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1971, pp. 249-264. https://doi.org/10.56577/FFC-22.249

in:

San Luis Basin (Colorado), James, H. L.; [ed.], New Mexico Geological Society 22 nd Annual Fall Field Conference Guidebook, 340 p. https://doi.org/10.56577/FFC-22

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GEOLOGICAL DEVELOPMENT OF THE BONANZA-SAN LUIS VALLEY-SANGRE DE CRISTO RANGE AREA, SOUTH-CENTRAL COLORADO

by

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INTRODUCTION

GENERAL

Interest in the Cenozoic geologic history of Colorado has intensified in recent years with increasing emphasis on research projects by U.S. Geological Survey geologists and university and industry personnel. The complex volcanic stratigraphy and the history of the geomorphic and structural development are only slowly being pieced together.

This paper summerizes contributions made by previous workers and work presently in progress by the authors in the area of the Bonanza volcanic field and northern San Luis Valley and Sangre de Cristo Range (fig. 1). This area is part of a comprehensive remote sensing test site where personnel of the Bonanza Remote Sensing Project (N.A.S.A. Grant NGL 06-001-015) at the Colorado School of Mines are investigating the application of remote sensing to geologic problem solving. Our work has entailed: (1) detailed and reconnaissance field mapping, (2) remote sensor data interpretation and field checking, and (3) compilation, field checking, and modification of geologic maps covering various portions of the area (fig. 2).

GEOGRAPHIC AND GEOLOGIC SETTING

Several factors influenced the choice of this area for concentrated geologic investigation: (1) It includes representative examples of fold-thrust structures produced during the Laramide orogeny; (2) Details of Cenozoic volcanism in the Bonanza volcanic field are critical to unraveling the history of volcanic activity in central and southwestern Colorado and understanding the relationships among individual volcanic fields (Bonanza, San Juan, Thirtynine Mile, etc); (3) The complex internal portion of the Rio Grande depression emerges from beneath Quaternary alluvial deposits in this area; (4) The structural link between the San Luis Valley and Arkansas River Valley occurs in this area.

Topographically the area consists of a horseshoe-shape of mountains including the northern Sangre de Cristo Range on the east, the high peaks of the Bonanza volcanic field and southern Sawatch Range on the west, and the Poncha Pass area separating the San Luis and Arkansas valleys on the north. The Villa Grove reentrant of the northern San Luis Valley occupies the center of the horseshoe (fig. 3).

Several hot springs emerge in the area (table 1). Mineral Hot Springs, a one-time resort, is at the southern edge of the area in the San Luis Valley. Valley View Hot Springs is several miles northeast of Mineral Hot Springs along the Sangre de Cristo Range front. Poncha Hot Springs, at the northern edge of the area near the town of Poncha Springs, is currently the source of hot water for the Salida municipal swimming pool.

TABLE 1.
TEMPERATURES OF LOCAL HOT SPRINGS

HOT SPRINGS	TEMPERATURES
Poncha Hot Springs	153° F
Mineral Hot Springs	90°-131° F
Valley View Hot Springs	87°-92° F

ACKNOWLEDGMENTS

Over the years numerous persons have studied the geology of various portions of the area. Of particular interest is the work of Burbank (1932), Gableman (1952), Litsey (1958), Van Alstine (1968; 1970), and Van Alstine and Lewis (1960). In addition, unpublished graduate theses by students of the Colorado School of Mines and the University of Colorado have contributed immeasureably to understanding the geology of the region.

We gratefully acknowledge the financial and moral support given us by the Bonanza Project team at the Colorado School of Mines. Pilots and crew aboard N.A.S.A. remote sensing aircraft have done an outstanding job of providing remote sensor data over most of the area.

We are indebted to Dr. Robert J. Weimer, Dr. Rudy C. Epis, and Dr. Keenan Lee of the Colorado School of Mines for critically reading the manuscript.

STRATIGRAPHIC SUMMARY

PRECAMBRIAN

Precambrian igneous and metamorphic rocks are exposed (1) in the Kerber Creek area, (2) within the Bonanza volcanic field, (3) at the southern end of the Sawatch Range, and (4) in the northern Sangre de Cristo Range. Very

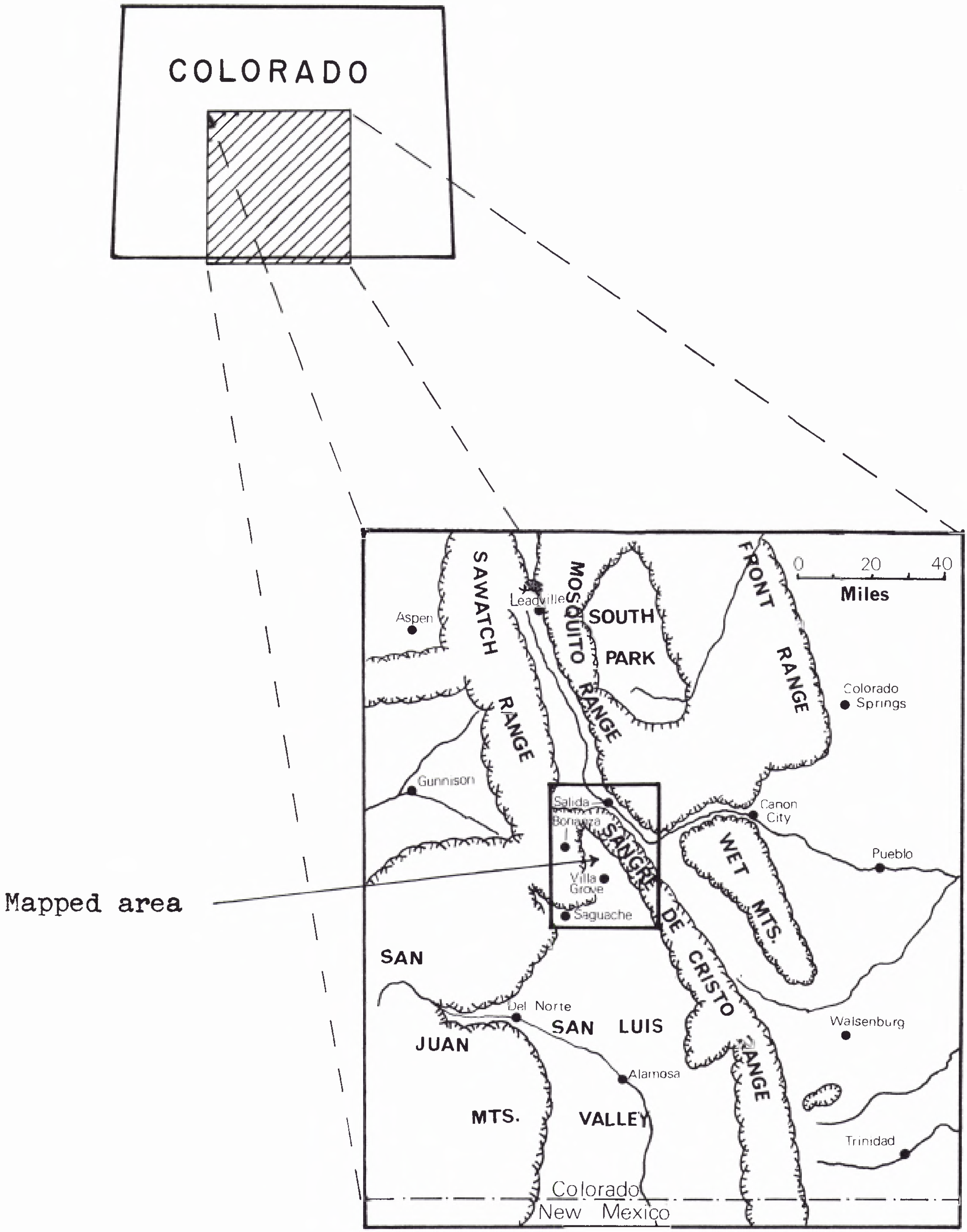


FIGURE 1.
Index map of Bonanza-Northern San Luis Valley-Northern Sangre de Cristo area.

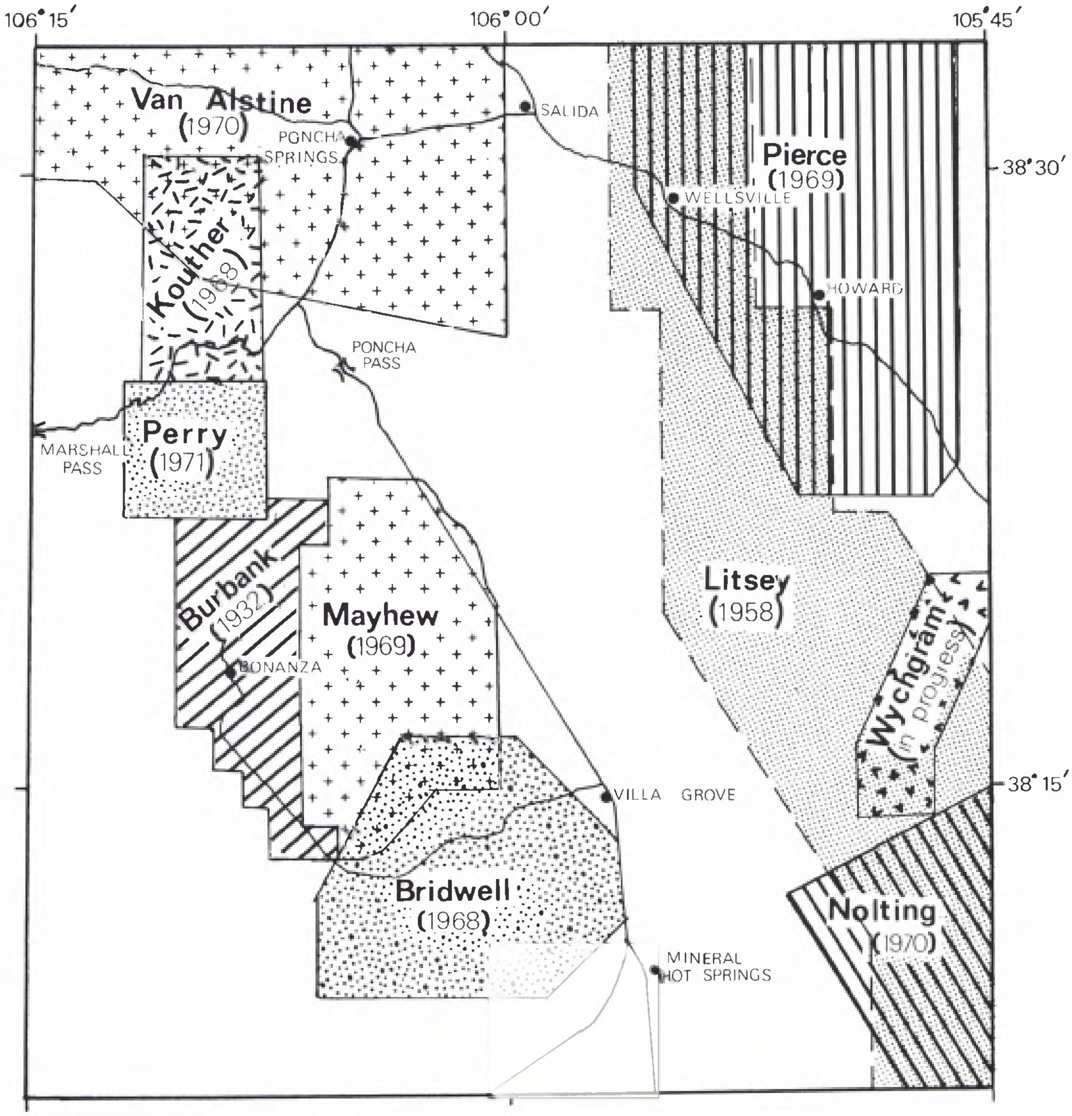


FIGURE 2.
Index of previous investigations in study area.

little detailed work has been done on the Precambrian rocks of the map area, and the summary will be correspondingly brief.

Southern Sawatch Range

Precambrian rocks of the southern Sawatch Range are exposed in the northwest portion of the map area (see plate 1, back pocket). The detailed work of Kouther (1968) and Perry (1971), and observations of the authors in this area are summarized below.

Metamorphic Rocks.—The texture and composition of the metamorphic rocks are variable, but these rocks can be generally grouped into three units: (1) muscovite-quartz schist, (2) amphibolite gneiss, and (3) quartz-feldspar gneiss. Remnant sedimentary structures have not been observed in the metasedimentary layers so the original stratigraphic sequence cannot be determined with certainty. Because of structural relations, the muscovite-quartz schist is believed to be the oldest unit and the quartz-feldspar gneiss the youngest. The older basement upon which the metamorphic rocks lie is not exposed in the map area; the metamorphic rocks are, therefore, the oldest rocks in the area.

Igneous Rocks.—Precambrian igneous rocks in this area consist of granodiorite, graphic granite, diorite, and pegmatite. This igneous sequence has intruded the older metamorphic complex. Occurrences of these rock types are local and represent only a small portion of the Precambrian terrain.

Bonanza Volcanic Field

Rocks of Precambrian age are exposed within the Bonanza volcanic field as a result of faulting and the exhuming of hills once covered by a sequence of Tertiary volcanic

FIGURE 3.

View southwest over extreme north end of San Luis Valley. North end of Sangre de Cristo Range lower left. San Luis Valley directly above. Ring of mountains in upper left is Bonanza volcanic field; note collapsed central portion. Snow-covered peak on extreme right is Ouray Peak. Prominent drainage channel in center of picture is Poncha Creek. Photo taken with panchromatic infrared film by Dr. Keenan Lee aboard N.A.S.A. C-130 remote sensing aircraft in June 1971.

rocks. In the northern part of the field, the Precambrian rocks consist of an older metamorphic complex similar to that of the southern Sawatch Range, which has been intruded by medium-grained aplitic granite (Burbank, 1932, p. 6). South of Kerber Creek, the Precambrian rocks are predominantly coarse-grained, porphyritic granite containing local xenoliths of gneisses and schists.

Kerber Creek Area

Precambrian and Paleozoic rocks are exposed over a wide area at the southeastern edge of the Bonanza volcanic field. The Precambrian rocks occur in the cores of the Central and Eastern anticlines (Burbank, 1932) and on the upper plates of the Kerber and Noland faults. The Precambrian rocks of these two areas are markedly different and distinct.

On the upper plates of the Kerber and Noland faults, coarse-grained, well-foliated, porphyritic granite containing potash feldspar phenocrysts from 10 to 20 mm long is exposed (Bridwell, 1968, p. 9). The granite contains local xenoliths of metamorphic rocks including hornblende-biotite gneiss and biotite-hornblende schist. A tectonic breccia composed primarily of this granite, but also including a few boulders of Paleozoic sedimentary rocks, is exposed at the nose of the ridge between Kerber and Little Kerber creeks. The breccia is probably an outlier of the sole of the Kerber fault.

Fine-grained biotite granite (aplitic granite of Burbank, 1932) occurs in the cores of the Central and Eastern anticlines. Xenoliths of quartz-mica gneiss and biotite schist occur in the granite (Bridwell, 1968, p. 9). Cross-cutting relationships suggest that the coarse-grained granite intruded into the metamorphic complex and was subsequently invaded by the fine-grained granite (Bridwell, 1968, p. 9). These same relationships have been observed just north of Saguache in the Precambrian rocks exposed in windows through the Bonanza volcanics.

Northern Sangre de Cristo Range

Precambrian rocks of the northern Sangre de Cristo Range have not been studied in detail. Gableman (1952) reported the occurrence of schists, fine-grained hornblende and biotite gneisses, quartzites, and granites. The metamorphic rocks have been intruded in varying degrees by dikes of granite and pegmatite, and several small granitic plutons. Foliation in the metamorphic rocks is generally well developed and at a distance is easily mistaken for stratification in the Paleozoic sedimentary sequence. The metamorphic foliation defines distorted north-trending isoclinal folds with steeply dipping limbs (Gableman, 1952, p. 1581).

The unconformity developed on Precambrian rocks below the Paleozoic sedimentary sequence generally displays less than 10 feet of relief. The weathering zone developed at this surface is generally thin, not exceeding 5 feet in most places (Litsey, 1958, p. 1147).

Cambrian

No rocks of Cambrian age have been reported in the northern Sangre de Cristo Range. In the Kerber Creek area the Late Cambrian Sawatch Quartzite (0-20 feet) is sporadically present at the base of the Paleozoic sedimentary sequence. The thickness of the Sawatch is variable, but locally it attains a thickness of 20 feet. Where present, the Sawatch lies on a relatively flat surface cut on Precambrian rocks. The Sawatch is composed of hard, fine- to medium-grained quartz sandstone containing lenses of quartz-pebble conglomerate in the upper portion (Bridwell, 1968, p. 11).

Ordovician

Manitou Formation (90-225 feet)

Throughout the map area, except where the Sawatch Quartzite is present, the Manitou Formation lies at the base of the Paleozoic sedimentary sequence, nonconformably overlying Precambrian crystalline rocks. Where the Sawatch Quartzite occurs below the Manitou the contact between the two units is gradational. This relationship observed by Bridwell (1968) suggests that the absence of the Sawatch Quartzite in some areas is due to non-deposition rather than erosion. The Manitou is a thinly-bedded, brown to gray dolomite and dolomitic limestone containing lenses and nodules of white to black chert aligned parallel to stratification. In the Kerber Creek area the chert is predominantly in the middle portion of the unit (Bridwell, 1968, p. 15). In the Sangre de Cristo Range chert is most prominent at the base and in a zone near the top (Gableman, 1952, p. 1582).

Faunal evidence from various locals in Colorado indicate an Early Ordovician age for the Manitou (Johnson, 1945, p. 18).

Harding Sandstone (60-116 feet)

The Harding Sandstone disconformably overlies the Manitou throughout the map area. The Harding is a hard, white, fine- to medium-grained quartz sandstone with a silica cement (Bridwell, 1968, p. 16). The quartz grains are generally well-rounded and well-sorted. Iron oxide from the oxidation of magnetite gives the Harding a red to brown coloration (Gableman, 1952, p. 1582). In the northern Sangre de Cristo Range the Harding has a basal zone of grayish-red to green shales with thin interbedded sandstones totaling 15 to 30 feet thick (Litsey, 1958, p. 1152). This shale section has not been reported to the west.

The Harding Sandstone is generally unfossiliferous. Fish plates have been identified by Kouther (1968, p. 34) and Bridwell (1968, p. 16) as belonging to *Eriptychius americanus* Walcott and *Astraspis desiderata* Walcott indicating a Middle Ordovician age for the Harding.

Fremont Formation (229-300 feet)

The Fremont Formation disconformably overlies the Harding Sandstone. The Fremont consists of gray, thick- to massive-bedded dolomite locally interlayered with thin sandy dolomites and cherty dolomites (Bridwell, 1968, p. 17; Gableman, 1952, p. 1583). Rough pit and cusp weathering surfaces are characteristic of most Fremont outcrops.

Although the Fremont is fossiliferous, preservation of fossils is generally poor. Horn corals and the chain coral *Halysites* are common, and fragmental brachiopod shells and straight cephalopod shells have been reported from the Fremont (Litsey, 1958, p. 1154). Remains of *Ephippiorthoceras sp.*, a straight-shelled cephalopod, were identified by Bridwell (1968, p. 18) in the Kerber Creek area, and Kouther (1968, p. 18) to the north along Droz Creek. The faunal remains in the Fremont indicate a Late Ordovician age (Bridwell, 1968, p. 18).

Silurian

No rocks of Silurian age have been discovered in the map area. Remnants of Silurian carbonate strata near the Colorado-Wyoming state line suggest that Silurian sedimentary rocks may once have covered the area, but have since been removed by erosion prior to the deposition of the first Devonian rocks.

Devonian

Chaffee Formation

The stratigraphic break represented at the contact between the Chaffee Formation and the underlying Fremont Formation is the largest gap in the pre-Pennsylvanian sedimentary record (Litsey, 1958, p. 1154). The Chaffee Formation consists of two members: the lower Parting Quartzite Member and the upper Dyer Dolomite Member.

Parting Quartzite Member (10-62 feet).—The Parting Quartzite is a lithologically variable unit containing resistant quartzite, varigated siltstones and shales, limestones, conglomerate, and friable sandstone (Bridwell, 1968, p. 19; Litsey, 1958, p. 1154). The unit is everywhere present in the Paleozoic section except in a small area near Bushnell Lakes in the northern Sangre de Cristo Range (Litsey, 1958, p. 1154). It is easily distinguished in the field by its overall red to pink coloration making it an excellent stratigraphic marker (Gableman, 1952, p. 1584). The Parting is thought to be of Late Devonian age based on fish remains (Behre, 1932).

Dyer Dolomite Member (87-123 feet).—The contact between the Dyer Dolomite and the underlying Parting Quartzite is gradational through several feet. The Dyer is composed of yellow- to tan-weathering microcrystalline dolomite, interlayered with thin-bedded cherty limestones (Litsey, 1958, p. 1155; Bridwell, 1968, p. 20). Fragments of fish bones, teeth, and plates in the Dyer suggest a Late Ordovician age (Johnson, 1945, p. 329).

MISSISSIPPIAN

Leadville Limestone (210-336 feet)

The Leadville Limestone disconformably overlies the Dyer Dolomite Member of the Chaffee Formation. The Leadville consists predominantly of blue to gray, fine-grained, massively-bedded limestone and gray to black, medium-bedded dolomite. Intraformational breccias are locally present particularly near the base (Litsey, 1958, p. 1157; Bridwell, 1968, p. 21).

The lower portion of the Leadville is generally chert-free, but thick-bedded irregular black and gray chert nodules are locally present in the upper portion (Gableman, 1952, p. 1586).

The thickness of the Leadville is quite variable due to extensive erosion, including the development of karst topography, prior to deposition of the first Pennsylvanian sediments.

Fossils are relatively rare in the Leadville. Litsey (1958, p. 1157) observed poorly preserved brachiopods and horn corals in the northern Sangre de Cristo Range. Faunal evidence elsewhere in the state indicates an Early Mississippian age (Kinderhookian or Osagian) for the Leadville (Johnson, 1945, p. 52).

PENNSYLVANIAN AND PERMIAN

Pennsylvanian and Permian rock outcrops cover more area than all of the pre-Pennsylvanian Paleozoic units combined. Because the stratigraphy of the Pennsylvanian and Permian rocks will be comprehensively treated elsewhere (see De Voto and Peel, this guidebook) only a few general remarks will be given here.

The older Pennsylvanian rocks consist of fine- to medium-grained clastic rocks and limestones, typically gray or black. The younger Pennsylvanian rocks are primarily fine- to coarse-grained micaceous clastic rocks characterized by red to brown colors. The Pennsylvanian-Permian and Permian units are primarily coarse to very coarse-grained clastic rocks, but they also include finer grained material and nodular limestones (Litsey, 1958, p. 1159-1161).

TERTIARY

Bonanza Volcanic Field

Oligocene volcanic rocks of the Bonanza volcanic field (Steven, Mehnert, and Obradovich, 1967; Epis and Chapin, 1968) cover most of map area west of the Villa Grove reentrant of the San Luis Valley. The volcanic rocks are primarily lava flows, breccias, tuffs, and ash-flow tuffs. Locally, irregular masses and dikes of rhyolite, latite, and monzonite porphyry occur in the extrusive sequence (fig. 4).

The volcanic sequence was subdivided by Patton (1916) and Burbank (1932) into Rawley Andesite, Hayden Peak Latite, Bonanza Latite, Squirrel Gulch Latite, Porphyry Peak Rhyolite, and Brewer Creek Latite. The lower part of the division (Rawley and Bonanza units) is applicable throughout the Bonanza area with relatively little modification. The units above the Bonanza Latite have rather limited distributions and considerable lithologic variation. Individual investigators have, therefore, divised somewhat different subdivisions for units above the Bonanza Latite (see Bruns, Epis and Weimer, this guidebook).

Rawley Andesite (200-2,600 feet).—The earliest flows, named for an occurrence on the slopes of Rawley Gulch, fluctuate markedly both in thickness and composition. The great variation in thickness is mostly due to the pre-volcanic topography present at the time of extrusion. The earliest flows were concentrated in topographic lows, but the Rawley sequence accumulated until even the hill-tops were buried.

The Rawley flows are predominantly andesites and latites. However, ash beds and lahar breccias are locally present in considerable quantities. The lahar breccias are generally quite thick and consist of blocks and boulders of andesite and latite in an ashy matrix.

Lithologic subdivisions within the Rawley have been made at many locations throughout the area, but correlation of these various units across the area has been impossible due to extreme lateral variation within the lithologic sequence. The Rawley is a conglomeration of units originating from several sources, some within and others outside of the Bonanza area. Correlation of these units is further hindered by complex structure and the erosion locally evident on the upper surface and between units within the Rawley.

Hayden Peak Latite (1,000-1,500 feet).—The Hayden Peak Latite is a series of latite, andesite, and rhyolite flows cropping out in the eastern part of the Bonanza volcanic field. Mayhew (1969, p. 11) observed that the Hayden Peak Latite and Rawley Formation were interstratified in the eastern Bonanza area and thus, are contemporaneous. In addition, flows of the Hayden Peak Latite are lithologically similar to the flows of the Rawley Formation. The authors have, therefore, considered the Hayden Peak Latite as part of the Rawley.

Bonanza Tuff (500-1,000 feet).—The Bonanza Latite of Burbank (1932), recently renamed the Bonanza Tuff (Mayhew, 1969, p. 14-15), overlies the Rawley Formation almost everywhere in the area. It consists of at least five cooling units of red to buff biotite-rich latite ash-flow tuff. Compaction foliation and flattened pumice lapilli are common. Typically the Bonanza Tuff contains abundant purplish andesite fragments. Because the Bonanza Tuff is such a distinctive unit and is present throughout the Bonanza volcanic field, it plays an important role in correlation and mapping of the total volcanic sequence.

In the central Bonanza volcanic pile the Bonanza Tuff is highly welded and only two units can be distinguished. Toward the south, particularly along the prominent ridge west of Findley Gulch, the Bonanza Tuff separates into five distinct cooling units (fig. 5). Northward along this ridge the various units merge together until they appear as one. This southward separation of the Bonanza into several cooling units indicates that the source of the Bonanza Tuff lies to the north where the temperature and thickness of the successive ash-flows was sufficient to weld them together as they cooled.

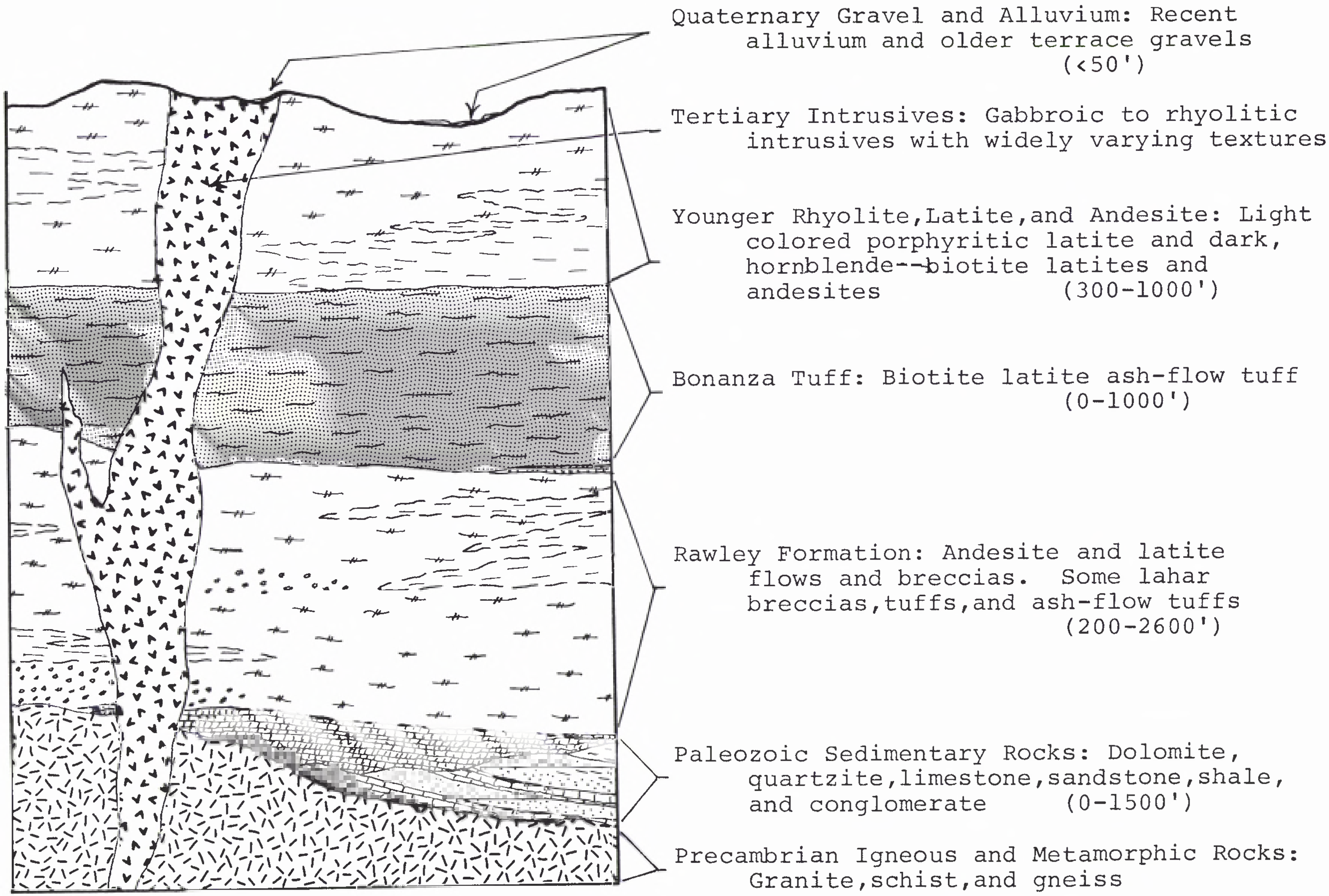


FIGURE 4.

Generalized columnar section of Bonanza area.

FIGURE 5.

Photograph showing five separate cooling units of Bonanza Tuff along ridge west of Findley Gulch (near Saguache, Colorado).

The erosion surface on which the Bonanza was deposited has more than 200 feet of relief locally, indicating that the Bonanza Tuff is considerably younger than the underlying Rawley Formation. Pseudo-synclinal structures that normally develop during compaction of an ash-flow in a valley are not present in the Bonanza area to any degree. The earlier ash-flows of the Bonanza Tuff quickly buried the pre-existing topography; the later Bonanza ash-flows spread out from the source in sheet-like masses producing units with broad, uniform distribution.

Younger Rhyolite, Latite, and Andesite Flows (300-1,000 feet).—Burbank (1932) divided the flows overlying the Bonanza Tuff into four units; Squirrel Gulch Latite, Porphyry Peak Rhyolite, Brewer Creek Latite, and Younger Andesite. With the exception of the Porphyry Peak Rhyolite, these are dark, hornblende-biotite latites and andesites. The Porphyry Peak is a light-colored biotite rhyolite which crops out in the vicinity of Porphyry Peak. Burbank (1932, p. 26) describes this unit as a sequence of flows and some intrusive rhyolite, but Perry (1971) believes that the Porphyry Peak Rhyolite is an endogenous dome.

Mayhew (1969) separated the flows above the Bonanza Tuff into three units which he called the Younger Andesite, Younger Ash-Flow Tuff, and Younger Latite. These units were not positively correlated with Burbank's upper units. Mayhew also distinguished a separate quartz latite unit which crops out on the upper slopes and summit of Hayden Peak. Burbank (1932) included this unit in the Hayden Peak Latite, but Mayhew believes it is definitely post-Hayden Peak Latite and may be younger than the Bonanza Tuff. Furthermore, he believes that the Hayden Peak Quartz Latite is an endogenous lava dome (Mayhew, 1969, p. 34).

Current work in the southern Bonanza volcanic field has revealed that a sequence of dark andesite and latite flows overlie the Bonanza Tuff in that region. This sequence has been tentatively called the Dry Gulch Andesite for excellent exposures along Dry Gulch northwest of Saguache. The Dry Gulch Andesite may prove equivalent to Burbank's Squirrel Gulch Latite, Brewer Creek Latite, and Younger Andesite.

OTHER VOLCANICS

Mapping in the Howard area has distinguished at least three volcanic units existing as scattered erosional remnants (Pierce, 1969, p. 71). These include (1) a gray, sanidine-rich, welded, lapilli tuff which may be equivalent to Ash-flows 1 and 2 of the Thirtynine Mile volcanic field to the north (Chapin and Epis, 1964), (2) other tuffaceous units mapped as Undifferentiated Tuff, and (3) a sequence of andesite and basalt lava flows. Pierce believes that the ash-flows are of Oligocene age and correlate with lower flows of the Thirtynine Mile volcanic field which are time equivalents of parts of the Rawley Formation in the Bonanza volcanic field. He correlates the andesite and basalt flows with probable Miocene-age flows mapped by Duhamel (1968) in the Waugh Mountain area of the Thirtynine Mile field (Pierce, 1969, p. 98).

Intrusive Rocks

Intrusive rocks ranging from rhyolite to gabbro are concentrated in the central portion of the Bonanza volcanic field. Emplacement of many of the smaller intrusive bodies was obviously fault controlled. The relative ages of the intrusives is often difficult to establish, but relationships that can be established seem to indicate that the more silicic intrusives represent late stages of the intrusive activity.

Several intrusives have also been mapped in the northeastern part of the map area. These include the Rito Alto stock east of Valley View Hot Springs, the Slide-Rock Mountain stock in the Hayden Pass area, and the Whitehorn stock in the Wellsville area to the north. These intrusives range in composition from rhyolite to monzonite and have intruded into Pennsylvanian-Permian sedimentary rocks (Burbank and Goddard, 1937; Toulmin, 1953; Rold, 1950; Litsey, 1958; Pierce, 1969; Nolting, 1970). According to Litsey (1958, p. 1168) the Rito Alto stock is probably Early to Middle Miocene. Pierce (1969, p. 68) found that the contact between the Whitehorn stock and the Pennsylvanian-Permian sedimentary rocks suggests a very Late-Laramide or post-Laramide emplacement.

Tertiary Sedimentary Units

Sediments deposited in a Tertiary trough between the Arkansas and San Luis valleys include several thousand feet of clays, silts, sands, and gravels with minor amounts of limestone and volcanic ash (Van Alstine, 1968, p. C158). Fossil horse teeth and camel bones (Powers, 1935, p. 189; Van Alstine and Lewis, 1960) found at localities in the Arkansas Valley indicate that these sediments are mainly of Pliocene age although the lower part of this sedimentary sequence is of Late Miocene age. These sediments can be correlated with the Dry Union Formation in the Leadville area (Tweto, 1961).

An equivalent formation was mapped by Pierce (1969) in the Howard area. He called this sequence the Pleasant Valley Conglomerate and postulated that it resulted from fluvitile deposition contemporaneous with the uplift of the Sangre de Cristo Range in Miocene and Pliocene time (Pierce, 1969, p. 98).

QUATERNARY

Quaternary sediments occur in the Arkansas Valley, the Howard area, the Villa Grove reentrant of the San Luis Valley, and along major drainage channels. Of primary interest are the large alluvial fans along both the east and west sides of the Villa Grove reentrant, and gravel-capped pediment surfaces on the west side of the Villa Grove reentrant and in the Howard area. Both alluvial fan deposits and pediment gravels are characterized by locally derived material.

In the Howard area, four pediment levels were mapped by Pierce (1969, p. 76-78). The four pediment surfaces are 265, 200, 110, and 70 feet above modern stream base, respectively. Pierce (1969) tentatively correlates the two highest surfaces with the Rocky Flats and Verdos surfaces developed along the eastern flank of the Front Range. These surfaces are interpreted by Scott (1963, p. 11) to be Nebraskan and Kansan age respectively.

On the west side of the Villa Grove reentrant, Mayhew (1969, p. 41) mapped three surfaces as pediments. Subsequent work indicates that only the highest surfaces are remnants of gravel-capped pediments now largely destroyed by erosion. Later alluvial fan deposits cover much of the area. The exact age of the pediment surfaces has not been determined; nor have these pediments been successfully correlated with the pediments in the Howard area.

Along the eastern side of the Villa Grove reentrant four ages of alluvial fans have been mapped. No pediments have been found. The different fans can be distinguished by their areal extent, degree of dissection, angle of slope, and amount of vegetative cover (table 2). The three older fans are outwash fans developed during Bull Lake and Pinedale (Wisconsinian) glacial stades (Scott, 1970, p. C17).

TABLE 2.
DESCRIPTIONS OF QUATERNARY ALLUVIAL FANS ALONG THE WEST FLANK OF THE SANGRE DE CRISTO RANGE

HOLOCENE	
Qaf 1	Small, steepy-sloped cones deposited along pre-existing erosional and fault scarps.
PLEISTOCENE	
Qaf 2	Large, gently-sloped, undissected fans supporting moderate vegetation growth.
Qaf 3	Large, steeply-sloped, dissected fans with sparse vegetation.
Qaf 4	Large, steeply-sloped, highly dissected fans with sparse vegetation. Only relatively small remnants preserved.

Two features, one along Carr Gulch and the other along Piney Creek, were identified on air photos as debris or mud flows. It appears that unconsolidated material deposited in the canyons moved in-mass out onto the surface of fan system 3. These features have not yet been studied in the field.

Pleistocene moranial material occurs at high elevations west of the Villa Grove reentrant. East of the reentrant moraines extend to the mouths of some canyons facing the San Luis Valley near the southeast corner of the map area (Nolting, 1970, p. 53). Effects of alpine glaciation have not yet been investigated in detail.

Quaternary sediments in the Bonanza mountains occur mostly along stream valleys. These include narrow strips of alluvium along some streams, a few small terrace remnants, and landslides. The stream terrace remnants are of particular interest because they are displaced along youthful faults.

GEOLOGIC HISTORY

PRECAMBRIAN

Details of the Precambrian geologic history of the map area are sketchy at best, however, a generalized sequence of events can be tentatively outlined.

Record of the Precambrian geological development of the area begins with the deposition of an unknown thickness of silicious clastic sediments, probably in Late Precambrian time. The basement upon which these sediments accumulated is not exposed anywhere in the map area.

The sediments were metamorphosed and intensely deformed. Pods and lenses of mafic magma were syntectonically emplaced in the sediments and subsequently metamorphosed to amphibolites (Pierce, 1969, p. 10). Both sediments and intrusives acquired strong primary foliation during this initial phase of deformation.

The metamorphic rocks were subsequently invaded by silicic to intermediate plutons, sills, and dikes. The oldest intrusive rock is the coarse-grained, porphyritic granite of the Kerber Creek area. Emplacement of this unit was followed by intrusion of aplitic granite of the Kerber Creek area. Foliation in both units suggests that they were emplaced syntectonically. Pegmatites crosscut both rock types (Bridwell, 1968, p. 9). Small local intrusions of granodiorite, diorite, and graphic granite invaded all older Precambrian rocks and post-date major Precambrian deformational episodes.

The Precambrian rocks were uplifted and underwent erosion in Late Precambrian (?) and Cambrian time before being submerged beneath the Late Cambrian sea.

PRE-PENNSYLVANIAN

During Early and Middle Cambrian time Colorado was a highland along the northeast-trending Transcontinental arch. By Late Cambrian the eastern and western seas had merged through a structurally low area on the arch called the Colorado sag (Haun and Kent, 1965, p. 1783). The map area was located in the Colorado sag on the north flank of the Sierra Grande uplift (fig. 6).

Fine-grained sand of the Sawatch Quartzite was deposited in the area during the Late Cambrian. Slight uplift of the Sierra Grande Highland raised the area above the sea and much of the Sawatch was stripped off. The

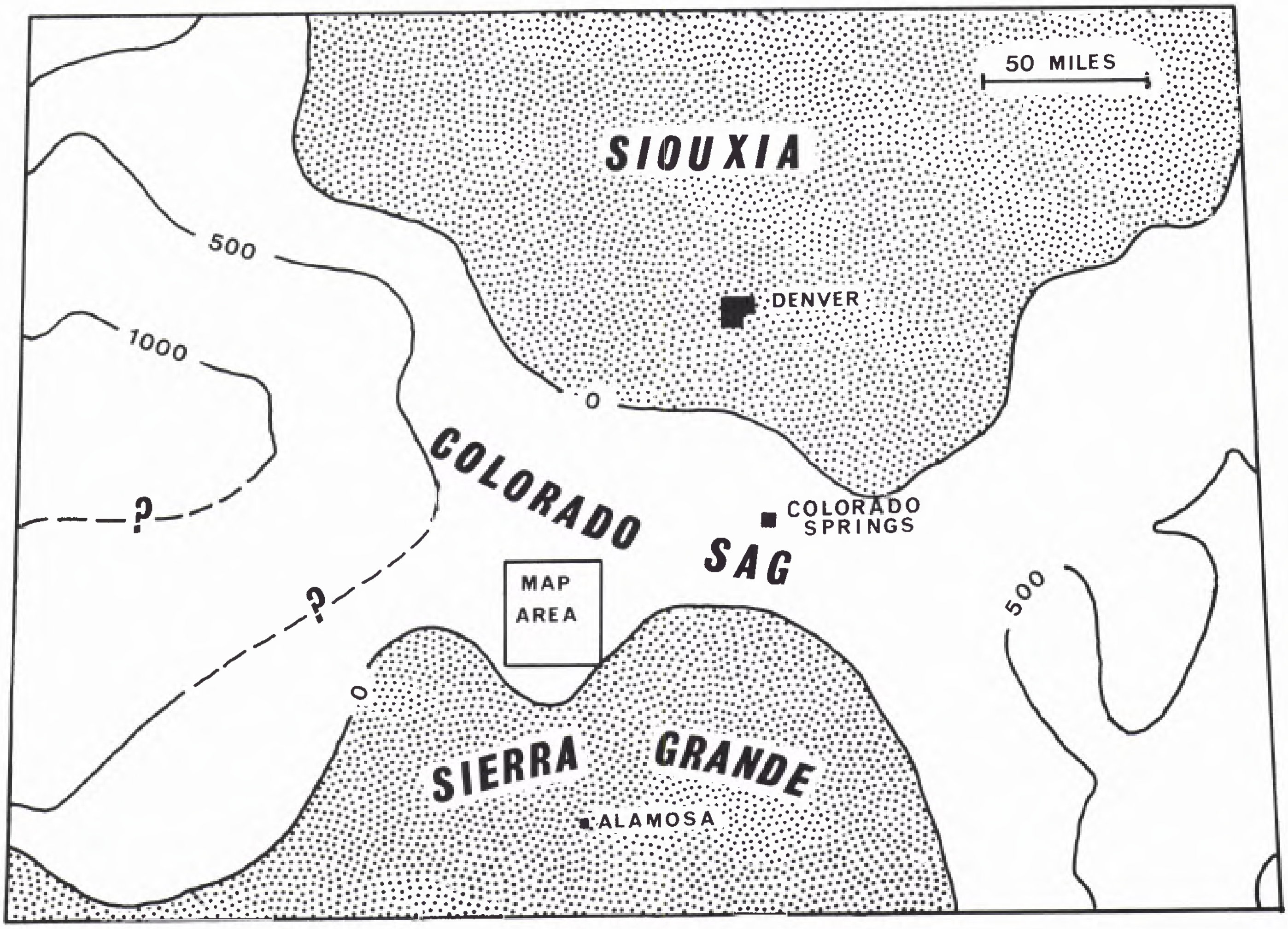


FIGURE 6.

Isopach map of Cambrian and Lower Ordovician rocks in Colorado outlining Early Paleozoic high areas. (Modified from Berg, 1960).

area then subsided and was once again covered by the sea (Gableman, 1952, p. 1582). As the sea returned to the area the Early Ordovician Manitou Formation was deposited over exposed Precambrian crystalline rocks and erosional remnants of the Sawatch Quartzite. The sea briefly retreated from the area before the Harding Sandstone was deposited in Middle Ordovician time. Brief uplift before the deposition of the Late Ordovician Fremont Formation is postulated for the eastern half of the area while continuous deposition took place in the western half.

Although Silurian strata do not occur in central Colorado, regional data suggest continuous marine deposition from Late Ordovician through Silurian time. In Early Devonian time the sea withdrew and a period of extensive erosion ensued lasting until the Late Devonian (Haun and Kent, 1965, p. 1784). In the map area all Silurian strata (if present) were removed and the Fremont Formation extensively eroded, but not entirely removed.

During Late Devonian the sea transgressed eastward from the Cordilleran geosyncline across the map area into eastern Colorado (Haun and Kent, 1965, p. 1785; Litsey, 1958, p. 1172). As the sea advanced over the area it reworked weathered debris on the surface into the Parting Quartzite Member of the Chaffee Formation. Deposition of these basal clastics was followed by carbonate sedimentation forming the Dyer Dolomite Member of the Chaffee.

In Early Mississippian time (Kinderhookian and Osagain) the Leadville Limestone was deposited across the map area. A northwest-southeast trending facies change at the base of the Leadville reveals that the eastern half of the map area was briefly raised above the sea prior to Leadville deposition. The facies change probably reflects an early pulse of the building of the ancestral Rockies which followed in Pennsylvanian and Permian time.

Near the close of Late Mississippian time broad regional uplift raised the area above sea level and widespread erosion lasting into Early Pennsylvanian time removed large quantities of Mississippian rocks (Litsey, 1959, p. 1172).

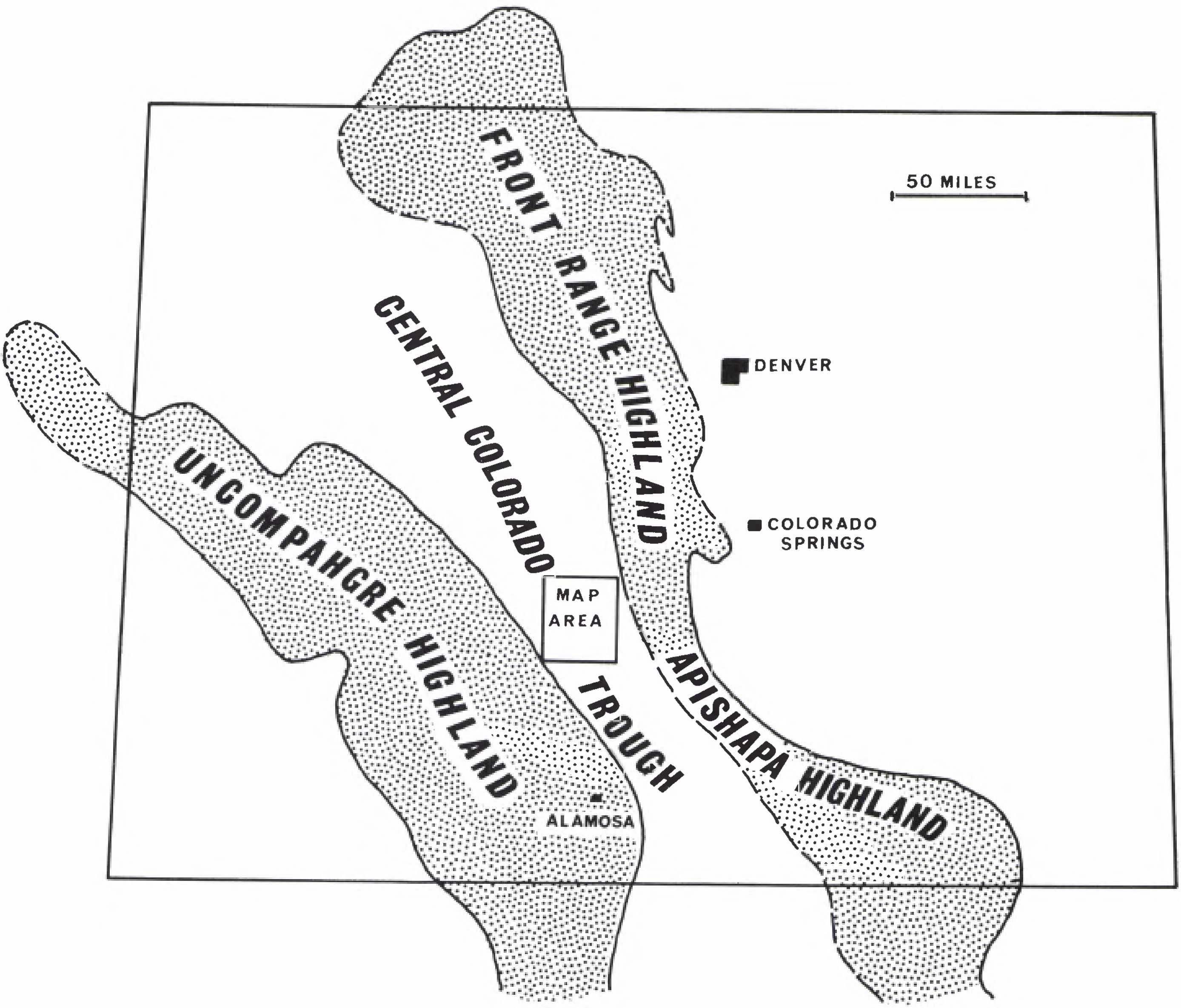


FIGURE 7.

General outline of major Pennsylvanian and Permian highland areas in Colorado. (Modified from Mallory, 1960).

PENNSLVANIAN AND PERMIAN

The Pennsylvanian and Permian geologic history of central and western Colorado was controlled by two northwest-southeast elongate highlands, the Front Range and the Uncompahgre. The map area was located in the relatively narrow structural and depositional trough between the two highlands generally referred to as the Central Colorado trough (fig. 7).

Initially fluvial sediments derived from older Paleozoic rocks on the rising highlands were deposited in the area by northwest-flowing streams (Pierce, 1969, p. 21). Fluvial sedimentation was intermittently interrupted by minor marine transgressions (Pierce, 1969, p. 94). Precambrian rocks were finally exposed and redbed deposition followed, periodically interrupted by carbonate deposition. Because the map area was located in a relatively narrow portion of the Central Colorado trough, minor movements in the nearby highlands frequently influenced depositional patterns.

The most vigorous uplift of the Uncompahgre and Front Range highlands took place during the Permian. In the Howard area at the northeast corner of the map (see plate 1, back pocket) movement along the Pleasant Valley fault displaced basement rocks as much as 10,000 feet and folded the older Paleozoic strata into a series of northwest-trending anticlines and synclines. Erosion beveled the Paleozoic strata and Permian fluvial sediments from the highland east of the Pleasant Valley fault spread over the beveled surface in angular discordance with the older Paleozoic strata (Pierce, 1969, p. 96).

At the same time, extremely coarse clastic sediments of the Crestone Conglomerate were being shed eastward into the Sangre de Cristo Range area from a highland (San Luis Highland) that occupied the present position of the San Luis Valley (Gableman, 1952, p. 1588). The highland was probably an eastward-projecting lobe of the Uncompahgre Highland. The alluvial fan deposits of the Crestone Conglomerate probably represent the upstream facies of the fluvial clastics which accumulated in the Howard area, all of which were shed into a narrow, deep, northwest-trending trough between the Front Range and the Uncompahgre Highland (Pierce, 1969, p. 97).

Aggregate thickness of the Pennsylvanian and Permian sediments that accumulated in the Central Colorado trough was great. In the Howard area between 10,000 and 18,000 feet of dominantly clastic sediments were deposited (Pierce, 1969, p. 3). In the northern Sangre de Cristo Range, south of Hayden Pass, more than 14,500 feet of clastic sediments accumulated (Litsey, 1959, p. 1172).

MESOZOIC

Rocks of Mesozoic age are not present in the map area. Regional considerations, however, indicate that Mesozoic strata once covered the area, but have been removed as a result of erosion following strong uplift associated with the Laramide orogeny in Late Cretaceous-Early Tertiary time.

By Early Mesozoic time only remnants of the ancestral Rockies were present in central Colorado. They were so subdued that they contributed little sediment. By Late Jurassic time (Kimmeridgian or Portlandian) the ancestral Rockies in central Colorado were finally buried beneath the continental-fluvial sediments of the Morrison Formation (Oriel and Craig, 1960, p. 43).

During Late Jurassic and Early Cretaceous time a north-south elongated seaway connecting the Arctic Sea and the Gulf of Mexico transgressed over the western interior (Weimer, 1970, p. 173). The map area appears to have been located on a deltaic plain near the western shore of the seaway during Early Cretaceous (Weimer, 1970, fig. 1-a, p. 160). In Late Cretaceous the sea expanded westward and marine sediments were deposited in the map area. Sedimentation ceased with the beginning of the Laramide orogeny in Late Cretaceous time.

LARAMIDE OROGENY

In central Colorado the Laramide orogeny began near the end of Cretaceous time and lasted into Late Eocene (Haun and Kent, 1965, p. 1794; Gableman, 1952, p. 1609-1610). Dating of the deformational episodes is difficult in the map area because erosion has removed any tectonically-derived sediments which may have accumulated as well as all Mesozoic strata.

Structural development during the Laramide took place in three major phases. On a regional scale this deformation was intimately related to the development of the broad anticlinal uplifts of the Front Range-Wet Mountain anticlines and the Sawatch arch.

The map area was on the southeastern flank of the Sawatch arch. As the arch rose, strata on the east flank were tilted. The present outcrop pattern of Paleozoic strata in the northern Sangre de Cristo Range, and in the Mosquito Range to the north, roughly outlines the east flank of the Sawatch arch.

The second major phase of deformation produced northwest-trending asymmetrical anticlines and synclines which, under continuing stresses, failed with westward-directed thrust faults. A similar sequence of events is recorded in the Paleozoic strata of the Kerber Creek area. Gableman (1952, p. 1610) interpreted the westward-directed stresses as related to relative westward movement of the Front Range and Wet Mountain anticlines.

The third phase of Laramide deformation is recognized only in the Kerber Creek area and in the Sangre de Cristo Range south of the Orient Mine (Gableman, 1952, p. 1574). It consisted of eastward and northward thrusting accompanied by folding. Thrusts of this phase, such as the Kerber and Noland thrusts of the Kerber Creek area, truncate the older Laramide structures. Burbank (1932, p. 287) attributed this period of deformation to northward and eastward movement of a highland which occupied the present position of the San Luis Valley. Boundaries of the highland are generally vague, but the eastern margin was probably near the eastern side of the present San Luis Valley from Sierra Blanca northward to the vicinity of Major Canyon, where it turned westward south of the Kerber Creek area.

By Late Eocene time the Laramide highlands were reduced to relatively low relief. However, local relief of up to 2,000 feet is indicated within the Bonanza volcanic field.

MIDDLE AND LATE TERTIARY

The advent of plutonism and volcanism in Oligocene time signaled a major change in the geologic phenomena controlling the tectonic development of the mapped area. Regional tension may have been a primary factor in allowing magma to rise along zones of weakness.

Volcanism accompanied by minor intrusive activity dominated the Oligocene epoch. Voluminous flows of basic to intermediate lavas were erupted from several local centers in and around the Bonanza volcanic field forming the Rawley Formation. Two flows near the base of this sequence have been dated by Van Alstine and Marvin (reported by Lipman and others, 1970, p. 2336) at 34.2 m.y. and 33.4 m.y. and thus, are age equivalents of flows in the Conejos and San Juan formations in the San Juan volcanic field to the southeast. The Rawley Formation also appears to be roughly equivalent in age and composition to the Lower Andesite of the Thirtynine Mile volcanic field (Epis and Chapin, 1968, p. 64-65). Locally, within the Bonanza field, the Rawley is greater than 2,500 feet thick.

In Late Oligocene time the pattern of volcanism in the Bonanza field shifted to explosive ash-flow eruption of the Bonanza Tuff. The switch from basic and intermediate volcanism to explosive ash-flow eruption parallel the trend observed by Lipman and others (1970) throughout south-central Colorado.

Following the extrusion of the Bonanza Tuff and the younger latites and andesites overlying it, the area centered around the town of Bonanza collapsed within a set of concentric ring fractures forming a caldera. The concentrac faults apparently controlled the emplacement of shallow silicic intrusions and endogenous domes along the rim of the caldera. Other fault patterns that developed include a set of poorly developed high-angle radial faults radiating outward from the central Bonanza area. The radial faults curve around and merge with concentric faults inward toward the central caldera. A set of high-angle shear faults, also formed during tilting, parallel the concentric faults but dip more gently toward the central caldera.

Collapse of the Bonanza center resulted from removal of support from below as the contents of the underlying magma chamber flowed out onto the surface. Normal faults bounding the southwest and northeast sides of the caldera are relatively well-developed and moved in a narrow zone. Displacement on the northwest and southeast portions of the rim is spread over broad zones. The present structural configuration of the Bonanza caldera (see plates 1 and 2, back pocket) may be due either to (1) an initial hinge-like subsidence of the caldera with the western part dropping farther than the eastern part, or (2) subsequent subsidence of the San Luis Valley and eastern rim of the caldera resulting in some degree of structural compensation for an original large displacement along the eastern rim of the caldera.

Sometime after the last Oligocene volcanic activity and before deposition of Late Miocene sediments of the lower Dry Union Formation, a fault-bounded trough extending from the Arkansas Valley southward into the San Luis Valley developed (Van Alstine, 1968; 1970). This trough was part of the Rio Grande depression, a complex series of horsts and grabens extending from southern New Mexico into central Colorado.

Within the trough clastic debris shed from the surrounding highlands accumulated. These sediments comprise the Miocene-Pliocene Dry Union Formation which is equivalent to a portion of the Santa Fe Group deposited in the Rio Grande depression in southern Colorado and New Mexico (Van Alstine, 1970, p. B46). The position of the trough is outlined by the San Luis-Arkansas trough, the Poncha Loop syncline, and the Villa Grove reentrant of the northern San Luis Valley. Contemporaneous with the development of the trough, a small graben, the Pleasant Valley graben, evolved in the Howard area. Coarse clastic sediments of the Pleasant Valley Conglomerate were dumped into the graben and subsquently faulted as the graben further subsided (Pierce, 1969, p. 85).

The eastern boundary fault(s) of the trough lies along the west side of the Sangre de Cristo Range and is largely buried beneath Quaternary sediments. In the northern part of the area, similarly trending steep faults in Precambrian rocks probably are the continuation of the eastern boundary fault system. Movement along this fault system in Miocene and Pliocene time raised the Sangre de Cristo Range to most of its present elevation.

Along the western boundary fault(s) the Dry Union Formation is often faulted, probably reflecting recurrent movement during development of the trough (Van Alstine, 1970, p. B48). The western boundary fault continues southward from the southwest edge of the San Luis-Arkansas trough into the Bonanza volcanic field where it joins the system of normal faults developed during collapse of the Bonanza caldera. Reactivation of these faults in the Quaternary is indicated by displaced gravels along Little Kerber Creek at the southern end of the fault system.

Late in the Pliocene or early in the Pleistocene, the trough connecting the San Luis and Arkansas valleys was fragmented by transverse faults. The largest of these transverse faults is the Salida-Maysville fault at the north end of the area. Movement along the Salida-Maysville fault raised the area south of the fault a minmium of 2,500 feet near Poncha Mountain.

Similar faults truncated the southern end of the San Luis-Arkansas trough. Erosion on the southern block removed much of the Dry Union Formation except for the sediments in the Poncha Loop syncline and in the O'Haver Lake area. South of the Poncha Loop syncline the Dry Union Formation, if present, is covered by Quaternary sediments. Many other minor faults served to further fragment the original structural and depositional trough connecting the San Luis and Arkansas valleys.

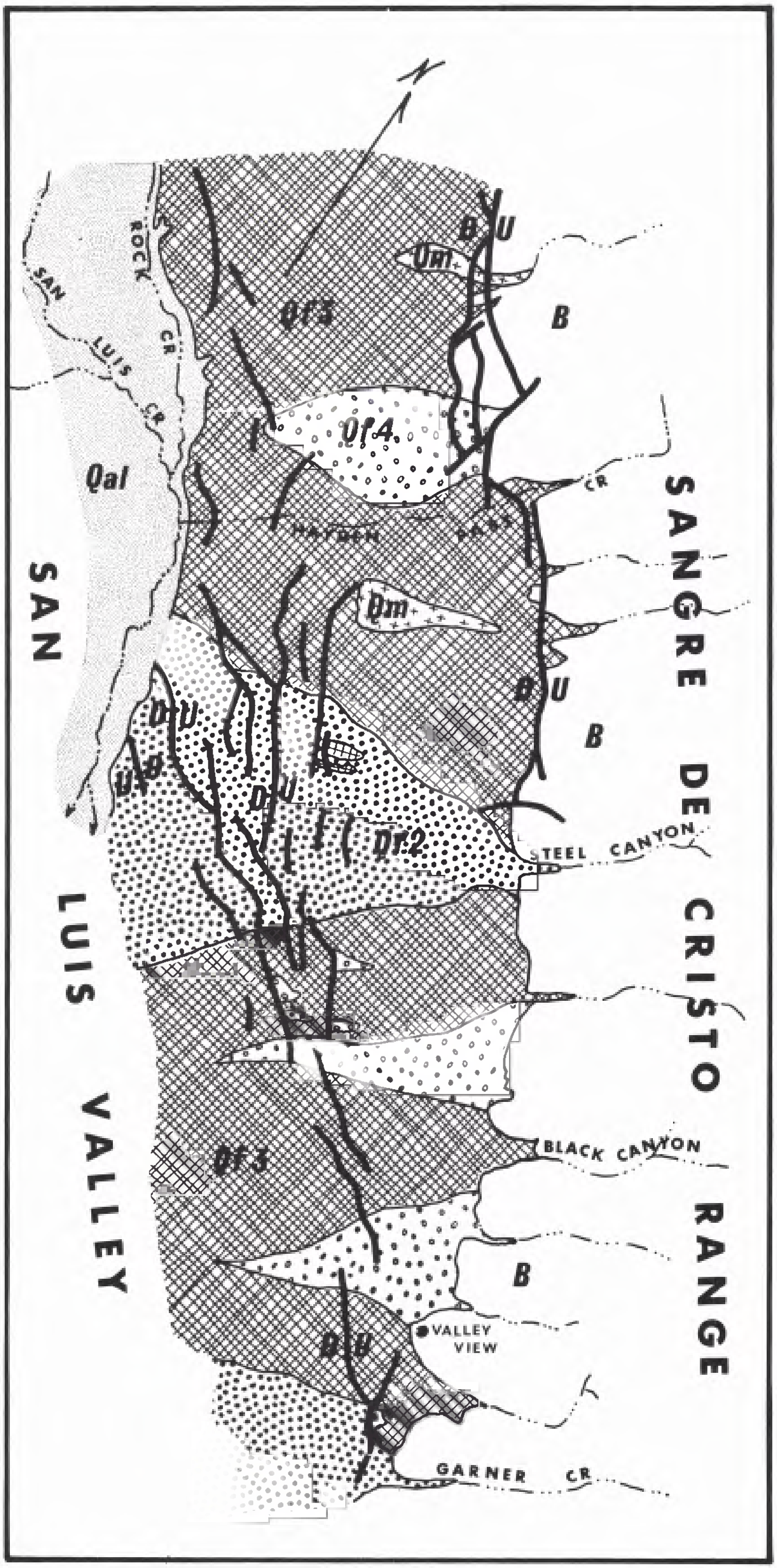
QUATERNARY

In Early Pleistocene time, regional climatic fluctuations produced periods of erosion alternating with periods of alluviation in the map area. Pediments were locally cut along the flanks of the mountain ranges during periods of erosion; gravels were deposited on the pediments during periods of alluvation. Each successive period of pedimentation tended to destroy the older gravel-capped surfaces.

During Late Pleistocene (Wisconsinian), alpine glaciers carved the scenic mountain peaks in the Sangre de Cristo Range, the Bonanza volcanic field, and the southern Sawatch Range. Morainal material was deposited in the high cirque basins and in some of the major canyons of the Sangre de Cristo Range. Outwash fans representing several stades of Bull Lake and Pinedale glaciation (Scott, 1970, p. C17) were deposited along the steep western front of the Sangre de Cristo Range and on the eastern side of the Bonanza volcanic field. Periods of erosion between episodes of fan deposition partially removed the earlier fan systems.

After, and probably during, deposition of Pleistoscene outwash fans along the Sangre de Cristo Range, the pre-Quaternary Sangre de Cristo fault system was reactivated displacing Pleistocene gravel as much as 20 to 25 feet. This Quaternary fault system bifurcates in the vicinity of Valley View Hot Springs. One branch continues north-northwest along the front of the Sangre de Cristo Range. The second branch trends more northwestward toward the town of Villa Grove.

Faults along the north-northwest branch displace the heads of nearly every alluvial fan along the range front (fig. 8). Displacement of faults along the northwest



EXPLANATION

FAULT

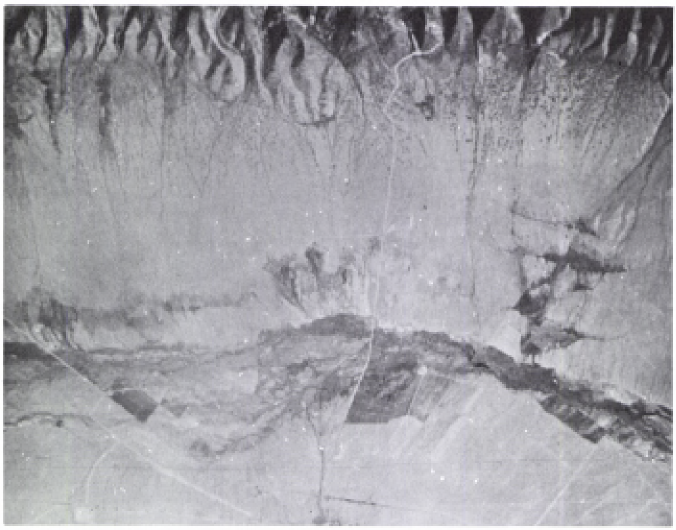


FIGURE 9.

Faults displacing Quaternary deposits and partially damming ground water. (East of Villa Grove).

Aerial photograph courtesy of Colorado School of Mines, Bonanza Project (101).

branch decreases to the northwest finally dying out north of Villa Grove. Along the central portion of this branch the faults have partially dammed groundwater circulation forming marshy and densely vegetated areas on the upslope-side of individual faults (fig. 9). Sense of movement along both fault systems is predominantly up on the east.

The north-northwest fault system apparently reflects recurrent movement along the pre-Quaternary Sangre de Cristo fault system. The northwest fault system roughly outlines a graben within the major part of the Rio Grande depression which may be filled with Miocene-Pliocene sediments. Gravity data (Gaca, 1965) indicates the presence of a narrow graben south and east of Villa Grove. Recurrent movement along the border of this graben has displaced the Quaternary gravels. North of the graben the thickness of the Quaternary deposits decreases rapidly.

In Holocene time small alluvial fans were formed, commonly at the base of pre-existing fault and erosional scarps. Recent erosion, particularly gullying, has greatly modified all older Quaternary features.

ECONOMIC GEOLOGY

Mineral deposits of the area vary widely in type and mode of occurrence. In the northeastern part of the area lime deposits from travertine and the Leadville Limestone have been mined as material for steel processing. Gypsum and bentonite deposits have also been worked from time to time. Other minerals in the northeast sector that might possibly become economically important are emuscovite, which is locally present in considerable quantities within the Precambrian rocks, and copper, which has been found in small quantities in Permian and Pennsylvanian sands interbedded with carbonaceous shales.

Further south, along the Sangre de Cristo Range, iron minerals were mined at the Orient Mine east of Valley View Hot Springs. The ore was mainly siderite from the Leadville Limestone.

In the San Luis Valley and its Villa Grove reentrant many deposits of sand and gravel are found which of excellent commercial grade. Several of these are being actively worked for materials for roads and other structures.

The Marshall Pass district which lies just to the northwest of the area has produced some uranium from quartzite beds in the Ordovician Harding Formation, from Eocene (?) soils lying on Precambrian rocks and from pitchblende and pyrite veins in the Belden and Leadville limestones along the Chester fault. It is possible that some mineralization of this sort extends southeastward into the Precambrian and volcanic terrain of the map area.

The Bonanza center, itself, has been the source of many varieties of base metal ores. The mineralization in the Bonanza district apparently occurred in two phases after major deformation in the area ceased. Silver, lead, gold, and zinc are the primary metals in the ore veins and they usually occur in a gangue of quartz. Burbank (1932, p. 60) divides the ore bearing veins into two classes: (1) quartz veins of relatively high sulfide content, carrying lead, zinc, copper and silver and (2) quartz-rhodochrosite-fluorite veins. The major production of the area was largely from veins of the first class which are mostly located in the northern part of the district. Veins of the second class are more common in the southern area and production in this part of the district was relatively small.

The total production of the Bonanza district is estimated at more than $9,000,000 prior to 1946 (Vanderwilt, 1947, p. 445) and this was mostly the output of the Rawley Mine. Production from the Rawley Mine ceased in 1930 with the sale of the Rawley mill. Subsequent attempts to revive the mine have proven sub-economic.

The major potential of the Bonanza district lies in the chance for the discovery of new, high-grade veins or large, lower grade mineral deposits that might occur at depth where Paleozoic carbonates or other favorable horizons have been buried in the volcanics and might have been subsequently mineralized.

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