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1966, pp. 56-65. https://doi.org/10.56577/FFC-17.56

in:

Taos-Raton-Spanish Peaks Country (New Mexico and Colorado), Northrop, S. A.; Read, C. B.; [eds.], New Mexico Geological Society 17th Annual Fall Field Conference Guidebook, 128 p. https://doi.org/10.56577/FFC-17

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GEOLOGY OF THE SANGRE DE CRISTO MOUNTAINS AND ADJACENT AREAS, BETWEEN TAOS AND RATON, NEW MEXICO

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INTRODUCTION

The Sangre de Cristo Mountains of northern New Mexico and southern Colorado are a north-trending chain of mountains located between the Rio Grande depression on the west and the Raton basin on the east. These three structural provinces have distinct physiographic expression as indicated in Figure 1.

The Rio Grande depression in this area is referred to as the Taos Plateau although to the north San Luis basin is more commonly used. Elevations range from approximately 7,000 feet at the rim of the Rio Grande Gorge to 8,000 feet at the foot of the mountains to the east. In addition the floor of the valley is studded with volcanic cones which rise as much as 1,000 feet above the surrounding surface.

The Sangre de Cristo Mountains, in general terms, can be subdivided into the Taos Range on the west and the Cimarron Range on the east. Separating these ranges lies the high park-like Moreno Valley. The Taos Range includes numerous peaks with summits between 12,000 and 13,000 feet, in addition to Wheeler Peak, elevation 13,173 feet—highest point in New Mexico. In the Cimarron Range, altitudes range approximately from 11,000 to 12,500 feet. To the south, the lava-covered Ocate Plateau stands at 9,000 to 10,000 feet above sea level. The floor of the Moreno Valley is 8,220 feet at the village of Eagle Nest and rises to 8,500 feet and more along its margins with the surrounding mountains.

The Raton basin lies in the western part of the Great Plains Province and is bounded by the Cimarron Range on the west in the vicinity of Ute Park. The plains region consists of the Las Vegas Plateau at elevations between 6,000 and 6,500 feet, and Raton Mesa, located north of a line from Cimarron to Raton, with elevations of 8,000 feet and more.

STRATIGRAPHY

A composite table of stratigraphic units with corresponding ages and thicknesses is shown in Figure 2. A brief description of the various lithologies is given below together with other pertinent data.

PRECAMBRIAN ROCKS:

Precambrian rocks principally occur in the Sangre de Cristo Mountains, and locally in the Moreno Valley.

In this area these metamorphic crystalline rocks have been subdivided by Clark (1966, p. 16) into a metaquartzite group, which includes muscovite-hematite gneiss and granulite, mica quartzite, graphite-mica gneiss, and sillimanite-mica gneiss. Another group with a high content of mafic minerals includes quartz-biotite schist and gneiss, hornblende gneiss, amphibolite, hornblendite, and chlorite schist. The aggregate thickness of these rocks may be as much as 10,000 to 12,000 feet. At a later date, intrusion of granites is represented today by pink and gray varieties of granite and granitic gneiss. In the Moreno Valley large areas of granitic biotite gneiss may represent another group of metasediments.

The Precambrian granite and granitic gneiss are often associated with zones of migmatites at the contacts with the mafic units. Simple pegmatites are relatively few. In the Taos Range copper mineralization, believed to be of Precambrian age, is found in a series of prominent northeasterly shears in the Rio Hondo mining district.

Precambrian units are to a large extent the result of regional metamorphism of pre-existing sedimentary and igneous rocks, although locally the effects of granitic intrusion are marked. Foliation, in general, is to the northeast and is present in most of the rocks to some extent.

DEVONIAN(?) AND MISSISSIPPIAN ROCKS:

Rocks that have been tentatively assigned to the Devonian(?) and Mississippian Systems crop out on the mountain peaks and around some of the glacial cirques west of the Moreno Valley. Isolated exposures of these rocks are found at Bear Lake, Old Mike, Wheeler Peak, Horseshoe Lake, and Lost Lake. In the field the gray limestones contrast sharply with the Precambrian crystalline rocks on which they rest. In the Raton basin these rocks are in the subsurface. Their total aggregate thickness may be 80 feet.

The lowest bed consists of a few feet of brown sandstone containing fragments of Precambrian rocks. This is overlain by medium- to thin-bedded medium gray limestone and dolomitic limestone. The thickness of these beds is about 25 feet and they have been assigned to the Espiritu Santo Formation of Devonian(?) age.

The upper beds consist of a massive ledge of limestone breccia which weathers light gray. This is overlain by sandstone, shale, and limestone, some of which may be reddish or green. The thickness of these beds may be as much as 40 to 50 feet and they have been correlated with the Tererro Formation at the type locality in the Pecos area

AGE	Lithologic Unit	Thickness
Recent	Alluvium, Eolian sand, Mudflow	-
Pliocene-Pleistocene	Pediment gravel	-
	Moraine	-
	Valley fill Basalts	-
Pliocene	High level gravel	135'
Miocene	Monzonite porphyry	-
	Quartz porphyry	-
	Biotite alkali granite	-
	Hornblende granite	-
	Rhyolite group	1,360-1,500'
	Latite group	520'
	Quartz diorite porphyry	-
	Andesite group	1,500'
Paleocene	Poison Canyon Formation	2,500'
	Raton Formation	1,700'
Cretaceous	Vermejo Formation	0 - 550'
	Trinidad Sandstone	0 - 300'
	Pierre Shale	2,300'
	Smoky Hill Marl	900'
	Fort Hays Limestone	10- 55'
	Carlile Shale	165 - 400'
	Greenhorn Limestone	20 - 60'
	Graneros Shale	400'
	Dakota Sandstone	30 - 60'
	Purgatoire Formation	100 - 150'
Jurassic	Morrison Formation	150 - 400'
	Wanakah Formation	30 - 100'
	Entrada Sandstone	40 - 100'
Triassic	Dockum Group	0-1,200'
Permo-Pennsylvanian	Sangre de Cristo Formation	5,300'
Pennsylvanian	Magdalena Group	5,000'
Mississippian	Tererro Formation	40 - 50'
Devonian(?)	Espiritu Santo Formation	25'
Precambrian	Diabase	-
	Migmatite	-
	Granite and granitic gneiss	-
	Mafic gneiss group	7,000(?)
	Metaquartzite group	5,000(?)

FIGURE 2

Stratigraphic units in the Sangre de Cristo Mountains and adjacent areas, northern New Mexico.

(Baltz and Read, 1960, p. 1759). There, fossil evidence indicates a Mississippian age for the containing strata.

PENNSYLVANIAN ROCKS:

Pennsylvanian strata assigned to the Magdalena Group are found in the western slopes of the Moreno Valley. At the crest of the Taos Range, small areas of these rocks remain either as erosional remnants adjacent glacial cirques or are preserved by structural mechanisms. The bulk of these sedimentary rocks, however, is poorly exposed in the forest-covered mountain slopes and because of this they have been mapped as one unit and not subdivided. These marine strata are represented by an alternating sequence of conglomerate, medium- to coarse-grained feldspathic sandstone and arkose, shale, and limestone. Limestone is arkosic and usually gray or dark gray. The most common types have a speckled appearance in the hand specimen, due to glassy quartz and cream to light brown feldspar grains. Fossil fragments may be present. Oolitic limestone is found in places. It is dark gray and contains oolites which give the rock a "birdseed" appearance. It is believed that these limestones may be useful in correlation with adjacent areas where rocks of similar material have been described.

In the Eagle Nest area the containing rocks are characterized by *Fusulina*, and this, coupled with an examination of the megafossil assemblage, suggests a middle Des Moines (upper Cherokee) age.

Thickness of Pennsylvanian strata is believed to be not less than 5,000 feet, based on measurements where the rocks rest either on Precambrian or Devonian(?)—Mississippian, and pass upwards transitionally into the overlying Sangre de Cristo Formation. Because of structural complications, an unknown interval between these limits, as yet, precludes more accurate estimates of thickness.

Pennsylvanian rocks do not crop out in the Cimarron Mountains but are found in the subsurface of the Raton basin where maximum aggregate thicknesses are about 5,000 feet.

The area of the present southern Sangre de Cristo uplift and the southern part of the Raton basin was the site of a geosyncline—the Rowe-Mora basin. This basin probably connected with the Central Colorado basin during much of Pennsylvanian and early Permian time and received sediment from adjacent uplifts.

In the southern part of the Rowe-Mora basin the Magdalena Group has been subdivided into the Sandia Formation (Atoka age) and the Madera Formation (Atoka through Virgil). The Madera Formation is further subdivided into the Lower Gray Limestone Member and the Upper Arkosic Limestone Member. To the north, an increase in thickness of Pennsylvanian sediments is accompanied by a change from shelf to marine geosynclinal facies.

Rocks of Des Moines age in the Colorado part of the Sangre de Cristo uplift have been referred to as the Madera Formation by Brill (1952, pl. 1 and p. 816-820), and Bolyard (1959, p. 1916). However, for the most part the Upper Arkosic Limestone Member is older than that found in New Mexico.

PERMO-PENNSYLVANIAN ROCKS:

Along the western margin of the Moreno Valley and in the Cimarron Mountains red nonmarine clastic rocks are exposed. They consist of coarse to medium arkosic sandstones alternating with thick intervals of siltstone and shale and a few thin limestones. These materials were deposited in piedmont alluvial plains.

Locally, this sequence of strata includes gray shale and siltstone beds that are carbonaceous and contain specimens of *Callipteris conferta* as well as other fossil plants that are indicative of the Permian(?) age of at least the lower part of the interval, according to Wanek and Read (1956, p. 85).

These strata have been named the Sangre de Cristo Formation. Surface work suggests that the formation contains rocks ranging in age from Late Pennsylvanian through Early Permian. To the south near Mora and in parts of the Raton basin the upper part of the formation changes markedly and can be differentiated into the Yeso Formation and the Glorieta Sandstone of Leonard age, beneath which are the arkose and red siltstone of the Sangre de Cristo Formation. The youngest formations are the San Andres Limestone of Leonard and Guadalupe age, and the Bernal Formation of Guadalupe age.

In the Taos Range well-silicified outcrops of conglomerate, sandstone, and siltstone are found at a number of places between the Precambrian basement and the overlying Tertiary andesite. These beds have been included by some in the Sangre de Cristo Formation although they may be much younger in age.

The Sangre de Cristo Formation is about 5,300 feet thick in the Moreno Valley, but thins in the Raton basin eastward over the Sierra Grande arch.

TRIASSIC ROCKS:

Rocks of Late Triassic age rest disconformably on the Permian in the Moreno Valley and in the Raton basin. In these and adjacent areas the strata are referred to as the Dockum Group. An extensive shallow-water continental environment of deposition is indicated by the deposits of sandstone, shale, and limestone conglomerate.

In the subsurface the Dockum group is 1,000-1,200 feet thick in the Las Vegas sub-basin but only 400 to 500 feet in the Cimarron Range and approximately 340 feet in the northern part of the Moreno Valley. Along the foothills east of the Sangre de Cristo Mountains in southern Colorado the equivalents of the Dockum Group are either very thin or absent.

In the Las Vegas sub-basin and southern Sangre de Cristo uplift the basal part consists of brown sandstone alternating with red shale overlain by an interval of red shale. These units are referred to as the Santa Rosa Sandstone and the Chinle Shale respectively, but in the Moreno Valley it is impractical to map these formations separately because of the uncertainty of the position of the contact between the two.

The general northward thinning of the Triassic appears to be due to gentle warping and erosion in early Jurassic time, rather than to regional variations in the amounts of Upper Triassic sediments that accumulated, although some have interpreted the information in a different manner.

JURASSIC ROCKS:

Jurassic rocks crop out in the Moreno Valley and are found in the subsurface of the Raton basin. They include the Entrada Sandstone, an equivalent of the Wanakah Formation, and the Morrison Formation.

The basal Upper Jurassic unit is the Entrada Sandstone. This sandstone has been called the Exeter, Wingate, or Ocate but is now generally correlated with the Entrada Sandstone of Utah. The Entrada Sandstone is a light gray to buff, friable, fine- to coarse-grained sandstone and has a clean appearance. In the area under consideration the thickness ranges from 40 to 100 feet. An eolian origin seems likely because of the tangential crossbedding that is commonly displayed.

Overlying the Entrada is a sequence of shale and thin limestone, gypsum, and thin sandstone. These rocks are present in the area of the Raton basin where they range in thickness from 30 to 100 feet. In the southern Sangre de Cristo uplift near Las Vegas the unit consists mainly of gray, finely laminated, fetid limestone which has been correlated with the Todilto Limestone of western New Mexico. According to Baltz (1965, p. 2060) the Todilto tongues out northward and eastward into the sequence described which characteristically contains angular fragments of jasper.

The Morrison Formation is found throughout the Raton basin and in the Moreno Valley. It is rarely well exposed at the surface. It consists of a series of light to buff sandstone, variegated shale, and siltstone of shallow-water nonmarine origin. Thickness ranges from 150 to 400 feet with considerable variation locally due to warping and erosion of the upper beds prior to the deposition of the overlying Cretaceous formations.

Part of the sediments of the Upper Jurassic are reworked Triassic rocks, although much was derived from highlands in central New Mexico, south of the Raton basin.

CRETACEOUS ROCKS:

Rocks of Cretaceous age in the Raton basin include the Purgatoire Formation, Dakota Sandstone, Graneros Shale, Greenhorn Limestone, Carlile Shale, Fort Hays Limestone, Smoky Hill Marl, Pierre Shale, Trinidad Sandstone, Vermejo Formation, and the lower part of the Raton Formation. The aggregate thickness of these predominantly marine sediments may be as much as 3,500 feet.

The Purgatoire Formation of Early Cretaceous age rests unconformably on the Morrison Formation and is present in most of the Raton basin. It has not been separated from the overlying sandstone in the Moreno Valley where the Dakota consists of two ledges separated by a siltstone bed. The Purgatoire consists of a conglomeratic sandstone overlain by a member composed of coaly shale and sandstone with aggregate thickness of 100 to 150 feet.

The Dakota Sandstone is a distinctive ledge-forming sandstone which weathers brown and is further characterized by veinlets of silica which develop a rugose surface. The Dakota is commonly 30-60 feet thick and may contain lenses of conglomerate or thin beds of gray shale.

The Graneros Shale overlies the Dakota Sandstone with an apparent transition. The Graneros Shale consists of dark gray siltstone and shale and thin beds of bentonite. The total thickness is nearly 400 feet.

The Greenhorn Limestone is composed of thin beds of blocky-weathering, dark gray, finely crystalline limestone interbedded with calcareous shale. It ranges from 20 to 60 feet in thickness.

The Carlile Shale rests conformably on the Greenhorn Limestone. It is a dark gray shale with calcareous beds, and in addition contains large tan or buff calcareous septarian concretions. Thickness ranges from 165 to about 400 feet in the Raton basin. Sections of the Carlile are not well exposed in the Moreno Valley owing to the fact that the soft beds weather into smooth grassy slopes.

The Fort Hays Limestone is the lower member of the Niobrara Formation. It consists of thin platy-weathering, medium gray finely crystalline limestone with intercalated calcareous shale. It crops out in the northern part of the Moreno Valley but exposures are generally very poor. The Fort Hays Limestone ranges in thickness from 25 to 55 feet in the northern Raton basin and 10 to 20 feet in the Las Vegas sub-basin.

The Smoky Hill Marl is the upper member of the Niobrara Formation, and consists of mostly shale with interbedded thin limestone and sandy shale. Griggs and Northrop (1956, p. 136) indicate an aggregate thickness of as much as 900 feet in the plains area.

The Pierre Shale is marine and consists mainly of dark gray non-calcareous shale. It contains several zones of calcareous concretions and approximately the upper 100 feet is composed of interbedded dark gray shale and gray sandstone which represents a transition and intertonguing with the overlying Trinidad Sandstone. The thickness of the Pierre Shale is as much as 2,300 feet southeast of Huerfano Park but farther south much of the Pierre has been removed by erosion and only the lower part is preserved.

The Trinidad Sandstone is an arkosic, buff to gray, fine- to medium-grained sandstone with some interbedded shale. The sandstone is 0-300 feet thick with its greatest thickness near the axis of the northern Raton basin.

The Vermejo Formation, which rests conformably on the Trinidad Sandstone, is composed of buff to gray shale, carbonaceous shale, coal beds, and gray arkosic sandstone. Minable coal occurs in the Vermejo, in particular the Raton coal bed, which lies in the lower part of the formation. Most of the coal is high-volatile bituminous rank and will coke. The Vermejo Formation attains a maximum thickness of 550 feet in the trough of the northern Raton basin but Johnson and others (1956, p. 128) indicate that it is absent a few miles east of Raton. Like the underlying

Trinidad Sandstone the Vermejo Formation is absent in the Moreno Valley and the overlying Raton Formation rests on older rocks.

Cretaceous and Tertiary rocks:

The Raton Formation of Late Cretaceous and Paleocene age crops out over most of the Raton Mesa region. It consists of fine- to coarse-grained arkosic sandstone, gray shale, and coal beds. At most places the base of the Raton is a pebble conglomerate. The Raton Formation is a swamp and flood-plain facies, which attains a maximum thickness of 1,700 feet in the trough of the basin. The York Canyon coal beds have recently been developed and will provide additional coking coal for steel plants in California.

In the central part of the Raton basin the Raton Formation grades vertically and laterally into the lowermost beds of the Poison Canyon Formation of Paleocene age. The sandstone beds of the Poison Canyon Formation are usually coarser grained than those of the Raton Formation, the shales contain lesser quantities of carbonaceous material, and coal is found only at a few places near the base. The Poison Canyon has a maximum thickness of 2,500 feet.

The orogenic events that produced the present Raton basin and its bounding uplift began in latest Cretaceous time. The Raton and Poison Canyon Formations are terrestrial rocks that record part of those earth movements.

Igneous rocks:

Igneous activity was initiated in the Red River area in early Tertiary time by a period of volcanism which resulted in the extrusion and deposition of andesite tuff, breccia, and flows, representing the earliest member of the volcanic series. These materials rest on Precambrian crystalline rocks except in some localities where lenses of conglomerate and fine-grained clastics are found at the base of the andesite. These sediments have a thickness as much as 100 feet, and have been assigned to the Sangre de Cristo Formation by some, although more recent work suggests that the fine-grained clastics are in part tuffaceous, and hence may be considered to be a member of the volcanic series. The andesites are gray and purple porphyritic hornblende-bearing units except in the Red River graben where they have become extensively propylitized due to the emplacement of acid igneous intrusives. The thickness of the andesite group is about 1,500 feet and may be as much as 1,700 feet in upper Red River Canyon and Foster Park.

The second member of the volcanic series is dark gray quartz latite porphyry, characterized by shining plates of black biotite and round, partly digested quartz grains. In upper Red River Canyon the latite appears to overlie the andesite and have an approximate thickness of about 520 feet. Elsewhere contacts with the country rocks suggest that latite also occurs in intrusive bodies. In addition intrusive breccia and numerous dikes have been mapped. Like the underlying andesite, the latite has been subject to alteration with the production of epidote and chlorite from the primary minerals.

The uppermost members of the volcanic series are rhyolitic in composition. These are light-colored, porphyritic rocks that occur as flows and tuffs in addition to plugs and dikes. Rhyolites are characterized by phenocrysts of orthoclase, sodic plagioclase, and rounded grains of quartz. Estimates of the thickness of rhyolite near Red River are near 1,360 feet, although farther north at Latir Lake thicknesses as much as 1,500 feet have been indicated by McKinlay (1956, pl. 1).

Over-all, nearly 3,000 feet of volcanics are preserved in parts of the Red River graben by high-angle faulting in Miocene time. South of lower Red River Valley the volcanics thin before they overlie the Precambrian basement and are absent in the Rio Hondo mining district. Immediately to the north they tend to thin although greater thicknesses have been recorded in the Latir Peak area.

The acid intrusive bodies which have been emplaced along the structurally depressed area between Questa and Red River are of major interest from an economic standpoint. The granites in this area have been named Flag Mountain (Bear Canyon), Sulphur Gulch (Questa Mine), and Red River stocks. Their composition is that of a biotite alkali granite. Textures vary from aplite to granite porphyry and inequigranular seriate facies. A fourth stock in the vicinity of Arroyo Seco and Cuchillo del Medio has similar composition and texture.

Of further interest in this area are the bodies of hornblende-bearing granite in Rio Hondo and Cabresto Creek. For the most part these granites are in contact only with Precambrian terrane. Textures are medium to coarse grained porphyritic. There is no associated alteration or mineralization. The granites have been tentatively assigned an early Tertiary age by numerous workers although a Precambrian age cannot be entirely ruled out.

Other intrusives in the Red River area include bodies of quartz porphyry and monzonite porphyry dikes. Alteration of the volcanics by these intrusions and the granitic stocks is widespread. Propylitic alteration is characterized by the appearance of chlorite and epidote, whereas, hydrothermal alteration resulted mainly in the formation of sericite, kaolinite, silica, and pyrite, localized in areas adjacent the intrusions, and fractures in the volcanic rocks. Rapid erosion of these areas has produced many yellow and red bare patches in the altered volcanics. The loose material is washed into numerous side gullies by torrential summer rains to form mudflows. The debris is then swept out of the side canyons into the floor of the Red River Valley, where the coarse material collects, dries, hardens, and assumes its characteristic buff color.

Following alteration, Carpenter (1960, p. 85) indicates that minerals of economic importance were introduced. Worthy of note are occurrences of molybdenite in veins and disseminations, and fissure deposits containing gold and silver. Over-all, intrusion of predominantly acid igneous bodies, alteration, ore-fluid injection, and faulting in the Red River district are rather closely spaced in time and apparently related to one another.

In the Moreno Valley, intrusion of quartz diorite and dacite porphyry sills and dikes into upper shales represents another phase of mid-Tertiary intrusive activity. Associated with these sills are contact-pyrometasomatic deposits of iron and gold. Elsewhere, in the flanks of Baldy Mountain, veins related to the porphyry occupy fissures in the sills and country rocks, and carry a pyrite-gold mineralization. In the Moreno Valley, gold in economic quantities was derived by erosion of the lodes on the flanks of Baldy Mountain and was deposited in stream gravel. Extensive lode and placer mining was carried out in the Elizabethtown-Baldy district before and shortly after the turn of the century.

LATE TERTIARY AND QUATERNARY DEPOSITS:

Coarse unconsolidated gravel overlies the volcanic series in the Red River area. It occurs on the tops of drainage divides north and south of Placer Creek, and above Foster Park Canyon. The base of the gravel is between 9,900 and 10,000 feet above sea level and is as much as 135 feet thick in places. Some consider the gravel to have been furnished by meandering streams prior to the final phase of high-angle faulting and assign to it a middle to late Tertiary age. Others have interpreted the deposits as evidence of an early stage of glaciation.

Miocene and post-Miocene high-angle faulting, subsequent to the extrusion of the volcanic series, disrupted the widespread erosion surface that had been formed on these and older rocks. The Southern Rocky Mountains geanticline was uplifted and a series of structural basins was developed. The Rio Grande-San Luis basin was initiated at this time on the western side of the Sangre de Cristo Mountains. Farther east the "parks" of Colorado and the Moreno Valley in New Mexico were developed.

Locally derived syntectonic materials, from the adjoining Taos and Cimarron Ranges, accumulated as gravel basin-fill in the Moreno Valley. Thickness of these deposits may be as much as 440 feet, although inliers of older rock show that the thickness is variable. The age of the gravel has been tentatively suggested as being late Tertiary or early Quaternary. The oldest part of this basin-fill is overlain in the southern part of the Moreno Valley by basic flows of igneous rock believed to be of similar age.

Farther north the gravels cannot be separated from the later deposits that are Quaternary in age and include recent fanglomerates. Quaternary alluvium occupies the flood plains of Moreno, Cieneguilla, and Six Mile Creeks, as well as the narrow courses of some of the mountain streams.

In the high country around Wheeler Peak, Gold Hill, and Latir Peak glacial cirques are well developed. Contained herein, and in the ice-sculptured valleys below, five stages of Wisconsin glaciation have been recognized.

Analogous events were taking place in the Rio Grande depression and in the Raton basin. In the Rio Grande trough several thousand feet of the Santa Fe Group accumulated. Included are sedimentary and volcanic units which range in age from Miocene to Pleistocene. At the base the Picuris Tuff is 1,250 to 1,750 feet thick and consists of water-laid tuff and coarse conglomerate. The Tesuque Formation overlies the Picuris Tuff. It is several thousand feet thick and consists of poorly consolidated sandstone and conglomerate. The Servilleta Formation unconformably overlies the Picuris and Tesuque Formations. The Servilleta Formation consists of interbedded basalt, sand, and gravel which have an aggregate thickness greater than 1,000 feet. Lambert (1966, paper in this Guidebook) indicates that the latest deposits are terrace and pediment gravel, alluvial-fan sand and gravel, and eolian sand. These deposits are several hundred feet thick and range in age from Pleistocene to Recent.

In the Raton basin epeirogenic upwarping, accompanied by normal faulting, occurred in late Tertiary time. Erosion was followed by deposition of the Ogallala Formation of Pliocene age which is mainly preserved east of the crest of the Sierra Grande arch. Basalt flows were extruded in late Tertiary and Quaternary time, capping the mesas in the vicinity of Raton and Ocate.

STRUCTURE

DESCRIPTION

The physiographic expression of the three major structural features—the Rio Grande depression, Sangre de Cristo uplift, and Raton basin—has already been outlined. To these must be added the small but important synclinal structure of the Moreno Valley, and the Red River graben.

The structure of the Sangre de Cristo Mountains in this area is dominated by the Taos horst and the apparent anticlinal-like core of the Cimarron Range, both of which expose Precambrian metamorphic rocks. The Taos horst is 17 miles long and approximately 10 miles wide. The western flank of the Taos uplift is marked by a sharp topographic break between the Rio Grande depression and the Sangre de Cristo Mountains. The Taos Range has been elevated along a zone which approximately parallels the present position of the mountain front on the west according to McKinlay (1957, p. 14). The amount of vertical displacement is estimated to be more than 7,000 feet. The eastern margin of the Taos Range is bordered by the Moreno Valley. The common slope of these two features is a complex zone of normal, reverse, and thrust faults (Fig. 3). The faults, in general, are aligned in a north-south belt about 7 miles wide. Thrusting in this area had first been recognized by Wanek and Read (1956, p. 82). The thrusts are considered to be stretch types, and are the result of faulting following folding. The dip of the thrust planes and axial planes of folds is to the west. Thrusts are complex in that they consist of low-angle segments which pass into tears and high-angle portions. Dip-slip and forward movement ranges from 2,000 to 9,000 feet. The thrusts are broken by high-angle normal faults which are also present on the east side of the Moreno Valley.

The synclinal nature of the Moreno Valley was first recognized by Ray and Smith (1941, pl. 1). However, the simple structural picture is complicated in the northern part of the valley by the Skully Mountain dome and the Iron Mountain anticline. These structures are the result of the emplacement of numerous sills of quartz diorite porphyry which accompanied the structural deformation of the area. The Moreno Valley is about 16 miles long and 3 to 4 miles wide. The floor of the valley is covered by late

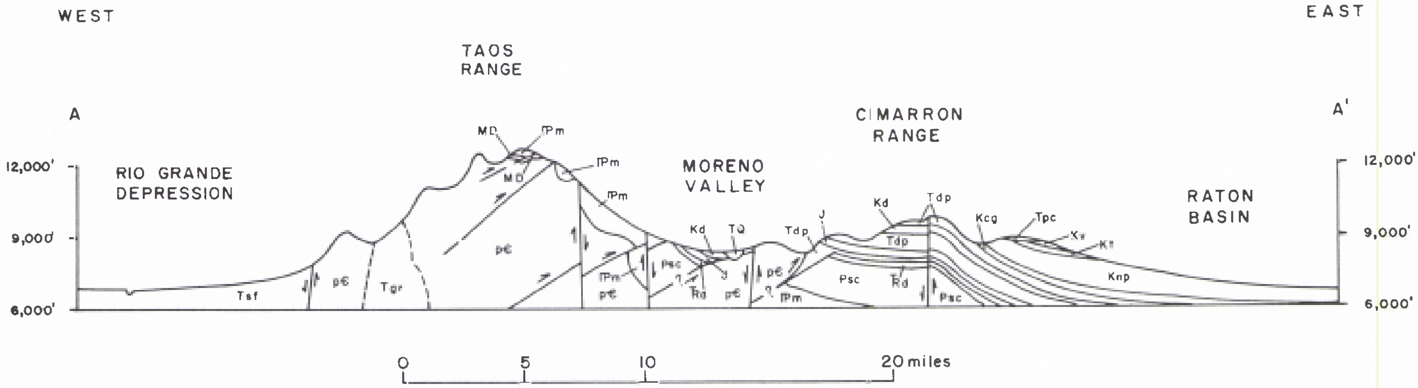

FIGURE 3

Structure Section of Sangre de Cristo Mountains and Adjacent Areas Between Taos and Cimarron, New Mexico.

Vertical scale greatly exaggerated

Undifferentiated Tertiary and Quaternary units (TQ), Santa Fe Formation (Tsf), Tertiary Granite (Tgr), Quartz diorite porphyry (Tdp), Poison Canyon Formation (Tpc), Vermejo Formation (Kv), Trinidad Sandstone (Kt), Pierre Shale and Niobrara Formation (Knp), Carlile Shale, Greenhorn Limestone, and Graneros Shale (Kcg), Dakota Sandstone (Kd), undifferentiated Jurassic (J), Dockum Group (TRd), Sangre de Cristo Formation (Psc), Magdalena Group (IPm), Mississippian and Devonian(?) (MD), undifferentiated Precambrian (p€).

Tertiary and Quaternary deposits which largely obscure exposures in the valley floor. The best attitudes are obtained in the forest-covered slopes on the western side of the valley where upper Paleozoic and Mesozoic strata dip eastward. At several localities in the Moreno Valley, Precambrian rocks are in contact with sedimentary rocks of various ages. These anomalies have been attributed to eastward movement of the Precambrian in diapiric fashion and will be further outlined in a discussion of the Cimarron Range.

The Red River graben truncates the northern part of the Taos horst. This structural feature is aligned in an east-northeast direction, stretching from near the western margin of the Taos Range to Van Diest Peak, 6 miles northeast of Red River village. Over-all the length is about 14 miles and the width ranges from 2 to 4 miles. The graben is a complex area broken by many cross faults which have resulted in a jumble of fault blocks. Along the axis of this structural trough nearly 3,000 feet of Tertiary lavas have been preserved. To the south the base of the volcanics is found on a high platform of Precambrian rocks, where the thickness diminishes until the rocks are absent south of Gold Hill. North of Cabresto Creek and Bonito Canyon, Precambrian mica quartzite is extensively exposed, but the thickness of the volcanics increases thereafter toward Latir Peak. Three stocks of granitic composition and minor intrusions of quartz porphyry have been emplaced along the graben. Associated with these intrusions are widespread alteration effects and mineralization, in particular molybdenum.

The Cimarron Range borders the Moreno Valley on its eastern side and is superficially an anticline-like mountain mass on which sedimentary rocks dip off a Precambrian core westward into the Moreno Valley and eastward into the Raton basin.

Within a radius of 5 or 6 miles of Eagle Nest the Precambrian has been found in contact with rocks ranging in age from Pennsylvanian to Cretaceous, and the question arises whether these contacts are sedimentary or faulted. A fault contact was adopted by Wanek and Read (1956, p. 82-83) to account for the small features found in the Moreno Valley and the much larger structural feature embodied in the Cimarron Mountains. The Precambrian crystalline rocks were considered to have moved upwards in diapiric fashion in the form of plungers of various sizes and with different inclinations to the horizontal. Elsewhere, and in particular in the floor of the Moreno Valley, contact of the Precambrian with sedimentary rocks of various ages might be ascribed to exposure of a flat fault marking the western flank of the postulated Cimarron Range plunger. The flat fault has been cut and displaced by a later high-angle fault as shown in Figure 3, but continues around the north plunge of the anticlinal mountain mass and connects with the steep Fowler Pass thrust fault on the east flank of the range. In consequence the range can best be interpreted as a nearly recumbent anticline the core of which is occupied by a plunger of Precambrian rocks which have a flat underthrust contact with sediments on the west side, and a high-angle overthrust contact with sediments on the east side as indicated by Baltz and others (1959). This diapiric structure is almost unique in the Rocky Mountains, having been reported previously only in the northernmost part of the Sangre de Cristos where Burbank and Goddard (1937, p. 957) encountered similar diapirism in Huerfano Park.

Robinson and others (1964, p. 116) consider that an explanation involving high-angle reverse faults alone is just as likely. Furthermore, Simms (1965, p. 58) found no evidence of flattening of the Fowler Pass fault with depth which is necessitated by the plunger hypothesis.

Another approach was offered by Baltz (1965, p. 2049) which postulates in the vicinity of Eagle Nest, a Paleozoic positive area referred to as the Cimarron arch. It was further suggested that the Laramide deformation invoked by Wanek and Read occurred on this positive area.

The third major structural feature is the Raton basin of southeastern Colorado and northeastern New Mexico. This is the southernmost of the Laramide intracratonic fold basins at the eastern margin of the Rocky Mountains. The northernmost part, in Huerfano Park, is intermontane, but most of the basin lies in the western part of the Great Plains. Throughout its length the Raton basin is bordered on the west by the Sangre de Cristo uplift. To the east the southern part of the basin is bordered by the broad, low, and locally ill-defined Sierra Grande arch. The shallow southern part of the Raton basin has been referred to as the Las Vegas sub-basin by Baltz (1965, p. 2042). The Raton basin is an asymmetrical downwarp with a north-south axis in the western part of the syncline. Preserved within this downwarp is a section of sedimentary units ranging in age from upper Paleozoic through Tertiary. The maximum aggregate thickness of sedimentary rocks in the Las Vegas sub-basin is near 12,700 feet, whereas the aggregate maximum thickness in the northern part of the basin is of the order of 25,000 feet. The length of the basin is about 175 miles in a north-south direction, and it is about 65 miles wide near the New Mexico-Colorado line.

STRUCTURAL EVOLUTION

In Precambrian time the area was included in a basin of deposition. Shallow to moderately deep seas deposited great thicknesses of quartz-feldspathic sands. Minor fluctuations and deepening of the basin are reflected in the accumulation of fine clastic materials and organic shale which were interbedded with thick beds of sand. Later the character of deposition changed so that vast quantities of argillaceous materials accumulated in a deepened basin. Igneous activity was not lacking, as basic and ultrabasic rocks, indicating the first stages of crustal unrest, became interbedded with muddy and calcareous sediments. Later in Precambrian time, compressional forces began to act on the sedimentary prism and a northeasterly grain was impressed sufficiently strongly on the metamorphosed rocks to survive all later events. New minerals were produced, and they became oriented in planes perpendicular to regional compression, thereby producing a northeasterly foliation which largely obliterated the sedimentary structures. During the later stages of regional metamorphism, the emplacement of granite characterized the first stage of orogenesis. The surrounding metamorphic rocks were profoundly affected, and, along the margins of the granites migmatitic rocks were produced. The ebbing regional compressive forces were still strong enough to impart a foliation to the granite. The final chapters of Precambrian tectonic history include the transfer of late-stage fluids into fractures in the granite and surrounding rocks, to become pegmatites and quartz veins. Later, intrusion of diabase dikes was possibly synchronous with regional uplift.

The positive area created in late Precambrian time appears to have been preserved throughout lower Paleozoic time as part of a broad, southwest-trending continental arch. By late Devonian(?) time the positive area had been sufficiently levelled to allow the transgression of a shallow sea. Due to repeated crustal warping sediments were only intermittently deposited through Mississippian time with unconformable relationships between the lithologic units.

Pennsylvanian time was marked by orogenic uplift in northern New Mexico and Colorado. Positive areas—the Ancestral Rocky Mountains—were produced and separated from one another by troughs in which vast quantities of marine sediments accumulated. The area of the present Sangre de Cristo uplift and Las Vegas sub-basin was part of the Rowe-Mora geosyncline which lay between the ancestral San Luis and the Sierra Grande uplifts. The San Luis uplift, on the western margin of the geosyncline, was part of a positive element throughout late Paleozoic and early Mesozoic time. Deposition continued into Early Permian time, but the character of sedimentation changed with the advent of a continental environment. The extent to which deposition continued in Permian time is in doubt as the upper formations are missing, but this is probably due in part to non-deposition following infilling of the trough, accompanying reduction of the positive areas to near base level.

Mesozoic time records the further accumulation of continental deposits of Late Triassic and Late Jurassic age as crustal warpings continued. But in Cretaceous time gradual deepening of a basin was accomplished and appreciable thicknesses of marine shale and limestone were deposited. The withdrawal of seas at the end of Cretaceous time presented the third major orogeny in the region.

Uplift was reflected by the accumulation of coarse clastic materials of Paleocene age. The present Sangre de Cristo Mountains were being formed by a series of closely spaced orogenic episodes culminating in a period of folding and thrusting to the east in late Eocene or early Oligocene time. The Raton basin was also formed at this time as a complementary downwarp to the Sangre de Cristo uplift. In late Oligocene and early Miocene time extrusion of a volcanic series was accomplished in north-central New Mexico and adjacent areas in Colorado. Later the volcanics were intruded by a series of bodies of acid igneous rocks along lines of structural weakness. This was accompanied by faulting, alteration, and mineralization in the Red River district, and intrusion and mineralization in the Elizabethtown district. The final phases of high-angle faulting took place in Miocene and Pliocene time. The eastern margin of the ancient San Luis uplift appears to be the downfaulted Rio Grande depression, while locally to the east the intermontane Moreno Valley was developed. Uplift of the intervening area resulted in the production of the Taos Range while the Red River graben was depressed on its northern side.

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