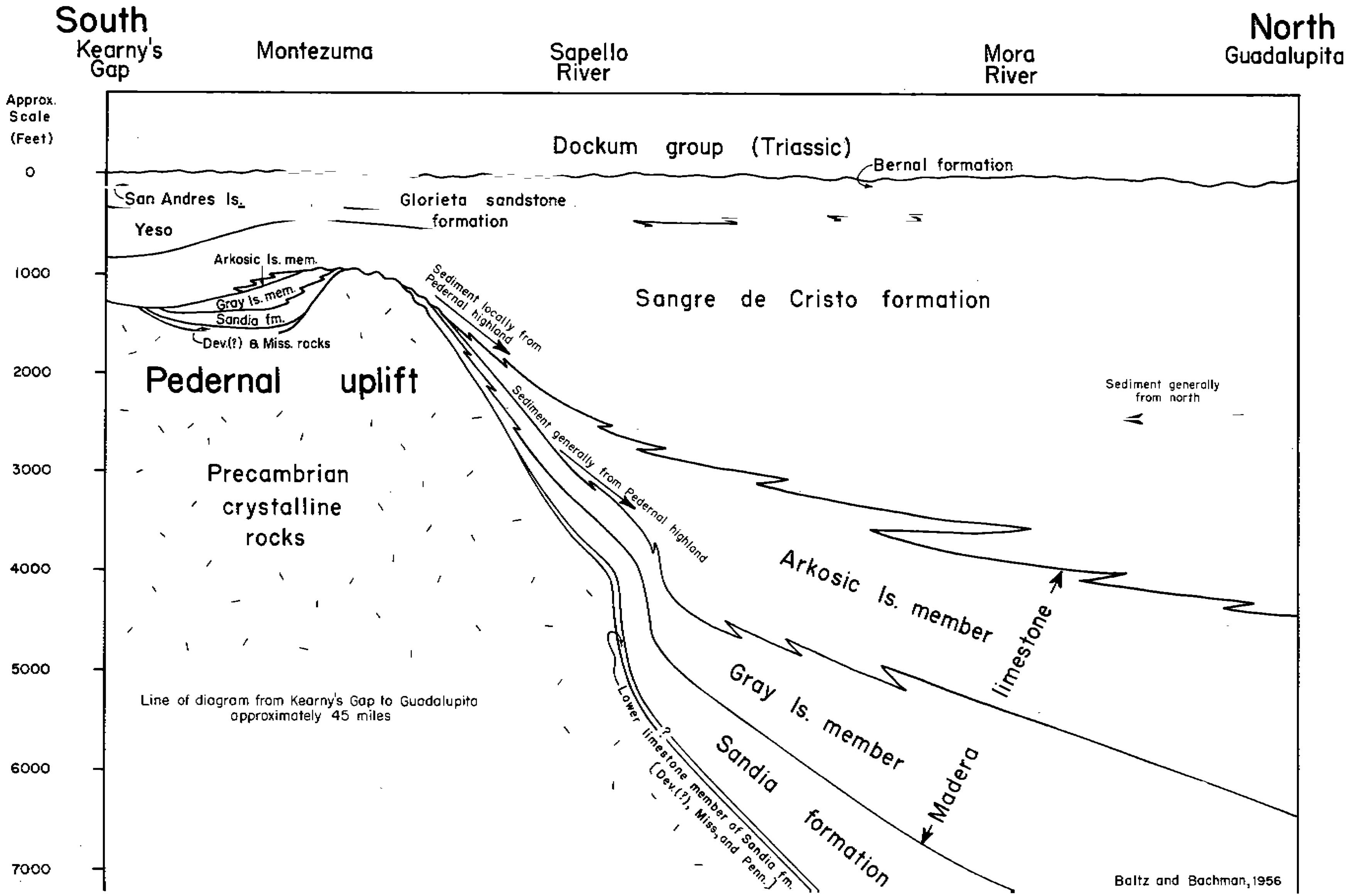


FIG. 2. RELATIONS OF PALEOZOIC ROCKS IN THE SOUTHEASTERN SANGRE DE CRISTO MOUNTAINS

Sandia formation – Precambrian rocks are overlain with unconformity by a thin but widespread and complex sequence of sandstone, limestone, and limestone breccia and conglomerate. These rocks have been mapped as the lower limestone member of the Sandia formation by Read and others (1944), and Northrop and others (1946). Recently Armstrong (1955) has removed the lower limestone member from the Sandia formation. This sequence is exposed along the crest of the Elk Mountain-Mora Range and in the lower mountains at the east foot of the range. It is also exposed at several places in the Creston Range, particularly in the lower part of the Gallinas River canyon west of Montezuma. Thickness ranges from 15 feet to more than 100 feet. In the southern Creston Range the sequence is absent at many places apparently due to Pennsylvanian erosion.

The lower limestone member of the Sandia formation has been considered by some authors to be of Mississippian age. Henbest (1946) correlated the member with the Leadville limestone of Colorado on the basis of a Mississippian species of foraminifera collected in the southern part of the mountains. Read and Wood (1947) also correlated the member with the Leadville on lithologic grounds. Armstrong (1955) has correlated the member with the Arroyo Penasco formation of Mississippian age of the Nacimiento Mountains of northwestern New Mexico. However, on the basis of lithology it is believed that the lower limestone member contains beds of Devonian(?) and Mississippian age.

The Sandia formation, exclusive of the lower member, is composed of thick beds of coarse-grained, conglomeratic sandstone, siltstone, carbonaceous shale, and some thin limestone. The lowest part of the unit commonly contains lenses of impure coal. The highest part of the unit is composed of black shale with thin interbeds of sandstone and marine limestone. Local intraformational unconformities and rapid facies changes are common in the southern part of the Creston Range. The upper part of the Sandia formation is unconformable on the lower limestone member, but is generally conformable with the overlying Madera limestone and intertongues with it near the Pedernal uplift.

The Sandia formation is thin, and at places absent in the southern part of the Creston Range. The formation thickens westward to more than 350 feet in the upper part of the Gallinas River. The formation thickens greatly to the north. More than 700 feet of Sandia rocks are exposed northwest of Sapello and the total thickness is greater inasmuch as the base is not exposed. The lower and upper parts of the unit have been cut out by thrusting at Mora River and to the north, thus the thickness is not known in the northern part of the Creston Range. Northwest of Mora, the Sandia formation may be more than 2,000 feet thick.

The Sandia formation was deposited in a mixed marine and nonmarine environment but is probably mainly marine in origin in this region. Locally, in the southeastern part of the mountains, the Pedernal uplift was the source of clastic sediments of the Sandia formation.

The Sandia formation, exclusive of the lower member, is considered to be Early Pennsylvanian (Morrow) in age (Read and Wood, 1947, p. 225).

Madera limestone – The Madera limestone is composed of two lithologically distinct units, a lower gray limestone member and an upper arkosic limestone member. The gray limestone member is composed of thin- to thick-bedded, crystalline and granular, fossiliferous limestone, and interbedded black shale, siltstone, and thin sandstone. In the southern part of the region the member is composed dominantly of limestone with shale and sandstone in subordinate amounts, but to the north the proportion of black shale increases and shale forms the greater proportion of the member. Westward-thinning tongues of well-sorted quartz sand occur at places in the southern part of the Creston Range adjacent to the Pedernal uplift and thick beds of sandstone are present elswhere in the member. In the southern Creston Range and the area immediately to the west four northwestward-trending anticlines of Pennsylvanian age have been recognized. Local angular unconformities in the Sandia formation and gray limestone member of the Madera formation show that intermittent submarine folding occurred on these anticlines throughout much of Early Pennsylvanian time. Clastic limestone, limestone-pebble conglomerate, and sandstone are common in the vicinity of the anticlines, and some of the limestones on the flanks of the folds exhibit reef-like, or biohermal, characteristics on a minor scale.

In the southern part of the Creston Range, south of Sapello, the gray limestone member is highly irregular in thickness, ranging from zero to more than 400 feet thick. The member thickens westward to about 750 feet south of Hermit's Peak. The member thickens northward and northwestward toward the center of the Rowe-Mora basin. At Mora River about 300 feet of the member are exposed but thrust faults have cut out an unknown amount of beds and the true thickness is not known. Northwest of Mora the member may be in excess of 3,000 feet thick.

The arkosic limestone member is composed of thick beds of gray and olive siltstone and shale; thinner beds of purple and red shale; fossiliferous gray limestone; and coarse-grained, conglomeratic arkosic sandstone. The contact with the underlying gray limestone member is gradational and transitional throughout most of the region. However, in the Creston Range adjacent to the Pedernal uplift the contact is locally unconformable. The large amount of sediments of the arkosic limestone member derived from Precambrian rocks indicates that older rocks must have been completely eroded from the Pedernal uplift at some places during deposition of this member. The contact of the gray limestone member and arkosic limestone member has been arbitrarily chosen at the base of the lowest sandstone bearing large quantities of fresh, unweathered feldspar. The contact with the overlying Sangre de Cristo formation is conformable and entertonguing exept near the Pedernal uplift where the Sangre de Cristo overlaps or truncates the the arkosic limestone member and rests on the gray limestone member of the Madera formation or on Precambrian rocks.

The arkosic limestone member is mainly marine in origin but contains some beds which are undoubtedly nonmarine. In a sense the entire member is a transition zone from the dominantly marine lower member to the dominantly nonmarine Sangre de Cristo formation. The Madera limestone is Middle and Late Pennsylvanian (Atoka, Des Moines, and Missouri) in age in the southeastern part of the Sangre de Cristos. To the north the formation may be no younger than Des Moines in age because of lateral replacement of the upper parts of the arkosic limestone member by lower beds of the Sangre de Cristo formation.

Pennsylvanian and Permian rocks

Sangre de Cristo formation. – The Sangre de Cristo formation crops out across the southernmost part of the mountains between Barillas Ridge and the Creston Range. To the north the formation crops out as a band of hogback ridges and intervening valleys along the entire length of the Creston Range to north of Guadalupita. Thin remnants are preserved in nearly continuous band along the east side of Barillas Ridge, east of Hermit's Peak, and east of Rociada. The formation is also exposed in the eroded central part of the Ocate anticline west of Ocate.

The Sangre de Cristo formation is composed of thick beds of coarse-grained, conglomerate arkosic sandstone; red, green, and gray shale and siltsone; and a few beds of gray or pink, earthy limestone. Carbonaceous shale and thin impure coal beds occur in the lower parts of the formation at places. The sandstone usually contains large amounts of slightly weathered coarse pink feldspar, and pebbles and cobbles of older sedimentary and crystalline rocks. In the area between Lucero and Guadalupita the lower part of the formation contains several beds of "granite wash" in which mineralogical sorting is so incomplete that the amount of feldspar is greater than that of quartz and other minerals. Thin beds of crystalline and granular limestone and nodular limestone are most common in the lower part of the formation but are present, in places, in the middle and upper parts. The limestone is commonly recrystallized. Marine fossils have been found in several limestone beds in the lower part of the Sangre de Cristo formation south of Coyote (Zeller and Baltz, 1954, p. 3). Other limestone beds are unfossiliferous and seem to be of fresh water origin.

The lower contact of the Sangre de Cristo formation is generally placed at the top of the highest marine limestone of the underlying Magdalena group. This contact is quite practical in the southern part of the mountains. However, in the region north of Sapello River a few thin marine limestones occur as much as 1,000 feet above the base of rocks which lithologically should be placed in the Sangre de Cristo formation. These limestones are probably tongues of the arkosic limestone member of the Madera formation into the predominantly nonmarine Sangre de Cristo formation.

The Sangre de Cristo formation is about 700 feet thick east of Barillas Ridge. In the southern part of the Creston Range the formation ranges from less than 500 feet thick to more than 700 feet thick. From Montezuma northward almost to Mora River outcrops of the Sangre de Cristo formation are within a zone of thrust faulting and complete thicknesses are not known. At Sapello River the formation is at least 2,000 feet thick. At Mora River it is about 3,500 feet thick, and at least 4,000 feet thick near Coyote with an unknown amount cut out by faulting.

During the early stages of Sangre de Cristo deposition the Pedernal uplift locally supplied a considerable amount of sediments but in later phases the Pedernal uplift apparently was completely buried by the Sangre de Cristo formation and most of these sediments are believed to have been derived from highlands to the east, north, and west of the present mountains.

The Sangre de Cristo formation ranges in age from Middle or Late Pennsylvanian to Early Permian. To the south the formation apparently is latest Pennsylvanian (Virgil) and Early Permian (Wolfcamp) in age. To the north the oldest beds are equivalent to part of the Madera formation and contain marine fossils of Middle or Late Pennsylvanian (Des Moines or Missouri) age. To the north the upper part of the Sangre de Cristo formation laterally replaces the Yeso formation and thus is of Leonard age.

Permian rocks

Yeso formation. – The Yeso formation crops out across the southern part of the mountains and as a narrow band in the Creston Range as far north as Lucero. The Yeso formation is composed of medium- to thick-bedded orange siltstone and fine- to medium-grained sandstone. Thin beds of gypsum have been observed at a few places. In places where the Yeso formation intertongues with the Sangre de Cristo formation thin beds of red shale are interbedded with orange siltstone.

The Yeso formation is overlain with apparent conformity by the Glorieta sandstone, although this formation overlaps it to the north. In many places the contact is transitional and there is some evidence of intertonguing.

In the southern part of the mountains the Yeso formation is about 500 feet thick and it thins irregularly northward by intertonguing with the Sangre de Cristo formation until it is no longer recognizable north of Lucero. Lithology and analogy with the Yeso formation in other parts of New Mexico indicate that the formation was deposited in a shallow sea which transgressed from the south. The Yeso formation is considered to be of Early Permian (Leonard) age.

Glorieta sandstone member of the San Andres formation.– In the hogback belt along the eastern front of the Sangre de Cristo Mountains the Glorieta sandstone member of the San Andres formation is a prominent cliff-forming unit. It is gray to tan on a fresh surface and usually weathers to tan or light brown. Typically it is composed of sub-round, clear, quartz and scattered grains of magnetite. Individual beds of the Glorieta sandstone member are medium to massive bedded and generally parallel. Well developed cross-lamination is common.

South of latitude 36°00' in the Sangre de Cristo Mountains, the Glorieta sandstone rests on the Yeso formation. From latitude 36°00', in the vicinity of Lucero, northward the Glorieta rests on the Sangre de Cristo formation. The basal contact of the Glorieta sandstone member is sharp to gradational. At places the lower few feet of the Glorieta sandstone member contains material reworked from underlying rocks. In the vicinity of Lucero conglomeratic material similar to that in the Sangre de Cristo formation has been observed near the base of the Glorieta sandstone member.

In the Sangre de Cristo Mountains the Glorieta sandstone member is variable in thickness. At Chapelle it is about 125 feet thick but near Romeroville it is almost 300 feet in thickness. At Kearny's Gap it is 220 feet thick, at Montezuma 110 feet thick, at Mora Gap about 180 feet thick, and in the vicinity of Ocate it varies from 250 to 275 feet in thickness. A few poor exposures of the Glorieta sandstone member have been observed about 10 to 15 miles north of Ocate. However, in this area the Glorieta is covered by basalt and it has not been observed farther to the north. The Glorieta sandstone member is absent in the Costilla Mountains on the New Mexico-Colorado boundary. The region northward from Ocate may have been one of nondeposition during Glorieta time but it is equally possible that the Glorieta sandstone disappears nothward by intertonguing with the Sangre de Cristo formation.

Fossils have not been found in the Glorieta sandstone member. However, its stratigraphic position indicates that it is of Leonard age.

Read and Wanek (in preparation) have revised the nomenclature of the San Andres formation and have treated the Glorieta as a separate formation.

Limestone member of the San Andres formation. – The limestone member of the San Andres is present only in the southern portion of the Sangre de Cristo Mountains. At points where observed it is quite thin as compared with its thickness in central and southern New Mexico. It consists of dark gray, thin- to medium-bedded, earthy limestone. A perroliferous odor is often present when the rock is freshly broken.

The limestone member of the San Andres is about 40 feet thick at Chapelle, about 20 feet thick at Romeroville, and 15 feet thick at Montezuma. At a point one mile north of Montezuma the limestone unit is absent and has not been observed elsewhere to the north in the Sangre de Cristo Mountains.

The limestone member of the San Andres is of marine origin and is of Leonard or Guadalupe age.

Bernal formation. – The Bernal formation is similar in general lithologic appearance to the Yeso formation. The Bernal formation is present in the southern part of the Sangre de Cristo Mountains and crops out as a thin band in the Creston Range northward to the general vicinity of Ocate and Guadalupita. It is composed of pink to brownish-red siltstone and fine-grained sandstone. Thin beds of gray, fine-to medium-grained sandstone are present. In the southern part of the Sangre de Cristo Mountains gypsum is not uncommon in the formation.

Owing to an erosional unconformity at the top of the Bernal formation the thickness is variable. At Chapelle it is about 145 feet thick; at Romeroville a little over 50 feet thick; at Kearny's Gap 100 feet; at Montezuma about 110 feet; at Mora Gap about 150 feet; and in the Costilla Range where the Glorieta sandstone member is absent the Bernal formation has not been recognized.

The Bernal formation is considered to be correlative with the Whitehorse group in southeastern New Mexico which would indicate Guadalupe age.

Triassic rocks.

Dockum group. – The Triassic system is represented in the Sangre de Cristo Mountains by strata of the Dockum group which crop out in the belt of hogbacks in the Creston Range and underlie the broad valley between La Cueva and Lucero. The Dockum group consists of reddish brown sandstone; red, purple, and green siltstone, and shale; and some beds of gray limestone-pebble conglomerate.

At the base of the Dockum group a series of thick sandstones and interbedded shale is recognizable as a separate mappable unit and has been set apart as the Santa Rosa sandstone. Dockum strata above the Santa Rosa sandstone are refered to the Chinle formation.

In the southern part of the Sangre de Cristo Mountains the Santa Rosa at most places consists of three or more ledge-forming, thick to massive beds of gray to brownish-red conglomeratic sandstone. These beds are separated by intervals of brownish-red to purple shale and siltstone, and thin beds of sandstone and limestone conglomerate. The sandstone contains rock fragments, weathered feldspar, and a high percentage of ferromagnesian minerals giving it a typically "dirty" appearance. Northward in the Sangre de Cristo Mountains the Santa Rosa sandstone is less distinct and in the vicinity of Ocate shale and siltstone are the dominant rock types.

At Chapelle the Santa Rosa sandstone is about 90 feet thick, and at Montezuma more than 350 feet thick. Considerable variation in thickness of the Santa Rosa sandstone may be attributed in part to the lenticular nature of the sandstone beds and in part to local intraformational unconformities.

Overlying the Santa Rosa sandstone is a sequence of brownish-red shale and siltstone with lesser amounts of sandstone and limestone-pebble conglomerate. These strata have been called the Chinle formation. Throughout most of the region the Chinle is divisible into a lower shale member, a middle sandstone member, and an upper shale member.

The Dockum group varies from about 900 to about 1,400 feet in thickness in the eastern part of the Sangre de Cristo Mountains. At Romeroville it is about 1,050 feet thick; at Kearny's Gap about 900 feet; at Montezuma about 1,400 feet; and in the vicinity of Ocate about 1,050 feet thick.

Naranjo formation. – As the Naranjo formation is considered to be correlative with some part of the Glen Canyon group of Triassic and Jurassic age in northwestern New Mexico and northeastern Arizona, it is here discussed with Triassic rocks. The Naranjo formation is present in the vicinity of Ocate and crops out as a narrow band in the hogback belt ot the Creston Range as far south as Sapello. It also has been recognized on Turkey Mountain, about 12 miles southeast of Ocate. At its type locality, east of Ocate, the Naranjo formation includes fine-grained sandstone and shale. In general the Naranjo formation is brownish-red in color. The shades of red are somewhat lighter than those of the underlying Dockum group, although a thin rind of dark brown color is often present on the weathered surface. The sandstones are argillaceous and are mineralogically similar to underlying Triassic rocks. The Naranjo formation usually forms thin rounded ledges which weather into platy or blocky fragments. Cross-lamination is common.

About 2 miles east of Ocate the Naranjo formation is about 65 feet thick. About 4 miles southeast of Ojo Feliz the Naranjo formation is about 55 feet thick. At a point about one mile east of La Cueva it is about 50 feet thick.

The contact of the Naranjo formation with the underlying Dockum group is gradational. The contact with the overlying Ocate sandstone is probably one of regional unconformity. In most places where the Naranjo formation is well-developed its contact with the Ocate sandstone is sharp.

Jurassic rocks.

Ocate sandstone. – The Ocate sandstone crops out in a narrow band in the hogback belt of the Creston Range and is present in a belt of outcrop south and east from Ocate. It is a light-gray thin-bedded to massive sandstone which usually forms a rounded ledge. Cross-bedding and cross-lamination are well developed. The sandstone is composed chiefly of fine- to medium-grained, well-sorted quartz sand. The quartz grains are typicaly subrounded to well-rounded and some grains are frosted.

In the southern part of the mountains, where the Naranjo formation is not present between the Ocate and Chinle formations, the lower part of the Ocate is light-red, finely conglomeratic, and contains sediments reworked from the Chinle. The Ocate sandstone is about 50 feet thick at its type locality about two miles east of Ocate. In general this thickness is rather consistent. However, at a point about one mile east of La Cueva the Ocate sandstone is about 75 feet thick and at Montezuma it is about 110 feet thick. At Kearney's Gap it is about 50 feet thick while at Romeroville it may not be over 40 feet thick.

Although the Ocate sandstone is probably correlative with the Entrada sandstone, or some portion of the San Rafael group, of western New Mexico, the difficulties in correlating some formations of the Jurassic System in western New Mexico have led to the proposal of the term Ocate sandstone in the eastern Sangre de Cristo Mountains. The Ocate sandstone and younger Jurassic rocks are probably all of Late Jurassic age.

Todilto limestone. – The Todilto limestone is present only in the southern portion of the Sangre de Cristo Mountains and has not been observed north of Sapello. It consists of a dark gray, thin- to papery-bedded limestone which usually omits a fetid odor when broken. In places there are thin interbeds of fine-grained sandstone and siltstone, and some limestone beds contain much rounded quartz sand. Bedding is generally contorted and wavy. Fish scales have been observed at a few places on bedding planes and two small, nearly complete fossil fish were found in the Todilto limestone about one mile north of Montezuma. The Todilto limestone is about 15 feet thick at Romeroville and Kearney's Gap, 19 feet thick north of Montezuma, and about 10 feet thick at Bonito Canyon.

Wanakah formation. – Above the Todilto limestone, or above the Ocate sandstone at places where the Todilto is absent, is a thin sequence of gray shale and calcareous sandstone, commonly containing small masses of pink jasper. This unit has been called the Wanakah formation by some writers. It has been found that the Wanakah formation as mapped in this region may include strata equivalent to the Todilto limestone, and some beds which may more properly belong in the lower part of the overlying Morrison formation. The Wanakah formation as mapped in the Ocate area is about 25 feet thick.

Morrison formation. – In the southern part of the Sangre de Cristo Mountains the Morisson formation may be divided into three parts. The lower one-fourth to one-third of the formation consists chiefly of thick sandstones with some interbedded shale. This unit is overlain by a sequence of brownish-red shale and siltstone which contains some interbedded sandstone. At the top of the Morrison formation is a sequence of interbedded greenish-gray shale with interbedded conglomeratic sandstone and nodular limestone. The Morrison formation is overlain with erosional unconformity by the Dakota sandstone.

In the eastern Sangre de Cristo Mountains the Morrison formation varies in thickness from about 175 to about 500 feet. At Romeroville it is about 500 feet thick and at Kearny's Gap 480 feet. At Montezuma it is 250 feet thick but one mile north of Montezuma a pre-Dakota "buried hill" is preserved and the Morrison formation is 415 feet thick. In the vicinity of Ocate the Morrison formation is about 150 feet thick and contains a higher percentage of sandstone than has been observed to the south in the Sangre de Cristo Mountains.

Cretaceous rocks.

Dakota sandstone. – The easternmost hogback ridges of the Creston Range are composed of sequence of sandstone and shale that have been referred to the Dakota sandstone.

In general, the Dakota sandstone in this area consists of a lower sandstone unit which comprises about one-half to two-thirds of the total thickness. This lower sandstone is overlain at places by black carbonaceous shale, which is variable in thickness. At the top of the Dakota is a sandstone that grades upward into the Graneros shale. The sandstone beds of the Dakota are gray to tan and weather to mottled light reddish brown. The grains are composed chiefly of quartz but rock fragments are common. Grain size varies from medium to coarse and lenses of pebbles are common in both the basal and upper sandstone units. The upper sandstone is, in general, somewhat finer grained and better sorted than the lower sandstone.

The Dakota sandstone ranges between 100 and 200 feet thick in the southeastern Sangre de Cristo Mountains. At Montezuma it is 190 feet thick. However, at a point one mile north of Montezuma a "buried hill" of the Morrison formation is preserved and only the upper 30 feet of the Dakota laps across the "hill".

It is likely that the lower part of the Dakota sandstone as above described includes beds that have been assigned to the Purgatoire formation elsewhere in northeastern New Mexico and southeastern Colorado. It also has been suggested (Northrop et al. 1946) that equivalents of the Purgatoire may be present in the upper part of the Morrison formation of the Las Vegas area.

Graneros shale. – The Graneros shale is present immediately to the east of the belt of hogbacks of the Creston Range. The Graneros shale consists of dark- to medium-gray shale. Thin beds of light-tan to brown bentonite which range from a fraction of an inch to a foot or more in thickness are common. Thin beds of argillaceous limestone and calcareous sandstone are locally present.

The contact of the Graneros shale with the underlying Dakota sandstone is transitional. Thin beds of Dakota-like sandstone are interbedded with gray marine shale at the base of the formation.

The Graneros shale is about 250 feet thick along the southeastern front of the Sangre de Cristo Mountains.

Greenhorn limestone. – The Greenhorn limestone is a conspicuous stratigraphic unit which frequently forms the cap rock of low cuestas along the eastern front of the Sangre de Cristo Mountains and on the plains to the east. It consists of dark-gray, finely crystalline limestone and interbedded shale. The limestone frequently weathers to a very light gray color and bedding is thin and regular. Dark-gray shale occurs throughout the formation and commonly the shale beds attain a thickness of several feet. At places the Greenhorn is composed mainly of calcareous shale. The strongly costate pelecypod *Inoceramus labiatus* is commonly present. The Greenhorn limestone is as much as 50 feet thick along the eastern front of the Sangre de Cristo Mountains.

Carlile shale. – The Carlile shale rests conformably on the Greenhorn limestone. It consists mostly of clay shale, and silty sandy shale. Thin beds of dark-gray ammonite-bearing limestone are common near the base of the formation. The Carlile shale weathers to gray, tan or light brown. Its average thickness is about 250 to 300 feet along the eastern side of the Sangre de Cristo Mountains.

Niobrara formation. – The Niobrara formation is the youngest formation of Cretaceous age preserved in the region of the southeastern Sangre de Cristo Mountains. This formation is preserved on three large hills east of the mountains northwest of Las Vegas. The Niobrara formation consists mainly of dark-gray shale which weathers light-gray to tan. The lower member, the Fort Hays limestone member, consists of calcareous shale and thin limestone beds 10 to 15 feet thick containing *Inoceramus deformis* and *Ostrea congesta.* The upper member of the formation is the Smoky Hill marl member. More than 300 feet of Niobrara is present in the area but the top of the formation has been eroded and original thickness is unknown.

Tertiary and Quaternary rocks.

Terrace and pediment gravels of probable late Tertiary and Quaternary age are present in the eastern part of the mountains and on the plains adjacent to the mountains. The gravels are preserved at several levels.

Basalt flows of probable late Tertiary and Quaternary age cap extensive areas in the vicinity of Ocate and east of Ocate. The basalt flows are present on several erosional surfaces and represent several periods of eruption from centers in the general vicinity of Ocate. Basalt dikes are present near Ocate, east of Sapello, and about six miles north of Las Vegas.

Several small Pleistocene glacial cirques indent the higher part of the east face of the Mora Range southwest of Mora. Only a small amount of debris was eroded from these cirques. The upper canyon of Rio de la Casa is a typical "U"-shaped glacial valley and cirques are present on either side of the valley in Rincon Bonito. A large boulder fan at the mouth of Rio de la Casa near Cleveland is believed to be in part of glacial origin.

STRUCTURE

Description

The southeastern part of the Sangre de Cristo Mountains is characterized by large asymmetrical folds and belts of imbricate thrusting. Deformation is progressively more intense from south to north. Principal structural features of the region are shown in Fig. 3, and structural profiles are shown in Fig. 4.

The southern part of the mountains is characterized by two large southeastward-plunging anticlines, the Tres Hermanos anticline at the west, and the Creston anticline at the east front of the mountains. Both folds are strongly asymmetrical, having steeply-dipping northeast limbs and long, gently-dipping southwest limbs. The northeast limb of the Tres Hermanos anticline is broken by a high-angle fault downthrown to the east. Displacement on this fault is progressively greater nothward and reaches more than 3,000 feet. East of the Tres Hermanos anticline is the Chapelle syncline, and east of the Creston anticline is the southern extension of the Jarosa syncline which parallels the eastern front of the mountains from north of Guadalupita to south of Las Vegas.

South of the upper Gallinas River the northwest-trending Tres Hermanos anticline terminates against a system of northeast-trending transverse or tear faults. Along these faults, and the westward-dipping thrust faults into which

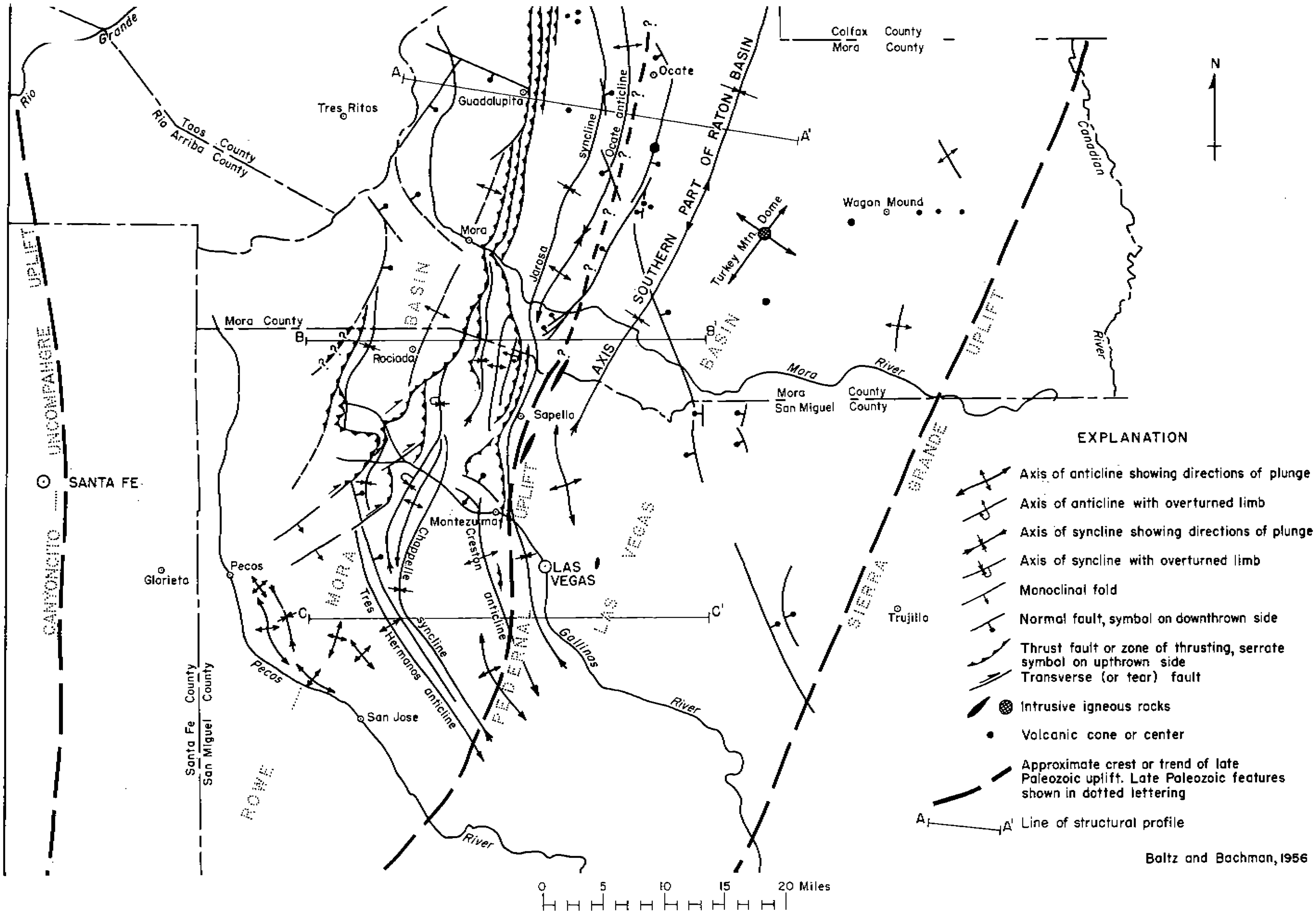
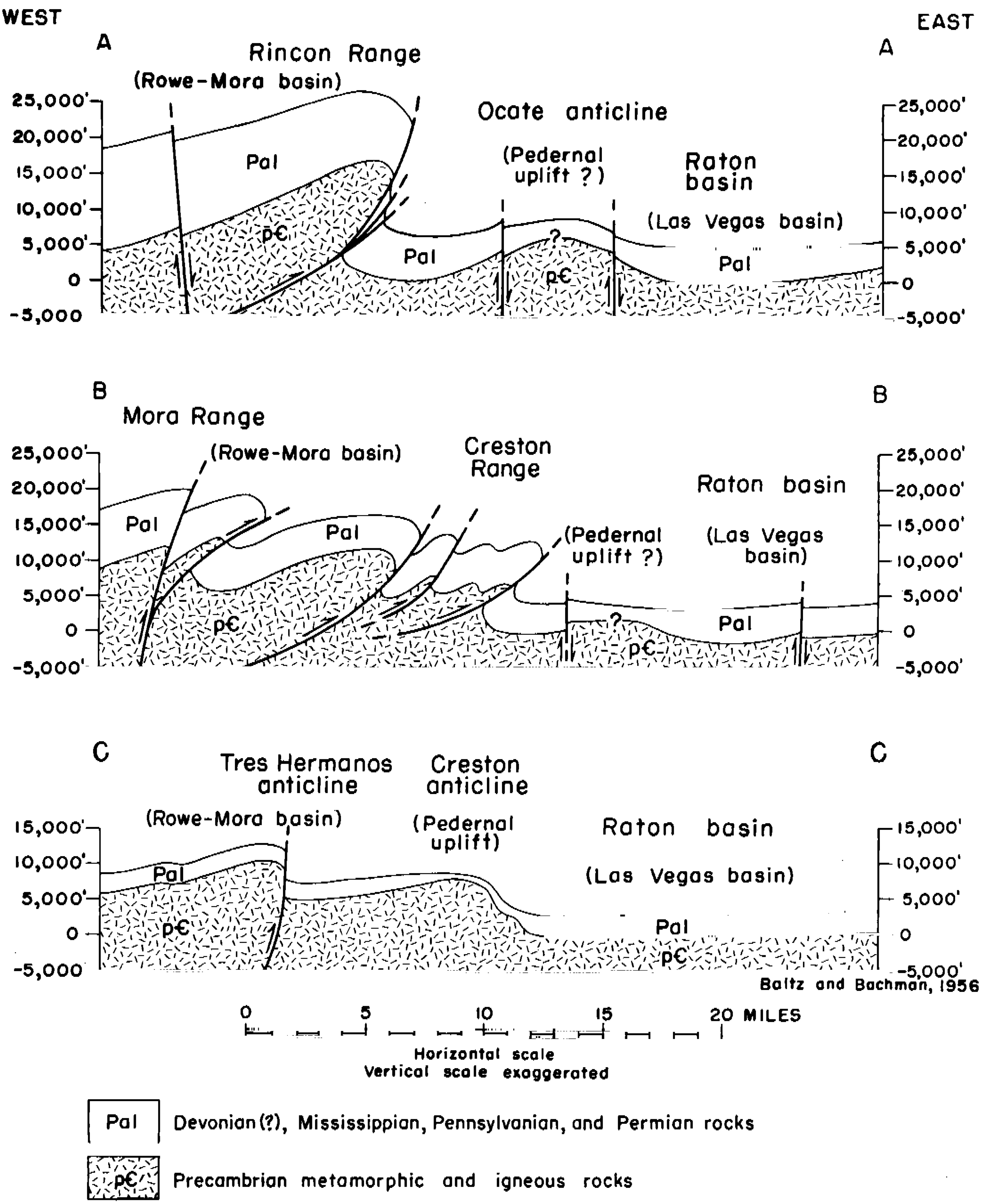


FIG. 3. PRINCIPAL STRUCTURAL FEATURES OF THE SOUTHEASTERN SANGRE DE CRISTO MOUNTAINS AND ADJACENT REGION IN NEW MEXICO



Lines of profiles shown on Fig. 3. Present topography is not shown. Profiles are in part hypothetical. In places, Paleozoic rocks have been restored on the basis of composite stratigraphic sections to indicate relation of Paleozoic features to Laramide structure. Names of Paleozoic features shown in parenthesis.

FIG. 4. STRUCTURAL PROFILES ACROSS PARTS OF THE SOUTH-EASTERN SANGRE DE CRISTO MTNS. AND ADJACENT REGION

they pass, several large blocks, including the Hermit's Peak block, have been uplifted and displaced to the northeast.

West of Hermit's Peak at the foot of Elk Mountain is a major westward-dipping low-angle thrust fault which passes southward into a southwest-trending tear fault. Farther to the north the Mora Range has been elevated along a high-angle fault downthrown to the east. Southwest of Mora vertical displacement on this fault may be more than 5,000 feet but northward the amount of displacement decreases rapidly.

The Creston anticline at the east front of the mountains is broken by a west-dipping high-angle thrust fault in the vicinity of Montezuma. To the north this fault passes into a complex zone of imbricate thrusts arranged in plan in an arcuate fashion convex to the east. The zone of thrusting east of Hermit's Peak, also arcuate and convex to the southeast, encroaches progressively northeastward on the zone of thrusts of the Creston Range. The two zones join near the Mora River to form a broad north-trending belt of imbricate thrust faults.

The Rincon Range appears to be on the west limb of a very large anticline which was overfolded and thrust to the east. The Ocate anticline is a structural "bulge" east of the mountains in front of this large overthrust block.

Structural evolution

The broad, general tectonic pattern of the southeastern Sangre de Cristo Mountains was developed in Precambrian time. During part of Precambrian time the region was part of a sedimentary basin of unknown dimensions in which a great thickness of sedimentary rocks and some volcanic rocks were deposited. Later in Precambrian time rocks of the region south of the latitude of Sapello were tightly folded, intruded by granite, and welded by a process of granitization into an area of great structural competence. North of the latitude of Sapello the bedded rocks were thrown into a series of folds and were faulted, but do not seem to have been intruded by large bodies of granite. These broad areas of differing structuaral competence appear to have controlled the general distribution of later structural features.

No Paleozoic rocks older than Devonian(?) are present and the region is assumed to have been part of a broad positive area during much of the Paleozoic era. In Devonian(?) and Mississippian time the region was epeirogenically depressed and received a very thin blanket of marine sediments.

In Pennsylvanian and Permian time the Rowe-Mora basin, Pedernal uplift, Las Vegas basin, and Sierra Grande uplift were developed, apparently as a result of compressive forces directed in components of an east-west direction. The deeper part of the Rowe-Mora basin developed in the area north of Sapello and received perhaps more than 15,000 feet of sediments, whereas in the area of granitized basement rocks to the south no more than 1,000-3,000 feet of Upper Paleozoic sediments accumulated.

During most of the Mesozoic era the region was subjected to periodic epeirogenic downwarping which permitted accumulation of 4,000-5,000 feet of sediments. Most of these sediments were deposited in Late Cretaceous time. There is some evidence of gentle folding in this region in Late Jurassic time.

Most of the folding and complex thrusting that involves Devonian(?) through lower Upper Cretaceous rocks resulted from regional compression in an east-west or northeast-southwest direction in latest Cretaceous and early Tertiary time. Sedimentary rocks of latest Cretaceous and early Tertiary age are not preserved in this region. However, rocks present in the Raton Mesa region and Huerfano Park in New Mexico and Colorado record several episodes of Laramide deformation of the Sangre de Cristo Mountains. These episodes range in age from Late Cretaceous (Montana) to Miocene (Johnson and Wood, 1956, p. 720)

During Laramide orogeny the area of the granitized basement complex in the southeastern Sangre de Cristo Mountains was only mildly deformed and the open, northwest-trending Tres Hermanos and Creston anticlines were formed in this area. The buried mass of the Pedernal uplift appears to have controlled the position of the Creston anticline. A smaller Paleozoic structure may have controlled in part the position of the Tres Hermanos anticline. Imbricate thrust faults and large anticlines were developed in the region north and west of Sapello in the area of less deformed Precambrian rocks and thick Paleozoic sediments. Compressive forces also rejuvenated the Paleozoic Sierra Grande arch, which forms the eastern boundary of the Raton basin.

Middle and late Tertiary epeirogenic movements uplifted the entire region, and uplift of the Truchas and Mora ranges along an east-west cross-range axis probably occurred at this time.

(Continued on next page)

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