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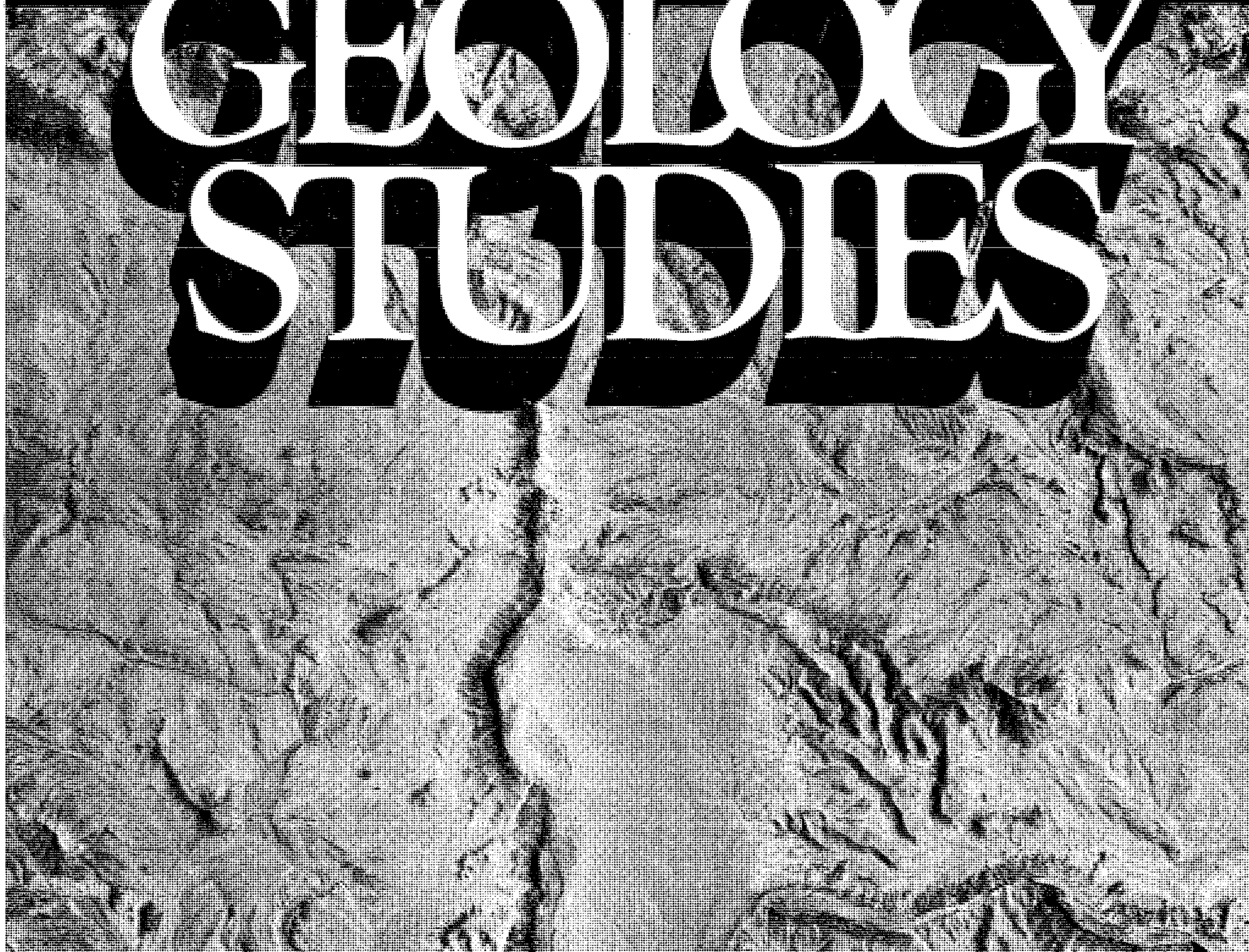

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BRIGHAM YOUNG UNIVERSITY GEOLOGY STUDIES

Volume 27, Part 1

THE GLORY OF GOD IS INTELLIGENCE

Cover: Aerial photograph showing exhumed stream paleochannels in the Cedar Mountain Formation near Green River, Utah. Courtesy Daniel R. Harris.

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Geology of the Sterling Quadrangle, Sanpete County, Utah*

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ABSTRACT.—Deformation of more than 5,000 m of Jurassic through Quaternary strata in the Sterling Quadrangle is best explained by repeated diapirism of the Jurassic Arapien Shale. Numerous angular unconformities and complex facies relationships in the strata have resulted from episodes of diapiric uplift and subsequent erosion in the area. New data on strata formerly called Morrison(?) Formation by Spieker (1949) permits their reassignment to the Tertiary portion of the North Horn Formation. Northerly trending faults and folds in Cretaceous through Quaternary strata adjacent to Sanpete Valley are attributed to the diapiric activity of the Arapien Shale in central Sanpete Valley. The structural interpretation of southern Sanpete Valley using these ideas is compatible with recent geophysical and drilling data in the area. Cretaceous rocks with favorable hydrocarbon potential, previously believed to be exposed at the surface, are now suspected to be located in the subsurface beneath the San Pitch Mountains.

INTRODUCTION

The Sterling Quadrangle has undergone a complex geologic history of sedimentation and diastrophism. Previous investigators have attributed local structural features to monoclinal development (Spieker 1949b) and to compressional tectonics (Gilliland 1963). As a result of new geologic mapping on a 1:24,000 scale, extensive diapirism in Sanpete Valley has been recognized, and rocks previously called Morrison(?) Formation (Jurassic) have been reassigned to the Tertiary portion of the North Horn Formation. This enables a more logical explanation for the development of Sanpete Valley and the structural features found in the adjacent San Pitch Mountains and Wasatch Monocline and suggests a reevaluation of the hydrocarbon potential of the area.

Because previous stratigraphic studies of formations in the Sterling Quadrangle have, for the most part, been adequate, the stratigraphy is not described again in detail. Structural analysis of the features is restricted to qualitative descriptions with cross sections of critical areas.

Location

The Sterling Quadrangle is in southern Sanpete County, near Manti, Utah (fig. 1). It lies in what has been termed geologically the "transition zone" between the Basin and Range and the Colorado Plateau. The western half of the quadrangle includes the southeastern end of the Gunnison Plateau (San Pitch Mountains), west of which typical Basin and Range structures predominate. The west flank of the Wasatch Plateau is located in the eastern half of the quadrangle with structures typical of both the Basin and Range and the Colorado Plateau present. Central Sanpete Valley bisects the study area and narrows to the south end as it intersects Sevier Valley (fig. 2).

Previous Work

Early work in the area included a description of the strata by Spieker and Reeside (1925). Spieker (1946) later made a paleogeographic reconstruction of central and eastern Utah visualizing at least three structural events and their effects on the sedimentary environments. Spieker (1946) divided the Wasatch Formation into three formations: the North Horn, Flagstaff, and Colton Formations. Spieker (1949a) discussed the sedimentary environments in which upper Cretaceous rocks were deposited in the light of associated orogenic activity. Spieker (1949b) listed fourteen separate movements of normal faulting and compressional folding and thrusting in the Sanpete area. Burma and Hardy (1953), Gilliland (1952, 1963), Hardy (1952, 1953), and Stokes (1956) all described evidences for orogenic activity in areas of central Utah. However, none of these investigators related the development of the Gunnison Plateau, Sanpete Valley, and the Wasatch Plateau to one another. Hardy and Zeller (1953) mapped the geology of the west central part of the Gunnison Plateau, and Babisak (1949) mapped its southeastern portion. Gunderson (1961) studied the distribution of the Price River, North Horn, and Flagstaff Formations in the area and interpreted their distribution as being an expression of the tectonic events described by earlier workers. LaRoque (1956, 1960) described the molluscan fauna of the Flagstaff Formation and on the basis of faunal assemblages reconstructed stages in the history of Lake Flagstaff. McGookey (1960) described in detail the early Tertiary stratigraphy of central Utah and outlined a history of the area. Doelling (1972) also described the Tertiary strata of central Utah. The microfauna of the Allen Valley Shale was described by Nikravesh (1964).

STRATIGRAPHY

Rocks in the Sterling Quadrangle range in age from Jurassic to Recent. Lithologies range from coarse clastics to shales

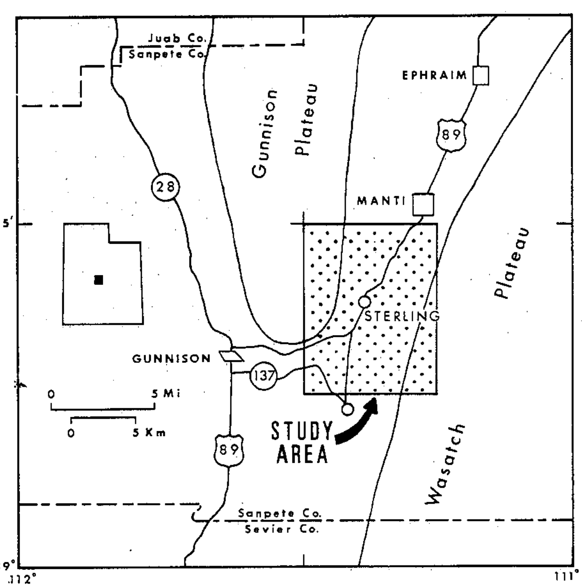


FIGURE 1.—Index map of study area.

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, March 1979. Thesis chairman: James L. Baer.

and from micritic to fossiliferous limestones, with some of them brecciated. Previous studies in the area by Spieker (1946, 1949a, 1949b), Spieker and Reeside (1925), Fagadau (1949), Faulk (1948), Glissmeyer (1959), Green (1959), Nikravesh (1963), Gundersen (1961), Hardy (1952), LaRoque (1956, 1960), and McGookey (1960) have defined most of the units in the study area. For the most part my studies have agreed with those of previous authors; therefore, a detailed redescription of each formation would be redundant. My descriptions are of a general nature except for exposures of North Horn and Flagstaff Formations in the Gunnison Plateau which will be discussed in more detail because of new formational nomenclature presented in this paper. Figure 3 is a general stratigraphic column of the formations in the Sterling Quadrangle.

Jurassic System

Arapien Shale

Spieker (1946) originally defined the Arapien Shale and divided it into the Twist Gulch and Twelvemile Canyon Members. The type section is in the hills west of the Wasatch Monocline and along the east side of Sevier Valley between Mayfield and Salina, Utah. Hardy (1952) raised the two members to formational rank; the lower, Twelvemile Canyon Member, was renamed the Arapien Formation; and the upper, Twist Gulch Member, was renamed the Twist Gulch Formation. Because of the intensely contorted nature of the exposures in the study area and also because the exposures appear to be generally of the same character, I will refer to these rocks collectively as the Arapien Shale.

The Arapien Shale exposures in the central part of the Sterling Quadrangle dip into the subsurface to the north and west of the town of Manti. Exposures are intermittent in the northern half of the quadrangle, being covered by middle and late Tertiary and Quaternary formations. In the southern half of the Sterling Quadrangle, exposures of the Arapien Shale are good and of wide areal extent. The exposures consist of very thinly bedded gray shale; light gray ripple-bedded sandstone and siltstone; red shale with abundant gypsum; and some gray, silty shale with gypsum. Hardy (1952, p. 81–89) gives a detailed description of the exposed Arapien Shale in sections 24 and 25, T. 19 S, R. 1 E and sections 19 and 30, T. 19 S, R. 2 E (fig. 4).

Cretaceous System

Sanpete Formation

The Sanpete Formation, named by Spieker (1946), forms hogbacks along the east side of Sanpete Valley between Manti and Sterling. The complete formation is probably not exposed here, but Spieker (1946) notes that a complete section is found in Salina Canyon, 42 km to the south. The Sanpete Formation consists of medium- to fine-grained, mostly calcareous sandstone and some shale and lenticular conglomerate. The environment of deposition was probably that of a delta prograding to the east into the Upper Cretaceous sea. A partial measured section is described in the appendix under the Indianola Group and is represented by units 1–11.

Allen Valley Shale

The type locality of the Allen Valley Shale, named by Spieker (1946), is in a small strike valley just west of Palisade Lake (fig. 4). The most definitive outcrop of the formation is located on a small knoll in the southwest corner of section 26, T. 18 S, R. 2 E. The only other area in which the Allen Valley Shale is exposed in the study area is in a small valley in N½, SE¼, section 4, T. 19 S, R. 2 E (fig. 4); however, the southeast exposures are mostly covered. Allen Valley Shale consists of gray to greenish brown shale and siltstone with some inter-

FIGURE 2.–Aerial view of Sterling Quadrangle. Major features are noted. View is to the south.

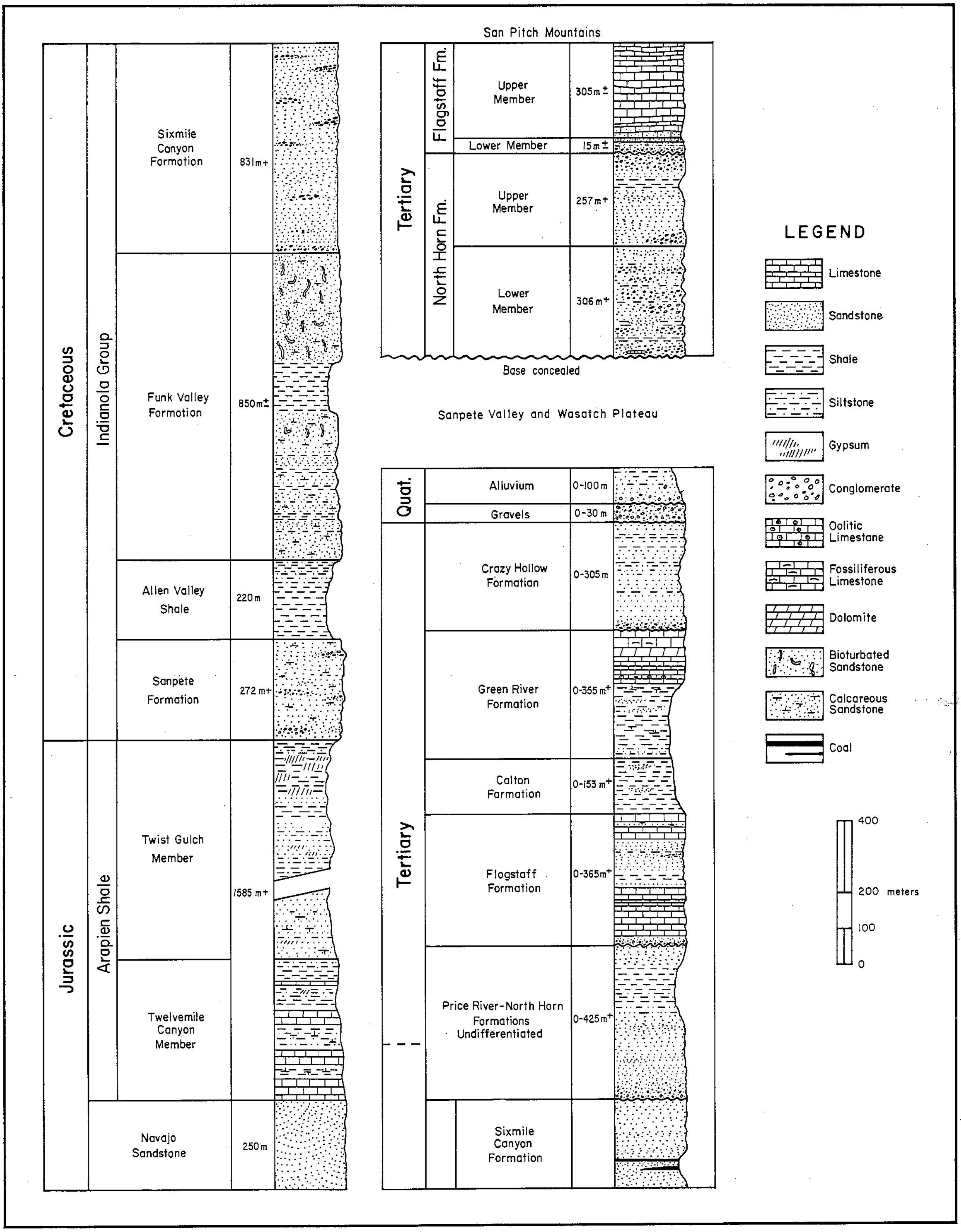


FIGURE 3.—Generalized stratigraphic column of rocks in Sterling Quadrangle.

bedded sandstone described in detail by Spieker (1946). A measured section is given in the appendix under the Cretaceous Indianola Group units 12–17. Nikravesh (1963) described the microfauna of the Allen Valley Shale and pictured the formation as being deposited by a westward transgression of the Mancos Sea. Appearance and disappearance of various species allowed her to reconstruct a history of this area during that time.

Funk Valley Formation

The Funk Valley Formation was originally named and described by Spieker (1946). The type section is from the strike valley of the Allen Valley Shale to the far east side of the valley in which Palisade Lake lies (section 26, T. 18 S, R. 2 E) (fig. 4).

Three units are recognizable in the Funk Valley Formation. The lower unit is a tan to whitish, fine- to coarse-grained sandstone with some interbedded shale. Some horizons in the sandstone contain pelecypod fragments. Towards the top of the unit the sandstones become highly bioturbated. The middle unit is a grayish marine shale that is mostly covered. The upper unit is a highly bioturbated fine- to medium-grained sandstone with occasional bleached horizons. Pelecypod debris and small ironstone concretions can occasionally be found. The sandstones become more uniformly bedded towards the top and are much more indurated.

The Funk Valley Formation represents a regression, transgression, and regression of the Mancos Sea. The bioturbated sands probably represent a near-shore environment with a high degree of biological activity (Reineck and Singh 1975). These sands are highly porous and would make excellent petroleum reservoir rocks. Transition from bioturbation to cross-bedded sands reflects the advancement of the delta to the east. A measured section is given in the appendix under the Indianola Group and is represented by units 18–47.

Sixmile Canyon Formation

Spieker (1946) named and described the Sixmile Canyon Formation. Its exposures lie east of the Funk Valley Formation in the Sixmile Canyon and Funk Canyon areas (fig. 4). I did not measure the Sixmile Canyon Formation; however, Spieker (1949b) gave a thickness of 843+ m. Spieker (1946) recognized three units in the Sixmile Canyon Formation. The lower unit is a gray conglomerate. The middle unit is a coal-bearing member containing fine-grained sandstone, gray shale, carbonaceous shale, and coal. The upper unit is a conglomeratic sandstone. The conglomerate facies does not seem to be as dominant as one might expect from Spieker's description. The Sixmile Canyon Formation appears to be a medium-grained sandstone with pebble conglomerate lenses within it. About all that can be seen of the coal is a few dump remains and covered adits. This formation further represents the eastward advance of the Cretaceous delta with the conglomeratic lenses representing distributary channels.

Price River Formation

The Price River Formation was originally defined by Spieker and Reeside (1925) as the sequence of gray sandstone, grit, and conglomerate lying between the Blackhawk Formation and the lower member of the Wasatch Formation near Castlegate, Utah. The only exposures present in the Sterling Quadrangle are at the mouth of Sixmile Canyon in sections 25 and 36, T. 18 S, R. 2 E and sections 30 and 31, T. 18 S, R. 3 E (fig. 4). The Price River Formation has been combined with the North Horn Formation as a map unit in this study because the two are lithologically similar. However, this combined map unit is found only along the west flank of the Wasatch Monocline on the east side of the Sterling Quadrangle.

Cretaceous-Tertiary

North Horn Formation

The North Horn Formation was originally considered by Spieker and Reeside (1925) to be the lower member of the Wasatch Formation. Spieker (1946) raised the lower member to formational rank and called it the North Horn Formation with the type locality in T. 18 and 19 S, R. 6 E, on North Horn Mountain in western Emery County. The formation in the type locality is dominantly red and purplish variegated shale with some sandstone and conglomerate and also freshwater limestone. In Sixmile Canyon and Funk Canyon the North Horn Formation consists of reddish to tan, medium-grained sandstone with red to purplish shale. A partial measured section from Twelvemile Canyon is given in the appendix. The environment of deposition for the North Horn Formation is considered to be a combination of fluviatile and lacustrine environments.

Tertiary

North Horn Formation

Spieker (1949), Babisak (1949), and Gilliland (1963) described the thick sequence of red channel conglomerate and tan sandstone cropping out along the east front of the San Pitch Mountains as being Morrison(?) Formation and Indianola Group undifferentiated, respectively. For reasons to be discussed in detail below, this sequence is herein assigned to the Tertiary portion of the North Horn Formation. In the San Pitch Mountains area, the North Horn Formation consists of a lower unit of predominantly red, massive channel conglomerate and coarse sandstone with interbedded shale. Whitish gray to pink limestone occurs near the base and stands out as ledges and white patches in the surrounding red shale and sandstone. The upper unit has a basal tan conglomerate then rapidly grades upward into fine- to medium-grained, cross-bedded sandstones with interbedded shales. A gray lenticular conglomerate is present at the uppermost exposure of the formation. A measured section is given in the appendix under Gunnison Plateau Section of the North Horn Formation.

Samples of shale taken near the base of the red conglomerate in the NE¼, SW¼, section 7, T. 19 S, R. 2 E, and from the upper tan units in SW¼, NW¼, section 7, T. 19 S, R. 2 E (fig. 4) were sent for palynological study to Peter K. Groth and E. T. Peterson of Amoco Production Company, Denver, Colorado. Although recovery was poor, they determined the age of the samples to be Tertiary and the environment of deposition to be freshwater. Separate samples of the limestone at the base of the conglomerate and of a calcareous shale near the same location in the NE¼, SW¼, section 7, T. 19 S, R. 2 E (fig. 4) were sent to Dan L. Pearson of Phillips Petroleum Company in Bartlesville, Oklahoma, to be tested for nannoplankton. The samples were barren of nannoplankton and indicate a freshwater origin for the limestone.

Previous workers in the area have called these red conglomerates Morrison(?) Formation (Jurassic) and the upper tan sandstones Cretaceous Indianola (Spieker 1949b, Gilliland 1963, Babisak 1949). However, the red conglomerates do not resemble the Morrison conglomerates found near Thistle and Salina, Utah, and although the upper tan sandstone looks like the Indianola sandstones on the opposite side of the valley, they also resemble sandstones found in the North Horn Formation.

The abundance of gastropods and charophytes in the limestones (fig. 5) and of algal oncolites (fig. 6) near the base suggests a Tertiary age for the conglomerates in the San Pitch Mountains. Also, for reasons to be discussed with the structural geology, the assignment of these rocks to the Tertiary portion of the North Horn Formation seems to better fit the structural configuration.

Tertiary System

Flagstaff Formation

The Flagstaff Formation was originally described as the middle member of the Wasatch Formation by Spieker and Reeside (1925). Later Spieker (1946) designated the middle member as the Flagstaff Limestone, raising it to formational rank. Gilliland (1951), however, noting that in areas of the Valley Mountains and parts of the western Gunnison Plateau, the Flagstaff Limestone also contained considerable sandstone and conglomerates, changed the name to the Flagstaff Formation. The type locality of the Flagstaff Formation is located at Flagstaff Mountain, T. 20 S, R. 5 E, in Sanpete County, Utah.

In the Sterling Quadrangle the Flagstaff Formation is exposed along the west flank of the Wasatch Monocline and along the top of the San Pitch Mountains. It generally consists of light brown to cream colored micritic limestone, calcareous sandstone, and some dolomitic limestone. In Twelvemile Canyon a tongue of fluvial sandstone and shale is exposed near the middle of the section. Fagadau (1949) details several measured sections of this formation from locations along the west flank of the Wasatch Monocline. A measured section of part of the Flagstaff Formation in Twelvemile Canyon is given in the appendix. No section was measured in the San Pitch Mountains. The Flagstaff Formation in the San Pitch Mountains is, however, different from the Flagstaff Formation found along the west flank of the Wasatch Monocline. Flagstaff micritic limestone in the San Pitch Mountains is brecciated (fig. 7), and the limestone on the east side of the study area is not. Also, at the base of the Flagstaff Formation on the west, there is an oncolite conglomerate with coarse sandstone (fig. 8), grading upward into a silty limestone and then into the brecciated micritic limestone. The development of these relations will be discussed below under geologic history.

Colton Formation

The Colton Formation was originally designated as the upper member of the Wasatch Formation by Spieker and Reeside (1925), but later given formational rank by Spieker (1946). The type locality is north of Colton, Carbon County, Utah. It consists of gray, salt-and-pepper sandstone, greenish buff sandstone and siltstone, and red and variegated shale. The Colton Formation in the Sterling Quadrangle is similar to that described in the type locality; however, the gray, salt-and-pepper sandstones are not present. In the Sterling Quadrangle tongues of greenish buff, cross-bedded sandstone interfinger with underlying Flagstaff Formation and the overlying Green River Formation making the location of a sharp boundary often impossible. Thickness of the Colton Formation ranges within the quadrangle from zero in some areas of central Sanpete Valley to 153+ m in parts of North Hollow in the southeast quadrant of the study area. The Colton Formation is absent in the San Pitch Mountains, but to the west it crops out on the west side of Antelope Valley in the northwest corner of the quadrangle. Small exposures are also located in sections 27, 28, 34, T. 18 S, R. 2 E (fig. 4), in Sanpete Valley. No section was measured in the study area; however, a complete section is located in section 11, T. 19 S, R. 2 E (fig. 4).

Green River Formation

In the Sterling Quadrangle the Green River Formation is exposed in the southern part of the area as cuestas along the west flank of the Wasatch Monocline and in central Sanpete Valley in unconformable contact on the Arapien Shale. Sections measured in and near the study area are given in the appendix. Generally the formation consists of a lower green shale unit and an upper thin to massively bedded limestone and dolomitic unit. The section in North Hollow contains two or three sandstone lenses not found in the west section in the Chalk Hills.

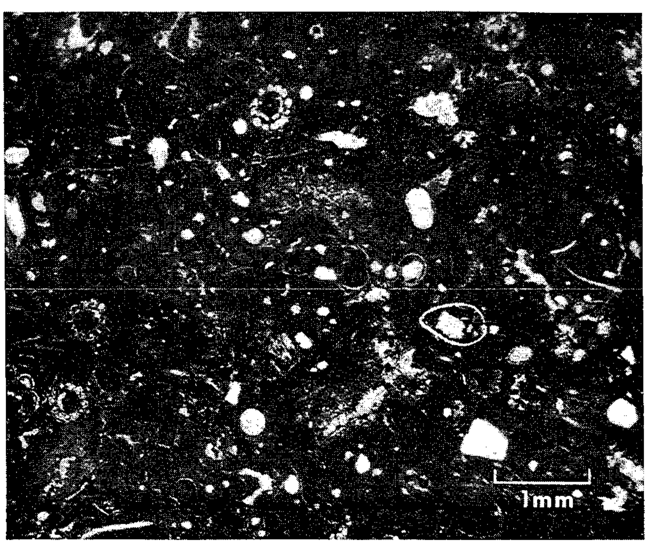


FIGURE 5.–Abundant charophytes and gastropod fragments make up freshwater limestones on east front of San Pitch Mountains. X16, crossed nicols.

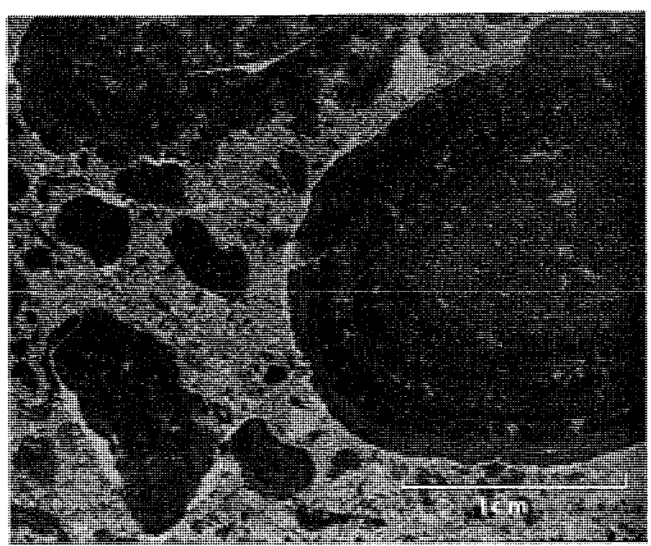


FIGURE 6.–Sandy limestone clast enveloped by algal filaments forming oncolite in lower membrane of North Horn Formation of San Pitch Mountains. X3.6.

An oolitic limestone facies near the middle of the formation can be traced throughout the study area and is comparable to some horizons found in the basal unit of Faulk (1948). In addition, algal reef float was found at the base of the cliffs in the Chalk Hills (section 14, T. 19 S, R. 1 E) west of the Sterling Quadrangle. Although not located in the measured section, the algal reef probably occurs somewhere in the middle of the formation in the Chalk Hills. This may possibly be correlated with part of zone B after Faulk (1948); however, no algal material was found in the east on the flanks of the Wasatch Monocline. The upper units of the formation throughout the study area contain silica in the form of chalcedony in fracture fillings and as chert nodules and lenses in some of the massive limestone beds. This may be the result of volcanic activity nearby. An apparent weathered ash bed occurs in the Chalk Hills section, unit 4.

Crazy Hollow Formation

The Crazy Hollow Formation was first described and named by Spieker (1949). The type section is located in Crazy Hollow, sections 5 and 8, T. 22 S, R. 1 E, in Salina Canyon. The formation there consists of red and orange sandstone, siltstone, and shale, light gray sandstone, and salt-and-pepper sandstone. Locally it contains broad conglomeratic lenses. McGookey (1960, p. 605) published a detailed measured section from the type locality.

In the Sterling Quadrangle the character of the formation is almost identical to that described above. The Crazy Hollow Formation was not measured, but a very good exposure occurs in the railroad cuts in section 22, T. 18 S, R. 2 E (fig. 4). In addition, patches of Crazy Hollow Formation occur on the cuestas of the Green River Formation in the southeast part of the quadrangle and on the Arapien Shale in central Sanpete Valley. The conglomerate facies of the formation is present in the study area only in the exposures in section 22, T. 19 S, R. 2 E (fig. 4) in the southeast part of the quadrangle. The Crazy Hollow Formation represents a sequence of fluvial deposits laid down during an erosional cycle following gentle uplift.

Quaternary System

The Quaternary System is represented in the Sterling Quadrangle by valley fill and stream gravels along the San Pitch River and Twelvemile Creek and also by a series of terrace gravels located at various elevations throughout the study area.

Terrace gravels in the area are generally composed of the same material. Babisak (1949) and Gilliland (1963) have called them Axtell Formation; however, they do not contain any volcanic clasts. Clasts of Indianola sandstone, North Horn sandstone, fossiliferous Flagstaff limestone, and micritic Green River units are easily identifiable in these gravels (fig. 9). The clasts range in size from about 0.4 m to fine sand. Color in the gravels, some of which are well lithified, range from grayish orange pink to a yellowish orange. Gravels on the west side of Sanpete Valley contain more quartzitic cobbles than on the east side, and the Flagstaff cobbles are the brecciated type found in the west part of the study area. The presence of these gravels at various elevations throughout the area is valuable in estimating relative amounts of vertical movement (fig. 10).

Three landslides are present in the Sterling Quadrangle. They occur only on the east side in association with the Wasatch Monocline. The largest landslide is found in Forbush Cove (fig. 11). Material from this slide can be found as far west as the town of Sterling (fig. 4). It is composed of material from the North Horn and Flagstaff Formations. Large springs are found in Forbush Cove, and the slide probably resulted from water saturation of shales in the North Horn Formation, with consequent collapse of the strata. The slide was probably quite fluid as indicated by the large area over which it spread and the low, generally nonhummocky profile it has in Sanpete Valley. The upper silicic and dolomitic units of the Green River Formation comprise the large slide southeast of Sterling (fig. 12). This slide, in contrast to the one in Forbush Cove, has moved only a few hundred meters. The slide has no fan at the foot, but appears to have piled up near the southeast corner of section 9, T. 19 S, R. 2 E (fig. 4). A smaller slide, affecting the lower shale units and some limestone units in the Green River

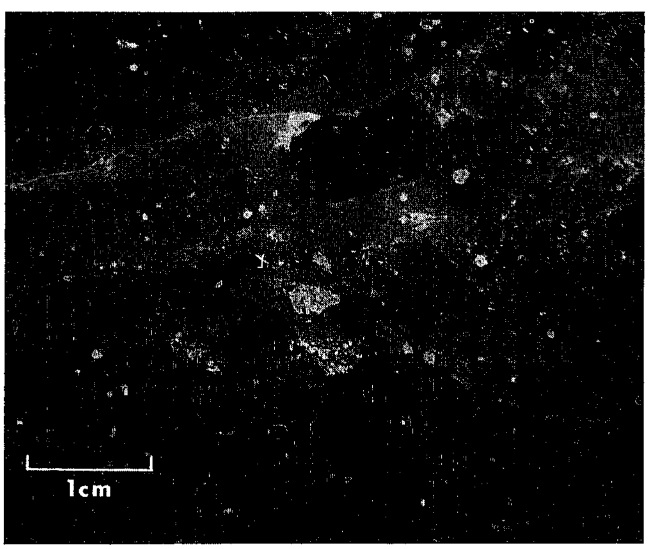


FIGURE 7.—Brecciated limestone in Flagstaff Formation of San Pitch Mountains. At least two phases of brecciation can be seen megascopically. X2.

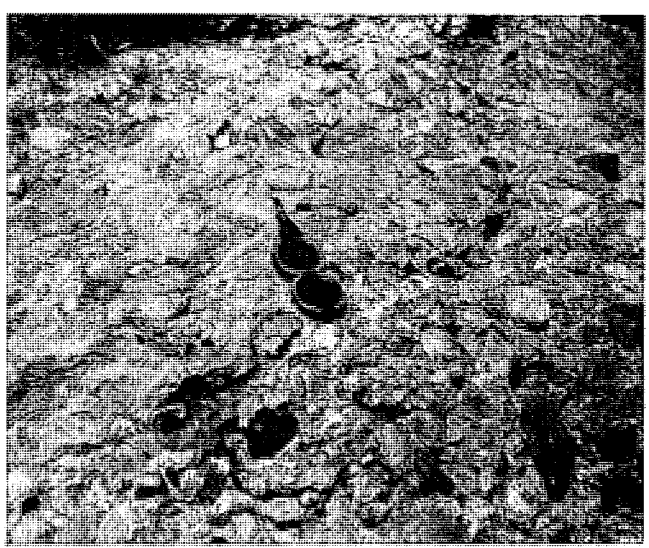


FIGURE 8.—Oncolite conglomerate facies of lower member of Flagstaff Formation in San Pitch Mountains. Oncolites are cored by quartzite cobbles identical to those in lower North Horn Formation.

Formation, has covered part of the Colton and Flagstaff Formations in section 4, T. 19 S, R. 2 E (fig. 4).

STRUCTURAL GEOLOGY

The Sterling Quadrangle can be divided into three structural regions (fig. 13):

1. East region, characterized by parallel normal faults and a monoclinal flexure.
2. Central region, characterized by a diapir of the Arapien Shale.
3. West region, characterized by three sets of normal faults and thrusting within the North Horn Formation.

All three regions contain angular unconformities. Both the east region and the west region have been greatly affected by the diapiric activity that has taken place in the central region.

East Region

Faults

Normal faults trend north-south to northeast-southwest along the east side of Sanpete Valley and Arapien Valley (fig. 4). The faults east of Arapien Valley in the southern half of the study area dip steeply to the east into the monocline and have displacements on the order of a few tens of meters (fig. 4, cross section A-A'). Maximum offset on these faults is probably only 30 m. Offset of upper Green River limestone units along these faults has formed a series of cuestas along the west flank of the Wasatch Monocline.

The parallel faults in the Palisade Lake area and in sections 3 and 4, T. 19 S, R. 2 E, trend more to the northeast-southwest than do those in the southern half of the study area. The faults are essentially parallel to the underlying Cretaceous beds. They dip steeply to the west, with the exception of the easternmost fault (section 35, T. 18 S, R. 2 E), which appears to dip steeply to the east. Offset along these faults is probably less than 15 m and can be seen only where the Flagstaff Formation is displaced. The faults are almost impossible to trace through the bioturbated sandstones of the Funk Valley Formation.

Faults along the east side of the Sterling Quadrangle are probably due in part to slippage along bedding planes in the underlying Cretaceous rocks. East of Arapien Valley they may have occurred in response to settling of the strata after the formation of the Wasatch Monocline. The faults in the vicinity of Palisade Lake are probably the result of gravitational adjustment following diapiric activity in that area.

Diapir

Some diapirism has occurred in the eastern region and is independent of major diapiric activity in the central region. This activity has created a small doubly plunging, northeasterly trending anticline, part of which is shown in figure 14. The dip of the overlying Green River and Flagstaff Formations clearly indicates the anticline at the base of the Wasatch Monocline. This "satellite" diapir is probably responsible for the high elevation and exposure of the Indianola Group. At no other place in the Sterling Quadrangle are these rocks exposed. The faults which parallel the trend of the axis probably bottom out in the underlying Arapien Shale and were formed in response to settling of the strata after uplift.

Unconformities

The double angular unconformity described by Spieker (1949b) is exposed near the mouth of Sixmile Canyon in section 25, T. 18 S, R. 2 E (fig. 15). Sixmile Canyon Formation strata dip 50–55° east and are capped by Flagstaff Formation dipping 53° west and by the combined Price River–North

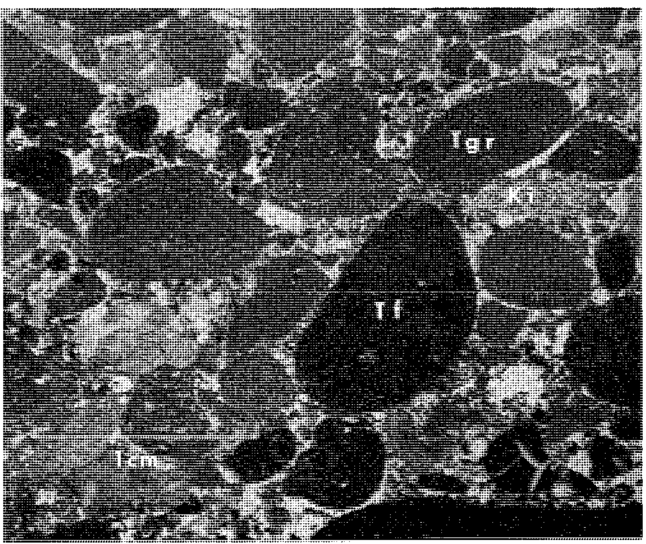


FIGURE 9.–Clasts found in Quaternary gravels represent sandstones of Indianola Group and North Horn, Flagstaff, and Green River Formations found in adjacent areas. X3.6.

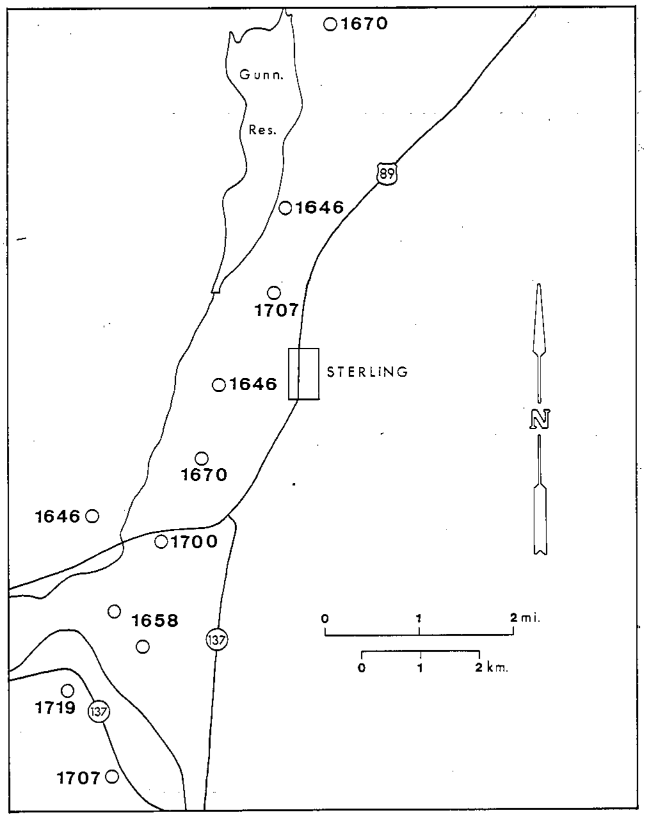


FIGURE 10.–Locations and elevations (in meters) of Quaternary gravels in Sterling Quadrangle. Note that a greater amount of recent uplift has occurred in southern part of study area.

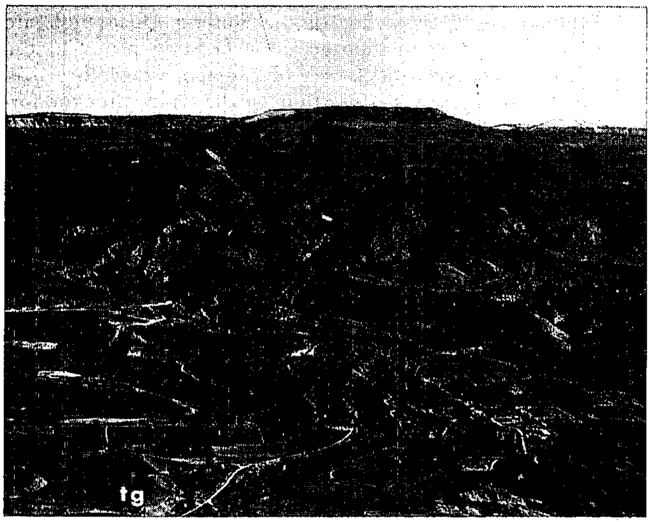


FIGURE 11.—Aerial view looking east onto Wasatch Plateau showing large landslide in Forbush Cove. Slide material can be found in all areas of lower part of photo.

FIGURE 12.—Aerial view looking southeast at landslide in Green River Formation south of Sterling.

Horn Formations dipping approximately 20° to the east in the immediate vicinity of this double angular unconformity. As can be seen in figure 4, the Sixmile Canyon Formation dips into the subsurface near the mouth of Sixmile Canyon. The Price River–North Horn Formation rapidly changes and dips to the west with the Wasatch Monocline a few hundred meters into the canyon. A few hundred meters to the right of the area shown in figure 15, the North Horn and Flagstaff Formations are in conformable contact. Immediately west of the double angular unconformity and also southeast of Sterling, middle Flagstaff Formation limestones (Kenneth O. Stanley pers. comm. 1978) lie unconformably on rocks of the Funk Valley and Sixmile Canyon Formations. The Flagstaff Formation in this area dips gently to the east off the east flank of the small anticline (fig. 14). The underlying Cretaceous rocks are overturned to the east in section 26 but are upright and dipping 50–55° to the east farther up Sixmile Canyon.

Spieker (1949b) attributed this configuration to a series of alternating eastward and westward dipping monoclines in this vicinity. His sequence of events does not explain, however, the existence of the North Horn–Flagstaff unconformity on the west side of Sanpete Valley in the San Pitch Mountains (fig. 16). For reasons to be discussed below, diapirism of the Arapien Shale is the most tenable process by which deformation has occurred in the Cretaceous through Quaternary strata. It better explains the structural similarities found on the east and west sides of Sanpete Valley (cross section C-C', fig. 4). Episodic diapirism in central Sanpete Valley and subsequent erosion have created the unconformable relationships throughout the Sterling Quadrangle.

In the south half of the eastern region in sections 21, 22, 23, 27, and 28, the Crazy Hollow Formation lies disconformably on the upper units of the Green River Formation—the result of a late episode of erosion and deposition.

Central Region

Diapir

The major structure in the central region of the Sterling Quadrangle is a large diapir of Arapien Shale. It has formed a northeasterly trending anticlinal structure (cross section B-B', fig. 4) that is complexly folded and overturned on the west side. Cretaceous through Quaternary rocks have been disturbed by the diapir.

The diapirism is considered to be the result of flowage of salt and gypsum-bearing shale in the Arapien Shale. Thickness

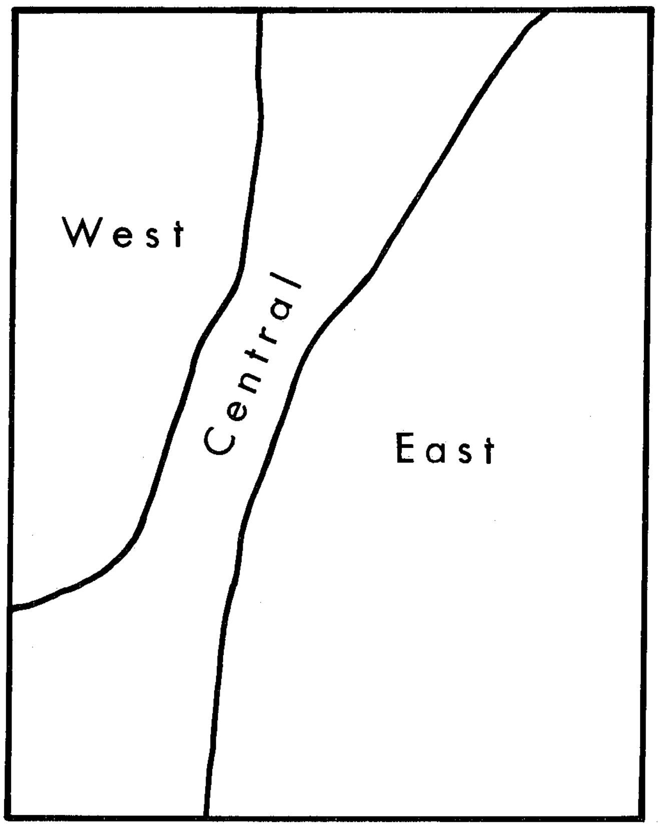


FIGURE 13.—Sketch map showing three regions in Sterling Quadrangle each characterized by similar structural features.

of Cretaceous rocks in the study area now is more than 2,100 m. At least 2,100 m of Cretaceous sediments also accumulated in what is now Sanpete Valley. This amount of sedimentary loading, according to Talbot's (1978) calculations, is sufficient to cause diapirism. Later Tertiary sedimentary loading could also activate the diapirism. High temperatures (386°F BHT at 15,555 ft below sea level, A. Paul Baclawski pers. comm. 1978) encountered in the Hanson-Moroni well in north Sanpete Valley suggest that heat flow in Sanpete Valley is high. According to Talbot (1978) temperatures of this magnitude could aid in causing diapirism by creating thermal convection within the salt body. Loading of thick Cretaceous and Tertiary sediments, in addition to high heat flow in Sanpete Valley, may be the reason for the large-scale diapirism of the Arapien Shale.

Diapirism in central Sanpete Valley has probably caused the deformation of post-Arapien strata in adjacent areas. Areas immediately east and west of the Sterling Quadrangle do not show structures indicative of strong compressive forces. Such forces would have been necessary to cause the high degree of deformation evident in the Jurassic through early Tertiary rocks in the Sterling Quadrangle. The overturning of the anticline to the west indicates directed stress from the east; however, it has been well documented that stresses during this period were directed toward the east. A gravity survey of the area indicates that low density material underlies central Sanpete Valley and parts of the Wasatch Monocline (Cook and others 1975). In light of this evidence and the calculations of Talbot (1978), diapirism of the Arapien Shale best explains the structures in the Sterling Quadrangle and adjacent areas.

Folding of the Colton and Green River Formations in sections 27, 28, 33, and 34, T. 18 S, R. 2 E (fig. 4) is due to the bifurcation of the main diapir creating a "satellite" diapir at the base of the Wasatch Monocline. Tilting, folding, and elevation of Quaternary gravels has resulted from more recent diapiric activity, particularly in the southern half of the study area.

Unconformities

Middle and late Tertiary and Quaternary rocks are in unconformable contact with the diapiric Arapien Shale throughout the length of the central part of the Sterling Quadrangle. In the hills located in sections 17 and 18, T. 19 S, R. 2 E (fig. 4), the Green River Formation lies unconformably on Arapien Shale (fig. 17). The Green River Formation is composed of medium-grained, tan, calcareous sandstone at the basal contact in this area. The sandstone is not brecciated, and its bedding planes are clearly defined. In the northern part of the study area (sections 27, 28, 33, and 34, T. 18 S, R. 2 E), the contact between the Colton Formation and the Arapien Shale is covered by alluvium. Other smaller exposures of the Green River Formation lying on Arapien Shale are present between the two areas mentioned above.

Originally, Spieker (1949b) described these contacts as strip thrusts. The oppositely dipping Green River exposures in sections 27, 28, 33, and 34, T. 18 S, R. 2 E were explained by a series of normal faults in addition to the strip thrust. The contact shown in figure 17 clearly shows that thrusting did not create these unconformable contacts. The brittle sandstones at the contact are not brecciated as might be expected in rocks found at the sole of a thrust. Also, the Arapien Shale at the contact does not show evidence of being deformed by thrusting. It seems more reasonable that a topographic high of Arapien Shale in the Green River Lake was gradually submerged as the sediments of the Colton and Green River Formations filled

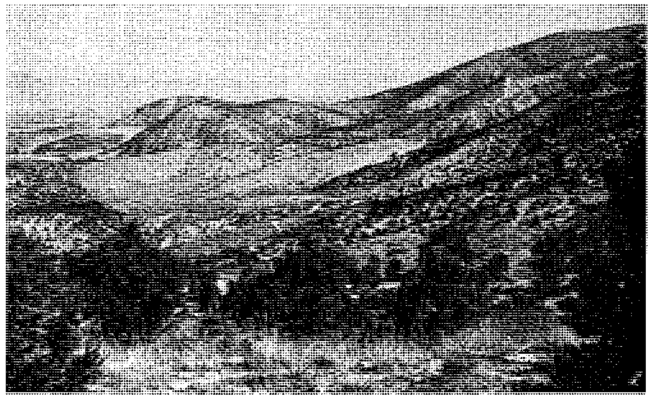


FIGURE 14.—View to north showing west flank of Wasatch Monocline (right margin) and east flank of small, doubly plunging anticline at center of photograph.

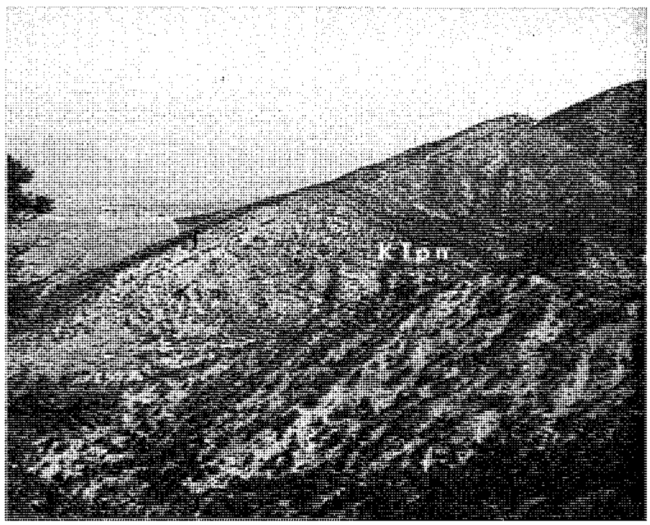


FIGURE 15.—Double angular unconformity of Spieker located at mouth of Sixmile Canyon. View is toward the north.

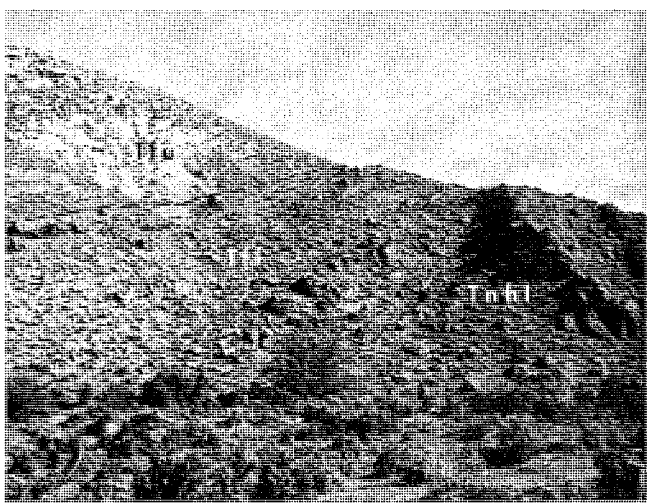


FIGURE 16.—View looking north at the North Horn–Flagstaff angular unconformity at south end of San Pitch Mountains.

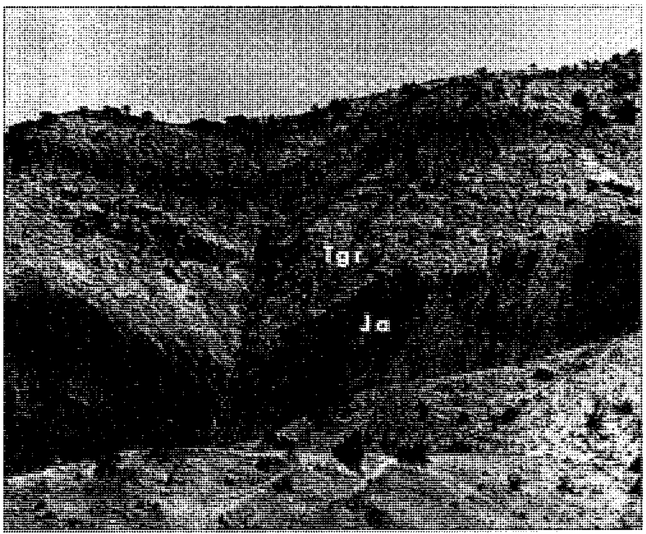


FIGURE 17.—View looking east at Green River Formation lying unconformably on Arapien Shale in section 14, T. 19 S, R. 2 E.

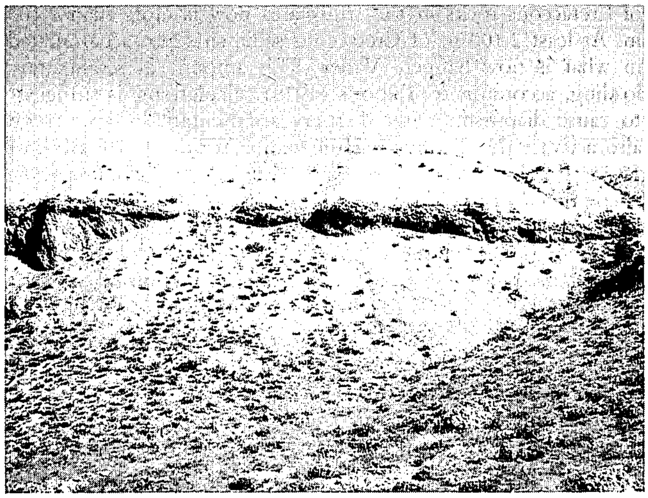


FIGURE 18.—View to the north of Quaternary gravels lying unconformably on overturned Arapien Shale in central portion of study area, section 18, T. 19 S, R. 2 E.

the lake. The contact itself (fig. 17) appears to be depositional and not of structural origin.

The Crazy Hollow Formation is in unconformable contact with both the Arapien Shale and the Green River Formation in sections 15, 22, and 27, T. 18 S, R. 2 E in the northern part of the study area. To the north of Ninemile Reservoir (fig. 4) another small patch of Crazy Hollow Formation lies on the Arapien Shale. The origin of this small patch is difficult to determine because of the poor exposure. The Crazy Hollow Formation in the north part of the Sterling Quadrangle was deposited following a period of uplift and subsequent erosion of the Green River Formation. This accounts for the angularly unconformable contact between the Crazy Hollow Formation and the Green River Formation.

Quaternary gravels lie unconformably on the Arapien Shale throughout the central region. These gravels are generally horizontal (fig. 18) but are tilted and folded in SW¼, SW¼, section 8, T. 19 S, R. 2 E, and E½, section 24, T. 19 S, R. 1 E (fig. 4). The different elevations of these gravels (fig. 10) indicate mobility of the Arapien Shale, during the Quaternary.

West Region

Faults

Normal faults and small-scale thrust faults occur in the west region but do not have the linear continuity of those in the east region. Three sets of normal faults occur in the San Pitch Mountains. Faults in sections 20 and 29, T. 18 S, R. 2 E (fig. 4), trend northwest-southeast and have a scissor type of displacement. The west block on these faults is upthrown, with the greatest displacement occurring at the southeastern end. These faults were formed as the central part of the San Pitch Mountains was uplifted. The remaining normal faults in the San Pitch Mountains do not show the scissor type of displacement. Determination of the amount of displacement on these faults is difficult because facies changes are too rapid to allow identification of marker beds. Faults in the central and southern sections of the San Pitch Mountains are probably the result of gravitational settling of the strata following uplift.

Small-scale thrust faulting has occurred within the North Horn Formation in the San Pitch Mountains. Bedding in the North Horn Formation indicates that the diapir in the central region has overturned the beds to the west 180°+ (fig. 19). Some overturned beds have segments of upright beds caught between them (fig. 20). Near the south tip of the San Pitch Mountains a large syncline in the lower North Horn Formation is exposed (fig. 21). The beds in the syncline are upright, but on the east limb they are almost vertical. Beds immediately to the east of the area shown in figure 21 are overturned to the west. The degree to which these rocks have been overturned and folded and the relationship of upright beds to those that are overturned, as described above, suggest that some thrusting has occurred within the formation. As the overturning and folding of the formation progressed, upright units (probably from the upper part of the formation) were caught between areas that were deforming at differing rates. It appears that the lower units deformed at a faster rate and were thrust by some upper units that were deforming at a slower rate. Figure 20 shows the resultant type of structure. The syncline at the south tip of the San Pitch Mountains may be a much larger remnant of the same sequence of events.

Diapir

The diapir as seen in the central region of the Sterling Quadrangle is not present in the west region. However, the effects of diapirism in central Sanpete Valley are clearly shown in the exposed rocks. Structures in the San Pitch Mountains indicate uplift similar to the doubly plunging anticline in the Palisade Lake area. The orientation of bedding planes in the upper Flagstaff Formation undulate in sections 29 and 30, T. 18 S, R. 2 E (fig. 4). The westward dip of the Flagstaff Formation is much greater in the central part of the San Pitch Mountains than it is in either the north or the south end.

The attitude of the beds in the Flagstaff Formation, together with the scissor faults described above, indicates that significant uplift has occurred in the central San Pitch Mountains. This uplift is also due to diapirism. The San Pitch Mountains in general appear to be doubly plunging, producing a structure similar to the one in the Palisade Lake area. The faults in the southern half of the San Pitch Mountains may also be due to collapse over a small diapir located beneath the area.

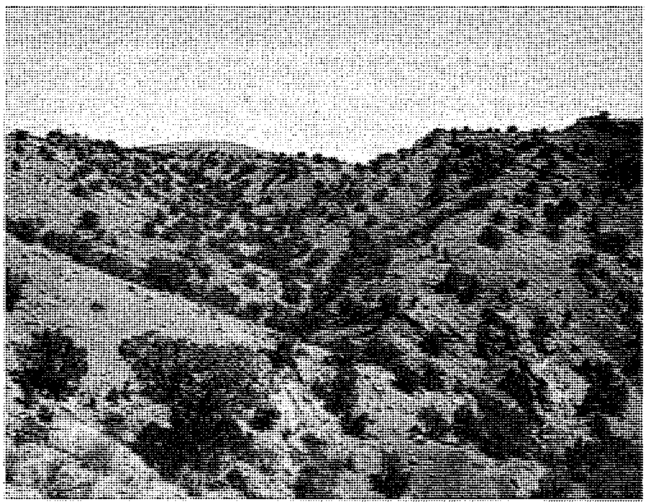


FIGURE 19.—View to the north of beds in North Horn Formation overturned to the west, section 7, T. 19 S, R. 2 E.

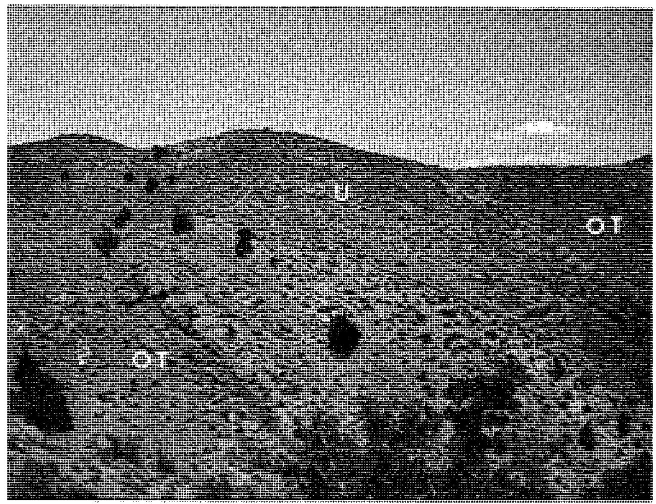


FIGURE 20.—Upright beds of North Horn Formation caught in lower units folded back over by the diapir. View looking north in section 7, T. 19 S, R. 2 E.

Unconformities

At the south end of the San Pitch Mountains, section 13, T. 19 S, R. 2 E, the North Horn–Flagstaff unconformity crops out (fig. 16). The North Horn Formation is overturned steeply to the west, and the Flagstaff Formation is upright and dipping to the west. The basal Flagstaff Formation at the contact ranges from a very coarse sand to an oncolite conglomerate (fig. 8). The oncolites are cored with quartzite cobbles identical to those found in the conglomerates of the North Horn Formation in the San Pitch Mountains. The contact shows evidence of Lake Flagstaff lapping onto a topographic high of North Horn Formation with valleys eroded into it. Although the Price River–North Horn Formation–Indianola Group unconformity (fig. 15) is not exposed here, its equivalent (the North Horn–Indianola unconformity) is located in the subsurface beneath the San Pitch Mountains (cross section B-B', fig. 4). Spieker (1949), Babisak (1949), and Gilliland (1963) interpreted the red conglomerates to be Morrison(?) Formation and the lower member of the Flagstaff Formation to be North Horn Formation. No angular unconformity between the North Horn Formation and the Flagstaff Formation was recognized by these investigators on this side of the Sanpete Valley. The reassignment of the red conglomerates to the North Horn Formation allows for a Flagstaff–North Horn unconformity on the west side of the Sanpete Valley. With the North Horn–Indianola unconformity located in the subsurface, the Sevier–Sanpete Valley anticline described by Gilliland (1963) is symmetrical (see fig. 22 for a comparison).

GEOLOGIC HISTORY

Structures in the Sterling Quadrangle indicate that its geologic history has been complex and structurally active since late Cretaceous time. The following sequence of events is envisioned for the Sterling Quadrangle area.

Jurassic Period

During the Jurassic Period the area was covered by a shallow sea, partially restricted from contact with the open sea. Hypersaline sea water in embayments resulted in the deposition of salt and gypsum in the Arapien Shale. The latest Jurassic Morrison Formation, present in Salina Canyon and near Thistle in Spanish Fork Canyon, is not present in the study area.

Cretaceous Period

The Cretaceous Period began with the deposition of the coarse clastics of the Sanpete Formation. These were the first sediments to reach the area from the Sevier orogenic front to the west. Cretaceous rocks in the area represent a deltaic sequence with a transgression of the sea represented by the Allen Valley Shale. Eventually the delta prograded its way eastward across the area, and fluvial continental deposits represented by the Sixmile Canyon Formation completely covered the area (fig. 23A).

Near the end of the Cretaceous Period, the salt and gypsum in the Arapien Shale started diapiric action in southern Sanpete Valley. Erosion of Cretaceous rocks as they were uplifted and simultaneous deposition of the Price River–North

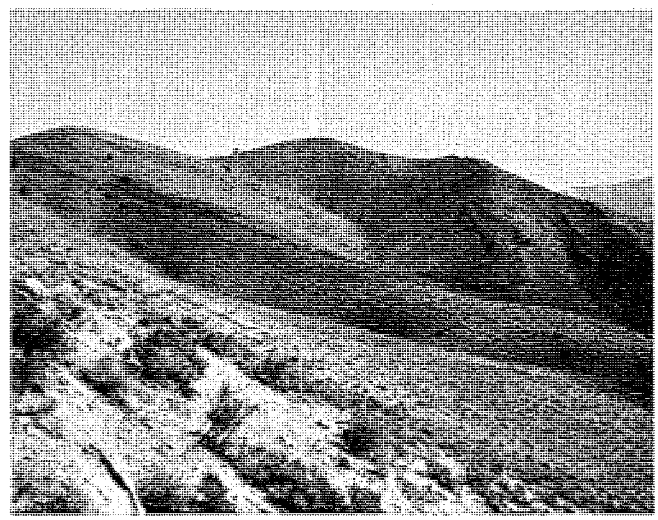


FIGURE 21.—Syncline in North Horn Formation, near southeast end of San Pitch Mountains, may be result of infolding by upper units in lower units as they were folded back and overturned by the diapir. View to the north.

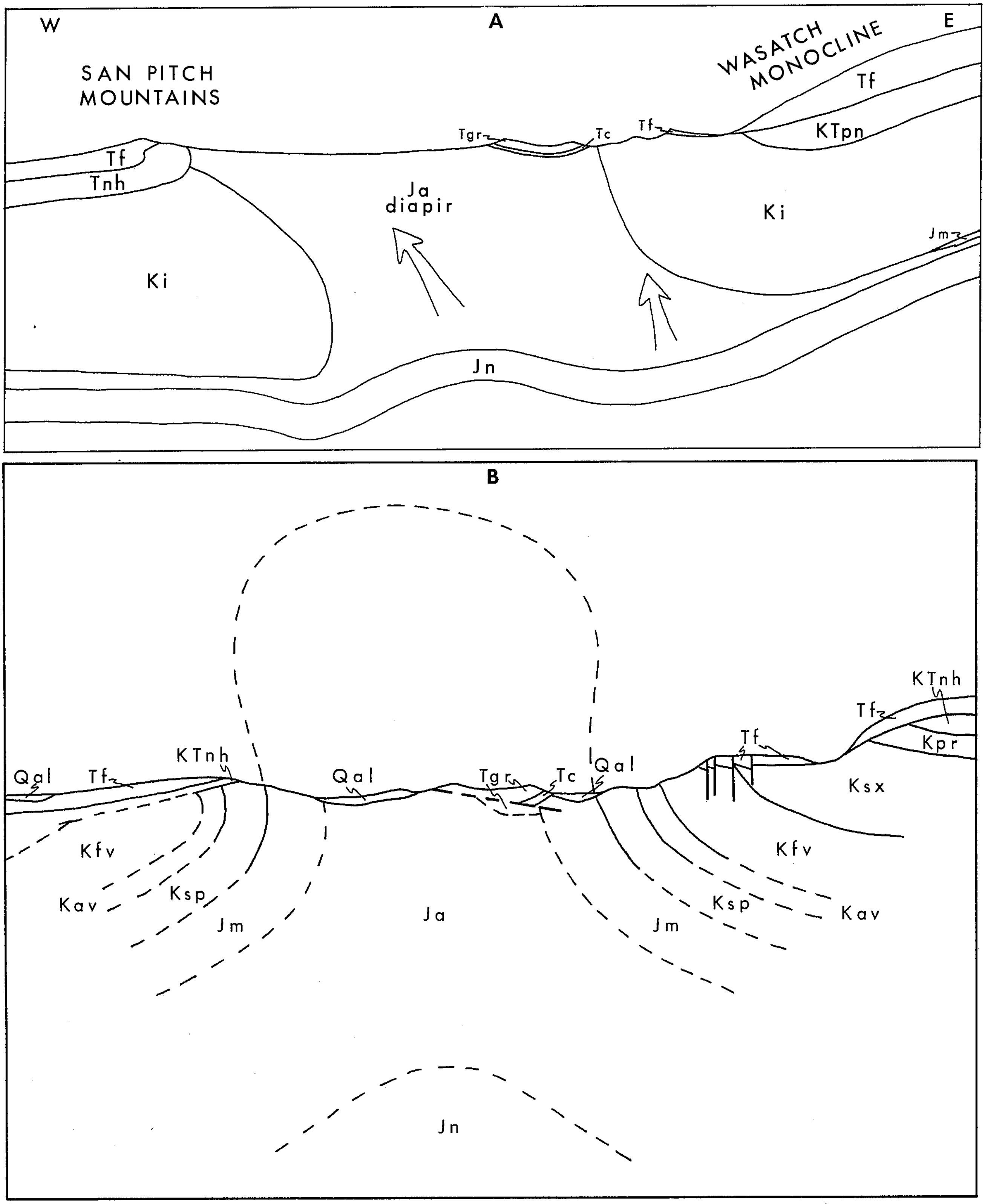


FIGURE 22.—Comparison of structural configuration proposed in this study (A) and that proposed by Gilliland (1963) (B). Note that the proposed interpretation of the Sterling Quadrangle allows for two episodes of uplift and erosion in the area of the San Pitch Mountains. Evidence for this is clear in Sixmile Canyon; however, previous investigators (Spieker 1949b, and Gilliland 1963) have not noted evidence for this sequence of events in the San Pitch Mountains area. New evidence presented in this study to show that what has been called Morrison(?) Formation is rather Tertiary North Horn Formation allows the Cretaceous Indianola Group-North Horn Formation unconformity to be located in the subsurface beneath the San Pitch Mountains. The development of the diapir of Arapien Shale in southern Sanpete Valley better explains the geological development of Sanpete Valley and allows for two episodes of uplift and erosion in the San Pitch Mountains area.

Horn Formation created a configuration like that shown in figure 23B. The size of the cobbles in the lower North Horn Formation in the San Pitch Mountains suggests that the source area for the North Horn Formation was closer than for the Cretaceous rocks. The upper part may have been partially derived from the eroded Cretaceous rocks in Sanpete Valley. This alternation of the sediment source for the North Horn Formation may explain the difficulty in stratigraphic correlation of the formation in the Sanpete Valley area.

Some freshwater lakes must have been present in the area during this time. Freshwater limestone with charophyte, gastropod, and some ostracod fragments occurs near the base of the conglomerates and as lenses within conglomerates. Rocks of the North Horn in the San Pitch Mountains are younger than those in Sixmile Canyon. They have been dated as Tertiary by P. K. Groth and E. T. Peterson (written comm. 1978).

Tertiary Period

The diapir grew upward following the deposition of the North Horn Formation and overturned on the west side putting the North Horn Formation at a high angle to the surface. Canyons were eroded in the anticline, and quartzite cobbles, eroded from the lower North Horn Formation, were washed around in Lake Flagstaff. Algal material accreted on these cobbles forming oncolites, which comprise part of the near-shore facies of the lower Flagstaff Formation in the San Pitch Mountains (fig. 8).

Lake Flagstaff lapped on the high of Cretaceous rocks in the Sixmile Canyon area until at least middle Flagstaff time (LaRoque 1960). This action created a pebble conglomerate facies found at the Flagstaff–Funk Valley contact. However, the oncolite facies found in the San Pitch Mountains is not present in the east side of the Sterling Quadrangle. Several areas remained exposed throughout Flagstaff time.

The Colton Formation was probably the first formation to overlap most of the highs that existed in Sanpete Valley. The relatively fine-grained clastic sediments of the Colton Formation may attest to a quiescent period of the diapir in which mild erosion dominated. Other areas were not submerged until middle Green River time (fig. 23C).

Following the deposition of the Green River Formation, the diapir again moved. After this movement an erosional phase occurred which stripped off areas of the Green River Formation. Crazy Hollow conglomerates and coarse sands were deposited disconformably on the Green River beds in the southeast part of the study area. In the northern part of the Sterling Quadrangle, Crazy Hollow Formation is in angular discordance with the Green River Formation and the Arapien Shale. This suggests that greater uplift occurred in this area prior to erosion and deposition of the Crazy Hollow Formation.

Diapiric movement continued, causing deformation of the Crazy Hollow Formation. In the northern part of the Sterling Quadrangle, the diapir bifurcated. Beneath the Palisade Lake area, vertical motion was directed eastward. Steeply dipping Cretaceous rocks were elevated creating a doubly plunging anticline independent of the main anticlinal diapir to the west. Following this uplit, gravitational settling along bedding planes in the Cretaceous rocks caused the small-scale faulting seen in the capping Flagstaff Formation.

Upward motion of the diapir in the area of Gunnison Reservoir was directed to the west. In the central and southern San Pitch Mountains the vertical and westward movement was much greater. The undulations in the Flagstaff beds and the scissor faults that occur to the northwest of the radio tower resulted as the central and southern parts of the mountains were uplifted.

Possibly contemporaneous with this episode of movement, basement faulting created the Wasatch Monocline. Following this vertical motion and draping of the overlying strata, the faults east of Arapien Valley developed as a response to readjustment of the strata.

Sometime after the development of the monocline and subsequent to the faulting, the slide in Forbush Cove occurred passing out of the cove through a canyon cut in the Cretaceous rocks. The streams then cut new canyons, bypassing the large slide in Funk's Canyon and cutting through the slide at the mouth of Sixmile Canyon. The slides in the Green River beds south of Sterling also occurred after faulting. These slides, however, were not as fluid as the one that came out of Forbush Cove.

Terrace gravels were deposited sometime during the Pleistocene when much more water was present in the area and base level was probably higher. These gravels were then elevated and tipped to various degrees throughout the study area by very recent activity within the diapir. In some areas of the quadrangle, folding of the gravels occurred in response to this recent activity.

ECONOMIC GEOLOGY

Petroleum possibilities in the area are good. Bioturbated sandstones in the Funk Valley Formation would make excellent reservoir rocks. Oil shows have been found in Cretaceous rocks in several wells drilled adjacent to the Sterling Quadrangle (Phillips Petroleum Co. No. 1 United States "E"; Phillips Petroleum Co. No. 1 United States "D"). Gas was found in the Ferron Sandstone in the Hanson-Moroni well in north Sanpete County. Oil may have accumulated in the Cretaceous rocks beneath an angular unconformity in the western part of the area.

Although the general structure of the Arapien Shale in Sanpete Valley is anticlinal, it is questionable whether or not the underlying Nugget Sandstone has also been so deformed. The diapir has created structures probably only in the Arapien Shale, although in the cross sections I show Nugget Sandstone deformed for emphasis of the anticline.

Coals of the Sixmile Canyon Formation were mined for local consumption; these deposits are now essentially mined out.

The Arapien Shale in the area contains gypsum in some horizons, but they are thin and discontinuous. Massive gypsum and salt of economical value are present in the subsurface and are, in part, responsible for the extensive diapirism in the Sterling Quadrangle.

The limestones of the Green River Formation, to the west of Antelope Valley, and possibly the Flagstaff Formation may be of commercial value for their high calcium content.

CONCLUSIONS

1. Periodic diapirism of the Arapien Shale in Sanpete Valley is responsible for the structural and stratigraphic relationships found in the Sterling Quadrangle today.

2. The assignment of the red conglomerate and tan sandstone in the San Pitch Mountains to the Tertiary portion of the North Horn Formation best fits the structural configuration of the area. Rocks of the Cretaceous Indianola Group are buried beneath the San Pitch Mountains in angular unconformity with the Tertiary portion of the North Horn Formation. This configuration adds the symmetry to the anticline that has been lacking in previous studies.

3. Folding and tilting of Quaternary units in central Sanpete Valley indicate that diapirism in southern Sanpete Valley is active at the present time.

4. The geologic history and stratigraphy indicate that hydrocarbon traps are possible at the northern end of the Sterling Quadrangle and beneath the San Pitch Mountains.

ACKNOWLEDGMENTS

Appreciation is expressed to Dr. James L. Baer, the committee chairman, for his suggestions on fieldwork, manuscript, and illustrations, and for stimulating discussions pertaining to the geological development of Sanpete Valley. Appreciation is also expressed to Dr. Lehi F. Hintze for his criticism of the map and cross sections and for suggestions on illustrations and manuscript. Thanks also to Doug Taylor, Robert Foote, Bob Ballou, and Steven Sperry for their aid in measuring sections, and to Peter K. Groth and E. T. Peterson of Amoco Production Company and Dan Pearson of Phillips Petroleum Company for their aid in fossil identification. Amoco Production Company has funded, in part, the expenses incurred during this study.

Special appreciation goes to my wife Rosalie who aided in the preparation of the manuscript and gave me encouragement throughout the project.

APPENDIX
MEASURED STRATIGRAPHIC SECTIONS

Indianola Group Section

The Indianola Group is well exposed in the study area and for the most part dips steeply or is overturned to the east. Type sections of the Sanpete, Allen Valley Shale, Funk Valley, and Sixmile Canyon Formations are located in the study area. Only a partial section of the group was measured. The measured section starts near the base of the Sanpete Formation in the southeast corner, NW¼, SE¼, SE¼, section 27, T. 18 S, R. 2 E, and goes east to the center of NW¼, SE¼, SE¼, section 26, T. 18 S, R. 2 E. The section stops near the top of the Funk Valley Formation. Brunton and tape were used to measure the section. Not compensating for several faults in the Funk Valley Formation that were crossed probably adds to the measured thickness. The actual fault locations and displacements are impossible to find in the highly bioturbated sandstones of the upper member of the Funk Valley Formation.

Unit	Description	Thickness (in meters) Unit	Total
Sixmile Canyon Formation (not measured)			
Funk Valley Formation			
47	Sandstone; grayish brown, calcareous, cross laminated.	12.6	12.6
46	Sandstone; light brown to grayish red, cross laminated at top, bioturbated and more indurated than unit 45.	32.0	44.6
45	Same as unit 44.	28.2	72.8

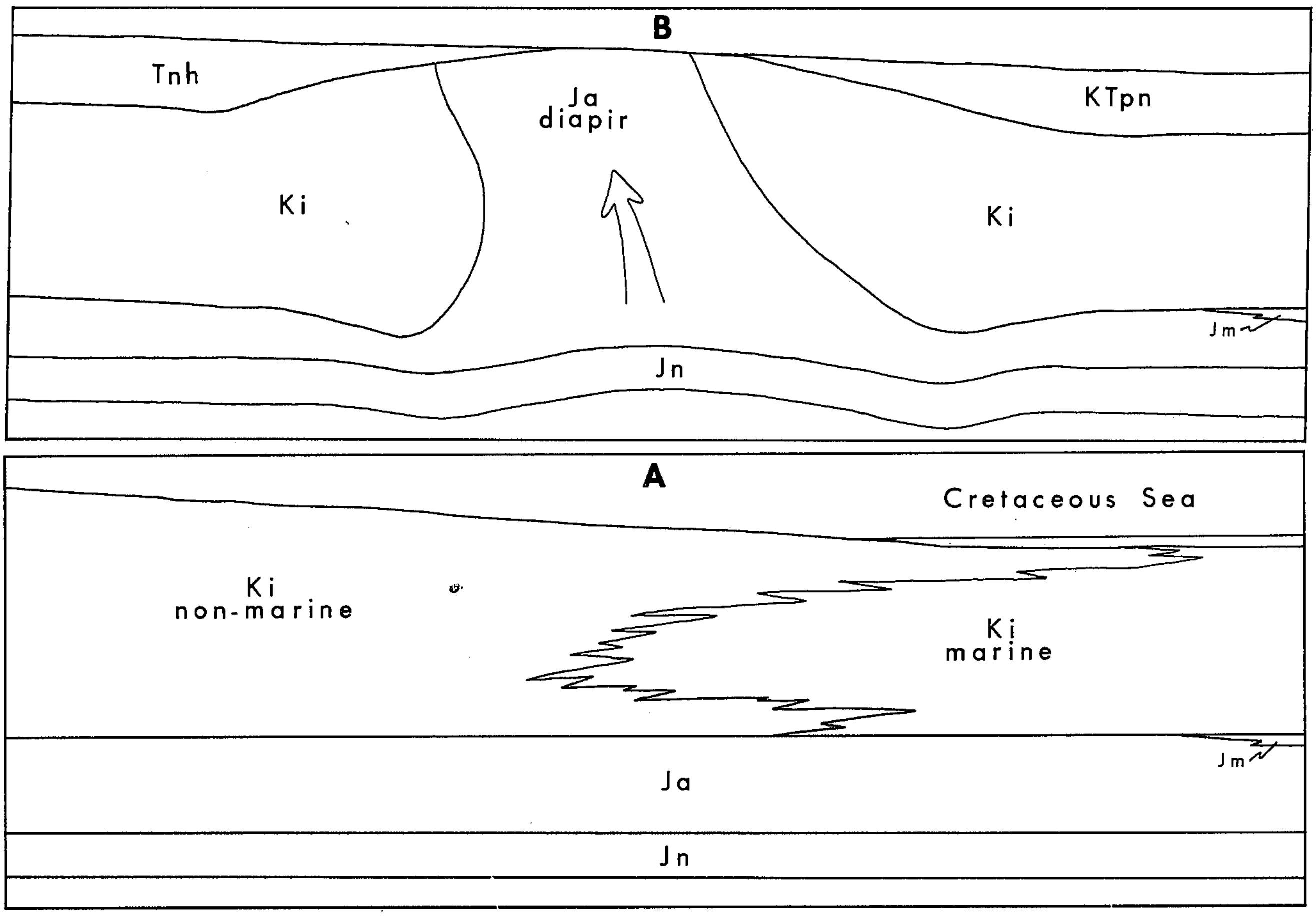
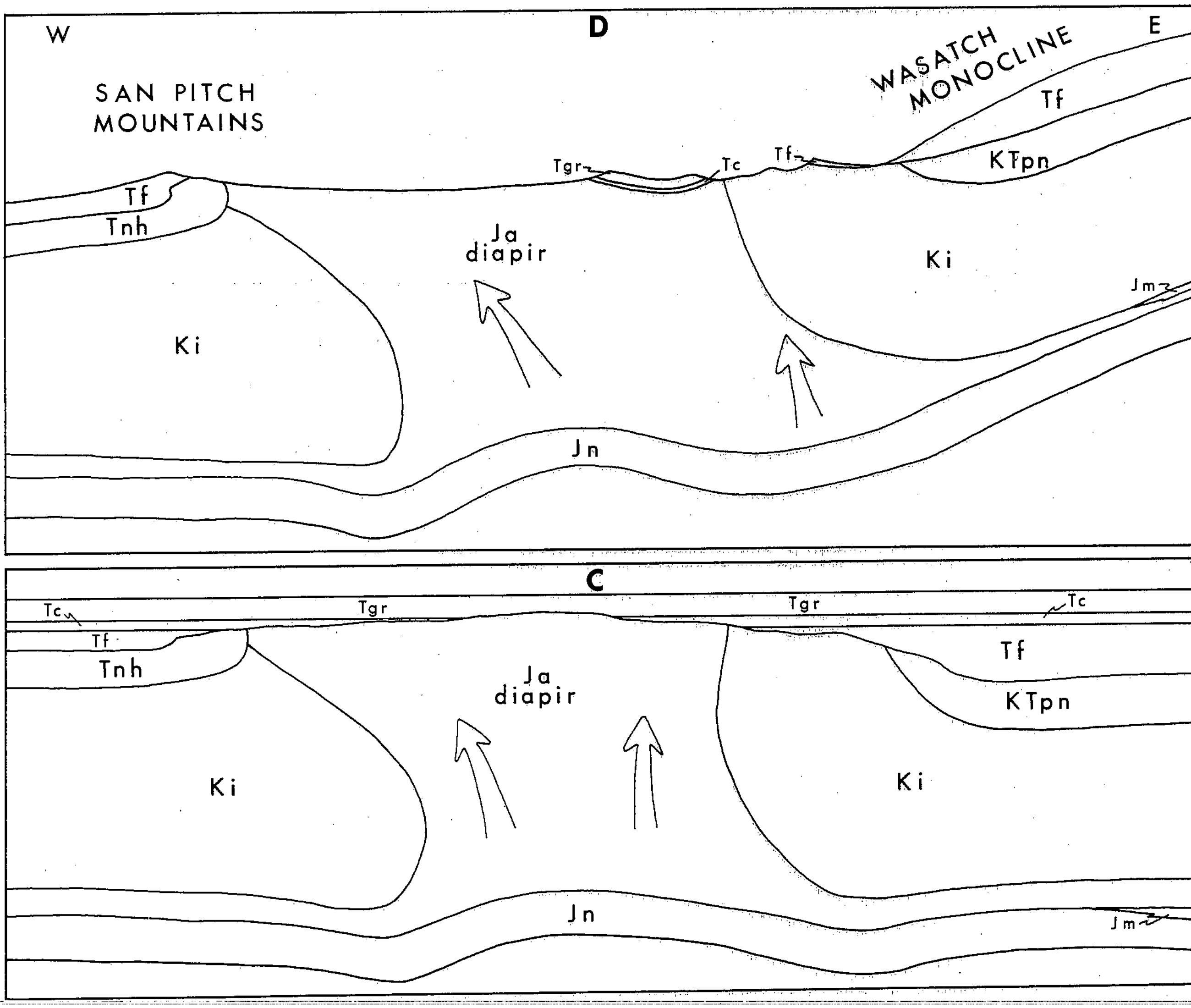


FIGURE 23.—Schematic representation of structural development of Sterling Quadrangle.

44	Sandstone; more indurated than below, some horizons highly bioturbated, some horizons weather to a reddish tan, others are whitish gray, upper is whitish tan color.	85.1	157.9
43	Same as unit 42.	13.6	171.5
42	Same as unit 42; some of the burrows appear to have iron concretions in them, some casts of pelecypods.	43.3	214.8
41	Sandstone; same as unit 40.	32.3	247.1
40	Sandstone as in unit 39; moderately bioturbated, bleached horizon, weathers to rounded ledges.	20.3	267.4
39	Sandstone as in unit 38; with small lenses of dark shale and thin beds of finely laminated silty sandstone, light brown to tan on weathered surfaces, grayish tan on fresh, calcareous and moderately to highly bioturbated.	46.0	313.4
38	Covered slope; top 30 m covers a light brown sandstone, calcareous, fine grained, some pelecypods within, but not well preserved.	85.5	398.9
37	Covered slope.	44.4	443.3
36	Sandstone; same as unit 35, upper 1.5 m are shaly light brown to ochre, form a small ledge.	16.4	459.7
35	Sandstone; light brown to tan, weathers to rounded surfaces, fine grained, dirty sand, bioturbated at some horizons.	22.3	482.0
34	Shale; yellowish brown to light gray to tan, some organic material, also some beds of sandy shale, some pelecypods in sandy shale.	20.3	502.3
33	Sandstone; light brown to tan, dark minerals within, calcareous, cross-bedded, some shale beds within, light gray or white.	24.4	526.7
32	Sandstone; light brown, weathers gray, cross-bedding is present.	49.8	576.5
31	Sandstone; light brown, calcareous, some cross-bedding medium to coarse grained, iron concretions 5–20 mm, some contain medium-grained clasts, larger ones about 50 mm are coarse sand, some bleached white zones along fractures.	8.6	585.1



30	Interbedded sandstone and shale; sandstone, light brown to tan, fine to medium grained; shale, yellowish brown.	22.3	607.4
29	Sandstone; light brown to tan, calcareous, cross-bedded, friable, fine to medium grained, some coarse lenses and shaly lenses.	18.4	625.8
28	Sandstone; shaly with a shale unit at base, cross laminated.	11.2	637.0
27	Sandstone; same as unit 26.	23.7	660.7
26	Sandstone; light brown to tan, ledge forming on top of ridge; same as units below.	29.7	690.4
25	Sandstone; same as unit 24, friable.	23.2	713.6
24	Sandstone; light brown to cream, red bed at 8.8 m up along slope, cross-bedded, shaly sand unit above red horizon, some friable horizons.	28.0	741.6
23	Sandstone; shaly, cross-bedded, slope and ledge former.	28.1	769.7
22	Sandstone as in unit 21.	6.0	775.7
21	Sandstone; light brown with a red horizon in the lower portion.	25.4	801.1
20	Sandstone; light brown, calcareous, friable, fine to medium grained, ledge, cross-bedded.	13.2	814.3
19	Sandstone as in unit 18.	8.2	822.5
18	Sandstone; light brown going to light gray, weathers gray, quartz with some dark minerals, calcareous, cross-bedding in light gray part, brown unit is hard, upper gray is friable, some fossil debris.	26.1	848.6
Allen Valley Shale			
17	Covered slope; shale lies below.	29.8	878.4
16	Covered slope.	27.4	905.8
15	Covered slope.	26.8	932.6
14	Shale same as in unit 13.	59.4	992.0
13	Shale as in unit 12.	32.0	1024.0
12	Shale; greenish brown to yellowish brown, thinly bedded some thin rippled sandy beds within.	45.3	1069.3
Sanpete Formation			
11	Sandstone; same as unit 10.	24.9	1094.2
10	Sandstone; thick to thin bedded, light brown to tan, fine to medium grained, slightly calcareous.	35.6	1129.8
9	Sandstone; alternating cream and tan beds, tan beds have dark minerals with quartz, fine grained, silty lenses within, slightly calcareous.	23.0	1152.8
8	Sandstone; cream color, fine to medium grained, cross-bedded, fair sorting, some beds laminated, becomes progressively lighter towards top then abruptly goes to tan.	15.0	1167.8
7	Sandstone; tan to light brown, ledge former, cross-bedded, tan on fresh surfaces, slightly calcareous, fine grained.	4.0	1171.8
6	Sandstone; light brown to tan, thin to medium laminar bedding, cross-bedded, medium grained.	19.4	1191.2
5	Sandstone; light brown, slope forming, mostly covered.	22.1	1213.3
4	Sandstone; light brown, fine to medium grained, slightly calcareous.	5.8	1219.1
3	Conglomerate; tan to light brown, clasts 1 mm to 15 mm, massive lenses of finer material, mostly quartzite clasts and quartz fines, fairly well sorted with rounded clasts.	4.7	1223.8
2	Sandstone; light brown to tan, calcareous, fine to coarse grained, interfingering with the conglomerates, cross-bedded.	8.1	1231.9
1	Sandstone; light brown to tan, fine to medium grained, calcareous, porous, conglomeratic lenses within (pebble size), thickly bedded, cross-bedded, friable.	22.2	1254.1
	Total thickness of Indianola Group		1254.1

Basal contact concealed beneath alluvium.

North Horn and Flagstaff Formations Section

Twelvemile Canyon

The North Horn Formation and Flagstaff Formation contact in Twelvemile Canyon is conformable. The North Horn Formation ends at the top of unit 10. The Flagstaff Formation is dominantly freshwater limestone with some very calcareous sandstone horizons within and a suite of fluvial sandstone and shale resembling the North Horn Formation near the base. The section was measured in N½, section 2, T. 20 S, R. 2 E, in Twelvemile Canyon.

		Thickness (in meters)	
Unit	Description	Unit	Total
Flagstaff Formation			
34	Limestone; light olive gray, weathers yellowish gray, finely crystalline, silicified material within, massive ledge.	3.9	3.9
33	Sandstone; fine to medium grained, very calcareous, light olive gray.	2.8	6.7
32	Sandstone; fine to medium grained, finer at top and more mud, slightly calcareous, cross-bedded at base, ledge former.	1.2	7.9
31	Limetone; cream colored, massive ledge, some shaly beds, dolomitic at some levels, oolitic at base, fossil debris within.	5.5	13.4
30	Mostly covered slope; top shows concretionary calcareous sandstone ledge.	11.7	25.1
29	Sandstone; fine to very fine grained, yellowish gray, weathers yellowish brown, slightly calcareous, two pink horizons within, ledge.	3.0	28.1
28	Sandstone; light brown to light olive gray, very fine grained, more dolomitic with more mud matrix at top, ledgy slope.	2.8	30.9
27	Dolomite; light olive gray, some pellets within at base, more calcareous and sandy at the top, ledgy slope.	1.6	32.5
26	Limestone; light brown, weathers whitish brown, has intraclasts within, slope, weathers flaggy.	2.9	35.4
25	Limestone; light brown, weathers whitish light brown, flaggy massively bedded, ledge.	23.9	59.3
24	Limestone in bottom ¾; light gray, oolitic or pelletal. Shale in upper ¼; brown, weathers light brown to whitish brown, thinly bedded, gastropods and other fossil debris.	6.9	66.2
23	Limestone; light orangish color, massive, weathers flaggy.	6.1	72.3
22	Limestone; gray to white on weathered surfaces, flaggy surface, massive ledge.	33.5	105.8
21	Sandstone; tan, calcareous, one meter at base is medium to very coarse grained.	18.3	124.1
20	Covered slope.	15.8	139.9

19	Sandstone; yellowish brown to brown, coarse becoming less coarse at the top, calcareous, very porous, lenses of very coarse sandstone, bed of oncolites near base.	19.0	158.9
18	Covered slope.	48.9	207.8
17	Covered slope, about one meter of tan, fine-grained sandstone exposed at the base.	41.2	249.0
16	Limestone; cream colored, weathers to yellowish light brown, thin to medium bedded, slope former, micritic.	23.2	272.2
15	Limestone; cream colored, weathers to yellowish white, massively bedded, vuggy, ledgy slope former.	14.2	286.4
14	Limestone; brownish gray, weathers light yellowish gray, micritic, rubble slope.	16.1	302.5
13b	Limestone; light gray to grayish yellow, fossils in the float, medium bedded.	15.7	318.2
13a	Sandstone; grayish brown to brown on weathered surfaces, calcareous, thickly bedded.	2.0	320.2
12	Limestone; light grayish brown, sandy towards top, outcrops show some gastropods, micritic.	13.5	333.7
11	Limestone; light grayisyh brown, mostly covered slope, possibly more sandstone below.	31.7	365.4
North Horn Formation			
10	Sandstone to pebble conglomerate; fine to coarse grained to pebbles .5 cm in diameter, white to light brown horizon, top weathers dark tan to brown.	16.0	381.4
9	Sandstone; light brown, tan to white, fine to coarse grained, cross-bedded with coarse to very coarse grained lenses.	18.2	399.6
8	Sandstone; light brown to tan to white, fine to coarse grained, coarser grained in lenses, cross-bedded, coarser towards the top, convolute bedding in top 4 m, white is well washed and friable, shale bed in lower ¼ is slightly calcareous.	26.7	426.3
7	Covered slope to top one meter; sandstone; light brown, fine grained, calcareous, ledge.	11.6	437.9
6	Covered slope.	15.9	453.8
5	Sandstone; lower ½ is white and friable as in unit 4; upper ½ is tan, hard, no sedimentary structure, thickly bedded, ledge former.	3.8	457.6
4	Sandstone and shale; bottom is rippled sandstone, grayish orange with dark grains interbedded with shale; top is sandstone, white, well sorted, very friable, cross-bedded to convolute.	10.5	468.1
3	Shale; mostly covered with some sandy ripple laminated beds within; blackish green in color.	36.0	504.1
2	Shale; dark greenish gray to moderate brown, poorly exposed, slope former, more sandy toward the top, some fine to medium grained sandstone beds within, sandstones are cross-bedded, grayish yellow, ledge-forming.	38.4	542.5
1	Sandstone; yellowish gray to yellowish orange, fine grained, slightly calcareous, small-scale ripple laminations at base becoming more medium-scale cross-bedded at the top; some convolute beds in the middle. Base of North Horn not exposed.	24.0	566.5
	Total measured North Horn and Flagstaff Formations		566.5

North Horn Formation Section

Gunnison Plateau

The North Horn Formation varies greatly from one part of the study area to another, but generally it becomes coarser to the west. The basal and upper contacts are not definitely present, and contacts with younger and older rocks are angular unconformities. The section was measured using Brunton and tape from center of SW¼, NE¼, section 4, T. 19 S, R. 2 E, to center of NW¼, SW¼, NW¼, section 7, T. 19 S, R. 2 E.

		Thickness (in meters)	
Unit	Description	Unit	Total
Flagstaff Formation—lower unit			
Unconformity			
North Horn Formation—upper unit			
38	Conglomerate; same as unit 37 but becoming coarser towards the top, with many more sandstone cobbles (tan) in a medium- to coarse-grained, gray sandstone matrix; forms small hogback at west end of small opening, appears lenticular.	18.7	18.7
37	Conglomerate; gray, fine-grained, abundant quartzite pebbles with some sandstone cobbles, all in coarse sandstone matrix, limestone pebbles more abundant—up to 15%.	12.9	31.6
36	Poorly exposed sandstone and shale, mostly covered slope.	22.7	54.3
35	Shale; black to dark gray with tan sandstone lenses.	27.7	82.0
34	Poorly exposed sandstone as above with shale; sandstone dark brown to tan.	13.1	95.1
33	Sandstone and interbedded shale; sandstone ledges, tan, fine to medium grained, shales are whitish tan.	19.7	114.8
32	Covered slope.	40.9	155.7
31	Poorly exposed sandstone, mostly covered slope.	18.3	174.0
30	Sandstone; same as unit 29, poorly exposed, bleached horizons outcrop, some horizons with iron concretions.	17.5	191.5
29	Sandstone; same as unit 28, upper unit has pocked weathered surface, medium to coarse grained, mostly dark tan to brown, cross-bedded.	12.2	203.7
28	Sandstone; same as unit 27 with bleached horizons in slope areas, calcareous, fine to medium grained, porous; tan units stand out as higher ledges than bleached units; cross-bedded.	13.7	217.4
27	Sandstone; tan to whitish gray, fine to coarse grained, cross-bedded, calcareous porous, bleached horizons.	14.7	232.1
26	Covered slope.	21.5	253.6
25	Conglomerate; tan, very coarse, with more abundant white quartzite cobbles, very large metamorphic pebble conglomerate cobbles and banded cobbles, manganese oxide staining in sandy matrix.	3.8	257.4
Top of lower unit			
24	Covered slope between conglomerate lenses.	13.1	270.5

23	Conglomerate; medium-grained sandstone lenses within, appear to be more limestone clasts.	5.2	275.7
22	Covered slope; float is rounded, dominantly quartzite cobbles, some up to 0.5–.6 m in diameter.	15.2	291.0
21	Conglomerate; red, channel.	6.9	297.9
20	Covered slope with lenses of pebble conglomerate outcropping to the north, probably a shale between conglomerate lenses.	30.6	328.5
19	Mixture of medium sandstone, cross-bedded to conglomerate not as coarse as in unit 15. Sandstones and conglomerates lens into one another, sandstones are well cross-bedded, fine to medium grained, ledge forming, occasional whitish to grayish horizons appearing to be massive or thickly bedded.	17.0	345.5
18	Shale; red, covered with quartz cobbles.	5.6	351.1
17	Conglomerate as in unit 15.	3.0	354.1
16	Mostly covered slope; occasional small ledge outcrops of pebble conglomerates coarse sandstone; spotty, however, indicating lenticular nature in shale.	13.5	367.6
15	Conglomerate; red, banded maroon quartzites as in units 9 and 14, coarse sandstone lenses within, 5–10% of cobbles are limestone.	8.8	376.4
14	Covered slope; quartzite pebbles and cobbles on the slope; maroon, tan, white, banded, a few limestone cobbles, channel conglomerates continue to the north.	28.8	405.2
13	Conglomerate going to medium to coarse sandstone upward.	5.3	410.5
12	Shale, red.	.5	411.0
11	Limestone; reddish gray to grayish brown, weathers to medium gray, lenticular.	.7	411.7
10	Shale; red to maroon.	2.4	414.1
9	Conglomerate; red channel conglomerate, mostly quartzite cobbles with little limestone in chert, coarse red matrix.	10.0	425.1
8	Shale, popcorn weathering, reddish to greenish gray, medium-grained sandstone lenses within.	29.9	454.0
7	Covered slope.	33.4	487.4
6	Covered slope.	24.7	512.1
5	Limestone; sandy, reddish to grayish, greenish gray limestone with silica stringers.	7.1	519.2
4	Covered slope.	17.2	536.4
3	Sandstone to pebble conglomerate; gray calcareous, dominantly quartz pebbles, some gray medium-grained sandstone near the top.	2.6	539.0
2	Covered slope, limestone and quartzite cobbles and pebbles in the cover.	16.8	555.8
1	Limestone; weathers whitish to grayish, spar stringers and blebs within, highly fractured.	7.5	563.3
	Total measured North Horn Formation		563.3

Basal contact concealed beneath alluvium.

Green River Formation Sections

The Green River Formation is exposed in several locations in the area, and only a partial section is measurable in any one location. The upper contact with the Crazy Hollow Formation is disconformable.

Chalk Hills Section

The section was measured in the ledges exposed in SE¼, SW¼, section 14, T. 19 S, R. 1 E.

Unit	Description	Thickness (in meters) Unit	Total
Green River Formation			
10	Limestone; sandy, tan to light brown to cream.	3.1	3.1
9	Limestone as in unit 10.	9.4	12.5
8	Limestone; light brown to cream, mottled ledges, with light brown chert lenses.	18.3	30.8
7	Limestone; light brown chert lenses or stringers.	6.6	37.4
6b	Limestone; tan on weathered surfaces, upper part has indistinct bedding, some pods of chert, forms massive ledge, appears micritic.	24.1	61.5
6a	Limestone; micritic to oolitic, very calcareous, forms lower part of ledge, at base oolites have brown coating, white on fresh surface, lower .4 m yellowish color.	5.8	67.3
5	Mostly covered slope; upper one meter has evaporite horizons in shale.	12.2	79.5
4	Interbedded shale and limestone; limestone is greenish as in unit 3; shale is grayish green, fissile; greenish gray volcanic ash at base with abundant biotite.	4.6	84.1
3	Sandstone with interbedded shale; sandstone weathers reddish brown, brown to tan on fresh surface; shale is tan to brown.	3.3	87.4
2	Shale; calcareous, same as unit 1.	6.6	94.0
1	Shale; calcareous, light green to yellowish green to gray, massive bedding.	1.8	95.8
	Total Green River Formation		95.8

Basal contact concealed beneath alluvium.

North Hollow Section

The section was measured in the steep slopes exposed in NE¼, SE¼, section 27, T. 19 S, R. 2 E.

Unit	Description	Thickness (in meters) Unit	Total
Green River Formation			
8	Dolomite; massive, ledge former, weathers white, some horizons are silicified, silicified horizons covered by lichens.	46.3	46.3
7	Limestone calcareous sandstone; weathers white, slope forming, interbedded shale and sandstone.	32.2	78.5
6	Limestone; thinly laminated, greenish brown to olive, platy slope float, weathers white in contrast to greenish white in unit 5, some sandy calcareous beds within.	87.4	165.9
5	Shale; greenish gray.	19.1	185.0
4	Sandstone and shale; green to grayish green, from top of unit, 4 m of interbedded shale and sandstone, sandstone is green to light brown, fine grained, convoluted bedding. From 70 to 80 m another horizon of interbedded shale and sandstone	104.4	289.4

	similar to that above, sandstone forms ledges.		
3	Shale; grayish green, slope former; platy float at top.	33.8	323.2
2	Shale; greenish gray with horizons to 3 m of medium-bedded, buff limestone with some fossil material (fish scales?).	17.3	340.5
	Total Green River Formation		340.5
Colton Formation			
1	Shale to shaly sandstone; ochte to brownish red, fragmented in outcrop, becomes more shaly towards top.	13.3	

Contact with Flagstaff Formation concealed by alluvium.

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