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Geology of Chama Quadrangle, New Mexico

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Abstract

The Chama quadrangle lies astride the central part of the Chama Basin, an elongate structure along the northeastern margin of the San Juan Basin.

Massive cross-bedded Precambrian quartzite of the Kiawa Mountain Formation crops out on the eastern margin of the quadrangle, the westernmost of the extensive exposures in the Tusas Mountains.

Nearly 400 feet of beds containing Desmoinesian fossils crop out just east of the quadrangle in Chaves Canyon, with only the lower 250 feet well exposed. Each recognizable group of beds thins onto the Precambrian surface. The lowest beds, mainly sandstone and siltstone, appear to be of talus origin. A disconformity separates these beds from the overlying arkosic sandstone and fossiliferous nodular limestone.

The Triassic Chinle Formation is about 500 feet thick and consists of red arkosic siltstone and sandstone with conglomeratic zones near the base and center. This unit lies on a smooth surface of Precambrian rocks, except for the inlier of Pennsylvanian rocks in Chaves Canyon.

The Jurassic Entrada Formation consists of about 250 feet of very well-sorted, friable, very fine-grained sandstone. Color zoning roughly divides the unit into three parts: a lower light reddish-brown, a middle pale yellow-orange, and an upper grayish-orange zone. Cross-bedding is most obvious in the middle part, although it is present throughout.

The Todilto Formation is either absent or covered throughout the quadrangle; it crops out east of the quadrangle south of Chaves Canyon. Where present, it is included on the map as part of the Morrison Formation.

Where exposed along the eastern margin of the quadrangle, the Morrison Formation is composed of interstratified units of mudstone and sandstone, with sandstone more abundant near the base. The mudstones are grayish green to pale red and are interbedded with grayish-green to light-gray quartz sandstone.

The Cretaceous Dakota Formation crops out on all major anticlines and domes, as well as holding up long dip slopes along the eastern margin of the quadrangle. It can be subdivided roughly into three units: a lower sandstone, a middle shale, and an upper sandstone. The lower cliff-forming sandstone member, about 185 feet thick, is pale orange to moderate yellowish brown, massive, cross-bedded and parallel-bedded, very fine- to coarse-grained, and locally conglomeratic. From 70 to 125 feet of dark-gray, platy, carbonaceous silty shale and very fine-grained sandstone conformably overlie this unit. A very light-gray, medium- to fine-grained, thick, parallel-bedded, cliff-forming sandstone ranging in thickness from 27 to 45 feet conformably overlies the middle unit. The topmost unit (which has been stripped from the domes and anticlines within the quadrangle) consists mainly of silt-

stone and shale with a capping sandstone that commonly contains pelecypod casts.

The Mancos Formation lies conformably above the Dakota and consists almost entirely of shale with some silty limestone beds, concretions, and numerous fossils. Within the Chama quadrangle, the total thickness could not be measured but is estimated to be at least 1700 feet. The lower part can be subdivided into mappable members which approximate those of Dane (1948). The Graneros Shale Member, generally poorly exposed, consists of about 120 feet of fissile, finely bedded, slightly sandy, clayey shale, with a few concretion zones in the lower part. Conformably overlying this, the Greenhorn Limestone Member consists of about 20 feet of limestone beds separated by shale units. The Carlile Shale Member consists of from 400 to 500 feet of olive-gray to black shale with a zone of highly fossiliferous, calcareous sandy beds near the middle (Juana Lopez Member of Dane, Cobban, and Kauffman, 1966). Thin bentonite beds occur throughout the section;, septarian concretions are common in the lower part. The Upper Mancos Undifferentiated includes all beds between the Carlile Shale Member and the Mesaverde Group, the Niobrara Calcareous Shale and Upper Shale members of Dane (1948). The base is designated at the lowest appearance of *Inoceramus grandis* prisms covered with *Ostrea congesta;* this also coincides with a color break from dark gray below to light gray above (caused by an increase in quartz sand content). A thin, yellow-buff, medium- to coarse-grained, calcareous sandstone or arenaceous calclithite crops out 10 to 20 feet above the base in the central part of the quadrangle. The upper contact is gradational and is chosen at the base of the lowest continuous massive sandstone.

The Mesaverde Group is not divisible in the Chama quadrangle, except for the southwest corner where a sharp transition upward into the coal-bearing sequence was found. Elsewhere it consists of 200 to 300 feet of massive-bedded, very fine-grained to fine-grained sandstone, commonly glauconitic, with a 10- to 15-foot shaly interval near the middle and thinner shaly intervals elsewhere in the section.

The top of the Mesaverde Group grades into the overlying Lewis Shale. A maximum thickness of 600 feet of Lewis is preserved in the northwestern part of the quadrangle. Erosion has removed the upper part of the Lewis Shale as well as any younger latest Cretaceous or earliest Tertiary units that may have been deposited prior to the deposition of the post-Laramide Eocene (?) Blanco Basin Formation.

The Blanco Basin Formation consists of 250 to 350 feet of arkosic conglomerate, sandstone, and shale. It comprises the basal prevolcanic Tertiary formation along the west front of the San Juan Mountains and northern Tusas Mountains. The El Rito Formation, a conglomerate composed of rounded Precambrian quartzite clasts in a red matrix, is the basal Tertiary formation along the west base of the southern Tusas Mountains and interfingers with the Blanco Basin Formation just north of Cañones Box on the eastern edge of the quadrangle. The Blanco Basin Formation is an alluvial fan deposit that is the upslope, coarse-grained facies of the Wasatch Formation of the eastern San Juan Basin.

Only the Conejos Quartz Latite of the extensive Tertiary volcanic and sedimentary sequence of the Tusas Mountains extends into the quadrangle. It consists of two recognizable subdivisions: a lower slope-forming unit of tuff and conglomerate and an upper, blocky, cliff-forming unit of flow breccia and agglomerate. Conglomerate clasts are principally of granitic and metamorphic rocks set in a matrix of tuff. Clasts of volcanic rocks are found near the eastern margin of the quadrangle. The flow breccia and agglomerate are composed of a dark purplish-brown, porphyritic-aphanitic quartz latite.

Gravels capping ridges 400 to 600 feet above the modern drainage levels and well above the terrace deposits assigned to the glacial events are here classified as Tertiary (?) terrace deposits. Two distinct levels can be recognized. Both sets slope south to southwest and suggest that an ancestral Chama River drained this area during the late Tertiary(?).

Quaternary deposits form an extensive veneer, in places completely obscuring the underlying bedrock relationships. Three major sequences of terrace deposits, each correlated with a glacial period; moraines where still recognizable as such; landslides commonly composed of glacial detritus, as well as the underlying formations; and recent alluvium have been delineated on the map.

Northwest-trending folds and faults superimposed on a larger structural terrace, the Chama Basin, dominate the Chama quadrangle. The Basin plunges northward into Colorado where it is partly buried by the Tertiary rocks of the San Juan Mountains. The Brazos fault zone, a west-trending transverse structure, lies just south of the quadrangle and can be traced for 50 miles from south of the Brazos Box westward into the San Juan Basin. It appears to be a feature along which there has been recurrent activity and which appears to be controlled by Precambrian stratigraphy and structure. South of the fault zone, the Chama Basin opens into a very shallow, broad, north-trending syncline.

The largest anticlinal structures, Willow Creek and Horse Lake anticlines, are in the southwest corner of the quadrangle. They bound the Brazos fault zone and constitute part of the Archuleta anticlinorium, the structural unit that separates the Chama Basin from the San Juan Basin on the west. Both anticlines are about 10 miles long, from 2 to 4 miles wide, and asymmetrical, with their crests immediately adjacent to narrow synclinal downwarps, whose troughs structurally are as much as 1000 feet lower.

The central part of the quadrangle has very low structural relief, except for elongate, narrow bands of faulting and tight folding. Dips as high as 32 degrees accentuate the contrast between these structures and the surrounding, nearly horizontal beds. Up to 5000 feet of structural relief between the Chama syncline and the Laramide monoclinal upwarp of the Tusas Mountains can be demonstrated in the Chama and adjacent Brazos Peak quadrangles. This slope is broken by a series of northwest-trending basement faults which have developed zones of faulting and elongate folding in the overlying sedimentary cover. These fault zones vary in throw, but most are less than a few hundred feet.

The Tertiary units of the Tusas Mountains are deposited across the truncated edges of these Laramide structures. The Tusas Mountains have a regional, gentle, east dip and are broken by long zones of northwest-trending faults. Some of these faults have had several periods of movement during Tertiary as well as Laramide time and possibly also even older movements.

Introduction

The Chama quadrangle lies astride the central part of the elongate Chama Basin along the eastern flank of the petroliferous San Juan. Basin (fig. 1). Within it, Mesozoic rocks in the subsurface of the San

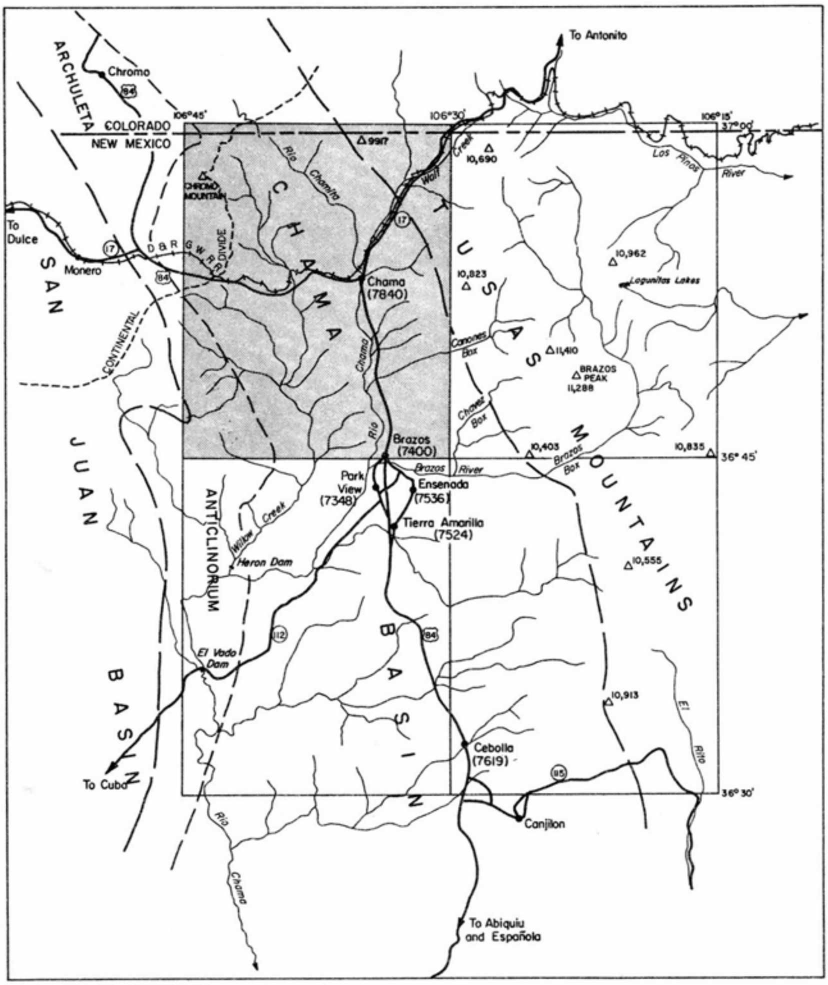


Figure 1

Index map showing location of Chama quadrangle, major drainage systems, highways, and railroad

Major physiographic and structural elements are delineated. Chama quadrangle is cross-hatched. Other quadrangles outlined are Brazos Peak (NE), Tierra Amarilla (SW), and Cebolla (SE).

Juan Basin are exposed. Along the eastern margin of the quadrangle the Mesozoic rocks are upturned and beveled off along the western flank of the Tusas Mountains. Tertiary clastic and volcanic rocks, the southeastern extension of the San Juan Mountains of Colorado, cover the truncated older rocks, and in the Brazos Peak quadrangle (Muehlberger, 1967) to the east these rocks rest directly on the Precambrian core of the uplift.

The Chama Basin can be thought of as a step between the monoclinal margins of the San Juan Basin on the west and the Tusas Mountains on the east. The floor of the basin southwest of the town of Chama is nearly flat except for several northwest-trending zones of complex structures that probably reflect differential movement of the basement. To the north of the flat area the basin plunges northward into Colorado. Just south of the Chama quadrangle it is transected by the Brazos fault, a major transverse structural feature. South of the fault, the basin expands into the shape of a broad, shallow saucer.

This report describes the rock units exposed in the quadrangle as well as the extension of these rocks into the southwestern part of the Brazos Peak quadrangle and the Pennsylvanian rocks that crop out at the base of the Chaves Box one mile east of the Chama quadrangle boundary. Rocks exposed in the Brazos Peak quadrangle are principally Precambrian and Cenozoic in age, whereas the Chama quadrangle is covered primarily by Mesozoic rocks. Only the lower units of Cenozoic age recognized in the Brazos Peak quadrangle cover the northeastern part of the Chama quadrangle. Structural features of the quadrangle are described and related to the regional tectonic evolution.

Glacial features and deposits abound in the Brazos Peak quadrangle; the principal Quaternary features of the Chama quadrangle are extensive outwash trains, terrace systems, and landslides.

PREVIOUS WORK

Dane and associates studied the Mesozoic rocks in the western part of the quadrangle as part of their extensive studies in the San Juan Basin (Dane, 1948, 1960a, 1960b; Beaumont, Dane, and Sears, 1956; Dane, Cobban, and Reeside). Dane's map and text (1948) provide the foundation of stratigraphic sequence and nomenclature used in this report. Cross and Larsen (1935; Larsen and Cross, 1956) delineated the stratigraphy of the Tertiary rocks as part of their study of the San Juan Mountains, Colorado. Atwood and Mather (1932) studied the Quaternary history of the San Juan Mountains, including the northeastern part of the Chama quadrangle.

Important studies in areas adjacent to this quadrangle include those of Wood, Kelley, and MacAlpin (1948) in Archuleta County, Colorado, to the north and Butler (1946) on Tertiary stratigraphy to the east.

PRESENT STUDIES

Mapping by Muehlberger and associates in the Chama and Brazos Peak quadrangles (fig. 1) and by Doney in the Cebolla quadrangle began in June 1955 under the auspices of the New Mexico Bureau of Mines and Mineral Resources. Unpublished theses covering parts of these quadrangles, as well as the northwestern part of the Tierra Amarilla quadrangle, were written by Adams (1957), Trice (1957), Davis (1960), Longgood (1960), St. John (1960), and Doney (1966). In addition, Dunn (1964) studied the Colorado part of the Chama Basin. The New Mexico work was summarized in papers, maps, and road logs in the New Mexico Geological Society guidebook (Beaumont and Read, 1960).

In addition to the projects by University of Texas students and staff, studies by other groups in the region made important contributions. Conley (1964) and McPeek (1965) detailed certain sedimentologic and stratigraphic aspects of the Cretaceous rocks in the immediate vicinity. Smith, Budding, and Pitrat (1961) reported on the geology of the southeastern Chama Basin. Current mapping of the Tierra Amarilla quadrangle by Dane and associates will essentially complete quadrangle mapping of the Chama Basin.

ACKNOWLEDGMENTS

The consistent co-operation of the land owners in this region is gratefully acknowledged, as our ability to traverse all the quadrangle has been a key factor in the successful completion of this project. The New Mexico Bureau of Mines and Mineral Resources provided financial support, as did grants-in-aid from the Geology Foundation and University Research Institute, The University of Texas. In addition to my graduate students (G. E. Adams, H. H. Doney, D. E. Dunn, J. H. Davis, T. E. Longgood, Jr., B. E. St. John, E. L. Trice), Brewster Baldwin and H. E. Dick worked with me for parts of the summers of 1958 and 1956, respectively.

Eugene Callaghan, former director of the New Mexico Bureau of Mines and Mineral Resources, initiated the project, visited the writer in the field, and assisted in other ways to ensure the success of the work. The active assistance of A. J. Thompson, present director of the New Mexico Bureau of Mines and Mineral Resources, made the completion of this project possible without further delays. To each of these, the writer is indebted.

Much of the material contained in this report came originally from my students' theses or from guidebook articles (Muehiberger,

1960). Petrography of Dakota and Mesaverde sandstones was by T. E. Longgood, Jr.; limestone petrography by B. E. St. John; Blanco Basin Formation petrography by G. E. Adams; Tertiary volcanic units and some Precambrian samples by E. L. Trice, Jr., with the remainder by me. W. H. Harris did detailed petrographic studies on samples of Cretaceous and Wasatch sandstones collected for comparison in the eastern San Juan Basin. I have attempted to give credit to the individual at the proper place in the text; the origin of some ideas, however, is lost in the past. Rewriting and possible errors in fact or distortion of original meaning is solely my responsibility.

GEOGRAPHY

Chama quadrangle lies along the New Mexico—Colorado line in Rio Arriba County, New Mexico (fig. 1). U.S. Highway 84 west and south of Chama is a paved all-weather highway. New Mexico Highway 17 northeast from Chama is unpaved and is closed by snow over Cumbres Pass during the winter. Other graded public roads extend up Rio Chamita and to the bases of the Cañones and Brazos boxes. All other roads are privately owned ranch or logging roads.

A high ridge with elevations near 9900 feet extends across the northeastern part of the quadrangle. It is cut by the Rio Chama and is grooved by Little Willow Creek and other lesser tributaries. The northwestern part of the quadrangle has a steep south- and west-facing escarpment capped by Chromo Mountain (9916 feet). In the southwestern corner of the quadrangle, Sawmill and Tecolote mesas rise to elevations of 8400 and 8700 feet, respectively. The remainder of the quadrangle comprises gently rolling country with only a few hundred feet of relief and averages about 7600 feet above sea level.

The Rio Chama and its principal tributaries, such as Willow Creek, drain all the quadrangle except for the northwestern corner, which is west of the Continental Divide where the streams drain into tributaries of the Colorado River. Rio Chama drains south and eastward and joins the Rio Grande near Espanola, 82 miles by highway from Chama.

Narrow, deep, nearly impassable canyons are locally known as "boxes." Only Cañones Box extends into the Chama quadrangle, but Chaves and Brazos boxes lie only a short distance to the east. These occur where the rivers have sliced into massive, resistant Precambrian quartzite that forms the face of the Tusas Mountains from Cañones Creek southeastward for nearly 10 miles. The imposing wall through which the Rio Brazos has cut its box rises abruptly more than 2500 feet above the Chama valley; it is truly an impressive sight.

The southeastern extension of the San Juan Mountains of Colorado includes the high country along the eastern margin of the Chama quadrangle. This mountainous belt extends south-southeastward to the latitude of El Rito and Ojo Caliente. Butler named this high country the *Tusas Mountains,* a term adopted for this report. He stated (p. 8), "Reflecting the character and structure of the underlying rocks, which consist mostly of slightly tilted and faulted Tertiary volcanic and sedimentary rocks, the highland belts have rather long, gentle east slopes and break off sharply on the west."

Several individual mountains stand above the general summit level of this region; these are mostly of Precambrian rocks, buried by the mantle of younger rocks, which are now being re-exhumed.

The greatest topographic relief, 3000 to 4000 feet, is along the west face of the Tusas Mountains where it breaks off into the Chama Valley. The steepest segment of the escarpment is along the Brazos Box.

The principal industries of the region include ranching (cattle and sheep), logging, tourists, fishing, and hunting. Chama and Tierra Amarilla, each with about 1200 inhabitants, are the only large towns in the region, although there are several small villages near Tierra Amarilla.

Stratigraphy

KIAWA MOUNTAIN FORMATION

Massive Precambrian quartzite crops out in the Cañones Box at the east margin of the quadrangle (fig. 2). This is the western end of nearly continuous outcrops of quartzite that extend for 35 miles southeastward along the Tusas Mountains to the Ortega Mountains near El Rito and La Madera. The boxes of this area, deep, slotlike gorges, cut into this unit (for example, Cañones, Chaves, and Brazos).

The quartzite is a massive, usually cross-bedded, medium- to coarse-grained, silica-cemented, pale-grayish, quartz sandstone and pebbly sandstone that has been metamorphosed here to greenschist facies and to higher grades farther southeast, as shown by adjacent schistose units. Nearly 5000 feet of this cross-bedded quartzite are exposed in Cañones Box (mostly east of the Chama quadrangle) before a green-schist layer is reached. Probably another 5000 feet are exposed below the greenschist. This thick unit is the upper part of the Ortega Quartzite of Just (1937) which, as subdivided by Barker (1958), is included as a part of Barker's Kiawa Mountain Formation. Barker's five members were not recognized in the Chama or Brazos Peak mapping, although the general northwest plunge of folds in the quartzite in this region suggests that his upper quartzite member and Jawbone Conglomerate Member (Barker, p. 25, 32) are the units present.

PENNSYLVANIAN ROCKS

Rocks containing Desmoinesian fossils are exposed at the base of the Chaves Box. They lie unconformably on Precambrian quartzite and are unconformably overlain by the Triassic Chinle Formation. On the sides of Chaves Canyon, the Chinle Formation oversteps the Pennsylvanian strata and in turn rests on the Precambrian higher along the mountain front. Elsewhere in the Chama and Brazos Peak quadrangles, along the mountain front, Triassic rocks rest directly on Precambrian rocks.

Poor exposures preclude measuring the total exposed section; it may be nearly 400 feet, although only the lower 250 were measured. Pronounced thinning of each recognizable group of beds onto the Precambrian surface also makes thickness estimates hazardous. For example, a massive sandstone near the middle of the measured section thins from 60 to 15 feet in a lateral distance of 400 yards.

The basal unit (fig. 3) consists of angular to subangular Precambrian quartzite clasts in 2- to 3-foot-thick beds alternating with beds of angular quartz sandstone of the same average thickness. The base of the unit is not exposed but because all observed beds thin toward the

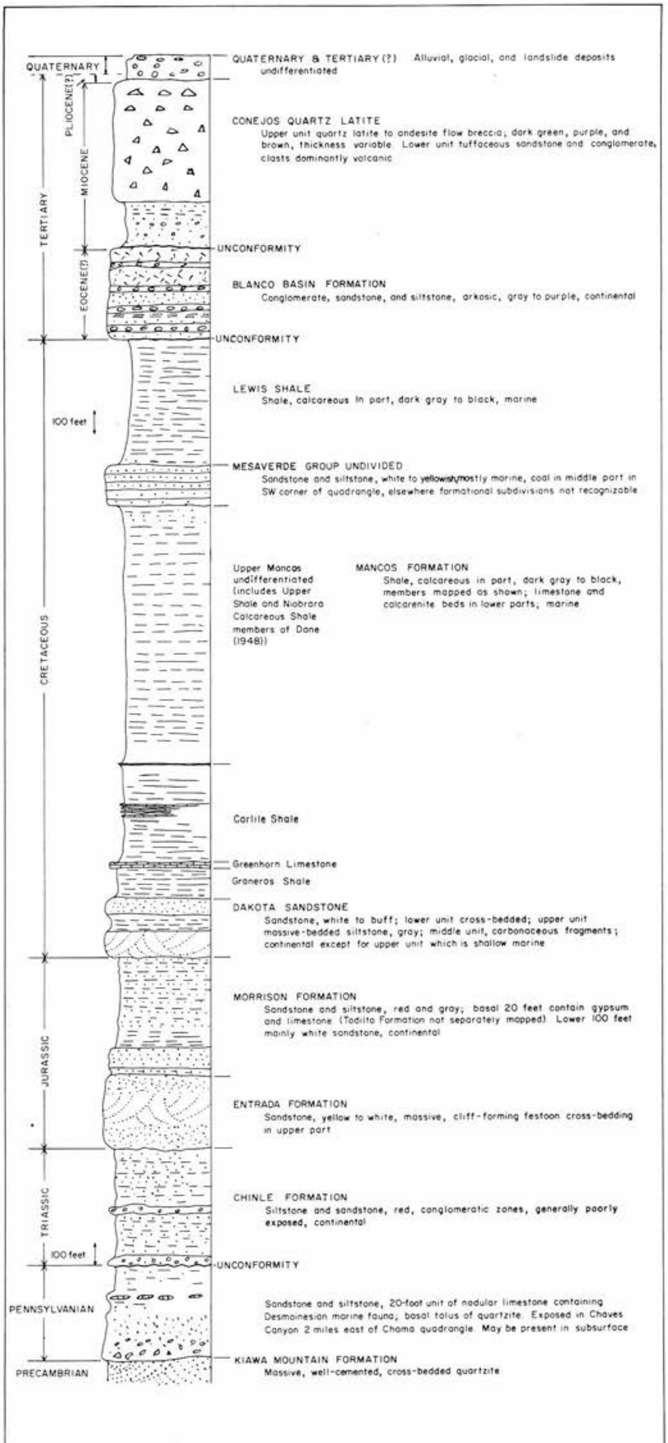


Figure 2

COMPOSITE STRATIGRAPHIC COLUMN OF ROCK UNITS EXPOSED IN THE CHAMA QUADRANGLE

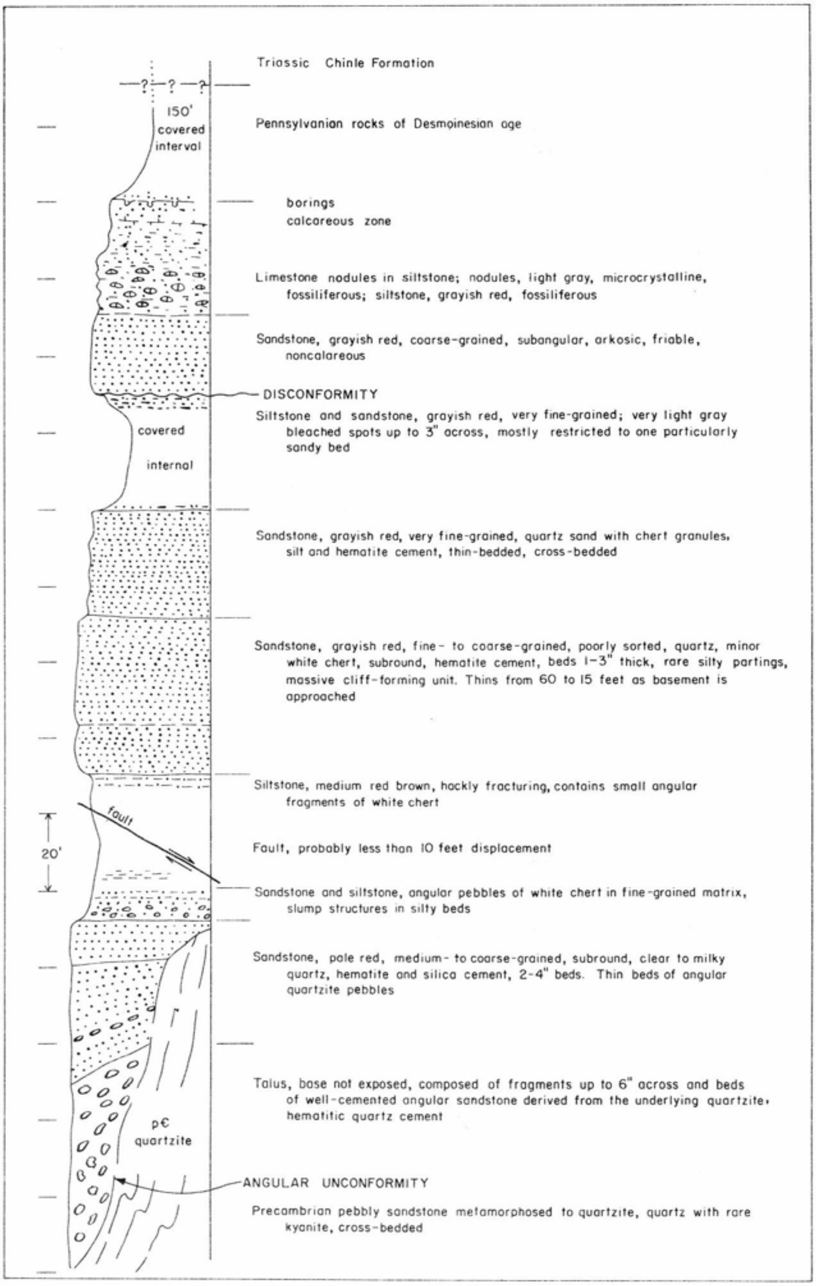


Figure 3

MEASURED SECTION OF PENNSYLVANIAN ROCKS EXPOSED IN CHAVES CREEK AT BASE OF CHAVES BOX

Precambrian surface, however, appears to be related to the base of the 1957). The exposed Precambrian surface has been stripped updip for a considerable distance and is remarkably smooth. If the breccia is a talus, then an immediate source area is a problem. The updip smooth Precambran surface, however, appears to be related to the base of the Triassic rocks, which lie unconformably across the Pennsylvanian. Thus any remaining Pennsylvanian topography could have been removed by pre-Chinle Formation erosion.

Sandstone and siltstone, composed of subangular to subround, moderately sorted quartz, constitute the bulk of the measured rocks. Under the microscope the quartz appears highly strained, a condition also typical of the underlying Precambrian quartzite. A disconformity separates these beds from the overlying arkosic sandstone and fossiliferous nodular limestone.

The arkosic sandstone is composed of angular to subangular grains of quartz and microcline. The predisconformity rocks could be older than Desmoinesian in age and possibly older than Pennsylvanian. However, disconformities and compositional alternations are common in the Hermosa Group (Wengerd and Matheny, 1958, p. 2058-2059) of the Four Corners region. Detailed study of this outcrop might permit accurate correlation with the Pennsylvanian cycles recognized within the Paradox basin (Elias, 1963; Wengerd, 1963).

The only fossils found were in the matrix and nodules in a 10-foot nodular limestone unit near the top of the measured section. The following fossils have been identified:

Wedekindellina euthysepta
Fusulina haworthi
Prismopora sp.
Bryozoa (two forms other than *Prismopora)*
Mesolobus sp.
Derbya sp.
Dictyoclostus sp.
Spirifer sp.
Neospirifer (j uveni le)
Composita sp.
Squamularia perplexa
Punctospirifer kentuckyensis
Crinoid fragments

These fossils, identified by S. P. Ellison, Jr. (microfossils) and J. Marvin Weller (macrofossils), constitute a middle Desmoinesian assemblage.

The upper contact is not exposed in Chaves Canyon where the section was measured. Approximately 150 feet of covered beds lie between known Triassic rocks and the fossiliferous Pennsylvanian beds.

A possible contact is exposed against the face of Chaves Box in a tributary about 100 feet south of Chaves Creek. Here the presumed topmost Pennsylvanian bed is a noncalcareous red siltstone that breaks into slabs less than an inch thick and is bored in its upper part. This bed lies about 30 feet above the Precambrian quartzite. The remainder of the beds below is mostly covered, although the units appear to be about 4 feet thick each and to be sandstone or siltstone and a subrounded pebble-cobble basal conglomerate of quartzite clasts. Each of these units as traced laterally appears to thicken away from the Precambrian surface—a feature typical of the Pennsylvanian beds studied in the main part of the outcrop area. The rocks overlying the bored zone are apparently disconformable at the outcrop examined; elsewhere, the contact is covered. These rocks consist of red siltstone, sandstone, and pebbly lenses in thin layers and were not observed to change laterally in thickness.

A well-preserved Desmoinesian flora was found along a fault in a thin-bedded, carbonaceous, gypsiferops, and micaceous siltstone in Arroyo del Cobre, 35 miles south of the Chaves Canyon exposures (Smith, Budding, and Pitrat, p. 5). This is the only known exposure of Pennsylvanian rocks along the eastern margin of the Chama Basin. The few wells that have penetrated to basement in the Chama Basin have not reported sedimentary rocks older than Triassic. It is possible that some of the lower beds reported as Triassic are older but were not recognized as such because both the Triassic and Pennsylvanian units are of similar lithology (Dane, 1948) and no rocks older than Triassic were known when these wells were drilled (Bieberman, 1960).

CHINLE FORMATION

The Chinle Formation is exposed along the face of the Tusas Mountains from Cañones Creek south to the Brazos Box. About 500 feet of red arkosic siltstone and sandstone with conglomeratic zones near the center of the formation constitute the entire exposed section.

Exposures are poor, distances to other outcrop areas of the Chinle Formation are great, and the probable fluvial origin make it pointless to subdivide the formation in this area. The coarseness of the basal and middle parts of the Chinle Formation suggests a correlation with the Agua Zarca and Poleo sandstones that Northrop and Wood (1946) recognized along the southwest margin of the Chama Basin. These were not recognized by Smith, Budding, and Pitrat in the region immediately to the east; instead, they distinguished lower sandstone and upper shale members. The extensive vertebrate collections from the southern margin of the Chama Basin are from the Petrified Forest Member (Colbert, 1960), which is correlative to the upper shale member of Northrop and Wood and Smith, Budding, and Pitrat. No fossils have yet been found in these beds in the Chama region.

The lowest exposed beds, about 25 feet thick, in Cañones Creek are well cemented, ferruginous, moderately sorted, subangular to subrounded, moderate reddish-brown and dark reddish-brown, quartz standstones. In a tributary canyon to the south, the basal beds are fine-grained siltstone. On the slope north of the Cañones Box, the basal beds are conglomeratic, with angular clasts of locally derived Precambrian quartzite. Elsewhere they may contain quartz pebble beds, as in Chaves Canyon and above the Chaves Box where the lower Chinle units are preserved east of a major fault. Thinning of the lower section is well shown in Figure 4.

Figure 4

CHAVES BOX SHOWING THINNING OF CHINLE FORMATION ONTO PRECAMBRIAN QUARTZITE

View northeast. Chaves Box is slot canyon at right. Prominent cliff-forming bed in left foreground is lower Chinle resting on Pennsylvanian which, as traced to right, crosses onto Precambrian and forms topmost part of cliff of Box. Wedging of covered section in Chinle can be observed by tracing nearly bare ridge in right middle onto Precambrian surface. Entrada forms cliffs in background.

About 250 feet of poorly exposed, grayish, orange-pink siltstone and medium- to coarse-grained arkosic sandstone overlie these basal beds. The arkose has a salt-and-pepper appearance caused by altered biotite and kaolinized feldspar. These beds are friable and thin-bedded and contain a hematite cement. One arkosic sandy zone near the top of the unit in Chaves Canyon has cross-beds that dip S. 20° E. and range from 1 to 2 inches thick.

A persistent ridge above the beds just described is held up by about 25 feet of coarse arkose and silty sandstone. Cement is hematite or chert; red chalcedony cements one bed in Nestor Canyon. Beds are commonly about one foot thick. The sandstone beds in Nestor Canyon are nearly pure quartz and white, except where cemented by hematite; those in Chaves Canyon are mostly arkosic, lensing, and bleached from reddish tones to light greenish-gray.

The upper 250 feet are generally covered but probably are similar to the lower 250-foot siltstone sequence in gross characteristics. The principal difference observed is the presence of several calcarenite and limestone-pebble conglomerate beds composed of rounded pebbles and coarse-grained sand of gray micrite with shell fragments, coarse sand grains of rounded, composite, strained quartz, and fine sand grains of well-rounded sparry calcite cemented by sparry calcite and micrite.

The lower and upper contacts were observed at single localities on the north wall of the Cañones Box. Here, what was probably originally an unconformity between the Chinle and the underlying Precambrian quartzite is now slickensided directly downdip of the contact. Elsewhere the basal contact appears to be an unconformity and is remarkably smooth. This is well displayed in Cañones Canyon and along the mountain front north of the Brazos Box where the smooth, stripped, Precambrian surface rises for several thousand feet above the valley floor. The smoothness of this surface cut across the highly resistant Precambrian quartzite is truly remarkable. Any topographic high on this surface is an outlier of the Chinle Formation. This ciastic formation of continental origin only locally contains detritus in its basal units derived from the Precambrian quartzite. In fact, its typical arkosic composition contrasts strongly with the underlying pure quartz quartzite. The origin of this planar surface on which the Chinle Formation was deposited is unknown and may be the result of several planations prior to its being covered by the Chinle.

Smith, Budding, and Pitrat stated that along the southern margin of the Chama Basin, the upper contact with the overlying Entrada Formation is unconformable. Along the north wall of Canons Canyon, the upper 20 feet of the Chinle consist of parallel-bedded, moderate orange-pink, well-sorted, subrounded quartz siltstone. Scattered, rounded, frosted quartz sand grains in the siltstone and one-half-inch-thick coarse-grained sandstone stringers are irregularly spaced throughout the exposed section. Its upper surface is sharp and apparently disconformable beneath the overlying festoon-bedded Entrada Formation. The absence of fossils and critical structural data preclude determining the true significance of this contact.

ENTRADA FORMATION

The massive, cliff-forming Jurassic Entrada Formation is exposed continuously from the south edge of the map area just west of the Brazos Box north to Cañonizaria Canyon. Farther north, the deep canyons of Little Willow and Wolf creeks expose the upper Entrada. The formation consists of about 250 feet of massive, parallel-, festoon-, and cross-bedded, fine-grained quartz sandstone whose color is very pale orange to grayish orange. Thin limonite coatings on the quartz sand grains cause the color variation.

Along the north wall of Cañones Creek, the Entrada consists of about 200 measured feet (another 50 to 100 feet are covered at the top) of very well-sorted, friable, very fine-grained quartz sandstone. Festoon cross-bedded units 3 to 4 feet thick are separated by silty layers as much as 4 inches thick. Limonite grain coatings are present throughout, although the cement is calcareous. A layer of 2- to 5-inch-thick iron-cemented concretions 40 feet above the base and a layer of current ripples (the apparent direction of current on the surface of the outcrop is west) relieve the monotony of the massive unit. The upper half of this unit is slightly darker in color and forms cliffs blocky in appearance compared to the smooth, rounded surfaces of the lower cliffs. The lithology of the two parts appears to be identical, although the upper unit may be slightly coarser grained.

In Nestor Creek, a tributary branching south from Cañones Creek, the Entrada is about 250 feet thick and consists of a lower, massive, cliff-forming, fine-grained quartz sandstone unit that has practically no visible bedding planes and is lighter in color than the overlying thin-bedded unit.

The Section measured in Chaves Canyon in the Brazos Peak quadrangle is at most 250 feet thick, probably closer to 230 feet. The lower 100 feet of very fine-grained sandstone is pale reddish-brown in contrast to the remainder, which is fine-grained and grayish-yellow. Calcite cement is present in the lower unit and in the basal part only of the upper unit. Hematite coats grains throughout. Oscillation ripples near the exposed base strike east-west.

The top 40 feet are composed of a grayish-orange, well-cemented, silica-cemented, medium-grained quartz sandstone brecciated in the lower 8 to 10 feet. This brecciated zone has been traced for more than half a mile northward into the north fork of Chaves Creek, where the top 30 feet of the Entrada are brecciated and recemented. In places, the breccia fragments are obviously composed of Precambrian quartzite and the unit appears to be a well-cemented talus in a fine-grained sand matrix. This suggests that the Entrada Formation overlaps the older sedimentary beds onto the Precambrian rocks, as has been shown to the north in Colorado (Read et al., 1949). The idea seems plausible because Pennsylvanian (and probably Triassic) rocks wedge onto the basement, both Pennsylvanian and Triassic rocks contain talus of Precambrian quartzite, and, in addition, the overlying Dakota Formation appears to rest on Precambrian rocks west of Brazos Peak and Grouse Mesa in the Brazos Peak quadrangle. Thus the Tusas Mountains appear to have been a persistent structural high.

The Chaves Canyon section is similar to the well-exposed section at Echo Amphitheater Campground 35 miles to the south in that both have a threefold color zoning of lower light reddish-brown, pale yellow-orange in the center, and a grayish-orange top unit. Thicknesses at Echo Amphitheater are 55, 116, and 92 feet, respectively. Cross-bedding is most obvious in the middle unit although all parts contain bedding typical of aeolian deposition. The Cañones section also has this threefold color distinction. If this color zoning holds farther north, then the 180 feet of the Entrada exposed in Little Willow Creek and the 250 feet exposed in Wolf Creek, near the Colorado state line, include only the upper two units.

Sharp, disconformable, basal contacts are well exposed along the southern margin of the Chama Basin *(see* Smith, Budding, and Pitrat's fig. 2B, p. 11, for a typical exposure of the contact in this region). In only one place north of Cañones Creek was the top of the Entrada observed where pitted sandstone beds of the lower Morrison Formation (the pits result from the leaching of gypsum) rest on massive Entrada. To the south at Echo Amphitheater, the Entrada is disconformably overlain by thin-bedded nonmarine limestone of the Jurassic Todilto Formation.

TODILTO FORMATION

The Jurassic Todilto Formation is either covered or absent throughout the Jurassic outcrop belt from the Colorado state line south to Cañones Canyon. South of Chaves Canyon to the southern edge of the quadrangle, as much as 20 feet of crinkly bedded, laminated, dark-brown, fetid crystalline limestone are exposed (or present). One exposure of this limestone was found east of the Chaves Box at about 9600 feet elevation. No gypsum beds overlay the limestone beds, such as those exposed at Echo Amphitheater 35 miles south or at other places along the southern margin of the Chama Basin (Smith, Budding, and Pitrat).

In the Chaves Canyon measured section, no Todilto Formation was found. However, a 10-foot covered interval lies between the Entrada Formation and the lowest Morrison Formation sandstone that could include the Todilto.

North of Cañones Creek, the sandstones mapped as basal Morrison Formation contain fragments of gypsum. The pitted surface results from leaching of the gypsum. Presumably, the gypsum pebbles eroded from Todilto outcrops in the region. North of this point, no float of Todilto lithologies was found. The extensive mantle of colluvial and glacial materials, the heavy forest cover, and the relative solubility of these beds might eliminate the Todilto from surface observation. A water well at the mouth of Little Willow Creek apparently penetrated the Todilto Formation.

These units are conformable with the underlying Entrada (Smith, Budding, and Pitrat) and the overlying Morrison wherever the contacts could be observed, but they have been included with the Morrison Formation on the geologic map.

Work by Kirkland (1958) shows that the laminations visible in the limestone member and lower part of the gypsum member are varves. The environment is interpreted as a saline rather than marine lake. By varve counts, the lake existed about 19,600 years.

MORRISON FORMATION

The Upper Jurassic Morrison Formation is exposed along the front of the Brazos uplift from the southern margin of the quadrangle north to Little Willow Creek, in the Rio Chama canyon northeast of Chama, and in Wolf Creek on the Colorado state line. Within the Chama Basin, the only exposures of the Morrison Formation occur in the canyon of the Rio Chama where it crosses the North El Vado dome six miles south of the Chama quadrangle (Dane, 1946; Davis) and south of El Vado Dam in the Rio Chama gorge.

The formation generally forms a steep, mantled slope, the most complete exposure being in Wolf Creek along the Colorado state line. The thickness of the Morrison, as computed from maps and cross sections, is about 435 feet. Wells in the Chama Basin indicate a thickness of about 700 feet (Dane, 1948). About 560 feet were penetrated in a water well at the north of Little Willow Creek east of Chama.

The formation along the eastern margin of the quadrangle is composed of interstratified units of mudstone and sandstone, with sandstone more abundant near the base. The basal sands in Wolf Creek are subrounded to subangular, very fine-grained quartz sandstone with a calcareous cement. The basal part consists of grayish-green to pale-red mudstone interbedded with grayish-green to light-gray, medium-grained, well-sorted, hematite-spotted, parallel-bedded, cliff-forming quartz sandstone. Two sand units 10 to 20 feet thick are present near the base. The sands have broad, gently dipping, cross-bedding within the individual beds which are 2 to 4 feet thick. The upper part consists of interbedded mudstone and sandstone in units 2 feet or less in thickness. The mudstone is grayish green to pale red and somewhat more abundant than the sandstone.

In contrast, the upper 98 feet of the Morrison Formation exposed in the Rio Chama gorge across the North El Vado dome (Davis) consist of thick sandstone units interbedded with variegated green and red shale. The silty, slightly friable, noncalcareous and slightly carbonaceous quartz sandstones occur as channels; maximum thicknesses of individual channels range from 15 to 25 feet. The cross-bedded sandstones fill scoured depressions in the underlying shale. The shale is in layers about 6 inches thick and is slightly micaceous, carbonaceous, and calcareous. These channels support the conclusion that the Morrison Formation is a fluvial deposit composed of both stream-deposited sediments (sandstones) and floodplain-deposited sediments (Craig et al., 1955).

The upper contact is disconformable with the overlying Dakota Formation both in Wolf Creek and in the Rio Chama Canyon.

If the Todilto Formation is missing, as the gypsum pebbles in the basal Morrison north of Cañones Creek suggest, then the lower contact is also an unconformity.

DAKOTA FORMATION

The Dakota Formation, a sequence of massive sandstone and interbedded siltstone, with an observed range in thickness from 180 to 390 feet, is exposed over much of the southern Chama quadrangle and along the front of the Tusas Mountains. All the major anticlines and domes of the Chama quadrangle are topographic highs as well, because erosion has stripped the sediments down to the uppermost massive sandstone of the Dakota. Narrow canyons cut into these structural and topographic highs expose the upper part of the Dakota section.

No attempt was made to subdivide the Dakota Formation because most exposures are of the uppermost beds only. Along the front of the Tusas Mountains it is possible to map the base of the upper, thick, massive sandstone as a separate unit because of its ridge-forming nature. It appears to be the same bed that caps the anticlines of the Chama Basin.

Sections of the Dakota Formation 391 and 385 feet thick were measured in the Rio Chama canyon northeast of Chama and at the fork of Little Willow Creek east of Chama (Adams). Sections 231 and 230 feet thick were measured in the north fork of Chaves Creek just east of the Chama quadrangle and in the Rio Chama gorge on the North El Vado dome a few miles south of the Chama quadrangle (Davis).

Dane (1948) reported thicknesses of 370 feet penetrated by the

Phillips—Helmerich and Payne El Vado No. 1 (choice of base questioned by Dane) on the South El Vado dome, and five miles farther south in sec. 33, T. 27 N., R. 2 E., he measured 186 feet for an outcrop section. The Willow Creek Oil Syndicate and E. T. Williams well on the Willow Creek anticline penetrated 180 feet of Dakota Formation. Both these wells spudded in on the top of the massive upper sandstone and thus should have penetrated virtually the entire Dakota section. In the Tierra Amarilla quadrangle, Dane (written communication, July 1966) reported 300 to 325 feet of Dakota, which might include 55 to 85 feet of possible Burro Canyon beds at the base.

Just north of U.S. 84 along Willow Creek, 114 feet of Dakota are exposed (Longgood). At the west base of El Cerro dome, 172 feet are exposed (St. John). At neither of these localities is the base exposed.

The Dakota Formation along the front of the Tusas Mountains can be subdivided roughly into three units: a lower sandstone, a middle shale, and an upper sandstone. The lower cliff-forming sandstone member, about 185 feet thick, is pale orange to moderate yellowish brown, massive, cross-bedded and parallel-bedded, very fine- to coarse-grained, and locally conglomeratic. Quartz, the dominant sand-sized material, is subround to round. Silty sizes are subangular. Minor amounts of chert are present. Channels are common with well-rounded, light-colored, chert and quartz pebbles in the basal cross-bedded units. Individual bedded units range from a few feet to 30 feet in thickness. A few observations on cross-bed directions in Chaves Canyon show a dominance of dip direction between southeast and southwest.

Conformably overlying this unit are from 70 to 125 feet of dark-gray, platy, carbonaceous, silty shale and very fine-grained sandstone. At Chaves Canyon, the lower 30 feet of this unit are composed of greenish-gray siltstone and pale red-purple sandstone which appears to be reworked Morrison Formation.

Conformably overlying this unit is a very light-gray, medium- to fine-grained, thick, parallel-bedded, cliff-forming sandstone that ranges from 27 to 45 feet in thickness. This sandstone holds up a second hogback in the Dakota Formation along the front of the Tusas Mountains.

An upper unit conformably overlying this member consists chiefly of black platy shale but contains beds of medium light-gray to light-gray, limonite-stained siltstone. The top few feet consist of a very light-gray, very fine-grained, thin, parallel-bedded, fucoidal sandstone containing pelecypod *(Gryphaea?)* casts. Where this top sandstone is missing, the top of the Dakota is chosen at the top of the next lower ridge-forming sandstone. Thus part of the change in thickness of the Dakota Formation and the overlying Graneros Shale in the measured sections is caused by defining the top of the Dakota as the uppermost continuous sandstone. On the top, held up by the stripped Dakota structural highs of the southwestern Chama quadrangle, are continuous sandstone beds. Discontinuous sandstone stringers occur in the lower Graneros as mapped. This may cut as much as 50 feet from the observed and measured Dakota thicknesses on these domes. In addition, all units in the Dakota vary in thickness as traced along strike. For example, the upper sandstone in Little Willow Creek is broken by a one-foot-thick shale into two beds 16 and 18 feet thick. The next overlying 15 feet of beds consist of one-foot shales with sand beds 3, 4, and 5 feet thick. These beds could well be lumped with the upper sandstone to be a 50-foot-thick unit. However, the lateral tracing and correlation of these beds is difficult; only the thickest beds form a prominent ridge that could be traced through the forest cover. Worm burrows mark this entire upper unit.

In the absence of fossils and because of the gradational nature of the contact with the Graneros, the Dakota Formation is included in the Upper Cretaceous (Dane, 1948). The Dakota is composed of flood-plain, swamp, and lagoonal deposits (Pike, 1947) except for the upper beds, which are littoral and grade into the overlying marine shale of the Mancos.

The Dakota disconformably overlies the Morrison. The contact surface is slightly undulating, and the Dakota contains fragments of Morrison.

The threefold division into sandstone-siltstone-sandstone with an additional capping siltstone along the Tusas Mountains front is not easily applicable elsewhere in the Chama region. The exposed 172 feet to the Dakota at the west base of El Cerro dome appear to be divisible into five parts. Only 2 feet of the lowest sandstone are exposed at creek level. Successively upward are 20 feet of siltstone, 32 feet of sandstone, 87 feet of siltstone (probably middle unit of mountain front section), and 31 feet of massive sandstone. The lower sandstone is an orange, very fine-grained, silica-cemented orthoquartzite. The quartz grains are well rounded and well sorted and have silica overgrowths. The middle sandstone grades upward from fine- to medium-grained and is also silica-cemented with patches of clay cement near the base. The upper sandstone is similar except for an upward decrease in grain size into the gradational contact with the silty Granerous Shale at the top (St. John).

In the Dakota exposures along Willow Creek north of U.S. 84, Longgood recognized three members: a lower sandstone with the base not exposed, a middle shale with interbedded sandstone, and an upper sandstone. The lower sandstone, with only the upper 25 feet exposed, is a subarkose containing feldspar, metamorphic rock fragments, rare biotite, muscovite, hematite, and lesser amounts of limonite and silica overgrowths in addition to a preponderance of subangular quartz. This unit contrasts sharply with the typical Dakota of this region and elsewhere (MacKenzie and Poole, 1962; Willard, 1964) that is typified by well-rounded quartz sandstones. It is more typical of the underlying Morrison Formation and may represent reworked Morrison similar to that of the middle Dakota beds exposed in Chaves Canyon. The next 62 feet of beds comprise mostly very fine-grained sandstone to siltstone with carbonaceous laminations that resemble the middle Dakota subdivision of the mountain front. The upper unit consists of 12- and 13-foot-thick sandstones separated by a 2-foot shale and siltstone unit. Nearly pure quartz grains, well rounded to rounded, well sorted, and medium- to fine-grained, compose the upper sandstones.

The 230-foot-thick complete Dakota section (described by Davis) in the Rio Chama gorge across the North El Vado dome six miles south of the Chama quadrangle has a fivefold subdivision very similar to El Cerro dome partial section. The thicknesses differ: lower sandstone, 20 feet; lower shale, 80 feet; middle sandstone, 30 feet; upper shale, 50 feet; upper sandstone, 50 feet. Size gradations within the middle and upper sandstone are the same as those at El Cerro, increasing upward from fine to medium coarse in the middle sandstone and decreasing upward from medium-grained to very fine-grained in the upper sandstone.

One distinct characteristic of the Dakota compared to the Mesaverde is the cleanness of its sandstone beds; it is nearly always an orthoquartzite. The grains are rounded, commonly frosted, and composed dominantly of quartz with minor amounts of feldspar in the middle sandstones and traces of ilmenite and magnetite. Hematite staining in the upper beds gives the rocks a reddish color, more pronounced on a weathered surface than on a fresh one. Quartz overgrowths are common in the upper sandstones, and many of the quartz grains in the upper member have two generations of overgrowths, one rounded and one angular.

Two outcrop areas of Dakota high in the Tusas Mountains in the Brazos Peak quadrangle suggest the possibility that the Dakota there rests on Precambrian. One set of outcrops, one mile east of the head of Cañones Box and at the northwest base of Grouse Mesa, has vertical to steep west-dipping Dakota capped by nearly horizontal beds of the Tertiary Blanco Basin Formation. The top of the section lies to the west and is cut off at the top by a major fault along which in late Cenozoic the west side dropped down. The north and east contacts of the Dakota abut a major landslide mass. The Dakota sandstone appears in two parallel outcrops (apparently the upper and lower sandstone units). If the covered interval between outcrops is the shaly middle Dakota and not faulted material, the apparent thickness of the Dakota exceeds 700 feet, twice as thick as any complete section along the front of the Tusas. Mountains.

Three miles southeast, at the west base of Brazos Peak, is a group of exposures of what appears to be upper Dakota sandstones ringed by glacial deposits. A short distance west, Precambrian outcrops at the same topographic elevation are upthrown along the same major fault that bounds the group of Dakota outcrops. The Dakota dips very gently westward, exposing about 50 feet of massive, fine-grained, parallel-bedded, friable quartz sandstone with minute specks of charcoal.

These outcrops might be fault-bounded, but no surface evidence for faulting is visible because of the veneers of glacial and landslide debris, so the nearby presence of Precambrian outcrops at the same topographic elevation is here considered evidence of Dakota deposition of Precambrian.

Some of the lower Dakota, as mapped, could be correlative with either the Burro Canyon Formation (Stokes and Phoenix, 1948), recognized to the west, or the Purgatoire Formation (Stose, 1912; Baldwin and Muehlberger, 1958), recognized east of the Rocky Mountain front. E. **H.** East *(in* McPeek, p. 25) recognized 60 feet of Burro Canyon at the North El Vado dome. These beds in this report are probably included in the upper Morrison Formation *(see* North El Vado dome measured section, Appendix A). McPeek also recognized 85 feet of Burro Canyon Formation farther south in his Rio Nutrias section. Smith, Budding, and Pitrat recognized the possibility of the lower Dakota beds being correlatives of Burro Canyon or Purgatoire Formation but mapped the entire Cretaceous sandstone facies in the southeastern Chama Basin as Dakota Formation. Dane (written communication, 1966) recognized that from 55 to 85 feet of Burro Canyon Formation might be present in the Tierra Amarilla quadrangle.

MANGOS FORMATION

The Mancos Formation consists almost entirely of shale with some silty limestone beds, concretions, and numerous fossils. Within the Chama region, the total thickness could not be measured but is estimated to be at least 1700 feet. Apparently the Mancos is a huge, wedge-shaped deposit which is thickest in western Colorado and pinches out in east-central Arizona (Pike; O'Brien, 1956).

Dane (1948) designated five members of the Mancos Shale along the eastern rim of the San Juan Basin. From oldest to youngest these are Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Calcareous Shale, and Upper Shale. Although these members are designated as formations in eastern Colorado and northeastern New Mexico, Dane (1948) considered them "lithologic equivalents" of the formations. In our mapping, we grouped the Niobrara Calcareous Shale and the Upper Shale into Upper Mancos Undifferentiated. The other subdivisions on the map are approximately equivalent to the units of Dane except for the base of Upper Mancos Undifferentiated, mapped at the lithologic change visible a few feet below the base of beds containing *Inoceramus grandis* prisms covered with *Ostrea congesta*. This is the approximate base of the Niobrara Calcareous Shale of Dane. Recent work demonstrated that beds of Niobrara age regionally truncate the underlying beds of Carlile age (Dane, 1960). Within the Carlile Shale Member, the calcarenite zone in the middle part has been designated the Juana Lopez Member of the Mancos Formation (Dane, Cobban, and Kauffman). This zone was recognized throughout the Chama quadrangle where it caps low mesas and holds up ridges, but it is not shown separately on the geologic map.

GRANEROS SHALE MEMBER

The Graneros Shale Member crops out as a band along the front of the Tusas Mountains and in rings surrounding the Dakota structural highs in the southwestern part of the Chama quadrangle. Generally poorly exposed, this member comprises about 120 feet of fissile, finely bedded, slightly sandy, calcareous clayey shale, with a few concretion zones in the lower part. The concretions are calcareous or dolomitic and range up to 5 feet in diameter, although they average 1 to 2 feet in diameter. Their yellowish-gray color strongly contrasts with the dark-gray to black color of the surrounding shale. The shale itself is a silty micrite (St. John) except in the bottom few feet where it grades upward from the Dakota sandstone lithology into dark silt. Thin bentonite beds are present, principally in the lower and upper parts.

The upper boundary with the Greenhorn Limestone Member is arbitrarily set at the base of the lowest occurrence of a continuous whitish-gray limestone bed followed stratigraphically upward by several closely spaced limestone beds in the black shale sequence.

Dane (1948) reported a thickness of 120 to 130 feet for the Graneros. Graphic solutions at several places generally agree with this thickness range. In the Rio Chama Canyon northeast of Chama, 97 feet of shale separate the Dakota from 12 feet of Greenhorn. On Willow • Creek at the southern edge of the Chama quadrangle, 153 feet of Graneros were measured by St. John.

Reeside (1924) and Pike reported the following common fossils in the Graneros: *Gryphaea newberryi* Stanton, *Exogyra columbella* Meek, *Scaphites vermiformis* Meek and Hayden, and *Inoceramus labiatus* Schlotheim.

GREENHORN LIMESTONE MEMBER

Conformably overlying the Graneros is a thin interval of alternating limestone and calcareous shale beds. Being more resistant than the bounding shale members, the Greenhorn forms low, white ridges. The thickness ranges from 12 feet (northeast of Chama) to 20 feet (near

Tecolote Point) to 26 feet (one mile south of El Vado Dam). These thicknesses are consistently less than those of Dane (1948), who reported 40 to 60 feet of Greenhorn, because we included only the limestone beds that form a prominent ridge and did not include the thinner and more widely spaced beds above our mapping top.

Whitish gray on a weathered surface and dark gray on a fresh surface, the Greenhorn is a thinly bedded, dense, slightly (mega-) fossiliferous, highly fractured limestone in beds 3 to 18 inches thick separated by intervals of calcareous shale of the same thickness range. The limestone is a pelletoid, limonitic, *Inoceramus—Globigerina* biomicrite (St. John) that also contains *Mammites* sp. and *Inoceramus labiatus* Schlotheim. A distinct petroliferous odor emanates from the freshly broken rock.

CARLILE SHALE MEMBER

Conformably overlying the Greenhorn, the Carlile Shale Member consists of 400 to 500 feet of olive-gray to black shale with a zone of calcareous sandy beds near the middle. Generally poorly exposed, it crops out across the southern two thirds of the Chama quadrangle. The calcareous sandy beds (Juana Lopez Member of Dane, Cobban, and Kauffman) near the middle of the section hold up low hills and form a convenient marker zone within this black shale unit.

The rocks are fissile, finely bedded, mudstone and claystone, locally silty, whose color is light brownish gray, with more yellowish colors in horizons containing oxidized iron-bearing minerals. Thin bentonite beds are scattered throughout the section but seem more abundant in the upper 200 feet. A few siltstone beds occur in the middle part of the section, the terrigenous particles of which are smaller than but mineralogically similar to the sand-sized particles of the Mesaverde Group. Selenite crystals coat some bedding surfaces or act as joint fillings. Septarian limestone concretions occur in the lower half of the unit and are yellowish brown, oblate, and from 1 to 5 feet wide. The septa exhibit two generations of calcite growth, the older, more abundant, light-brown rhombohedrons surrounding the younger, clear-white, cavity-filling crystals.

Near the middle of the Carlile section, thin, sandy, highly fossiliferous, calcareous beds constitute an easily recognized marker zone. These beds are in part the correlative of the Juana Lopez sandstone of Rankin (1944; Dane, 1960a,b). Dane, Cobban, and Kauffman defined a Juana Lopez Member of the Mancos Shale and gave a reference section near La Ventana, Sandoval County, New Mexico. These beds range from 165 feet thick on Willow Creek just south of U.S. 84 to 225 feet east of Tecolote Point to 239 feet on the Rio Chama where it empties into El Vado Reservoir about five miles south of the Chama quadrangle. Immediately below this zone is a giant septarian concretion zone. The concretions are as much as 3 feet thick and 5 feet in diameter with distinctive orange color and a dark-gray, waxy luster, coarsely crystalline calcite filling wedge-shaped joints.

Generally three distinctive, resistant, thin beds and interbedded shale constitute the Juana Lopez marker zone. The lowest is a cross-bedded, commonly ripple-marked, sandy limestone a few inches thick and sparsely fossiliferous with fragments of fish scales and carbonized wood. The middle bed is a cross-bedded calcarenite a few inches thick that contains abundant *Ostrea lugubris*. Capping the low hills, the upper bed, a thin, grayish-orange, parallel-bedded calcarenite, contains *Scaphites warreni, Baculites* sp., and *Prionocyclus wyomingensis,* as well as abundant pelecypods. This zone is probably 15 feet or less in thickness, although it may be as much as 50 feet thick in the southern Chama quadrangle. Low relief and the mantling of the surface by the calcarenite fragments generally preclude any accurate measurements.

This calcarenite zone is in turn overlain by about 150 feet of dark shale similar to the lower shale of the Carlile.

The upper contact with the Upper Mancos Undifferentiated is not easily discernible. The members occur in areas of low relief and the shales readily weather to soil, which in turn supports a thick growth of grass; therefore, the contact is everywhere concealed and, as shown on the geologic map, is accurate to perhaps 50 feet stratigraphically. The characteristics used in the field to distinguish the upper Carlile from the overlying member were the change in color from yellowish gray or light brown to light gray, the appearance of sparse to locally abundant *Inoceramus grandis* prisms covered with *Ostrea congesta,* and a change from very fine bedding to thick bedding.

Dane (1948) reported a thickness of about 500 feet for the Carlile Member. Adams measured a like amount near Chama, St. John measured 434 feet near Tecolote Point, and Davis measured 402 feet south of the Chama quadrangle along the Rio Chama at El Vado Reservoir.

UPPER MANCOS UNDIFFERENTIATED

Both Rankin and Pike mapped the Upper Mancos Undifferentiated as part of two groups, the Colorado and Montana, in ascending order. Dane (1948) in the eastern San Juan Basin mapped two members of the Mancos Formation, in ascending order, Niobrara Calcareous Shale and Upper Shale. Each of these men separated the units on gross lithic differences and faunal evidence. In the subsurface, the top and bottom of the Niobrara are not easily distinguishable on electric logs (Bozanic, 1955), although McPeek showed the base of the Niobrara on a regional electric log section along the east side of the San Juan Basin. In the field, Dane (1948) described the Niobrara as a calcareous shale and declared that ". . . the occurrence of *Inoceramus grandis,* even as fragments, is apparently a reliable guide to the recognition of the Niobrara."

The Upper Mancos Undifferentiated, as used in this report, includes all beds between the Carlile Shale and the Mesaverde Group. It is calcareous, gypsiferous, finely bedded, highly fissile shale. On a fresh surface the color is dark gray, weathering to light gray. The lower 200 to 300 feet are clayey, but upward, silt-sized particles mineralogically similar to the sand-sized material of the overlying Mesaverde increase in amount toward the top of the unit. This silt in many localities marks the disappearance of abundant fossils.

The base of Upper Mancos Undifferentiated is selected at the lowest appearance of *Inoceramus grandis* prisms covered with *Ostrea congesta.* This coincides with a color break—a light gray for the Upper Mancos Undifferentiated, a dark gray for the underlying Carlile—and approximately coincides with the base of the Niobrara Calcareous Shale Member of the Mancos Shale, as mapped by Dane (1948). This eliminates the basal faunal zone of *Inoceramus deformis* Meek of Niobrara age, recognized by Cobban and Reeside (1952), which near U.S. Highway 84 west of Willow Creek is at least 30 feet thick (Dane, oral communication, July 1958). No recognizable field distinction was observed at this level, however; therefore, a field lithic distinction (counting fossil pieces as lithic detritus) was used.

Dane (1960a,b) presented regional evidence of an unconformity truncating Carlile age beds beneath the basal Niobrara faunal zone in the northern San Juan Basin. Our paleontologic work is inadequate to corroborate his study.

A marker bed 10 to 20 feet above the lowest occurrence of abundant *Ostrea congesta* on *Inoceramus grandis* prisms crops out in a small area in the central Chama quadrangle. It parallels the base of the Upper Mancos Undifferentiated for about five miles north and west from the west bank of the Chama River one mile north of its junction with Cañones Creek. From 3 to 12 inches thick where exposed, the bed is a yellow-buff, medium- to coarse-grained, calcareous sandstone. Fish scales, lignite (?) fragments, and phosphatic pellets (probably coprolite) are recognizable (Folk, oral communication, 1962).

A nearly continuous mantle of surficial material obscures the outcrop of the Upper Mancos Undifferentiated and is the principal reason for not subdividing the unit. Lithologic changes observed in this unit are gradual and it is highly unlikely that a consistent contact could be mapped in the Chama quadrangle to distinguish units within the Upper Mancos Undifferentiated.

Septarian calcareous concretions appear in the upper 600 feet but are most abundant in the upper 400 feet. Often the septa completely weather out, and the concretions, which are sometimes slightly fossiliferous, are seen only as fragments. Where whole, they attain a maximum diameter of 4 feet and stand out vividly because of their contrasting yellow-orange color. Sharks' teeth and fish scales and an abundance of invertebrate marine fossils are found in the uppermost part of the unit. The shale also becomes silty and lenses of sandstone become more frequent as the Mesaverde contact is approached.

The upper contact with the Mesaverde is conformable and is chosen at the base of the lowest occurrence of continuous, thick, massive sandstone. Both above and below this contact, lenses of lithology typical of each unit occur, but none are persistent enough to be mapped across the area.

The thickness of the Upper Mancos Undifferentiated was not measured. Much of the unit has slid or slumped and readily exhibits present-day soil creep. Graphically, its thickness was determined to be about 1100 feet. If the Niobrara Calcareous Shale and Upper Shale members mapped by Dane (1948) are combined, their total thickness ranges from 1100 to 1300 feet.

MESAVERDE GROUP

The Late Cretaceous rocks of the San Juan Basin known as the "Mesaverde" have undergone many nomenclatorial changes since they were first mapped and classified as a group by Holmes (1877, p. 244). Mapping in isolated areas with unknown correlations caused a proliferation of named units. Lateral tracing of units, linking by surface and subsurface mapping, and a more thorough understanding of the geologic processes involved permitted Beaumont, Dane, and Sears (p. 2156-2161) to unify the nomenclature of the Mesaverde Group. For the eastern San Juan Basin, the applicable named units are, in ascending order, Point Lookout Sandstone, Menefee Formation, and La Ventana Tongue of the Cliff House Sandstone. In the Chama region, this recognized threefold subdivision of the Mesaverde cannot be recognized because the Menefee Formation, which contains coal and other continental deposits, feathers out to the northeast of the Monero coal field (Dane, 1948) and the marine La Ventana Tongue of the Cliff House Sandstone then rests directly on the marine Point Lookout Sandstone.

Subdivision is possible on the Tecolote Mesa syncline in the southwest corner of the Chama quadrangle and in the trough of the Chama syncline three miles south of Tierra Amarilla, where sharp transitions from the Point Lookout Sandstone to the overlying coal-bearing Menefee Formation occur. The belt of Mesaverde outcrops ringing Chromo Mountain and extending to Chama in the northwestern part of the quadrangle contains 10 to 15 feet of shale dividing two massive sandstone units. Poor exposures in the upper Rio Chamita northwest of Chama made it impossible to determine whether this shale unit was present. The Menefee just west of the Chama quadrangle has become almost entirely sandstone with no coal (Dane, 1948). Therefore, I could not determine where the shale unit of the northwestern Chama quadrangle fits into the named sequence.

On Tecolote Mesa, 195 feet of a partial section of the Mesaverde Group were measured (Appendix A, section TM); neither the base nor the top is present. The lower 116 feet can be assigned to the Point Lookout Sandstone, the remainder to the Menefee Formation. The sandstones are very fine-grained to fine-grained, massive- to thick-bedded, cliff-forming units, dusky yellow to very light gray on fresh surfaces and yellowish gray to yellowish brown on weathered surfaces. In mineralogy, all but one bed are similar, containing quartz (dominant), clay (kaolinite), K-feldspar, lesser amounts of plagioclase, chlorite, sericite, muscovite, biotite, and opaque minerals with significant amounts of limonite and glauconite. Cement is clay and limonite. Grains are poorly sorted and angular. The exceptional sandstone bed is a 7-foot-thick silty sandstone of nearly pure quartz but with minor amounts of shiny, black, carbonaceous fragments. It forms a prominent ledge near the top of the outcrop. A thin coal seam occurs one foot above the base of the impure arkose unit (28 feet measured) that caps the ridge and overlies the orthoquartzite unit. The top of a 5-foot-thick coal seam lies 22 feet below the orthoquartzite bed. Glauconite was recognized in all but the orthoquartzite bed.

Large-scale cross-bedding is visible in a 15-foot-thick unit 63 feet above the measured base. The cross-bedded units are about 2 feet thick and about 20 feet long on the cliff face. Direction of dip was not determined. A two-foot-thick silt- and clay-ball conglomerate in a sand matrix lies 22 feet above the base of the cross-bedded sand.

The thick, massive sandstones form steep cliffs with broadly curving smooth faces. "Pocket weathering" is particularly noticeable on the lower cliff-forming sandstones.

The most continuous exposures are along the south-facing scarp south and east from Chromo Mountain to Chama (fig. 5). Three measured sections, the first 1.5 miles south of Chromo Mountain by Longgood (Continental Divide section, Appendix A, point with elevation labeled 8790), the second 5 miles to the east on a southward-jutting promontory by Longgood and Muehlberger (Willow Creek section, Appendix A, location 36° 54' 30" N., 106° 38' 20" W.), and the third on Rabbit Peak (1 mile west of Chama) by Muehlberger; detailed sedimentary petrography on the western two sections by Longgood (Appendix B); and scattered observations on the remaining outcrop area furnish the basic data for the summary that follows (Longgood).

Bed thicknesses range from 39 feet in the upper part of the formation to 2 inches near the Mesaverde—Mancos contact along the outcrop belt south of Chromo Mountain. Most beds are 3 to 10 feet thick

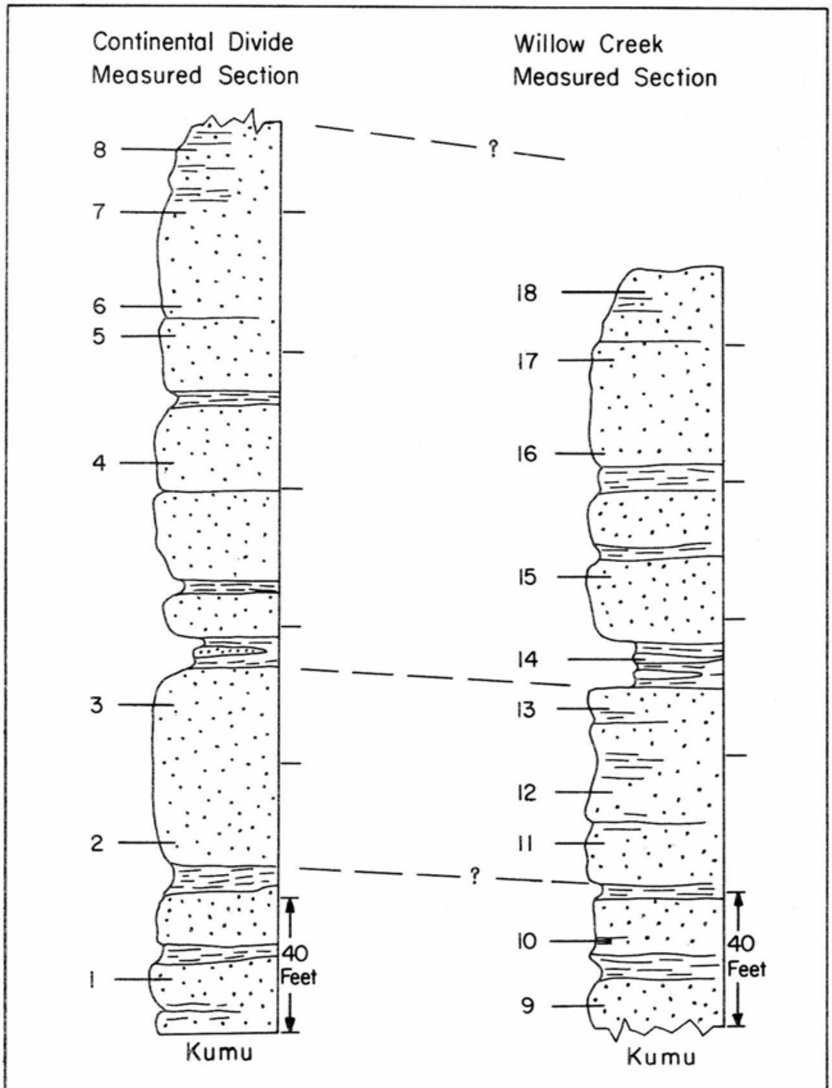


Figure 5

PROFILES OF TWO MEASURED SECTIONS OF MESAVERDE GROUP (Appendix B) showing stratigraphic position of thinsections described in Table 1.

and average 4 feet. In general, the thickest beds occur near the middle of the formation. Most bed thicknesses vary laterally; shale partings in massive sandstones appear and laterally subdivide a massive cliff into several lesser units.

Bedding is determined by (1) heavy-mineral concentrations in laminae, commonly of hematite and ilmenite; sometimes biotite, leucoxene, and zircon are also present; (2) change in cement (cements are calcite, clay, and hematite-limonite) or the quantity of cement which changes weathering resistance or color; (3) pockets or thin layers of clay; (4) change in type of bedding (most bedding is parallel but some beds have distinct, very broad cross-beds; the cross-bedded units are commonly more tightly cemented, usually by sparry calcite, and have an intergranular iron stain; the combination gives the beds a dark color, and they protrude as small ridges); (5) interbedding of shale or siltstone beds with the sandstone (cementation of the sandstone is less near the shale contact); and (6) change in mineralogy.

The broad cross-beds are more pronounced and abundant in the upper part of the formation; dip is toward the northeast. Scattered throughout the section, but more abundant in the upper part, are zones 5 to 10 feet in width which resemble stream channel deposits or subaqueous current channel deposits. They have a darker color and are less tightly cemented than the surrounding rock; cement is clay and limonite. The channel fills (?) characteristically contain abundant fossils including sharks' teeth, fish scales, pelecypod casts, shell fragments, and plant fragments. Grain size is slightly larger than in the surrounding rocks. Channel orientation is not well known because of the shape of the outcrops (nearly vertical planes) but they seem to strike northeast or northwest. Asymmetrical ripple marks observed at several localities indicate a current moving in a N. 45° E. direction. Worm burrows occur on the upper surface of many beds; they are particularly abundant near the top and base of the formation. Randomly oriented, the burrows are usually 3 to 4 inches long and $1/_4$ to $1/_2$ inch in diameter.

The lower sandstones (beds below the "main shale break"; *see* Appendix A, sections CO and WC) are yellowish gray to light olive gray, massive, parallel-bedded, clay-, iron-, and calcite-cemented, slightly friable, and very fine- to fine-grained. Near the base, the rock is silty but becomes coarser grained upward. It contains a few scattered fossils, mostly sharks' teeth and fish scales. Glauconite was recognized only in the top 25-foot-thick massive sandstone in the Willow Creek measured section. The lower, thinner bedded sandstones at both Continental Divide (fig. 6) and Willow Creek sections contain a higher proportion of quartz plus chert (conversely less feldspar) than the upper, more massive sandstones. The unit thins from about 110 feet at Continental Divide section to about 100 feet at Willow Creek section (fig. 7) to less than 50 feet at Rabbit Peak. In addition, the massive sandstones break up with shale partings so that part of the thinning is the lensing out of basal sandstones into shales, which are thus dropped from the Mesaverde Formation.

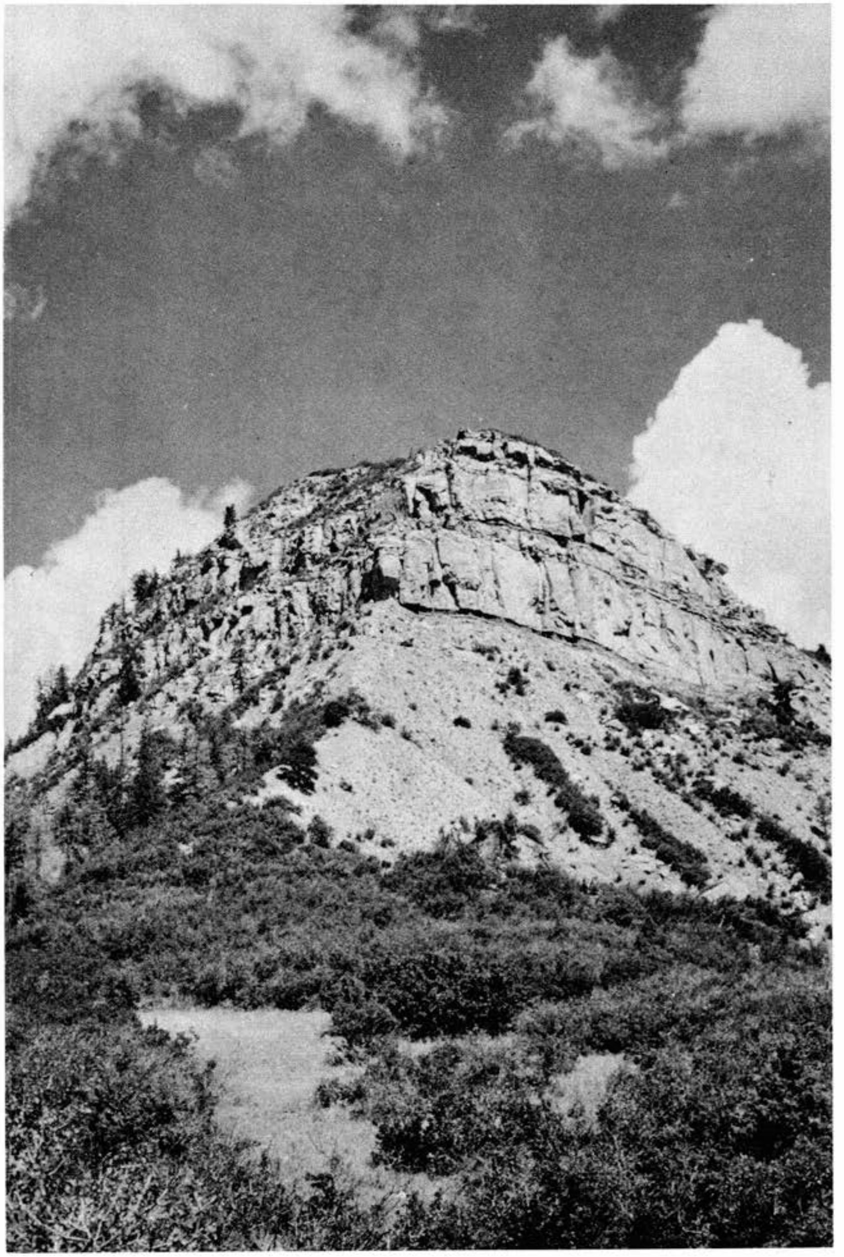


Figure 6
VIEW TO NORTH AT MESAVERDE GROUP OF CONTINENTAL DIVIDE MEASURED SECTION
Compare with graphic log of Figure 5. Base of section near top of slope cover.

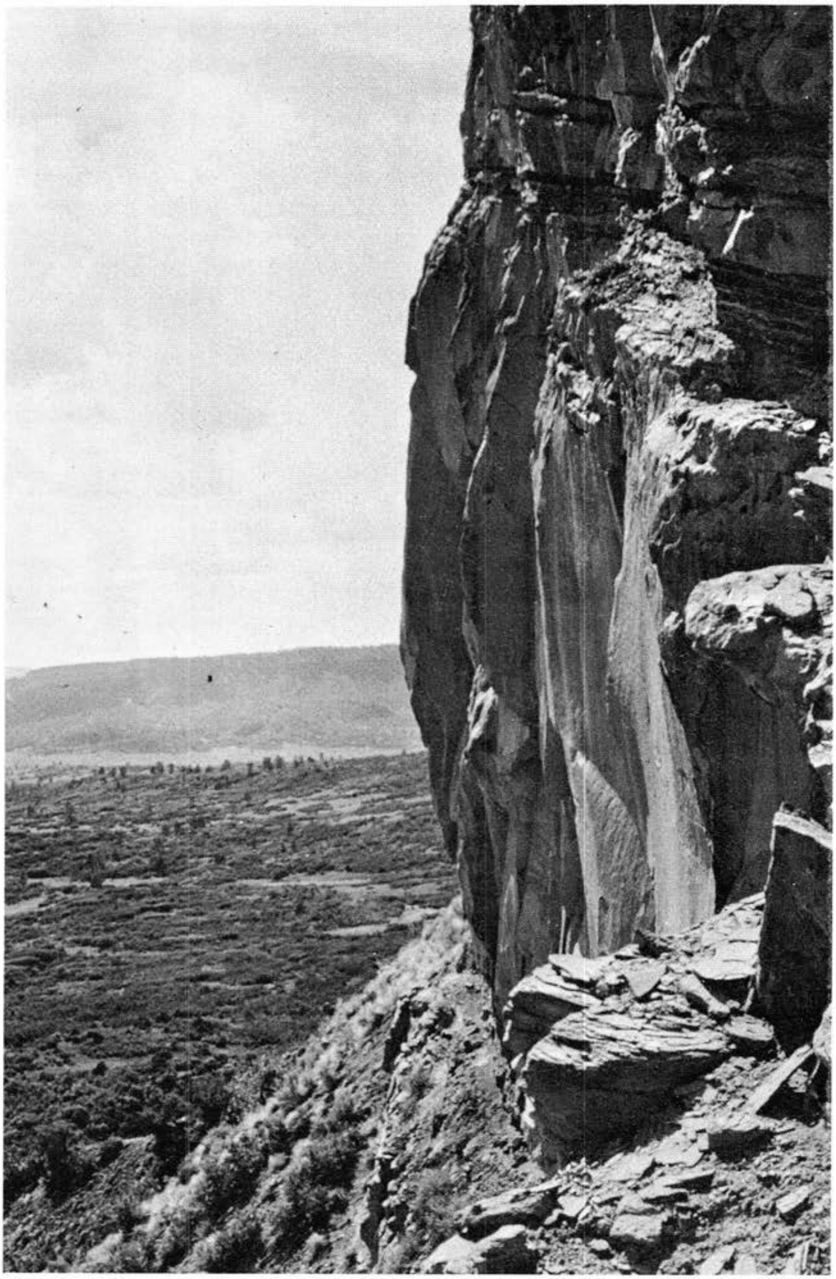


Figure 7
VIEW TO SOUTHWEST ALONG LOWEST SANDSTONES OF MESAVERDE GROUP AT WILLOW CREEK MEASURED SECTION

Near the middle of the Mesaverde is a shale unit, generally 10 to 15 feet thick. Because of covered intervals, it is not known whether this shale is continuous over the 5 miles between the Continental Divide and Willow Creek sections (fig. 8) or whether it continues eastward another 3 miles to Rabbit Peak. Because all other units can be demonstrated to be lenticular, it seems reasonable that this shale interval is also lenticular; it is easily spotted because it lies near the middle of the cliff. At Willow Creek section, a 5-foot-thick shale unit in the lower sandstone wedges out in less than 200 feet in a belt of continuous exposure.

The shale unit ("main shale break," Appendix A) at each measured section has uniform lithologic features, probably representing the same environment at each locality. The unit as a whole is medium-to dark-gray, parallel-bedded, alternately shaly siltstone and silty shale. The beds measure 1 to 2 inches thick, but locally siltstone lenses attain a thickness of 6 to 8 inches. Plant fragments, coal fragments, and fish scales abound throughout. Resin drops V_8 inch in diameter are present. On bedding and joint surfaces, tabular selenite crystals occur commonly with "fish-tail" twinning. Large septarian, unfossiliferous, calcareous concretions, 1 to 3 feet in diameter, occur at the contact with the overlying sandstone member. Bedding goes around the concretions and the shale is compressed under the larger ones.

The upper sandstones (beds above the "main shale break," Appendix A) are dark yellowish brown to moderate yellowish orange, massive, parallel and cross-bedded, calcite- and iron-cemented, and fine- to very fine-grained, with silt and shale partings or in thin beds. The beds become thinner toward the top of the formation and less tightly cemented. The rock contains pelecypod shells, casts, and internal molds, sharks' teeth, and fish scales, most abundant in the channel fills (?) described above. Hematite and glauconite are abundant. The latter is so abundant, especially in the upper part, that the rock has a mottled appearance. Measured thicknesses range from 155 feet to 110 feet, west to east. At Rabbit Peak, 60 feet are present under a terrace-gravel cap; how much has been removed by erosion is unknown although an eastward thinning is recognizable.

Thinsection studies of samples (table 1) from the Continental Divide and Willow Creek sections show that the sandstones have a marked similarity laterally and vertically. This is graphically illustrated in the triangular diagram of Figure 9. The thinsection numbers are shown in stratigraphic position on the profile log, shown in Figure 5. The thinsection descriptions by Longgood are also appended. The only significant mineralogic variation observed is the lesser amount of feldspar in the lowest and highest samples than in the remainder of the formation. Conley recognized the same relation at the Chromo anticline, just north of the Chama quadrangle.

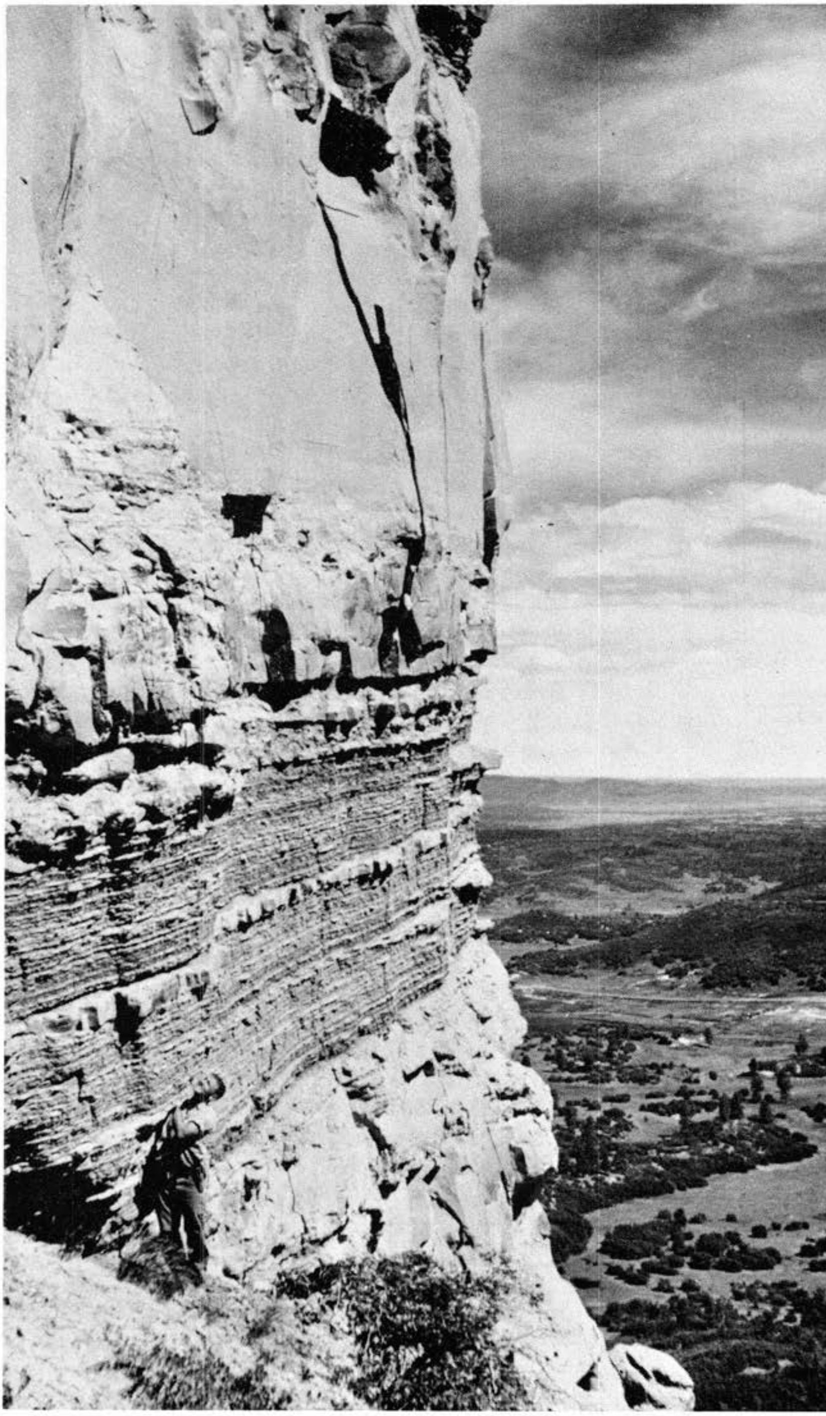


Figure 8

View to southeast along main shale break of Mesaverde Group at Willow Creek measured section

Units 12 to 15 of Figure 5 visible in this photo.

Differences in the two sandstone members were found at each measured section, but they were not consistent between the two locations. At the Continental Divide section, leucoxene is very abundant below

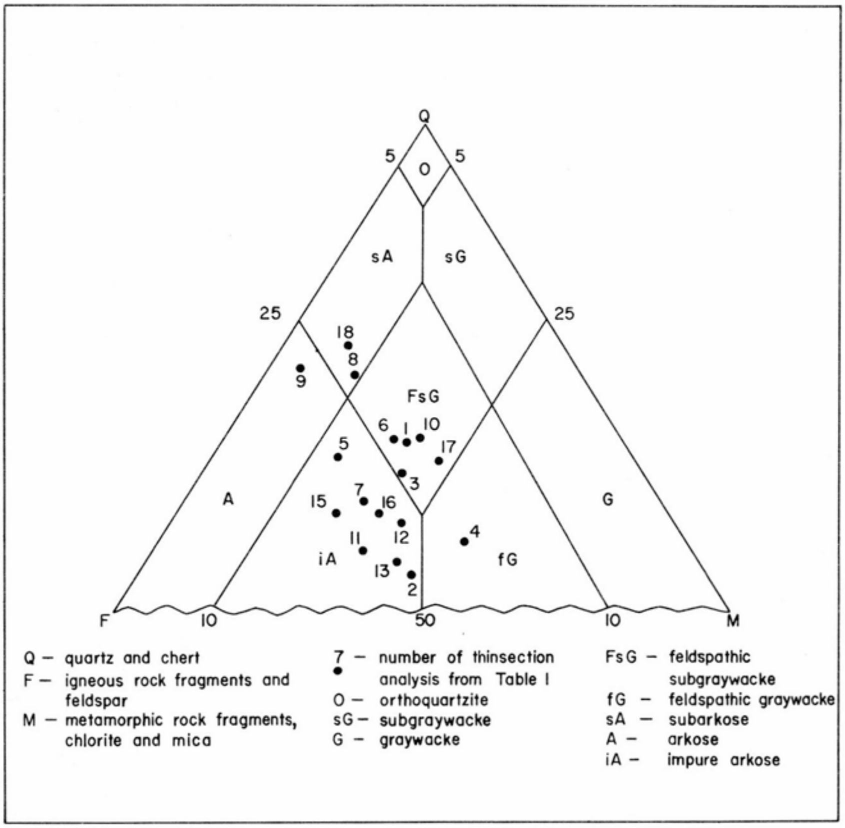


Figure 9

DIAGRAM SHOWING CLASSIFICATION OF MESAVERDE ROCKS TABULATED IN TABLE 1 AND SHOWN IN FIGURE 5

The relative per cent of each pole fraction is based on the assumption that the sand fraction comprises 100 per cent of the rock.

the main shale break but rare above. At the Willow Creek section, zircon is much more abundant above the main shale break; mica, below. Quartz with rounded overgrowths is most prominent below the main shale break at Continental Divide and above the main shale break at Willow Creek.

A typical specimen of the Mesaverde as seen in thinsection is fine-grained rock composed of two or more types of quartz, potash

TABLE 1. MINERAL CONTENT OF THINSECTIONS SHOWN IN FIGURES 5 AND 9

THIN-SECTION NUMBER	IGNEOUS QUARTZ IGN. ROCK FRAGS. (%)	METAMORPHIC QUARTZ, META. ROCK FRAGS. (%)	CHERT (%)	FRESH FELDSPAR (%)	ALTERED FELDSPAR ALTERATION PROD. (%)	CEMENT (%)	†HEAVY MINERALS (%)	GLAUCONITE (%)	MISCELLANEOUS
				CONTINENTAL DIVIDE MEASURED SECTION					
8	45	7	3	6	13 *sericite kaolinite	11 hematite	9 *zircon hematite garnet leucoxene tourmaline chlorite	6 fresh and slightly altered	Trace of agate Rounded limestone grains
7	41	11	4	5	17 *sericite kaolinite	12 hematite	3 *hematite chlorite	7 fresh	Trace of mica
6	40	12	4	6	11 sericite	15 calcite	*hematite *zircon tourmaline chlorite apatite	6 fresh and altered	Two varieties of glauconite, dark and light green
5	25	9	1	9	11 sericite	32 calcite	10 *hematite *zircon leucoxene chlorite	3 fresh	Many inclusions, chiefly zircon, in quartz

4	35	29	7	4	14 sericite	4 *sericite hematite	4 *chlorite zircon ilmenite apatite	1 altered	2 % biotite
3	48	14	14	7	11 sericite	4 calcite	3 *hematite *leucoxene chlorite tourmaline	x	Calcite cement attacked by dolomite Rounded overgrowths on some quartz
2	36	23	4	8	17 sericite	6 *sericite kaolinite	7 *leucoxene *zircon garnet chlorite apatite	x	Rounded overgrowths on some quartz Trace of mica Trace of limestone fragments
1	34	14	3	4	12 *kaolinite sericite	25 calcite	9 *leucoxene *zircon hematite garnet chlorite tourmaline	x	Trace of mica Few rounded overgrowths on quartz
				Willow Creek Measured Section					
18	35	3	2	7	11 sericite	21 calcite	12 *hematite *zircon garnet chlorite ilmenite apatite	8 fresh	Rounded overgrowths on some quartz 3% biotite, imbedded in hematite blebs 5% rounded, iron-stained limestone fragments

TABLE 1. MINERAL CONTENT OF THINSECTIONS SHOWN IN FIGURES 5 AND 9 (cont)

THIN-SECTION NUMBER	IGNEOUS QUARTZ IGN. ROCK FRAGS. (%)	METAMORPHIC QUARTZ, META. ROCK FRAGS. (%)	CHERT (%)	FRESH FELDSPAR (%)	ALTERED FELDSPAR ALTERATION PROD. (%)	CEMENT (%)	†HEAVY MINERALS (%)	GLAUCONITE (%)	MISCELLANEOUS
				CONTINENTAL DIVIDE MEASURED SECTION					
17	37	18	tr.	7	8 sericite	15 *calcite limonite	4 *zircon *hematite magnetite garnet	11 fresh	Rounded overgrowths on some quartz 3% rounded, iron-stained limestone fragments
16	33	16	tr.	9	19 *sericite kaolinite	7 *calcite limonite	6 *zircon *hematite ilmenite chlorite magnetite	7 fresh and altered	Trace of mica 2% rounded, iron-stained limestone fragments
15	42	14	4	5	26 sericite	3 kaolinite	3 *hematite zircon leucoxene chlorite	3 slightly altered	Rounded overgrowths on some quartz Trace of mica Two varieties glauconite, dark and light green
14	36	19	2	5	11 sericite	24 calcite	3 *pyrite zircon chlorite leucoxene	x	Pyrite occurs in aggregates of perfect hexagon and pyritohedron crystals

13	35	22	tr.	5	21 kaolinite	8 *calcite clay	8 *ilmenite *leucoxene chlorite hematite zircon garnet	1 altered	Few rounded over-growths on quartz Trace of mica
12	36	23	11	9	17 *sericite	3 *calcite chert	1 *hematite chlorite leucoxene	tr.	Chert cement in one part of slide Rounded overgrowths on some quartz Trace of mica
11	40	16	2	6	23 *sericite kaolinite	5 *opal calcite	6 *zircon hematite tourmaline chlorite	x	Opal cement replacing calcite 2% mica Few limestone fragments
10	42	15	1	6	10 sericite	20 *clay limonite calcite	6 *hematite *chlorite zircon pyrite sphene	x	Trace of biotite Large rounded limestone fragments
9	44	8	5	8	16 sericite	8 hematite	8 *hematite zircon leucoxene ilmenite chlorite garnet	x	3% mica

† Heavy minerals listed in order of decreasing abundance
* in greatest abundance
tr.: trace, less than one per cent
x: not present

feldspar, muscovite, biotite, and iron oxides. It also contains lesser amounts of zircon, apatite, tourmaline, magnetite, ilmenite, limestone fragments, chert, and hematite. This suite of minerals suggests an igneous-metamorphic, as well as an older sedimentary, source.

The presence of glauconite indicates a marine environment for much of the Mesaverde in the northwestern Chama quadrangle. Conley found glauconite in all sandstone beds at the Chromo anticline a few miles to the north. His section is nearly 50 per cent shale and probably represents an area farther seaward than the Chama quadrangle outcrops. These environments probably include all the transitional complex between coastal continental and shallow, nearshore marine.

Both upper and lower contacts of the Mesaverde are gradational and arbitrary. Their positions move stratigraphically, depending on location, because the highest and lowest laterally persistent sandstones are the bounding beds by definition. What is meant by "laterally persistent" (in this report) is that the sandstone continues for the length of the outcrop. In addition, it is probably more massive-bedded and thicker than the immediately underlying or overlying sandstones and may be coarser grained. Although gradational, the shale-sandstone or sandstone-shale transition is a relatively easy contact to map, particularly because of the cliff-forming nature of the sandstones.

LEWIS SHALE

A maximum thickness of about 600 feet of Lewis Shale is preserved around Chromo Mountain in the northwestern part of the Chama quadrangle. Much of the area underlain by the Lewis has been and is subject to conditions conducive to mass movements; it is therefore mapped as Quaternary landslide.

Where exposed, the Lewis is very similar to the upper part of the underlying Upper Mancos Undifferentiated. It is a fissile, dark-gray, parallel-bedded shale containing scattered marine fossils and abundant septarian calcareous concretions. Selenite crystals 1/8 to 1/4 inch thick are found in many places along bedding and joint planes. Bedding passes around the concretions. Oblate and light yellowish-brown, the concretions range from 3 to 8 feet across. Mostly they occur randomly in the shale, but at a few localities they appear to be grouped along particular horizons. The septa are light-brown, "dogtooth spar" calcite crystals. In general, the concretions are unfossiliferous, but some contain plant fragments, broken shells, and rounded *Inoceramus* prisms typical of those in the Mancos Shale.

Gradational with the underlying Mesaverde Group, the contact is chosen at the top of the highest massive continuous sandstone. A few sandstone beds typically occur above this horizon, but they become thinner and discontinuous upward into the section.

Erosion has removed the upper part of the Lewis Shale as well as any younger latest Cretaceous or Earliest Tertiary units that may have been deposited prior to the deposition of the post-Laramide Eocene(?) Blanco Basin Formation. Dane (1948) reported a thickness of about 2000 feet west of the Chama quadrangle where the Lewis is overlain by the Upper Cretaceous Pictured Cliffs Sandstone.

TERTIARY ROCKS

Two formations of known Tertiary age crop out in the Chama quadrangle, Blanco Basin and Conejos, in ascending order. Tertiary (?) terrace deposits also are described in this report. The Blanco Basin Formation rests with an angular unconformity across older rock units. The Conejos Quartz Latite is the basal formation of the extensive Tertiary volcanic and clastic sequence found in the adjacent Brazos Peak quadrangle.

BLANCO BASIN FORMATION

Cross and Larsen applied the name *Blanco Basin Formation* to arkosic conglomerate, sandstone, and shale that form the basal Tertiary beds along the west front of the southeastern San Juan Mountains from near Pagosa Springs, Colorado, southeast to Chama.

The formation is named from Blanco Basin, Summitville quadrangle, Colorado, but the only measured section given is near the northeasternmost corner of the Chama quadrangle. The formation was recognized as being post-Laramide and pre-Conejos Quartz Latite and assigned an Oligocene (?) age. In addition, Cross and Larsen correlated it with the Telluride Conglomerate of the western San Juan Mountains because of the lithologic and stratigraphic similarity of the two formations. Van Houten (1957) proposed an upper Paleocene and lower Eocene age for the Telluride Conglomerate on evidence that the rocks underlying it are lower Paleocene instead of Eocene, as had been believed earlier. Van Houten further stated that the Blanco Basin Formation and the Telluride Conglomerate are probably coarse arkosic facies of the San Jose Formation of the San Juan Basin. The San Jose Formation west of the Chama quadrangle constitutes the bulk of the Wasatch, as mapped by Dane (1948). Petrographic data described below suggest that the Blanco Basin and (at least) the lower Wasatch are lithologically identical and thus probable correlatives, a fact which supports Van Houten's age assignment.

In the Brazos Peak quadrangle, north of Cañones Box, the Blanco Basin Formation appears to interfinger with the El Rito Formation.

The El Rito is the basal Tertiary unit of the southern Tusas Mountains. Kelley and Silver (1952) suggested on a correlation chart that the El Rito and Galisteo Formations are lateral equivalents and that they are the time equivalents of the bulk of the San Jose Formation, mainly Eocene.

For reasons detailed below, an Eocene (?) age is assigned to the Blanco Basin Formation for the Chama quadrangle.

The Blanco Basin Formation consists of 250 to 350 feet of well-indurated, cliff-forming, arkosic conglomerate interbedded with arkosic sandstone and siltstone. The siltstone and the matrix of the coarser beds range in color from light gray to pale red-purple, with the red tones being dominant. Sorting is poor in the sandstone and conglomerate; a wide range of angular to subangular mineral and rock fragments constitute the clasts; well-rounded grains are also present. The siltstones are well sorted. Clay is the main cement, but locally the conglomerate beds may also have calcite cement. Beds range from less than 1 foot to 25 feet in thickness. Bedding is marked by changes in grain size, such as cobble conglomerate on siltstone, which reflect sedimentation units carried by transporting mediums of differing competency. Occasionally smooth, well-marked, parallel-bedding planes are found, although scour is common, so irregular bedding planes are the rule.

Pink granite, granitic gneiss, mica schist, and mica gneiss are the larger clasts in the conglomerate. Quartz, feldspar, and clay constitute the bulk of the remainder of the smaller clasts and matrix material. Both quartz and feldspar grains are angular to subangular and all sizes from granule to silt. About one per cent of the quartz grains is well rounded; they probably derived from pre-existing sedimentary rocks. Microcline is the dominant feldspar with oligoclase less abundant; both are altered predominantly to kaolin; chloritization is more usual in the conglomerate clasts. Hematite, a common cement, is concentrated in and near altered ferromagnesian minerals. Volcanic rock fragments were not found. The conglomerate fragments clearly show a metamorphic-igneous complex as the principal source of detritus for the formation. The well-rounded quartz grains suggest a reworking of older sandstone units; however, some of the quartz under the microscope is composed of composite grains that are highly strained, identical in appearance to that in the Precambrian quartzite or in the El Rito Formation. The siltstones may also be partly derived from earlier red-bed units such as the Morrison and Chinle, units which the Blanco Basin Formation now rests on in an angular relationship.

The angularity, poor sorting, and bedding characteristics suggest short-distance transport under conditions typical of alluvial fan deposition. The term "fanglomerate" could readily be applied to these rocks. Outcrops of igneous and metamorphic rocks east and north of the Chama quadrangle show the same variety of rock and mineral types as those found in the clasts of the Blanco Basin Formation. A source in this direction is the most probable.

Petrographic comparison by W. H. Harris (written communication, 1960) of samples collected by Muehlberger in outcrops along New Mexico Highway 17, south of Dulce, show that the Wasatch of Dane (1948) is identical in mineralogy to but finer grained than the Blanco Basin Formation. The principal difference is that the Wasatch samples are calcite-cemented or have a recrystallized chlorite matrix (finer comminution of chlorite schist grains?), whereas the Blanco Basin has a detrital kaolin matrix. Authigenic kaolin cement is present in both formations. Packing is looser in all Blanco Basin thinsections; hence, a higher clay percentage. Only the coarser grained Wasatch rocks were sampled, so no comparisons are available for the silt or finer grained units. Dane (1946) described the basal part of the Wasatch north of T. 29 N., R. 2 W. (samples for thinsection study were from T. 30 N., **R.** 2 W.), as "white and buff, pebbly arkose and conglomerate."

Dane also indicated a northeasterly source for the Wasatch, as the conglomerate beds thin southwestward into a sequence of shales. Further, he stated that "the prevailingly arkosic and granitic composition of the Wasatch, as contrasted with the Animas, reflects the exposure of the plutonic core of the mountains to erosion." The generally coarser grains and identical relationships recognized in the Blanco Basin Formation lead to the conclusion that the formation was deposited near the mountain front as an alluvial fan (plain) sequence and the Wasatch of Dane (1946, 1948) represents the floodplain deposits of the same sedimentary cycle. The concept of a pediment surface truncating Laramide structures in the Chama quadrangle and elsewhere along the mountain front suggests that deposition began to the west in the San Juan Basin. Progressive burial of the toe of the pediment surface as the Wasatch basins were filled led to the deposition of what is now known as the Blanco Basin Formation late in Wasatch time. The later erosion of the connecting beds across the Chama Basin prohibits any certainty of correlation.

No vertebrate remains have been found in the lower part of the Wasatch in the area sampled; thus is it not known whether the Wasatch here extends below the Eocene to include beds of Paleocene age (the Tiffany fauna, recognized along the northwestern San Juan Basin). No fossils have yet been found in the Blanco Basin Formation. Thus the Blanco Basin Formation is assigned to the Eocene (?), with the question mark indicating uncertainty as to whether it might not include beds of Oligocene age as well.

The maximum measured thickness is 388 feet; another section with an unknown amount covered at the base is 268 feet thick; graphically, the total maximum thickness in the Chama quadrangle is about 400 feet. Larsen and Cross reported a thickness of 575 feet for a measured section just north of the Chama quadrangle.

CONE JOS QUARTZ LATITE

The Conejos Quartz Latite is the basal formation of the Potosi Volcanic Series (Larsen and Cross). Only the lowest two, Conejos Quartz Latite and Treasure Mountain Rhyolite, of the six formations included in the series extend into New Mexico. Both formations crop out extensively in the Brazos Peak quadrangle; only the Conejos extends westward into the Chama quadrangle. Andesite breccia caps Chromo Mountain near the northwestern corner of the quadrangle and is included with the Conejos because of petrographic similarities.

The Conejos, one of the most widespread volcanic formations of the San Juan Mountains, covers 10,000 square miles and averages 1600 feet thick (Larsen and Cross). The formation consists of quartz latite tuff, breccia, agglomerate, flow breccia, sandstone, conglomerate, and flows.

In the Chama quadrangle, the Conejos consists of two recognizable subdivisions (not separated on the map), a lower slope-forming unit of tuff and conglomerate and an upper, blocky, cliff-forming unit of flow breccia and agglomerate.

The tuff of the lower unit is light orange, aphanitic, and altered to clay. Subangular to well-rounded clasts of granitic and metamorphic rocks in a tuff matrix constitute the loosely consolidated conglomerate of the lower unit. Clasts of volcanic rocks are found near the eastern margin of the quadrangle. No measurements of thickness were made but graphical solutions indicate a thickness of 150 to 250 feet, with the thickest section preserved on the ridge north of Chama.

The upper unit consists of poorly sorted flow breccia and agglomerate. The clasts are angular fragments of dark purplish-brown, porphyritic-aphanitic quartz latite ranging in size from very fine-grained sand to cobbles. Some fragments measure several feet across. The phenocrysts, 5 to 20 per cent of the rock, are tabular plagioclase, biotite, hornblende, and pyroxene, in decreasing abundance. This unit dominates the ridge east of Chama, where it is about 500 feet thick. It is virtually absent over most of the ridge north of Chama, which, because of its resistance to erosion, suggests that it was never deposited there or that, at best, only the feather edge of the breccia deposit covered the ridge.

Longgood indicated that the andesite porphyry breccia of Chromo Mountain is a volcanic neck with associated flow remnants. Two stages of eruption were distinguished by color differences and a narrow "baked" zone along the contact. The older outer core breccia is an andesite porphyry containing phenocrysts of zoned plagioclase, potash feldspar, hypersthene, and augite with accessory magnetite and zircon. All minerals are aligned, the flow structure being best shown by the feldspar crystals. Abundant basaltic hornblende, partly chloritized, is present in one thinsection. The younger inner core breccia consists of fragments of the outer core and andesite clasts with phenocrysts composed of zoned plagioclase, hypersthene, and augite with accessory zircon, magnetite, and apatite. Those rocks resemble the Conejos breccia units found in and east of Chama quadrangle and are thus included here with the Conejos.

Dane (1948) reported isolated andesite blocks at several localities on the Mesaverde-capped ridges west and southwest of Chrorno Mountain. Rounded quartzite boulders and other metamorphic rocks are associated with the andesite blocks at localities most distant from Chromo Mountain. The present elevations of these blocks range from 8700 to 7600 feet—clearly all have been let down to their present positions. Dane postulated a land surface at or not far above the level of the highest block that was "probably of late Pliocene age." Instead of the explosive emplacement from Chromo Mountain postulated by Dane, a fluvial mechanism seems more probable. Blocks of Conejos breccia are scattered over the Chama quadrangle and rounded quartzite cobbles are nearly ubiquitous. Although probably lag gravel deposits from an earlier surface that extended westward from the crest of the range, they may be outlying remnants of older and higher erosion surfaces of unknown affiinities but clearly earlier than the remnants of Tertiary(?) terrace deposits preserved in the Chama quadrangle.

The contact between the Conejos and the underlying Blanco Basin Formation was not observed. Evidence of the drastic change in cementation and source area indicates that it is at least a disconformity and possibly an angular unconformity. Larsen and Cross assigned a Miocene age to the Conejos Quartz Latite. If the Eocene age postulated here for the Blanco Basin Formation is correct, then a considerable span of time is not recorded in the rock between the deposition of the two formations. The source of some of the granitic and metamorphic clasts of the lower unit of the Conejos could well be the Blanco Basin Formation; the other clasts probably were derived from Precambrian outcrops east and north of the Chama quadrangle. Topography carved into Precambrian rocks and covered principally by the Conejos, as well as younger formations, has been re-exhumed in the Brazos Peak quadrangle (Butler, 1946; Muehlberger, 1967).

TERTIARY (?) TERRACE DEPOSITS

Gravels capping ridges 400 to 600 feet above modern drainage levels and well above the terrace deposits assigned to the glacial events are here classified as Tertiary(?) terrace deposits.

The gravels contain particles ranging in size from large boulders to coarse sand. Parent rocks represented in these deposits include, in decreasing order of abundance, volcanics (chiefly Conejos breccia), quartzite, schist, Blanco Basin Formation, and Mesaverde Group sandstone. The quartzite clasts are well rounded, suggesting an earlier stage of rounding (possibly the El Rito Formation is the parent source which now is exposed on the top of the mountain front south from Cañones Creek). Largest and least rounded are the quartz latite breccia fragments (Conejos source), some of which reach 4 feet in diameter, although they average 10 to 12 inches. These breccia fragments comprise 75 per cent of the gravels.

Two distinct levels can be recognized. Those north and west of Rabbit Peak exceed 8700 feet and might well be remnants of one period of erosion. Those in the central part of the quadrangle rise less than 8200 feet in elevation and probably comprise a younger erosion surface, because if projected northward, their surface of deposition would lie several hundred feet below the probable grade of the streams represented by the northern remnants. The southwest and south slopes of all remnants suggest an ancestral Rio Chama system draining southward to join the Rio Grande. Rio Chama has cut canyons through the resistant Dakota Formation south of the Chama quadrangle. Along the southern rim of the Chama basin, 25 miles south of the quadrangle, the top of the Dakota Formation is about 8200 feet elevation in the area now occupied by the Rio Chama Canyon. This might well have been a temporary base level to southward-draining streams and could be the base level to which the higher drainage systems are related. Once the Rio Chama cut down to the level of the Dakota Formation at the southern rim, it continued trenching upstream into the Dakota.

A closer, local base level affecting the Rio Chama and Willow Creek gradients was reached when the Rio Chama cut to the top of the Dakota at about 7550 feet elevation on the North El Vado dome, five miles south of the Chama quadrangle. The lower set of gravel caps could well relate to this event.

Correlation of the Tertiary(?) gravels of the Chama quadrangle with an ancestral Rio Chama implies a connection with the Rio Grande and the probability of an integrated Rio Grande drainage to the Gulf of Mexico. When this system developed is not certain, although the evidence of Strain (1959) suggested that the Rio Grande below El Paso, Texas, is at least no older than Blancan, a vertebrate stage straddling the Pliocene—Pleistocene boundary. This suggests that the Pliocene age here assigned to the Tertiary(?) terrace deposits is in error and that an age assignment in the early Pleistocene would be a more reasonable postulate, and thus these might be glacial deposits correlatable with other pre-Wisconsin tills recognized in the region (Richmond, 1957, 1962).

Whether these deposits might correlate with the Los Pinos Gravels, extensively developed on the southeast flank of the San Juan Mountains, is also unknown. According to Atwood and Mather, the Los Pinos Gravels accumulated on a broad erosion surface, the San Juan peneplain. Possibly the residual boulders west and southeast of Chromo Peak ascribed by Dane (1948) to deposits from the explosive eruption of Chromo Peak are lag remnants of the Los Pinos Gravels surface.

QUATERNARY ROCKS

Quaternary deposits form an extensive veneer, in places completely obscuring the underlying bedrock. Three major sequences of terrace deposits, each correlated with a glacial period; moraines where still recognizable as such; landslides commonly composed of glacial detritus; and recent alluvium have been delineated on the map. In addition, lag materials veneer much of the remainder of the quadrangle but are not shown separately on the map. The distribution of Quaternary units is approximately correct, but the age assignments are preliminary. Careful geomorphologic mapping is needed throughout this region before events can be properly correlated to the recognized sequences in the San Juan Mountains.

TERRACE DEPOSITS

Terrace surfaces were mapped throughout the quadrangle. Because of their steep margins, the mapped boundary also delineates the terrace deposit under the surface. Along the Rio Chama, eleven different terrace levels can be distinguished and mapped. Several of these are local subdivisions for the sequence east of Chama. Based on elevations above present stream grade, the terraces fall into three distinct groups, here correlated directly with the named glacial epochs of the San Juan Mountains, from oldest to youngest: Cerro, Durango, and Wisconsin (Atwood and Mather; Richmond, 1962). Whether these correlations and age assignments are valid is not certain.

The oldest group, Qtz, Qty, Qtx, listed according to decreasing elevation above present stream grade (therefore also decreasing age), is correlated as Cerro-age glacial outwash sequences; some may be kame terraces. Generally 250 to 350 feet above present streams, the gravel deposits range from 5 to 60 feet thick. Interesting drainage changes were observed along the Continental Divide west of Chama, where the eastward-sloping surface, underlain by Qtx at Center triangulation point (fig. 10), clearly continued westward for an unknown distance past the present-day Continental Divide in what now is part of the Rio Amargo, a tributary of the Navajo River. Atwood and Mather showed Cerro-age terminal moraines near the New Mexico—Colorado line in

Rio Chamita. They believed these moraines were formed along an ancestral Navajo River to the north that drained down the Rio Chamita to the Rio Chama. In post-Cerro and pre-Durango time, the headwater region was captured by the present Navajo River and thus diverted from the Rio Chama drainage. This transferred a 75-square-mile area west across the Continental Divide.

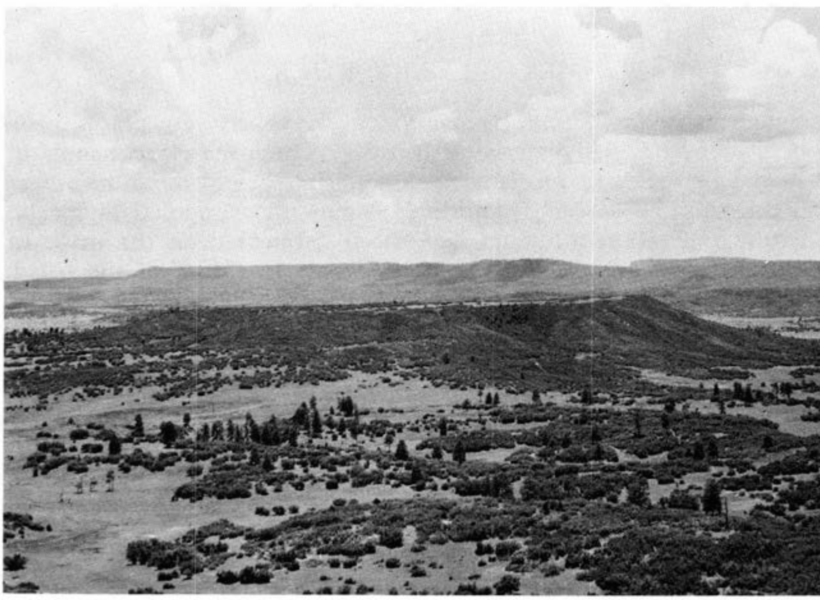


Figure 10

VIEW TO SOUTHWEST ACROSS CERRO-AGE TERRACE CAP ON CENTER MESA

Continental Divide comes toward viewer from right end of mesa; illustrates the eastward migration of the Continental Divide in this region.

The high terrace deposits near the mouth of the Brazos Box at the southeast edge of the Chama quadrangle are here included in Cerro-age deposits because of relative topographic positions, although it can be argued with equal force that they are actually remnants of the Tertiary(?) terrace deposits.

The intermediate group, Qtm, Qtl, Qtk, listed in decreasing elevation above present stream grade, is correlated as Durango-age glacial outwash sequences and lies from 50 to 250 feet, depending on downstream position, above present grade. The older two form extensive slope veneers east of the Rio Chama. The youngest, Qtk, forms an extensive bench on which U.S. Highway 84 rests for long stretches.

The contrast between the scattered remnants of Qtl and Qtm, south of Chama along the east side of the Rio Chama, and the continuous surface of Qtk makes it seem that they should not be grouped as part of one glacial stage. The sequence of terraces from the mouth of Little Willow Creek and its probable correlation with these deposits is the reason for including Qtk with Durango- rather than Wisconsin-age terrace deposits. Basalt covers a Durango terrace near Tierra Amarilla just south of the map area. The basalt comes from the cones straddling the middle Brazos Box (Doney).

Another shift of the Continental Divide, probably minor, took place after the deposition of Qtl, west of Chama. The minor tributary, now draining west from the canyon east of the spur labeled 8687 (approximately lat. 36°56', long. 106°43'), appears to have been the headwaters from the Qtl remnant now forming the Continental Divide two miles north of U.S. Highway 84. The steep headwater gradients along its west side suggest that the Divide continues to migrate eastward.

The youngest group, Qtg, Qtc, Qtb, less than 40 feet above present grade, is listed in decreasing order of age. Qtb and Qtc are recognized as local divisions only near Chama. Qtg, on which the town of Chama rests, is extensively developed and, near the southern margin of the quadrangle, is less than 10 feet above present grade. The gravel deposit measures less than 35 feet thick under Chama, according to data from water wells in the town.

MORAINES

Moraines are mapped only where their positions and topographic shapes are unquestioned. An unknown amount of morainic material whose upper surface has been planed off by glacial outwash is included in terrace deposits. Other morainic material involves extensive areas of landsliding and is included under that map unit.

The best developed system of moraines (lateral, terminal, and recessional) appears in the northeast corner of the map area, in the wedge between the Chama River and Wolf Creek. Here a hummocky, bouldery, lateral moraine towers several hundred feet above the ground moraine of Wolf Creek. It is traversed by both the Denver and Rio Grande Western Railroad and New Mexico Highway 19. At least five distinct remnants of recessional moraines are outlined. Because of their excellent preservations, a Wisconsin age is assigned to them. Atwood and Mather also assigned them to a Wisconsin age; they appear to fit terrace deposit Qtg best. Terrace deposit Qtk remnants east and northeast of Chama appear to require an ice-front contact on their west side, which would mean that Chama had been under ice at that time, thus representing Durango glacial time. Small morainal belts, mapped near the headwaters of the Rio Chamita and upper Willow Creek, are probably Wisconsin in age because of their excellent preservation.

LANDSLIDE DEPOSITS

Landslides are common and extensive in the mountainous parts of the quadrangle. Areas underlain by the Mancos Formation are particularly susceptible to sliding. Parts of these slide masses appear to be still active; the involvement and burial of glacial deposits indicates that their main movement is post-Wisconsin, although they were certainly active during earlier interglacial stages. This continuing capability to slide results in a constant maintenance problem for roads and railroads.

ALLUVIUM

Alluvium is mapped in modern stream bottoms. Its thickness is generally unknown, although it is probably about 30 feet or less. In Willow Creek where the present stage of arroyo cutting exposes the underlying bedrock for long reaches, the alluvial fill is less than 10 feet. The Rio Chama, in general, flows in alluvial materials, although in the Chama reach itself, locally exposed bedrock shows a thickness of alluvium of 20 feet or less.

Structure

The Chama quadrangle occupies the central segment of the narrow, elongate Chama Basin which here is essentially a structural terrace separating the San Juan Basin on the west from the Tusas Mountains on the east (fig. 11). The relatively stable terrace bench (Chama basin,

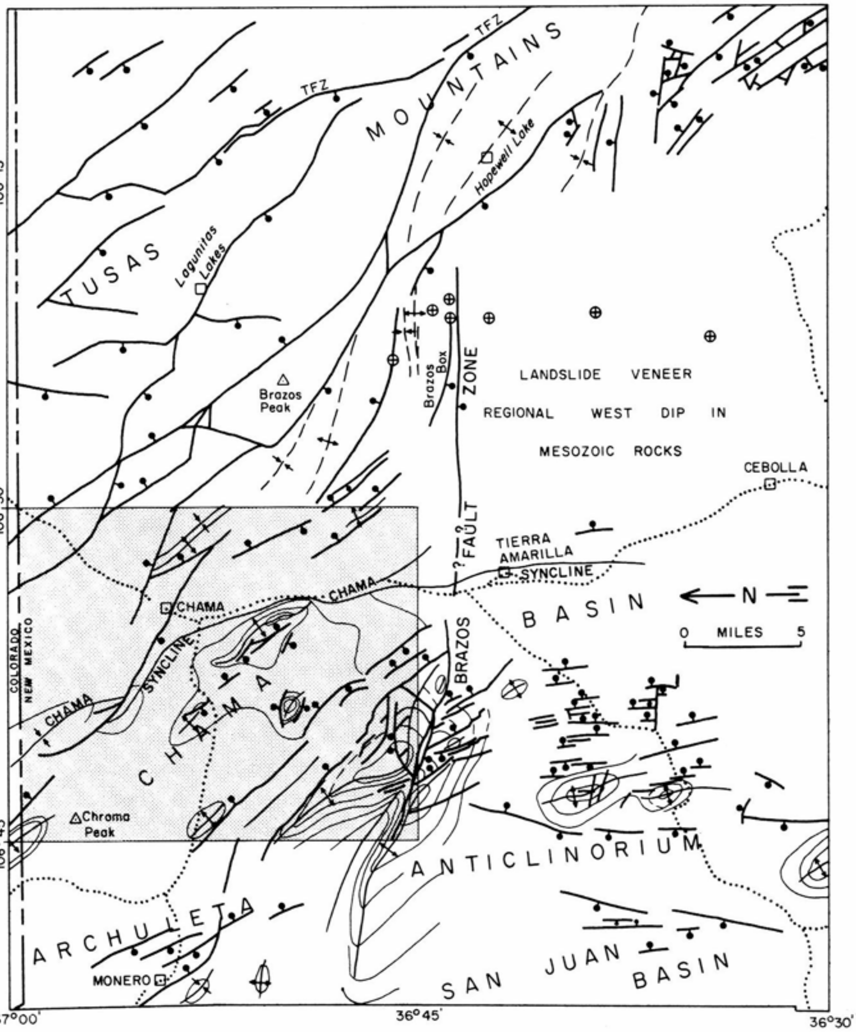


Figure 11

STRUCTURAL FEATURES OF CENTRAL CHAMA PLATFORM AND ADJACENT REGIONS platform, or embayment; see Kelley, 1955, p. 101-103 for all three usages) has been faulted and folded but on a very modest scale compared with the thousands of feet of displacement on the flanking monoclinal structures. The Brazos fault zone, a west-trending transverse structure just south of the quadrangle, divides the New Mexico part of the basin into two structurally distinct elements. South of the fault zone, the basin forms a very shallow, broad, north-trending syncline; north of the fault, numerous northwest-trending fault and fold zones transect the nearly flat floor of the basin. This area displays a variety of structural features that are either absent or not recognizable farther north or south. Delineation and description of these structures aid in interpreting structure in the less exposed neighboring regions.

The Chama quadrangle is dominated by northwest-trending folds and faults superimposed on a larger structural terrace, the Chama Basin. Discussion of local structural features progresses from southwest to northeast, followed by a brief structural resume of the Tusas Mountains to the east.

WILLOW CREEK—HORSE LAKE ANTICLINE COMPLEX

The largest anticlinal structures in the Chama Basin lie along its western boundary, which has been named the *Archuleta anticlinorium* in Colorado (Wood, Kelley, and MacAlpin). Without these anticlinal highs, the Chama Basin within this quadrangle more aptly could be called the *Chama platform* or *Chama terrace*. The Archuleta anticlinorium is a complex of folds and faults forming the east margin of the San Juan Basin; elsewhere the basin is rimmed by a monoclinal fold.

In Colorado, the Boone Creek and Chromo anticlines mark the east side of the Archuleta anticlinorium and the Newton Mesa and Montezuma anticlines mark the west side (Wood, Kelley, and MacAlpin). The deep Klutter Mountain syncline separates these belts of anticlines.

In New Mexico, the relations are not so clearly defined. The continuation of the eastern belt of anticlines could be marked by the Dos Lomas anticline, although it is of very minor structural relief and is included here as part of the Chama Basin (fig. 11). The western belt is defined by the fault zone that passes through Lumberton and Monero. In this belt also occur the Monero dome and the Willow Creek anticline. South from the western edge of the Chama quadrangle, the Horse Lake anticline and North El Vado and South El Vado domes mark the belt. Farther south, but offset to the west, are the Gallina and French Mesa anticlines.

Willow Creek and Horse Lake are large, broad anticlines that face each other across a narrow, tightly downfolded and faulted zone (fig. 12). Both anticlines are asymmetrical with their crests immediately adjacent to the downwarp. Both upwarps are about 10 miles long and from 2 to 4 miles wide. Both axial traces change strike at their culminations so that the two traces together have the general shape of an open V, with the angle at the point of closest approach. The sides of the

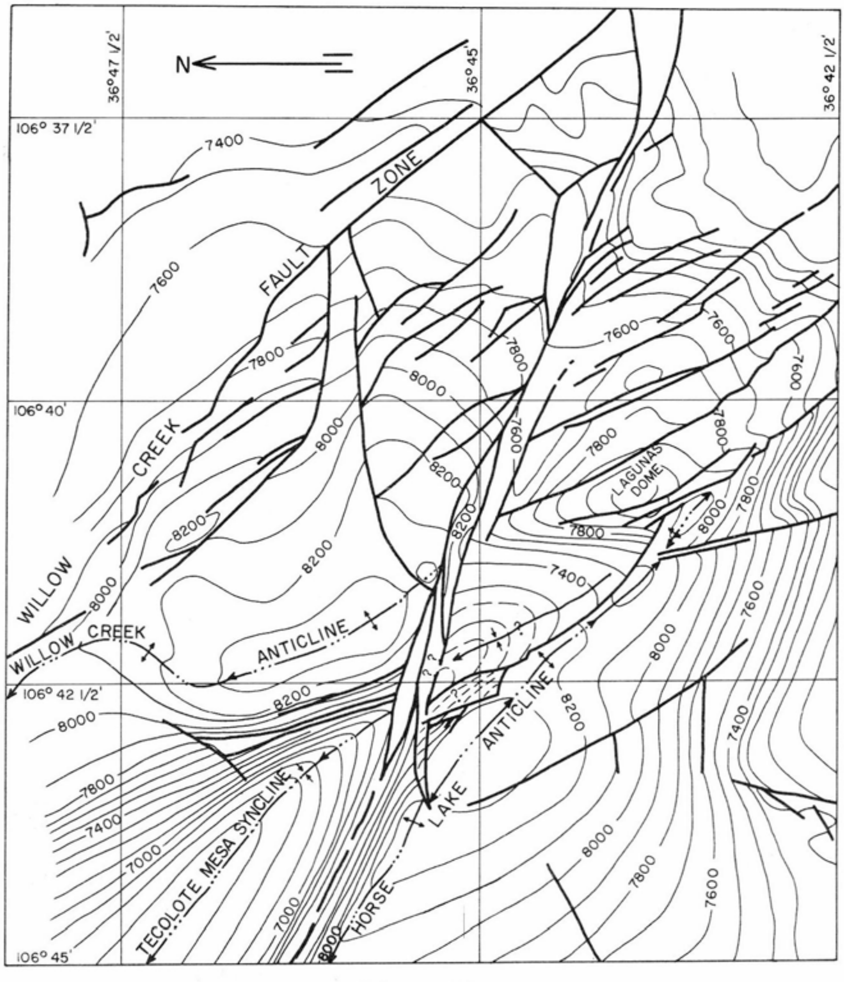


Figure 12

STRUCTURE CONTOUR MAP OF THE WILLOW CREEK AND HORSE LAKE ANTICLINES

Shows the main structural features of the Archuleta anticlinorium in northern New Mexico. The Brazos fault zone is represented by the belt of west-northwest-trending faults near the center of the map. Contours drawn at 100-foot intervals on top of the Greenhorn Limestone Member of the Mancos Formation. (Modified from J. H. Davis (1960) and B. E. St. John (1960))

V, which coincide with the highest parts of the anticlines, are about one mile apart, with 1500 feet of relief inferred in the trough between.

The asymmetrical Lagunas dome, on the east flank of the Horse Lake anticline, is bounded on the west by the syncline that plunges northwest toward the Tecolote Mesa syncline. These two synclines are probably separate and distinct in origin rather than being faulted parts of the same syncline. The shape of the small, unnamed syncline is mostly speculative because of the lack of exposures, except around the south and east edges.

Tecolote Mesa syncline plunges west-northwest to open out west of the quadrangle. The steepest flank lies along the faulted margin against the Willow Creek anticline. Here, as shown in Figure 13, the progressive tightening has caused rupturing of the Dakota Formation and decollement-type thrusting in the steep flank of the fold. Continued tightening caused the Mancos to break across bedding and to foreshorten the exposed section down to the Greenhorn Limestone.

The gentle east flank of the Willow Creek anticline has numerous long faults with small throw. The Willow Creek fault zone forms the effective east margin of the anticline and coincides with a monoclinal flexure along the edge of the fold. Throw changes rapidly along the zone and locally is reversed.

BRAZOS FAULT ZONE

A continuous zone of faulting extending in a west-northwest direction separates the Tecolote Mesa syncline and Willow Creek anticline on the north (fig. 12) from the Horse Lake anticline and Lagunas dome on the south. This zone comprises part of a longer zone of structural discontinuity (fig. 11) herein named the *Brazos fault zone* (earlier called *Brazos flaw* by Muehlberger, 1960). The regional importance of the Brazos fault zone can be seen in Figure 11. Faults and folds south of it trend nearly north, whereas north of it they trend northwesterly. Intensity of deformation lessens to the south with a broader, flatter Chama Basin.

There appears to have been recurrent activity along the Brazos fault zone which apparently was controlled by Precambrian stratigraphy and structure. Major northwest-trending folds and faults in the Precambrian units of the Tusas Mountains turn west along the fault zone east of the Brazos Box. These folds and faults when traced farther, again turn northwestward before plunging under the younger rocks near the Colones Box. Pre-Triassic and post-Paleozoic movement along this zone appear to be distinct possibilities. Laramide and late Cenozoic deformations are delineated in Figure 11. Late Pleistocene (post-Durango and pre-Wisconsin glaciation) basalt cones cluster along the fault zone east of the Brazos Box.

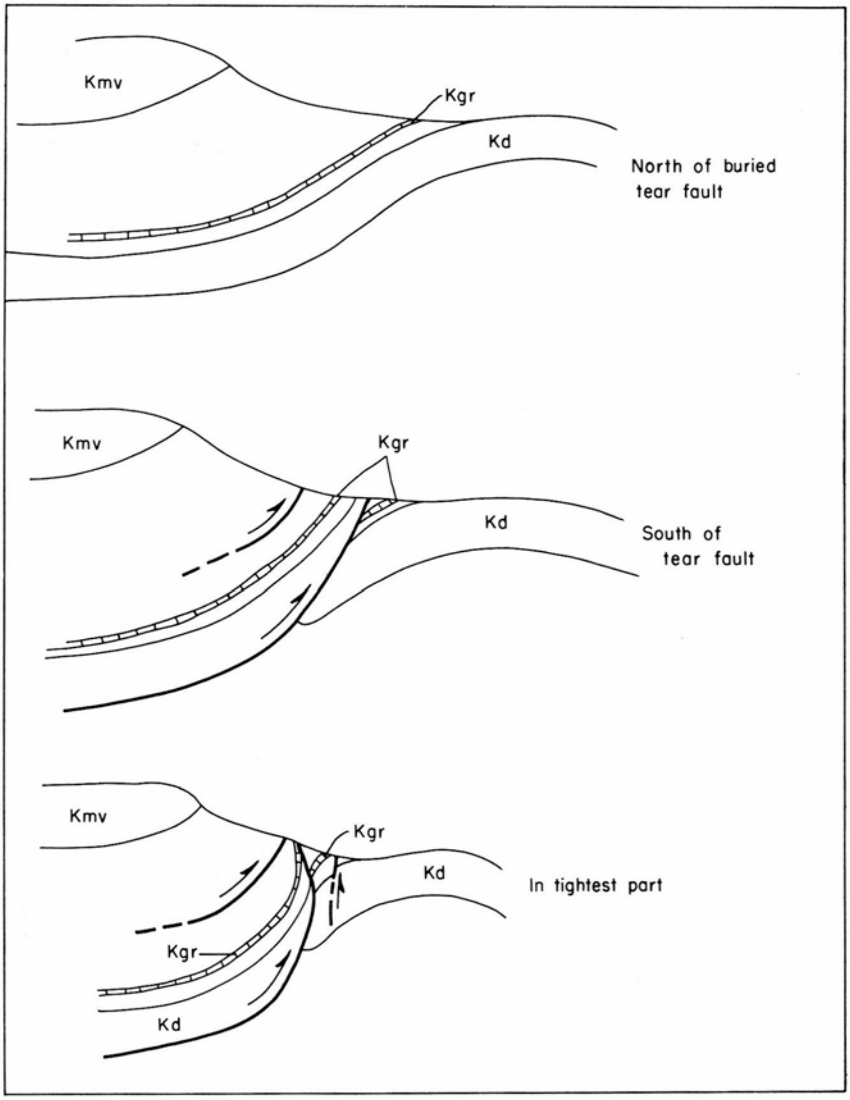


Figure 13

SCHEMATIC SECTIONS ILLUSTRATING STRUCTURE BETWEEN TECOLOTE MESA SYNCLINE AND WILLOW CREEK ANTICLINE

Dane's (1948) warping of structure contouring and Kelley's (1955, fig 2), joint traces show that this fault zone can be traced west-northwest along Cordova Canyon and westward for 40 miles or more to the San Juan River. The present appearance is of a scissors-type motion with the north side up across the Chama Basin to the Tusas Mountains and with the north side down in the San Juan Basin.

WILLOW CREEK FAULT ZONE TO CHAMA SYNCLINE

Except for local tight folds, structural relief is very low between the Willow Creek fault zone and the Chama syncline throughout the central Chama quadrangle.

The Willow Creek fault zone and Azotea fault, both down to the east with throws up to 400 feet over short distances, bound a block that is mainly a broad syncline. This syncline is first recognizable north of the transverse structures crossing the Willow Creek anticline, and it increases in depth northwestward to beyond the quadrangle. Just beyond the map edge it breaks into a fault, down to the northeast, that increases in throw westward to become the Monero fault zone with a maximum throw of about 1000 feet (Dane, 1948).

Small anticlines flank the Azotea fault and alternate sides along its trace. Only the Azotea anticline and El Cerro dome are large enough to have acquired names, and both lie northeast of the fault. The Azotea anticline is at least two miles long and has as much as 200 feet of closure. El Cerro dome is flanked by nearly east-striking faults and has a very tight domical shape with more than 400 feet of closure. This dome sits athwart the regional trends and has the appearance of a disharmonic structure in which the Dakota Formation buckles up and the underlying incompetent beds crumple into the available space.

Extending southeast from just north of U.S. Highway 84 at Willow Creek is an elongate group of narrow, tight-crested, faulted folds, the main one of which is named *Dos Lomas anticline.* Dips as high as 32 degrees mark the steep east flank of the structure. The west flank dips very gently, a few degrees at most. In some respects this is a small-scale replica of the folds on Little Willow Creek or those along the southeast corner of the area, except that the steep flank of Dos Lomas occurs on the east rather than on the west.

The structural features described expose either or both the Dakota Formation and Greenhorn Limestone Member of the Mancos Formation at the surface. Both these units make excellent structural marker horizons, which accounts for the structural detail shown on the geologic and structure contour maps (pls. 1 and 2). Elsewhere, the shale units of the Mancos Formation crop out at the surface and the lack of marker beds in thick sequences of black shale force a smoothing out and generalization of the structure mapped. Faults with 100 feet of throw may be common but remain unrecognized.

The Chama syncline extends the length of the quadrangle. In the southern half, it strikes north and nearly coincides with the bed of the Rio Chama. Just south of Chama, it turns northwest and becomes nearly coincident with the northwest-trending Sargent fault. The change in strike of the axis coincides with a structural divide, and the syncline plunges gently northwest and south away from the divide. There may be an en echelon set of faults or folds in this position, causing deflection of the Chama syncline where it lies between Dos Lomas anticline and the set of faulted folds in the southeast part of the quadrangle between Cañones and Chaves creeks. The westward deflection of the top of the Carlile at Cañones Creek suggests undetected structural complexities in this vicinity that the structure contour map only hints at. To the northwest, the Chama syncline opens into a large depression at the head of Willow Creek. Beyond this point, the Chama syncline lies east of the Sargent fault zone, as shown by Wood, Kelley, and MacAlpin. On their map, the Chama Basin consists of a slope that dips northeast under the Tertiary volcanic units; the east side of the basin thus is buried.

The Sargent fault probably extends northwest out of the Chama quadrangle to become the major fault bounding the east flank of the Chromo anticline. The Mesaverde has about 2000 feet of structural relief on the Chromo anticline (Wood, Kelley, and MacAlpin). It is highly asymmetrical with a gentle west flank and a nearly vertical east flank. Well data show that the basement steps down to the east across the fault from the fold crest by at least 2000 feet (L. S. Carlson, personal communication, 1960). The Sargent fault southeast from the Chromo anticline decreases in throw from a probable maximum of nearly 2000 feet down to the northeast along the Chromo anticline to nothing near the headwaters of Willow Creek where it changes sense of throw. From here southward it increases to a maximum throw near Chama of about 700 feet down to the southwest. It continues southeast of Chama with rapidly decreasing throw until it becomes unrecognizable on the outcrop. Along the strike in the Cañones Box, several faults occur that offset Tertiary units. These are discussed later with the structures of the monoclinal front of the Tusas Mountains.

TRANSITION FROM CHAMA BASIN TO TUSAS MOUNTAINS

The trace of the Chama syncline marks the east edge of the broad, relatively featureless Chama Basin and the western base of the Laramide monoclinal uplift into the Tusas Mountains. Structural relief of

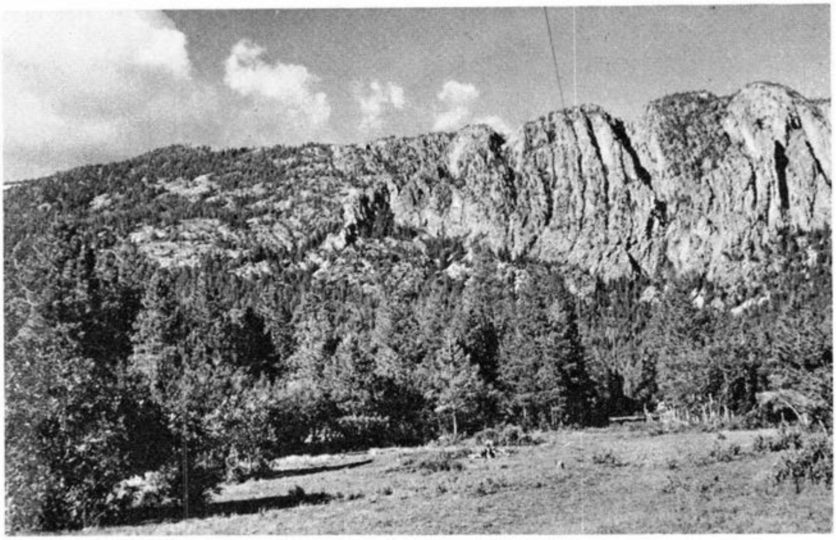


Figure 14
FRONT OF TUSAS MOUNTAINS JUST NORTH OF BRAZOS BOX
More than 2000 feet of relief are present up the quartzite face. View east.

3000 feet between the Chama syncline and the Tusas Mountains is demonstrable within the Chama quadrangle (pl. 2) and, by including the southwestern part of the Brazos Peak quadrangle, nearly 5000 feet can be demonstrated (fig. 14).

This dip slope is broken by a series of northwest-trending basement faults that have developed zones of faulting and elongate folding in the overlying sedimentary beds. These fault zones vary in magnitude of throw but most are less than a few hundred feet. In Chaves Canyon (fig. 15), a pair of these faults displays the transition of deformation types between the basement and its cover. Figure 16 is a diagrammatic sketch of the features visible north from the Chaves Box. A grabenlike structure in the Precambrian (not truly a graben because both faults dip in the same direction), downthrown about 200 feet, has relatively narrow, sharp, fault boundaries. The overlying 500-foot-thick Chinle Formation is nonresistant to erosion; the nature of deformation within the Chinle is unknown, although it appears probable from the style of deformation in the overlying units that faulting in the Chinle becomes distributive upward from the Precambrian contact. The 300foot-thick massive sandstones of the overlying Entrada Formation step down into the downthrown block along a series of closely spaced parallel joints. The next overlying unit, the Morrison Formation, consists of 500 feet of sandstone and shale units nonresistant to erosion, which also appear to distribute the deformation. The overlying Dakota, 300 feet of mostly massive sandstone, appears to bend down into the downthrown area with only joints perpendicular to bedding being the accommodating fractures.

Similar-appearing folds but on a larger scale are well exposed in Little Willow Creek. A parallel pair consisting of a tight, narrow anticline flanked on the east by a similarly shaped syncline plunge northwest off the uplift. The cover of Tertiary rocks at the updip ends of these folds, as well as nonrecognition of faults in the Precambrian of the upper Cañones Box at the proper position, suggests that these folds might not have the same origin as the drape features just described from the Chaves Box, although they are in comparable structural locations along the Brazos slope. The anticline appears to rise above regional dip and the synclinal axis marks the position of the resumption of regional dip. The folds also terminate abruptly at the north against a major regional fault. This suggests a décollement origin for this anticline in which the Dakota slid slightly down regional slope and crinkled into the observed folds.

The fault that terminates the Little Willow Creek folds to the north is the western end of the West Brazos Peak fault. It may continue to the northwest up Rio Chamita but lack of outcrop data prevents useful speculation. Where this fault cuts the Tertiary sequence in the Chama quadrangle, the throw is down to the west by small amounts. The Tertiary overlap truncates the Little Willow Creek folds. Thus, this fault has at least two stages of movement, Laramide and late Tertiary. Farther southeast along the west base of the Brazos Peak horst (fig. 11), the late Tertiary throw is up to the east by about 1500 feet; yet on the upthrown side, blocks of Dakota Formation are preserved. To preserve the Dakota, the Laramide displacement must have been downthrown on the east by many thousands of feet. The West Brazos Peak fault can be traced continuously to the southeast past the Hopewell mining district for a minimum known length of. 30 miles.

In the northeast corner of the quadrangle, the exact locations and exact displacements of the East Brazos Peak and Lobato faults are unknown, but they are probably downthrown to the east. The East Brazos Peak fault extends beyond the Brazos Peak quadrangle to the change of throw at the junction with the Tusas fault zone (Butler; Barker), a known length of nearly 50 miles.

Lagunitas fault shows two periods of movement, with the resultant shown on the structure contour map. North of the Chama River, the Tertiary units are down to the southwest about 100 feet. At the same location, the Mesozoic units are down to the northeast by about 1000 feet.

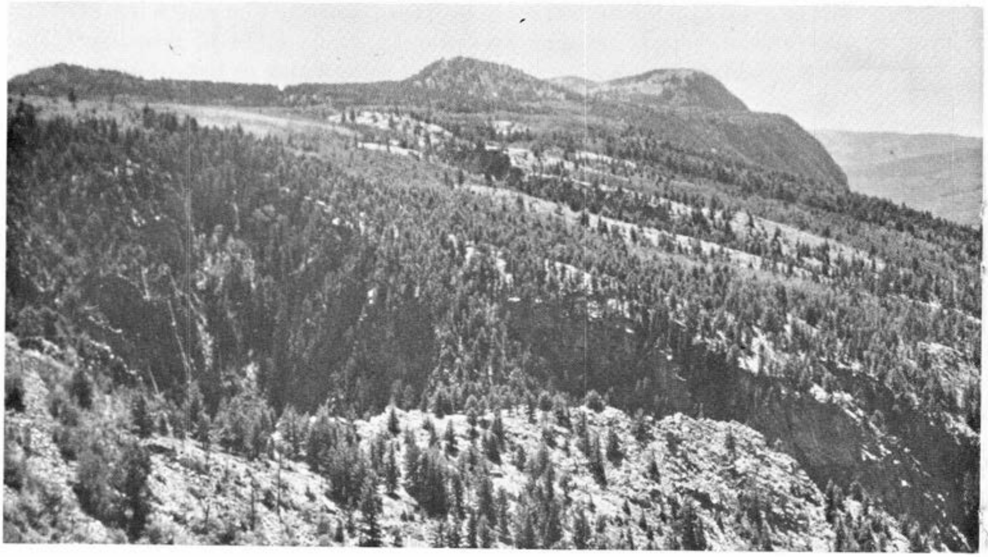
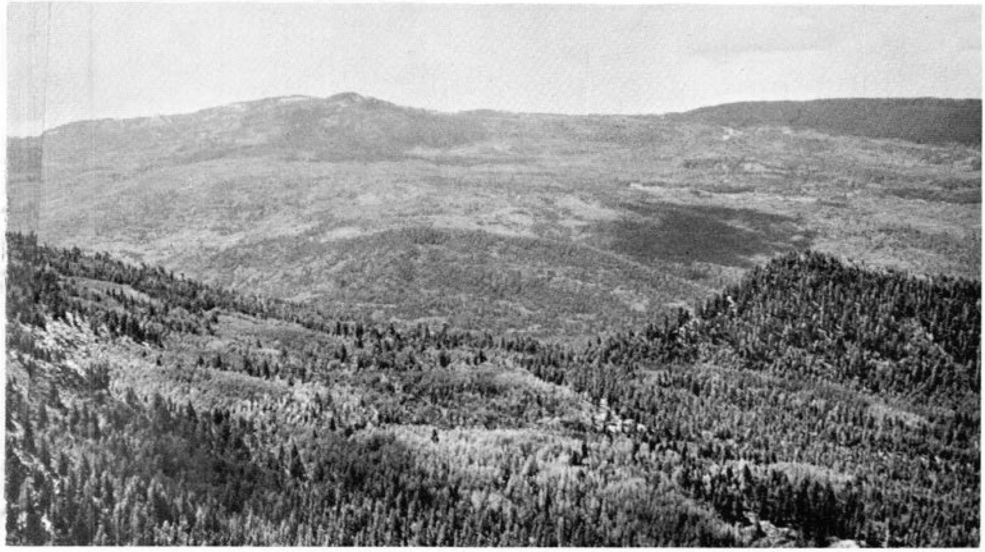


Figure
VIEW SOUTHWEST ALONG FRONT
Cliff tops of Figure 14 form ridge in left middle ground. Chaves Box in foreground trees and dropping of Precambrian surface along edge of Chaves Box. Brazos fault capped with basal Tertiary formations dipping gently east (left) and Mesaverde

PERIODS OF FAULTING

Three major faults of the Brazos Peak quadrangle demonstrating two periods of faulting extend into the Chama quadrangle: the Chaves, West Brazos Peak, and Lagunitas. The Laramide throw on each is greater than the Tertiary and is also associated with the upwarp of the Tusas Mountains.

Late Cenozoic regional eastward tilting of the Tusas Mountains occurred. How far west across the Chama quadrangle did that tilt continue? It is assumed that the east tilting was associated with the late Cenozoic faulting stage. The only direct evidence for tilting in the Chama quadrangle is in the northeast corner where the Tertiary units are still preserved. The rest of the extensive fold and fault structures in the Mesozoic rocks in the quadrangle I assume to be Laramide in origin (pre-Blanco Basin deposition). These structures have undergone minor movements during the late Cenozoic tilting, but no stratigraphic evidence so far demonstrates it. The hinge line of the eastward tilting might extend west as far as the north-striking dike swarm 15 to 20 miles west of the Chama quadrangle (Dane, 1948; Wood, Kelley, and MacAlpin). If so, then unfolding of the regional east tilt would



15

OF TUSAS MOUNTAINS

is rimmed by Precambrian quartzite. Grabenlike structure outlined by light-colored zone separates fore and middle grounds from background ridge. Background ridge (in shadow at right) dipping west into Chama Basin.

nearly eliminate any closure (on a regional basis) across the Chama Basin in the quadrangle. This would mean free migration of hydrocarbon fluids updip to the outcrop from the San Juan Basin and free access of fresh water downdip from the Tusas Mountains.

NATURE AND ORIGIN OF FAULTING

This entire descriptive section on structure discussed the *throw* of the faults. The slip direction has not been determined for any fault in the area; therefore the basic stress patterns are not known.

The major features consist of north-striking, up to the east Laramide monoclines superimposed on northwest-trending structural blocks containing Precambrian structures parallel to the margin of the blocks. Paleozoic deformations have poorly known trends, but these appear to be north to northwest (Wengerd and Matheny).

Vertical motions seem to dominate the region, although advocates of wrench-fault tectonics could invoke horizontal motions to explain the changing sense of throw along a fault during any deformation or the reversal of sense of throw at a given point during successive deformations. If wrench faulting is present, the Brazos fault zone had a

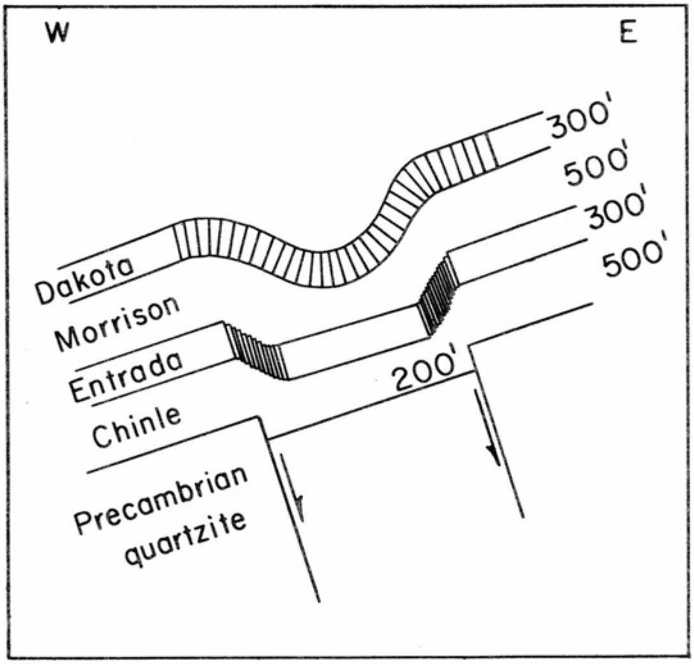


Figure 16

DIAGRAMMATIC VIEW NEAR THE HEAD OF CHAVES BOX

Shows transition from faulting in the Precambrian quartzite through closely spaced jointing in the Entrada to folding in the Dakota. Lowest part of this is shown in Figure 15.

left-lateral component of slip with a maximum compressive stress oriented along an east-northeast line. Minor décollement also appears necessary to explain the El Cerro dome and Little Willow Creek folds, as well as the Dos Lomas anticline belt, although basement faulting may ultimately have been responsible for what can be observed at the surface.

SUMMARY OF STRUCTURAL EVENTS

Much of the structural history of the Chama quadrangle must be inferred from areas outside it. Within the quadrangle, the main demonstrable events are Laramide and younger, although the younger are only partly recorded here and are better displayed in the Tusas Mountains (Butler; Muehlberger, 1967).

Precambrian history included deposition of a thick sequence of sedimentary and volcanic rocks, intrusion of granitic rocks of varying composition (Barker), and three periods of regional dislocation, all of

Precambrian age, as shown by Precambrian pegmatites injected along axial planes of third-deformation folds (Bingler, 1965).

The results of Paleozoic and Mesozoic deformations are largely unknown, although the Tusas Mountains appear to have been structurally high at several times in the past. This is indicated by the wedging, coarsening, or overlap onto the Precambrian during the following intervals: (1) Desmoinesian Pennsylvanian, (2) pre-Chinle truncation and removal, (3) Chinle, (4) Entrada (in Colorado on Piedra River; Read et al.), (5) Dakota, and (6) Animas (in Colorado; Wood, Kelley, and MacAlpin).

Laramide (post-Animas pre-Blanco Basin) deformation produced the major structures observed and delineated on the map with structure contours. Post-Laramide movements caused regional tilts, reactivation of some fault zones, and regional uplift. If we assume a picture of basement fault blocks making a set of steps, the Chama Basin represents a splintered tread between the steep risers of the San Juan Basin to the west and the Tusas Mountains to the east. The Archuleta anticlinorium appears to be a group of uplifts above the tread level, as do the lesser fold-fault structures of the Chama Basin within the Chama quadrangle. These uplifts have asymmetric shapes disharmonic with respect to each other and appear to be at least disharmonic, if not décollement, with respect to the basement. Their eccentric shapes suggest that a horizontal component of motion as well as vertical is required to satisfy the dynamics necessary to reconstruct the structures in their present shape.

Whether the structures of the Chama Basin have been reactivated since the Laramide deformation is unknown. However, the major faults that extend from the eastern Chama Basin into the Tusas Mountains have had several periods of movement. For example, Lobato and West Brazos Peak faults were downthrown on the east by at least 1100 feet during the Laramide. Throw might be several thousand feet greater on the West Brazos Peak fault near Brazos Peak, if no major Laramide folds are involved from the outcrop edge of the Dakota east across the 3-mile outcrop span of the Precambrian quartzite to the Dakota outliers along the east side of the West Brazos Peak fault. Post-Laramide displacements along these faults show a reversal of throw with the west side down about 100 feet on the Lagunitas fault at Rio Chama and 1000 feet on the West Brazos Peak fault near Brazos Peak. Near the southeast corner of the Brazos Peak quadrangle, the basal units of the Los Pinos Gravels are displaced less than 100 feet, indicating that the main down-to-the-west faulting along the West Brazos Peak fault occurred prior to Los Pinos deposition and post-Treasure Mountain Rhyolite (all Miocene formations).

Similarly, the East Brazos Peak fault is 1000 feet down to the east in the central Brazos Peak quadrangle (post-Treasure Mountain

Rhyolite), with small down-to-the-east throws in the north-central part of the quadrangle and down-to-the-west throws in the southeast part of the quadrangle (post-lower Los Pinos Gravels) that increase to the southeast where the fault joins the Tusas fault zone. Butler demonstrated at least two periods of movement along the Tusas fault zone after deposition of the Los Pinos Gravels. The Tusas and Lagunitas fault zones (fig. 11) show down-to-the-west throws for their main displacement which was post Los Pinos Gravels.

The post-Los Pinos displacements and eastward tilting of the Tusas Mountains probably result from the downdropping of the Rio Grande depression (Butler). How far west the eastward tilting continued into the Chama Basin is not known because of the removal of the Cenozoic rock cover. The base of the Conejos cap on Chromo Peak is about the same elevation as the Conejos north of the town of Chama; this is suggestive evidence that the eastward tilting does not continue this far west. The Chama syncline may represent the approximate western limit of the eastward tilt into the Rio Grande depression. A line down the south-trending line of late Pleistocene cinder cones east of the Brazos Box might mark a hinge line that is the western boundary of the eastward tilting for this part of the Rio Grande depression (fig. 11, Doney).

This hinge line indicates active faulting and volcanism almost to the present and makes one wonder whether it is all over yet.

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Appendix A

MEASURED SECTIONS

Most of the following measured sections have been taken directly from the thesis of the student credited for the section. All sections were measured by steel tape or Jacobs staff and Brunton compass methods. Each section has been given a name for ease of discussion. Several sections lie in adjacent areas to the south (Tierra Amarilla quadrangle) and east (Brazos Peak quadrangle) and represent basic data necessary for understanding the stratigraphy of the Chama quadrangle.

Approximate locations of the sections listed in this appendix are shown in Figure 17. Additional partial or complete sections of certain formations have not been included here but can be found in the original theses (Adams; Davis; Doney; Dunn; Longgood; St. John; Trice).

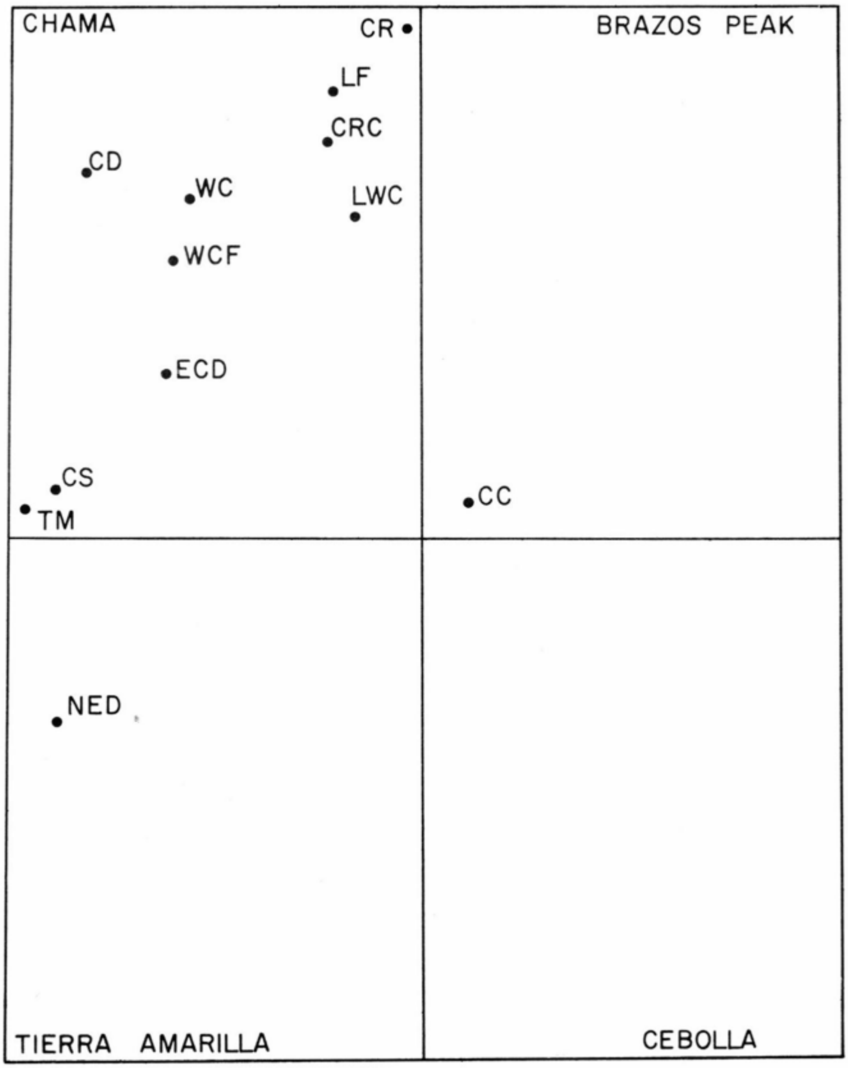


Figure 17

APPROXIMATE LOCATIONS OF MEASURED SECTIONS DESCRIBED IN APPENDIX A

For accurate locations, see geologic map (pl. 1). Letter abbreviations correspond to those listed after name of measured section.

Chaves Canyon Section (CC)

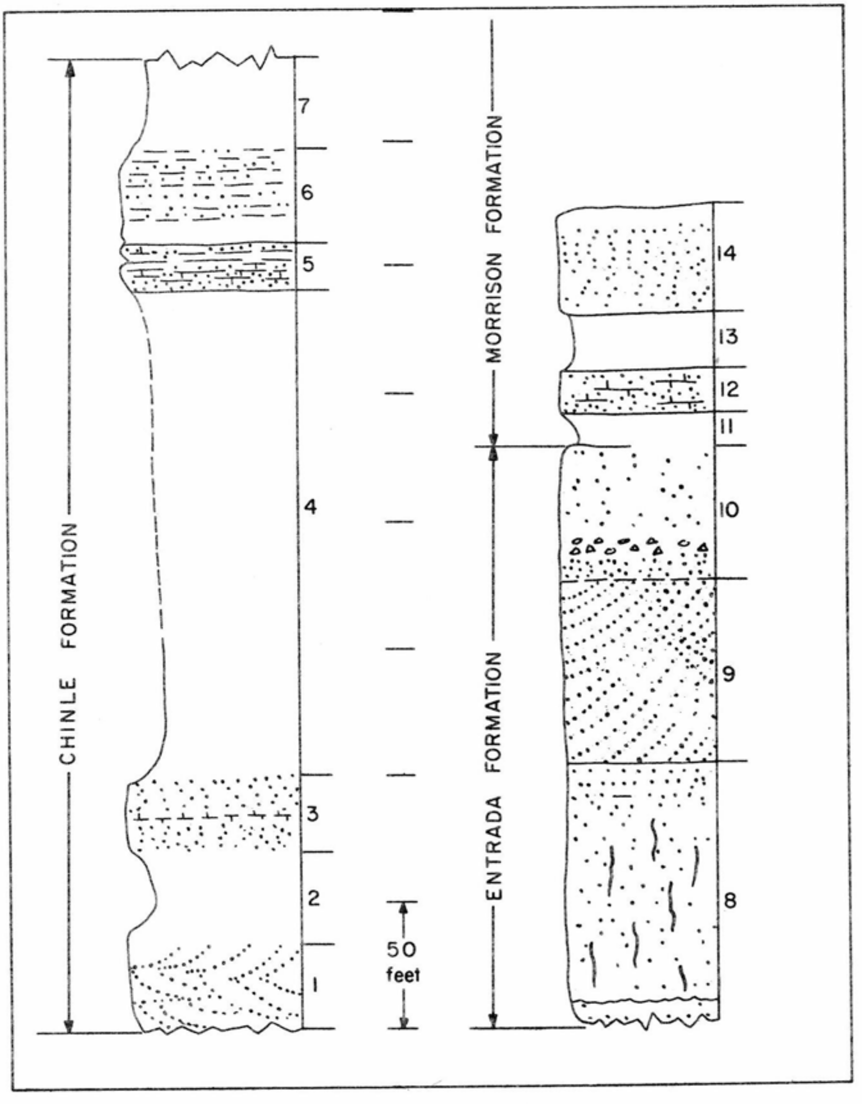
Formations: Chinle, Entrada, lower Morrison

Location: Along bed of Chaves Creek approximately 2 miles northeast of southwest corner of Brazos Peak quadrangle; description of underlying Pennsylvanian units is in Figure 3

Measured by: W. R. Muehlberger and H. H. Doney

Date: 3 August 1955

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	Morrison Formation	
14.	Sandstone, medium-grained, well sorted, hematite spots, very pale orange, quartz, parallel-bedded, cliff-forming, in units 2-4 feet thick	40
13.	Covered interval, float suggests primarily reddish siltstone and sandstone	20
12.	Sandstone, very fine-grained, well sorted, limy cement, may be Todilto–Wanakah interval	21
11.	Covered interval, contact with underlying formation not exposed	9
	Entrada Formation	
10.	Sandstone, medium-grained, quartz, silica cement, extremely well cemented, grayish orange, in 1- to 2-foot beds, parallel-bedded, lower part consists of breccia composed of well-cemented sandstone resting on a thin shale	43
9.	Sandstone, fine-grained, quartz, calcareous near base, elsewhere light hematite cement, grayish yellow, festoon bedding begins 20 feet above base of unit. Top inch strong hematite cement. Two inches of relief on surface at base of unit	83
8.	Sandstone, very fine-grained, pale reddish brown with yellowish-gray bleached streaks, quartz, calcareous and hematitic cement, friable, very thinly laminated, forms prominent cliffs, weathers into large, rounded, blocky knobs, crests of oscillation ripples near base strike east. Base of unit not exposed	105
	Chinle Formation	
7.	Covered interval	38
6.	Sandstone, siltstone, pebbly conglomerate, composed of limestone, sandstone, chert, and quartz clasts; reddish shale, poorly exposed, bottom half covered	44
5.	Sandstone, conglomerate, limy clasts of limestone, bedded limestone, coarse-grained limestone, silty zones between two 4- and 3-foot-thick beds, reddish	14
4.	Covered interval	150-200
3.	Arkose, sandstone, silty sandstone, blocky fracture, appears fluvial in origin, pale red, sandstone lenses bleached to light greenish gray	27
2.	Covered interval	31
1.	Sandstone, medium to coarse grain, poorly sorted, arkosic, pale red, cross-beds dip in S. 20° E. direction, beds 1 inch to 2 inches thick, few pale green silty zones, massive. Base not ex-	39 +



CHAVES CANYON SECTION

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	posed, may be as much as 150 feet to base of Chinle Formation and top of Pennsylvanian unit in creek bottom	@ 150 c.i.
	Lower Morrison Formation measured	90
	Entrada Formation	231
	Chinle Formation, total estimated thickness	493 + 50 ±

North El Vado Dome Section (NED)

Formations: Dakota and Morrison

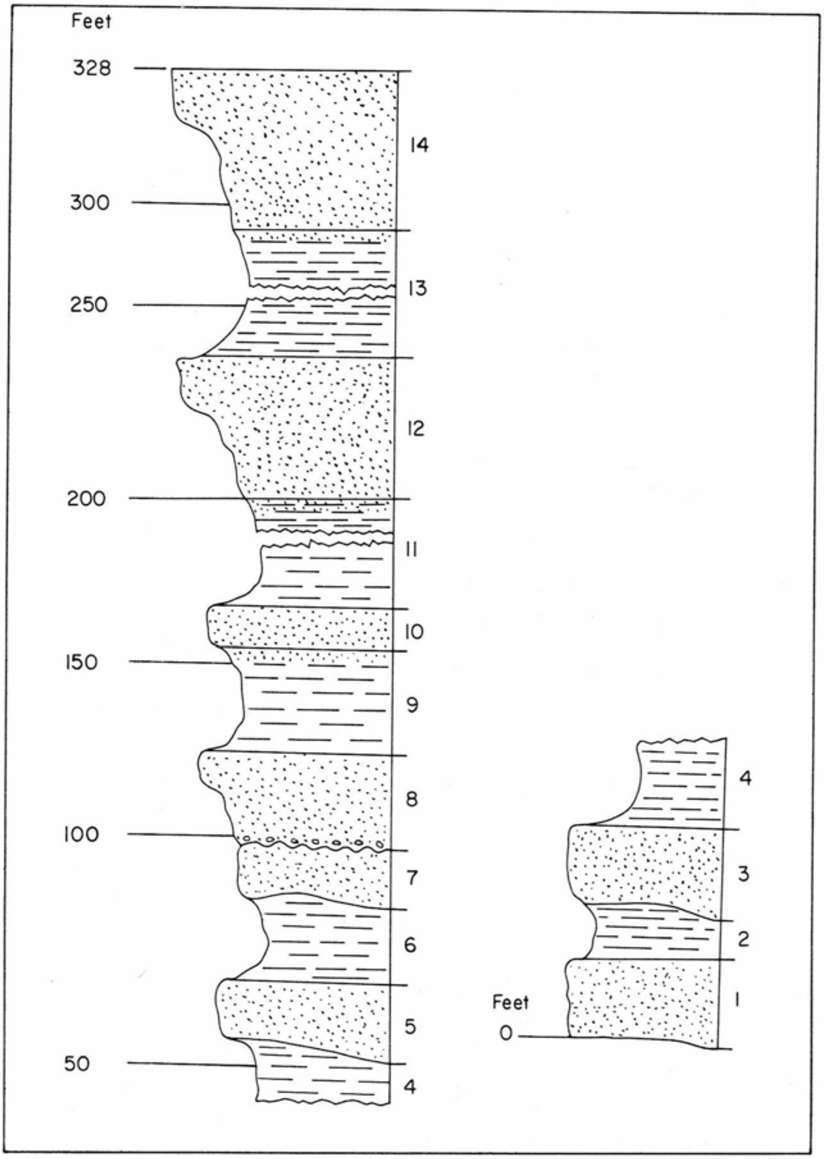
Location: Approximately 2000 feet west of intersection of Willow Creek and Rio Chama, in the Chama Gorge

Measured by: J. H. Davis

Date: 7 August 1959

Remarks: Strike of beds is east, dip is 4° N; section line is north. Measurement of section began at the lowest undisturbed outcrop of the Morrison Formation

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	Dakota Formation	
14.	Sandstone (orthoquartzite), light gray to grayish orange on the fresh surface, weathers to a pale orange to brownish-orange color, massive with the top 10 feet overhanging the rest of the unit as a ledge, grain size grades from very fine at the top to medium fine at the base; hard, compact, sorting ranges from poor at the base to well sorted at the top; subangular to subround quartz grains with siliceous cement and some ferruginous cementing in the top 15 feet: iron-stained near the base and top; some carbonaceous material near the base, worm workings on the top surface but otherwise unfossiliferous. Unit is the uppermost sandstone member of the formation and forms the rim of the Chama Gorge; joints: N. 15° E., vertical; N. 55° E., vertical; N. 75° W., vertical	50
13.	Shale, dark gray to light gray on weathered surface, lightness in color increases toward the top, dark gray to black on the fresh surface, unit becomes very silty toward the top, which may influence the color change; crumbles easily, slightly micaceous, slightly carbonaceous, noncalcareous, nonfossiliferous, and very poorly bedded; contains sand lenses with maximum thicknesses of 6 inches to 1 foot, and a prominent sandstone bed 2½ feet thick about 25 feet above the base. Sand is very fine- to fine-grained, contains clay-cemented quartz grains with occasional feldspar grains intermixed, colored light gray on fresh surface and grayish orange on the weathered surface, some carbonaceous material	50
12.	Sandstone (orthoquartzite), same colors for fresh and weathered surfaces as unit 14, upper 20 feet massive, lower 10 feet have interfingering shale tongues, top 10 feet cross-bedded	



North El Vado Dome Section

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	with bedding planes dipping predominantly east; top 6 feet overhang as a ledge; very fine-grained at the base, grading to fine-grained at the top, well sorted at the base, becoming less so toward the top; grains are quartz with minor amounts of weathered feldspar cemented by clay and ferruginous material near the base and by siliceous cement toward the top; gradational contact with underlying unit with the contact of the base of the unit chosen at the base of the first continuous sandstone bed; iron staining common near the base and top, nonfossiliferous	30
11.	Silty shale, dark gray to light gray on weathered surface, dark gray to black on fresh surface, some silty sand stringers similar to those in unit 13, with a maximum thickness of 1 foot; jarosite with pale yellow color observed in fractures of the unit, some carbonized wood fragments; otherwise same as unit 13	30
10.	Sandstone (orthoquartzite), very fine-grained throughout, grayish orange on the weathered surface, light gray to brownish gray on the fresh surface; resistant quartz grains cemented by silica in the top of the unit, by clay in the bottom of the unit, causing an overhanging ledge; gradational contact with unit 9, friable on the weathered surface in the base; nonfossiliferous	10
9.	Silty shale, same as unit 11	40
8.	Sandstone (orthoquartzite), same lithology as unit 12 except for the grain size distribution which grades from fine at the top to medium-grained sand at the bottom; unit is cross-bedded throughout with the bedding planes dipping predominantly east. The basal contact of this unit is a disconformable surface under which rests the Jurassic Morrison Formation. A pebble-sized conglomerate incorporating small pieces of the latter formation is about 1 foot thick and lies above the disconformable surface in the basal unit of the Dakota Formation	20
	Total measured thickness of the Dakota Formation	230
	Morrison Formation	
7.	Sandstone (orthoquartzite), pale orange on the weathered surface, light gray to grayish brown on the fresh surface; massive, medium-grained, parallel bedding except for a 2-foot-thick layer of cross-bedding (bedding planes dip east and west) 3 feet from the base of the unit; unit compact, hard, poorly sorted, with subangular to subround quartz grains cemented by silica; limonite stain; sparsely distributed carbonaceous material, nonfossiliferous; basal contact gradational with underlying unit, top contact is a disconformable surface; thickness of the bed is variable; unit is a channel sand	6
6.	Shale, arranged in layers approximately 6 inches thick with alternating colors of pale red to pale green on the fresh surface, weathering to a pale grayish green to grayish brown; unit becomes progressively more silty toward the top; top 5	

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	feet dark gray to black on the fresh surface; crumbles easily, slightly micaceous, slightly carbonaceous, calcareous with sparsely distributed pea-sized iron-stained concretions throughout the interval	20
5.	Sandstone (orthoquartzite), same as unit 7 except for cross-bedding in the top 8 feet of the unit; thickness of the unit is not constant, indicating deposition as a channel sand; base of unit rests on a disconformable surface similar to the upper contact of unit 7, except that the surface is only about 6 inches thick	11
4.	Silty shale, light gray to dark gray on the weathered surface, dark grayish brown to dark gray to black on the fresh surface; middle of the unit less silty than rest of the shale; slightly calcareous, slightly micaceous, carbonaceous; contains iron-stained concretions throughout up to 4 mm in diameter	25
3.	Sandstone (orthoquartzite), same as unit 5	20
2.	Shale, pale green on the fresh surface, grayish green on the weathered surface; very little silt, poorly bedded; slightly calcareous, carbonaceous, micaceous, and nonfossiliferous	2
1.	Sandstone (orthoquartzite), grayish orange to brownish orange on the weathered surface, pale to very pale orange on the fresh surface; massive, very fine- to fine-grained, round to subround quartz grains grading upward to a medium-grained sand; cross-bedded throughout with bedding planes dipping east and west; slightly friable, well sorted at the base becoming less so toward the top of the unit; siliceous cement, noncalcareous, nonfossiliferous, and only slightly carbonaceous. Iron-stained concretions with a maximum thickness of 6 mm sparsely distributed; thickness of unit varies, similar to unit 5; rest of formation covered by alluvium and landslide material	14
	Total measured thickness of Morrison Formation	98
	Grand total measured thickness of MS-2	328

Chama River Canyon Section (CRC)

Formation: Greenhorn Limestone and Graneros Shale members of the Mancos Shale and the Dakota Sandstone

Location: West side of the Chama River Canyon, latitude 36° 56′ 06″ N., longitude 106° 33′ 14″ W.

Measured by: G. E. Adams, W. R. Muehlberger, and G. S. Wade

Date: 20 June 1955

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
24.	Top of hill	
	Greenhorn Limestone Member, Mancos Shale	
23.	Limestone; light gray to black, thin-bedded	12

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	Graneros Shale Member, Mancos Shale	
22.	Covered interval; probably gray to black, thin-bedded shale	97
	Total Mancos Shale	109
	Dakota Sandstone	
21.	Sandstone; very light gray, thick, parallel-bedded, compact, hard, very fine-grained, well sorted, subangular to subround quartz grains, limonite stain, fucoidal, casts of *Inoceramus* sp., forms ledge.	3
20.	Covered interval; probably siltstone	19
19.	Siltstone; medium light gray to light gray, thin-bedded, limonite stain	5
18.	Covered interval; probably siltstone	3
17.	Siltstone; medium light gray to light gray, thin-bedded, limonite stain	3
16.	Covered interval; probably siltstone or shale	8
15.	Siltstone; medium light gray to light gray, thin bedded, limonite stain	3
14.	Shale, light gray dry, grayish black to black wet, thin-bedded	11
13.	Sandstone; very light gray, massive, parallel, compact, hard, very fine-grained, well sorted, subangular quartz grains, siliceous cement, forms ledge	45
12.	Covered interval; probably dark gray to black carbonaceous shale	126
11.	Sandstone; very pale orange, massive, parallel-bedded, compact, hard, fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, limonite stain, forms ledge	12
10.	Sandstone; pale yellowish brown to very pale orange, massive, parallel-bedded, compact, hard, fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, limonite stain, forms ledge	26
9.	Sandstone; pale yellowish brown to very pale orange, massive, parallel-bedded, compact, hard, medium-grained, moderately sorted, subangular to subround quartz grains, siliceous cement, limonite stain, forms ledge	35
8.	Sandstone; moderate yellowish brown, massive, cross-bedded, compact, hard, fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, limonite stain, forms ledge	9
7.	Sandstone; moderate yellowish brown, massive, cross-bedded, compact, hard, fine- to medium-grained, poorly sorted, subangular to subround quartz grains, siliceous cement, limonite stain, granule conglomerate lenses, forms ledge	15
6.	Sandstone; moderate yellowish brown, massive, cross-bedded, compact, hard, fine- to medium-grained, moderately sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, forms ledge	30
5.	Sandstone; moderate yellowish brown, massive, cross-bedded, compact, hard, medium-grained, poorly sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, granule conglomerate lenses, forms ledge	11.5

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
4.	Sandstone; moderate yellowish brown, massive, cross-bedded, compact, hard, medium-grained, poorly sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, granule conglomerate lenses, forms ledge	6
3.	Sandstone; grayish orange, massive, faintly cross-bedded, compact, hard, medium-grained, moderately sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, forms ledge	18
2.	Sandstone; pale orange, thick, cross-bedded, compact, hard, medium-grained, moderately sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, in lower 1½ feet siltstone fragments up to 1 foot in diameter, forms ledge	2.5
	Total Dakota Sandstone	391
	Morrison Formation	
1.	Sandstone; very pale orange, thick, parallel-bedded, compact, hard, medium-grained, poorly sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, distinct disconformity at top with 3 feet of relief, forms slope, base concealed by landslide debris in canyon bottom	7 +
	Total measured section	507

LITTLE WILLOW CREEK SECTION (LWC)

Formation: Dakota Sandstone

Location: N., longitude 106° 32′ 14″ W.
North side of Little Willow Creek at first fork, latitude 36° 53′ 39″

Measured by: G. E. Adams

Date: 28 June 1955

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
26.	Top of hill	
	Dakota Sandstone	
25.	Covered interval; probably siltstone and shale	54
24.	Sandstone; light brown, thick, parallel-bedded, compact, hard, very fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, forms ledge	3
23.	Siltstone; light gray	1
22.	Sandstone; light gray, thick, parallel-bedded, compact, hard, very fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, forms ledge	4
21.	Siltstone; light gray	1
20.	Sandstone; light brown, thick, parallel-bedded, compact, hard, very fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, forms ledge	5
19.	Siltstone; light gray	1.5

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
18.	Sandstone; light brown, massive, parallel-bedded, compact, hard, very fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, forms ledge	18
17.	Siltstone; light gray	1
16.	Sandstone; dark yellowish orange, massive, parallel-bedded, compact, hard, fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, forms ledge	16
15.	Covered interval; probably siltstone or shale	20
14.	Sandstone; dark yellowish orange, thin, parallel-bedded, compact, hard, fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, limonite stain, forms ledge	1
13.	Sandstone; dark yellowish orange, thick, parallel-bedded, compact, hard, fine-grained, well sorted, subangular to subround quartz grains, siliceous cement, limonite stain, forms ledge	3
12.	Covered interval; probably black carbonaceous thin-bedded shale	76
11.	Sandstone; grayish yellow, massive, parallel-bedded, compact, hard, fine-grained, well sorted, subangular to subround quartz grains, limonite stain, siliceous cement, forms ledge	11
10.	Covered interval; probably shale	11
9.	Sandstone; white, massive, parallel-bedded, slightly friable, hard, fine- to medium-grained, well sorted, subangular to subround quartz grains, siliceous cement, limonite stain, forms ledge	8
8.	Siltstone; light gray	1
7.	Sandstone; yellowish gray, massive, cross-bedded, compact, hard, fine- to coarse-grained, poorly sorted, subangular to subround quartz grains, siliceous cement, limonite stain, granule conglomerate lenses, forms ledge	23
6.	Sandstone; pale yellowish brown to dark yellowish brown, massive, cross-bedded, compact, hard, fine- to coarse-grained, poorly sorted, angular to subround quartz grains, siliceous cement, limonite stain, granule conglomerate lenses, forms ledge	45
5.	Covered interval; probably shale or siltstone	10
4.	Sandstone; pale yellowish orange, massive, cross-bedded, compact, hard, medium-grained, well sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, forms ledge	10
3.	Sandstone; pale brown to light gray, massive, cross-bedded, compact, hard, fine- to coarse-grained, poorly sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, granule conglomerate lenses, forms ledge	15
2.	Sandstone; grayish orange, massive, cross-bedded, compact, hard, fine- to coarse-grained, poorly sorted, subangular to subround quartz and chert grains, siliceous cement, limonite stain, granule conglomerate lenses, forms ledge	30
1.	Sandstone; pale yellowish orange to dark yellowish orange, massive, cross-bedded, compact, hard, fine-grained, moderately sorted, subangular to subround quartz and chert grains,	

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	siliceous cement, limonite stain, forms ledge, base concealed by landslide debris in canyon bottom	16 +
	Total Dakota Sandstone	384.5
	Total measured section	384.5

Willow Creek Fault Section (WCF)

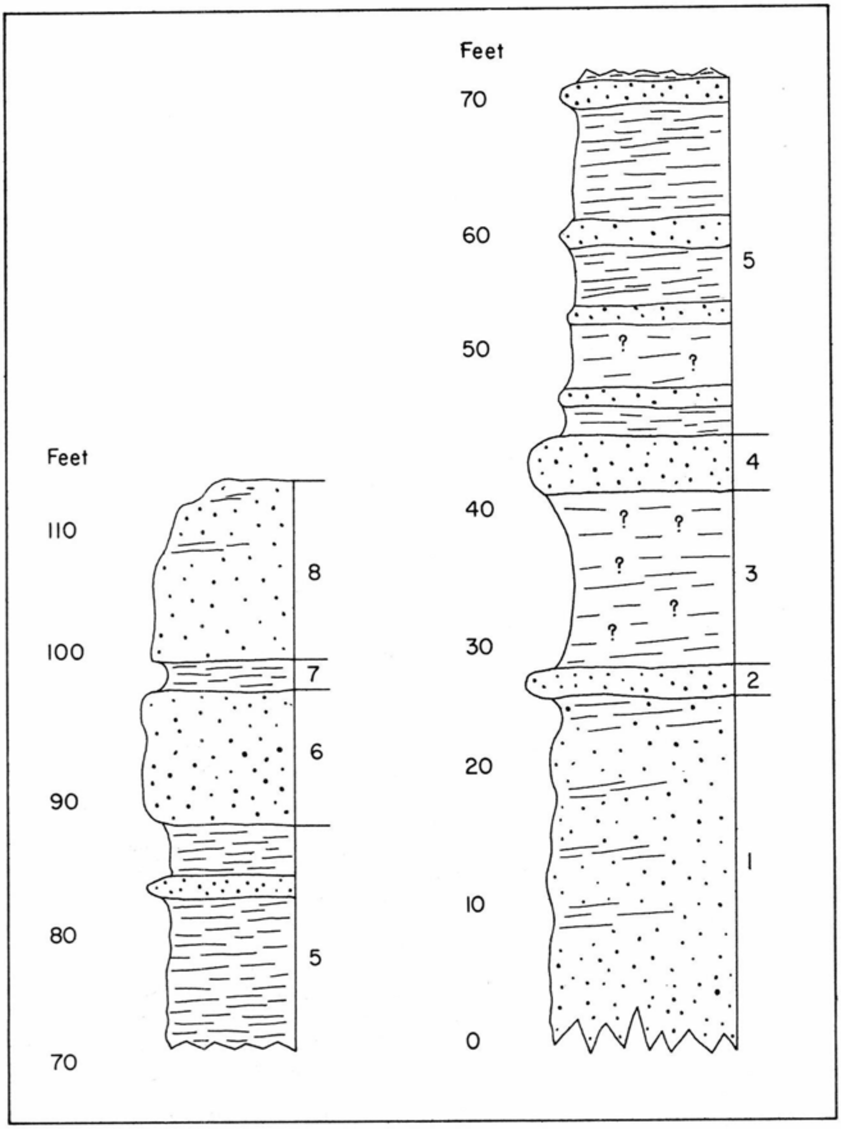
Formation: Dakota

Location: North of highway at Willow Creek on east side of the Willow Creek fault, latitude 36° 52′ 56″ N., longitude 106° 39′ 00″ W.

Measured by: T. E. Longgood, Jr., and Agatha Dunham

Date: 11 September 1958

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	The top of the unit is slightly eroded and the contact with the overlying Graneros shale is covered by talus and vegetation.	
8.	Sandstone (orthoquartzite), grayish orange-pink (5YR 7/2) and moderate red (5R 5/4) on fresh and weathered surfaces, respectively, parallel-bedded, weak siliceous and hematitic cement, friable, medium-grained, subrounded, quartz, trace of feldspar, some concentrated hematite blebs, hematite-stained laminae, very pronounced on some weathered surfaces, beds 3-6 inches thick alternating with half-inch shale partings forming stair-step erosion profile, caps hill	13
7.	Covered interval, probably shale	2
6.	Sandstone (orthoquartzite), very pale orange (10YR 8/2) and moderate red (5R 5/4) on fresh and weathered surfaces, respectively, parallel-bedded, some localized cross-beds outlined by faint iron stain, siliceous and clay cement, slightly friable, fine-grained, well sorted, subround, quartz, traces of feldspar in middle of unit where clay cement is prevalent, worm burrowings on some upper surfaces, beds 6-12 inches thick, forms ledge	12
5.	Sandstone (orthoquartzite), alternating with covered intervals, grayish orange (10YR 7/4), thinly bedded, parallel laminations outlined by concentration of ilmenite and coal fragments, siliceous cement, very fine-grained, well sorted, angular to subangular, quartz, weathered feldspar, sandstone stringers 3-6 inches thick occur 5-8 feet apart and stand out on slope, forms slight recess	43
4.	Sandstone (orthoquartzite), very pale gray (N8) and light brown (5YR 5/6) on fresh and weathered surfaces, respectively, parallel-bedded, siliceous cement, slightly friable, fine-grained, fairly well sorted, subangular, quartz, trace of weathered feldspar, some localized concentrations of ilmenite (few grains weathered to leucoxene), beds 2 feet thick with sporadic laterally appearing 3-inch shale breaks, forms ledge	4
3.	Covered interval, probably shale	13



WILLOW CREEK FAULT SECTION

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
2.	Sandstone (orthoquartzite), very light gray (N8), parallel-bedded, siliceous cement, very slightly friable, fine-grained, poorly sorted, subangular, quartz, minor weathered feldspar, localized concentrations of ilmenite (some grains weathered to leucoxene) show as laminations, forms ledge	2
1.	Sandstone (subarkose), yellowish gray (5Y 7/2), massive, parallel-bedded, occasional protruding sandstone ridges, tight siliceous cement, medium-grained, very well sorted, subround to round, quartz, minor feldspar, trace of heavy minerals, worm burrowings on upper bedding surfaces; much of this unit is covered with talus; base of unit not exposed	25+
	Units 1-5 may all be part of a single unit, as described by St. John. The sandstone beds in the lower part are thicker than those in his equivalent stratigraphic horizon	
	Total measured Dakota section	114+

El Cerro Dome Section (ECD)

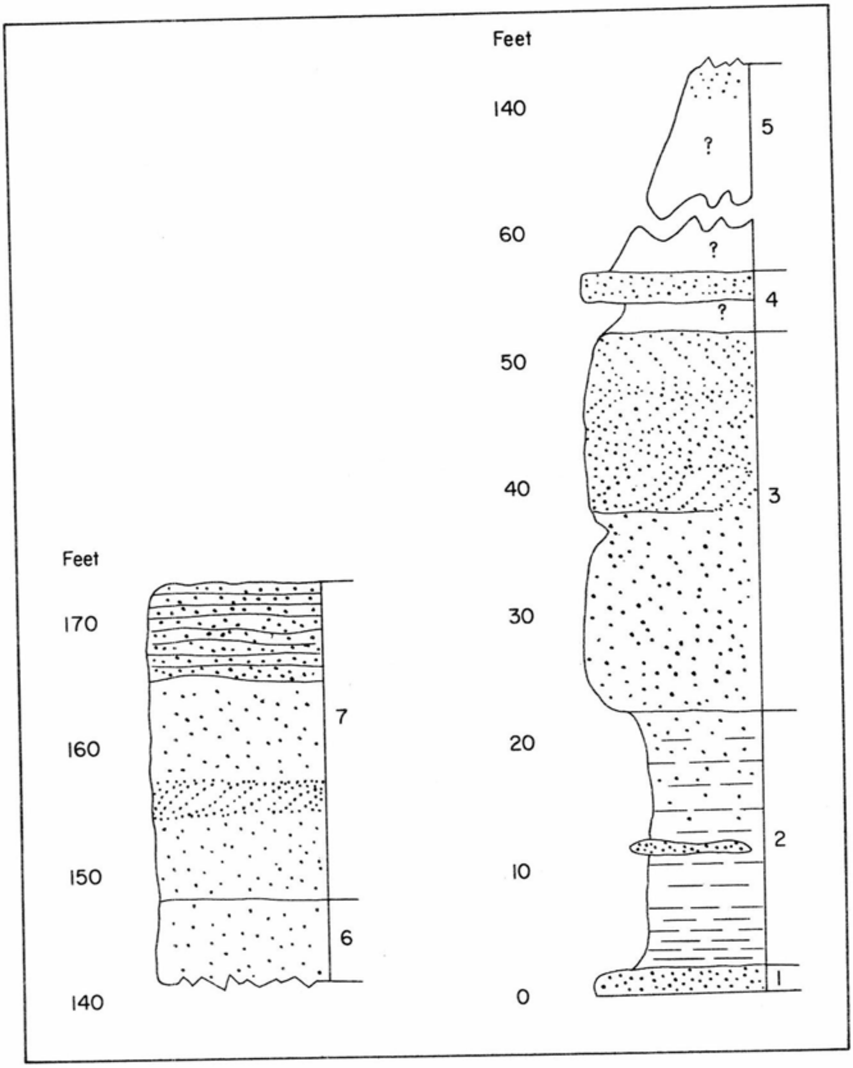
Formation: Dakota

Location: On the west side of the creek wall 1400 feet north of a large corral. Top of Dakota selected at top of uppermost massive sandstone that forms a dip slope

Measured by: B. E. St. John

Date: 9 September 1958

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
7.	Sandstone (orthoquartzite), very fine-grained, fresh surface varies from pale orange-brown (10YR 7/2) to moderate yellow-brown (10YR 5/4), weathered surface varies from very pale yellowish orange (10YR 8/6) to grayish orange (10YR 7/4), grains are quartz with overgrowths, subround, mature, some carbonaceous material at base and also 20 feet above base, silica cement with some ferruginous cement at top, beds 6 inches to 2 feet thick, massive cross-bedding 8 to 10 feet above base continues to top, uppermost sandstone silty; joints N. 10° W. 85° W.; N. 60° E. 80° NW.; N. 56° W. 71° SW.	25
6.	Sandstone (orthoquartzite), fine-grained, fresh surface olive-gray (5Y 4/1) and weathered surface pale orange (10YR 8/3), subrounded mature quartz grains with stained silica cement, forms a cliff	6
5.	Debris-covered slope, exposure at top reveals a soft, easily weathered, dark organic material, gypsum-cemented, fine-grained quartz sandstone (orthoquartzite), grains subrounded; slope seems to be shale	87
4.	Sandstone (orthoquartzite), medium- to fine-grained, fresh surface yellowish gray (5Y 7/2) and weathered surface grayish red (5R 3/2), quartz grains subround with silica overgrowths, upper 2 feet cross-bedded sandstone and lower 3 feet debris-covered slope	5



EL CERRO DOME SECTION

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
3.	Sandstone (orthoquartzite), very fine-grained at base to fine-grained at top, fresh surface yellowish gray (5Y 7/3) and weathered surface moderate yellow (5Y 7/5), grains mostly quartz with some glauconite and minor amounts of feldspar, cement both ferruginous and clayey near base grading upward into silica cement and overgrowths, upper sand subround and mature with only minor amounts of feldspar; unit 2 shows a gradational change into this unit, contact chosen at first continuous sandstone bed, cross-bedding and interfingering of shale near base, sand more thickly bedded toward top; hematite stains 3 feet from base, 2-foot-thick layer forms recess 14-16 feet from base, uppermost bed 13 feet thick shows massive cross-bedding; joints N. 50° W. 75° NE.; N. 37° E. vertical	27
2.	Silty shale, medium dark gray (N4) at base and light gray (N7) near top, crumbles easily, base of sandstone lens 2 to 18 inches thick 9 feet above base, sand very fine- to fine-grained contains quartz and weathered feldspar with clay cement, fresh surface light gray (N7), weathered surface has grayish yellow (5Y 8/4) sulfur in fractures in shale, lens contains carbonized wood fragments	20
1.	Sandstone (orthoquartzite), very fine-grained, grayish orange (10YR 7/4) on fresh surface and dark yellowish orange (10 YR 6/6) on weathered surface, beds ½ inch to 4 inches thick, quartz grains silica-cemented but friable on weathered surface; joints N. 47° W. 83° NE.; N. 75° E. vertical; N. 47° W. 7° SW.	2
	Base not exposed, measured from lowest exposure of sandstone in creek bottom	
	Total composite measured thickness of Dakota Formation	172+

Carlile Section (CS)

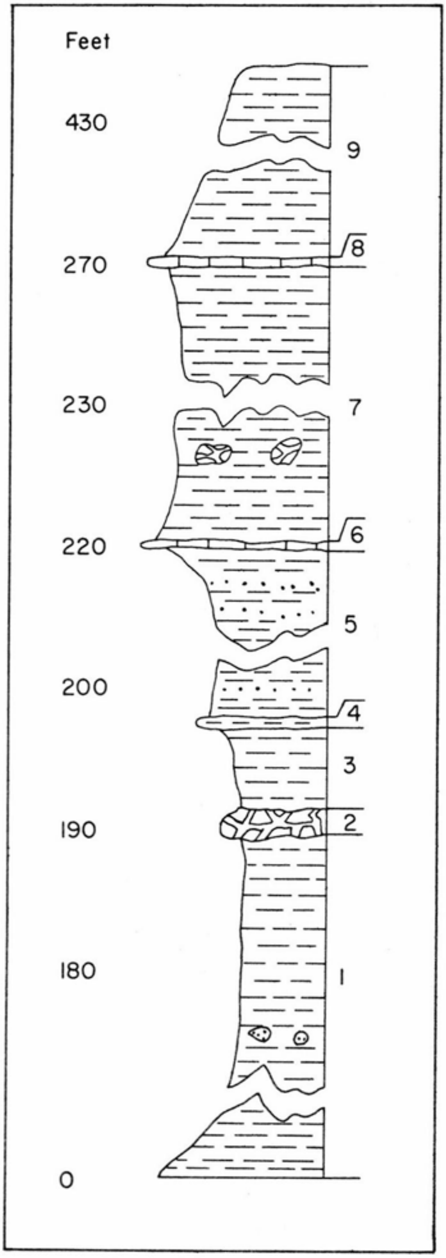
Formation: Mancos; Carlile Member

Location: Gully on the south side of a large earthen water tank. Top of section designated at the first appearance of *Ostrea congesta* attached to *Inoceramus grandis prisms*. This contact is based on faunal and soil color changes

Measured by: B. E. St. John

Date: 8 September 1958

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
9.	Shale, fresh surface dark gray (N3), weathered surface olive-gray (5Y 4/1), much of interval is brush-covered	158 ±
8.	Fossiliferous limestone (fossiliferous calcarenite), fresh surface grayish black (N2.5), weathered surface yellowish gray (5Y 6/2), contains abundant pelecypods, fish scales, and marcasite crystals	0.5



CARLILE SECTION

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
7.	Shale, color same as unit 9, crumbles easily, 8 feet above base are some limestone concretions 2 to 3 feet in diameter, medium gray (N5.5) on fresh surface, a distinctive grayish yellow-orange (10YR 7/5) on weathered surface; concretions have crystalline calcite septa	50
6.	Limestone, fresh surface medium brownish gray (N5.7/0.3), weathered surface olive-gray (5Y 4/1), contains carbonaceous wood fragments and abundant fish scales, flakes into sheetlike layers	0.5
5.	Shale, dark gray (N3) on fresh surface and olive-gray (5Y 4/1) on weathered surface, very thinly bedded, contains a few thin, resistant, sandy layers	20
4.	Shale, fresh surface olive-gray (5Y 2.5/1) and weathered surface dark yellowish brown (10YR 4/2), noncalcareous, iron-stained, resistant, contains small gypsum crystals	0.5
3.	Shale, fresh surface olive-black (5Y 2.5/1) and weathered surface brownish orange (10YR 6/3), crumbles easily, iron-stained along weathered edges	12
2.	Limestone septarian concretion, fresh surface medium dark brownish gray (N4/0.1) and weathered surface yellowish gray (5Y 7/2), not actually a bed but completely crosses the narrow wash through which this measured section was taken, 3 feet thick and 5 feet in diameter, dark waxy calcite fillings in wedge-shaped joints form dark gray (N3) coarsely crystalline septa	3
1.	Shale, olive-black on fresh surface (5Y 2/1) and olive-gray (5Y 5/1) on weathered surface, thinly laminated and crumbles easily, most of interval is brush-covered, some small silty limestone concretions 175 feet above base show cross-bedding and have medium gray (N5) fresh color, olive-grayish brown (5Y 5/3) weathered color	190±
	Base of Carlile chosen at top of last limestone bed of the Greenhorn Member. Attitude of contact is N. 23° W. 66° SW. Section measured in S. 65° W. direction along gully bottom	
	Total calculated thickness of Carlile Member	434±

CONTINENTAL DIVIDE SECTION (CD)

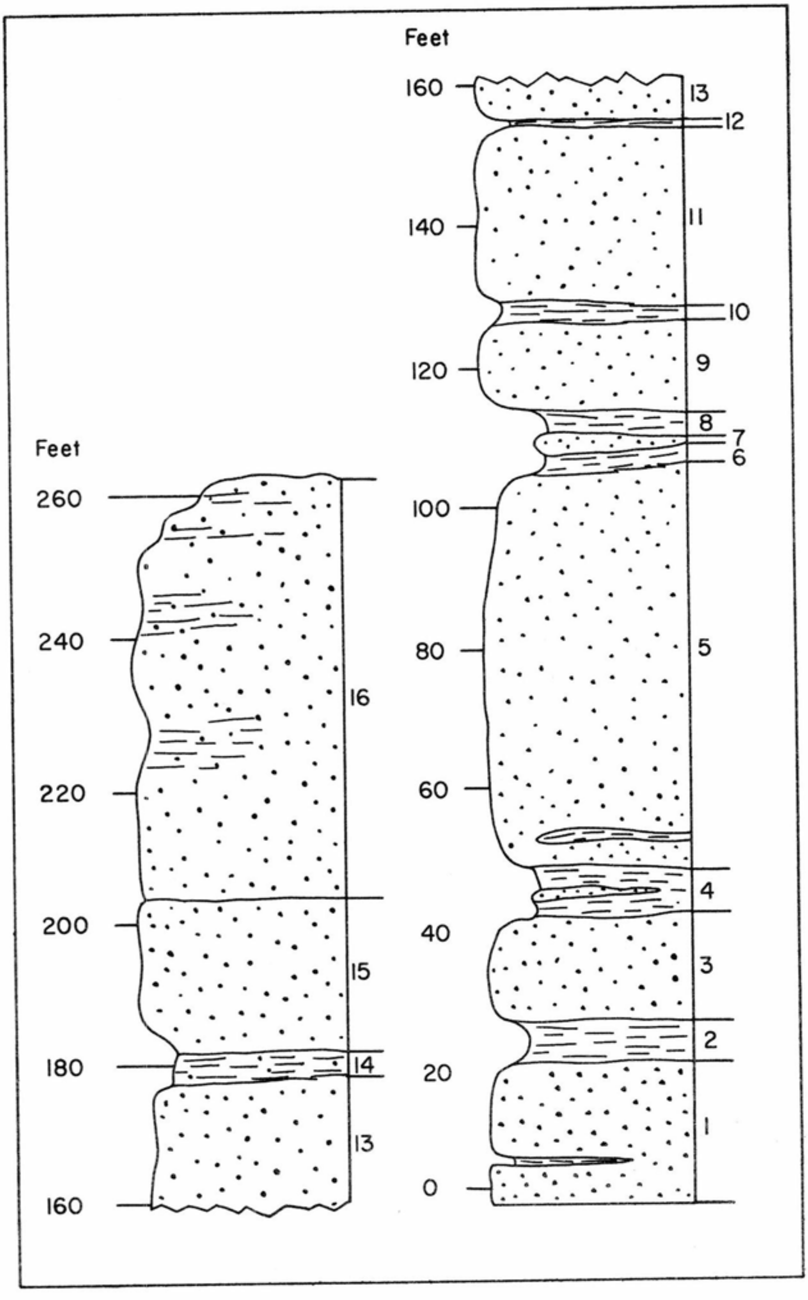
Formation: Mesaverde sandstone

Location: Southeast side of prominent scarp near base of Chromo Peak, latitude 36° 56′ 13″ N., longitude 106° 43′ 25″ W.

Measured by: T. E. Longgood, Jr.

Date: 8 September 1958

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	The formation caps the scarp, but section is incomplete because erosion has removed the upper few feet	
16.	Sandstone (arkose), pale yellowish brown (10YR 6/2), to dark	



CONTINENTAL DIVIDE SECTION

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	yellowish orange (10YR 6/6) bottom to top, parallel-bedded, beds 2-3 feet thick, calcareous, limonitic, and clay cement alternating bed to bed, beds with clay and/or iron cement much more friable than others, fine-grained, poorly sorted, subangular, quartz, weathered feldspar, abundant fresh and weathered glauconite, 21 feet up from base shaly siltstone occurs containing abundant plant and coal fragments giving rock banded light and dark appearance, localized limonite-cemented zones, some bedding and joint surfaces coated with gypsum, forms ledge with stair-step weathering profile	59
15.	Sandstone (arkose), dark yellowish brown (10YR 4/2) and pale yellowish brown (10YR 6/2) on weathered and fresh surfaces, respectively, massive, upper 4 feet composed of parallel 1-foot beds, tight sparry calcareous cement, nonfriable, very fine-grained, fairly well sorted, angular to subangular, quartz, weathered feldspar, abundant fresh and weathered glauconite, distinct limonite banding in upper part of section, from base upward 15 feet ½- to 1-inch diameter limonite concretions occur, forms prominent scarp	21
14.	Siltstone, pale yellowish brown (10YR 6/2), thinly parallel-bedded, limonite stain between laminae, limonite concretions ½- to 1-inch diameter throughout, near lower contact unit becomes shaly, clay cement, very friable, contains minor glauconite, forms slight recess	4
13.	Sandstone (arkose), pale brownish orange (10YR 6/4), massive, clay and limonitic cement, slightly friable, fine-grained, upper 6 feet very fine-grained, poorly sorted, angular, quartz, abundant weathered feldspar, thoroughly weathered glauconite, numerous iron-cemented sandstone concretions ½- to 1-inch diameter weathering out in top 3 feet, patchy limonite streaks, in upper part 1- to 2-foot parallel beds, entire unit pocket-weathered to greater degree than other units, forms ledge	25
12.	Sandstone (arkose), pale yellowish brown (10YR 6/2), parallel-bedded, tight calcareous cement, fine-grained, poorly sorted, angular to subangular, quartz, abundant weathered feldspar, dark heavy minerals, 6-inch sandstone lens bounded by 3-inch shale breaks, neither of which is laterally persistent, forms small ridge in minor recess	1
11.	Sandstone (arkose), moderate yellow brown (10YR 5/4), massive, parallel-bedded, clay cement, very friable, fine-grained, fairly well sorted, angular to subangular, quartz, chert, weathered feldspar (most feldspathic unit in section), trace of weathered glauconite, 15 feet above base 8-foot-thick sandstone bed very tightly calcareous-cemented stands out as ridge and is darker in color than surrounding sandstone, selenite crystals on all bedding and joint surfaces, forms ledge	25
10.	Shale and siltstone alternating, shale olive-gray (5Y 4/1), siltstone moderate yellowish brown (10YR 5/4), fissile, beds 3-4 inches thick laterally discontinuous, limonite concretions 2- to 3-inch diameter in siltstone, forms recess	3

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
9.	Sandstone (subarkose), dusky yellow (5Y 6/4), parallel-bedded, clay cement, very friable, fine-grained, fairly well sorted, subangular, quartz, weathered feldspar, chert, some badly weathered glauconite, 1- to 2-foot-thick beds, nonpersistent small shale lenses throughout, gradational above and below, forms ledge	12
8.	Shale and sandstone alternating, shale medium gray (N5), sandstone pale yellowish brown (10YR 6/2), beds 2-3 inches thick change thickness and lithic character laterally away from measured section, ½- to ¼-inch selenite layers along bedding and joint surfaces, forms recess	4
7.	Sandstone (subarkose), moderate yellowish brown (10YR 5-4), broadly cross-bedded, hard, tight sparry calcareous cement, fine-grained, fairly well sorted, subangular to subround, quartz, weathered feldspar, slight case-hardened, forms ledge	2
6.	Shale, olive-gray (5Y 4/1), fissile, beds ½- to 1-inch thick nonpersistent along strike, gypsum coating on bedding and joint surfaces, forms recess	3
	Units 6, 7, 8 all pinch in and out along strike and coalesce on cliff face into massive, poorly cemented standstone with intermittent 7-inch shale breaks	
5.	Sandstone (subarkose), moderate yellowish brown (10YR 5/4), very broadly cross-bedded, bedding outlined as small ridges by very tight sparry calcareous cement, poor calcareous cement, very friable, fine-grained, fairly well sorted, subangular to subround, quartz, weathered feldspar, chert, slightly case-hardened, beds have semiconchoidal fracture on grand scale, some shale lenses in lower few feet, grains become slightly larger toward top and unit becomes more poorly cemented and more feldspathic, contains scattered small coal fragments, forms prominent scarp	56
4.	Shale and siltstone alternating, shale olive-gray (5Y 4/1), siltstone moderate yellowish brown (10YR 5/4), 1- to 3-inch parallel beds but neither shale nor siltstone is persistent, all bedding and joint surfaces have ⅛- to ¼-inch selenite crystals often twinned, veinlets of gypsum randomly appear in shale, siltstone poorly cemented and very friable, small nonfossiliferous septarian calcareous concretions occur in upper 6 inches, septae of concretions are ¼-inch-thick light brown calcite, forms recess	7
	Moved east around cliff to continue upward from bottom	
3.	Sandstone (impure arkose), pale yellowish brown (10YR 6/2), parallel-bedded, thicker bedded in lower part of unit than toward top, calcareous and clay cement, slightly friable, very fine-grained, poorly sorted, angular to subangular, quartz, slightly weathered feldspar, traces of micaceous minerals, fossiliferous on under side of lower contact, fossils include organisms, impressions, and molds, selenite crystals in all joints and along bedding surfaces, spotty coatings of gypsum on weathered surface, forms ledge	15

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
2.	Shale, medium gray (N5), slightly silty, fissile, contains plant and coal fragments, some localized water seepage from bedding surfaces, forms recess	6
1.	Sandstone, (impure arkose), pale yellowish brown (10YR 6/2), massive, some very broad cross-beds outlined by iron-cement, gypsum and clay cement, very friable, very fine-grained, fairly well sorted, angular, quartz, weathered feldspar, chert, muscovite, some coal fragments, toward top cement changes to sparry calcite then back to gypsum at upper contact, thin shale lenses appear in central part, gradational with underlying Upper Mancos Undifferentiated, forms ledge	20
	Lower contact chosen at first appearance of massive sandstone; some sandy stringers appear below this contact, because of the gradational character of these two units, but the contact used when mapping is one most likely found by other workers	
	Total measured Mesaverde section	263

Willow Creek Section (WC)

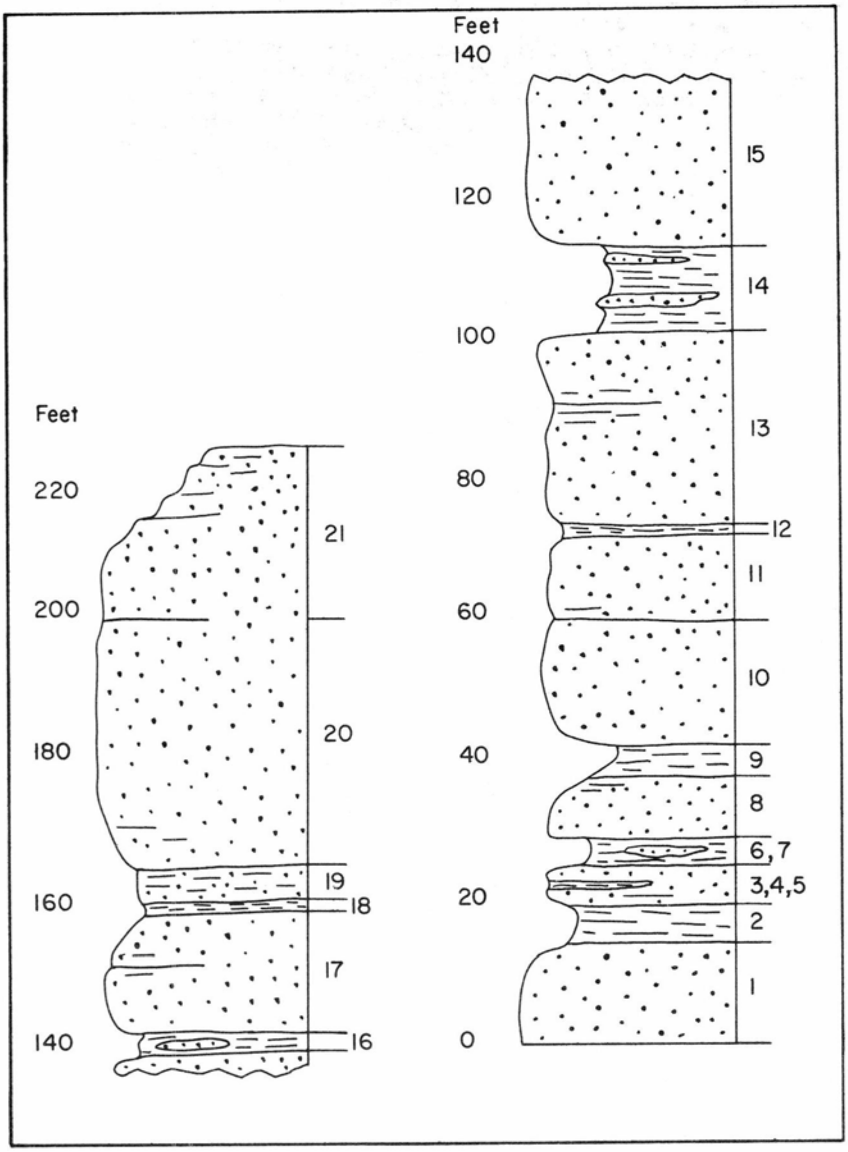
Formation: Mesaverde sandstone

Location: South face of scarp on main cliff, latitude 36° 54′ 30″ N., longitude 106° 38′ 27″ W.

Measured by: T. E. Longgood, Jr., and W. R. Muehlberger

Date: 15 June 1958

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	Top of cliff covered by talus and heavy vegetation. The top of the Mesaverde has eroded, so this is a slightly shortened section. The upper contact, for mapping purposes, was selected where Mesaverde rubble no longer lay strewn about and where bedded shale was uncovered by digging	
21.	Sandstone (arkose), near dark yellowish orange (10YR 6/6), parallel-bedded, within each bed are very broad cross-beds widely spaced, calcareous and limonitic cement, iron cement more pronounced and calcite more sparry in middle third of unit, lower third slightly friable, very fine-grained, fairly well sorted, subangular to subround, quartz, weathered feldspar, abundant fresh glauconite, upper 10 feet less tightly cemented and thinner bedded forming stair-step weathering profile, forms ledge	25
20.	Sandstone (impure arkose), near pale yellowish orange (10YR 8/6), parallel-bedded, clay and limonitic cement, very friable, fine-grained, fairly well sorted, subround, quartz, chert, weathered feldspar, abundant fresh glauconite, some local iron stains in lower 10 feet, few limonite-cemeted sandstone concretions 2-3 inches in diameter in upper 5 feet, 3-inch-thick very highly limonitic cemented zone 6 feet	



WILLOW CREEK SECTION

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	from top, upper 25 feet cemented with sparry calcite, forms scarp	35
19.	Shaly sandstone, pale yellowish brown (10YR 6/2), parallel-bedded, lenses of shale appear and disappear laterally, some localized iron stains, gradational above and below, forms ledge	6
18.	Sandy shale, light olive-gray (5Y 6/1), slightly fissile, unit changes thickness laterally, selenite crystals along bedding and joint surfaces, some gypsum veinlets, forms recess	2
17.	Sandstone (arkose), dark yellowish orange (10YR 6/6), massive, parallel-bedded, very slight calcareous cement, extremely friable, fine-grained, well sorted, subangular, quartz, weathered feldspar, weathered glauconite, plant fragments, pocket-weathered, some localized iron stains along bedding surfaces, forms ledge	14
	In the upper part of this measured section, two distinct colors of glauconite, dark and light green, often occur in the same rock, the difference probably due in part to different chemical compositions	
16.	Siltstone and shale alternating, medium dark gray (N4) to light olive-gray (5Y 6/1), 2- to 3-inch-thick parallel beds, siltstone slightly calcareous-cemented, forms recess	4
15.	Sandstone (subarkose), light olive-gray (5Y 6/1), massive, parallel-bedded, clay cement, fairly friable except in lower 5 feet where it is extremely friable, medium-grained, poorly sorted, subangular, quartz, weathered feldspar, chert, few heavy minerals, plant fragments, distinct limonite stains on some bedding surfaces, greater quartz concentration than in lower units, forms scarp	24
14.	Siltstone and shale alternating, shale medium dark gray (N4), siltstone light olive-gray (5Y 6/1), parallel-bedded, beds 2-3 inches thick, very thin (½ inch) laminae show up within each siltstone, scattered calcareous concretions 6-8 inches in diameter in central part of unit, channel (?) sands dispersed throughout, westward from this locality distinct cross-beds in siltstone, sandstone lens to west, sandstone similar in most respects to unit 7 of this measured section, resin pockets in shale, forms recess	14
13.	Sandstone (subarkose), moderate yellowish brown (10YR 5/4), parallel-bedded, calcareous and limonitic cement, slightly friable, very fine-grained, fairly well sorted, subangular to subround, quartz, weathered feldspar, chert, some small wood fragments, slightly case-hardened, 2- to 5-foot-thick beds, 15 feet from base good siltstone break, upper part is very slightly shaly, forms ledge	25
12.	Shale, light olive-gray (5Y 5/2) and dark yellowish orange (10YR 6/6) on fresh and weathered surfaces, respectively, along bedding surfaces high concentration of wood fragments, lower part silty with some larger foreign shale pebbles, small sandstone lenses in lower part laterally variable in thickness, upper part more fissile, scattered gypsum veinlets in upper part, forms shallow recess	1

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
11.	Sandstone (arkose), yellowish gray (5Y 7/2), broadly cross-bedded, clay cement, extremely friable, fine-grained, fairly well sorted, subangular, quartz, weathered feldspar (local concentration in this unit), chert, plant fragments, very small pockets of limonite stain, shale streaks variable laterally, upper 3 feet more shaly than below, gradational upward into overlying unit, forms ledge	13
10.	Sandstone (subarkose), yellowish gray (5Y 7/2), parallel-bedded, massive 2- to 3-foot beds, clay cement, friable, fine-grained, fairly well sorted, subangular, quartz, weathered feldspar, micas, trace of glauconite, no grooves on basal surfaces as on lower units, forms ledge	18
	From units 9 to 10 moved to west edge of point to continue upward from base of measured section	
9.	Siltstone, yellowish gray (5Y 7/2) and grayish orange (10YR 7/4) on fresh and weathered surfaces, respectively, broad cross-beds outlined by clay concentrations, some local parallel laminae outlined by iron stains, clay and limonitic cement, slightly friable, gypsum crystals on bedding and joint surfaces, wood and coal fragments, lenses of sandstone and shale ½ inch to 8 inches thick, liesegang banding, lenses may be channel deposits, base of overlying sandstone as well as channels has ripple marks striking N. 30° W., forms deep recess	5
8.	Sandstone (subarkose), light olive-gray (5Y 6/1), massive, parallel-bedded, bedding outlined by tightly cemented ridges and concentration of heavy minerals, lower 6 feet clay and iron-cemented grading to sparry calcite cement in next foot, rest is clay cement, fairly friable, fine-grained, poorly sorted, angular to subangular, quartz, slightly weathered feldspar, some patchy iron stains, lower 6 feet of sand thins to 1 foot along strike with diminishing limonite cement, calcite concretions and sandstone pebbles in upper 4 feet, 6-inch-thick stringers of shale irregularly spaced in upper 2 feet, contains ¼- to ½-inch diameter hematite-cemented blebs of quartz grains, some local slumping in shaly upper 1 foot, forms ledge	9
7.	Sandstone (subarkose), light olive-gray (5Y 6/1), parallel-bedded, laminae within beds outlined by concentrations of wood fragments and dark heavy minerals, calcareous cement, nonfriable, very fine-grained, fairly well sorted, angular, quartz, weathered feldspar, trace of fresh feldspar, very compact, contains plant fragments, base of unit has impressions of small pelecypods, worm burrowings, forms ledge	1
6.	Mudstone, light olive-gray (5Y 6/1), parallel-bedded, clay cement, fairly friable, some small pockets with limonite stain, contains reworked pebbles and granules of lower units (maybe 5 and/or 2), forms recess	4
5.	Sandstone (subarkose), yellowish gray (5Y 7/2), massive, clay cement, very friable, very fine-grained, poorly sorted, subangular, quartz, weathered feldspar, worm burrows on basal surface of several beds, plant fragments, beds outlined by thin seams of gypsum or silt partings, ripple marks strike N. 30°	

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	W. and are 10 feet from crest to crest, becomes slightly shaly in upper 6 inches, forms ledge	3
4.	Siltstone, yellowish gray (5Y 7/2) and light olive-gray (5Y 5/2) on weathered and fresh surfaces, respectively, parallel-bedded, shale lenses laterally discontinuous, clay cement, shale similar to unit 2, dark greenish gray (5GY 4/1), 2- to 3-inch-thick beds, some plant fragments, forms recess	1
3.	Sandstone (subarkose), near dusky yellow (5Y 6/4), parallel-bedded, clay cement, fairly friable, very fine-grained, fairly well sorted, angular, quartz, weathered feldspar, metamorphic rock fragments, very similar to unit 1 except finer grained and more poorly cemented, forms ledge	2
	May be diastem here; appears to be 1 and 2 feet of relief on upper surface of unit 2	
2.	Shale and mudstone alternating, shale dark greenish gray (5GY 4/1), mudstone pale olive (10Y 6/2), parallel-bedded, mudstone breaks with semiconchoidal fracture; 2- to 3-inch beds, contain abundant plant fragments, gypsum seams in joints and along bedding surfaces of both mudstone and shale, few scattered small fossil impressions, forms recess	6
1.	Sandstone (impure arkose), near light olive-gray (5Y 5/2) and moderate yellowish brown (10YR 5/4) on weathered and fresh surfaces, respectively, massive, parallel-bedded, bedding outlined by ¼-inch-thick ridges of tighter cement and larger grains, ridges slightly redder and browner than remainder of unit, ridges vary from 2-3 feet apart and persist laterally, clay and limonitic cement, slightly friable, very fine-grained, moderately sorted, subangular, quartz, weathered feldspar, chert, gradational with underlying Upper Mancos Undifferentiated, some shaly streaks interspersed throughout, forms ledge	14
	Basal contact chosen at first massive sandstone bed. Because the Mancos and Mesaverde contact is gradational, some sandstone stringers occur stratigraphically lower but are generally thin and discontinuous. Furthermore, this contact can be traced over most of the area except where covered by landslide material	
	Total measured Mesaverde section	226

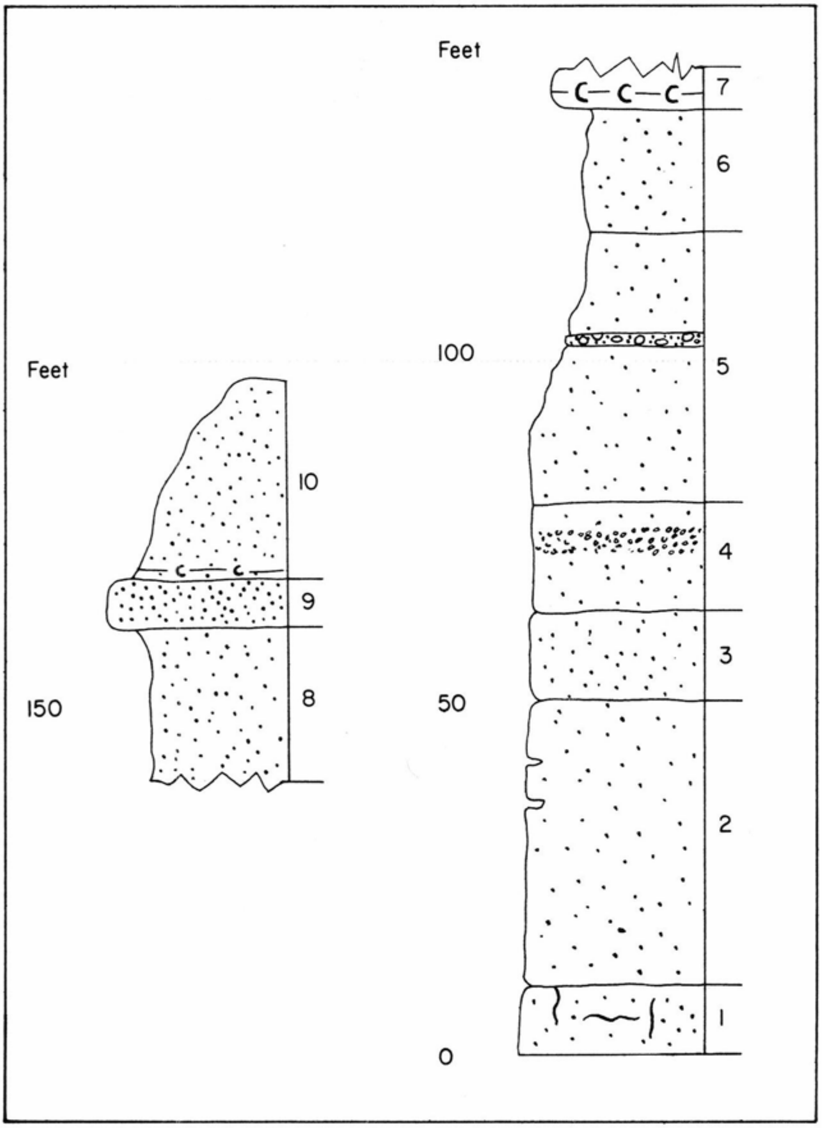
TECOLOTE MESA SECTION (TM)

Formation: Mesaverde

Location: Vertical cliff south of Vertical Angle Bench Mark, United States Coast and Geodetic Survey "Horse-1935-No. 1." Top of section at bench mark, characterized by loose cobble-sized sandstone fragments. Upper Mesaverde eroded away

Measured by: B. E. St. John

Date: 8 September 1958



TECOLOTE MESA SECTION

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
10.	Sandstone (impure arkose), very fine-grained, cobble-sized fragments, contains feldspar, quartz, and glauconite, fresh surface yellowish orange (10YR 7/6) and weathered surface reddish brown (10YR 6/4), forms a sandy soil slope with small coal layer 1 foot above base; clay and ferruginous cement; description of thinsection from top of unit in St. John (p. 31)	28
9.	Silty sandstone (orthoquartzite), contains quartz grains and some shiny black carbonaceous material, fresh surface is light gray (N7) and weathered surface very pale orange (10YR 8/1), forms a ledge, dips 16 degrees due north	7
8.	Sandstone (impure arkose), fine- to medium-grained, fresh surface very pale orange (10YR 8/2) and weathered surface pale yellowish brown (10YR 6.5/2), contains quartz, feldspar, glauconite, and hornblende, subangular and submature, clay cement	22
7.	Coal (subbituminous), fresh surface grayish black (N2.5) and weathered surface light olive-gray (5Y 7/1), low grade, breaks into rectangular fragments up to 6 inches in size	5
6.	Sandstone, same as unit 8	17
5.	Sandstone (impure arkose), fine-grained, fresh surface brownish orange (10YR 6/3) and weathered surface yellowish brown (10YR 6/2), contains quartz, glauconite, carbonaceous material, gypsum crystals, and clay cement; slope begins 13 feet above base, lower 13 feet vertical; 2-foot-thick silt- and clay-ball conglomerate 22 feet above base; pebbles cemented with sandstone, some pebbles of silt and others pure clay	38
4.	Sandstone (impure arkose), fine-grained, fresh surface brownish orange-yellow (10YR 5/5) and weathered surface grayish orange (10YR 7/4), contains quartz, feldspar, glauconite, clay and ferruginous cement, subangular, friable, forms a vertical cliff, massive cross-bedding 2 feet high by 20 feet long; description of thinsection from base of unit in St. John (p. 30)	15
3.	Sandstone (impure arkose), very fine-grained, very light gray (N8) at bottom and dusky yellowish gray (5Y 6/3) at top, bottom has clay cement; iron stains along fractures; subround quartz with minor amounts of muscovite and glauconite at bottom, subround quartz, muscovite, weathered feldspar, clay and ferruginous cement at top	13
2.	Sandstone (impure arkose), very fine-grained, fresh surface dusky yellowish gray (5Y 6/3) and weathered surface yellowish gray (5Y 7/2), contains subround to subangular quartz, muscovite, biotite, glauconite, and weathered feldspar with clay cement, ferruginous stain, massive-bedded, some pothole type of weathering horizontally into cliff face, about 6 inches to 1 foot in diameter	40
1.	Sandstone (impure arkose), very fine-grained, fresh surface dusky yellow (5Y 6/4) and weathered surface yellowish gray (5Y 7/2), ferruginous stains, vertical and horizontal joints about 1 foot apart, massive-bedded, friable, forms vertical face, contains quartz, feldspar, glauconite, muscovite, and clay	

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	cement, subangular, submature; description of thinsection from base in St. John (p. 30)	10 +
	Base of Mesaverde not exposed, measurement began at first exposed sandstone in place; contact between Mancos and Mesaverde is debris-covered	
	Total measured thickness of Mesaverde sandstone	195 +

Chama River Section (CR)

Formation: Blanco Basin

Location: Along northern boundary, east of Chama River, latitude 36° 59′ 47″ N., longitude 106° 30′ 53″ W.

Measured by: G. E. Adams

Date: 21 June 1955

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
22.	Covered interval; landslide debris, probably lower part of the Conejos Quartz Latite	190
	Blanco Basin Formation	
21.	Conglomerate; pale yellowish orange, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, argillaceous cement, forms ledge	42
20.	Siltstone; pale red, interbedded with pale red sandstone	4
19.	Conglomerate; dark yellowish orange to pale red, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite and metamorphic rock grains, argillaceous cement, forms ledge	6
18.	Siltstone; pale red	2
17.	Sandstone; pale red, massive, parallel-bedded, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz and feldspar grains, argillaceous cement, forms ledge	4
16.	Covered interval; probably siltstone	32
15.	Conglomerate; moderate yellowish orange, massive, parallel-bedded, compact, hard, muddy sandy pebble gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic grains, calcareous and argillaceous cement, forms ledge	105
14.	Siltstone; light gray	1
13.	Conglomerate; pale yellowish orange, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	7
12.	Siltstone; light gray	3
11.	Conglomerate; dark yellowish orange to pale yellowish	

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	orange, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	9
10.	Siltstone; light gray	4
9.	Sandstone; pale red, massive, parallel-bedded, interbedded pale red siltstone, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz and feldspar, argillaceous cement, granule conglomerate lenses, forms ledge	9
8.	Covered interval; probably siltstone	11
7.	Sandstone; pale yellowish orange to pale red, massive parallel-bedded, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz, feldspar, and granite grains, argillaceous cement, granule conglomerate lenses, forms ledge	14
6.	Siltstone; grayish yellow to light gray	1
5.	Sandstone; light greenish gray to yellowish gray, massive, parallel-bedded, interbedded with light gray siltstone, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz and feldspar, argillaceous cement, granule conglomerate lenses, forms ledge	17
4.	Covered interval; probably siltstone	31
3.	Conglomerate; moderate yellowish orange, massive, parallel-bedded, compact, hard, muddy sandy pebble gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	19
2.	Covered interval	11
1.	Sandstone; grayish orange-pink to moderate yellowish orange, massive, parallel-bedded, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz and feldspar, calcareous and argillaceous cement, granule conglomerate lenses, forms ledge, base concealed by landslide debris	55 +
	Total Blanco Basin Formation	388
	Total measured section	578

Lobato Fault Section (LF)

Formation: Blanco Basin

Location: West side of stream along Chama fault, latitude 36° 58′ 15″ N., longitude 106° 33′ 04″ W.

Measured by: G. E. Adams

Date: 28 May 1956

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
22.	Covered interval; probably quartzite gravel of Conejos Quartz Latite	13

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	Blanco Basin Formation	
21.	Siltstone; pale red, thin, parallel-bedded	4
20.	Covered interval; probably siltstone	21
19.	Sandstone; pale red-purple, thick, parallel-bedded, compact, hard, muddy very fine to coarse sand, poorly sorted, angular to subangular quartz and feldspar grains, calcareous and argillaceous cement, forms ledge	1
18.	Sandstone; pale red-purple, thick parallel-bedded, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz and feldspar grains, argillaceous cement, forms ledge	1
17.	Siltstone; pale red-purple	1
16.	Conglomerate; pale yellowish orange, thin, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	1
15.	Siltstone; pale red-purple, thick, parallel-bedded, compact, hard	2
14.	Covered interval; probably siltstone	19
13.	Conglomerate; pale yellowish orange, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	16
12.	Sandstone; light greenish gray to pale red, thick, parallel-bedded, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz and feldspar grains, argillaceous cement, forms ledge	2
11.	Conglomerate; pale yellowish orange, thick, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, argillaceous cement, forms ledge	3
10.	Siltstone; light gray to medium light gray, thick, parallel-bedded	4
9.	Conglomerate; dark yellowish orange, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	6
8.	Conglomerate; dusky red to very light gray, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	44
7.	Covered interval; probably siltstone	23
6.	Conglomerate; moderate red, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, argillaceous cement, forms ledge	4
5.	Sandstone; dark yellowish orange, thick, parallel-bedded, compact, hard, muddy very fine sand, poorly sorted, angular	

UNIT NO.	DESCRIPTION	THICKNESS IN FEET
	to subangular quartz and feldspar grains, argillaceous cement, forms ledge	2
4.	Sandstone; dark yellowish orange to pale yellowish orange, thin, parallel-bedded, compact, hard, muddy very fine sand, poorly sorted, angular to subangular quartz and feldspar grains, argillaceous cement, forms ledge	1
3.	Covered interval; probably siltstone	28
2.	Conglomerate; dark yellowish orange to light brown, massive, parallel-bedded, compact, hard, muddy sandy granule gravel, poorly sorted, angular to subangular quartz, feldspar, granite, and metamorphic rock grains, calcareous and argillaceous cement, forms ledge	25
1.	Covered interval; base covered by landslide debris in canyon bottom	60 +
	Total Blanco Basin Formation	268
	Total measured section	281

Appendix B

SEDIMENTARY PETROGRAPHY

The petrographic descriptions below are by T. E. Longgood, Jr., whose work attempted to determine whether distinctive mineralogic changes might permit subdivision of the Mesaverde Group Undivided in the northern Shama quadrangle. No useful consistent changes were found. In addition to the Mesaverde samples, two from the Dakota Formation are included.

The descriptive sequence and terminology follow those of Folk (1957):

I. Reference number, location, formation, stratigraphic level within that formation (see fig. 5 for graphic log showing location of Mesaverde thinsections described)

II. Rock name (in sequence: sorting, grain size, prominent cement, textural maturity, notable clastic constituents, main rock name)

III. Microscopic description

A. Texture: Fundamental end members—per cent terrigenous, allochemical, and orthochemical minerals; *fabric*—general homogeneity, packing, porosity, perfection of orientation and how expressed; *grain size—for* the samples (mean size, sorting, unimodal or bimodal), per cent of each fraction (gravel, sand, mud); textural maturity and or inversions; authigenic cements, percentage and distribution.

B. Mineral Composition: Terrigenous minerals—quartz, chert, feldspar, mica, rock fragments (igneous, metamorphic, sedimentary); heavy minerals, clay minerals; allochemical minerals—pellets, glauconite, fossils; orthochemical minerals.

The following properties are described for each of the above minerals: name; percentage present; occurrence in slide and distribution pattern; physical orientation; grain size, mean size, size distribution; sphericity, sphericity sorting, variations with grain size; variation of roundness with grain size; etching, surface and contact features; overgrowths; inclusions; freshness, alteration products, variations in alteration; varieties of single mineral species; affinities and antipathies of occurrence.

CONTINENTAL DIVIDE SECTION

I. Thinsection 1, Mesaverde, 20 feet above base (labeled 10b-Kmv-110)
II. Moderately sorted very fine sandstone; calcareous submature feldspathic subgraywacke
III. A. Terrigenous 75%, orthochemical 25%; homogenous, loosely packed, no porosity because clay and cement fill all pore spaces, slight orientation of grains parallel with bedding; median 0.090 mm, sand 100%; submature, sparry calcite cement 25%
B. Quartz 34%, uniformly distributed, slightly oriented, mean size 0.100 mm, most is equidimensional, subangular to subround, rounded overgrowths on few grains, apatite and zircon inclusions, few grains vacuolized; chert 3%, slightly larger and more angular than quartz; feldspar 17%, uniform, mean size 0.080 mm, slightly rodlike, subangular to subround, 50% fresh and remaining sericitized and kaolinized in varying amounts, plagioclase (andesine and albite) and microcline; mica less than 1%, detrital fresh biotite and muscovite; phyllite fragments rounded and smaller than either quartz or feldspar, metamorphic quartz includes recrystallized metaquartzite and composite grains (14%); heavy minerals 9%, including garnet, zircon, leucoxene, chlorite, hematite, and tourmaline, of which leucoxene and zircon are the most abundant
I. Thinsection 2, Mesaverde, 55 feet above base (labeled 10b-Kmv-114)
II. Very poorly sorted fine sandstone; sericitic immature impure arkose
III. A. Terrigenous 100%; homogeneous, closely packed nonporous, no grain orientation or mineral loci; median 0.125 mm, sand 90%, silt 4%, clay 6%; immature; sericite and kaolinite cement 6%, more abundant near altered feldspar grains
B. Quartz 36%, random distribution, mean size 0.125 mm, irregular, subround to round, rounded overgrowths on few grains, zircon inclusions, fresh; chert 4%, larger than quartz and more rounded; feldspar 26%, evenly distributed, unoriented, mean size 0.1 mm, slightly lathlike, subangular to subround, one third fresh, two thirds altered to sericite, alteration nearly complete on most grains, microcline, orthoclase, and plagioclase (andesine); trace of detrital biotite and muscovite; metamorphic rock fragments 25%, phyllite and mica schist particles finer than quartz, recrystallized metaquartzite and strongly undulose composite grains, mean size 0.100 mm, rounded, irregular, slightly vacuolized; heavy minerals 7%, include garnet, hematite, chlorite, zircon, leucoxenized ilmenite, and apatite, of which leucoxene, zircon, and garnet are most abundant; few rounded limestone grains
I. Thinsection 3, Mesaverde, 95 feet above base (labeled 10b-Kmv-115)
II. Moderately sorted fine sandstone; calcareous submature cherty feldspathic subgraywacke
III. A. Terrigenous 90%, orthochemical 10%; homogeneous, closely packed, 5% pore space, no grain orientation or mineral loci; median 0.200 mm, sand 100%, trace of clay resulting from alteration of feldspar; submature; calcite cement 5% evenly distributed, some calcite changed to dolomite
B. Quartz 51%, randomly scattered, unoriented, mean size 0.200 mm, near equidimensional, subround to round, 10% of quartz has rounded overgrowths, large zircon and hematite inclusions in most grains, fresh, some slightly undulose; chert 15%, random distribution, slightly smaller than quartz, well rounded, limonite coating on some grains; feldspar 20%, randomly scattered, unoriented, same size as quartz or slightly smaller, slightly elongate, subangular to subround, one third fresh, two thirds altered to sericite and kaolinite, few grains completely altered to sericite, microcline,

plagioclase (andesine) , and minor orthoclase; less than one per cent biotite; metamorphic rock fragments 15%, most are recrystallized metaquartzite and strongly undulose composite quartz grains, rounded, near equidimensional, slightly smaller than quartz and feldspar; heavy minerals 3%, include hematite, chlorite, tourmaline, and leucoxene, of which the most abundant is hematite; less than one per cent sericite

I. Thinsection 4, Mesaverde, 165 feet above base (labeled 10b-Kmv-119)

II. Moderately sorted fine sandstone; ferruginous, submature, micaeous, feldspathic graywacke

III. A. Terrigenous 100%; mica and ilmenite concentrated along cross-bedded surfaces, tightly packed but not well enough to crenulate grain boundaries, nonporous, grain orientation parallel to cross-beds; median 0.120 mm, sand 95%, clay 5%; submature; sericite and hematite cement 5%

B. Quartz 35%, random distribution, oriented parallel with cross-bedding, mean size 0.125 mm, slightly elongate, subangular to subround, most grains have zircon and apatite inclusions, fresh; chert 7%, smaller and more rounded than quartz; feldspar 20%, random distribution, unoriented, mean size 0.100 mm, near equidimensional, subangular to subround, 75% altered to sericite, alteration in varying amounts but uniform for all species, plagioclase (albite), microcline, and orthoclase, microcline most abundant; biotite 4%, detrital, angular, trace of muscovite; metamorphic rock fragments 30%, mostly recrystallized metaquartzite and strongly undulose composite quartz grains, others mica schist and phyllite grains, latter grains smaller and more rounded than all other clastic grains, chlorite alteration of some schist particles; heavy minerals 6%, include ilmenite, apatite, chlorite, and zircon, of which chlorite is most abundant; trace of altered glauconite, alteration product is chlorite

I. Thinsection 5, Mesaverde, 200 feet above base (labeled 10b-Kmv-121)

II. Moderately sorted very fine sandstone; calcareous submature subarkose

III. A. Terrigenous 64%, allochemical 3%, orthochemical 33%; homogeneous, loosely packed, unoriented; median 0.125 mm, sand 100%; submature; sparry calcite cement 33%

B. Quartz 25%, random distribution, unoriented, mean size 0.120 mm, irregular, equidimensional, subangular to subround, inclusions are zircon, apatite, and rutile, fresh; chert 1%, angular, slightly larger than quartz; feldspar 20%, random distribution, unoriented, mean size 0.110 mm, near equidimensional, subangular to subround, half is altered to sericite, most is completely altered but rest only partly changed, orthoclase and plagioclase in near-equal amounts; metamorphic rock fragments 9%, phyllite, talc schist, mica schist, and recrystallized metaquartzite, random distribution, subangular to subround, slightly smaller than quartz, some schist attacked by dolomite; heavy minerals 11%, include chlorite, tourmaline, hematite, leuxocene, and zircon, of which hematite and zircon are most abundant; glauconite 3%, mean size 0.250 mm, fresh and slightly altered to limonite, rounded

I. Thinsection 6, Mesaverde, 210 feet above base (labeled 10b-Kmv-122)

II. Moderately sorted very fine sandstone; calcareous, submature, hematitic, glauconitic, feldspathic subgraywacke

III. A. Terrigenous 76%, allochemical 6%, orthochemical 18%; homogeneous, closely packed, unoriented; median 0.100 mm, sand 95%, silt 5%; sub-mature; sparry calcite cement 18%

B. Quartz 40%, random distribution, unoriented, mean size 0.105 mm, slightly rodlike, subangular to subround, zircon and tourmaline inclusions, fresh; chert 4%, larger and more rounded than quartz, microcrystalline variety; feldspar 18%, random distribution, unoriented, mean size 0.100

mm, subangular to subround, 65% altered to sericite in varying degrees, orthoclase, microcline (most abundant), and plagioclase (andesine); metamorphic rock fragments 13%, random distribution, rounded, slightly smaller than quartz or feldspar, biotite schist, recrystallized metaquartzite, strongly undulose composite quartz grains, and few chlorite schist grains; heavy minerals 6%, include hematite, apatite, zircon, tourmaline, and chlorite, of which hematite is most abundant; glauconite 6%, random distribution, mean size 0.300 mm, well rounded, light green and dark green varieties, few broken fragments off larger grains

I. Thinsection 7, Mesaverde, 240 feet above base (labeled 10b-Kmv-124)

II. Moderately sorted silty very fine sandstone; ferruginous, submature, glauconitic, feldspathic subgraywacke

III. A. Terrigenous 79%, allochemical 7%, orthochemical 14%; homogeneous, closely packed, pores 5%, unoriented; median 0.075 mm, sand 85%, silt 15%; submature (no clay minerals but some clay-sized cement); hematite cement 14%

B. Quartz 42%, random distribution, unoriented, mean size 0.070 mm, ranges from coarse silt to coarse very fine sand, larger grains more equidimensional than smaller grains, subangular to subround, few zircon inclusions and bubble trains, slightly vacuolized; chert 4%, well rounded, mean size 0.065 mm, two grains of chalcedonic chert, remainder microcrystalline chert; feldspar 23%, random distribution, unoriented, mean size 0.075 mm, range 0.080 mm to 0.050 mm, subangular to subround, large particles most rounded, partial alteration on 75% of feldspar, altered to sericite and kaolinite, the former being most prominent; few grains of orthoclase, mostly microcline and plagioclase (andesine and albite), degree of alteration highest on plagioclase; scattered angular detrital biotite and muscovite (less than 1%); metamorphic rock fragments 12%, include recrystallized metaquartzite, phyllite, and some strongly undulose composite quartz grains, rounded and smaller than average quartz grains; heavy minerals 3%, include chlorite and hematite, the latter by far the most abundant

I. Thinsection 8, Mesaverde, 225 feet above base (labeled 10b-Kmv-125)

II. Moderately sorted very fine sandstone; ferruginous, mature, glauconitic subarkose

III. A. Terrigenous 94%, allochemical 6%; homogeneous, loosely packed, 12% porosity, slight grain orientation parallel with length of slide (best seen in polarized light); median 0.100 mm, sand 100%; mature; hematite cement 7%

B. Quartz 35%, random distribution, slight length orientation, mean size 0.100 mm, very slightly elongate, subround to round, few grains spherical and well rounded, zircon and rutile inclusions, fresh; chert 3%, one grain of agate and one of chalcedonic chert, remainder microcrystalline chert, rounded and slightly larger than quartz; feldspar 17%, random distribution, unoriented except plagioclase which is oriented with quartz, mean size 0.100 mm, subround to round, most slightly elongate, some spherical, fresh 5%, sericitized 7%, kaolinized 4% (percentages are of the total rock), microcline and plagioclase (andesine) but mostly orthoclase; metamorphic rock fragments 6%, subround to round and slightly smaller than either quartz or feldspar, mostly recrystallized metaquartzite fragments but also strongly undulose composite quartz grains and few mica schist grains; sedimentary rock fragments 7%, limestone grains, some are nuclei in hematite blebs, well rounded, slightly larger than any other terrigenous fraction; heavy minerals 9%, include zircon, garnet, hematite, tourmaline, leucoxene, chlorite, **and** apatite, of which zircon is most abundant and hematite next; allochemical glauconite 6%, some fresh but most slightly altered to limonite and/or chlorite, rounded, most particles are larger than any other grains but some are fragments and splinters of broken grains, small particles more altered than others

WILLOW CREEK SECTION

I. Thinsection 9, Mesaverde, 5 feet above base (labeled 10b-Kmv-BP-1)

II. Moderately sorted very fine sandstone; ferruginous, submature, cherty subarkose

III. A. Terrigenous 100%; homogeneous, loosely packed, friable, porosity 7%, no grain orientation or mineral loci; median 0.100 mm, sand 95%, silt 4%, clay 1%; submature; hematite cement 5%, most of which is stain from altering hematite and ilmenite

B. Quartz 44%, random distribution, unoriented, mean size 0.100 mm, nearly spherical, subangular to subround, zircon and tourmaline inclusions, fresh; chert 5%, mean size 0.125 mm, well rounded except for the silt-sized grains which are subangular; feldspar 22%, random distribution, mean size 0.090 mm, subround, feldspar more rounded than similar-sized particles of quartz, 40% fresh, remainder altered to sericite, most of the alteration only partial, orthoclase (most abundant), microcline, and plagioclase (albite and andesine); biotite and muscovite 3%, detrital angular grains, packing of the sediment has bent most of the mica during consolidation, biotite is leached of much iron and magnesium, leaving the flakes colorless and almost nonpleochroic, 2% recrystallized metaquartzite and strongly undulose composite quartz, more rounded and smaller than the other grains; heavy minerals 8%, include ilmenite (in varying stages of alteration to leucoxene), zircon, hematite, chlorite, apatite, leucoxene, garnet, and tourmaline, of which leucoxene, hematite, and zircon are the most abundant

I. Thinsection 10, Mesaverde, 30 feet above base (labeled 10b-Kmv-BP-8)

II. Very poorly sorted silty very fine sandstone; calcareous, immature, feldspathic subgraywacke

III. A. Terrigenous 100%; homogeneous except for concentration of mica, hematite, and ilmenite along bedding surfaces, the latter two altering to limonite staining the surrounding grains, loosely packed, distinct layering parallel with the length of slide, grain orientation parallel with layering more pronounced nearer the layers; median 0.075 mm, sand 75%, silt 20%, clay 5% has antipathy for weathered feldspar; clay cement 20% is mostly iron-stained kaolinite; calcite cement surrounds and connects grains

B. Quartz 42%, random distribution, oriented parallel with layering, mean size 0.090 mm with a range from very fine silt to fine sand size, elongate, angular to subangular, apatite, zircon, and bubble train inclusions, some slightly vacuolized but most fresh; feldspar 16%, random distribution, oriented parallel with layering, mean size 0.075 mm, size ranges from very fine silt through very fine sand, elongate, very angular to angular, one third fresh and two thirds altered, alteration nearly complete to sericite (some sericite altering to muscovite), orthoclase and plagioclase (andesine); less than 1% biotite, leached, nonpleochroic, very small relative to other grains; metamorphic rock fragments 15%, include phyllite and recrystallized metaquartzite, the former is small and well rounded whereas the latter is approximately the same size as the other materials but less rounded; sedimentary rock fragments 1%, include rounded large limestone fragments and reworked, large, rounded shale fragments from underlying units; heavy minerals 6%, include chlorite, zircon, hematite, sphene, and pyrite, of which hematite, chlorite, and zircon (largest) are the most abundant

I. Thinsection 11, Mesaverde, 55 feet above base (labeled 10b-Kmv-BP-10)
II. Moderately sorted very fine sandstone; opaliferous, submature, impure arkose
III. A. Terrigenous 95%, orthochemical 5%; homogeneous, tightly packed but weakly cemented, very slight grain orientation parallel with length of slide; median 0.125 mm, sand 100%; submature; cement 5%, calcite was the original cement but is replaced by opal; only ghosts of the original calcite are seen

B. Quartz 40%, random distribution, slight grain orientation parallel with length of slide, slightly elongate, subangular, mean size 0.125 mm, few grains of pegmatitic ("bull") quartz and quartz with rounded overgrowths, no apparent size variation with varieties, rutile and zircon inclusions are rare, fresh; chert 2%, rounded and smaller than common quartz; feldspar 30%, random distribution, unoriented, mean size 0.100 mm, near equidimensional, subangular, 20% fresh, 80% altered, alteration is mostly sericitization but some is kaolinization, alteration nearly complete on most grains, orthoclase and microcline; biotite and muscovite (together 2%), detrital angular particles bent during compaction of the sediment; metamorphic rock fragments 17%, mostly recrystallized metaquartzite and strongly undulose composite quartz but a few grains are phyllite and mica schist, evenly scattered, smaller than quartz, well rounded; few well-rounded limestone fragments, mean size 0.175 mm; heavy minerals 6%, include zircon (very well rounded), hematite, chlorite, tourmaline, leucoxene, and apatite, of which zircon and tourmaline are most abundant

I. Thinsection 12, Mesaverde, 70 feet above base (labeled 10b-Kmv-BP-11)
II. Well-sorted fine sandstone; chalcedonic and calcareous, mature, cherty, impure arkose
III. A. Terrigenous 97%, orthochemical 3%; homogeneous, tightly packed, very faint grain orientation parallel with the length of the slide (best seen in polarized light); median 0.175 mm, sand 100%; mature; calcite (2%) and chalcedonic quartz (1%) cement, both secondary as they appear only where there has been porosity and not where the grains are closely packed, chalcedonic cement restricted to one side of slide

B. Quartz 36%, randomly scattered, oriented parallel with length of slide, mean size 0.180 mm, near equidimensional, subangular to subround, some grains have rounded overgrowths (these grains exhibit strong undulose extinction), few grains have zircon and rutile inclusions, fresh; chert 11%, random distribution, spherical, round, mean size 0.210 mm, fresh; feldspar 26%, uniformly distributed, unoriented, mean size 0.150 mm, subangular to subround, one third fresh, two thirds altered in varying degrees, alteration is sericite but none of the grains is completely obscured by the alteration product; scattered detrital biotite (less than 1%), smaller than common quartz; metamorphic rock fragments 23%, recrystallized metaquartzite and strongly undulose composite quartz, randomly scattered, round, mean size 0.125 mm, fresh; heavy minerals 1%, include chlorite, leucoxene, and hematite (most abundant)

I. Thinsection 13, Mesaverde, 92 feet above base (labeled 10b-Kmv-BP-13)
II. Moderately sorted very fine sandstone; calcareous, submature, ilmenitic, impure arkose
III. A. Terrigenous 94%, orthochemical 6%; homogeneous, closely packed, no grain orientation or mineral loci; median 0.100 mm, sand 98% clay 2%; submature; calcite (6%) and clay (2%) cement, clay is stained by iron mainly from decomposed ilmenite and hematite

B. Quartz 35%, uniformly distributed, unoriented, mean size 0.100 mm, slightly elongate, subangular to subround, few grains have slightly rounded overgrowths, relatively free of inclusions, fresh; feldspar 26%, randomly scattered, unoriented, mean size 0.090 mm, near equidimensional, subangular to subround, 20% fresh, 80% altered in varying amounts to sericite and kaolinite, the latter alteration most complete, altered feldspars a little more rounded than the fresh grains, orthoclase and plagioclase (andesine and albite); few scattered detrital biotite grains, some are leached; metamorphic rock fragments 22%, include recrystallized metaquartzite, strongly undulose composite quartz and mica schist, rodlike, subround to round, randomly distributed, mean size 0.075 mm; heavy minerals 8%, include leucoxene, chlorite, hematite, zircon, garnet, apatite, tourmaline, and ilmenite; ilmenite, leucoxene, and chlorite in order of abundance; glauconite 1%, mean size 0.35 mm, very round, slightly altered to chlorite and limonite

I. Thinsection 14, Mesaverde, 104 feet above base (labeled 10b-Kmv-BP-14ch)

II. Poorly sorted very fine sandstone; calcareous, submature, pyritic, feldspathic subgraywacke

III. A. Terrigenous 76%, orthochemical 24%; homogeneous, closely packed, grain orientation parallel with length of slide, no mineral loci; median 0.070 mm, sand 75%, silt 25%; submature; sparry calcite cement 24%

B. Quartz 36%, uniformly distributed, oriented, slightly rodlike, angular to subangular to subround, the smaller the particle the more angular and less spherical, zircon and apatite inclusions in some grains, fresh; chert 2%, slightly larger and more rounded than common quartz; feldspar 16%, random distribution, unoriented, mean size 0.063 mm, angular to subangular, one third fresh, two thirds altered, alteration product is sericite more complete on the smaller grains, orthoclase and microcline; metamorphic rock fragments 19%, include phyllite, composite quartz and mica schist, rounded and smaller than average grain of common quartz; heavy minerals 3%, include zircon, leucoxene, chlorite, and pyrite; pyrite, the most abundant, occurs in aggregates of cubes and pyritohedrons

I. Thinsection 15, Mesaverde, 136 feet above base (labeled 10b-Kmv-BP-15b)

II. Moderately sorted very fine sandstone; submature, glauconitic, impure arkose

III. A. Terrigenous 97%, allochemical 3%; homogeneous, closely packed, 3% porosity, distinct grain orientation parallel with width of slide, no mineral loci; median 0.125 mm; sand 97%; clay 3%; submature; kaolinite cement 3% most abundant near altered feldspar grains

B. Quartz 42%, uniformly distributed, oriented parallel with width of slide, mean size 0.120 mm, unimodal distribution of sizes that range from 0.063 mm to 0.135 mm, slightly elongate, subangular to subround, few very small grains with rounded overgrowths, rare inclusions of zircon, few grains vacuolized; chert 4%, rounded, mean size 0.100 mm, spherical microcrystalline chert, few grains chalcedonic chert; feldspar 31%, random distribution, unoriented, mean size 0.100 mm, near spherical, angular to subangular, 17% fresh, 83% altered to sericite, alteration complete on only few grains, microcline and plagioclase (albite) ; few grains of angular, fine sand-sized biotite, brown, very pleochroic, oriented parallel with quartz; metamorphic rock fragments 14%, include recrystallized metaquartzite and strongly undulose composite quartz grains which feature intense crenulations of mutual grain boundaries, mean size 0.080 mm, round, vacuolized; heavy minerals 3%, include magnetite, ilmenite, leucoxene, zircon, hematite, and chlorite, of which hematite, zircon, and leucoxene are most abundant; kaolinite 3%, affinity for weathered feldspar, in some places obscured by limonite stain; glauconite 3%, mean size 0.090 mm, very well rounded, altered partly to chlorite, dark green and light green varieties, dark green grains are more spherical

I. Thinsection 16, Mesaverde, 165 feet above base (labeled 10b-Kmv-BP-17)

II. Moderately sorted very fine sandstone; calcareous, submature, glauconitic, impure arkose

III. A. Terrigenous 86%, allochemical 7%, orthochemical 7%; homogeneous, very loosely packed, 8% porosity, no grain orientation or mineral loci; median 0.120 mm, sand 90%, silt 8%, clay 2%; submature; iron-stained calcareous cement 7%

B. Quartz 33%, uniform distribution, unoriented, mean size 0.115 mm, nearly spherical, subangular to subround, some straight-line contact boundaries between quartz grains, few air bubbles as inclusions, fresh; scattered chert grains, round and smaller than quartz; feldspar 28%, randomly scattered, unoriented, mean size 0.075 mm, near equidimensional, subangular to subround, one third fresh, two thirds altered in varying amounts to sericite and kaolinite, none of the alteration is complete, orthoclase and microcline; few grains of sand size angular detrital biotite; metamorphic rock fragments 16%, randomly scattered, rounded, recrystallized meta-quartzite, phyllite, and slate fragments, slightly vacuolized or chloritized; limestone grains 2%, well rounded, very small, heavy iron stain covers most grains; heavy minerals 6%, include hematite, zircon, ilmenite, chlorite, and magnetite, of which zircon and hematite are the most abundant, some of the hematite is very round large blebs which may be altered glauconite; kaolinite 2%, most prominent in proximity to altered feldspar grains; glauconite 7%, scattered, mean size 0.40 mm, well rounded, some etched by dolomite, few grains altered in varying amounts to chlorite or hematite-limonite

I. Thinsection 17, Mesaverde, 195 feet above base (labeled 10b-Kmv-BP-18)

II. Moderately sorted fine sandstone; calcareous, mature, glauconitic, feldspathic subgraywacke

III. A. Terrigenous 74%, allochemical 11%, orthochemical 15%; homogenous, very loosely packed, no grain orientation or mineral loci; median 0.150 mm, sand 100%; mature; iron-stained sparry calcite cement 15%

B. Quartz 37%, random distribution, unoriented, mean size 0.130 mm, spherical, subround to round, few grains have rounded overgrowths, rare rutile inclusions, fresh; feldspar 15%, randomly distributed, unoriented, mean size 0.125 mm, round, 50% fresh and 50% partly altered to sericite, micro-dine, and plagioclase; metamorphic rock fragments 18%, include recrystallized metaquartzite, very strongly undulose quartz, composite quartz grains with crenulated boundaries, and phyllite fragments, the latter altering to sericite; sedimentary rock fragments 3%, rounded, small, iron-stained limestone fragments; heavy minerals 4%, include magnetite, zircon, hematite, and garnet, of which zircon is the most abundant and slightly rounded and large as average common quartz grain, very clear; glauconite 11%, mean size 0.40 mm (more than twice the size of other grains), well-rounded, fresh

I. Thinsection 18, Mesaverde, 216 feet above base (labeled 10b-Kmv-BP-20)

II. Moderately sorted fine sandstone; calcareous, mature, glauconitic subarkose

III. A. Terrigenous 72%, allochemical 8%, orthochemical 20%; homogeneous, loosely packed, no grain orientation or mineral loci; median 0.150 mm, sand 100%; mature; sparry calcite cement 20%

B. Quartz 35%, uniform distribution, unoriented, mean size 0.130 mm, near equidimensional, round, few larger grains have rounded overgrowths, few scattered large zircon and tourmaline inclusions; chert 2%, smaller than quartz and well rounded; feldspar 16%, randomly distributed, unoriented, mean size 0.125 mm, subround to round, one third fresh, two thirds slightly altered, alteration mostly sericite and most prevalent on plagio-clase, few grains show chlorite alteration product, orthoclase (most abundant) and plagioclase (andesine); mica 3%, biotite embedded in hematite blebs, small and rounded; metamorphic rock fragments 3%, recrystallized metaquartzite, -rounded and smaller than other grains; limestone grains 5%, coated by hematite, small and well rounded, some etched by dolomite on outer perimeters; heavy minerals 11%, include tourmaline (blue), zircon, garnet, hematite, apatite, chlorite, and ihnenite, of which fresh hematite, zircon, and garnet are the most abundant, zircons and garnets small and well rounded; glauconite 8%, mean size 0.35 mm, well rounded, mostly fresh, few grains altering to limonite

WILLOW CREEK FAULT SECTION

I. Thinsection 10b-Kd-131, Dakota, 107 feet below top of formation (7 feet above base of exposure)

II. Well-sorted, medium to fine sandstone; siliceous, immature, kaolinitic, and hematitic subarkose

III.*A. Terrigenous 90%, orthochemical 10%; homogeneous, very well packed (crenulation of boundaries on some touching grains), slightly porous (6%), no orientation; median 0.210 mm, sand 93%, clay 7%; immature, textural inversion in that the sediment is well sorted and most grains exhibit some rounding; silica 10%, clay 7%, hematite 2% cement

B. Quartz 60%, random distribution, unoriented, mean size 0.250 mm, near equidimensional, subangular, many grains etched by dolomite, 22% of the quartz has overgrowths, the silica is postconsolidation of the sediment as all the overgrowths show no evidence of rounding and are not present where there was little or no porosity previous to cementation, some grains have zircon inclusions and more than 75% have bubble trains, fresh; chert 1%, very well rounded and much smaller than the average quartz; feldspar 10%, random distribution, mean size 0.200 mm, subangular to subround, altered grains are coated by hematite, nearly equal portions of fresh, kaolinized, and sericitized grains, alteration where present nearly engulfs whole grain obscuring original species, orthoclase; metamorphic rock fragments 14%, random distribution, subangular, dolomite etching of some grains, most grains are fresh, strongly undulose composite quartz grains and recrystallized metaquartzite, the former being the most abundant; heavy minerals 2%, include hematite and ilmenite, the former being the most abundant; clay (mostly kaolinite) 7%, growing in place as evidenced by its splitting overgrowths from host quartz grains; silica and hematite cement with the former more abundant by tenfold

I. Thinsection 10b-Kd-l38, Dakota, 4 feet below top of formation

II. Well-sorted, medium to fine sandstone; siliceous, hematitic, immature orthoquartzite

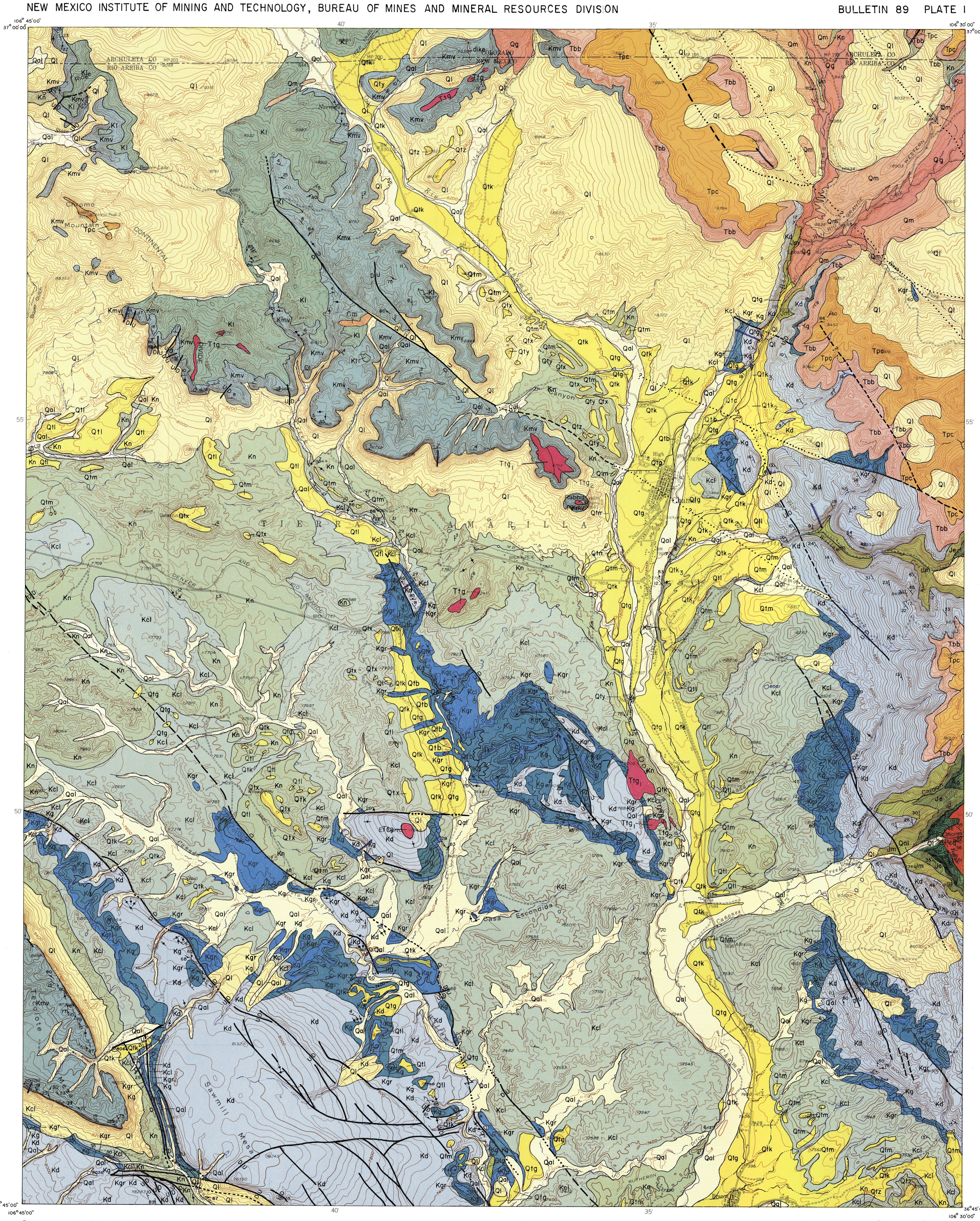
III. A. Terrigenous 89%, allochemical 6%, orthochemical 5%; homogeneous, tightly packed, porosity 8%, no orientation of grains; median 0.250 mm, sand 95%, clay 5%; immature, textural inversion in that the sediment is well sorted and most grains are rounded, but the 5% clay constituent changes the textural maturity from an otherwise mature or supermature rock; silica cement 5% and hematite cement 6%, the silica was deposited during deposition, whereas the hematite was deposited later by ground water and/or decomposition of the hematite heavy minerals

B. Quartz 68%, random distribution, unoriented, mean size 0.300 mm, spherical, subround, round, and well rounded, overgrowths on 22% of quartz, some overgrowths are second generation, the one-generation overgrowths are often rounded, showing redeposition of an older sandstone, bubble trains (in 90% of quartz), zircon, and tourmaline inclusions, fresh; chert

3%, slightly smaller and more rounded than quartz; feldspar 4%, randomly scattered, unoriented, subangular, mean size 0.200 mm, fresh, orthoclase 95% and microcline; heavy minerals 2%, include tourmaline and hematite, of which the latter is by far the most abundant and slightly larger than the former; metamorphic rock fragments are recrystallized meta-quartzite 3.5% and strongly undulose composite quartz 3%, randomly distributed, rounded, slightly smaller than feldspar, some exhibit silica overgrowths in optical continuity with the composite grains; clay 5%, kaolinite; silica and hematite cement 11%, hematite surrounds the host grains with younger overgrowths as well as present cement

Index

Numbers in **boldface** indicate main sections.



Base map enlarged from U.S. Geological Survey Chama fifteen-minute quadrangle, New Mexico

Geology by William R. Muehlberger (1955-1960), Gordon E. Adams (1955), Theodore E. Longgood, Jr. (1958), Bill E. St. John (1958). The University of Texas.

EXPLANATION

QUATERNARY

Recent

Qal — **Alluvium**
Gravel, sand, and silt in stream bottoms

Ql — **Landslide Deposits**
Chiefly shale, friable sandstone and blocks of volcanic and sedimentary rock

Pleistocene ?

Qm Qg — **Moraine**
Till, undifferentiated as to age
Qm = *lateral or terminal moraine*
Qg = *ground moraine*

Qtb, Qtc, Qtg, Qtk (3, 2, 1), Qtl, Qtm, Qtx, Qty, Qtz — **Terrace Deposits**
Qtb, Qtc, Qtg = *Wisconsin-age*
Qtk, Qtl, Qtm = *Durango-age*
Qtx, Qty, Qtz = *Cerro-age*

TERTIARY

Pliocene

Ttg (Ttg_1, Ttg_2) — **Tertiary (?) Terrace Deposits**
Ttg_1, Ttg_2 : *local subdivisions showing relative age*

UNCONFORMITY

Miocene — *Potosi volcanic series*

Tpc — **Conejos Quartz Latite**
Lower unit of gravel, sand, and silt; largely derived from volcanic rocks. Upper unit of flow rock, flow breccia, and tuff ranging from basalt to rhyolite

UNCONFORMITY

Eocene?

Tbb — **Blanco Basin Formation**
Sandstone and arkosic pebble conglomerate chiefly derived from Precambrian plutonic igneous and metamorphic rocks

UNCONFORMITY

CRETACEOUS

Upper Cretaceous

Kl — **Lewis Shale**
Dark, bentonitic marine shale

Kmv — **Mesaverde Group undivided**
Massive sandstone to interbedded sandstone and shale

Mancos Formation

Kn — **Upper Shale and Niobrara Calcareous Shale Members of Dane, Undivided (1948)**
Upper shale member: dark to light gray, highly fissile shale; becomes sandy near the top; generally covered with landslide deposits
Niobrara calcareous shale member: white weathering, highly fissile shale containing abundant Inoceramus grandis fragments; near base throughout central portion of quadrangle is thin, yellow-buff, medium- to coarse-grained, calcareous sandstone or sandy calclithite

Kcl — **Carlile Shale Member**
Black shale; includes Juana Lopez calcareous sand beds in middle part

Kgr — **Greenhorn Limestone Member**
Foraminiferal limestone interbedded with shale

Kg — **Graneros Shale Member**
Black shale

Kd — **Dakota Sandstone**
Vitreous quartz sandstone with carbonaceous silty sand in the middle part

UNCONFORMITY (?)

JURASSIC

Jm — **Morrison Formation**
Light-gray quartz sandstone grading downward into grayish-green to pale-red mudstone. May include Wanakah Formation at base (gypsum pebbles in basal sandstone)

Je — **Entrada Formation**
Massive, grayish-orange friable festoon-bedded quartz sandstone

TRIASSIC

Ћc — **Chinle Formation**
Orange-pink siltstone and arkosic sandstone

UNCONFORMITY

PRECAMBRIAN

P€q — **Kiawa Mountain Formation**
Massive, cross-bedded quartzite

Formation Contact
Dashed where approximately located, dotted where concealed

Fault
Dashed where approximately located, dotted where concealed, U, D show apparent relative movement

Strike and Dip of Bed

Horizontal Bed

Strike and Dip of Joint

Vertical Joint

Location of Measured Section

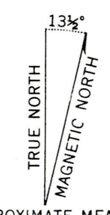
GEOLOGIC MAP OF CHAMA FIFTEEN-MINUTE QUADRANGLE, NEW MEXICO

by W. R. Muehlberger, G. E. Adams, T. E. Longgood, and B. E. St. John, 1963

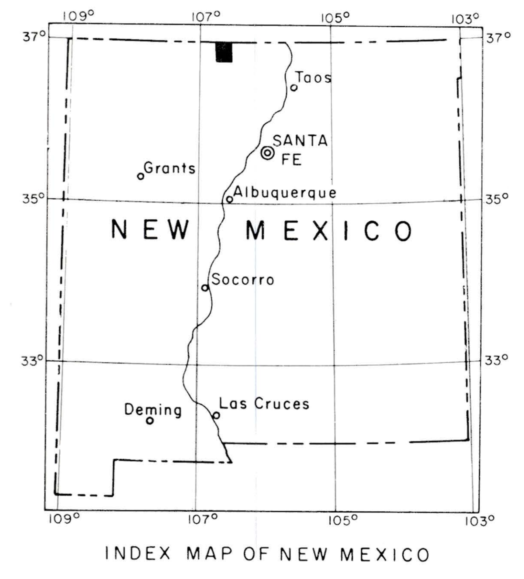
Scale 1:48,000

1 0 1 2 3 4 Miles

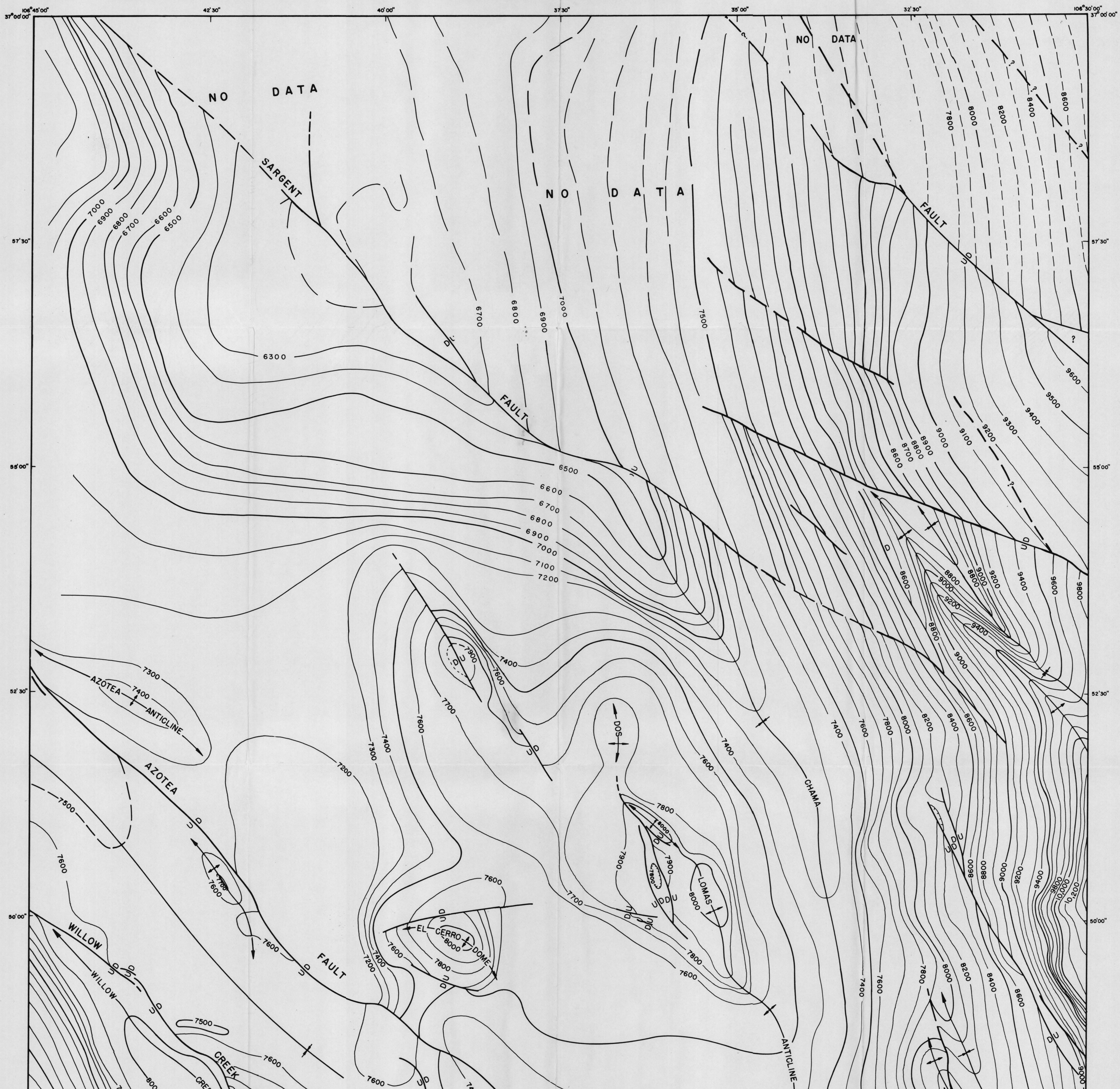
CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL



APPROXIMATE MEAN DECLINATION, 1955



INDEX MAP OF NEW MEXICO



Western one-half modified from structure maps by T. E. Longgood Jr. (NW), B. E. St. John (SW)

STRUCTURE CONTOUR MAP OF CHAMA QUADRANGLE, NEW MEXICO

by W. R. Muehlberger, May 1960

Scale 1:48,000

1 0 1 2 3 4 Miles

100-foot contours on top of Greenhorn limestone