GEOLOGY OF THE SOUTHERN PART OF THE FRA CRISTOBAL RANGE SIERRA COUNTY, NEW MEXICO

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GEOLOGY

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SOUTHERN PART OF THE FRA CRISTOBAL RANGE

SIERRA COUNTY, NEW MEXICO

By

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ABSTRACT

The southern part of the Fra Cristobal Range and adjacent parts of the Cutter sag were completely re-mapped in the present study. Although much of the master's thesis is correct, some questionable information and therefore some erroneous interpretations were included previously. In this revision, the sacrifice of a small amount of strike-and-dip control, was more than compensated by the selection of only high quality data.

Precambrian, Cambrian, Ordovician, and Pennsylvanian rocks are exposed in the northern part of the range. Permian rocks were mapped in the southern part. Detailed sections were re-measured and each unit was sampled. The Abo is a typical red-bed formation (493 feet thick). Four general members were described in the Yeso formation: 1.) lower clastic, 2.) lower-middle limestone, 3.) upper-middle evaporite, and 4.) upper clastic (total 1239 feet thick). Also the San Andres was subdivided into: 1.) Glorieta sandstone, 2.) transition member, and 3.) main limestone member (total measured 369 feet thick, but top is eroded; a more representative thickness for the area is about 500-600 feet).

Upper Cretaceous rocks were mapped in the Cutter sag. Sandstone, shale, and conglomerate units occur within the Dakota, Mancos, Mesaverde (main body and Ash Canyon member), and McRae (Jose Creek and Hall Lake members) formations. In Tertiary time, the Santa Fe formation was deposited in the Rio Grande depression, and basalt dikes were intruded.

Quaternary development of pediment surfaces sloping westward to the Rio Grande Valley and eastward to the Jornada del Muerto was followed by widespread extrusion of basaltic lavas upon these surfaces.

Laramide normal faults, closed and overturned folds, and thrusts (to east) trend northwest to north within the Fra Cristobal uplift. Vertical movements during middle Tertiary produced normal faults and open folds with dominant north to northwest trends. Most of the relief of the uplift relative to the adjoining Jornada del Muerto and Rio Grande depressions culminated in this deformation.

To the south in the Cutter sag, a prominent set of northeast trending longitudinal faults developed in upper Tertiary time. They are normal faults down to the west, but many also show right-lateral drag. The Hot Springs fault exhibits a suggestion of left-lateral drag.

Force analyses are discussed for each principal deformation in this area. Diastrophism probably was continuous from the beginning of the Cenozoic era to the present day.

Strike-slip faulting may have been an important mechanism in the formation of the Rio Grande graben. The fact that most of the large displacement faults are down to the west suggests that the structural history of this depression was more complex than that of the Jornada. It is hoped that the data and interpretations presented in this report will be of help in predicting and deciphering structures in the adjoining depressions.

INTRODUCTION

Geography

The Fra Cristobal Range is located in north-central Sierra County, New Mexico, and forms a part of the discontinuous chain of north-trending mountains on the east side of the Rio Grande. Elephant Butte Reservoir lies along the western base of the range (Fig. 1). Bounded by longitude 107°00' west to 107°15' west and latitude 33°14' north to 33°23' north, the map accompanying this report (Fig. 2) covers about 140 square miles of the southern end of the range and adjoining lowlands.

All of the land in the eastern part of the map lies within the Pedro Armendaris Grant, owned by the Victorio Land and Cattle Company. Mr. Irving Goetz gave permission to enter this property. Land adjacent to Elephant Butte Reservoir is part of the Rio Grande National Wildlife Refuge. Surveyed land in the western part of the map is State and Federal acreage. The map area covers parts of Townships 11 and 12 South, Ranges 2, 3, and 4 West.

Accessibility is a major problem in the study of the Fra Cristobal Range. Most all of the eastern shore of Elephant Butte Reservoir is accessible by boat except when the water level is low. A road on the east side of the Santa Fe Railway intersects three "jeep" trails (marked by gates in the fence) at 2.4, 6.6, and 11.4 miles north of Engle, New Mexico. These trails have been washed out in several places, and are nearly impassable after a heavy rain or snowfall. The southernmost route goes near the southern tip of the range, north of the lava flows. The middle route goes to the mouth of the canyon between

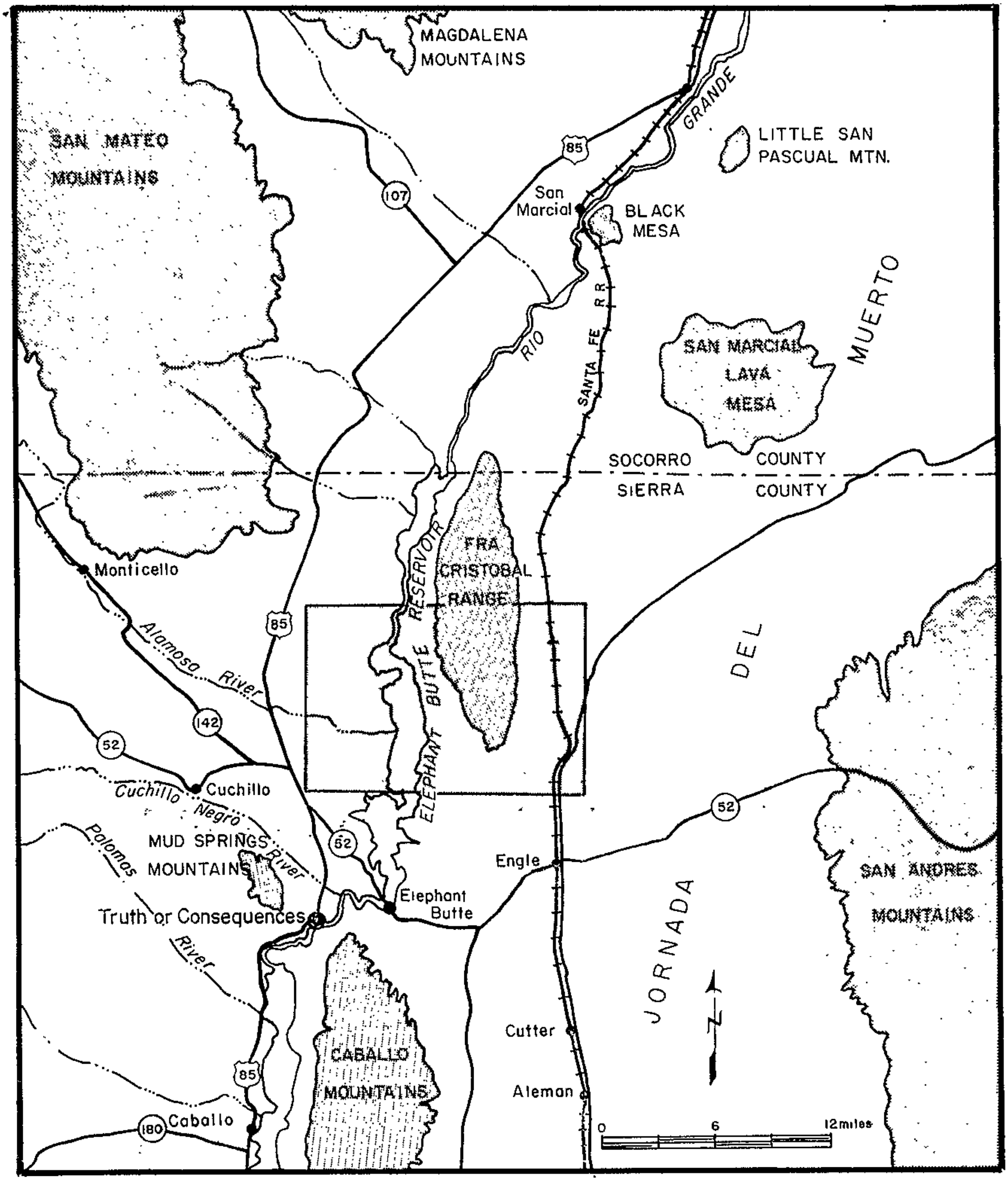


Figure I. Map of south-central New Mexico showing location of mapped area.

Triangle Mesa and Shotgun Ridge, immediately south of Shumard Cone. The northern route joins a rough power line road which generally follows the Abo/Magdalena contact across the northern part of the map area to the Rio Grande.

Fenneman (1930) shows the Fra Cristobal Range to lie within the Mexican Highland Section of the Basin and Range Province. The Rio Grande Valley, locally termed Engle Valley, lies to the west, and the Jornada del Muerto Valley lies to the east of the range. Elevations within the map area vary from over 6200 feet on top of Triangle Mesa to 4305 feet on the shore of Elephant Butte Reservoir. The Santa Fe Railway generally follows the 4800-foot topographic contour. (U.S.G.S., 1958).

Most of the mountainous uplands comprising this range consist of high limestone ridges and peaks separated by deep valleys. Drainage seems to be controlled not only by the form of the uplift, but also by zones of structural weakness. However, because the structural trends are seldom near right angles to one another, rectangular drainage patterns are virtually absent, with dendritic patterns predominating. At the southern extremity of the range the upland zone changes rather abruptly into an area of low ridges and valleys capped by lava mesas and cones. It is here that the Cuchillo and Jornada pediment surfaces (which slope away from the range to the west and east, respectively) are believed to be coextensive. The geomorphic expressions of certain structural features and each of the rock units are discussed later in the text.

Best conditions for field work prevail in the fall and spring. Summer temperatures may exceed 100° F, and the mean monthly low for the winter is 41° F. Most of the rain occurs in the summer, but the climate is definitely arid. Winter snow on the Jornada del Muerto may not melt for several weeks in the shadows of the San Andres, Fra Cristobal and Caballo Mountains.

Cresote bush, cactus, and yucca are the dominant plant types in the lowlands adjoining the Fra Cristobal Range. Some grasses are present on hill slopes. A few sparsely scattered trees, mostly juniper, grow along the drainage areas. Salt cedar grows adjacent to Elephant Butte Reservoir.

Previous Work

Whereas almost no detailed geologic work on the Fra Cristobal Range had been published prior to 1954, many references in the literature were found on this small, but not insignificant area. Results of this research may be found in Thompson (1955).

Under the direction of Dr. V. C. Kelley at the University of New Mexico, a mapping program was begun concerning the geology of the south-central part of the State. Beginning with the bulletin by Kelley and Silver (1952) on the Caballo Mountains, the program has been extended northward to include the Fra Cristobal Range. Bushnell (1953) in the McRae Canyon area, Thompson (1955) in the southern part of the range, Jacobs (1956) in part of the central western front, and McCleary (1960) in the northern part, have all contributed to the mapping project in a series of master's theses.

Much additional information of a regional nature may be found in the foregoing works, especially in Kelley and Silver (1952). Specific references and credits will be made later in this text where necessary for perspective.

In November, 1955, the New Mexico Geological Society held their sixth annual field conference in the Sierra County area. The guidebook of this conference contains many excellent articles, maps, and road logs which are useful to the geologists who are interested in this region.

Present Investigation

Emphasis in this work has been placed on the structural geology of the southern part of the Fra Cristobal Range. By mapping this complex area, it is hoped that a better understanding of the adjoining Rio Grande and Jornada del Muerto depressions may be reached. Stratigraphic sections of the Permian formations were measured, but the Cretaceous and Tertiary rocks are so highly faulted that few of the units are in normal contact.

Although much of the original investigation (Thompson, 1955) was correct, some questionable data and therefore some erroneous interpretations were included. The author believed that a complete revision was necessary which would contain only selected data. A large gain in high quality, objective information is obtained for the sacrifice of a small amount of control. Moreover, because the author acquired an additional five years experience, and had a cataract operation fully correcting impaired vision, the present investigation is a significant improvement over the earlier work.

Field data were plotted on contact prints of aerial photographs to a scale of 1:31,680 (2" = 1 mile), subsequently transferred to a mosaic, and then to an overlay base map of the same scale. Stratigraphic sections of the Permian rocks were measured with a Brunton clinometer, and samples of the units were examined under a binocular microscope. An abundance of kodachrome slides were taken on the many ground traverses and on one airplane flight. These pictures provide a graphic record of the stratigraphy and structure.

In spite of the fact that the author had walked over all of it previously, the entire area was re-worked. The southern half was covered during the writer's vacation in the fall of 1959, and the northern half in his 1960 fall vacation. About twenty-five total days were spent in the field during this revision.

Acknowledgements

Again, the writer must first of all express appreciation to Doctor V. C. Kelley, Professor of Geology at the University of New Mexico, who has always shown great interest in and given encouragement to this project. It is hoped that this revision will be of the quality he desires for incorporation into a forthcoming bulletin on the geology of the Fra Cristobal Range.

Mr. W. G. McCampbell, District Geologist for Humble Oil & Refining Company in Roswell, New Mexico, granted permission to pursue this study. As a geologist with Humble, the author has realized this problem has little direct value in petroleum exploration, and has undertaken the project at his own expense and on his own time (vacations and after hours).

On the other hand, the report should be of some indirect value to Humble in tectonic analyses of south-central New Mexico. Furthermore, the author appreciated the opportunity to clear his conscience of the inadequacies of the former work, as well as greatly improve his knowledge of field geology.

Mr. R. D. Holt, also of Humble, has given his time generously to the editing of the map and text.

STRATIGRAPHY

Nomenclature of the rock units discussed in this report conforms to that of Kelley and Silver (1952) and Bushnell (1953). Terminology is consistent generally with definitions in the American Geological Institute's Glossary of Geology and Related Sciences (1957). However, the beddedness terms of Kelley and Silver (1952, pp. 30-31) are used:

Laminated--less than 1 inch thick

Thin-bedded--1 inch to 1 foot thick

Medium-bedded--1-3 feet thick

Thick-bedded--3-6 feet thick

Massive--6 feet or more thick

Representative samples were collected from each measured unit in the Abo, Yeso, and San Andres formations. Samples of the characteristic lithologies of each of the other stratigraphic units exposed in the mapped area were also collected.

Textures and colors of the rocks described below, especially in the measured sections of the Permian, are as they appear on the sample chips under a binocular microscope. Colors of the fresh surfaces were described wet under white light (and plotted on the columnar section).

Correlation of the rock units was hindered by the complex faulting in the mapped area. Gross lithology correlations were reliable within the scope of the current project. If further detail is desired on a larger scale, it would be possible to refine the formational units into members or even beds that may be traced for some distance.

Most of the statements in this section are objective and are intended mainly for description of the rock units. As the emphasis in this work is on structural geology, this discussion does not deal with much interpretive stratigraphy.

Pre-Permian Rocks

Precambrian, Cambrian, Ordovician, and Pennsylvanian formations are exposed in the northern part of the Fra Cristobal Range (Jacobs, 1956; and McCleary, 1960). They occur in the subsurface of the mapped area, but Devonian and Mississippian rocks may also be present.

On the west escarpment of the northern part of the range (and some small outcrops on the east side), the Precambrian is composed mostly of granite gneiss. The dark Cambrian Bliss sandstone is 75 feet thick, but is truncated such that Pennsylvanian rocks overlie Precambrian in the latitude of Fra Cristobal Peak. Farther south near Amphitheater Canyon, the Ordovician El Paso group is present above the Bliss and below the Pennsylvanian.

In the El Paso group, the Sierrite formation consists of 123.5 feet of limestone with some chert and shale. The overlying Bat Cave formation is 78 feet thick, and is composed of a limestone, conglomerate, dolomite sequence. The conglomerate is atypical of the Bat Cave. The truncation of the El Paso group lies south of the Bliss truncation.

The northern limit of the Devonian Percha formation may lie near the middle of the Fra Cristobal Range in the subsurface. Also the Mississippian Lake Valley formation may be present in the form of erosional remnants.

Pennsylvanian rocks comprise most of the northern part of the Fra Cristobal Range. In the lower Pennsylvanian, the Red House formation consists of 530 feet of limestone and shale. Overlying it is the Nakaye formation, 700 feet of limestone and chert. The youngest Pennsylvanian unit is the Bar B formation, 258 feet of shale and limestone. Some Permian beds (Bursum ?) may be present in the upper part of the Bar B.

Permian Rocks

Permian rocks of the southern part of the Fra Cristobal Range have been subdivided conventionally into the Abo, Yeso, and San Andres formations. Their first adequate definition was made by Lee and Girty (1909, p. 12) when they subdivided the Manzano group into these formations, but erroneously assigned them a Pennsylvanian age. Abo Canyon in the Manzano Mountains, Mesa del Yeso (12 miles northeast of Socorro), and Rhodes Pass in the San Andres Mountains are the respective type localities of these formations.

Needham and Bates (1943) attempted to establish the definition of these units more precisely by measuring detailed sections at each type locality. Most all geologists use this nomenclature in discussions of the Permian of west-central New Mexico.

For further detail than is found in the following pages, the reader is referred to the Descriptive Stratigraphic Sections in the back of this report. A convenient reference is the columnar section, Figure 3.

Abo formation

Outcrop of the Abo formation in the Fra Cristobal Range is confined mostly to the northern and northeastern parts of the mapped area. A few scattered outcrops are present in the northern part of the range.

Many units of the Abo are slope-formers, but some prominent ledges of sandstone occur in the lower part. Generally the softer units are weathered and partly covered, but the more resistant beds are well exposed. Faulting disrupts the continuity of the Abo, yet this formation is relatively undeformed over much of the area.

Dark red claystone is the dominant and distinguishing rock type of the Abo. This lithology is found in the slope units for the most part, but some of the ledges contain interbedded claystone. Some claystone is silty and calcareous.

Red siltstone and sandstone ledges are also characteristic of the Abo. Thin-bedded siltstone units are mostly composed of quartz with some argillaceous and calcareous constituents. The red color is probably due to staining by hematite cement. In the lower Abo, chalcedony concretions and limestone nodules occur within the siltstone beds. Gray clay galls are present in the upper units.

Fine- to very fine-grained quartz and minor potash feldspar are the principal mineral types comprising the sandstone units. Most of the sandstone beds are argillaceous and calcareous, and again the red color is due to the hematite cement. Some of the colors are orange-red and purple-red, and many of the units weather red-brown. None of the sandstone is friable. Laminated, thin- and medium-bedded units are also festoon cross-bedded, but some parallel bedding is evident. Current ripple marks were not observed in the measured section, but are found on many of the sandstone beds in other parts of the mapped area.

Only two thin conglomerate units are described in the lower part of the Abo measured section. The lower ledge is medium-bedded and is composed of granule to pebble size claystone particles which are subrounded to subangular. The higher, more prominent ledge is thin- to medium-bedded, and is composed of coarse-grained to granule size limestone particles with a red claystone matrix.

Long claw reptile tracks, about one inch in length, were found in Unit 12 of the measured section. However, they are more abundant near the Magdalena inlier to the north at about the same stratigraphic level. This occurrence is described in some detail by Thompson (1955). These specimens are on display at the University of New Mexico Geology Museum.

No angular divergence is perceptible at the sharp contact between the dark red Abo claystone and sandstone formation above, and the gray limestone of the Bar B formation (of the Magdalena group) below. This vivid contact is further accentuated by the dull yellow color in the uppermost Bar B. Descending ground-waters have leached the Abo and deposited a limonite stain on the limestones below.

Although the contact of the Abo with the overlying Yeso is gradational, dark red colors are generally confined to the Abo. Also, the Yeso is composed of more calcareous sandstone, gray claystone, and limestone, in predominantly parallel beds.

A total of 493 feet of Abo was measured. This thickness, as well as the lithologic types described, should be representative for the Fra Cristobal area.

Many of the sandstone ledges are traceable for some distance. However, the Abo was correlated over the mapped area on a gross lithology basis.

Obviously, the Abo formation was deposited in a continental floodplain environment. The rate of deposition must have been moderate to slow as evidenced by the preponderance of fine clastics.

Yeso formation

All of the outcrops of the Yeso formation in the Fra Cristobal Range are confined to the northern part of the area mapped in this work. Of the three Permian formations in the Manzano group, the Yeso is the most widely distributed in this area.

Considering the fact that the Yeso is a slope-forming unit beneath the resistant San Andres mesas and ridges, it is relatively well exposed. However, the high degree of incompetency exhibited by the Yeso where involved in folding or faulting (especially in the western part of the mapped area) makes stratigraphic studies of this formation difficult to impossible.

For discussion purposes the Yeso may be divided into four general lithologic members. In ascending order they are: 1.) a lower clastic unit, 2.) a lower-middle carbonate unit, 3.) an upper-middle evaporite unit, and 4.) an upper clastic unit. These units may be equivalent to the Meseta Blanca, Torres, Cañas, and Joyita members of the Yeso as used by some workers.

About one mile north of Saddle Peak, two outliers of the lower clastic member are exposed on prominent mesas. Elsewhere this unit occurs in low hills near stream level.

Ledges in this member are formed by sandstone and siltstone beds. Quartz is the dominant mineral, but some feldspar and mica are present. Many of the sandstones and siltstones are calcareous and argillaceous. A wide variety of colors includes dark red, red-brown, pink, orange, yellow, green, gray, tan, and white. Yellow limonite stain is apparent in places.

Grains range from fine to medium in size and are rounded, subrounded or subangular. Most of the sandstones are well indurated, or even quartzitic, but some are slightly friable.

Stratification includes laminated, thin-bedded, and medium-bedded types. In the lower part cross-bedding is present, but mostly even (parallel) bedding predominates. Some of the surfaces are ripple-marked.

Shale and claystone occur in the slopes of the lower clastic unit, and are interbedded in some of the ledges with the sandstones and siltstones. Red and light red claystone is confined to the lower part. Some channels (about one-foot in relief) have been cut into the claystones and filled with siltstone. In the upper part, green and gray shale is present. Several covered intervals probably conceal additional claystone and shale units.

Boundaries are gradational with both the underlying Abo formation and the overlying carbonate member. Yet the lithologic and bedding differences make this a distinct unit.

Next above is the lower-middle limestone member. Many ledges, some of which are prominent, characterize this member.

Limestone beds form the resistant ledges. Brown and gray are the most common colors on fresh surfaces. Some dark brown and black units are present which weather to brown and gray. Many of the limestones are argillaceous, and some are cherty, silty, or sandy. A fetid odor is common on fresh fracture of the dark limestones. In the upper part of this member, some have dead oil stain.

Dense to finely crystalline textures prevail in the micritic limestones. Skeletal limestones are minor. A calcarenite composed of fine- to medium-grained, subrounded calcite grains occurs in the lower part of the member. Oölites are found at its base.

Some of the limestones contain fractures which are filled with calcite. A slight amount of small vuggy porosity occurs in a light gray, dense, cherty limestone which is dolomitic. Probably the dolomitization and solution porosity developed during diagenesis and possibly during weathering of the present exposure. However, one brown, finely granular, dolomite sequence with scattered vuggy porosity is present.

Productid brachiopods, notably Dictyoclostus sp., and some scaphopods, small cephalopods, and algae are found occasionally in the limestone beds of this lower-middle carbonate unit of the Yeso. Moreover, this unit contains the only fossils found in the Yeso.

Interbedded with the limestone ledges are sandstone and claystone slopes similar to the lower clastic unit of the Yeso. Red, orange, and light gray calcareous sandstones are composed of fine- to medium-grained quartz. Most are well cemented, but some of the sandstones are friable. The claystones are yellow, calcareous, and silty with some limonite stain.

Thin- to medium-bedded limestones alternate with thin-bedded sandstones. All bedding in this member is parallel as no cross-bedding, irregular bedding or channel-and-fill surfaces were observed.

Outcrops of the upper-middle evaporite member are found in the slopes below the cliffs of the San Andres formation. Much of this unit is covered, and good exposures are rare.

White to light gray, laminated gypsum is the dominant lithology. Both crystalline and fibrous textures are present. Vertical furrows on the yellow to tan weathered slopes are typical of the gypsum occurrences.

Interbedded with the gypsum are rock types similar to those found in the underlying carbonate unit. Slight ledges are formed by the thin- to medium-bedded limestone and dolomite which are gray and brown in color, and have a dense texture. Some small vugs in the argillaceous dolomite may be due to dissolving of gypsum. Yellow, fine-grained, quartz sandstones are a minor part of this sequence.

In the main line of the measured section, no gypsum was observed. To obtain a representation of this lithology it was necessary to move about 600 feet to the north. Here the thickest sequence of gypsum in the vicinity of the measured section is present. However, actual tracing of beds back to the line of the measured section was prevented by a small covered slope. Nevertheless, a pronounced thinning of each gypsum interval southward was seen, and the net thickness of 43 feet for the non-gypsum beds in the evaporite member corresponds very closely to the 41 feet of limestone and sandstone in what is correlated as the equivalent unit in the line of measured section.

Probably the missing gypsum has been leached by solution. In other areas, complicated folding may squeeze gypsum out of the section, but it does not seem likely to have occurred in the relatively undeformed rocks of this locality. Also this is not readily explained by depositional differences because of the abrupt thinning of each gypsum unit. No faulting is present in the beds above and below this member which can be traced across both localities.

At the top of the Yeso is the slope of the upper clastic member. The entire unit is composed of thin-bedded, fine- to medium-grained quartz sandstone. Red and light gray colors dominate the lower part of the section. Yellow to white colors occur near the top, but the uppermost bed is red. A few of the sandstones are friable. Contact with the overlying Glorieta sandstone member of the San Andres formation is sharp but conformable.

The total measured thickness of 1239 feet for the Yeso formation may be considered as representative of the Fra Cristobal area. Actually, the measured section is the only locality in the entire range where both the top and base bound an unfaulted sequence. It would be possible to measure other sections of the individual members, but a great deal of faulting and folding has deformed the incompetent Yeso formation over much of the mapped area.

Correlation of the Yeso was accomplished generally on a gross lithology basis, although some beds were traced for considerable distances (even across faults). The light red, orange, yellow, and gray clastics are easily differentiated from the dark red colors of the Abo. The carbonates are similar to those of the San Andres, but the presence of abundant interbedded clastics serves to distinguish the Yeso limestones and dolomites. However, some of the prominent limestone ledges in isolated fault blocks may be confused with the San Andres.

Deposition of the lower clastic member probably occurred near a shoreline transition from continental to dominantly marine conditions. The absence of coarse clastics suggests that the rate of deposition was moderate to slow. Further transgression of the Yeso sea to the north is evidenced by the lower-middle limestone member.

Stagnant conditions in a silled basin resulted in the deposition of the upper-middle evaporite member. Finally a minor regression is suggested by the upper clastic member.

San Andres formation

Perhaps the most striking exposures in the southern part of the Fra Cristobal Range are those of the San Andres formation. Bold, sheer escarpments on the sides of rugged-topped ridges and peaks lend a very picturesque setting to this formation at the tapering end of the range. Nonresistence to erosion of the underlying Yeso formation has resulted in a most irregular plan view of the San Andres outcrops.

Three general lithologic units within the San Andres formation in ascending order are: 1.) Glorieta sandstone member, 2.) a transition member, and 3.) a main limestone member. Because the lower two members usually crop out in the slopes below the cliffs of the main limestone, they are not mappable on the present scale.

Yellow to tan, very fine-grained, well sorted, and rounded quartz grains are characteristic of the Glorieta sandstone member. However, some fine-to-medium size grains are present in other localities. The sandstone is usually well cemented with siliceous and dolomitic material. Some limonite and hematite staining is present.

Bedding is usually not discernible in the 15-foot Glorieta sandstone member, so it appears to be massive. The basal contact with the Yeso formation in the measured section on the north slope of Shotgun Ridge is not well exposed, but elsewhere it is sharp yet conformable. The upper contact is also fairly sharp, but the lithologic type is very similar to that of the sandstones in the transition member.

Dolomite, limestone, and sandstone beds form the ledges and slopes of the transition member. In the lower part the brown to dark brown dolomite is thin-bedded, finely crystalline, and micritic. Some beds have fractures filled with calcite, hematite, and limonite. Intercalated are light gray or yellow, thin-bedded sandstones which are composed of quartz grains that are very fine-grained to fine-grained, well sorted and rounded, and well cemented.

Near the middle of the transition member is a medium-bedded, light-brown, fine- to medium-crystalline dolomite with intercalated brown to gray, dense to finely-crystalline limestone. Limestone is more abundant in the upper part of this unit.

Next above is a very prominent sandstone ledge. The sandstone is thick-bedded and is composed of white, well-rounded, medium- to coarse-grained quartz. Some calcareous cement is present, but the sandstone is generally slightly friable. It weathers a distinctive dark brown (hematite stain).

At the top of the transition member are some medium-bedded ledges of limestone and sandstone. The sandstone beds are similar to the ones immediately below, but the limestone beds are tan, fine- to medium-crystalline, and brown, dense to finely crystalline, slightly cherty, with minor calcarenite and replaced fossil fragments.

Most of the San Andres formation is characterized by the main limestone member. In the lower part is a very prominent cliff-forming ledge. It is medium- to thick-bedded, brown to dark brown, dense to medium crystalline limestone, with minor chert nodules. Fragmental limestone and calcarenite beds are present. Some poorly preserved nautiloids, brachiopods (mostly Dictyoclostus sp.), and gastropods occur in the sequence.

Overlying the cliff unit are ledges and slopes of thin- to thick-bedded limestone. Most of the limestone is brown to dark brown, and dense to finely crystalline. Several fractures and some vugs are present, but they are filled with calcite. One tan to white, chalky bed is distinctive. Some calcarenite and algal (?) fragments occur near the top of the measured section.

Unfortunately, the San Andres formation is eroded on top of Shotgun Ridge. Therefore, the 369 feet of San Andres in the measured section does not represent the total thickness of the formation in the Fra Cristobal area. However, the lithologic types described are representative of all the San Andres outcrops in the mapped area.

Down-faulted on the southwest slopes of Shotgun Ridge is the upper part of the San Andres, which is overlain disconformably by the Cretaceous Dakota sandstone. Originally it had been hoped that a marker bed (such as the light colored, chalky limestone) found in the measured section would permit definite correlation with the section on the down side of the fault, and so that measurement of the San Andres could continue to the Dakota contact. No such marker bed was observed, and the section in the down-faulted block of upper San Andres is not well exposed.

Possibly 500 to 600 feet of San Andres is exposed on Triangle Mesa. However, one would have to cross many faults to measure a section there, and no Dakota outcrops are present; therefore, such a section would still be incomplete.

Maximum marine transgression is represented by the dark, basinal, limestone facies of the San Andres formation. Some geologists have viewed the sheer cliffs from a distance and have supposed that an organic reef section was present. Upon close inspection, the bedded limestones are seen to possess a nearly equal resistance to erosion, causing the illusion. Furthermore, all of the bedding in the San Andres is parallel, with no mounding or irregular bedding.

No Triassic, Jurassic, or Lower Cretaceous rocks are present in the mapped area. However, the Sun Oil Company No. 1 Victorio Land and Cattle Company well, located approximately 12 miles northeast of the mapped area, encountered a 170-foot red shale interval of possible Triassic age.

Cretaceous Rocks

Upper Cretaceous rocks of the Dakota, Mancos, Mesaverde, and McRae formations have been mapped in the area covered by this report. Originally the Dakota was defined by Meek and Hayden (1862; in Wilmarth, 1938) from a locality in Dakota County, Nebraska. Mancos Valley in southwest Colorado is the type locality of the Mancos shale (W. Cross, 1899; in Wilmarth, 1938). Holmes (1877; in Wilmarth, 1938) described the type section of the Mesaverde formation at Mesa Verde, also in southwest Colorado.

Kelly and Silver (1952) applied this system of nomenclature to the Caballo Mountains area. Furthermore, they defined a new formation, the McRae, from old Fort McRae (east of Elephant Butte Reservoir). This formation overlies the Mesaverde and may contain beds of Tertiary age.

In the McRae Canyon area, Bushnell (1953) subdivided the Mesaverde formation into an unnamed main body and overlying Ash Canyon member, and the McRae formation into the Jose Creek and Hall Lake members. The type sectionsof these named members are south and southeast of Kettle Mountain, immediately south of the boundary of the present work. These members were found to be mappable in this study.

Complete, unfaulted, and well exposed sections of the Cretaceous formations and members are lacking in the mapped area of this report. For this reason, no detailed section measuring was attempted. Only descriptions useful in field differentiation of the units are stressed in the following discussion.

Dakota sandstone

A few, small outcrops of the Dakota sandstone are found at the south end of the Fra Cristobal Range. One is an inlier on the Fra Cristobal anticline. Other small outcrops may be present in this area but were not mappable. As mentioned previously, the Dakota is present on top of the San Andres exposure on the southwest slope of Shotgun Ridge.

In these few outcrops the Dakota is a clear to light gray, medium-grained, quartz sandstone. The grains are subrounded to subangular and well sorted. With some white clay in the matrix and no calcareous cement, the sandstone is slightly friable. Where quartzitic, with a slight amount of calcareous cement (and no clay), the sandstone is hard.

The Dakota is thin-bedded and some places weathers rust-brown. Its contact with the underlying San Andres formation is one of apparent disconformity, for no dip divergence was seen on the south-west side of Shotgun Ridge. A fault surface cuts out the top of the Dakota in this locality, and the sandstone is overlain by a dark, red-brown layer of chalcedony, which was probably deposited by mineralized waters in the fault zone.

The contact with the overlying Mancos shale is sharp but conformable at the inlier on the Fra Cristobal anticline. About 50 feet of Dakota is exposed, but the total stratigraphic thickness may be much greater.

Correlation of the Dakota in the map area is based on lithology and position in the sequence. The Dakota is considered to be the basal clastic unit of a marine transgression.

Mancos shale

Outcrops of the Mancos shale occur in slopes to the southwest of Shotgun Ridge, and on the axial portion of the Fra Cristobal anticline. The soft shale valley lies south and west of the range proper.

Characteristically, the Mancos is gray to dark gray, calcareous, clean (not silty), and weathers with some limonite stain. A few thin, flaggy limestones near the base contain pelecypods.

Near the top of the Mancos the shales are greenish gray, and they grade upward into the Mesaverde formation. About 400 feet of Mancos is estimated as a maximum thickness for this area, but the relatively poor exposures prevent accurate measurements.

No problem exists in distinguishing the dark Mancos shale from any other formation in the Fra Cristobal area. Following the Dakota, the lower, dark gray shale of the Mancos represents marine transgression; however, the thin, upper greenish gray shale suggests a regression and gradation to the continental Mesaverde facies.

Mesaverde formation

Main body of the Mesaverde formation. South of the Fra Cristobal Range proper lies a series of alternating low ridges and valleys where the moderately dipping main body of the Mesaverde formation crops out. This unit is the most widely distributed of the Cretaceous rocks and probably underlies much of the Jornada del Muerto pediment gravel to the east. A small exposure in the northern part of the area is on the downthrown side of the Fra Cristobal fault, east of Massacre Gap.

Olive drab shale with intercalated buff to light gray sandstone beds is the main lithology of this stratigraphic unit. Fine- to medium-grained quartz, with some feldspar, is the dominant mineral type in the sandstones. Most grains are subangular, but angular and subrounded types occur. Sorting is fair, but some clay matrix, and very fine-grained through coarse-grained quartz is observed. Well cemented and quartzitic, the sandstones seldom are only slightly friable or calcareous. Usually the sandstones weather olive to reddish brown, but a few exhibit yellow limonite stain.

In the upper part, some thin, granule-to-pebble conglomerate beds alternate with the shale and sandstone beds. Some red shale is present but rare.

Silicified wood specimens are locally abundant. Black and dark gray are the usual colors. A few fossil logs measure up to two feet in diameter and five feet in length.

The sandstones of the main body of the Mesaverde are usually thin-bedded, but some are medium-bedded in this area. Many of the beds are lenticular, and cross-bedding is not uncommon. At least 2,000 feet is exposed in the mapped area, but the total thickness of this unit is estimated near 3,100 feet (Bushnell, 1953). Contacts with both the underlying Mancos shale and overlying Ash Canyon conglomerate appear to be gradational.

The preponderance of olive-drab shale and relatively clean sandstone distinguishes this stratigraphic unit from the others in the area. Further refinement may be accomplished by tracing individual beds, but the interruptions due to faulting make this process difficult. Deposition rates apparently increased with time as this unit was laid down in a near-shore, possibly swampy, continental environment.

Ash Canyon member. Only one outcrop of the Ash Canyon member of the Mesaverde formation was mapped in the southern part of the area, a synclinal hill bounded by faults. Granule to pebble size chert conglomerate and intercalated sandstone occur in thin to thick beds with some sweeping cross-beds.

Conglomerate fragments are subrounded to subangular, elongate more than spherical, and composed of clear or gray chert which often appears black in hand specimen. Poor sorting is indicated by the presence of fine-grained quartz sandstone in the matrix. The grains are well cemented with silica. Intergranular porosity may be present, but low permeability is apparent.

Bushnell (1953) measured 112 feet of this member at the type locality. It is differentiated from the coarse clastics of other units by its non-volcanic, and "clean" aspect. The conglomerate sequence marks an increase in rate of deposition and suggests that the area was farther removed from marine conditions.

McRae formation

Jose Creek member. Nearly all the exposures of the Jose Creek member are found in the southwest part of the area. Only one small fault block of the member is found in the northern part. Generally this unit is non-resistant to erosion and is found in valleys and on slopes. McCleary (1960) mapped an important outcrop of Jose Creek at the northern tip of the Fra Cristobal Range.

Dark green, olive drab, gray, and some purple shale units with intercalated dark green or gray, "dirty" appearing sandstone beds are the main lithologic types. Other colors of the sandstones include red, white, and purple. Quartz is minor as most of the grains are composed of plagioclase feldspar and chlorite; however, some orthoclase feldspar and black ferromagnesian minerals are present.

Sorting of the very fine to medium size grains is usually poor. Most particles are angular to subrounded. Selected samples suggest that none of the sandstones is friable. In fact, most are well indurated, but calcareous cement is absent.

Rarely some clean, white, medium- to coarse-grained quartz sandstones appear. Conglomerates of coarse sand to granule size particles (with usual composition and texture of the sandstones) are found mostly in the upper part of the Jose Creek. Thin beds of tan chert also occur in the upper section. Light gray silicified wood fragments are locally abundant.

The individual thin to medium beds of sandstone are separated by shale units. Bedding is regular but not exactly parallel; however, almost no cross-bedding is evident. Some beds are lenticular.

Bushnell (1953) measured 394 feet of Jose Creek at the type locality. The contact exhibiting unconformable relations with the underlying Ash Canyon member cannot be observed in the mapped area, but was demonstrated in the work of Bushnell (1953, p. 24).

Beds may be traced in a great deal of the Jose Creek member, but correlations were based mainly on gross lithology because of the complex faulting. Both the andesitic intrusive centers to the south and the exposed Precambrian terrane to the north were source areas for the clastics as inferred from their composition. Textures suggest that the distance of transport was not great, and that deposition rates were moderate. A continental environment is indicated by the plant fossils.

Hall Lake member. Outcrops of the Hall Lake member of the McRae formation are extensive in the southwest part of the mapped area (especially along the east shore of the reservoir), but are absent in the northern part. Generally the member is found in valleys, slopes, and low hills, but some of the more resistant units form ridges.

Thick maroon and dark purple shale intervals are the most distinctive and conspicuous rock types in the Hall Lake. Sandstone types are similar to those of the Jose Creek. Subangular, fine- to coarse-grains of white plagioclase feldspar, cream chert, and light green chloritic material are dominant. Purple clay is often found in the matrix. In spite of the poor sorting, some permeability is indicated.

Both plagioclase and orthoclase feldspar occur with minor quartz in the basal conglomerates of the Hall Lake. The particles are subangular and subrounded, and coarse-grained to pebble in size. Green, purple, and red colors blend into an overall greenish cast in hand specimen.

The clastic units are thin- to thick-bedded, and also are lenticular. No important angular divergence is seen along the Hall Lake/Jose Creek contact, but it is not well exposed. In spite of the presence of the basal conglomerate, the Hall Lake locally may be gradational with the Jose Creek. Bushnell (1953) estimated the thickness of the Hall Lake member to be at least 2,900 feet.

Correlation of the Hall Lake is dependent upon the presence of the thick sections of maroon and purple shale. Although the sandstones contain more plagioclase feldspar than those of the Jose Creek, they are similar otherwise. Rapid deposition is indicated by the conglomerate beds, but the thick shale units in the upper part of the Hall Lake suggest a moderate rate of subsidence. The environment may have been in a continental floodplain.

Cenozoic Rocks

Tertiary and Quaternary rocks are found in the valleys and lowlands adjacent to the Fra Cristobal Range. Down-faulted on the west side of the range is the Miocene to Pliocene Santa Fe formation. It was named originally by F. V. Hayden in 1869 (in Wilmarth, 1938). Extreme variations in lithology and beddedness of the Santa Fe suggest that it was derived from the bounding uplifts during the formation of the Rio Grande depression. Conglomerates of granule to cobble size particles range in composition from dark, basic igneous types to light colored chert and quartz. A dark volcanic conglomerate is present in the Santa Fe east of Black Bluff Canyon, adjacent to a branch from the Hot Springs fault.

Farther north along the Hot Springs fault, where it is downthrown against the Yeso formation, the Santa Fe is mostly white to yellow sandstone. Quartz and some white feldspar compose the medium-grained particles, which are well sorted and subrounded, loosely cemented, and very friable. Broad, sweeping, festoon cross-beds are seen in exposures along the east shore of Elephant Butte Reservoir.

The eastward-sloping Jornada pediment surface extends for many miles beyond the northeast and southeast boundaries of the mapped area. Included with the Jornada pediment gravel is some silt and minor amounts of caliche. A dip of 22° south was taken near the

Fra Cristobal fault zone on a conglomerate in the Jornada pediment which was derived from the Yeso formation. Bushnell (1953, p. 53) states that the thickness ranges from less than 50 feet to more than 200 feet. Jornada pediment gravel underlies the basalt flows in the south.

On the other hand, the pediment blankets of the westward-sloping Cuchillo surface on the west side of the Fra Cristobal Range are seen to occur both above and below lava flows. In one instance this 100- to 200-foot thick blanket, containing layers derived from the San Andres limestone, is quite extensive and conceals the Hot Springs and other major faults. Over much of the area the Tertiary and Quaternary sediments were mapped together as it is sometimes difficult to separate the Santa Fe formation from the younger Cuchillo pediment gravels.

Three Tertiary basalt dikes are found in the vicinity of Kettle Mountain. The main one trends northwest-southeast and continues into the McRae Canyon area. These dikes are vertical and show no baking or drag where they have been intruded into the Hall Lake member; however, they have been disrupted by later faulting.

Several Quaternary basalt cones and associated flows are found in both the Engle and Jornada valleys as well as on the lowlands south of the Fra Cristobal Range. Composition of these flows is mostly olivine basalt. The large multiple cone structure on the Fra Cristobal fault, east of Triangle Mesa, contains several volcanic bombs about six inches in length. From his descriptions, it is believed that this is the lava flow which greatly impressed G. G. Shumard (1859) on his excursion through the Jornada del Muerto.

Mineralization took place along many of the faults and left deposits of hematite and quartz. Some thin stringers of barite were found northeast of Little Kettle Mountain. One small, non-commercial deposit of botryoidal psilomelane was found on a low hill west of this mountain.

Talus piles, lacustrine deposits, and alluvium are locally quite extensive. However, they were not mappable on the present scale.

STRUCTURE

Mapping of the structural geology in the southern part of the Fra Cristobal Range was accomplished by Brunton compass survey. In the present work, nearly the entire area was traversed on foot, and most of the structures were "walked-out" in the field. Although detailed in scope, this study may be considered as reconnaissance for plane-table, structure contour mapping. However, further refinement of the stratigraphic sequence would be necessary if such a project is attempted.

The present map scale (2" = 1 mile) is sufficiently large for adequate representation of most of the structures in this area. Yet many folds and faults within the incompetent Yeso formation in the northwest part of the area may only be shown on a map at twice or even four times this scale.

One of the major improvements over the previous investigation (Thompson, 1955) is the quality of the strike-and-dip control. This writer has been impressed by the fact that an attempt to acquire abundant control by integrating questionable values (i.e. possible cross-bedding, apparent dips, possible erosion surfaces, possible slump, etc.) with reliable data can confuse structural analyses.

Nearly all the strikes-and-dips shown in the present work are within the accuracy limits of the Brunton compass and clinometer.

By far the great majority of them were taken in drainage notches where true attitudes of beds are obvious. Yet the control still crowds the cartographic space.

Another technique gained from the previous experience concerns the selection of data to be mapped. Here again the scale of the map is the main limiting factor. Usually the strikes-and-dips recorded in the field were substantiated by photogeology. Values change radically over very short distances in some areas, mostly near fault zones. However, each attitude is representative of at least the area under the symbol, and many extend to the limits of the particular fault block, or to some mid-point between an adjacent attitude in the same block.

Technical terminology and principles of interpretation generally are consistent with Billings (1954). Background material on regional tectonics may be found in Kelley and Silver (1952), Kelley (1952), and Kelley (1955).

In following the present discussion, constant reference to the geologic map (Fig. 2), and the supplemental structure sections (Fig. 4) is strongly recommended. Principally with regard to the description and interpretation of the strike-slip faulting discussed in the earlier thesis (Thompson, 1955), this text constitutes a major correction.

Regional Setting

The Fra Cristobal Range is one of the discontinuous chain of north-south trending uplifts which separates the Rio Grande and Jornada del Muerto depressions. Generally the range may be viewed as an east-tilted fault block. The bounding faults intersect at both the north and south ends. Specifically, the area within the range is disturbed by overturned folds, thrusts and normal faults.

McCleary (1960) mapped a large, north-south trending syncline, overturned to the east (in the Paleozoic formations), along the crest of the range. He postulates a companion overturned anticline on the west side where Precambrian granite is now exposed. Long, west dipping thrust faults (parallel to the overturned folds) bring Precambrian granite over Pennsylvanian Magdalena and Permian Abo. The rest of the northern part of the range is not complex, yet some prominent normal faults and upright folds are present. Strike-slip movement is minor as only two right-lateral faults were mapped in this area.

North of the Fra Cristobal uplift is the San Pascual platform. To the south lies the Cutter sag and the Caballo uplift.

Some overturned folds and minor thrusts were mapped during the present work in the southern part of the range, but a greater number and larger displacements of the normal faults are apparent compared to the northern part. High-angle faulting with some pronounced lateral movements complicate that part of the Cutter sag adjacent to the Fra Cristobal uplift.

Farther south in the McRae Canyon area (Bushnell, 1953) normal faults, some open folds, and minor strike-slip faults are present, but the structural picture is somewhat simpler in this portion of the Cutter sag. However, in the Caballo uplift again are seen the overturned folds, thrusts and normal faults.

Overall, the Jornada del Muerto depression appears to be a large syncline. On the other hand it is faulted on the west limb, and many complex folds and faults may be covered by the thin bolson deposits.

Structural relief is more pronounced in the Engle basin to the west of the Fra Cristobal uplift, than in the Jornada. The Engle basin is one of the many in eschelon, north-trending basins comprising the Rio Grande depression. High-angle faults are the most common structures in the depression. However, lateral components of movement may be as nearly important as vertical ones. Indeed the basins may have been forced down by shearing along the faults, as well as by tensional movements.

In Paleozoic time, the stratigraphic record suggests that only epeirogenic movements affected the Fra Cristobal area. Although downwarping of geosynclinal proportions was attained in the Cretaceous period, the first evidences of orogeny deforming the section in the mapped area are the overturned folds and thrusts believed to be Laramide in age. In Miocene and Pliocene time, high-angle block faulting with lateral shearing, and broad, open folding occurred. Recent earthquakes and fresh fault scarps suggest that diastrophism may have continued to the present day.

Dating of the structures is accomplished by analogy with other areas (e.g. the Caballo Mountains). For not only are the ages of the rock sequences poorly defined, but also nearly all of the Tertiary rocks have been removed by erosion from the mapped area.

Some question exists as to whether the Fra Cristobal area should be included with the Rocky Mountain system or the Basin and Range province. The Laramide folds and thrusts, and the trends, suggest the former. But the high-angle, block faulting producing the uplifts and depressions in middle and upper Tertiary time is typical of the Basin and Range. Kelley (1955) recognizes the problem but prefers to designate the area as a southern extension of the Eastern Rockies belt.

Folds

Few structures which can be mapped definitely as folds are found in the southern part of the Fra Cristobal Range. Many dip reversals near faults are classified as drag. It is possible that at one time many north-south trending anticlines and synclines were present, but have been so modified by later faulting that they can no longer be recognized. Finally, it should be stressed that there are some folds which are not mappable at the present scale, but most of them are also associated with faulting.

To lay a foundation in the descriptive part of this text for the analysis to follow, it is necessary to make clear the distinction between open and closed folds. No generally accepted reference has an adequate definition of these terms. Rather than repeat the discussion from an ealier work (Thompson, 1955, pp. 33-34), only the salient points are mentioned.

Dr. V. C. Kelley (personal communication) suggests that if the interior angle of a fold is greater than or equal to 90°, the fold is open, whereas if it is less than 90°, the fold is closed. To define "the interior angle" the present writer suggests that it be designated as the smaller angle formed by the intersection of the tangents drawn to a simple fold at the points of inflection.

In most cases the interior angle is equal to the supplement of the sums of the dips of the two tangents. (However, in the case of an overturned fold, the calculation is slightly more complicated.) This method is best employed when examining folds from the map view. For viewing unexaggerated structure sections, a 90° drafting triangle may be used to judge the simple differentiation between open and closed folds.

Closed folds

Only one small area of closed folds is indicated on Structure Section A-A' (Fig. 4). Adjacent to the Hot Springs fault a series of closely spaced overturned synclines and anticlines are present in the Yeso formation which cannot be shown exactly on the section, much less on the map.

The area of the closed folds is less than one-quarter of a mile wide and about one-half a mile long. The folds trend northwest-southeast and are overturned to the northeast. The overturned limbs dip as low as 64° to the west. Average distance between axes is about 100 feet.

Much flowage has taken place on these isoclinal folds. Sandstone, shale, and limestone beds comprise the Yeso in this area, but some gypsum may have been squeezed out of the section. It is likely that these folds tend to die out with depth in the more competent Abo formation. Furthermore, they may not appear in restored sections of the overlying San Andres.

On the east side of the belt, the complex folds have been modified by later faulting down to the west. Farther east the many faults down to the west, with steep west dip on the upthrown sides, may have been folds originally.

Open folds

Near the north end of the mapped area a synclinal axis is drawn through the Magdalena inlier in the amphitheater outcrop of the Abo formation. The axial trace is about one mile long, trends northeast-southwest, but curves to trend north-south. Plunge is to the south. Gentle dips on the limbs are nearly symmetrical, ranging from 5° to 7°.

At the south end of the Fra Cristobal uplift, the bounding faults intersect and die out to the south in the Fra Cristobal anticline. Its north-south trending axial trace is mapped for nearly two miles in the Dakota, Mancos, and Mesaverde formations before it plunges southward beneath the Quaternary lavas. Dips on the west limb average 20°, whereas those on the east limb average over 30°, producing a definite asymmetry to the east (see Section C'-C', Fig. 4).

To the west is a one-half mile wide syncline hill in the Ash Canyon member. Bounded by faults on all sides, the axial trace of the fold trends northeast-southwest for one mile paralleling two major faults down to the west. Near the mid-point of the axis, where the syncline is best developed, the axial surface dips slightly to the west with dips on the west limb up to 16°, and on the east limb up to 10°.

From the general convergence of dips on either side of this fold, it may be supposed that most of the south-central part of the mapped area was occupied at one time by a much larger syncline. If so, it has been modified by later faulting to such an extent that only the axial portion is preserved in the gentle downfold mentioned above.

An axial trace of less than one-half mile is mapped on a northeast-southwest trending syncline northeast of Kettle Mountain. This short fold plunges rather steeply to the south with dips of 21° to 39° on the limbs. Most of the length of the trace of the axial plane is in the upper Jose Creek, but the south end plunges into the basal part of the Hall Lake member. This syncline is also bounded by two prominent faults downthrown to the west.

Faults

Evidence of faulting abounds in the southern part of the Fra Cristobal uplift and adjacent parts of the Cutter sag. A few fault and fault-line scarps are present, but most of the faults were located by mapping structural attitudes and the distribution of stratigraphic units. Solid fault symbols on the geologic map represent those faults whose position was determined both in the field and on aerial photographs. Dashed symbols indicate approximate positions of those faults which could not be located accurately, but which were necessitated by field data.

Well developed drag structures are present along most of the faults, but other features such as slickensides, breccia, etc. rarely were observed. Silicification and hematite mineralization mark many of the fractures in the Permian rocks, but are not definite evidences of faulting. Geomorphic criteria are useful in indicating possible faults; however, no fault was drawn based on them alone.

Selection of a significance level above which a given fault is mapped and below which it is omitted was a difficult problem in this area. On the other hand, it is a necessary consideration if the available cartographic space is to be utilized efficiently. In general, if a fault has less than 50 feet of throw and/or is less than one-half mile long, it was deleted. Displacement estimates are only approximate because no detailed topographic control is available.

The following discussion is mainly descriptive with interpretations deferred to a later section. As a general order, the faults on the west and south sides of the area (Cutter sag) are discussed first, and those on the north and east (Fra Cristobal uplift) are described toward the latter part. Nearly all the faults are normal, but some strike-slip and **thrust** faults are mapped.

Hot Springs, Double Canyon, and related faults

Originally named by Kelley and Silver (1952, p. 159), the Hot Springs fault has been mapped from the northern part of the Caballo Mountains, through the McRae Canyon area (Bushnell, 1953), through the area of this report (Thompson, 1955), to the northern end of the Fra Cristobal Range (Jacobs, 1956, and McCleary, 1960) where it forms a prominent west-facing fault-line scarp.

Less than 7 miles of the 30-mile length is concealed by Elephant Butte Reservoir. The Hot Springs fault trends N 25° E in the Caballo Mountains, from N 20° E in the southern part of the Cutter sag to N 35° E near the north end, abruptly turning to N 10° W in the southern part of the Fra Cristobal uplift, and gradually back to N 30° E at the north end of the uplift.

Measured dips of the normal fault surface range from 60° to 75° to the west. On the upthrown side (east) in the Fra Cristobal and Caballo Mountains, Precambrian rocks are exposed. Progressively toward the Cutter sag, younger formations from the Paleozoics to the Hall Lake member of the McRae are exposed along the fault. Throughout most of the length of the Hot Springs fault, the Tertiary Santa Fe formation is exposed (or is present beneath Quaternary alluvium) on the downthrown (west) side. Where Santa Fe abuts Precambrian, the stratigraphic throw is estimated to be 8,000 feet.

However, in the Caballo area some small outcrops of Precambrian and Paleozoic rocks are mapped on the downthrown side. Right-lateral separation of these outcrops is apparent relative to the uplift. On the other hand, Kelley and Silver (1952, p. 160) have observed left-lateral drag on the upthrown side of the Hot Springs fault.

Jacobs (1956) and McCleary (1960) mapped local outcrops of San Andres and Bar B downthrown against Precambrian in the northern part of the Fra Cristobal Range. Steep dips to the west in these outcrops suggest vertical drag on the Hot Springs fault.

In the southern part of the range (Fig. 2), the Yeso formation is upfaulted against the Santa Fe. Here also vertical drag is indicated by the dips to the west in the Yeso. Much of the length of the Hot Springs fault in this area is marked by silicification and hematite mineralization. Although definite displacement is not demonstrated, the map pattern suggests that this fault has disrupted the Quaternary lava flows.

Farther south, part of the Hot Springs fault is buried by the Cuchillo pediment gravel. East of Black Bluff Canyon in the northern part of the Cutter sag, the main body of the Mesaverde is on both sides of the fault, (Fig. 4, Section B-B'), but some left-lateral drag is seen. (Note that in the earlier work, Thompson, 1955, right-lateral drag was reported. More detailed mapping has shown this conclusion to be in error.) Two branch faults displace the Jose Creek member and the Santa Fe formation down to the west. Santa Fe probably is faulted against the Hall Lake member in Elephant Butte Reservoir as observed northwest of Little Kettle Mountain, on Long Point, and in the McRae Canyon area (Bushnell, 1953).

Nearly parallel to the Hot Springs fault in the Cutter sag is a series of northeast-southwest trending normal faults, spaced about one-half to three-quarters of a mile apart, and downthrown to the west.

Most important of these is the <u>Double Canyon fault</u>. Very prominent right-lateral drag features are present on both sides of the fault. Here Hall Lake abuts Jose Creek with throw of about 2,500 feet (Fig. 4, Section C-C'). Displacement is less at Double Canyon where Hall Lake is on both sides of the fault. Notice that the Tertiary dike is not offset appreciably.

Over two miles of the Double Canyon fault is mapped from the reservoir to Little Kettle Mountain. North of that point it appears to join an east-northeast trending fault, down to the southeast, thus indicating rotational movement relative to the main part of the fault. On this short one-mile extension only a few hundred feet of stratigraphic throw is likely, for the Jose Creek is downthrown against the upper part of the main body of the Mesaverde. It terminates against the next of the principal faults.

This next northeast trending fault (immediately west of the northeast turn in Section B-B', Fig. 4) is mapped for only 1 1/2 miles, but its north end is buried beneath the Cuchillo pediment gravel. To the south it terminates against one of the transverse faults. A minimum of 500 feet of throw is estimated where the main body of the Mesaverde is present at the surface on both sides of the fault. Prominent right-lateral drag is evident on the west (down) side of the fault.

Farther east, the next main fault forms the northwest boundary of the synclinal hill in the Ash Canyon member. As seen in Section C-C' (Fig. 4) about 500 feet of throw is estimated where the Ash Canyon is faulted against Jose Creek. This fault dies out at its north end, or here becomes a strike fault and is not obvious beyond. However, it is mapped for nearly 4 miles to the south and continues into the McRae Canyon area.

The southeast boundary of the Ash Canyon outcrop is the next main fault. Again 500 feet or less is the estimated throw where Ash Canyon is down-faulted against the main body of the Mesaverde. Some small right-lateral drag features are observed near the north end before the fault terminates against one of the southwest boundary faults of the Fra Cristobal uplift. It is about 4 1/2 miles long, but continues also into the McRae Canyon area beneath the Quaternary lava. A dip of 81° W is recorded on the fault surface immediately south of Double Canyon.

The easternmost of the main faults lies to the west of the Fra Cristobal anticline. The south end is covered by lava, but it is mapped for over 2 miles before it is interrupted by an east-west transverse fault. An additional one-mile extension is offset about one-eighth of a mile to the west. The northern end curves into another of the boundary faults of the Fra Cristobal uplift. Again the throw is on the order of 500 feet where the main body of the Mesaverde is on both sides of the fault.

Many short transverse faults are present within the blocks bounded by the main northeast trending set of faults. Most of them are less than one mile long and have less than a few hundred feet of throw. Some trend northwest-southeast, others trend east-northeast--west-southwest. No consistent displacement is obvious, for part of them are downthrown to the south, the rest to the north. Both right-lateral and left-lateral offsets in the dikes are observed along some short faults near Kettle Mountain.

Perhaps the most important of these transverse faults is the one partly covered by the lava on Little Kettle Mountain. Hall Lake is down-faulted against the main body of the Mesaverde suggesting a stratigraphic throw of at least 500 feet. Some botryoidal psilomelane mineralization is associated with this fault.

Faults in the Shotgun Ridge - Triangle Mesa area

At the south end of the Fra Cristobal Range is a set of uplifted normal fault blocks, the highest of which comprise Shotgun Ridge and Triangle Mesa. Boundary faults include the Fra Cristobal fault zone and the Massacre Gap fault which are discussed later.

The southwest boundary fault is also a demarcation between the Fra Cristobal uplift and the Cutter sag. It trends northwest-southeast and is mapped for nearly 1 1/2 miles before its north end is buried by the Cuchillo pediment gravel. Vertical slickensides are found on the well exposed fault surface, which dips 71° to the west. Hematite mineralization and silicification are abundant along the fault. Although physiographically prominent, the actual displacement along the fault is not great. On Section B-B' (Fig. 4) only 250 feet of throw is indicated where Mancos is downthrown against Dakota. However, notice the steep west dip on both sides of the fault.

What happens to the northward extension of this fault beneath the Cuchillo gravels? Unfortunately, the largest area of Quaternary cover within the uplift-sag creates one of the most perplexing structural problems. To the north and east are the Permian rocks of the Yeso and San Andres. To the south are outcrops of the Mesaverde. Most of the dips are to the southwest, but the discordant east dip of the Mesaverde on the west side suggests that a prominent fault lies beneath the gravels. For the sake of simplicity, the fault described above is extended questionably to the west-northwest. Very probably the concealed structure is much more complex.

At the northeast end of the gravel a northwest-southeast trending fault is mapped for one-half mile between its point of burial and its termination against the Double Peak fault. It is downthrown to the west displacing complicated fault blocks of Yeso and San Andres. The steep 70° W dip (in the San Andres) adjacent to the fault on the downthrown side is probably vertical drag.

Next to the northeast is another northwest-southeast trending normal fault down to the west. It appears on Section B-B' (Fig. 4) as the fault east of the "southwest boundary fault" described above. Less than 200 feet of throw is indicated. San Andres limestone is on both sides for most of the two miles of length, but one canyon cuts down to expose a small inlier of Yeso on the upthrown side. Yeso is also at the surface on the up side south of Shotgun Ridge.

Nearly 400 feet of throw is shown on the north-south trending normal fault on the west side of Shotgun Ridge (Section B-B', Fig. 4). This fault extends for nearly 2 1/2 miles, across Triangle Mesa, to the Massacre Gap fault. San Andres and Yeso are exposed on both the downthrown (west) and upthrown sides.

About one-quarter of a mile to the east is another north-south fault, subparallel to the one described above over much of its 2 1/2 mile length, but the two intersect at its south end. Mostly this fault is down to the west about 150 feet (Section B-B', Fig. 4). However, at the south end of Triangle Mesa the San Andres and Yeso beds on the east side dip steeply toward the fault such that here it is down to the east.

Three normal faults are downthrown toward the north, southwest, and southeast sides of Triangle Mesa. They are one to 1 1/2 miles long, and displace only the San Andres and Yeso formations at the surface. On the southeast face of the mesa the fault is rotational with the displacement increasing southward.

Faults between the Hot Springs and Double Peak faults

In the northwest part of the mapped area are several normal faults which trend northwest-southeast, or north-south, and are down to the west. Silicification and hematite mineralization is common along them. The Yeso formation is at the surface over most of this structural element west of the Double Peak fault.

Only about 100 feet of throw is shown on the four faults at the west end of Section A-A' (Fig. 4). Note the contortions in the plastic Yeso which are not reflected in the underlying Abo or Magdalena. Although these faults are only one-eighth to one-quarter of a mile apart, steep drag is common on the upthrown sides, whereas relatively gentle east dip or west dip (drag?) is present on the downthrown sides. One of the better exposed fault surfaces has a dip of 84° to the west. Length varies from one-half to 1 1/4 miles. The shortest one is terminated at its north end by a transverse fault.

This one-eighth mile long transverse fault trends northeast-southwest. Upper Abo is against lower Yeso, downthrown to the northwest. This fault ends against a small Abo inlier which is on the upthrown side of another northwest-southeast trending normal fault.

The latter is about 1 1/4 miles long, is down to the west, and only slightly displaces the Abo and Yeso formations. Similarly, another fault (about one-quarter mile east) is one mile long and down to the west, although it has a slightly more northerly trend. These two faults abut the prominent northeast-southwest trending fault near the northwest end of the mapped area. Upper Magdalena is against middle Abo indicating a stratigraphic throw of about 200 feet, downthrown to the southeast. It ends against the fault described below.

Next is a fault which trends generally north-south, is over 2 1/2 miles long in the mapped area and continues for another 2 1/4 miles into the northern part of the range (McCleary, 1960, Fig. 3). At the surface to the north, the Magdalena is on both the up (east) and down (west) sides. Farther south the Magdalena is upfaulted against lower Yeso, indicating a stratigraphic throw of over 500 feet. Some Abo is on the upthrown side, but mostly Yeso outcrops on both sides along the rest of the fault. A horse of Jose Creek appears on the down side in Section A-A' (Fig. 4). Here a throw of about 150 feet is shown on the top of the Abo. Note that this fault displaces the "root" of the overthrust north of Double Peak. Although the exact location of the southernmost part is obscured by the complex dips, this fault is believed to terminate against the Double Peak fault.

A recumbent closed fold in the Yeso, inclined to the east, was seen on the downthrown (west) side of the north-south trending fault forming the northwest boundary of the Jose Creek horse. Only about 100 feet of throw or less is shown on this fault in Section A-A' (Fig. 4). Over most of its 1 3/4 miles length the Yeso formation is on both sides. Its intersection with a one-half mile long, northwest trending transverse fault was the locus for a Quaternary intrusive. Two other short transverse faults (one bifurcates) are mapped on the upthrown side of this fault, and may be displaced extensions of some of the faults on the downthrown side. This prominent north-south fault also ends against the Double Peak fault.

A 1 1/8 mile long fault in the south part of this structural element is terminated by the Hot Springs fault at its north end and the Double Peak fault at its south end. This fault generally trends north-south, and is downthrown to the west. Probably less than 100 feet of throw is present, for lower Yeso is at the surface on both sides except where covered by Quaternary flows. Much silicification and hematite mineralization is seen along the fault zone.

Double Peak and related faults

Perhaps the most complex structure in the northern part of the mapped area is the Double Peak fault. Apparently the movement has been rotational. South of the "pivot point", immediately east of Double Peak, the fault is an upthrust (down to the east). Northward it becomes a normal fault down to the west.

The upthrust (south) part trends northeast-southwest for 2 1/2 miles. Yeso is exposed on both sides over most of this length, but the south end is covered by Cuchillo pediment gravels. A small triangular fault block of San Andres is mapped on the upthrown side, but the exposure is not large enough to deny the possibility that these limestones are middle Yeso. Detailed mapping on a larger scale would show more highly contorted and faulted relationships in this much disturbed area.

A dip of 70° W is seen on this fault west of the prominent San Andres cliffs on the downthrown side. On the west side, Yeso is at the same topographic elevation as the lower San Andres on the east side. These displacement and dip relationships, plus some small drag features comprise the evidence for this portion being mapped as an upthrust.

Beyond Double Peak, the fault trends northward and finally curves northwestward. This normal displacement part is over 1 1/2 miles long. Accurate dip of the surface was not measurable, but it appears nearly vertical or dipping steeply to the west. Yeso is down on the west against Abo on Section A-A' (Fig. 4) where a throw of about 400 feet is shown. Abo and Magdalena contacts are slightly displaced near the north end before the fault ends against one of the north-south trending faults discussed previously. Some drag also supports the conclusion that this north extension is a normal fault.

The three-quarters of a mile long overthrust trending northwest from Double Peak may be considered a branch of the Double Peak fault. Middle Yeso has been thrust eastward over middle and lower Yeso. Relationships have been greatly simplified to be shown on Section A-A' (Fig. 4). Although the fault surface is slightly undulatory, it does have an average dip of 35° west. Multiple contortions in the form of closed anticlines and synclines (trending north-south) are seen beneath the thrust sheet where the prominent drainage cuts across the trace of the fault. Folding is nearly absent on the upper side, but a small monoclinal fold dipping to the west was observed south of the drainage. As mentioned previously one of the north-south faults displaces the northwest end from its "root". The many closed and overturned folds to the west may be related to this overthrust. However, recall the highly plastic nature of the Yeso lest the disastrophic significance of this deformation be over-emphasized.

Less than a mile north of Double Peak is a three-quarters of a mile long transverse fault which parallels the northwestward trend of the north end of Double Peak fault. It drops Yeso down to the west against Abo, but where Section A-A' (Fig. 4) crosses it, the fault only displaces Yeso at the surface. The throw here is shown to be about 100 feet or less.

Also parallel and down to the west, but to the northeast of the Double Peak fault, is another three-quarters of a mile long fault. It displaces the Abo/Magdalena contact, yet this fault appears to die out a short distance both to the north and south.

Faults in the Saddle Peak area

Most of the mapped area east of the Double Peak fault and northwest of the Massacre Gap fault is relatively undeformed. However, this is typical of the east side of the Fra Cristobal uplift.

An obvious exception to the above generalization is the prominent set of northeast trending normal faults. The first extends for 1 1/2 miles from the Double Peak fault (intersection is south of Double Peak) and appears to die out to the north in the Abo outcrop. In Section A-A' (Fig. 4) the Yeso is down-dropped to the east against

Abo with a throw of over 600 feet. One excellent exposure of the fault surface shows it dipping 62° E.

The second fault curves westward into the first one (described above) at its south end, but also trends northeast for over 2 1/2 miles, ending at the Fra Cristobal fault zone. Although some complex contortions are seen at the south end, the throw is about 200 feet on Section A-A' (Fig. 4) where the Yeso is displaced. On the other hand the throw increases northward to possibly as much as 300 feet where Abo is downthrown against Magdalena. Another excellent dip was measured on this fault surface; it is 89° E.

Much of the Saddle Peak area may be considered as a northeast trending graben with these two faults forming the northwest boundary and the Massacre Gap fault the southeast boundary. As seen on Section A-A' (Fig. 4), this graben is asymmetrical with the greater displacement on the northwest side.

A one-half mile long splay fault, located about one-quarter of a mile north of Saddle Peak, branches northeastward from the fault set described above. It only slightly displaces the Yeso, probably less than 50 feet down to the south, and dies out before reaching the line of the Yeso measured section.

Northeast of Double Peak is an east-west trending transverse fault nearly one-half mile long. Lower Yeso is down to the south against upper Abo on this normal fault.

Three normal faults one-half to three-quarters of a mile long are mapped to the west of Saddle Peak, within the graben area. Because they trend northwest-southeast they are classified as transverse faults. Displacements are slight as only the Lower San Andres and upper Yeso are involved. All are downthrown to the west. Many other small faults are present, but are not mappable on the present scale.

Massacre Gap fault

The Massacre Gap fault is nearly 3 miles long, and is expressed by a prominent northeast-southwest trending drainage which cuts through the southern part of the Fra Cristobal uplift. A projected base of the San Andres from Triangle Mesa and the ridge of Saddle Peak to the Massacre Gap fault would probably show a throw of less than 100 feet. On the other hand the displacement down to the northwest is unusual, and it forms the southeast side of the graben in the Saddle Peak area mentioned earlier.

Yeso is on both sides of the fault over much of its length. Poor exposure does not permit reliable extension of the Massacre Gap fault to the southwest, but it appears to end against a northwest-southeast trending fault. To the northeast it displaces the Yeso about 100 feet or less as seen on Section A-A' (Fig. 4). The unusual situation of Abo on the downthrown side adjacent to the Yeso on the upthrown side is explained by the small displacement and the fact that the Abo is much lower in elevation. Furthermore some small patches of Abo are not mappable on the up side. The Massacre Gap fault terminates to the northeast against the Fra Cristobal fault zone.

Faults east of Massacre Gap

Two northeast-southwest trending normal faults are seen on the east end of Section A-A' (Fig. 4) west of the Fra Cristobal fault zone. They displace the lower and middle Yeso down to the east less than 100 feet. Each is less than three-quarters of a mile long, but they are terminated at both ends by other faults.

An east-west transverse fault less than one-half mile long is mapped south of the faults described above. It normally displaces the Yeso only slightly and is down to the north.

To the southwest is a northwest-southeast trending normal fault over one mile long. Although Yeso outcrops on both sides, the stratigraphic throw may be over 100 feet. It ends against the Fra Cristobal fault zone and the Massacre Gap fault. No evidence was seen for its equivalent north of the Massacre Gap fault, but here it may be a strike fault and therefore hard to detect. Possibly it may lie beneath the 166-foot covered interval (Unit 19) in the Yeso measured section.

Fra Cristobal fault zone

The prominent eastern boundary of the Fra Cristobal uplift was named the Fra Cristobal fault zone in the earlier work (Thompson, 1955). It intersects the western boundary faults at both the north and south ends of the range. The fault zone trends northeast and north in the southern part of the Fra Cristobal Range for 6 miles. McCleary (1960) mapped it with a north and northwest trend for an additional 10 miles in the northern part of the range.

At lease two normal faults are present in the zone. The eastern one is well exposed only at the south end where Mesaverde on the east is downthrown against San Andres. Steep 81° dips to the east indicate pronounced vertical drag. Much silicification and hematite mineralization are present. Northward this fault is mostly buried by Jornada pediment gravels.

East of Shotgun Ridge the western fault emerges from beneath the Jornada cover where it intersects or branches from the eastern fault. Only the middle Yeso is displaced, but abundant silica and hematite mark the fault trace. About 250 feet of throw is shown on Section B-B' (Fig. 4), whereas on the eastern fault probably Mesaverde is against Yeso with a possible range of stratigraphic throw from 1000 feet to as much 3500 feet. The Quaternary intrusive centers associated with Shumard Cone appear to be related to the Fra Cristobal fault zone.

North of Shumard Cone reworked Mesaverde is seen in the Jornada bolson deposits near the position postulated for the buried eastern fault. In some of the drainages a short distance to the east, very small outcrops of east-dipping Mesaverde sandstone are observed.

The two faults may be coincident west of the small outcrop of Mesaverde. However, they undoubtedly separate again to the north. Over 300 feet of throw is shown on the western fault, Section A-A' (Fig. 4), where Yeso is exposed on the upthrown side and seems likely to be present on the downthrown side under the Jornada cover. Here again the probability of Yeso against Mesaverde on the eastern one indicates a stratigraphic throw of 1000 to 3500 feet.

At the northeast end of the mapped area the western member of the Fra Cristobal fault zone is exposed. Limestones of the middle part of the Yeso are downthrown against Abo and Magdalena. This suggests a maximum stratigraphic throw of about 1100 feet.

In the northern part of the range the western fault dies out into a syncline. The eastern fault remains buried, but probably intersects the Hot Springs fault beneath the Quaternary lavas a short distance north of the Fra Cristobal Range.

Other Structures

Some folds and a multitude of faults could not be mapped on the present scale. Along some faults are many small definite drag features and local weird contortions.

Joints were not emphasized in the present investigation because of the abundant faulting. Moreover, the good exposures eliminated any need for indirect evidence of major structures from joint studies. On the other hand, many shear and tension fractures were observed whose orientations confirmed fold trends and fault movements.

Several non-diastrophic structures are present. One of the main advantages in re-mapping this area was the previous experience with the possible slump, collapse, and solution structure dips. These dips were eliminated with a great deal of certainty during this revision.

Structural Analysis and Interpretation

Following the descriptions of structures in the previous sections, this part is devoted to analysis and synthesis of the data presented. Three major periods of deformation are distinguished -- Laramide (?), middle Tertiary and upper Tertiary. Age determination by analogy to the structures of the Caballo Mountains (see

Kelley and Silver, 1952) is necessitated by the fact that most of the rock units of nearly the same age as the folding and faulting have been removed by erosion.

Laramide folds and faults

Overturned folds and thrust faults are characteristic structures of late Cretaceous to early Tertiary -- or Laramide -- age in this region. Trends are generally to the northwest or north, and the usual direction of asymmetry and thrusting is eastward.

Many of the closed folds in the northwestern part of the mapped area appear to be of the Laramide type (see Section A-A', Fig. 4). The northwest trending closed and overturned folds adjacent to the Hot Springs fault are asymmetrical to the northeast. Their vertical extent is probably confined to the Yeso formation, for they are too tight to be projected very far upward or downward.

Also the northwest trending faults in this area are considered as Laramide, but the steep dips on the upthrown sides suggest asymmetry to the southwest. They displace the folds, and therefore are younger. On the other hand, these faults are displaced by north-south faults, and are probably older.

Movements along the Double Peak fault may have been complex, but a simple explanation is possible. Initially it may have been an arcuate normal fault, convex to the east (as it is now) and down to the west. Several faults terminate against it, and because no offsets are seen, the Double Peak fault is probably an older structure. Later the overthrust (directed to the east) merged to produce the upthrust on the southern part of the Double Peak fault. Another possible, but seemingly less likely, interpretation would be for the high-angle fault dipping west to have been subjected to rotational movement with the west side displaced such that the north end was down, and the south end was up. The weakness lies in the failure to explain the overthrust which developed northwest of the pivot point.

What significance is attached to the fact that above the overthrust is gentle folding, whereas below is complex, tight folding? Could be that the up side remained passive during an underthrust. Comparatively, an underthrust has a greater mechanical advantage than an overthrust. However, the complex folding may be a result of higher confining pressure beneath the thrust deforming the plastic Yeso formation.

Later normal faulting has displaced the root of the overthrust. The small recumbent fold (asymmetrical to the east) west of the Jose Creek horse may have been related to the overthrust.

Some of the north and northeast-trending faults between the Hot Springs and Double Peak faults may be upthrusts. The few east dips adjacent to the faults may be drag. If so, these faults should also be included in the Laramide age group. However, they are mapped as normal faults because they appear to dip steeply to the west in the same general direction as most of the beds.

Objectively one may question the diastrophic significance of these relatively low displacement faults and complex folds in the plastic Yeso formation which are classified here as Laramide. If they appeared in more competent beds, definitely they would be analagous to the other Laramide structures in the region. Problems of this kind may be solved if enough quantitative data on strength of materials were available, but such considerations are beyond the scope of the present work.

Could such overturned folds and thrusts be a mere byproduct of Tertiary normal faulting? Is it probable that the northwest trending faults with steep drag developed as transverse faults? Because most of the Tertiary faults are of the normal gravity type, very complex secondary forces (including horizontal compression) would need to be postulated if all of these structures were attributed to the same deformational period. Therefore, it seems more likely that a separate Laramide orogeny produced these complex structures in the northwest part of the mapped area.

The northwest trend of the overturned folds and the overthrust fault suggests that the principal Laramide force axis should be a horizontal compression oriented northeast-southwest. The asymmetry and thrust direction to the northeast implies an unequal stress distribution. Secondary dilatation following the compression probably produced the tension perpendicular to the northwest trending normal faults.

Middle Tertiary folds and faults

As in the Caballo Mountains most of the normal faulting in the Fra Cristobal area seems to have occurred during middle Tertiary, probably Miocene, time. High-angle, normal faults with vertical drag and slickensides are characteristic. Trends are usually oriented north or northwest, rarely northeast. The faults of this age group displace the Laramide structures, and in turn are displaced by the upper Tertiary northeast trending faults.

Uplift of the Fra Cristobal horst and relative lowering of the Rio Grande and Jornada del Muerto depressions were the most significant developments during this deformation interval. Accompanying the uplift, or slightly preceding it, was a gentle warping. Most of the evidence has been masked by later faulting, but the broad syncline in the Abo formation (near the north end of the mapped area) probably was formed then.

Also, it is likely that the Fra Cristobal anticline beyond the south end of the uplift is a southern remnant of a large fold which was later broken by the boundary faults. The postulated large syncline to the west is only expressed by the general convergence of dips in the Cretaceous beds, but it has been disrupted by younger faults trending northeast. Even the gentle syncline in the Ash Canyon, which may be a remnant of the axial portion of the larger downfold, trends parallel to the younger faults.

In spite of the rather small displacements along the fault limiting the southwest side of the Fra Cristobal uplift, this fault does provide a definite physiographic boundary of the range. The pronounced southwest dips in the San Andres outcrops, and also the less steep dips on the downthrown side in the Cretaceous beds, suggest a monocline or a west limb of a large anticline existed prior to faulting.

Considering the view in Section B-B', Fig. 4, the southwest boundary fault and the parallel fault to the northeast seem to have displaced the west limb of an anticline. This fold was probably the northward extension of the Fra Cristobal anticline discussed previously. However, farther north, especially along the parallel fault to the northeast, the older structure may have been a monocline. Gentle southwest dips on the west side of Triangle Mesa give way to much steeper dips, and finally low dips in the Cutter sag.

Adjacent to the Jornada del Muerto depression the east dips along the southern part of the Fra Cristobal fault zone imply that here the east limb of the anticline was faulted. North of Shumard Cone the dips are more erratic, less indicative of a previous fold. The northwest (north part) and north (middle) trends of the Fra Cristobal fault zone parallel other faults of the middle Tertiary deformation. At the south end the northeast trend may be explained if the pre-existing large anticline plunging to the south actually controlled the position of the Fra Cristobal fault zone.

Locally the faults in the Shotgun Ridge - Triangle Mesa area have large vertical separations. On the whole, however, they are relatively insignificant. They are considered merely as adjustment faults of the main period of uplift. Possibly the fault on the southeast side of Triangle Mesa is of much more recent origin. Its rotational movement, with the throw increasing southward, may have resulted from slumping of the protruding edge of the San Andres limestone outcrop.

The only important northeast trending faults within the Fra Cristobal uplift bound the Saddle Peak graben. More displacement is seen on the faults to the northwest than on the Massacre Gap fault. In the earlier work (Thompson, 1955) these faults were thought to have had strike-slip movements. Re-examination of the evidence demonstrates only vertical movements. Mainly for this reason, they are included in the middle Tertiary group. No explanation is readily apparent for the anomalous northeast trend. The short transverse faults within the graben are of the small adjustment type.

In the northwestern part of the mapped area, the north-south faults which disrupt the Laramide structures are believed to be of middle Tertiary age. Not much displacement is indicated, but the Jose Creek beds in the small horse are over 4000 feet below their normal stratigraphic position. Just why the horse is located immediately west of the klippe is an enigma. Surely such results of extreme tension and extreme compression are attributable to separate deformation periods.

Movement along the Hot Springs fault has been recurrent, but probably began in middle Tertiary. Vertical displacement is dominant where it forms the west boundary of the Fra Cristobal uplift. Clearly it is younger than the Laramide structures it disrupts. On the other hand, no fanglomerate facies appears in the Santa Fe formation (also reported to be Miocene in age) where it abuts the Yeso formation along the Hot Springs fault. Therefore, the movement here is judged to be post-Santa Fe in age. Estimates of the stratigraphic throw is complicated by the likely possibility that the Santa Fe overlies different age rocks along the strike of the fault. Actually it may well be part of a fault zone with several blocks dropped down to the west.

Unfortunately the Cuchillo pediment gravel conceals the southwestern end of the Fra Cristobal uplift. Many significant facts concerning the bounding faults, especially the Hot Springs fault would be learned if the cover were not present. The most serious problem is the relationship with the younger faults in the Cutter sag to the south.

From the evidence available, the principal force orientation during middle Tertiary was probably an early east-west horizontal compression of limited intensity (producing the folds), followed by an effective east-west horizontal tension of much greater magnitude (producing the faults). Differential vertical uplift could have produced the tension. Several of the small faults formed during this time were probably of near surface origin and only extend to shallow depths. However, some of the larger ones, especially the Hot Springs fault and the Fra Cristobal fault zone, may displace Precambrian basement. Moreover, some confining pressure was needed to permit development of the pronounced drag observed along the faults.

Upper Tertiary folds and faults

The last important deformation within the mapped area probably occurred during upper Tertiary (Cascadian). Recurrent movements along the middle Tertiary faults may have taken place, but the most significant development was the origin of the northeast trending normal faults with strike-slip components in the Cutter sag. They displace the older, northwest trending faults, but do not appear to disrupt the Quaternary lava flows.

South of the Cuchillo pediment gravel the Hot Springs fault trends northeast, and this part is interpreted as upper Tertiary in age. A great deal of its length is covered by Elephant Butte Reservoir. However, some important relationships were studied east of Black Bluff Canyon.

Two branch faults down-drop the Jose Creek and Santa Fe formation to the west, but the main fault-line scarp and trend of the Hot Springs fault continues northeastward and displaces only the Mesaverde. These two blocks must be local structures, for Santa Fe is faulted against Hall Lake south of Black Bluff Canyon, and Santa Fe is against Yeso farther north on the west side of the Fra Cristobal uplift. On the north side of Black Bluff Canyon, a volcanic conglomerate facies is present in the Santa Fe adjacent to the westernmost of the branch faults. The lithology is very similar to parts of the Jose Creek. If derived from the Jose Creek, the conglomerate could suggest a Santa Fe (Miocene?) age for the branch faults.

On the other hand, strike-slip movement is indicated on the main part of the Hot Springs fault in this area, and by analogy is more characteristic of upper Tertiary faulting. In the earlier work (Thompson, 1955) right-lateral movement was mapped. Although the evidence is not as clear as on some other strike-slip faults, this revision studied the fault in detail and changed the interpretation to left-lateral based on drag.

Because Kelley and Silver (1952) had suggested left-lateral drag on the Hot Springs fault in the Caballo Mountains, the right-lateral drag discussed in the earlier work appeared incongruous. However, several possible explanations were given for the occurrence of opposite movements along the same strike-slip fault. The general logic of these explanations is still valid, but this revision of the data to show left-lateral drag in both areas eliminates the need for the complex interpretation.

Perhaps the best evidence of strike-slip movement in this area is the large, obvious right-lateral drag structure (east of Flying Eagle Canyon) along the Double Canyon fault. The "synclinal" drag on the west (downthrown) side is more steeply and tightly folded than the broad, south plunging "anticlinal" drag on the east (upthrown) side. The northeast trend of the fault suggests the lateral movement was upper Tertiary in age. However, the amount of horizontal displacement is problematic. Almost no offset is seen in the trend of the Tertiary dike where it crosses the fault east of Double Canyon. Of course, the dike may be younger than the fault. No other structures are correlative on opposite sides to permit estimates of the strike-slip separation.

Another northeast trending fault, of probably upper Tertiary age, exhibits right-lateral drag. On this fault (about 1 1/2 miles northeast of Little Kettle Mountain) the "synclinal" drag is prominent on the west (downthrown) side, but no corresponding "anticlinal" drag is evident on the east (upthrown) side. An explanation of this phenomenon must await more definitive data on the plastic behavior of rocks during deformation.

Along this same fault note the one-quarter mile right-lateral separation of an east-northeast trending transverse fault, with Mesaverde on its upthrown (northwest) side and Jose Creek on its downthrown (southeast) side. It is uncertain if the offset is due to strike-slip movement, because it may be explained by normal displacement and erosion along the longitudinal fault.

Alluvial cover obscures the actual relationships at the south end of this fault. If indeed it terminates against the east-northeast trending transverse fault the latter may be considered as the older structure. Some attention should be given to the possibility that this longitudinal fault may be an in echelon (discontinuous) relative of the Double Canyon fault, which seems to die out northward at about the same latitude as the southward termination of this fault.

No definite lateral drag or offset was observed on the northeast trending longitudinal fault which forms the northwest boundary of the Ash Canyon outcrop. On the other hand, the somewhat involved transverse faulting on both sides of the fault may confuse such evidence. Nevertheless, note the generally consistent southeast dip on both sides. The obvious exception is the east limb of the steeply plunging syncline in the Jose Creek northeast of Kettle Mountain. Could it be that this fold is an expression of right-lateral drag? Although the possibility may not be denied, it seems unlikely that drag would be found only in one place along a fault unless a complex structural history had occurred. In any event, this northeast trending syncline appears to be related to the bounding faults.

Similarly the syncline in the Ash Canyon trends northeast, paralleling its longitudinal bounding faults. Recall that this gentle downfold was designated as a possible remnant of the axial portion of a much larger fold formed during middle Tertiary.

Along the southeast boundary fault (of the Ash Canyon outcrop), small right-lateral drag features are seen near its north end. This fault does disrupt one of the northwest trending, middle Tertiary faults, but the amount of lateral separation is insignificant.

The easternmost (west of the Fra Cristobal anticline) of the upper Tertiary longitudinal faults does not show any obvious suggestion of strike-slip movement. The fact that its south end, and the offset to the north, trend north-south could imply that at least parts of the fault were originated in middle Tertiary time.

Development of the transverse faults between the longitudinal ones may have followed one of several patterns, or combinations of these. Perhaps the most interesting possibility pertains to an origin associated with the strike-slip faulting. Analysis shows the maximum compression axis to intersect a given strike-slip fault such that an acute angle is formed, with the apex on each side pointing in the same direction as the relative lateral movement arrows. Fractures should develop parallel to the maximum compression, and therefore perpendicular to the maximum tension. Subsequently during later uplift these fractures could become normal faults.

Note that the acute angle (although somewhat large) formed by the northwest trending transverse faults, in the vicinity of Little Kettle Mountain, points in the same direction as the left-lateral arrow on the southeast side of the Hot Springs fault. Similarly, the branch faults east of Black Bluff Canyon intersect at an angle also in accord with the left-lateral arrow.

Also the east-northeast trending transverse faults east of Little Kettle Mountain make acute angles with the Double Canyon fault, and its in eschelon relative to the northeast, corresponding to the right-lateral arrows on these faults. Other examples may be cited.

Conversely, many of the transverse faults form an acute angle pointing opposite to the strike-slip arrows. Some interpreters could explain this relationship as due to a secondary tension resulting from elastic dilatation after the primary compression. However, many other explanations may seem just as likely.

The orientation of transverse faults may be used to suggest an origin relating to associated longitudinal strike-slip faults. Conversely, it is illogical to attempt to prove strike-slip movement based on the orientation of transverse faults alone.

Some of the small faults may have had a local development. The three short strike-slip faults near Kettle Mountain, two left-lateral and one right-lateral, indicate a local horizontal compression oriented northwest-southeast.

In spite of the spectacular evidence of strike-slip components of movement along several faults in the Cutter sag, the dominant movement in upper Tertiary was vertical. Nearly all the faults are primarily normal faults.

Many transverse faults displace or terminate against the longitudinal ones, and therefore the latter are considered older. Nevertheless some of the transverse faults are offset by the longitudinal faults such that the latter are probably younger. However, it seems likely that both the longitudinal and transverse faults developed more or less contemporaneously.

The main effective force orientation during upper Tertiary in the Cutter sag is considered to have been with the maximum compression axis vertical (gravity), the intermediate axis trending northeast-southwest (parallel to the longitudinal faults), and the least axis trending northwest-southeast (maximum tension). The origin of most structures in this area may be explained by this principal force orientation, or resulting second- and third-order directions.

However, in at least two cases the intermediate axis was oriented northeast-southwest. In one such case the effective maximum force was directed north-south or northwest-southeast to produce the left-lateral drag on the Hot Springs fault. In the other, the maximum force was directed about east-northeast -- west-southwest to produce the right-lateral drag on the Double Canyon fault and its relative to the northeast. It is likely that these theoretical orientations may be only possibilities, if the forces produced the lateral movements along previously existing faults. Any of a nearly 90° spread of force directions could be used to explain such movements.

Quaternary faults

No undissected fault scarps were observed within the mapped area. Yet parts of several fault or resequent fault-line scarps are only slightly modified.

Possibly the entire Quaternary deformation was confined to movements on pre-existing faults. Few faults disrupt the Quaternary lava flows; however, note the displacement suggested by the map relationships along the Hot Springs fault west of Double Peak. Nearly all of the basalt extruded from the intrusive center has been eroded from the upthrown side, whereas flows abut the fault on the downthrown side. On the other hand it is possible that these flows were extruded from the fault.

Origin of the Quaternary basalt cones and flows is believed to be incidental to, rather than a cause of, faulting in this area. Fault zones appear to be the loci for centers of igneous activity (e.g. Shumard Cone). No radial patterns are present to suggest that intrusion played any active role in structural development.

Finally, evidence that diastrophism has continued to Recent time is given by recorded earthquakes in the region. A newspaper account states that one occurred February 22, 1904, 1:00 a.m. suggesting that fissures in the San Marcial lava flow opened up "large enough to conceal a horse and rider" (memorandum from Dr. S. A. Northrop, August 13, 1954).

Summary and Conclusions

During the Laramide orogeny northwest trending normal faults, closed and overturned folds, and thrusts were formed in the northwest part of the mapped area. The principal direction of thrusting and asymmetry is to the east and northeast. However, much of the complex structure may exist only in the plastic Yeso formation, and may not be reflected in the more competent older and younger beds.

Vertical uplift during middle Tertiary time produced open folds and normal faults with dominant north to northwest trends in the Fra Cristobal uplift. Most of the relief of the uplift relative to the adjoining Jornada del Muerto and Rio Grande depressions culminated in this deformation.

In the upper Tertiary time a prominent set of northeast trending longitudinal faults developed in the Cutter sag. All are normal faults down to the west, but some show evidence of strike-slip movement. Right-lateral drag is obvious on three of these faults, and left-lateral drag is fairly evident on one. Many transverse normal faults (and a few open folds) were formed between the longitudinal ones.

The time divisions quoted above are arbitrarily based on the field evidence available and analogy with other areas. Diastrophism may actually have been continuous from the beginning of the Cenozoic era to the present day.

Trends were useful in grouping the major structures of the same ages. Local evidence at intersections was generally employed to determine the relative ages of different trends. However, such analysis is limited by the fact that no one trend is necessarily confined to one age group. Furthermore, structures of the same age groups may have had different orientations in different areas.

Force analyses were discussed for each important deformation. Wide deviations of the axis orientations in both time and space are noted. Couples could have been substituted for effective compressions. In most cases it was assumed that the forces producing the initial fractures were the same ones that produced subsequent faulting.

Judging by the low amounts of vertical displacement on many faults, they may not extend to basement. Tension probably was more important than shearing as inferred from the conspicuous absence of breccia, mylonite, etc.

One of the most important lessons learned by the present author during this revision is that there is no substitute for good vision and experience in field work. Quality of such elemental data as the strike-and-dip depends upon one's ability to ascertain true bedding, slump, erosion and many of the other pitfalls confronting the beginning geologist. Furthermore, the mere indiscriminate gathering of field data does not constitute an end in itself. Depending primarily on the scale of the map and the grade of structures to be shown, careful attention must be given to the data selected for mapping, lest a distortion of very local significance be included which would confuse structural analyses. Only through experience can such judgment be developed.

In spite of the tremendous increase in quality of data, the map of the current report is quite similar to that of the original work. Although many of the previous interpretations still hold true, several were revised or discarded, especially with regard to strike-slip faulting.

One of the most interesting structures within the mapped area is the Hot Springs fault. Where it forms the western boundary of the Fra Cristobal uplift it trends north and northwest, paralleling the structures of middle Tertiary age. Clearly the fault is younger than the Laramide folds and faults that terminate against it. Here also the Hot Springs fault is probably younger than the Santa Fe formation it displaces. Movement may have been recurrent in Quaternary time, for the basalt flows appear to have been displaced.

Farther south the Hot Springs fault turns to trend northeast, paralleling the structures of upper Tertiary age. Here it separates the Cutter sag from the Rio Grande depression. Movement on this apparently younger part of the fault may have begun in Santa Fe time, for a volcanic conglomerate on the downthrown side of a branch fault seems to have been derived from the Jose Creek on the upthrown side. Some lateral displacement is indicated on the main part of the Hot Springs fault. The previous interpretation of right-lateral drag is discarded in favor of the later discovered left-lateral evidence. However, the drag is not as clearly developed as on the right-lateral faults to the east.

Greater displacements (both normal and strike-slip) on the faults on the west side of the area, and the fact that many of them are downthrown to the west, suggest that the Rio Grande depression (Engle basin) has had a more complicated structural history than that of the Jornada to the east. Perhaps the data and interpretations given in this text on the Fra Cristobal uplift and Cutter sag will be of some help in predicting and understanding the structures of these adjoining depressions.

GEOLOGIC HISTORY

After the Precambrian orogeny, metamorphism, and intrusion, the Fra Cristobal area was subjected to several broad warpings to the south which gave rise to local unconformities in the dominantly carbonate pre-Permian Paleozoic rocks. The sharp change from a marine environment in the Pennsylvanian period to a continental floodplain environment in Permian Abo time appears to have been one of conformity. A gradual change back to marine conditions is indicated by the Yeso and San Andres formations.

If deposition recurred during Triassic, Jurassic, or Lower Cretaceous, the evidence has been removed by subsequent erosion. Clastic sedimentation dominated in Upper Cretaceous and Tertiary time. The Dakota sandstone is the basal unit of a marine transgression. Dark gray shale in the lower Mancos is a continuation of the transgression, but the green shale in the upper part suggests a regression and transition into the continental facies of the Mesaverde.

Conglomeratic units in the upper part of the main body of the Mesaverde formation and in the Ash Canyon member reflect the beginnings of the Laramide disturbance. Rapid subsidence allowed for deposition of orogenic suites of sediments contained in the Jose Creek member of the McRae formation. In Hall Lake time floodplain sediments were deposited at a slower rate. Finally the deformation reached its peak producing overturned folds and thrusts.

In middle Tertiary, uplift of the Fra Cristobal Range along the Hot Springs fault was accompanied by the deposition of the Santa Fe formation in the Rio Grande depression. Open folding and normal faulting occurred during this period as did the broad warping of the Jornada del Muerto.

The upper Tertiary deformation in the Cutter sag consisted of high-angle faulting, horizontal shearing, and local open folding. Dissipation of this diastrophism probably has continued to the present day.

Basalt dikes were intruded in late Tertiary time. In early Quaternary, pediments began to form on the slopes of the Fra Cristobal uplift. Basaltic cones erupting along major faults covered the pediment surfaces with lava flows.

DESCRIPTIVE STRATIGRAPHIC SECTIONS

Southern Part of the Fra Cristobal Range
Sierra County, New Mexico

Shotgun Ridge Section

Sec. 1, T12S, R3W (projected)

Located about 8.5 miles northwest of Engle, New Mexico, accessible by following the road along the Santa Fe Railway north of Engle 6.6 miles and turning left (west) onto a jeep trail; section begins (Unit 1) about half way up the north slope of Shotgun Ridge, traces around to the east side, and ends at the top of the ridge; measured from bottom up; traced across one small fault; dips range from 13° to 7° to the southwest and west; samples were collected from each unit.

Top Eroded (Cretaceous Dakota sandstone overlies Permian San Andres limestone on down-faulted block west of Shotgun Ridge.)
San Andres formation (Permian):

Unit No.		Thickness	Cum.
	Main limestone member: (top eroded, estimated 200' below base of Dakota)		
4	LIMESTONE: medium-bedded; upper part -- dark brown to brown, dense to finely crystalline, some algal fragments; middle part -- dark brown, dense to finely crystalline, slightly fractured, brown, dense to finely crystalline, sucrosic, and tan, fine- to medium-grained calcarenite; lower part -- tan to white, dense to finely crystalline, "marker bed", chalky, fragmental, fractured, and dark brown, dense to finely crystalline, slightly fractured, some large vugs filled with calcite; entire unit weathers brown, dark brown, and forms slope on top of ridge......................	82'	82'
3	LIMESTONE: medium- to thick-bedded; dark brown; dense, micritic, slightly fractured, calcite filling; deep weathering; ledge.....	40'	122'
2	LIMESTONE: thin- to medium-bedded; light brown, brown, and dark brown; dense to finely crystalline, micritic; several fractures and some vugs filled with calcite; slope.... (shift to north end of Shotgun Ridge)	38'	160'
1.	LIMESTONE: medium- to thick-bedded; upper part -- light brown to brown; dense to finely crystalline, micritic, slightly fractured, with calcite filling; middle part -- brown, dense to finely crystalline, fractured, and dark brown, dense to finely crystalline, fragmental, slightly skeletal; lower part -- brown to dark brown, fine to medium crystalline,		

Unit No.		Thickness	Cum.
	some calcarenite and replaced fossil fragments, minor chert nodule concretions; entire unit weathers dark brown; very prominent ledge; some poorly preserved nautiloids....	96'	256'
Transition member:			
7	LIMESTONE AND SANDSTONE: interbedded, medium-bedded; limestone -- tan, fine to medium crystalline, and brown, dense to finely crystalline, slightly cherty, some calcarenite, some skeletal (replaced with calcite); sandstone (near base) -- white, weathers brown, quartz, calcareous cement, medium- to coarse-grained, well rounded, slightly friable, weathers brown; ledges......................	28'	284'
6.	SANDSTONE: thick-bedded; white, weathers dark brown; quartz, calcareous cement; medium- to coarse-grained, well rounded, slightly friable; very prominent ledge.....	13'	297'
5	LIMESTONE AND DOLOMITE: interbedded, medium-bedded; limestone -- brown to gray, dense to finely crystalline, micritic, slightly fractured, calcite filling; dolomite (increasing in lower part) -- light brown, fine to medium crystalline, slightly fractured, with some small veinlets and vugs filled with calcite; ledges...........................	33'	330'
4	DOLOMITE AND SANDSTONE: (poor exposure) interbedded, thin-bedded; dolomite -- brown to dark brown, finely crystalline; sandstone -- yellow to tan, quartz, calcareous cement, limonite stain, subrounded, well sorted, well cemented; slope...........................	8'	338'
3	DOLOMITE: thin-bedded; brown to dark brown, finely crystalline; fractures filled with limonite and hematite; nodular weathering, ledge..................................	3'	341'
2	DOLOMITE AND SANDSTONE: (poor exposure), interbedded, thin-bedded; dolomite -- brown to dark brown, finely crystalline, slightly fractured; sandstone -- light gray to tan, quartz, with dolomitic and siliceous cement, some hematite due to weathering, very fine-grained, rounded, well sorted, well cemented; slope..................................	11'	352'

Unit No.		Thickness	Cum.
1	DOLOMITE: thin-bedded; brown to dark brown, finely crystalline, micritic; vertical fractures filled with calcite and hematite; ledge....................................	2'	354'
Glorieta member:			
1	SANDSTONE: (poorly exposed, bedding not discernible); yellow to tan; quartz, siliceous and dolomitic cement, some limonite and hematite stain due to weathering; very fine-grained, rounded, well sorted, well cemented; ledge............................	15'	369'
Base of San Andres formation	Total San Andres (top eroded)	369'	

Yeso formation below (contact mostly covered by talus, but well exposed in steep cliff on north side of canyon).

Saddle Peak Section

Secs. 19, 30, T11S, R2W (projected)

Located about 11 miles north-northwest of Engle, New Mexico, accessible by following the road along the Santa Fe Railway north of Engle 11.4 miles and turning left (west) onto a jeep trail; section begins (Unit 1) on south side of main NW-SE canyon (access trail), follows southwestward along main tributary drainage, finally turns right (west) up side canyon to near top of ridge northwest of Saddle Peak; measured from bottom-up; crossed possible fault; dips range from 8°, to 14°, back to 9°, to southwest; samples were collected from each unit.

San Andres formation, Glorieta sandstone member above, conformable with Yeso below.

Yeso formation (Permian):

Unit No.		Thickness	Cum.
	(upper clastic member)		
36	SANDSTONE: thin-bedded; quartz; red at top, yellow to white, light gray, and red again near base; fine- to medium-grained, some friable; slope........................	116'	116'
	(upper-middle evaporite member)		
35	In line of section: LIMESTONE AND SANDSTONE: interbedded, thin-bedded; limestone -- gray to brown, some argillaceous, sandy, and cherty, fetid odor, dense, micritic; sandstone -- light gray, red, quartz, calcareous cement, fine-grained, ledges, (41' thick)........		
	However, about one-eighth mile to north: GYPSUM, LIMESTONE, SANDSTONE AND DOLOMITE: (poor to fair exposure) interbedded: limestone (11') -- thin-bedded, gray to brown, dense, slight ledge; gypsum (43') -- laminated, white to light gray, weathers yellow-tan, some crystalline, some fibrous, vertical furrows on slope form distinctive weathering pattern; limestone (16') -- thin- to medium-bedded, as above, with some interlaminated gypsum, as above, slight ledge; gypsum (59') -- as above, with some interbedded dolomite, thin-bedded, dark brown, dense, very argillaceous, with some vugs		

Unit No.		Thickness	Cum.
	(may be due to dissolved gypsum), and some interbedded sandstone -- thin-bedded, yellow, quartz, argillaceous, very fine-grained, well cemented, slope; limestone (16') -- thin-bedded, as above, with some interlaminated gypsum, as above, slight ledge; gypsum (22') -- as above, with minor limestone, thin-bedded, as above, slope....................	167'	283'
	(Lower-middle limestone member)		
34	SANDSTONE AND LIMESTONE: interbedded, thin-bedded; sandstone -- red-orange, quartz, slightly calcareous, fine-grained, friable; limestone -- gray to brown, argillaceous near base of unit, dense, micritic; slight ledges....................................	28'	311'
33	LIMESTONE AND DOLOMITE: thin- to medium-bedded; limestone -- dark brown, dark gray, fetid odor, some dead oil stain, dense to finely crystalline, some brachiopod molds (productids ?); near top -- some dolomite, light brown, very silty, finely granular; prominent ledges..........................	39'	350'
32	LIMESTONE AND SANDSTONE: interbedded, alternating in 10' to 15' units, thin- to medium-bedded; limestone -- dark gray, dark brown, some dead oil stain, dense to finely crystalline, some granular; sandstone -- light red, orange, quartz, fine-grained; ledges......................	74'	424'
31	SANDSTONE AND LIMESTONE: thin-bedded; sandstone (upper part) -- red, some light gray, slightly calcareous, quartz, fine- to medium-grained, some friable; limestone (lower part) -- brown, some silty, dense to finely crystalline, slightly skeletal; slope.......	33'	457'
30	SANDSTONE: thin-bedded; red, some light gray; quartz; fine-grained, well cemented; slope....................................	28'	485'
29	LIMESTONE: thin- to medium-bedded (thin-bedded at top); dark gray, black, brown; some sandy, argillaceous, fetid odor; dense to finely crystalline, some skeletal (fossil hash); fractures filled with calcite; prominent ledge...........................	25'	510'

Unit No.		Thickness	Cum.
28	DOLOMITE, SANDSTONE, AND CLAYSTONE: upper 2' -- claystone, laminated, yellow (limonite stain), silty, calcareous; next 20' -- dolomite, thin-bedded, brown, tan, some sandy, finely granular, some scattered vuggy porosity; bottom 4' -- sandstone, light gray, quartz, calcareous, fine-grained, friable; slope (in stream)........................	28'	538'
27	SANDSTONE AND CLAYSTONE: interbedded, thin-bedded; sandstone -- red, orange, quartz, fine-grained; claystone (some) -- yellow limonite stain, calcareous; slope (meander scar)....................................	27'	565'
26	LIMESTONE, CALCARENITE, AND SANDSTONE: interbedded, thin- to medium-bedded; limestone -- brown, dark gray dense to finely crystalline, some light gray, dolomitic (dolomitized during weathering), cherty, dense, slight amount of small vuggy porosity, calcarenite -- clear calcite, medium- to coarse-grained, subrounded; sandstone (minor) -- light gray, quartz, fine-grained; ledges (in stream bottom).................................	47'	612'
25	COVERED: slopes...........................	5'	617'
24	LIMESTONE: thin- to medium-bedded; dark gray, brown, weathers brown to gray; fetid odor, dense to finely crystalline, fine-grained oolitic at base, some sparsely skeletal beds; fractured; very prominent ledge............	26'	643'
	(lower clastic member)		
23	SANDSTONE AND LIMESTONE: interbedded, thin-bedded; sandstone -- pink, light gray, quartz, calcareous, fine- to medium-grained, rounded, some friable; limestone (minor) -- gray, medium crystalline*; ledges..................	28'	671'
22	COVERED: slopes..........................	55'	726'
21	SANDSTONE: thin- to medium-bedded; yellow; quartz, calcareous, abundant limonite stain; fine-grained, well cemented; prominent ledge..	12'	738'
20	SANDSTONE: thin-bedded; light red-brown; quartz, arkosic - potash feldspar, slightly calcareous; fine-grained; ledges...........	27'	765'

Unit No.		Thickness	Cum.
	(cross fault in Unit 19?)		
19	MOSTLY COVERED WITH SOME SILTSTONE AND SANDSTONE: interbedded, bedding indistinct, probably thin-bedded; siltstone -- tan to light gray, quartz, argillaceous; sandstone -- clear to white (some light red-brown), quartz, calcareous, fine- to medium-grained, slightly friable; slope.......	166'	931'
18	SANDSTONE AND SILTSTONE: interbedded, thin-bedded; sandstone -- light red-brown, quartz, slightly argillaceous, fine-grained; siltstone (some) -- light gray, quartz, very calcareous, argillaceous; ledges............	54'	985'
17	SANDSTONE AND SHALE: interbedded (alternating in 2' to 5' units), laminated to thin-bedded; sandstone -- white to light gray, quartz, slightly calcareous, fine-grained, slightly friable, some interbedded -- red-brown, argillaceous; shale (some) -- gray; slight ledges....................................	33'	1018'
16	COVERED: probably red-brown sandstone; slope....................................	6'	1024'
15	SANDSTONE: laminated to thin-bedded; light gray, quartz, slightly calcareous, quartzitic, fine-grained; interbedded (in alternating 2' units) -- red-brown, quartz, slightly calcareous, slightly argillaceous, fine- to medium-grained; ledge......................	11'	1035'
14	COVERED (by stream debris); probably shale and sandstone, thin-bedded, red-brown, light gray; slope...............................	43'	1078'
13	SANDSTONE: thin- to medium-bedded; red-brown, quartz, fine- to medium-grained, subangular, pitted; and light gray, quartz, shaly, fine-grained; prominent ledge.......	11'	1089'
12	SANDSTONE, SILTSTONE, AND SHALE: interbedded, laminated to thin-bedded; sandstone -- light gray, quartz, minor ferromagnesian flakes, some limonite stain, calcareous, fine- to medium-grained, subrounded, well cemented; siltstone -- tan, quartz, very calcareous; shale -- light green; ledges...............	17'	1106'

Unit No.		Thickness	Cum.
11	SHALE, SILTSTONE, AND LIMESTONE: interbedded; shale -- gray-green, calcareous; siltstone -- laminated to thin-bedded, gray-green, calcareous; limestone -- varved, tan, gray, dense, scale-like texture; slope (meander scar)..........	12'	1118'
10	CLAYSTONE: red; slope........................	8'	1126'
9	SILTSTONE: laminated to thin-bedded (very even, parallel bedding); orange-red; quartz, argillaceous, slightly calcareous; ledges...	12'	1138'
8	CLAYSTONE AND SILTSTONE: interbedded; claystone -- red; siltstone -- thin-bedded, red, some minor channel-and-fill deposits; slope..	31'	1169'
7	SILTSTONE: thin- to medium-bedded; red; quartz, very argillaceous, calcareous; ledge....................................	3'	1172'
6	CLAYSTONE AND SILTSTONE: claystone -- light red, silty; minor siltstone -- light red, in channel-and-fill deposits; some low dipping fractures filled with green clay; slope.....	6'	1178'
5	SANDSTONE: thin-bedded, slightly cross-bedded; pink to white; quartz, slightly calcareous, limonite stain; fine-grained, subrounded, well cemented; ledge...............	25'	1203'
4	CLAYSTONE AND SILTSTONE: claystone -- light red, silty; some siltstone -- light red, in channel-and-fill deposits, one-foot relief; slope....................................	6'	1209'
3	SILTSTONE: thin-bedded; dark red; quartz; argillaceous, calcareous; ledge.............	2'	1211'
2	CLAYSTONE: light red; slope................	3'	1214'
1	SILTSTONE: laminated to thin-bedded, mostly parallel bedding with minor cross-bedding; red-brown; quartz, argillcaeous, slightly calcareous; ledge.........................	25'	1239'
	Base of Yeso formation Total Yeso	1239'	

Abo formation below: gradational contact with Yeso is at top of dark red claystone and siltstone overlying prominent sandstone ledge in bottom of stream.

North Trail Section

Sec. 19, T11S, R2W and Sec. 24, T11S, R3W (projected)

Located about 12 miles north-northwest of Engle, New Mexico, accessible by following the road along the Santa Fe Railway north of Engle 11.4 miles and turning left (west) onto a jeep trail and thence right (northwest) onto a power-line road; section begins (Unit 1) about 300 feet south of power-line road, continues up slope to west, proceeds to east side of high mesa to south, and ends about 175 feet below top of mesa; measured from bottom-up; on east limb of syncline; dip 7° to south; samples were collected from each unit.

Yeso formation above, gradational contact with Abo below (Yeso sandstones are lighter colored - pink, orange, etc., and more evenly bedded than Abo, shale is light gray, calcareous)

Abo formation (Permian):

Unit No.		Thickness	Cum.
37	CLAYSTONE AND SILTSTONE: interbedded, thin-bedded; claystone -- orange to red, non-calcareous; some siltstone -- red, quartz; slope..............................	17'	17'
36	SILTSTONE: laminated to thin-bedded; red; quartz; vertical joints, blocky weathering; ledge................................	2'	19'
35	CLAYSTONE: red; slope.......................	10'	29'
34	SILTSTONE AND CLAYSTONE: interbedded, thin-bedded; siltstone -- red, quartz, large gray clay galls, veinlets of silica, blocky weathering; claystone (in middle of unit, -- red; ledges................................	8'	37'
33	CLAYSTONE: red; slope......................	10'	47'
32	SILTSTONE: thin-bedded; red, quartz, upper part is slightly calcareous with light gray, siliceous clay galls; veinlets of silica, vertically jointed; ledges................	3'	50'
31	CLAYSTONE AND SILTSTONE: interbedded, thin-bedded; claystone -- red, sandy; siltstone -- red, quartz, argillaceous, slope...........	8'	58'

Unit No.	(trace to northwest)	Thickness	Cum.
30	SANDSTONE: laminated to thin-bedded; orange-red, quartz, slightly argillaceous, slightly calcareous; fine-grained; slight ledge....................................	1'	59'
29	COVERED: probably claystone, red; slope...	6'	65'
28	SANDSTONE: medium-bedded; dark red; quartz, argillaceous, slightly calcareous; fine-grained, very well cemented; vertical fractures filled with calcite; prominent ledge..	2'	67'
27	CLAYSTONE: red; calcareous, silty; slope...	6'	73'
26	SANDSTONE: laminated to thin-bedded, cross-bedded; purple to red; quartz, calcareous; prominent ledge...........................	6'	79'
25	COVERED: probably claystone; red; slope...	7'	86'
24	SANDSTONE: thin- to medium-bedded; orange-red; quartz, slightly calcareous; fine-grained; ledges....................................	22'	108'
23	(same as Unit 25)..........................	18'	126'
22	SILTSTONE: thin-bedded; dark red; argillaceous, non-calcareous; slight ledge...............	6'	132'
21	(same as Unit 25)..........................	26'	158'
20	SANDSTONE: thin- to medium-bedded, parallel bedding; orange-red, weathers red-brown; quartz, slightly calcareous; fine-grained; fairly prominent ledge......................	39'	197'
19	(same as Unit 25)..........................	28'	225'
18	SANDSTONE: thin- to medium-bedded, highly cross-bedded, festoon; orange-red; quartz, slightly calcareous, slightly argillaceous; prominent ledge (top of bluff)......................	16'	241'
17	(same as Unit 25)..........................	11'	252'
16	SANDSTONE AND CLAYSTONE: sandstone -- thin- to medium-bedded, some cross-bedded, orange-red, quartz, calcareous, slightly argillaceous, much vertical jointing; intercalated in middle of unit -- 3' claystone -- red; ledge.........	12'	264'

Unit No.		Thickness	Cum.
15	(same as Unit 25).........................	22'	286'
14	SILTSTONE AND CLAYSTONE: siltstone -- thin-bedded, red, argillaceous, calcareous; intercalated in middle of unit -- 2' clay-stone -- red; ledge.........................	6'	292'
13	(same as Unit 25).........................	13'	305'
12	SANDSTONE: laminated to thin-bedded; red-orange; quartz, potash fedlspar, argill-aceous, slightly calcareous; prominent ledges; reptile tracks.....................	12'	317'
11	(same as Unit 25).........................	16'	333'
10	CONGLOMERATE, CLAYSTONE, AND SILTSTONE: thin-to medium-bedded; conglomerate of limestone -- tan, gray, very finely crystalline in coarse-grained to granule size particles; claystone -- red, in matrix of conglomerate; some inter-bedded siltstone -- red, argillaceous; pro-minent ledge............................	7'	340'
9	CLAYSTONE: (partly covered) red; calcareous; slope....................................	39'	379'
8	SANDSTONE AND CLAYSTONE: interbedded, thin-bedded; sandstone -- red, quartz, argillaceous, calcareous, with sericite flakes, very fine-grained; claystone -- red, calcareous; ledges..	8'	387'
7	CLAYSTONE: (partly covered) red, calcareous; slope....................................	66'	453'
6	SILTSTONE, LIMESTONE, AND CLAYSTONE: thin-bedded; siltstone -- red, argillaceous, calcareous, some gray limestone nodules; intercalated claystone, red; ledge.........	4'	457'
5	CLAYSTONE: red; very slightly calcareous; slope....................................	8'	465'
4	CONGLOMERATE: medium-bedded; gray; sil-iceous claystone particles, calcareous, with red-brown claystone in matrix; granule to pebble size, subrounded to subangular; some fractures filled with sparry calcite; ledge.....................	1'	466'

Unit No.		Thickness	Cum.
3	CLAYSTONE AND SILTSTONE: interbedded, claystone -- red; siltstone -- thin-bedded; red (weathers gray), argillaceous, with tan chalcedony concretions, some limestone granules near base of unit; slope.....	23'	489'
2	SILTSTONE: thin-bedded; red, weathers red-brown; argillaceous; some gray lime concretions; ledge..............................	1'	490'
1	CLAYSTONE: gray, red; some nodules of gray limestone; slope............................	3'	493'
	Base Abo formation — Total Abo	493'	

Bar B formation (Pennsylvanian) below: sharp, but conformable contact with Abo; 3' siltstone immediately below contact; next below is a thin-bedded gray limestone sequence with yellow limonite stain in upper part (stain due to leaching of overlying Abo).

REFERENCES

AMERICAN GEOLOGICAL INSTITUTE (1957) Glossary of geology and related sciences: Washington, 325 pp.

BILLINGS, M. P. (1954) Structural geology: New York, 514 pp.

BUSHNELL, H. P. (1953) Geology of the McRae Canyon area, Sierra County, New Mexico: Unpublished master's thesis, Univ. of New Mexico, 106 pp.

FENNEMAN, N. M. (1930) Physiographic provinces of the United States (Map): U. S. Geol. Survey.

JACOBS, R. C. (1956) Geology of the central front of the Fra Cristobal Mountains, Sierra County, New Mexico: Unpublished master's thesis, Univ. of New Mexico, 45 pp.

KELLEY, V. C. (1952) Tectonics of the Rio Grande depression of central New Mexico: Guidebook of the Rio Grande Country, central New Mexico, Third field conference: New Mexico Geol. Soc., pp. 92-105.

------, (1955) Regional tectonics of south-central New Mexico: Guidebook of south-central New Mexico, Sixth field conference: New Mexico Geol. Soc., pp. 96-104.

------, and SILVER, CASWELL (1952) Geology of the Caballo Mountains with sepecial reference to regional stratigraphy and structure and to mineral resources, including oil and gas: Univ. of New Mexico Pub. in Geol., No. 4, 286 pp.

LEE, W. T. and GIRTY, G. H. (1909) The Manzano group of the Rio Grande Valley, New Mexico: U. S. Geol. Survey Bull. 389, 141 pp.

McCLEARY, J. T. (1960) Geology of the northern part of the Fra Cristobal Range, Sierra and Socorro Counties, New Mexico: Unpublished master's thesis, Univ. of New Mexico, 59 pp.

NEEDHAM, C. E., and BATES, R. L. (1943) Permian type sections in central New Mexico: Geol. Soc. America Bull. vol. 54, pp. 1653-1667.

NEW MEXICO GEOLOGICAL SOCIETY (1955) Guidebook of south-central New Mexico, Sixth field conference, 193 pp.

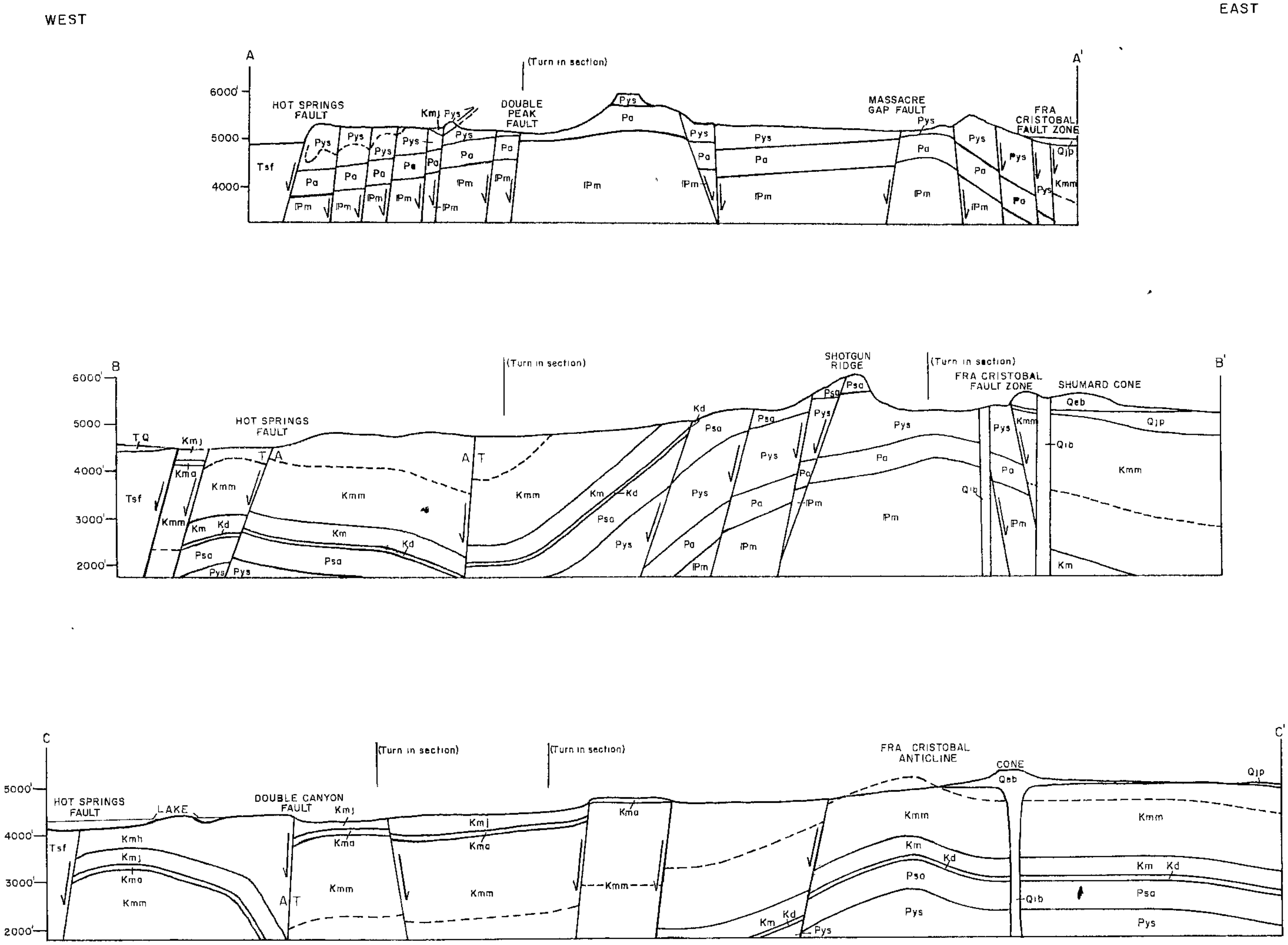
SHUMARD, G. G. (1859) The geological structure of the "Jornada del Muerto", New Mexico: St. Louis Acad. Sci. Trans. (1858), vol. 1, pp. 341-355.

THOMPSON, SAM III (1955) Geology of the southern part of the Fra Cristobal Range, Sierra County, New Mexico: Unpublished master's thesis, Univ. of New Mexico, 75 pp.

U. S. GEOLOGICAL SURVEY (1958) Tularosa, New Mexico, topographic quadrangle: Scale: 1:250,000.

WILMARTH, M. G. (1938) Lexicon of geologic names of the United States: U. S. Geol. Survey Bull. 896, 2396 pp.

Figure 4. Structure sections of the southern part of the Fra Cristobal Range



Horizontal scale: 2 inches = 1 mile
(For explanation see figure 2, A=Away, T=Toward)

S T III, 1961

GEOLOGIC MAP OF THE SOUTHERN PART OF THE FRA CRISTOBAL RANGE

SAM THOMPSON III

1961

FIGURE 2

COMPOSITE PERMIAN SECTION

FRA CRISTOBAL RANGE
SIERRA COUNTY, NEW MEXICO

Fig. 5