STRATIGRAPHY, STRUCTURE, AND HALOKINETIC HISTORY OF FISHER VALLEY QUADRANGLE, GRAND COUNTY, UTAH

by

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PURPOSE AND SCOPE

The Fisher Valley quadrangle in southeastern Grand County, Utah is within the Canyonlands section of the Colorado Plateau physiographic province and is situated within the fold and fault belt of the Paradox sedimentary basin. Fisher Valley is the collapsed crest of a long northwest-trending anticline cored by salt of the Pennsylvanian Paradox Formation of the Hermosa Group. The surrounding uplands consist of eolian, fluvial, lacustrine, and marine sedimentary rocks of Permian through Cretaceous age. Triassic and Jurassic eolian and fluvial sandstones are the major rock types of the region.

This report describes the stratigraphy and structural geology of the Fisher Valley area based on detailed geologic mapping (scale 1:24,000). It provides an interpretation of the salt tectonism and halokinetic history based on fold and fault relations and sedimentologic variations, and assesses the geomorphic history of Fisher Valley.

The Fisher Valley quadrangle is located in southeastern Grand County, Utah, approximately 4 mi west of the Utah - Colorado state line and 17 mi east - northeast of Moab, Utah (fig. 1). The southern third of the quadrangle lies within the Manti La Sal National Forest.

Fisher Valley is situated in the west-central part of the map area. Other prominent features include: the Cottonwood graben (northeast of Fisher Valley), Polar mesa (east of Fisher Valley), and Seven Mile mesa (north of Fisher Valley and Cottonwood graben) (fig. 2). The

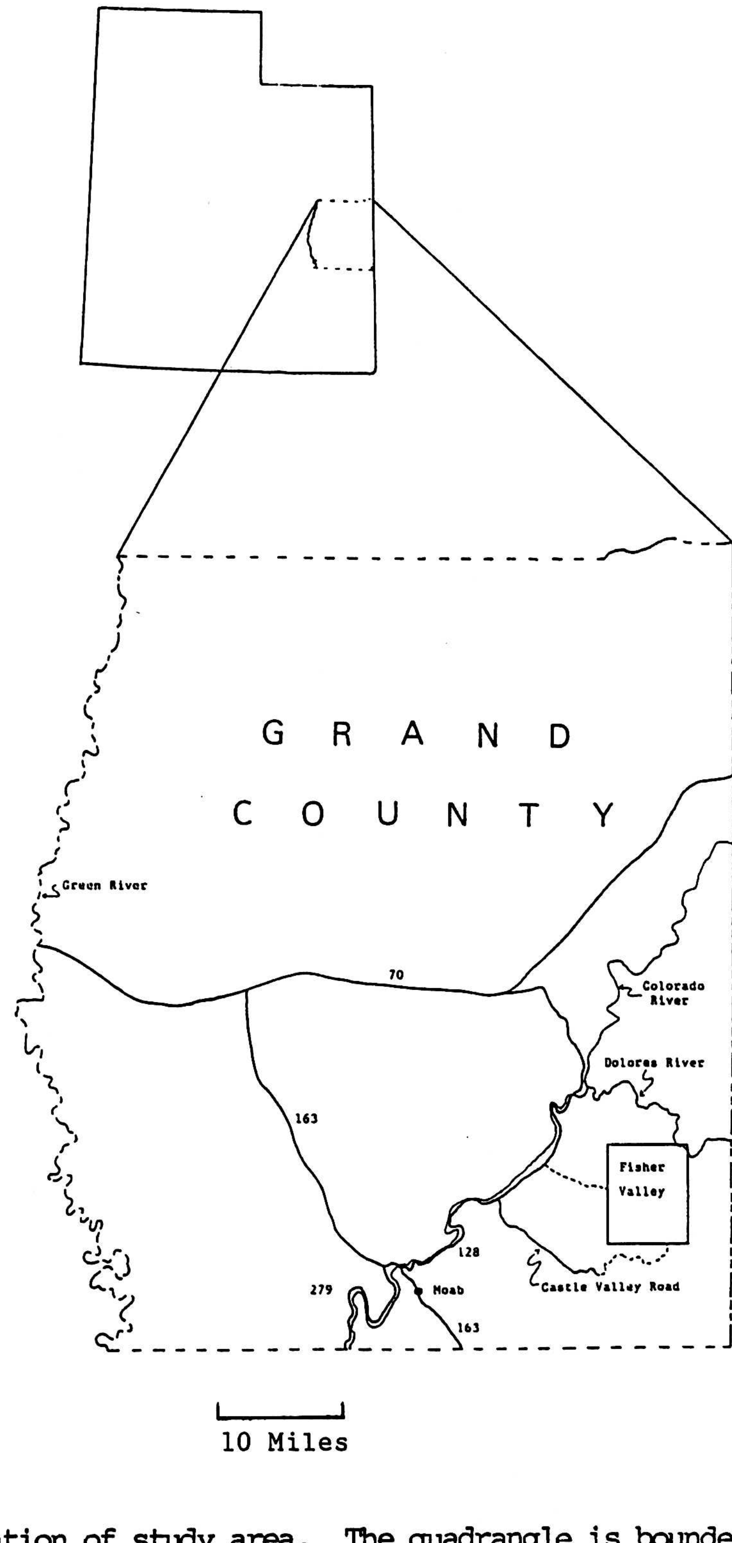
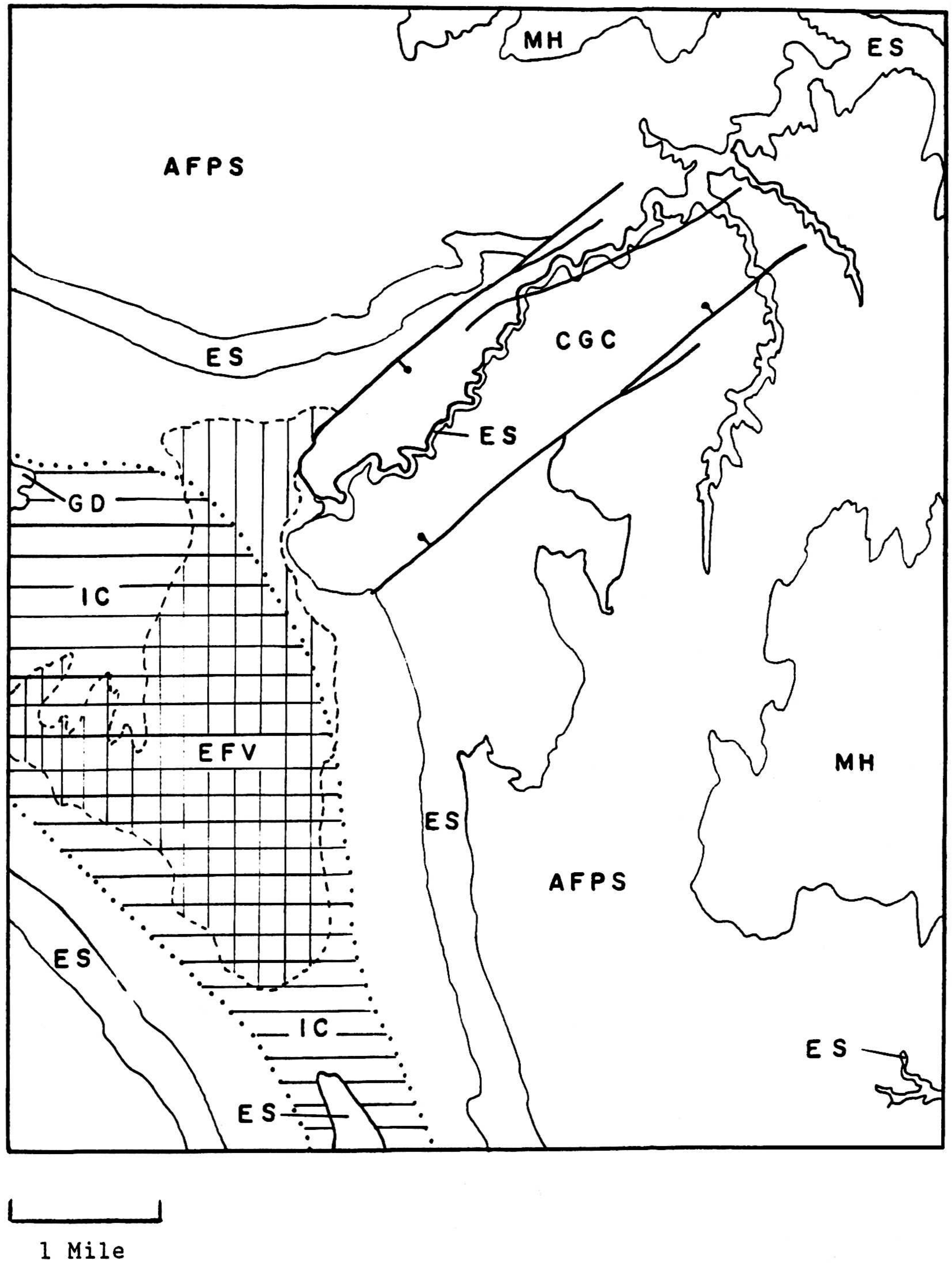


Figure 1. Location of study area. The quadrangle is bounded by latitudes 38° 45' to the north, 38° 37' 30" to the south, longitude 109° 15' to the west and 109° 07' 30" to the east.



ES Escarpment section
AFPS Anticline Flank & Plateau section
MH Mesa Highland section
CGC Cottonwood Graben collapse
EFV Eolian sand-filled valley
GD Gypsiferous Diapir section
IC Inferred Collapse section

Figure. 2 Physiographic sections of Fisher Valley

Dolores River, which drains the Uncompahgre uplift in Colorado, flows north through the extreme northeast corner of the map area.

METHODS OF INVESTIGATION

Aerial photographs of the Fisher Valley quadrangle were visually interpreted with the aid of a 2x pocket stereoscope and a 3x mirror stereoscope during the spring of 1987. Stereographic coverage of (1:40,000 black and white and 1;70,000 color infrared aerial photographs) the Fisher Valley quadrangle was obtained from ASCS-USDA. Several of the 1:40,000 black and white aerial photographs were enlarged to a scale of 1:25,600 to enhance structural and lithologic subtleties. Digitized 1:25,600 black and white, and 1:70,000 C.I.R. images, prepared at the Department of Geography at the State University of New York at Geneseo, were manipulated with the aid of Dr. Duane Nellis, Department of Geography, Kansas State University to help discriminate rock type and vegetation. Stratigraphic contacts and surface lineaments were delineated on the aerial photographs.

The Fisher Valley quadrangle was mapped in the field during the summer of 1987. This began with an examination of all stratigraphic units exposed at outcrops in and around the Fisher Valley area. Stratigraphic analysis included the study of detailed measured sections, types of stratification, facies changes, unconformity surfaces, and local thickness variations. Fold, fault, joint, and bedding attitudes were determined with a brunton compass and plotted on 1:40,000 black and white aerial photographs (9" x 9"). This information was transferred to an orthophotoquad (differentially rectified photo) of the Fisher Valley quadrangle at a scale of 1:24,000.

Nomenclature used to describe cross-stratification and stratification follows that of Mckee and Weir (1953). In the field study of cross-stratification, most measurements were made of the azimuth of the dip of one cross-stratum in each separate cross-stratified conformable unit. Though directions of some trough cross-beds were estimated, no orientations were determined in beds affected by depositional soft-sediment deformation. Cross-bed orientations were determined and plotted until a visually obvious grouping was obtained or no more cross beds could be found. Selection bias was controlled by determining the orientation of each cross-stratified unit as encountered.

PREVIOUS WORK

Pioneers Powell (1875, 1876), Gilbert (1877), and Dutton (1880, 1882, 1885) investigated the geology of the Colorado Plateau. Their field reports were the major literature on this region through the 1930s. The first description of the geology of the area surrounding Fisher Valley was compiled by Peale (1877, 1878). Early stratigraphic studies were conducted by Dutton (1885), Cross (1907), Gilluly and Reeside (1928), Baker (1933), and Stokes (1944). More recently Peterson and Pipiringos (1979), and Pipiringos and O'Sullivan (1978) have conducted detailed stratigraphic studies emphasizing correlation of formations across the western interior of the United States and principal unconformities in Triassic and Jurassic rocks across the Colorado Plateau. The regional structure and tectonic history of the Paradox basin has been described by McKnight (1940), Shoemaker (1954), Kelley (1958), Fetzner (1960), Baars (1966), Baars and Stevenson (1981), and Szabo and Wengerd (1975). Salt anticlines, which are a major feature in the fold and fault belt of the Paradox basin, have been studied and described by Dane (1935), Shoemaker and others (1958), Jones (1959), Elston and others (1962), Cater (1970), Doelling (1983), and Doelling and others (1988).

Williams (1964) compiled geologic, structural, and uranium-deposit maps of the east-central section of Utah and the adjacent west-central section of Colorado at a scale of 1:250,000. Colman and Hawkins (1985) mapped the surficial Pliocene-Quaternary deposits of the Fisher Valley - Professor Valley area.

ACKNOWLEDGMENTS

I gratefully acknowledge the assistance provided me by my major professor, Dr. Jack Oviatt, who introduced me to the geology of the Canyonlands, Utah, suggested and guided me in this project and took time to visit the study area on several occasions. I would like to express my appreciation for the assistance provided me by Dr. David McConnell, who took valuable time to review early versions of the geologic map and cross-sections and of the discussion of halokinetic deformations in the region. Thanks are extended to D.L. Taylor and his family for allowing access to their land and for their hospitality. A graduate student grant from the Utah Geological and Mineral Survey that partially funded this project is greatly appreciated. I owe thanks to my family for their love, encouragement, and financial support. Thanks are extended to Barb Zumwalt for her love, encouragement, and help in preparing this manuscript.

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S T R A T I G R A P H Y

The sedimentary rocks exposed in the Fisher Valley quadrangle range in age from Middle Pennsylvanian to Early Cretaceous (300 - 100 million years ago). Figure 3 is a generalized stratigraphic column for the Fisher Valley area. The oldest exposed rocks are evaporites, shales, limestones, and sandstones of Pennsylvanian age. The rise of the ancestral Uncompahgre highland to the northeast is recorded in a series of arkoses of Pennsylvanian (?) and Permian age (Elston and Shoemaker, 1960; Elston and others, 1962; and Baars, 1962). Contemporaneous deformation and movement of the Pennsylvanian evaporites along northwest-trending salt anticlines resulted in local thinning of Permian through Jurassic (?) clastic sediments over the rising salt. Thickness of the Cutler, Moenkopi, and Chinle Formations varies considerably due to syn-depositional halokinetic (salt-related) deformation. Continental deposition prevailed from Late Triassic until Late Cretaceous time and is recorded in a picturesque sequence of eolian sandstones and fluvial sandstones and siltstones. Upper Jurassic sediments are the first deposits which blanketed and covered the salt anticlines (Dane, 1935). The Kayenta and Navajo Formations were deposited with thickness variations over the area due to a regional thinning of these units toward the east. Pliocene and Quaternary units appear to be the only rocks deposited since the Early Cretaceous that have not been subsequently eroded.

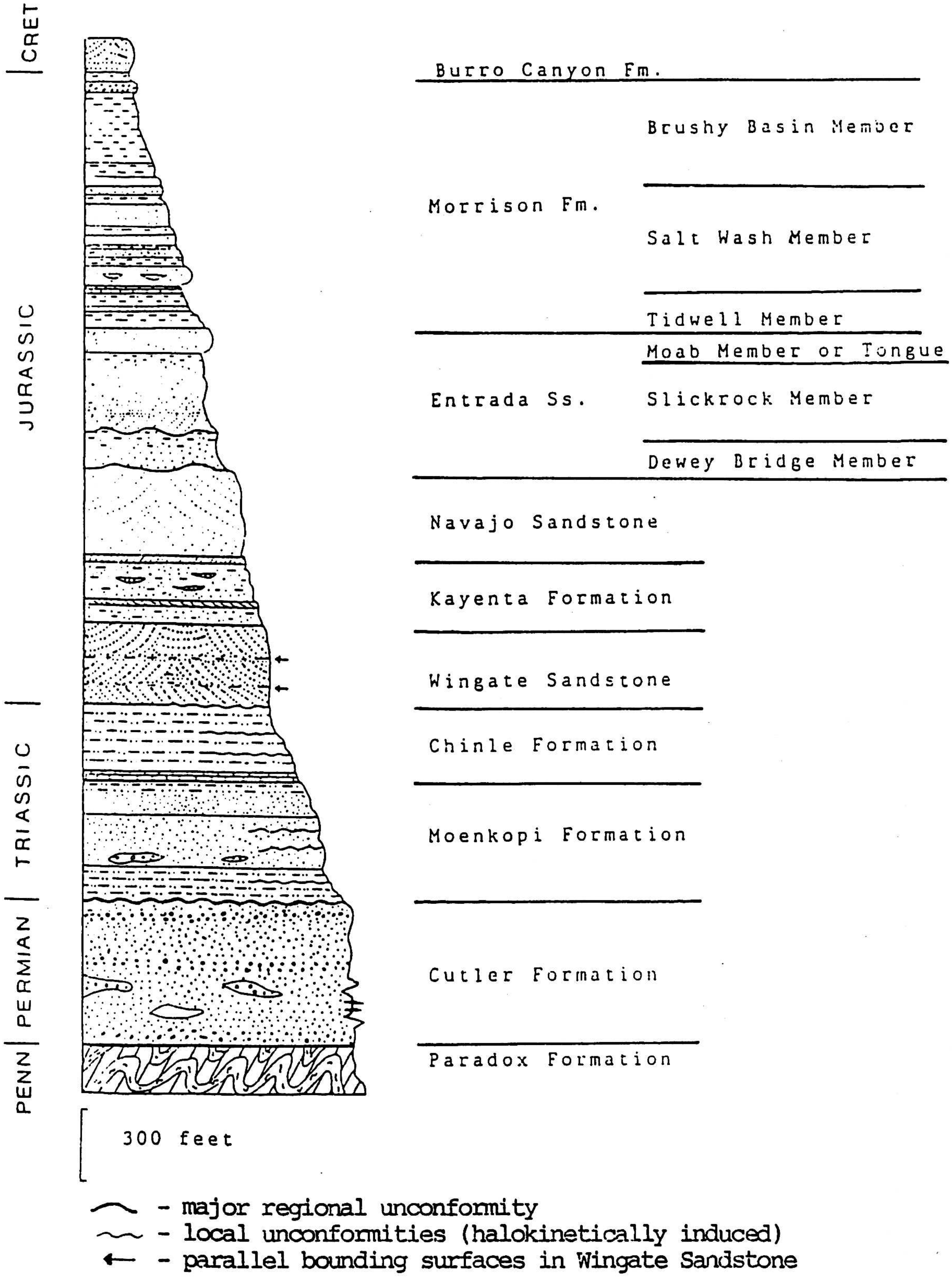


Figure 3. Generalized stratigraphic section of bedrock formations in the Fisher Valley area.

HERMOSA GROUP

Pennsylvanian rocks in the Paradox basin were first named by Cross and Spencer (1900), who applied the name Hermosa Formation to a sequence of limestones, sandstones, shales, and evaporites exposed along Hermosa Creek north of Durango, Colorado. Baker and others (1933), on the basis of conodonts, assigned a Pennsylvanian age for the highly contorted black shales, dolomites, and gypsum beds that crop out in Paradox Valley, Colorado, and named these beds the Paradox Formation. Bass (1944) recognized that the Paradox Formation was a facies within the main body of the Hermosa, and he assigned it member rank. Wengerd and Metheny (1958) renamed the lower and upper members of the Hermosa Formation the Pinkerton Trail and Honaker Trail Formations, respectively. The cyclicity of the Middle Pennsylvanian evaporites and carbonates has lead to continued confusion over stratigraphic nomenclature. Herman and Barkell (1957), Elston and others (1962), Hite and Lohman (1973), Gard (1976), Hite (1972, 1977), and Hite and Buckner (1981) assigned the Middle Pennsylvanian strata to the Hermosa Formation and divided it into three members. Borden (1952), Wengerd (1958), Wengerd and Metheny (1958), Wengerd and Strickland (1954), Baars and others (1967), and Young (1983) assign three formations to the Hermosa Group: the Pinkerton Trail, Paradox, and Honaker Trail Formations.

Paradox Formation

The Paradox Formation crops out only near the extreme western edge of the Fisher Valley quadrangle along Onion Creek, where it forms the exposed core of the Fisher Valley anticline and Onion Creek diapir (fig. 4). The Paradox generally forms rounded hills, but where it is entrenched it forms rough, irregular badlands and cutbanks with fluted walls. The Paradox outcrop along Onion Creek is so complexly folded, faulted, and brecciated that it was not possible to determine the stratigraphic sequence, percentage of rock types, or true thickness. Thickness was estimated at 150+ ft.

The exposure along Onion Creek represents a weathered, dissolved remnant of the Paradox Formation. The large proportion of soluble salt in the Paradox Formation, which is as great as 70% (Shoemaker and others, 1958), is not evident at the surface. Surface exposures or "caprock" consist of silty shale, gypsum, sandstone, and limestone. Dark gray to black, platy, thinly laminated to thinly bedded crumpled shale is the most abundant rock type. Stratification appears to have been originally horizontal and laterally continuous, and lacks recognizable sedimentary structures in those blocks not brecciated by the diapiric emplacement of the salt unit. Subangular to subrounded, fine-grained sand is sprinkled throughout many of the shale units, though many are devoid of any coarse terrigenous debris. Minor quantities of carbonaceous debris are present as disseminated lenses. Thin-bedded gypsum, contorted gypsum nodules, and gypsum in fracture voids are ubiquitous in the shale horizons. The shale occurs as layers

Figure 4. Paradox Formation caprock (gypsiferous rocks) as exposed in the Onion Creek diapir, on the crest of the Onion Creek - Fisher Valley anticline. Folded Quaternary sediments in middleground and folded Cutler Formation in background adjacent to the Onion Creek diapir, far left.

inches to several feet thick and is often interbedded with fine-grained, light brownish-gray to light greenish-gray sandstone. The sandstone consists of subangular quartz and orthoclase grains and minor quantities of glauconite and opaque grains. The sandstone is thinly bedded to indistinctly bedded and up to 5 in. thick.

Porous, sucrosic whitish-gray gypsum is a dominant lithology in the Paradox Formation. Beds of white to gray crystalline gypsum up to 25 ft thick are intricately folded. These gypsum beds, though they appear homogeneous because of strong surface weathering, are actually internally heterogeneous. The gypsum contains a host of incorporated shale, sand, and contorted clasts, and it has a variety of deformed structures and a few primary (?) sedimentary structures. In places the gypsum contains white to light-gray bands of hard nodular gypsum. These bands are relatively clean, and free of inclusions and deformed structures. Because of the strong weathering, reprecipitated gypsum tends to coat the surface of the exposure (Onion Creek diapir) and gives the illusion that gypsum composes most of the formation, though it probably composes only 50 % of the exposed Paradox Formation. Sandstone is a subordinate lithology but is well preserved and exposed in the contorted beds of the diapir. The light brownish-gray sandstone consists of fine to medium-grained quartz grains, which are subangular to subrounded, and well-sorted. Feldspar, glauconite, muscovite, hematite, and a suite of opaque minerals and silt-size particles are abundant in the sandstone. The sandstone beds are thinly bedded and up to 2 ft thick. Thin beds of fine-grained unfossiliferous, sandy limestone (micrite) are well exposed. These light gray to dark brown-gray limestone beds are thickly laminated, though some are indistinctly bedded, generally less than 1 ft thick, and contain abundant fractures filled with gypsum and late-stage calcite.

The relative abundance of lithologies at the surface is not representative of the Paradox Formation in the subsurface. According to well logs (Shoemaker and others, 1958) the Paradox averages 18% shale and siltstone, 4% gypsum and anhydrite, 3% limestone and dolomite, and 2% sandstone and conglomerate. The remaining 73% consist of soluble salt.

Logs of several wells drilled into the Paradox fold and fault belt indicate that salt has been leached out to depths ranging from 600 to 1,000 ft. Active leaching is probably still continuing as illustrated by salt-water springs draining the west end of Fisher Valley. The springs on the east side of the Onion Creek diapir are undoubtedly fed by La Sal Mountains runoff that infiltrates the eolian and alluvial sand deposits that underlie Fisher Valley. The salt water that enters Onion Creek updip from the Onion Creek diapir indicates dissolution of evaporites beneath Fisher Valley.

Honaker Trail Formation

The Honaker Trail Formation does not crop out in the field area, although it is exposed in the adjacent Professor Valley quadrangle. In the salt anticline region the Honaker Trail Formation has been studied by Dane (1935), Elston and others, (1962), Melton (1972), Gard (1976), and Doelling (1983, 1985).

The unit is composed of fossiliferous limestone, sandstone, arkosic sandstone, siltstone, and shale. The thickness of the unit varies nonuniformly due to early salt flowage in the underlying Paradox salt. The Honaker Trail may not have been deposited over salt-induced topographic highs (Doelling, 1988).

In Fisher Valley the Cutler Formation is in fault contact with the Paradox Formation, and therefore the Honaker Trail Formation probably has been truncated during the upward movement of the Paradox diapiric salt mass.

CUTLER FORMATION

The Cutler Formation of Wolfcampian age was named by Cross and Howe (1905) for exposures of arkosic conglomerate near Ouray, Colorado. At the type area, the Cutler includes the lower strata that were originally referred to as the Dolores Formation (Cross and Spencer, 1900). Use of the name Cutler Formation was extended into the Monument Valley region, Arizona and Utah, by Baker and Reeside (1929) where the Cutler Formation contains eolian sandstone and red siltstone. Individual lithologic units have received names as members and tongues. In the central Paradox basin, the Cutler has been divided, in ascending order, into Halgaito Tongue, Cedar Mesa Sandstone Member, Organ Rock Tongue, De Chelly Sandstone Member, and Hoskinnini Tongue (Baker and Reeside, 1929, p. 1413; Baker, 1933, 1936). The Hoskinnini is now considered Triassic in age by the U.S. Geological Survey (Stewart, 1959; Read and Wanek, 1961, p. 7). In the salt anticline region the thick conglomeratic facies of the Cutler remain undivided.

In southwestern Colorado and adjacent southeastern Utah the name Rico Formation was given to a sequence of beds in the San Juan Mountains which are well exposed near the town of Rico, Colorado (Cross and Spencer 1900, p. 59-66). The formation was originally described as a transitional sequence gradually changing upward from the marine strata of Pennsylvanian age to continental red beds of Permian age. The Rico Formation has long been a subject of uncertainty and disagreement not only as to what beds should be included but also as to age (Cater, 1970). Baars (1962, 1975) has suggested the name Rico be dropped because its use masks complex but important regional stratigraphic relationships. The stratigraphy and depositional environments of the Cutler Formation have been extensively studied since Baker and Reeside's (1929) regional correlation and are documented in numerous publications, including Kunkel (1960), Baars (1961, 1962, 1975), Kirkland (1963), and Campbell (1980, 1981). Paleogeography of the Cutler has been addressed most recently by Peterson (1977), and Campbell (1980, 1981).

Regionally the Cutler consists predominantly of maroon, red, purple, and light-red mottled arkosic sandstone, arkose, arkosic conglomerates, and subordinate sandy mudstone. Quartz, fresh feldspar, and micaceous minerals, and pebbles, cobbles, and boulders of granite, gneiss, schist, and quartzite are the major constituents of the Cutler Formation. These rocks and minerals were derived from the Precambrian crystalline rocks of the ancestral Uncompahgre uplift (Kirkland, 1963). The thickness of the rock sequence varies considerably. The Cutler forms a thick asymmetric lens that thickens abruptly to the northeast, against the Uncompahgre uplift, and thins gradually to the southwest and southeast. Adjacent to the uplift in the Dolores River Canyon, near Gateway, Colorado, the Pure Oil Co. Gateway No. 1 well penetrated more than 7800 ft of arkosic sandstone before reaching the Precambrian basement. According to Baars (1975), more than 15,000 ft of arkose has been drilled adjacent to the southwest flank of the Uncompahgre uplift. The thick sequence of clastics overlying the ductile Paradox Salt facilitated the movement of salt away from the thickest Cutler deposition. The mobile salt encountered northwest-trending normal fault blocks and was deflected upward to form large linear diapiric structures (Baars, 1966). The salt diapirs controlled the flow of Permian streams, and therefore restricted the distribution of coarse sediments to the synclines surrounding the diapirs (Baars, 1975). The Cutler is very thin or missing over all of the salt anticlines, mostly as a result of depositional thinning, but also through pre-Chinle erosion (Kunkel, 1960).

In the Fisher Valley area only the upper 1600 ft of the Cutler Formation are exposed, but in the adjacent Professor Valley quadrangle more than 3048 ft are exposed and have been described by M. Jensen and R. Stanecliff (Doelling, 1981). Their measured section is included in this thesis (appendix 1), but my observations of the Cutler Formation are the basis for the following discussion. The Cutler Formation consists of pale reddish-purple to pale reddish-brown fine- to medium-grained arkosic sandstone and pale reddish-brown granule- to cobble-conglomerate. The arkosic sandstone consists of fine- to medium-grained, angular to subrounded well-sorted quartz and feldspar grains. These deposits are characterized by horizontal stratification, although some trough cross-stratification is evident. The finer-grained horizontally stratified sandstones are generally thinly laminated to thinly-bedded; the coarser, medium-grained horizontally stratified sandstone is generally thinly-bedded to massively bedded. Trough cross-stratification and tabular-planar cross-stratification is small- to medium-scale and generally restricted to the coarser, and medium-grained sandstone. Trough cross-stratification sets are lenticular and are slightly to non-plunging. Foreset cross-strata are generally thinly cross-bedded, concave upward, and dip 20-24 degrees. Tabular-planar cross-stratification sets are non-plunging. The foreset cross-strata are generally thickly laminated, straight to weakly concave upward, and they dip at low angles. Other sedimentary structures included well defined scour and fill features, ripple marks, ripple lamination, and worm tubes.

Conglomeratic beds are composed of pale reddish-brown to pale reddish-purple, granule- to cobble-size clasts in a medium-grained to coarse-grained sandstone matrix. The cobbles are generally subrounded to rounded and up to 0.75 ft in diameter. Conglomerate is found in discontinuous bands, as clasts suspended in a sand-grain matrix, and at the base of scours as lenses.

The basal contact of the Cutler Formation is not exposed in the Fisher Valley area because the Cutler is in fault contact with the Paradox Formation. The Cutler crops out in the floor of Fisher Valley adjacent to the Onion Creek diapir and at several locations along the eastern and southern ends of Fisher Valley. Cutler strata forms well exposed ledge-and-slope topography beneath the soft slope-forming Moenkopi Formation.

MOENKOPI FORMATION

Ward (1901) proposed the name Moenkopi (originally "Moencopie") for a section of reddish-brown siltstone and sandstone about 300 ft thick near the junction of Moencopie (Moenkopie) Wash and the Little Colorado River in north-central Arizona. Gregory (1916, p. 79) first used the revised spelling, Moenkopi. Because of facies changes and pinchouts of underlying Permian strata the term Moenkopi was first applied incorrectly in southeastern Utah. Emery (1918) and Moore (1922) correctly used the term as it is now recognized. Longwell and others (1923), Baker and Reeside (1929), and McKee (1954) correlated the Moenkopi over much of the Colorado Plateau. In east-central Utah and west-central Colorado, the Moenkopi of Middle (?) and Early Triassic age was first delineated by Baker and others (1927, p. 796-798), and was subsequently mapped by Baker (1933), Dane (1935), McKnight (1940), Shoemaker (1955, 1956a), and Cater (1955a, 1955b). Later, four members within the formation were recognized (Shoemaker and Newman, 1959), which are in ascending order: the Tenderfoot, Ali Baba, Sewemup, and Pariott Members. Comprehensive stratigraphic and lithologic studies were completed by Stewart (1959), Cadigan (1971), Irwin (1971), and Stewart and others (1972). Detailed stratigraphic facies and depositional environment analyses of the Moenkopi were presented by Blakey (1972, 1973, 1974).

In the Fisher Valley quadrangle the Moenkopi consists of reddish-brown to chocolate brown, micaceous thinly laminated siltstone, sandy siltstone, very fine to fine-grained sandstone (locally cross-stratified) and minor conglomerate lenses. The formation is approximately 514 ft thick but thickness varies erratically due to syn-depositional salt flowage in and adjacent to the Fisher Valley salt anticline. These thickness changes can be seen on the north wall of Fisher Valley where the thickness varies more than 45 ft in less than 1/4 mi.

Several intraformational unconformities exist in those outcrops that are nearest the axis of the collapsed anticline or in the regions of thickened salt adjacent to the anticline. Both the upper and lower contacts of the Moenkopi Formation are unconformities. The formation overlies the Cutler with an angular discordance ranging from 2-3 degrees on the northeast-plunging limb of the Fisher Valley anticline, to 6 degrees locally along the west wall of Fisher Valley.

Within the area of investigation the formation comprises two lithologically distinct units. The lower unit consists of lavender cliff-forming silty sandstone and lavender ledge-forming conglomeratic arkosic sandstone interbedded with reddish-brown very fine to coarse-grained sandstone and silty mudstone. The upper unit consists of moderate reddish-orange, slope-forming fissile siltstone and ledge-forming reddish-brown to lavender sandstone interbedded with dark reddish-brown sandstone, siltstone, and mudstone. These two general lithologic units can be further subdivided using the nomenclature of Shoemaker and Newman (1959).

The Tenderfoot Member was named by Shoemaker and Newman (1959, p. 1838) for outcrops along the north and west sides of Tenderfoot Mesa about 4 mi southeast of Gateway, Colorado. According to Shoemaker and Newman (1959), the Tenderfoot Member consists of pale reddish-brown micaceous siltstone that forms a nonresistant unit below the ledge-forming Ali Baba Member. The Tenderfoot is cut out by an angular unconformity at the base of the Ali Baba Member, and is not recognized in the Fisher Valley area.

The Ali Baba Member of the Moenkopi Formation was named by Shoemaker and Newman (1959) for exposures on the Ali Baba Ridge in Sinbad Valley. In the Fisher Valley area the Ali Baba Member consists of sandstone, and sandstone interstratified with siltstone and minor conglomeratic lenses. The Ali Baba Member in Fisher Valley composes the entire lower unit of the formation. Sandstone is generally pale reddish-brown to moderate reddish-brown, cliff-forming, very fine to medium-grained, micaceous, and arkosic. Layers of sandstone are 1-30 ft thick, and indistinctly stratified and cross-stratified in trough and planar sets. Set heights generally are less than 1 ft. Lower contacts of many of the sand bodies contain scoured surfaces. Intervening siltstone units are moderate reddish-orange to reddish-brown slope-forming, thinly laminated to thinly-bedded and marked by asymmetric ripple marks. Ripple marks and cross-bedding foreset strata orientations have been plotted on a rose diagram (fig. 5) to help determine gross paleocurrent direction. Conglomeratic lenses are

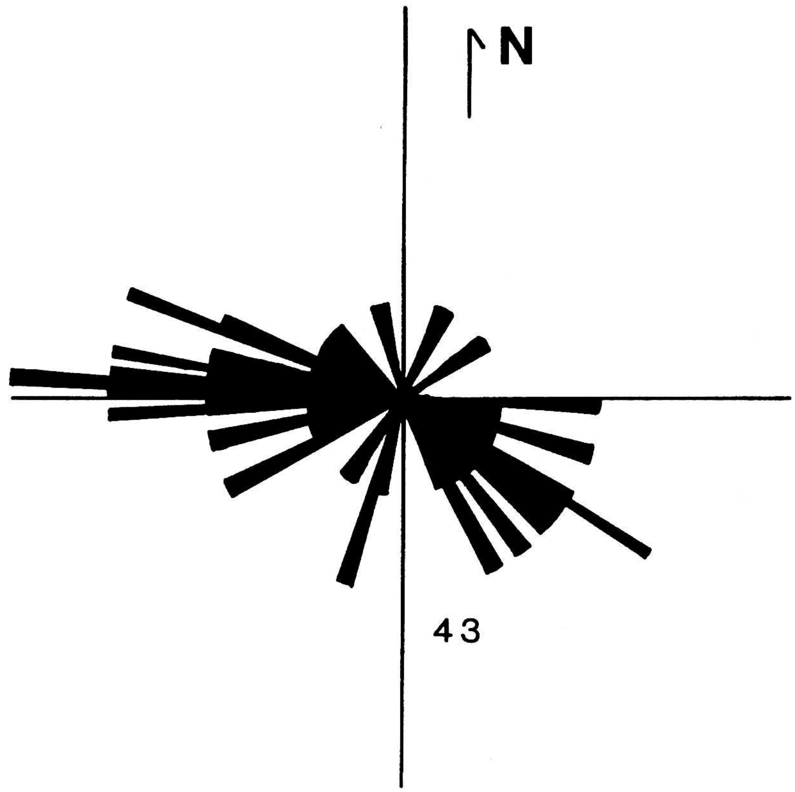


Figure 5. Paleocurrent data for fluvial deposits in the Moenkopi. Rose diagram shows dispersion of data and number of observations. Data mainly obtained from crossbeds, scour marks, and asymmetric ripples. Dominant flow is toward the west and east. The bimodal orientation of paleocurrent data may suggest either tide-dominated fluvial deposits or misidentification of asymmetric ripple marks.

generally pale reddish-brown to purplish-brown, and consist of granules, pebbles, and cobbles of Precambrian crystalline rocks. These 3-30 ft thick lenses exhibit scoured basal contacts and sharp upper contacts, and are restricted to the lower 40 ft of the Ali Baba Member. A discontinuous lense of bedded gypsum and a thin zone of nodular gypsum, not found in the measured section, was identified near the base of the Ali Baba on the west wall of Fisher Valley, near the western edge of the field area. The Ali Baba Member thickness is 330 ft but varies erratically due to salt flowage in the underlying Pennsylvanian Paradox Formation.

The Sewemup Member of the Moenkopi Formation was named by Shoemaker and Newmam (1959, p. 1838) for exposures on Sewemup Mesa, which forms the east wall of Sinbad Valley. In Fisher Valley the Sewemup Member conformably overlies the Ali Baba, and forms the lower part of the upper unit of the formation. The contact is gradational and is placed above the highest prominent ledge-forming sandstone of the Ali Baba Member. The Sewemup Member is composed of interbedded sandstone, siltstone, and subordinate amounts of mudstone. Predominant lithology of the member is pale reddish-orange to grayish-red slope-forming micaceous siltstone. Siltstone is thinly laminated to thinly-bedded and distinctly ripple marked. Symmetric and asymmetric ripple marks were identified; those clearly asymmetric were plotted (fig. 5) with Ali Baba paleocurrent indicators. There were no recognizable differences in paleocurrent directions between members of the Moenkopi.

Sandstone in the Sewemup is generally reddish-brown to light brown, locally ledge-forming, fine-grained, silty and slightly micaceous. The mudstone is dark reddish-brown, slope forming, thinly laminated to indistinctly bedded. The Sewemup Member is 140 ft thick but varies considerably. On the north wall of Fisher Valley the Sewemup Member and overlying Pariott Member thicken by more the 40 ft adjacent to the Fisher Valley anticline. Thickening occurs over the monoclinal folding of the underlying Ali Baba Member. Folding of the Moenkopi by syn-depositional deformation is illustrated in figure 6. The Sewemup Member commonly forms a slope, which is broken in places by resistant ledges.

The Pariott Member of the Moenkopi Formation was named by Shoemaker and Newman (1959 p. 1838) for exposures on Pariott Mesa on the north side of Castle Valley. In the Fisher Valley quadrangle the member consists of sandstone and interbedded subordinate mudstone. The sandstone is moderate reddish-brown to light brown, ledge and slope-forming, fine to medium-grained, micaceous, gritty, and cross-stratified. The basal sandstone fills scours on the Sewemup upper contact. Many of the sandstone bodies are lenticular, contain a coarse-grained basal layer (lag deposit), display an upward-fining sequence, and are cross-stratified in many places. The mudstone is commonly grayish-purple to dusky purple, slope-forming, and thinly to massively bedded. Ripple laminae are not as abundant as in the underlying Ali Baba Member. The Pariott Member is approximately 40 ft thick but varies due to deformation in the underlying formations caused by salt flow. The Pariott Member, the upper part of the upper unit of the formation, forms an earth slope broken in places by thin resistant ledges. The upper contact with the Chinle is an unconformity, which locally, as at the southwest end of Cottonwood graben, is angular. Conditions of

Figure 6. Folded and faulted Ali Baba Member of the Moenkopi Formation is overlain by undeformed Ali Baba strata. Depositional thinning of upper part of Ali Baba is evident.

deposition of the Moenkopi vary from tidal mudflat to fluvial. Symmetric ripple-marked mudstones were deposited in fluvial-dominated tidal mudflats. Cross-stratified, asymmetric ripple-marked sandstones and interstratified siltstones were deposited in fluvial channels. The bimodal orientation of paleocurrent data suggest that fluvial environments may have been tide-influenced. The source area for the sediments in the Fisher Valley region was the ancestral Uncompahgre uplift (Dane, 1935, p. 45).

The Moenkopi Formation crops out along the base of the escarpments that surround Fisher Valley. The upper half of the Ali Baba, and the entire Sewemup and Pariott Members are well exposed although the lower half of the Ali Baba is commonly covered with Quaternary talus deposits. The upper part of the Ali Baba and the entire Sewemup and Pariott Members are well exposed along the northeastern end of Cottonwood Creek and the Dolores River Valley.

CHINLE FORMATION

The Chinle Formation of Late Triassic age was named and described in Chinle Wash on the Navajo Indian Reservation in northern Arizona by Gregory (1917). Gregory (1917, p. 42-43) recognized four divisions of the Chinle Formation, which he referred to as D, C, B, and A in ascending order. Subsequently, Witkind and Thaden (1963), applied the names Monitor Butte Member to division D, Petrified Forest Member to division C, Owl Rock Member to division B, and Church Rock Member to division A. According to O'Sullivan and MacLachlan (1975), near the type locality the members of the Chinle are well defined and easily mapped, but northward from Arizona into Utah some of the individual members lose much of their individual characteristic lithologies. Therefore, informal names for some of these units have been applied in east-central Utah. Chinle regional stratigraphy has also been documented by Stewart (1956, 1969), MacLachlan (1957), Stewart and Wilson (1960), Robeck (1958), Poole and Stewart (1964), Irwin (1971), Stewart and others (1957, 1972), and O'Sullivan and MacLachlan (1975). A subdivision of the Chinle Formation that is useful in the salt anticline region has been established by Stewart and others (1972). This sequence includes, in ascending order: mottled strata, basal sandstone, Petrified Forest Member, "Black Ledge", and Church Rock Member (Doelling, 1985).

In the Fisher Valley area, the Chinle Formation consists of moderate reddish-brown, slope-forming, very fine-grained sandstone to siltstone with a basal discontinuous limestone unit. Lithology of the sequence as recorded in the measured section (appendix 1) is monotonous. The basal six ft of the formation consist of very light gray, heterogeneous limestone (calcarenite) lenses. The unit ranges in composition from dense indistinctly bedded limestone to a thinly laminated, very quartz rich (fine sand) limestone. The upper 3 ft are composed of grains that appear to be detrital in origin, though they are probably locally derived. The lower limestone unit disconformably overlies the Moenkopi Formation. This basal limestone unit is probably part of the Owl Rock Member. The Owl Rock Member is part of the upper half of the Chinle and was first identified by Witkind and Thaden (1963,

p. 31), in exposures near Kayenta, Arizona. This limestone is probably stratigraphically equivalent to a basal white gritstone zone of the Chinle along the Colorado River at Big Bend, a few miles southwest of Fisher Valley (Stewart and Wilson, 1960).

Above the basal limestone unit, the remainder of the Chinle Formation consists of moderate reddish-brown, very fine-grained sandstone and siltstone. In the sandstone, sand grains are dominantly quartz, very fine-grained, subangular to subrounded and well-sorted. The unit is generally calcareous and micaceous. The sandstone is thinly laminated to indistinctly bedded and often occurs as irregular lenses or layers that interfinger with siltstone layers. Horizontal stratification is the dominant bedding type, but locally the sandstone contains small-scale, low-angle cross strata and ripple-marked layers. Wedge-planar and tabular-planar cross-stratification are the dominant type of cross-stratification. These planar cross-sets are non-plunging and set heights are generally less than 2 ft. Foreset cross-strata are thinly to thickly cross-laminated, straight to weakly concave up and dip at low angles. The lack of well exposed cross-stratification prevented the analysis of paleocurrents.

The siltstone is similar in composition to the sandstone, but is composed of subangular to subrounded, coarse silt-size quartz grains. From a distance, the siltstone appears to be horizontally stratified, but on close examination, bedding is indistinct and the siltstone appears structureless. The slope formed by the Chinle is covered with small (1/4"x1/4"x3/8") "prism like", angular fragments weathered from the siltstone horizon.

Locally, the top few feet of the Chinle Formation is similar in composition and texture to the overlying Wingate Sandstone. The contact between the Chinle Formation and Wingate Sandstone is sharp and in many places is an angular unconformity. Units in the Chinle and Wingate Formations that are similar, though separated by a well defined unconformity appear gradational and may represent an initial influx of Wingate-like material. The formation characteristically weathers to form a reddish-brown, earthy slope broken only by thin resistant ledge-forming sandstones. From a distance the Chinle Formation and Moenkopi Formation look very similar, but several distinctions were observed. The Chinle displays a more brilliant red tone as compared to the browner units of the Moenkopi. In addition, the Chinle lacks arkose, well developed stratification, and ripple bedding, all of which are abundant in the Moenkopi. The Chinle Formation crops out in the walls surrounding Fisher Valley, and in the Cottonwood, Thompson, and Dolores River Canyons. The slope-forming Chinle Formation lies below the massive sheer cliff formed by the Wingate Sandstone.

The Chinle Formation in the Fisher Valley area probably correlates with the Church Rock Member as described by Stewart and others (1972). The basal limestone unit is equivalent to the Owl Rock Member which is a subdivision of the lower part of the Church Rock Member. Most of the formation is equivalent to the Church Rock Member. The regional paleocurrent and depositional environment studies of Poole (1961), Stewart and others (1972), Ash (1975), Blakey and Gubitosa (1983), Carr and Paull (1983), and Dubiel (1984) have helped to clarify the depositional environments of the Chinle. In general, medium and fine-grained sandstones were deposited in a variety of fluvial, lacustrine, deltaic, and continental sabkha environments. Mudstones and siltstones were deposited on fluvial floodplains, and in abandoned fluvial channels on lacustrine and sabkha mudflats. The Owl Rock Member which contains freshwater invertebrate fossils (Stewart and Wilson, 1960), undoubtedly represents lacustrine deposits. Cross-stratified sandstones, scour and fill features, channel structures developed in sandstone units (including basal lag deposits), and homogeneous siltstone units of the Chinle Formation in the Fisher Valley area, indicate fluvial channel and floodplain deposits. Poole (1961) suggested that sediment transport (stream direction) in east-central Utah was toward the west. Parr (1965), who investigated sedimentary structures around the Moab anticline was unable to obtain consistent paleocurrent trends. Lithology of the formation and regional paleocurrent orientations determined from directional data by Poole (1961) indicate that Chinle streams were draining the ancestral Uncompahgre uplift in western Colorado.

GLEN CANYON GROUP

The name "Glen Canyon Group" was first applied by Gilluly and Reeside (1928) and Gregory and Moore (1931) to a group of rocks having a similar lithologic character and areal extent. However, Baker and others (1927) were the first to publish the name "Glen Canyon Group". The group was named after Glen Canyon along the Colorado River in southeastern Utah, where it is typically exposed. As defined by Gilluly and Reeside (1927), the Glen Canyon Group originally included the Wingate Sandstone (Dutton, 1885), the Todilto Member of the Morrison (Gregory, 1917), and the Navajo Sandstone (Gregory, 1917). The Kayenta Formation (Baker and others, 1931) was later introduced to replace what was first considered to be a sandstone facies of the Todilto Member.

Until recently the Wingate Sandstone and Kayenta Formation (lower and middle formations of the Glen Canyon Group) were thought to be Triassic in age. Pipiringos and O'Sullivan (1978, P. A18-19) and Imlay (1980), however, have suggested a Jurassic age for the Glen Canyon Group.

Wingate Sandstone

The Wingate Sandstone of Jurassic age was originally described by Dutton (1885, p. 136-137) from exposures in the cliff north of Fort Wingate, New Mexico. The upper 300 ft of Dutton's type sandstone is now recognized (Baker and others, 1947, p. 1667) as the Entrada Sandstone of the San Rafael group. In northern Arizona, the Wingate Sandstone is composed of two mappable units: the lower, Rock Point Member, which consists of reddish-orange, thin-bedded siltstone and sandstone, and the upper, Lukachukai Member, which consists of reddish-brown, cliff-forming, cross-bedded, fine-grained sandstone (Harshbarger and others, 1957). In the Fisher Valley area, the Wingate Formation consists entirely of the upper Lukachukai Member. The name Lukachukai was proposed for the sandstone that forms the vertical cliffs in the escarpment northeast of Lukachukai, Apache County, Arizona (Harshbarger and others, 1957). The Wingate Sandstone averages about 300 ft thick in northeastern Arizona, but thins rapidly to the east, south, and west (Silver, 1948, p. 68-61; Rappaport and others, 1952, p. 18; Harshbarger and others, 1957). The Wingate is an eolian deposit with a northwestern source (Baker and others, 1927; Dane, 1935; Poole, 1962).

In the Fisher Valley area, the Wingate Sandstone is a moderate reddish-orange to moderate orange-pink, cliff-forming, well-sorted, fine-grained, cross-stratified eolian quartz sandstone. Lithologically the Wingate Sandstone is uniform throughout as illustrated in the measured section (appendix 1). The Wingate Sandstone is accessible or traversable only where the formation has been shattered by faulting. Sand grains are dominantly quartz with a subordinate amount of feldspar. They are very fine to fine-grained, subangular to subrounded, well-sorted, and often stained yellow. A few coarse, well rounded and polished sand grains are present at the base of large trough cross-sets.

The unit is divisible into cross-stratified layers 4-70 ft thick by laterally continuous bedding surfaces. The thick horizontal layers are generally cross-stratified though cross-stratification is faint and often indistinct on weathered surfaces. Medium and large scale trough and wedge-planar cross-sets are the dominant type of cross-stratification in the Wingate Sandstone. Trough cross-bed sets are lenticular, non-plunging to slightly plunging and up to 15 ft thick. Foreset cross-strata composing the sets are generally thickly cross-laminated to thickly cross-bedded and concave up. Wedge-planar cross-stratification sets are non-plunging and up to 7 ft thick. Foresets are thickly cross-laminated and straight to weakly concave upward. Large trough cross-strata truncated by bounding surfaces may have been misinterpreted as wedge-planar cross-stratification. The upper part of both wedge-planar and trough cross-sets are very similar but the base of trough cross-sets are generally concave upward. Cross-stratification zones are truncated by laterally continuous parallel surfaces. Above these horizontal surfaces, feldspathic, silt is very abundant. Thin wavy-laminated siltstone beds are locally developed superjacent to these surfaces.

The concept of "multiple parallel truncation bedding planes" was first proposed by Stokes (1968, p. 510) to explain smooth parallel surfaces in eolian blanket sandstone formations of the Colorado Plateau. This hypothesis implies that the laterally continuous, smooth parallel surfaces observed in the Wingate in Fisher Valley may be the product of erosion, rather than deposition. Dune fields are planed-off to the water table by wind action (deflation), leaving a smooth surface. These horizontal bounding surfaces have also been interpreted as forming with the migration of interdune areas or formed during periods of low sediment availability (McKee and Moiola, 1975; McKee and others, 1977; Brookfield, 1977; Rubin and Hunter, 1981; and Kocurek, 1981). More recently Loope (1984, 1985) has interpreted smooth parallel bounding surfaces found in Upper Pensylvanian and Lower Permian sandstones of southeastern Utah as deflation surfaces. Nation and Blakey (1988) have correlated these parallel planes and believe several of these surfaces are isochronous and can be used to delineate magnitude and timing of regional and local syn-depositional structural events.

The Wingate Sandstone lies unconformably above the Chinle Formation. Locally the unconformity is angular, such as adjacent to the southwest end of Cottonwood graben (SW1/4, SW1/4, sec. 30, T. 24 S., R. 25 E.), and along the east wall of Fisher Valley (E1/2, sec. 6 and E1/2, sec. 7, T. 25 S., R. 25 E.). The rather sharp contact has been interpreted as the J-O unconformity (O'Sullivan and Green, 1973, p. 76; Pipiringos and O'Sullivan, 1978, p. A19). The contact between the Wingate Sandstone and the Kayenta Formation appears gradational. In Fisher Valley, the Wingate Sandstone forms a reddish-orange, nearly vertical cliff that rims the walls surrounding Fisher Valley and the Cottonwood, Thompson, Burro, and Dolores River canyons.

Kayenta Formation

The sequence of rocks now referred to as the Kayenta Formation of Jurassic age was originally described by Gregory (1917, p. 56) as a sandy facies of the Todilto Member. Baker and others (1931) introduced the term Kayenta Formation to replace Todilto Member where applied to the red sandy unit overlying the Wingate Sandstone in the Glen Canyon region of the Colorado River.

In the Fisher Valley quadrangle, the Kayenta is a grayish-orange-pink to grayish-red, ledge-forming, fine to medium-grained, irregularly stratified calcareous sandstone with subordinate intraformational conglomerate and siltstone units. Most of the sandstones tend to be grayish-orange-pink with interstratified grayish-red siltstones and light reddish-brown conglomerates.

The sandstone is composed chiefly of colorless quartz, but plagioclase (?) feldspar, biotite, chlorite, magnetite, and chert fragments are present. Most of the grains are coated with a thin film of brown iron oxide. The major cementing material is calcite, though silica and iron oxide are evident locally. Grain size ranges from very fine to medium and most grains range in shape from subangular to subrounded, though some are angular.

Lenticularity is typical of all beds comprising the Kayenta Formation. Intertonguing between these lenses is common and results in abrupt changes in lithologic character. Much of the sandstone is thickly laminated to thinly-bedded and weathers platy. Many of the sandstone lenses are as much as 15 ft thick and show prominent cross-stratification.

Two distinct channel morphologies were identified within the Kayenta Formation. The larger and thicker channel is represented by intraformational conglomerates that are cross-stratified. Trough and tabular-planar cross-beds are the dominant cross-stratification type. A smaller channel morphology or secondary channel consists of stacked, thickly laminated, straight foresets composed of typical Kayenta sandstone with scattered coarse sand, granules, pebbles (lag), and silt grains. Trough and wedge-planar cross-stratification is the dominant stratification within the formation. Cross-set heights are generally 1-3 ft thick and non-plunging. Foresets are straight to weakly concave upward and dip at low angles. Orientation of foreset strata and scour marks were plotted on a rose-diagram and display a bimodal distribution (fig. 7). The strong westward orientation indicates major stream

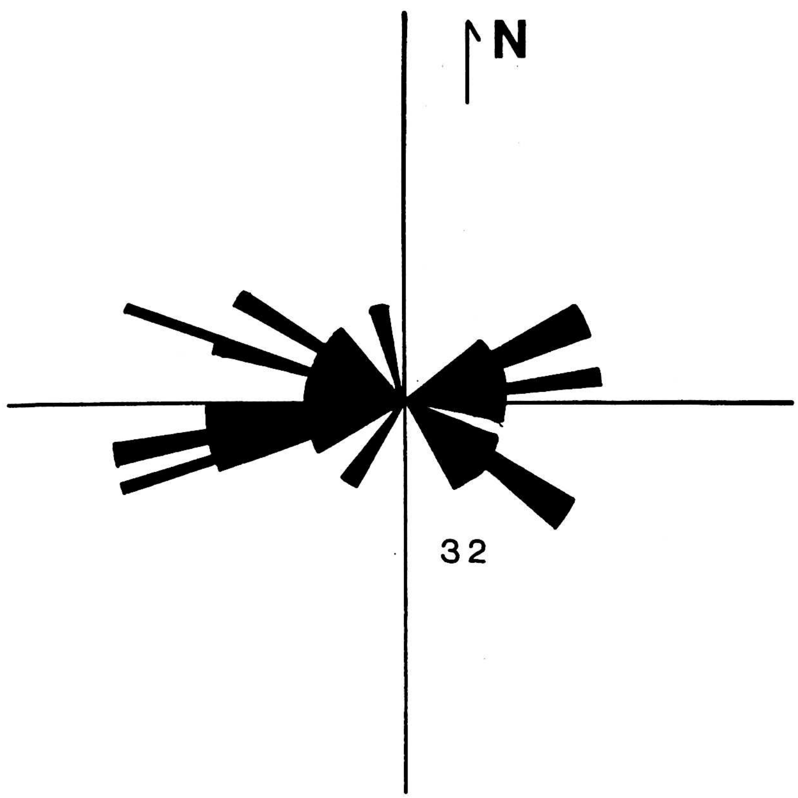


Figure 7. Paleocurrent data for fluvial deposits in the Kayenta Formation. Rose diagram shows dispersion of data and number of observations. Data mainly obtained from crossbeds and scour marks. Dominant flow was toward the west and east. The bimodal orientation of paleocurrent data may suggest misidentification of scour marks.

direction, and sediment dispersion probably was toward the west. The eastward orientation of paleocurrent data (fig. 7) may be the result of misidentified symmetric ripples as asymmetric ripples.

Zones of contorted beds were identified in a few of the sandstone lenses near the base of the formation. These zones appear to be compressional and consist of high-angle asymmetric folds. These zones are much less contorted than similar zones found in the overlying Navajo Sandstone.

The siltstone units within the formation are moderate reddish-brown, thinly laminated and micaceous. These beds are generally horizontally stratified, discontinuous, and comprise less than 5% of the formation. Intraformational conglomerates are generally restricted to the larger channel-sandstone bodies. These conglomerates are purplish-brown to light grayish-brown, and consist of irregularly distributed, angular to rounded pebbles of quartz, quartzite, chert, and red and gray mudstone fragments. The formation intertongues with the overlying Navajo Sandstone and the exact upper contact is difficult to determine. The top of the formation displays typical Kayenta lithology reworked into Navajo-style, trough cross-sets. Thickness of the unit is approximately 217 ft, but varies considerably throughout the field area and noticeably thins to the east, toward the Uncompahgre uplift.

The basal part of the Kayenta appears to be more thoroughly cemented than the upper portion and forms a resistant ledge that protects the underlying Wingate Sandstone. The upper part is less resistant and weathers to a slope that is marked by a series of ledges and narrow platforms. The Kayenta crops out over broad areas and forms extensive dip slopes. The dip slope on Seven Mile Mesa is almost entirely composed of the Kayenta Formation. The formation is also exposed in the vertical escarpments that bound Fisher Valley. In the northern escarpments that bound Fisher Valley (Seven Mile Mesa) most of the Kayenta Formation has been stripped off, though the basal portion of the formation is present.

Navajo Sandstone

The Navajo Sandstone was named by Gregory (1917) for extensive outcrops on the Navajo Indian Reservation in Arizona and Utah. No specific type area was designated except for the "Navajo Country". The Navajo Sandstone, the upper-most formation of the Glen Canyon Group, is a thick sequence of cliff-forming, cross-stratified quartzose sandstone that is present over the western 2/3 of the Colorado Plateau. It crops out as sheer cliffs, large domal masses and broad hummocky expanses of bare rock. The Navajo Sandstone achieves a maximum thickness of 2380 ft (695m) in the Zion National Park area near Carmel Junction in southwestern Utah (Gregory, 1950). The formation thins eastward and pinches out near the Utah-Colorado and Arizona-New Mexico state lines by the J-2 unconformity described by Pipiringos and O'Sullivan (1978).

In the Fisher Valley quadrangle, the Navajo Sandstone consists of yellowish-gray, cliff-forming, fine to medium-grained, cross-bedded quartzose sandstone. The unit displays contrasting colors that vary between shades of very light gray to pale orange. Light gray is the dominant color in the lower 1/5 of the section; the upper 4/5 consist of various shades of pale orange. Color change bears no recognizable relationships to lithology or bedding and in many places cuts across stratification.

Lithology of the sequence as recorded in the measured stratigraphic sections (appendix 1) is monotonous. Feldspar, magnetite, ilmenite, and glauconite are minor constituents. Calcite seems to be the dominant cementing agent in the lower 1/3 of the unit and at the extreme top. Silica cement seems to dominate the middle part of the section. Other features, including grain size, grain rounding, stratification, and foreset dip directions, show change throughout the sections.

Sand grains range in size from very fine to medium. A subtle coarsening upward sequence was identified. The minority of medium-size grains in the lower part of the section are scattered in a fine-grained matrix. In the upper 2/3's of the section, medium-size grains are the dominant grain size. Silt is a minor component of the unit and is generally absent in the upper 1/3 of the section. Sand grains in the formation are well-sorted. Lack of silt in the upper part of the section indicates a change in the flow regime and or a change in sediment availability. Sand grains are generally well rounded, polished and often frosted. Fine-size grains are less well rounded and their surfaces are conspicuously less frosted. Macroscopic field observations did not permit determination of the cause of surface textures. Mechanical and/or diagenetic chemical precipitation and corrosion may have caused the surface textures evident on Navajo sand grains (Freeman and Visher, 1975). Rare well-rounded coarse chert grains are limited to the base of trough cross-sets.

The Navajo Sandstone displays three basic bedding types: cross-stratification, horizontal stratification, and contorted stratification. Cross-stratification is dominant in the Navajo Sandstone. Near the base of the formation, tabular-planar, wedge-planar, and trough (festoon) cross-sets alternate with horizontally stratified sandstones. Horizontal bedding planes that truncate cross-strata may mark the position of ancient water table levels (Stokes, 1968; Loope, 1984, 1985). In these cross-beds, set heights are generally less than 6 ft. Many of the dissected wedge-planar sets may be remnants of large-scale trough cross-bedding. In the upper part of the formation, where cross-set heights are generally greater than 6 ft, trough cross-stratification dominates and is often associated with contorted stratification. In the trough cross-stratified sandstone, set heights range from 8 in. to 14 ft. Foresets are thinly cross-laminated, inclined 13 to 34 degrees, and many are curved (concave upward) at the base. Foreset dip directions were measured in several localities, sec. 20, 21, 28, 7, R. 25 E., T. 24 S., and were plotted on a rose-diagram (fig. 8). Correction for regional tilt was unnecessary because structural dip in those sections measured was generally 2-4 degrees and therefore tilt affect on the orientation of directional data is negligible.

Horizontal strata are present in the lower portion of the Navajo Sandstone. Sandstone similar in lithology to the overlying cross-stratified portions of the Navajo occurs in horizontally-stratified layers that range from a few inches to 10 ft thick. A prominent horizontally stratified, discontinuous zone 1.7 ft thick, consisting of dark reddish-brown, thinly laminated sandy siltstone is found

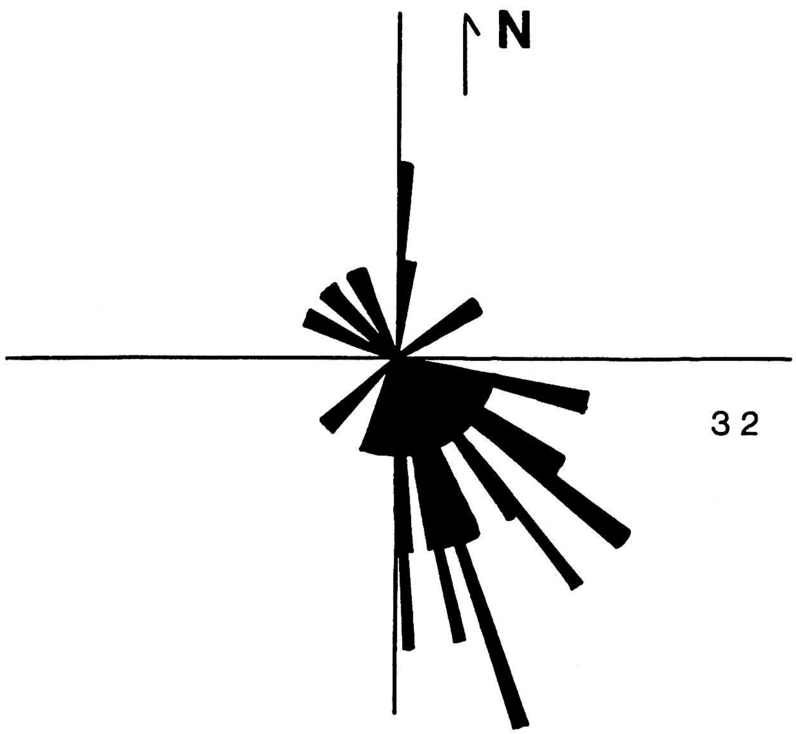


Figure 8. Paleocurrent data for eolian deposits in the Navajo Sandstone. Rose diagram shows dispersion of data and number of observations. Data obtained from crossbeds. Dominant flow was toward the southeast.

approximately 100 ft above the base of the Navajo Formation. Lack of well defined stratification and bedform morphology prevents an accurate interpretation of the depositional environment of the siltstone units. I interpret these thin lenticular siltstones to represent eolian interdune sediments deposited during periods of low sediment supply. The reddish-brown color is probably related to the high proportion of silt and increased permeability, which has allowed iron oxide to infiltrate the horizon.

Zones of contorted beds were identified in the middle to upper part of the section (NW1/4, SW1/4, sec. 14, R. 24 E., T. 25 S.). These zones appear to be compressional and consist of elaborate high-angle asymmetrical folds and flame structures. Many bedding planes do not lose their integrity when distorted but remain as discrete traceable units in the distorted zone. Contorted zones found in the field were everywhere underlain by large-scale cross-strata. The relationship with overlying beds was not determined for lack of exposure. Previous workers have observed contorted zones in eolian sandstones of the Colorado Plateau (Marzolf, 1969; Jordan, 1965; Kiersch, 1950; and Sanderson, 1974).

Minor but conspicuous thin (less than 1.5 ft) lenses of light gray cherty limestone and cherty dolomitic limestone are present near the top of the Navajo. The limestone is generally horizontally stratified and thinly laminated. Chert nodules range in color from gray to red and weathered nodules often have a zoned appearance; they are reddish-gray on the interior, and very light gray on the exterior. These discontinous carbonate lenses are thought to be formed in ephemeral lakes among dunes (Gregory, 1950; Mullens, 1960).

Although the large-scale trough cross-strata foresets in the sandstone appear to dip in many directions, the rose diagram (fig. 8) illustrates that foresets dip predominantly to the south-southeast. These orientations indicate northwesterly winds similar to those that prevailed during deposition of the Wingate (Poole, 1962, p. D149). Sediment source area was undoubtedly to the northwest as suggested by Jordan (1965), and Stanley and others (1971). The initial source of sand probably was stream beds in the nearby region, as evidenced by the interfingering of Kayenta fluvial deposits with Navajo eolian deposits. The Navajo phase of eolian sand sea development seems to have ended with a brief period of regional erosion in the middle Bajocian (Pipiringos and O'Sullivan, 1975, 1978; and Peterson and Pipiringos, 1979). The upper contact of the Navajo is marked locally by chert pebbles, and cobbles of limestone that have been replaced by chert. This chert-pebble unconformity surface is well exposed at the south end of Polar Mesa. The chert pebbles are thought to have been derived from weathering of chert nodules from carbonate interdune or lake deposits within the Navajo (Pipiringos and O'Sullivan, 1975; and Gilland, 1979).

The Navajo Sandstone has generally been interpreted as having been deposited by eolian processes in an interior desert environment (Poole, 1962; Tanner, 1965; Stokes, 1968; Picard, 1977). However, there have been other contrasting interpretations. Stanley and others (1971, p. 77), suggested that the Navajo Sandstone was deposited as a shallow marine and coastal dune complex. Freeman and Visher (1975) suggested that the Navajo was deposited in a tide-dominated shallow-marine environment. Doubts about the eolian origin of the Navajo cross-strata has been reduced by new information on eolian cross-strata (Hunter, 1977, 1981; Fryberger and Schenk, 1981; and Kocurek and Dott, 1981).

In the Fisher Valley area maximum thickness of the Navajo is approximately 264 ft. Lack of exposure of a complete section and poor accessibility prevented the measurement of a complete section. The Navajo visibly thins to the east and pinches out on the east (west-dipping) flank of the Sagers Wash syncline. The pinch-out is visible to the northeast of Cottonwood graben from Sevenmile and Polar Mesas. The Navajo conformably overlies and intertongues with fluvial deposits of the Kayenta Formation and is unconformably overlain by the littoral Dewey Bridge Member of the Entrada Sandstone.

SAN RAFAEL GROUP/ENTRADA SANDSTONE

The San Rafael Group was named after the San Rafael Swell in east-central Utah and was applied to a group of rocks having a similar lithologic character and areal extent. The San Rafael Group is represented in the Fisher Valley area by one formation, the Entrada Sandstone.

ENTRADA SANDSTONE

The Entrada Sandstone was named by Gilluly and Reeside (1928, p. 76-78) from exposures at Entrada Point in the northern part of the San Rafael Swell. Gilluly and Reeside (1928) included the earthy sandstones and subordinate shales at this location in the San Rafael Group and assigned them a Late Jurassic age. Work by Baker and others (1927, p. 804), Baker (1933, p. 49-50), Dane (1935, p. 94), and Imlay (1952a) laid the ground work that allowed Wright and others (1962) to further define the Entrada Sandstone by separating it into three members. These are, in ascending order: the Dewey Bridge Member, Slickrock Member, and Moab Sandstone Member or Moab Tongue.

Although the Entrada Sandstone does not attain the great thickness of other eolian sandstone formations in the Colorado Plateau region, it has the widest aerial extent (Poole, 1963, p. 395; Tanner, 1965, p. 564). The Entrada sandstone is also one of the youngest eolian sandstones in this region, representing the termination of a long period of eolian deposition that began in the Permian and ended in the late Jurassic.

The age of the San Rafael Group in east-central Utah is poorly constrained. The Entrada in northeast and east-central Utah is apparently unfossiliferous (Kinney, 1955; Hansen, 1965). McKnight (1940, p. 94) discovered ornithopod dinosaur tracks in the top of the Moab Sandstone Member just below Courthouse Spring in Grand County, Utah. Baker and others (1936, p. 8) also discovered dinosaur tracks in the Moab Member, 15 mi north of Moab, Utah. Unfortunately these tracks did not yield additional information on the age of the Entrada Sandstone.

The Dewey Bridge Member

The Dewey Bridge Member of the Entrada Sandstone, the lowermost unit of the San Rafael Group, is a thin sequence of slope-forming, horizontally bedded siltstone, mudstone, and sandstone, and includes strata previously mapped as Carmel. The Dewey Bridge Member in east-central Utah is approximately 45-130 ft thick, and near its sandy edge in Colorado it is only 9-47 ft thick (Craig and Shawe, 1975). The Carmel Formation, which is considered correlative to the Dewey Bridge Member, is considered to be Middle Jurassic to early Late Jurassic (middle Bajocian to middle Callovian) according to Imlay (1948, 1953). These age assignments are based on the ammonites: Stemmatoceras, and Chondroceras (Defonticeras).

In the Fisher Valley area the Dewey Bridge consists of moderate reddish-orange, soft, horizontally bedded, silty sandstone (see measured section, appendix 1). The unit crops out as an earthy slope that forms a platform from which the cliffs of the Slickrock Member of the Entrada Sandstone rise. All of the unit, except the lower 3-4 ft of light gray sandstone and limestone, is consistently darker than the underlying Navajo Sandstone and overlying Slickrock Member. The unit consists predominantly of silty fine-grained sandstone with minor siltstone beds. Except for the upper 3-4 ft the member consists of a very subtle coarsening-upward sequence.

The lower few feet of the unit consist of light gray, horizontally stratified, very fine-grained quartz sandstone. The sandstone is overlain by a reddish-gray lenticular, sandy, cherty limestone that displays abundant convoluted laminations. A thin (less than 3 ft thick) light gray, thinly-bedded, fine-grained sandstone overlies the carbonate unit. The terrigenous sandstone unit appears to be reworked Navajo Sandstone material. The limestone appears to have been deposited in shallow lacustrine ponds. The light gray sandstone and reddish-gray limestone appear to be similar to lithologies found at the top of the Navajo but these beds are clearly above the unconformity surface developed at the upper Navajo contact. The dominant and remaining part of the section (upper 23 ft of the unit), consists of moderate reddish-orange to dark reddish-brown, thickly bedded, fine-grained silty sandstone and interbedded siltstone. The dominant sandstone unit contains sparse well rounded, frosted, medium to coarse sand grains. These grains are generally amber to white quartz and have been previously described and named "Entrada Berries" by Wright and others (1962).

Baker (1933) was the first investigator to recognize that Navajo paleotopography played a role in controlling where Carmel (Dewey Bridge equivalent) sediments were deposited. Evidence of Navajo paleotopographic control in the Fisher Valley area consists of local thinning and thickening of the Dewey Bridge in the following locations: secs. 4, 5, 6, T. 24 S., R. 25 E. and SE1/4, NW1/4, sec. 34, R. 25 E., T. 24 S.. Thinning of the formation over paleotopographic highs near Polar Mesa is accentuated by regional thinning of the formation toward the east. Disruption and deformation of bedding surfaces was identified throughout the Dewey Bridge Member. Contorted beds are often bowed into irregular folds as much 30 ft in amplitude and 100 ft in wave length (figure 9). This apparent soft sediment deformation affects the lower part of the overlying Slickrock Member as well. This deformation is well exposed in sec. 6, R. 25 E., T. 24 S., on Sevenmile Mesa. Locally the thickness of these deformed beds varies by more than 15 ft. The member thins to less than 8 ft in sec. 4, R. 25 E., T. 24 S.. At this location, the dark reddish-brown silty sandstone comprises the entire formation. It is not clear whether the missing basal units were deleted by pre-folding erosion or were never deposited. This prominent local thinning may be due to cumulative affects caused by thinning in crestal areas of folds, thinning above subtle Navajo topographic highs, and a regional thinning of the unit toward the east.

If these deformed and bowed zones straddle and are constrained by Navajo topographic highs, several possible scenarios develop. 1) The basal, reworked lithology (reworked from the Navajo) may not have been deposited on these topographic positive areas. This would require that Navajo topographic highs exceed 30 ft (Dewey Bridge minimum thickness subtracted from maximum thickness). Such a statement is unrealistic because in the field area it is doubtful that local relief on the top of the Navajo prior to Dewey Bridge deposition exceeded a few feet. 2) Navajo topography played a role in controlling the localization of soft-sediment deformation in the overlying Dewey Bridge Member. It has been suggested that these folded structures deformed as a result of

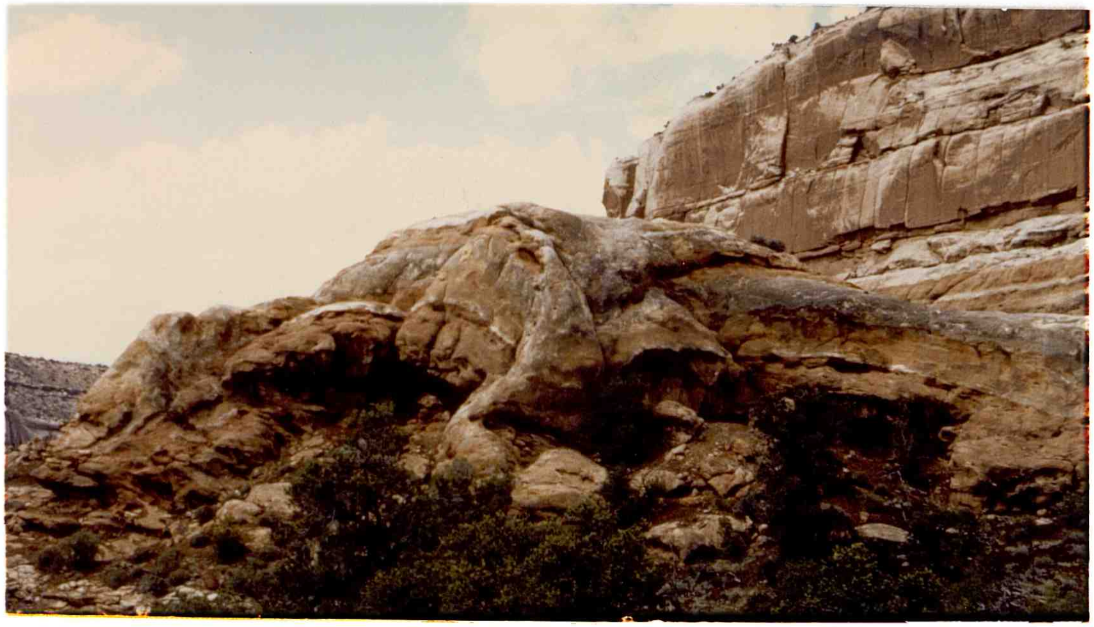


Figure 9a. Contorted, folded Dewey Bridge Member of the Entrada Sandstone. Apparent soft-sediment folds are as much as 30 feet in amplitude and 150 feet in wave-length. Deformation affects the overlying Slickrock Member.

Figure 9b. Contorted, folded Dewey Bridge and Slickrock Members of the Entrada Sandstone. View northwest from Polar Mesa.

differential loading of unconsolidated water-saturated silty sand (Dane, 1935, p. 92; Craig and Shawe, 1975, p. 159).

The depositional environment of the Dewey Bridge is poorly understood as is the method of water saturation. Varied depositional environments, including eolian sand sheet, alluvial fan, marginal marine, and tidal flat have been postulated for the Dewey Bridge. The Dewey Bridge is underlain and overlain by eolian sand sea deposits, yet my analysis of the unit in the Fisher Valley area, near Dewey Bridge (the type locality of the unit), and in Arches National Park, indicates a subaqueous, marginal-marine depositional environment. Clay rip-up clasts, scour and fill structures, flame structures, different lithologies and bedforms, and the inferred deformation of water-saturated sediments, suggest subaqueous deposition rather than eolian deposition followed by water saturation and post depositional deformation.

The unit thins noticeably to the east-southeast. Thickness on Sevenmile Mesa reaches a maximum of 46 ft but averages 35 ft. The Dewey Bridge is very thin and discontinuous at the base of Polar Mesa. In a fault block exposure adjacent to the southeast bounding fault of Cottonwood graben, the unit exceeds 40 ft in thickness, which is 10 ft more than expected for this location. This anomalous thickness, which is found in an exposure near the center of the field area, indicates either 1) a strong Navajo paleotopographic low near the location of Cottonwood graben or 2) salt deformation during Dewey Bridge time. Cottonwood graben, which was undoubtedly constrained by salt dissolution and collapse (see description and interpretation of the Cottonwood graben), may have been the site of subsurface salt flow (normal to the trend of the Fisher Valley anticline) during Dewey Bridge deposition.

Slickrock Member

The Slickrock Member of the Entrada Sandstone, named by Wright and others (1962, p. 2062), comprises what was previously mapped as the lower part of the Entrada in east-central Utah and the entire Entrada section in adjacent Colorado. The bare, smooth, generally unjointed cliffs and slopes of the member suggested the early popular name of "Slickrock or "Slickrim" in southwestern Colorado and southeastern Utah (Coffin, 1921, p. 63). The type section of the Slickrock Member is located about one mile west of the old town of Slick Rock, Colorado, about 50 mi southwest of Moab, Utah. The Slickrock Member is bracketed by well dated formations above and below and is considered Late Jurassic (late Callovian) in age.

In the Fisher Valley quadrangle the Slickrock is composed of reddish-orange to light yellowish-gray, rounded cliff-forming, fine-grained, cross-stratified quartzose sandstone with scattered well rounded, coarse sand grains. The unit is covered with a thin veneer of light yellow, fine-grained Holocene eolian sand. Lithology of the sequence, as recorded in the measured stratigraphic section (appendix 1), is fairly uniform throughout. Mineralogy, grain size, grain rounding, and sorting, show little change throughout the section. Stratification, silt content and degree of cementation do exhibit subtle variations. The unit is calcareous and calcite is the dominant cementing agent. The unit consists of very fine- to medium-grained quartz with a subordinate amount of feldspar (less than 10%). Medium to coarse sand-size grains are sprinkled throughout the unit. These well rounded, frosted, and polished grains, named "Entrada Berries" by Wright and others (1962), are most noticeably found in horizontally stratified units and near the base of small-scale trough cross-stratification. The lower 2/3,s of the formation is noticeably more fine-grained than the upper 1/3, though the upper part of the section displays a subtle fining-upward sequence. Sand grains are generally subrounded to well rounded and well-sorted.

The Entrada Sandstone contains a relatively wide suite of sedimentary structures. The most common structure present is trough and wedge-planar cross-stratification. Cross-stratification is in marked contrast to the prominent, well defined, sweeping tangential foresets of the Navajo Sandstone. Much of the cross-stratification in the Entrada is faint and indistinct especially on weathered surfaces. Cross-stratification in the Entrada is generally medium- to large-scale.

Two types of trough cross-stratification are present. These are medium- to large-scale eolian trough cross-sets and rare small-scale, subaqueous (?) trough cross-stratification. The medium- to large-scale trough cross-stratified units consist of the same lithology and macroscopic grain morphology as found in the surrounding, non-cross-stratified horizons. Trough sets are lenticular, plunge at low angles and are concave upward. Foreset cross-strata generally dip 17-25 degrees. Cross-bed sets are generally 4-12 ft thick and many exceed 50 ft in length. Cross-bed length is often hard to trace on weathered surfaces. Though no foreset strata were traced into adjacent cross-bed sets (dunes) it is apparent that these cross-strata are laterally continuous and may cross successive large-scale, dune massifs developed in the Entrada. The small-scale trough sets are lenticular, non-plunging, and concave upward. A few of the small-scale troughs contain coarser grains at the base of the sets than are found in the surrounding rock. Wedge-planar cross-sets are generally restricted to the top of horizontally stratified zones. Wedge-planar sets are small to medium scale, plunging, and are less than 4 ft thick. Foreset cross-strata are generally thinly cross-bedded, straight to weakly concave upward and dip at low angles. Some of the wedge-planar cross-sets may actually be the remnants of truncated low angle, trough cross-sets. Small scale tabular-planar cross-stratification is generally low angle. Planar sets are non-plunging and are usually 2 ft thick. The cross-strata composing the sets are thinly cross-bedded, straight to weakly concave upward, angular at lower bounding surfaces and dip at low angles.

Horizontal stratification is dominant in the middle part of the section and is present independently of cross-stratification. More than 50 ft of the middle part of the formation consists of horizontal stratification. Individual strata are generally thin-bedded.

Unlike the Navajo where cross-beds continually truncate one another, cross-stratified units in the Entrada often are defined at top and bottom by parallel to sub-parallel surfaces. These horizontal bounding surfaces, previously considered to be water-deflation surfaces (Stokes, 1968) have been reinterpreted as forming with the migration of interdune areas (McKee and others, 1977; Brookfield, 1977; Rubin and

Hunter, 1981; and Kocurek, 1981). The horizontally stratified sand bodies overlying the cross-stratified sands are interpreted therefore as interdune deposits. These horizontally stratified zones in the Entrada are lithologically similar to the cross-stratified sands, though they often contain silt and are less well cemented.

Paleocurrent directions, which indicate paleowind orientations, were determined from cross-stratification (fig. 10). Foreset orientations were measured from the medium and large scale trough stratification and wedge-planar cross-stratification. The small scale trough cross-stratification and tabular-planar cross-stratification were not included in the analysis because of their possible subaqueous origin, and general lack of well defined, measurable foresets. Directional data orientations indicate strong southward paleocurrents (fig. 10). These directions are in agreement with regional paleocurrent orientations documented by Poole (1963), Tanner (1965), and Kocurek (1981).

The Entrada crops out as a prominent cliff that rims Polar and Blue Chief Mesas and in a fault block exposed against the southeast bounding fault of Cottonwood graben. Commonly the lower third of the formation forms a steep slope below a smooth cliff formed by the upper part of the formation.

Moab Member

The uppermost member of the Entrada Sandstone is called the Moab Member or Moab Tongue. The light-colored sandstone was named the Moab

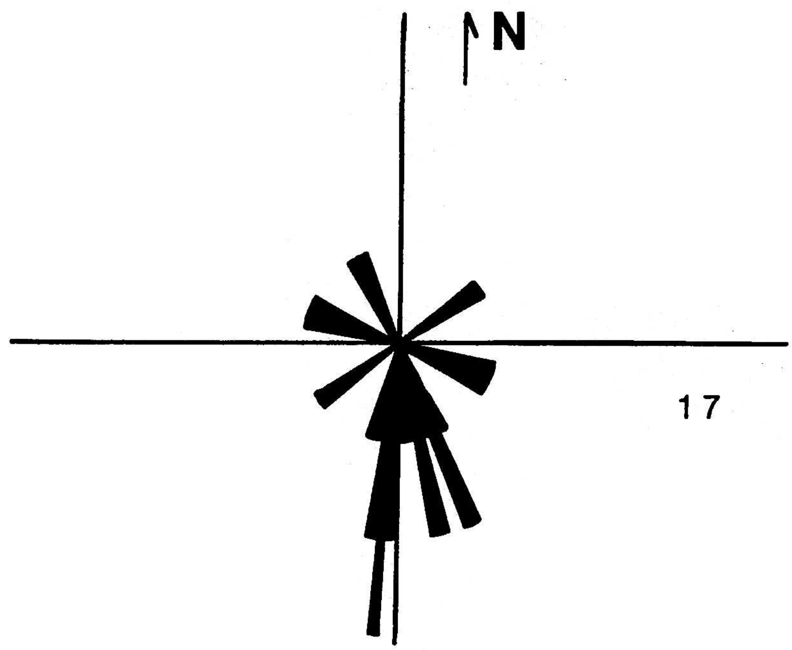


Figure 10. Paleocurrent data for eolian deposits in the Slickrock Member of the Entrada Sandstone. Rose diagrams shows dispersion and number of observations. Data mainly from crossbeds. Dominant flow was toward the south.

Sandstone by Baker and others (1927, p. 804), Baker (1933, p. 49-50), and Dane (1935, p. 94). No type section has been specified, but a typical section was described by Baker and others (1927) near Dewey Bridge, approximately 5 mi north-northwest of the Fisher Valley quadrangle. The Curtis Formation, which is correlative with the Moab Tongue (O'Sullivan, 1981), has been assigned an Oxfordian age (Imlay, 1948, pl. 4; 1952a; 1952b, p. 1748-1749) based on fossils identified by Imlay (1948).

In the Fisher Valley area, the Moab Member consists of very light gray, cliff-forming, medium-grained, quartzose sandstone. The majority of the sand grains are rounded and a small percentage of grains are frosted. The homogeneous sand body is well-sorted; coarse sand grains or "Entrada Berries" found in the Slickrock Member were not identified. The unit displays horizontal, massive bedding and low angle wedge-planar and trough cross-stratification. Limonite staining and calcite-filled fractures are ubiquitous. The horizontally stratified units are generally thickly laminated to very thinly bedded. Wedge-planar cross-sets are small scale, non-lenticular and non-plunging. Foresets are generally thickly laminated, straight and dip at low angles. Trough cross-sets are small scale, lenticular (?) and non-plunging. Foresets are generally very thickly laminated to very thinly bedded, concave upward and dip at varying angles. Consistent lithology and faint stratification on weathered surfaces prevented analysis of directional data.

In outcrop the Moab Member appears similar to the Slickrock Member but can be separated by a distinct, poorly cemented silty sandstone (formation contact). In addition, upon close inspection, the high quartz content, coarser average grain size, better sorting, absence of coarse grains ("Entrada Berries") and paler color of the Moab Member help distinguish it from the underlying Slickrock Member. The Moab Member conformably overlies the Slickrock Member. A prominent set of non-resistant bedding planes that contain silty material and prominent iron oxide and limonite staining are transitional between the two members. The Moab Member crops out in Cottonwood graben adjacent to the southeast bounding fault and as a prominent rounded cliff that rims Polar and Blue Chief Mesas.

MORRISON FORMATION

The Morrison Formation of Late Jurassic age (Kimmerdgian to Postlandian?) was first defined by Eldridge (1896, p. 60-62), who designated exposures near Morrison, Colorado, as the type section. However, Cross (1894, p. 2) was first to publish the name "Morrison" using it to designate equivalent beds in the Pikes Peak quadrangle, southeast of the type section. The type locality has been moved (Waldschmidt and Leroy, 1944), the formation redefined, and either restricted or expanded, by several authors (Lee, 1902, 1920, p. 185; Mook, 1916; Waage, 1955 p. 25; and Peterson and Turner-Peterson, 1980). The regional depositional environment of the Morrison Formation has been addressed most recently by Blakey and others (1983). In the Fisher Valley area the Morrison consists of three members, which are, in ascending order, Tidwell, Salt Wash, and Brushy Basin. The Morrison

Formation on the Colorado Plateau is a terrestrial, dominantly fluvial sequence containing large amounts of sediment derived from volcanic sources, particularly in the upper part (Craig and Shawe, 1975, p. 162).

Tidwell Member

In previous publications strata of the Tidwell Member have been mapped as the Summerville Formation (Baker, 1933; Dane, 1935; and McKnight 1940). This miscorrelation of Jurassic strata was identified by O'Sullivan (1980a, 1980b, 1981), who confirmed that an unconformity (J-5) is present at the top of the Moab Member of the Entrada Sandstone. O'Sullivan showed that this unconformity is correlative with the unconformity found at the top of the Summerville Formation in the San Rafael Swell, and therefore the Moab Member correlates with the Summerville and Curtis Formations farther west. Peterson and Turner-Peterson (1980, p. 306-308) suggested the resurrection of the informal name "Tidwell Member" for strata lying above the Summerville Formation and below the Salt Wash Member of the Morrison Formation, in the Henry basin region. The name "Tidwell Member" first appeared on unpublished and unauthored maps in the files of the U.S. Atomic Energy Commission.

In the Fisher Valley quadrangle the Tidwell Member consists of moderate reddish-brown to light gray, interbedded fine-grained sandstone and siltstone and in the upper portion of the unit, thin bands of light gray, thinly-laminated aphanitic limestone (micrite). The sandstones of the formation range from reddish-brown, silty, and very fine-grained, to light reddish-orange, clean, and fine- to medium-grained. The composition of the sandstone is dominated by quartz with a subordinate amount of feldspar (less than 10%), chert fragments, and chlorite (?). Mica and opaque minerals are distributed throughout the sandstone but comprise less than 1% of the total mineral assemblage. The sandstone is calcareous, moderately calcite-cemented and appears to be massively bedded, though stratification is undoubtedly masked by strong surface weathering. Locally, in hand dug trenches, poorly preserved thickly laminated to thinly-bedded sandstone horizons were identified. Sandstone beds are thicker and more abundant in the lower part of the section.

The siltstone of the formation is moderate reddish-brown, ripple-laminated, and contains disseminated limonite (yellow) stained well-rounded quartz grains. In the basal siltstone unit nodular lenses of medium-grained, very calcareous sandstone are evident (24-27 ft above the Moab/Tidwell contact).

Limestone appears approximately 57 ft above the base of the formation and remains in the upper part of the section interbedded with sandstone and siltstone. The limestone is moderate gray to light gray, thinly to thickly laminated and beds range in thickness from 5 in. to 2 ft. Terrigenous clay partings and algal (?) laminations are abundant in the limestone horizons.

Previous investigators have not been able to fully understand the depositional environment of the Tidwell Member. Dominance of thin horizontal, laterally continuous bedding planes, absence of lenticular bed sets and scour surfaces suggests a subaqueous, shallow, quiet water depositional environment. Absence of abundant dessication features, evaporite minerals, bioturbation, and fossils suggest the depositional environment was probably not a tidal flat, as many workers have inferred. Lack of fossils, deep red color, and gradational contact with the overlying fluvial Salt Wash Member suggest a continental environment. I propose that the Tidwell was deposited in a deltaic floodplain environment with high-energy (storm influenced) lagoon or lacustrine pond subenvironments. The lacustrine (?) limestones are inferred to have formed during drying periods.

The Tidwell/Moab contact is sharp and unconformable, yet the lower few feet of the Tidwell Member may actually be transitional with the underlying Moab Member wheras the Tidwell/Salt Wash contact appears gradational, conformable and often hard to discern in the field. The Tidwell member crops out along the rim of Polar and Blue Chief Mesas and in Cottonwood graben adjacent to the southeast bounding fault and forms a red slope below the sandstone ledges and siltstone slopes of the Salt Wash Member. The Tidwell slope in many places is covered with talus from the overlying Salt Wash and Brushy Basin Members.

Salt Wash Member

The Salt Wash Sandstone Member of the Morrison Formation was named by Lupton (1914, p. 127) for exposures a few miles east of the town of Green River, Utah. Subsequent workers, including Gilluly and Reeside (1928), Baker and others (1936), Stokes (1944), Imlay (1952a), and Craig and others (1955) have extended this name to rocks composing the lower part of the Morrison throughout much of the Colorado Plateau.

The Salt Wash Member consists dominantly of interstratified ledge-forming cross-stratified sandstone and slope-forming mudstone (Craig and Shawe, 1975, p. 162). The Salt Wash Member is interpreted as a broad alluvial fan of stream deposited sediment derived from a source southwest of south-central Utah (Craig and others 1955, P. 150; Peterson, 1980, 1986). The member contains uranium and vanadium deposits; the most noteworthy concentrations and largest deposits are in the Urovan mineral belt in west-central Colorado and east-central Utah (Fisher and Hilpert, 1952; Peterson and Turner-Peterson, 1980; Peterson, 1980).

In the Fisher Valley area the Salt Wash Member of the Morrison Formation consists of alternating sandstones and mudstones. Sandstones are generally very light gray to grayish-pink, very fine to medium-grained and lenticular-bedded. The sandstones are tuffaceous and composed dominantly of quartz, with a subordinate amount of feldspar (probably less than 5% of the total mineral assemblage). Calcite is the dominant cementing agent. Individual sandstone units are composed of lenticular beds that truncate subjacent beds. Truncation surfaces are both irregular and smooth, and represent scoured surfaces.

A vast majority of the lenticular sandstone bodies are cross-stratified. Small and medium scale trough cross-stratification is the dominant cross-stratification type, though small-scale tabular-planar cross-stratification is evident. The trough cross-stratification sets are generally slightly-plunging to non-plunging and less than 6 ft in thickness. Cross-strata composing the sets are cross-laminated. Foreset strata are concave upward and dip 12-24 degrees. Trough foreset orientations were recorded and plotted on a rose diagram (fig. 11). Directional data indicate a strong westerly sediment transport direction.

Grain size varies within lenticular bodies as well as from lens to lens. Coarser grains (medium to coarse sand), however, are usually restricted to the base of cross-set troughs. Grain size varies within the lenses as well as from lens to lens. Thicker channels and those that contain coarser-grained carbonaceous debris are more prevalent near the top of the Salt Wash Member. Some of the lenticular sand bodies display cross-stratification that "dies out" up section; foreset strata dip at progressively smaller angles upsection ("wedge-like") until planar horizontal stratification is dominant. This loss of cross-stratification may be the result of channelization. Those beds that do not display this loss of cross-stratification upsection are either truncated by overlying lenticular sand bodies or are truncated by nearly horizontally bedded or broadly lenticular siltstone bodies.

Sandstone units of the Salt Wash Member in the Fisher Valley area contain uranium and vanadium. The mineralized zones are closely related to carbonaceous debris that lines the bottom and sides of channel-sand bodies. The major uranium bed, which is called the "Pay off Sand" on Polar Mesa (Eicher and Bivens, 1955), is located about 20-30 ft below the Salt Wash/Brushy Basin contact. The lowest mineralized zone is about 75 ft above the Tidwell/Salt Wash contact. Sedimentology and depositional environment of the formation as related to uranium deposits has been described by Turner-Peterson (1979), Huffman and others (1980), and Peterson and Turner-Peterson (1980).

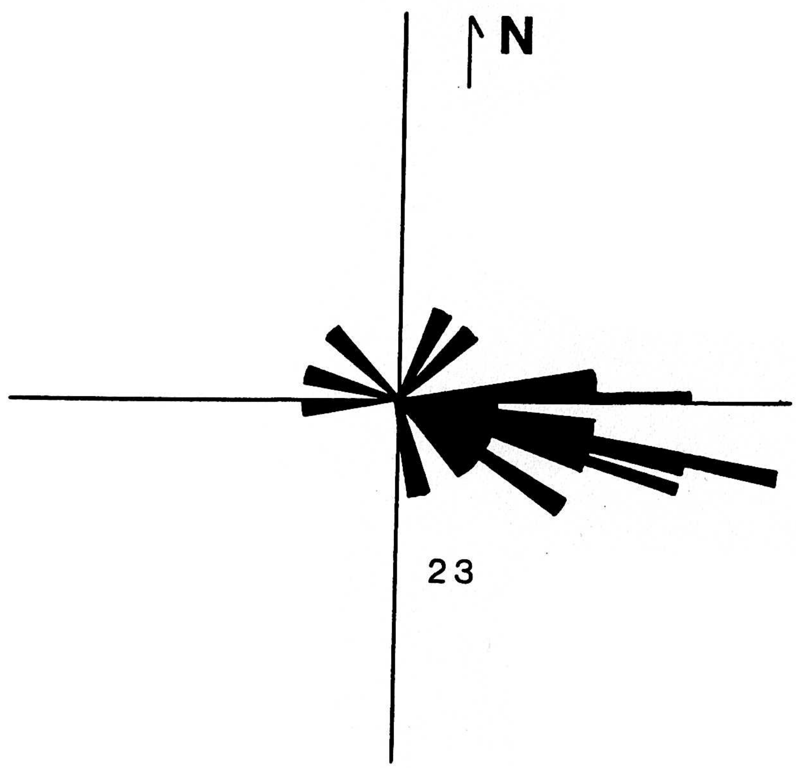


Figure 11. Paleocurrent data for fluvial deposits in the Salt Wash Member. Rose diagram shows dispersion of data and number of observations. Data mainly collected from crossbeds and scour marks. Dominant flow was toward the east.

The dominantly mudstone strata consist of moderate reddish-brown, silty claystone. Mudstones are horizontally bedded, but broadly lenticular, and range in thickness from several inches to 8 ft. Mudstone intervals are generally indistinctly to massively bedded, yet some zones display horizontal wavy laminations.

The Salt Wash in the Fisher Valley area is approximately 250 ft thick. Limited aerial exposure of the unit prevented determination of thickness changes across the area. Contact with the underlying Tidwell Member appears gradational, conformable and interfingering. The Tidwell/Salt Wash contact is placed at one of three points: 1) the base of a channel sandstone ledge, where it rests upon horizontally stratified, reddish-brown, interbedded siltstone and sandstone of the Tidwell, 2) at the top of the highest limestone bed overlain by lenses of mudstone, siltstone, and sandstone, or (3) where limestone beds are absent at the base of lenticular mudstones, siltstones, or sandstones. Although a basal channel sandstone seems the most obvious base for the Salt Wash, and at the measured section locality it was the lowest unit in the Salt Wash, the channel sandstones are not consistently the basal strata of the member. Change from parallel bedding to lenticular bedding and the absence of thin lacustrine limestones at the base of the Salt Wash are consistent changes and are diagnostic of the contact as represented in the Fisher Valley area.

The Salt Wash forms a steep, ragged slope, consisting of cliff-forming sandstone ledges alternating with slope-forming mudstone units and is overlain by the slope-forming Brushy Basin Member of the Morrison

Formation. The Salt Wash crops out as a steep slope that rims the top of Polar and Blue Chief Mesas.

Brushy Basin Member

The Brushy Basin Member of the Morrison Formation was named by Gregory (1938, p. 59) for exposures in Brushy Basin, a few miles north of Blanding, Utah. Regional correlation of the unit has been rigorously analyzed (Stokes, 1944; Craig and others, 1955; Freeman and Hilpert, 1956; Craig and Cadigan, 1958; Shawe and others, 1968; Cater, 1970; Craig and Shawe, 1975). Petrography and mineralogy of the Brushy basin has been described by Cadigan (1957, 1967), and Keller (1962). Uranium formation and occurrence in the unit was documented by Waters and Granger (1963). According to Craig and Dickey (1956) and Craig and Cadigan (1958), the member is recognized over much of the Colorado Plateau. The southwest boundary of the member, a line extending from Laguna, New Mexico, through Gallup, New Mexico to near Escalante, Utah, represents pre-Dakota erosion. Toward the northeast the boundary is an arbitrary limit of recognition beyond which the Brushy Basin cannot be distinguished from correlative Salt Wash strata.

In the Fisher Valley area the Brushy Basin strata consist of very poorly exposed variegated mudstone, muddy siltstone, and muddy sandstone with a subordinate amount of conglomeratic sandstone. The mudstones and siltstones are generally purple reddish-brown, and locally greenish-gray. Bedding in the mudstone and siltstone is indistinct and masked by severe surface weathering. According to Stokes (1952), Keller (1962), and Cadigan (1967), the dominant clay mineral in the mudstone and siltstone is smectite, which due to its swelling properties produces a "popcorn" weathered surface. Abundance of montmorillonite, and the presence of relict volcanic glass shards replaced by montmorillonite (Waters and Granger, 1953), analcite, and books of biotite attest to the volcanic origin of some of the mudstone and siltstone grains (Cater, 1970).

Sandstones are moderate reddish-brown to light gray, fine-grained, with angular to sub-rounded quartz grains. These sandstone units are thinly-bedded to indistinctly bedded, lenticular, 6 in. to 4 ft thick and moderately well cemented. Small angular to sub-angular chert fragments and reworked calcareous mudstone clasts are sprinkled throughout the unit. The sandstone bodies commonly form thin blocky ledges which are often covered by slope-wash from overlying mudstones. Thin pebble-conglomerate lenses are scattered throughout the lower part of the formation, but are often covered by slope-wash. A prominent 8-10 ft thick, ledge-forming conglomerate is found approximately 83 ft below the top of the unit. The conglomerate consists of grayish-red to moderate brown, interstratified lenticular conglomerate and conglomeratic sandstone. Conglomerate contains well-rounded pebbles of green, red, pink, and brown chert up to 3 in. in diameter, and petrified wood fragments. Conglomeratic sandstone is composed of coarse-grained, subrounded to well-rounded grains that are stratified into cross-laminae. Large well-rounded pebbles are scattered throughout the unit but predominate at the base of cross-sets and above scour surfaces. Conglomerate and conglomeratic sandstones are interstratified, trough cross-stratified at low angles, and display well developed scour and fill features. The conglomerate is found as large talus blocks (mapped as Qmtb) on underlying benches at several places.

The relative proportions and distribution of lenticular mudstone, siltstone, sandstone, and "channel" conglomerate units, low angle trough cross-stratification, scour and fill features, and petrified-wood fragments indicates fluvial floodplain and channel deposition.

Outcrops of the Brushy Basin are very poorly exposed and form a smooth slope above the ledge-forming Salt Wash Member. The only part of the unit that is well exposed is the 8-10-ft thick conglomerate horizon. The Salt Wash/Brushy Basin contact, though locally covered by slope-wash debris, was placed at the top of the highest identifiable Salt Wash sandstone. The contact appears gradational, conformable, and interfingering. Lower mudstones of the Brushy Basin appear to be transitional with the upper mudstones and siltstones of the Salt Wash Member. The gradational and interfingering contact between the two members indicates a subtle change in the Morrison depositional environment.

BURRO CANYON FORMATION

Coffin (1921, p. 97-100) first divided the predominantly non-marine basal Cretaceous deposits of the Colorado Plateau, which had earlier been called Dakota, into the Post-McElmo Group and restricted Dakota. Later, Stokes and Phoenix (1948) applied the name Burro Canyon Formation to the "Post-McElmo" beds, for exposures in Burro Canyon, San Miguel

County, Colorado. Earlier Stokes (1944, p. 965) had applied the name Cedar Mountain to a unit of varicolored mudstone and conglomeratic sandstone occurring at approximately the same stratigraphic position as the Burro Canyon, on Cedar Mountain at the northern end of the San Rafael Swell, Emery County, Utah. Stokes (1952) concluded that the Burro Canyon and Cedar Mountain Formations are sufficiently distinct to warrant separate formation names and proposed that the Colorado River serve as an arbitrary boundary between the Burro Canyon on the east and the Cedar Mountain on the west.

In the Fisher Valley quadrangle the Burro Canyon Formation consists of pale yellowish-orange to greenish-gray, cliff-forming, fine-grained quartzose sandstone. The sandstone is composed of sub-rounded, clear quartz grains with subordinate amounts of chert, feldspar, and micaceous debris. Approximately 10 % of the grains are frosted. The sandstone displays both horizontal stratification and cross-stratification. Cross-stratified zones consist of wedge-planar and trough cross-beds and set heights are generally less than 2 ft. Limited exposure of the unit prevented a comprehensive study of stratification types and therefore cross-bedding orientations were not analyzed. Thin lenses and discontinous bands of conglomeratic sandstone, composed of medium to coarse-grained, sub-angular quartz, white to gray chert pebbles and pink quartzite (?) pebbles are distributed throughout the unit. The lenses are most pronounced at the base of scour and fill structures (channel lag deposit). Conglomeratic beds are less abundant and occur at the base of those horizontally stratified sandstones that truncate cross-stratified beds.

The basal contact of the formation was placed at the base of the first sandstone above the variegated mudstone of the Brushy Basin Member of the Morrison Formation. Locally, lenticular sand bodies of the Burro Canyon fill scour surfaces on the upper Brushy Basin bedding surface. The Burro Canyon Formation crops out over a very narrow area on Polar Mesa and forms a light-colored broken cliff above the colorful slope of the Brushy Basin.

QUATERNARY-TERTIARY SEDIMENTS

PREVIOUS INVESTIGATIONS

Sediments in the Onion Creek and western Fisher Valley area were first described by Dane (1935) in his reconnaissance study of the Salt Valley anticline region. Shoemaker (1954) mapped deformation in the Onion Creek salt diapir and identified deformation and unconformities in the overlying Cenozoic deposits. Richmond (1962) recognized two volcanic ash beds (later identified as Bishop ash and Lava Creek B ash by Izett, 1981) in the Fisher Valley sediments. The depositional history, structure, and age relationships of the Pliocene and Quaternary deposits in the Onion Creek and western Fisher Valley area have been described and mapped by Colman (1983), Colman and Hawkins (1985), and Colman and others (1986, 1988).

I have subdivided the unconsolidated sediments in the Fisher Valley area into twelve mappable units. The sediments were deposited by eolian, alluvial, and mass-wasting processes. Minor man-made deposits exist in the area. Sand is the most abundant textural component in the Quaternary units, and is primarily derived from the surrounding consolidated Upper Paleozoic and Mesozoic sandstones. Fine to medium-grained sand is undoubtedly derived from the Kayenta Formation, Wingate, Navajo, and Entrada Sandstones. The maximum thickness of these sediments (Pliocene and Quaternary package) rarely exceeds 300 ft, yet, according to Biggar and others (1981) and Colman (1983) these are the thickest deposits of late Cenozoic age in the Paradox basin and perhaps the entire Colorado Plateau.

EOLIAN DEPOSITS

Eolian Sand Sheet (Qes)

Thick accumulations of eolian sand (Qes) blanket the floor of Fisher Valley. The sand sheet is composed of unstratified, reddish-brown, calcareous, non-indurated fine sand and silt. Deposits reach a maximum exposed thickness of 30 ft. Two groundwater wells were drilled in the floor of Fisher Valley. One near the center of Fisher Valley penetrated more than 300 ft of unconsolidated and semiconsolidated sand. The other well, located west of the center of the valley, penetrated more than 220 ft of the same sediment (D.L. Taylor, 1987, personal communication). Thickness of the sand sheet is probably greater than the exposed 30 ft but cannot be determined from the well information because during the drilling process the eolian sand was not differentiated from underlying sediment (colluvium and possibly basin-fill sediments). Thin, irregularly shaped, isolated eolian sand accumulations are found capping the Kayenta and Navajo dipslopes throughout the quadrangle. Thin discontinuous eolian sand sheets are also found on Polar Mesa.

The eolian deposits found above the Kayenta stratigraphic level tend to be lighter in color and less silty than those found in Fisher Valley (Cutler/Moenkopi stratigraphic horizon). Those eolian sand deposits found above the Kayenta are derived primarily from the poorly indurated sections of the Slickrock Member of the Morrison Formation and the Burro Canyon Formation.

Eolian Sand Dunes (Qed)

Locally on the floor of Fisher Valley, the eolian sand sheets display dune morphology. The dunes are subtle topographic features and amplitudes of the dunes rarely exceed 3 ft. Composition of the dune sands is identical to the adjacent eolian sands. Dune accumulations are restricted to the extreme western edge of Fisher Valley, where they constitute part of the bluffs which rim Onion Creek.

ALLUVIAL DEPOSITS

Four distinct alluvial units were differentiated and subsequently mapped. These are alluvial channel deposits, two distinct alluvial basin fill deposits (upper and lower), and alluvial sand deposits.

Alluvial Channel Deposits (Qal)

Alluvial channel deposits (Qal) are found in the field area along Fisher and Onion Creeks and the Dolores River. The channel deposits are composed of moderate reddish-brown, calcareous, thickly laminated to thinly bedded, fine to coarse sand with subordinate amounts of rounded gravel and cobbles. The deposits are generally non- to slightly-indurated. Subtle scour and fill structures are present throughout the unit. The alluvium underlies and forms terraces along the entire length of Fisher Creek in Cottonwood Canyon and some of its larger tributaries, including Thompson and Burro Canyons. Alluvial deposits in Thompson and Burro Canyons are too small and discontinuous to map.

Fisher Creek in Cottonwood Canyon is spring fed and only flows actively during summer storms, therefore the alluvium in Cottonwood canyon undoubtedly interfingers with colluvium and eolian deposits. The alluvium that underlies Fisher Creek at the southern end of Fisher Valley interfingers with eolian sands. Alluvium on North Beaver Mesa is restricted to a tributary of Beaver Creek and appears to be relatively free of colluvial and eolian deposits. Alluvium also underlies the Onion Creek channel and forms 2-3 ft high terraces.

Weak soil development is present in the upper part of the section along Fisher Creek in Cottonwood canyon (NW1/4, sec. 20, T. 24 S., R. 25 E.) and in Onion Creek (NW1/4, sec. 26, T. 24 S., R. 24 E.). Soil development was not evident in the alluvium at the southern end of Fisher Valley or in the deposits on North Beaver Mesa.

Aluvial Basin-Fill Deposits

Alluvial basin fill sediments have been subdivided, based on gross lithology, into two units following Colman (1983) and Colman and Hawkins (1985). Lower basin-fill sediments (Qab_2) are well exposed in the floor of the erosional amphitheater of Onion Creek on the northwest end of Fisher Valley. Overlying basin-fill sediments (Qab_1) are exposed in the walls of the amphitheater. The erosional amphitheater is cut into a

Pliocene/Quaternary sedimentary basin that lies east of the Onion Creek diapir. Thickness of the deposits, bedding, and unconformity relationships indicate that the basin is ovate with the long axis parallel to, and lying on the collapsed axis of the Fisher Valley anticline. Therefore, the geometry of the erosional amphitheater roughly corresponds to the western 2/3's of the sedimentary basin (plate 1).

Lower basin-fill deposits (Qab_2).--Lower basin-fill deposits are reddish-brown, calcareous, fine to coarse sand, interbedded with clast- and matrix-supported, subangular to subrounded gravel. The lower part of the section is moderately indurated; the upper is slightly indurated. Scour and fill structures, tabular-planar and wedge-planar cross-stratification is evident throughout the section. Tabular-planar and wedge-planar cross-stratification sets are generally small scale, and non-plunging. Foreset cross-strata are thinly laminated to thinly bedded, straight to weakly concave upward and dip at low angles, mostly less than 15 degrees. Toward the edge of the basin, sediments coarsen, and subangular to subrounded matrix-supported gravel beds, which are separated by bands and lenses of medium to coarse sand, are the dominant sediment. The unit contains a minimum of three buried soils which are exposed near the center of the sedimentary basin (sec. 26, T. 24 S., R. 25 E.) but are not evident near the basin edges. Several angular unconformities exist in the upper part of the unit and are well defined near the edges of the basin. Near the Onion Creek diapir cemented gravel beds 2-10 ft thick grade into uncemented gravel away from the diapir.

The age of the lower basin-fill unit is fairly well constrained. The unit contains the Bishop ash (0.73 M.Y old: Izett, 1981), which ranges from 2 to 5 ft. The variable thickness and large portion of sand in the upper part of the section indicates local reworking of the ash into topographic lows. According to Colman (1983), and Colman and others (1988) paleomagnetic analysis indicates reversed polarity in much of the lower part of unit below the Bishop ash bed, but the lowermost 60 ft of exposed sediments are of normal polarity. Therefore the basal parts of the unit probably were deposited during the Gauss Normal Polarity Chron. If so, the basal parts are more than 2.5 m.y old and late Pliocene in age. The upper part of the section is younger than the Lava Creek B ash bed (0.61 m.y. old; Izett, 1981), which is found at the base of the overlying Qab_1 basin-fill sediments.

Upper basin-fill deposits (Qab_1).--Upper basin-fill deposits are well exposed in the walls of the erosional amphitheater in the Onion Creek area at the northwest end of Fisher Valley. Qab_1 sediments in the Onion Creek area consist of reddish-brown, calcareous, thinly to massively bedded, slightly to moderately indurated sand. Low-angle wedge-planar and trough cross-stratification and scour and fill features are abundant, especially in the upper 3/4's of the unit. Cross-stratification is very similar to that found in the lower basin-fill sediments. The basal 10-30 ft of the unit is thickly laminated to thinly bedded and contains, at its base, a 3 ft thick layer of Lava Creek B volcanic ash. The remainder of the unit consists of thin to medium-bedded, locally cross-bedded coarse sand and gravel beds, which are generally overlain by massive eolian sand. The eolian sand locally contains moderately to well developed soil horizons. The unit is capped by a well developed calcic soil.

Alternating eolian/alluvial deposits indicate several depositional cycles. Cyclic deposits thin and sediments coarsen toward the edges of the depositional basin. Near the edge of the basin, subangular to round, moderately indurated matrix- and clast-supported gravel and cobble beds are the dominant deposits. Scour and fill structures and minor sand lenses are evident in the gravel beds. The Qab_1 sequence is conformable within itself near the center of the basin but angular unconformities become evident stratigraphically near the edges of the basin. An angular unconformity separates the upper basin-fill sediments (Qab_1) from the lower basin-fill sediments (Qab_2). On the eastern edge of the basin, adjacent to the floor of Fisher Valley, only the upper calcic soil is evident. Secondary carbonate buildup in this calcic soil suggests an age of approximately 0.25 my B.P. (Colman and Hawkins, 1985; Colman and others, 1988). Colluvial deposits (Qac) that rim the floor of Fisher Valley appear to be continuous with the upper part of the Qab_1 sediments farther west in the Onion Creek exposures. Soils which are present in the Qab_1 sediments were not identified in the colluvium, and therefore these deposits have not been positively correlated. Colluvial sediments (Qac) that rim the floor of Fisher Valley were deposited on a surface that dips gently northwest toward the exhumed sedimentary basin. These deposits may reflect the waning influx of alluvium from Fisher Valley into the depositional basin. At present eolian sand deposits (Qes) cover what may be a continuous sheet of Qab_1 sediments below the floor of Fisher Valley.

Alluvial Sand (Qas)

Alluvial sand (Qas) deposits consist of grayish-yellow to very light gray, thinly laminated to thinly bedded, fine to very coarse sand with a subordinate amount silt and scattered pebbles. Alluvial sand deposits differ from the alluvial channel deposits (Qal) in that they 1) lack gravel and cobbles, and scour and fill features, and 2) display thin horizontal stratification, and the alluvial sand contains laminations of carbonaceous (peat) debris 1/4 in. to 3/4 in. thick. The thin horizontal stratification, and surrounding basin configuration indicate that the sediments were deposited in a quiescent (?) pond environment. Colman and Hawkins (1985) suggested that this alluvial sand deposit represents the marshy, former valley bottom of Onion Creek. They obtained a radiocarbon age of 9330 $\pm$ 150 yr B.P. from a peaty sand zone near the middle of the unit. The unit is exposed approximately 85 ft above the present junction of the two main forks of Onion Creek, and in other patches too small to map. Colman (1983) suggests, based on the radiocarbon dates and the stratigraphic condition of the alluvium, that there has been a minimum of 85 feet of downcutting in the last 9330 years. Maximum thickness of the unit is 28 feet.

COLLUVIAL DEPOSITS

Colluvial Deposits (Qac)

Colluvial deposits and alluvium mixed with slope-wash debris (Qac), are found around the margins of Fisher Valley, and at several locations in Thompson and Burro Canyons that are too small to map. These deposits are generally a downslope continuation of coarser talus deposits. The colluvium most likely interfingers with Qab_1 sediments and may underlie part or all of the southern end of Fisher Valley. Colluvium consists of moderate reddish-orange to moderate reddish-brown, calcareous, thickly bedded, fine to coarse sand and angular to subangular gravel and cobbles. The deposit is generally non- to slightly-indurated with an exposed thickness ranging from 2 to 12 ft, but may be as great as 100 ft (?) beneath the eolian sand that blankets the floor of Fisher Valley. Ground water wells drilled in the center of Fisher Valley indicate more than 300 ft of semiconsolidated to unconsolidated sediments, and two distinct water-saturated zones (D. L. Taylor, 1987, personnal comm.). The aquifers are fed by La Sal Mountain runoff, and are used for irrigation and consumption by livestock.

SLUMP DEPOSITS

Slump Deposits (Qms(b))

Slump deposits are not common in the Fisher Valley quadrangle and are restricted to Polar Mesa. The slumps are crescent-shaped in map view, concave upward in cross-section, and occur as two distinct stacked masses. Slump deposit Qms(b) occurs solely within outcrops of Brushy Basin. Even though the transport distance appears to have been minimal (less than 200 ft laterally and 80 ft vertically), and movement occurred along distinct slippage planes, the slump debris is incoherent and indicates that the unit acted ductily. It is probable that the slump has experienced secondary flow and slumping. Debris which formed the slump moved northeast, normal to strike (down dip).

TALUS DEPOSITS

Talus Deposits (Qmt)

Talus deposits (Qmt) consist of rock-fall debris such as blocks, boulders, and smaller angular fragments that have fallen by gravity from overlying units. The most pronounced talus deposits occur as cones and sheets on the Fisher Valley floor beneath the Wingate Sandstone cliffs. Talus rests on the Chinle, Moenkopi, and Cutler Formations and is derived primarily from the Wingate Sandstone with subordinate amounts of Kayenta and Chinle debris. Talus cones are generally fan or wedge-shaped, convex upward in cross-section and attain a maximum thickness (70 ft) where they are adjacent to the cliff-forming Ali Baba Member of the Moenkopi Formation. Talus deposits in sheet form (distal to active cone deposits) were most likely fed by cone debris deposited during the erosional retreat of the Wingate cliffs to their present positions. Cone deposits are the most recent talus debris. Cone or fan-shaped deposits similar to those found in Fisher Valley (involving the same parent rock) are evident in the northeast end of Cottonwood Canyon and in the Dolores River valley near the northeast edge of the mapping area.

Abundant talus deposits are scattered along the rim and base of Polar Mesa. Debris is derived from the Tidwell, Salt Wash, and Brushy Basin Members of the Morrison Formation. Talus deposits covering the Salt Wash and Tidwell Members generally is found in patches too small to map. Larger cone shaped deposits are found covering the Slickrock and Dewey Bridge Members of the Entrada Sandstone and on the prominent bench formed by the top of the Navajo Sandstone.

Talus deposit involving Brushy Basin strata Qmt(b)

Talus deposit Qmt(b) consists of boulders of conglomeratic sandstone derived from the Brushy Basin Member. These rare scattered boulders are found lying on the Navajo bench at the base of Polar Mesa and locally near the base of the Brushy Basin Member at the south end of Polar Mesa.

Talus deposit involving Wingate strata Qmt(w)

Talus deposits Qmt(w) consist of blocks, boulders, and smaller angular fragments derived solely from the Wingate Sandstone. The rock-fall responsible for the talus debris was witnessed by members of the Taylor family during the late summer of 1985. A similar rock fall, at nearly the same location, occurred in 1983 (D. L. Taylor, 1987, personal communication). The rockfall deposits are located on the east wall of Fisher Valley, approximately 1 mi southeast of the Taylor ranch.

MAN-MADE FILL (Mine dump deposits (Qfd))

Several man-made mine dumps, (Qfd) are scattered across Polar Mesa. The deposits consist of angular cobbles of Salt Wash Sandstone. The mine debris was "stockpiled" and forms domes and cones, 30-150 ft in diameter and generally less than 10 ft in height. Several of the deposits are crescent-shaped and fringe the abandoned mine workings.

STRUCTURE

INTRODUCTION

The evolution of salt structures such as salt domes, salt pillows, and salt diapirs, has been addressed in the literature by Powers (1926), Harrison (1927), Atwater and Forman (1959), Trusheim (1960), Bishop (1978), and Seni and Jackson (1983). Salt pillows or salt-cored anticlines and salt diapirs are both present in the Fisher Valley quadrangle and make up most of the structures in the region. The orientation, magnitude, and mode of formation, of the anticlines in the fold and fault belt are well constrained by field and subsurface data. However, little is known about salt-diapir or cupola morphology and mechanisms of emplacement, especially of those that are unexposed or are too small to be detected on aeromagnetic and gravity surveys or seismic profiles.

The emplacement history of diapirs has been extensively documented, yet controversy remains concerning the dominant process of formation. DeGoyler (1925), Barton (1933), Nettleton (1934), Trusheim (1960), Sannemann (1968), Kupfer (1970, 1976), Smith and Reeve (1970), O'Neill (1973), Stude (1978), and Kent (1979) favor intrusion (non-piercement) as the dominant process of diapir emplacement. Loocke (1978) advocated an extrusive (piercement) emplacement history. Bishop (1978) suggested that diapirism typically occurs by extrusion or alternates between intrusion and extrusion. Sediment downbuilding, during which a structural high or crest of the structure remains more or less stationary and relatively close to the depositional surface while the surrounding sediments compact and sink, has been suggested as a plausible mechanism for diapirism by Barton (1933), Bornhauser (1958), and Johnson and Bredeson (1971).

The salt anticlines in the Paradox basin fold and fault belt have been discussed extensively in the literature. Their general character, and the broad outline of their structural history were discussed by Powers (1926), Prommel and Crum (1927), and Harrison (1927). Investigations by Powers (1926), and Harrison (1927) into the salt domes of Colorado-Utah introduced new theories on the mechanism of emplacement of salt bodies and the possible cause of salt movement.

Structural details and deformation history of the salt anticline region were subsequently revealed through the work of Baker (1933), Dane (1935), and McKnight (1940). More recent investigations have added much detail to our knowledge of the salt structures and their genesis (Stokes, 1948, 1956; Stokes and Phoenix, 1948; Cater, 1954, 1955a, 1955b, 1964, 1970; Shoemaker and others, 1958; Hite and Gere, 1958; Elston and Landis, 1960; Elston, 1960; Elston and Shoemaker, 1960, 1961; Hite, 1960, 1961, 1972, 1975; Elston and others, 1962; Szabo and Wengerd, 1975; Stromquist, 1976; McGill and Stromquist, 1979; Huntoon, 1982, 1988; Doelling, 1983, 1988; and Oviatt, 1988). Aeromagnetic and gravity surveys of the Paradox basin compiled by Joesting and Byerly (1956, 1958), Joesting and Plouff (1958), Byerly and Joesting (1959), Joesting and Case (1960), and Case and Joesting (1972) have been used to interpret the salt anticline structures.

The structural and geomorphic evolution of the salt anticlines of the Paradox region is illustrated in figure 12. Initial growth of the anticlines at the end of the Pennsylvanian was caused by lateral flow of

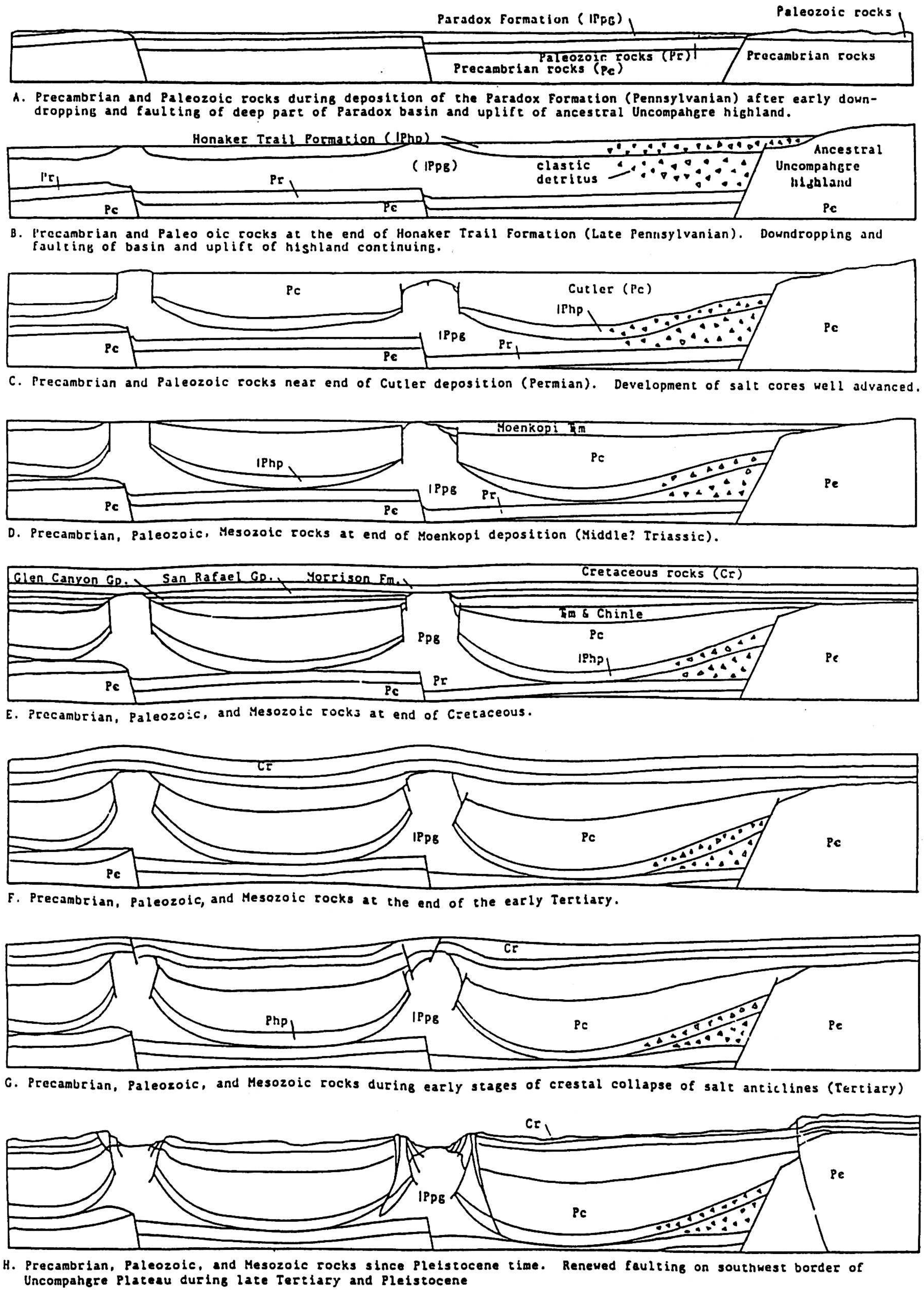


Figure 12. Structural evolution of the Gypsum Valley and Paradox valley anticlines (modified after Cater, 1970).

salt of the Paradox Formation from areas adjacent to the anticlines. By the close of the Mesozoic, salt in the peripheral flanking regions was greatly thinned. Collapse of the anticlines appears to have been resulted from the erosional stripping of Triassic - Cretaceous overburden and progressive downward dissolution of the caprock by rain and ground water circulating through fractures. During the Cenozoic, salt flowage into the core of the anticlines continued to produce local structural anomalies, including diapirs.

Arguments supporting regional Late Pennsylvanian to Late Permian compression have been widely used to explain the genesis of the salt anticlines (Baker 1933; Dane 1935; Shoemaker and others, 1958; Kelley 1958). Shoemaker and others (1958) attributed the origin of the anticlines to decollement folding resulting from Pennsylvanian-Permian compressional forces related to the ancestral Uncompahgre uplift. Stokes (1948) and Jones (1959) demonstrated there was no regional Permian folding event, and that the salt anticlines were initiated without compressional stress. Jones (1959) suggested that the anticlines formed by differential loading. Investigators including Shoemaker and others (1958) and Elston and Shoemaker (1961) indicated that the anticlines were sharply defined features separated by 8-10 mi of essentially undeformed strata.

Regional syncline pairs that are evident at the surface are post Mancos features. Several mechanisms may be hypothesized as the cause of the folding (synclines) including: i) shortening of the sedimentary sequence during the Late Cretaceous - Early Tertiary Laramide orogeny (Cater, 1970); ii) thermal activation of salt flowage during the Oligiocene LaSal intrusive event (Hunt, 1958; Bodell and Chapman, 1982);

and iii) sediment downbuilding and salt flow in syncline areas during the Jurassic through Tertiary (Baars and Stevenson, 1981).

Several authors, including Cater (1970), Doelling (1988), and R.W. Ely (1988, personal commun.) have proposed that the rocks of the Paradox basin were folded during the latest Cretaceous to early Eocene Laramide orogeny. It is suggested by Cater (1970) and Doelling (1983, 1988) that regional compression formed synclines between the anticlines and accentuated the diapiric salt anticlines.

Baars and Stevenson (1981), argued that the salt anticline features show little or no effects from Laramide disturbance. Dyer (1983), in his study of jointing in sandstones in Arches National Park, found no evidence of horizontal compressive deformation. In the Fisher Valley area, there is no evidence of secondary small-scale folds, thrust faults, or any other structural feature that would indicate horizontally orientated maximum principal stress. It is possible that the broad so-called "folded" synclines may actually have been formed by Cretaceous-Tertiary salt flowage away from the incipient syncline locations to form down-folded structures. Salt may have flowed into anticlinal regions where active dissolution, salt removal, and collapse were occurring. Absence of any rocks of Middle Cretaceous to middle Tertiary age in the Fisher Valley area precludes assessment of the contribution of sediment loading and Laramide deformation to the structural fabric.

FISHER VALLEY ANTICLINE

Regional Relationships

The Fisher Valley anticline is the northeastern-most salt anticline in the Paradox basin. It forms a broad kidney-shaped bulge on the large salt structure from which the Salt Valley, Cache Valley, Onion Creek, and Sinbad Valley anticlines also rise (fig. 13). The Salt Valley - Cache Valley - Onion Creek -Fisher Valley - Sinbad Valley anticline is the longest anticlinal structure, has a more irregular trend, and shows a greater number of structural variations than any other anticline in the region (Shoemaker and others 1958; Jones, 1959).

The Fisher Valley anticline is situated mid-way along this 50 mi-long anticlinal trend. The axis trends north-northwest where it enters the southern end of Fisher Valley and the map area, and bends west-northwest near the central portion of Fisher Valley. The arcuate shape of the axis and other axes (Salt Valley-Cache Valley) have been attributed to drag folding along a deep-seated shear zone (Kelley and Clinton, 1960; Hite, 1975; Baars, 1976), and to deformation associated with emplacement of the La Sal Mountains (Hunt, 1958; Colman, 1983). The fold axis plunges northwest and is followed by the Fisher Creek and Onion Creek drainages, which were localized by it.

The northeast flank of the Fisher Valley anticline is bounded by Sagers Wash syncline northeast of the map area. Sagers Wash syncline trends parallel to the Fisher Valley anticline and the Uncompahgre uplift. The northeast flank of the syncline is formed by the southwest flank of

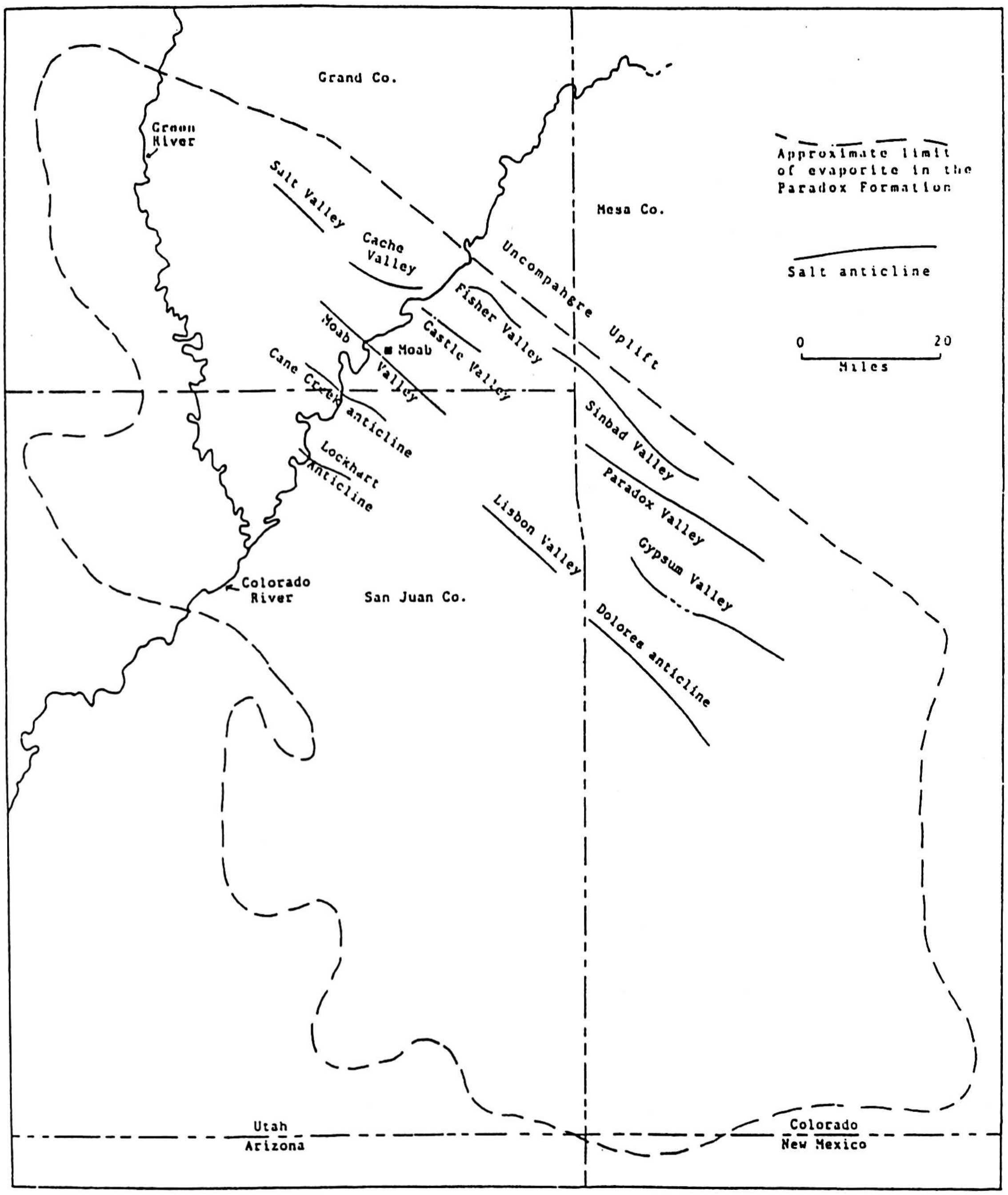


Figure 13. Index map of the Paradox basin, southeastern Utah and southweastern Colorado, showing major structures, the Fisher Valley anticline and approximate limits of evaporite in the Paradox Formation (modified after Hite, 1961; and Hite and Buckner, 1981).

the Uncompahgre Plateau anticline. The northeast flank of the Fisher Valley anticline is 7-8 mi wide (down-dip) and the cuesta-like rims dip away from the valley at an average of 4-7 degrees. The southwest limb of the Fisher Valley anticline and the northeast limb of the Castle Valley anticline form an intervening syncline. The southwest flank is 4-8 mi wide (down-dip), and the rim that bounds the valley dips less than 10 degrees southwest. However, in the valley walls below the rims steeper dips are recorded.

Salt cores that underlie the collapsed features along anticlinal axes in the Paradox basin are separate masses that are probably connected at depth to a mass of salt that runs the length of the anticlines (Shoemaker and others, 1958). Shoemaker and others (1958) envision these separate salt cores or plugs as prominent fingers or cupolas that extend upward from a main salt mass. The salt cores are either individual plugs or composite masses. The Fisher Valley anticline has been considered to be underlain by two salt cells: 1) the Onion Creek diapir salt cell; and, 2) the salt cell that underlies Fisher Valley (fig. 14; Shoemaker, 1954; Shoemaker and others, 1958; Elston and Shoemaker, 1961).

Local Structure

The geologic structure of the Fisher Valley quadrangle is shown on the geologic map with structure contours (plate 1) and by six cross-sections (plate 3). Structure contours in the area of investigation are drawn on the base of the Kayenta Formation (top of the Wingate Sandstone). The top of the Wingate was chosen as a datum plane for the construction of

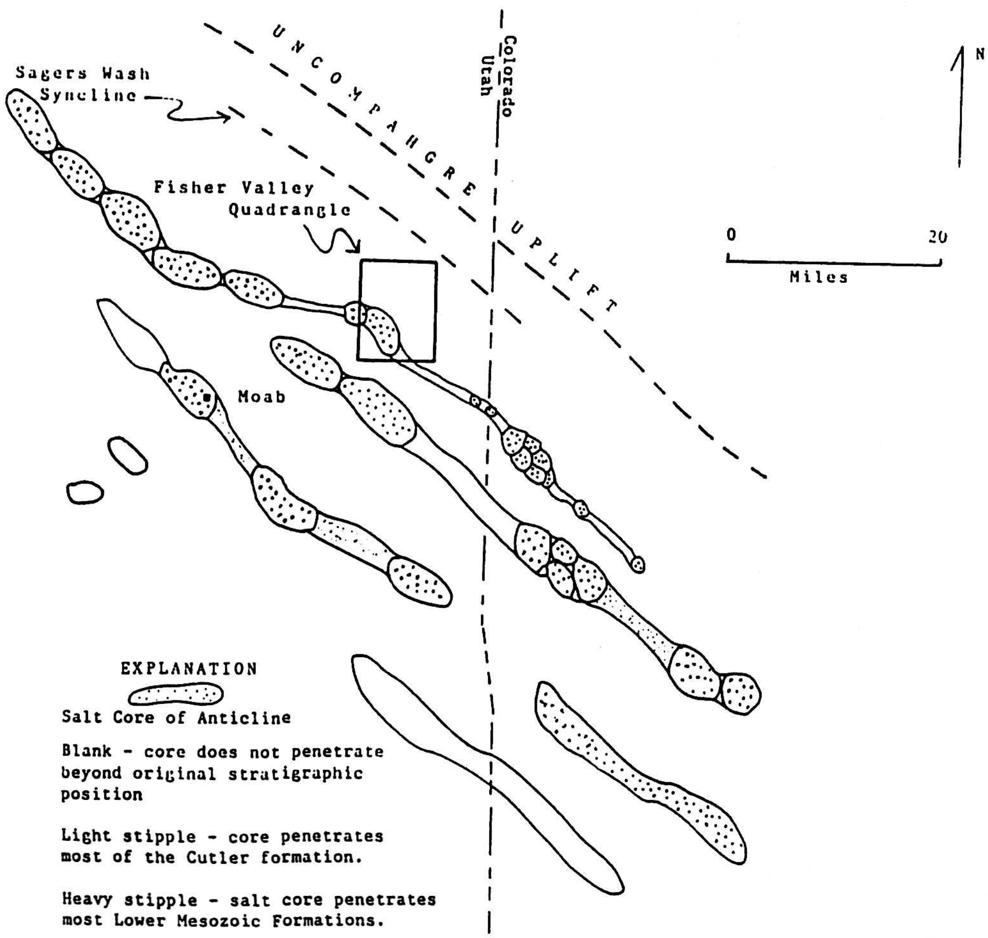


Figure 14. Plan view of major salt cores that form the salt anticlines. The salt core that underlies Fisher Valley anticline is composed of two smaller masses; one forms the Onion Creek diapir and the other underlies Fisher Valley (modified after Shoemaker and others, 1958)

a structure contour map because: 1) the Wingate/Kayenta contact is sharp, easily recognized in the field and is exposed over a wide area; 2) Post-Paradox formations below the Wingate were deposited during local diapiric events and therefore thickness changes (depositional thinning over salt highs, differential compaction over shallow subsurface intrusive salt masses, and thickening in synclinal troughs), and relief on unconformity surfaces cannot be accurately determined; 3) Formations above the Wingate are seldom exposed across the study area. The Kayenta/Navajo contact was considered as a datum, but the gradational contact makes its exact location imprecise; and, 4) Although unconformities exist within the Wingate-Burro Canyon interval, the consistent thickness and lateral continuity of the Wingate suggests that extending this datum beneath the cover of overlying beds in the Polar Mesa region, should give an accurate picture of regional structural patterns.

A series of cross-sections, A-D (plate 3), were constructed to help unravel the deformational history of the area. The cross-sections represent: 1) an east-northeast transect across the southern end of Fisher Valley, 2) a north-south transect across the east end of the Onion Creek area and adjacent Quaternary depositional basin, 3) a northwest transect across Cottonwood graben, and 4) a northeast transect on strike with the Cottonwood graben structure. Alternative interpretations of cross-sections, AA" and DD", are presented to illustrate contrasting hypotheses for the geomorphic and structural histories of the area.

Because of the scarcity of subsurface data in the area of investigation, cross-sections were modeled after Shoemaker (1956a), Cater (1955b), and Doelling (1988). The cross-sections should be viewed as one (two in the cases of cross-sections AA" and DD") of several possible viable constructions as a great deal of interpretation was embodied in their production. Balanced cross-sections in salt-deformed terrains are often unattainable because many units (such as the Cutler, Moenkopi and Chinle Formations in the field area) were deposited during local salt-tectonic events. This is not a problem, however, in construction of the structural cross-sections in the Fisher Valley area. Due to the small scale it is impossible to represent accurately all the subtle salt-induced stratigraphic irregularities that exist. A description of these irregularities is included in the sections on unconformities and sedimentologic features.

The Honaker Trail, Cutler, Moenkopi, and Chinle Formations are attenuated over the Fisher Valley anticline. Regional thinning of the Cutler Formation toward the northwest, and thinning and absence of the Honaker Trail Formation adjacent to salt highs is documented in numerous publications (Dane, 1935; Jones, 1959; Shoemaker and others, 1958; and Doelling, 1983), and based on surface and regional subsurface data. Thinning of the Permian Cutler strata is easily illustrated on the cross-section but thinning in overlying Triassic strata is less well depicted (plate 3). Both thicknesses of units in the anticlinal crests, and the locations of pinchouts are speculative. Lack of subsurface data adjacent to the crest of the anticline, and collapse and removal of the crestal area of the anticline, prohibit accurate description of the structure.

Cross-section A-A' (plate 3) is a transect across Fisher Valley and is inferred to represent youthful geomorphic and structural development. The cross-section schematically illustrates a series of fault blocks that have collapsed into a salt-dissolution void, the collapsed crest of the salt-cored Fisher Valley anticline. Bounding faults on both sides of the valley show equal displacement and though strata are shown to have collapsed in a convex-upward fashion ("anticline-like") into the salt void area, it is entirely possible that the strata collapsed in a concave-upward fashion ("syncline-like") into the faulted area. The magnitude of slip and orientation of the faults bounding Fisher Valley are not known. Exposed valley-bounding faults in the Paradox fold and fault belt show consistent variations in magnitude of slip. In the fold and fault belt, faults bounding the southwest-side of vallies display larger stratigraphic offsets than do the northeast-side bounding faults (Shoemaker and others, 1958; Cater, 1955a, 1964; Jones, 1959; Hite, 1975; and Doelling, 1983).

Cross-section A-A" (plate 3) shows Fisher Valley in a stage of geomorphic maturity with the Paradox Formation near the surface, and concealed only by alluvium and eolian sand. It is probable that caprock developed in the upper several hundred feet of the salt sequence during periods of extrusion, during periods of intense ground water circulation and/or rain water infiltration, or after the salt was exhumed during erosion. Doelling (1985, 1988) postulated that the caprock in the Salt Valley anticline may have developed when salt was exhumed during erosion. From structural (bedding attitudes and anticline geometry), stratigraphic (unconformity relationships), and sedimentologic (lack of abundant gypsiferous debris in strata surrounding the anticline) evidence, it is doubtful that the Fisher Valley anticlinal core was a true extrusive piercement structure, or that the core was exhumed during erosion. Therefore, caprock may have developed during periods when the anticlinal core was subjected to ground-water circulation. Thin discontinuous lenses of gypsiferous debris in basal Moenkopi strata in exposures on the west wall of Fisher Valley suggests that Paradox evaporites may have been locally exposed periodically.

Relatively flat topography in the floor of Fisher Valley indicates that Quaternary sediments have totally masked the irregular surface of either 1) fault blocks as illustrated in structural interpretation A-A', or 2) caprock as illustrated in structural interpretation A-A". There has been little or no recognizable Holocene dissolution, collapse, or uplift of the Paradox salt beneath the Holocene sediments. This does not preclude subtle Quaternary salt movement in the anticlinal area. Quaternary sediments, that underlie the eolian blanket sands on the floor of Fisher Valley (Qac, Qab_1/Qab_2 sediment types on the cross-sections), cannot be positively correlated with those sediments that fill the sedimentary basin adjacent to the Onion Creek diapir.

Modelling of Valley-Bounding Faults

Cross-section B-B' (plate 3) is of the Onion Creek area and the Quaternary sedimentary basin that lies east of the Onion Creek diapir. The cross section depicts the salt-cored anticline in a mature state. The Paradox Formation lies very near the surface, overlain only by its associated caprock and by Quaternary sediments. The fault which bounds the southern edge of the salt mass is inferred to be a moderate to high angle reverse fault, or more likely a fault zone (not depicted on the map or cross-section). High angle to near-vertical normal faults that are evident in a series of fault blocks near the base of the southwest wall of Fisher Valley (SE1/4, SE1/4, sec. 3, T. 25 S., R. 24 E.), at several localities farther west in the Professor Valley quadrangle, and at the southern end of Fisher Valley (SE1/4, sec. 13, T. 25 S., R. 24 E.), indicate that normal faulting played a role in valley formation. These normal faults exposed at the surface are spatially related to shallow subsurface faults (probably high angle reverse faults), which previously had allowed Paradox strata to be uplifted and juxtaposed against younger Permian rocks. Normal faulting probably occurred after formation of the anticline during dissolution and collapse. The magnitude and orientation of the faults at depth, and their role in valley formation cannot be determined from the relatively limited fault exposures.

If the southwest valley-bounding fault (queried on map), exists along the entire length of Fisher Valley, and has greater normal displacement than the queried northeast valley-bounding fault, then the fault-block rocks would have undergone a slightly different collapse history than that implied by cross-section B-B'. Several structural interpretations can be hypothesized based on the inferred structural relationships. 1) Major normal offset accompanies faulting on the southwest side of the valley with little displacement occurring on the northeast side; this would create a half-graben structure. Greater offset on the southwest faults would require a great deal of salt dissolution adjacent to the southwest margin of the valley floor (location of the bounding fault), and they would also require either, folding adjacent to the northeast side of the valley and/or a suite of antithetic faults in the same location to allow for area displacement beneath the "hinge" of this half-graben structure.

2) Fault blocks may have fallen into the salt-dissolution area to form an asymmetric syncline with steep limbs on the southwest side, adjacent to maximum dissolution.

Undoubtedly there are several other interpretations that could produce similar structures and fault combinations. Further structural fault modelling will not be discussed for lack of surface data and analogous models in the region. Those interested in structural patterns associated with salt structures are referred to Withjack and Scheiner (1982), Seni and Jackson (1983), Goldstein and Collins (1984), and Collins (1988).

COTTONWOOD GRABEN

Local Structure

The Cottonwood graben structure extends from Fisher Valley along an average N50°E strike for approximately 5 mi. This graben is located on the northeast limb of the Fisher Valley anticline, and is oriented normal to the arcuate bend in the anticlinal trend (plate 1). The graben ranges in width from 1.2 to 1.5 mi with up to 1400 ft of structural relief across the bounding faults. The southeastern edge of the graben is bounded by a steep (86°), northwest-dipping for most of its length, normal fault but bifurcates into a pair of faults near the middle (sec. 21, T. 24 S., R. 25 E.). Cumulative throw on the fault pair is the same as the main fault. Because the floor of the graben is bowed, and tilted to the southwest along much of its length, displacement on the graben-bounding faults varies along strike. Maximum displacement on the fault is about 1100 ft at a point approximately one mile northeast of the southwest end of the graben (NE1/4, NW1/4, sec. 29, T. 24 S., R. 25 E.; plate 1). Displacement diminishes to zero at the northeast end, and to 800 ft at the southwest end of the graben.

The northwestern edge of the graben is bounded by a series of en-echelon southeast-dipping normal faults with antithetic northwest-dipping normal faults. Southeast-dipping faults are nearly vertical (84 -90^{o}). Antithetic faults are less extensive with slightly shallower dips (70 - 85^{o}). Slip on these secondary faults has resulted in inward clockwise rotation of some fault blocks viewed along a northeast-trending rotational axis. The fault with the largest displacement represents the northwest-most limit of the graben; maximum downthrow of more than 1400 ft occurred at a point 1.6 mi. northeast of the southwest end of the graben (NE1/4, NW1/4, sec. 19, T. 24 S., R. 25 E.; plate 1). Displacement diminishes to zero to the northeast, and to 1000 ft near the southwest end of the graben. The other faults display less than 400 ft of vertical displacement. The Cottonwood graben resembles a similar northeast-trending graben adjacent to Sinbad Valley as described by Shoemaker and others (1958) and Cater (1970).

Cross-section C-C' (plate 3), crosses the Cottonwood graben normal to the long axis of the graben. Graben-bounding faults are equally prominent. At depth, the graben is undoubtedly constrained by these two faults, though faults within the graben, which probably were generated near the Paradox-Honaker Trail or Paradox-Cutler contact, dissect the fault block. It is unknown whether Honaker Trail strata are present beneath the graben. The Paradox is nowhere exposed at the surface either in the graben, or further northeast along strike of the structure in the Dolores River canyon. There is no evidence to indicate anomalous deformation in the floor of the graben, and therefore the Paradox probably does not exist in the shallow-subsurface (less than 3500 ft). Fractures in, and adjacent to, the graben, however, may contain minor accumulations of salt. The cross-section and structure contour map (plate 1) suggest that the graben is coincident with the axis of a subtle northeast-trending arch.

Faults bounding the Cottonwood graben are moderately well exposed at the surface. Eolian sand, colluvium, and talus commonly conceal the location of faults within the graben. Indistinct stratification and poor exposures of the Chinle and Moenkopi make the determination of stratigraphic offset across faults which cut these formations difficult. The rocks underwent brittle faulting and rigid body translation and rotation during graben formation; there is no evidence of folding adjacent to the bounding faults. However, subtle folding of the floor of the graben along an axis perpendicular to the bounding faults is evident (plate 1, 3).

Throw on the bounding faults of the the Cottonwood graben diminishes to the northeast where the floor of the graben merges with the more steeply dipping horsts on either side. Thus the floor of the graben underwent counterclockwise rotation about a northwest-trending subhorizontal "hinge" at the northeast end of the graben. The surface representation of the hinge of the graben (where surface faults visibly die out in the exposed Kayenta Formation) lies approximately one mile southwest of the Dolores River (plate 1). Brittle deformation ceased at the location of the hinge on the surface. The hinge line area is situated just southwest of the known northeast limit of Paradox salt deposition, as inferred from well log and seismic data (Wengerd and Strickland, 1954; Hite and Gere, 1958; Hite 1960, 1961; Elston and Shoemaker, 1961).

The "hinge like" geometry of the Cottonwood graben is most likely due to preferential dissolution of Paradox evaporites from the southwest end of the graben. A wedge-shaped salt mass probably thickens from a minimum near the axis of Sagers Wash syncline, to a maximum in the salt-cored Fisher Valley anticline.

The graben is bowed as illustrated on the map (inferred from structural contours), and on cross-sections D-D' and D-D" (plates 1 and 3). The floor of the graben dips northeastward, but less steeply than the bedrock on either side, except for the more steeply dipping beds at the southwest end of the graben. The location of greatest structural displacement near the center of the graben is due to the bowed, concave-upward shape of the graben.

The southwestern extension of the graben is masked by thick Quaternary eolian sands, although two small, near vertical, northwest-trending faults cut the extreme southwestern end of the graben. Rotation of small fault blocks toward the valley occurred along these faults. These fault blocks are probably bounded on the southwest by northwest-trending antithetic faults that lie covered beneath valley alluvium, colluvium, and eolian sands. Stratigraphic and structural relationships indicate that these blocks could not have simply rotated or fallen into a salt dissolution void. To account for the area displacement beneath the faults either antithetic faults (to the southwest) or ductile deformation (beneath the faulted area) must be assumed to produce a viable structural cross-section. There is no evidence to indicate that the brittle faults at the surface are accompanied by ductile deformation in the shallow subsurface. It can be argued that dissolution of the salt-cored anticline, beneath the faulted area, could have produced ductile deformation. Dissolution of the salt mass may have resulted in the formation of a solution breccia produced by the collapse of overlying rocks. Though ductile deformation is not evident it is probable that dissolution accompanied antithetic faulting at the southwest end of the graben.

The two northwest-trending faults bounding the southwest end of the graben may have formed either: 1) during the waning phase of graben collapse, 2) as subsidiaries to a larger fault network that rims the collapsed floor of Fisher Valley, or 3) as a result of simultaneous collapse of Fisher Valley and the Cottonwood graben.

Cross-section D-D' (plate 3) is a transect parallel to the Cottonwood graben. The cross-section illustrates an early or immature stage in the development of the Fisher Valley anticline which is situated adjacent to the southwest end of the graben. Normal faults queried on the cross-section constrain the geometry of the valley and the southwest end of the graben. Queried normal faults represents zones of ductile flow that suggests an earlier stage of salt movement into the anticline core that juxtaposed Pennsylvanian evaporites and Triassic sandstones. Subsequent dissolution of the salt core has caused downfaulting of the overlying strata along the queried normal faults.

Cross-section D-D" (plate 3) represents an alternative interpretation of geomorphic maturity of Fisher Valley and immaturity of the graben structure. In this model, Paradox salt is at the near-surface in Fisher Valley (concealed by alluvium and eolian sand) and has most-likely undergone several episodes of dissolution, collapse, and possible reactivation to form diapiric structures. During these processes the overlying Triassic and Jurassic units have been incorporated into the salt and or removed by erosion.

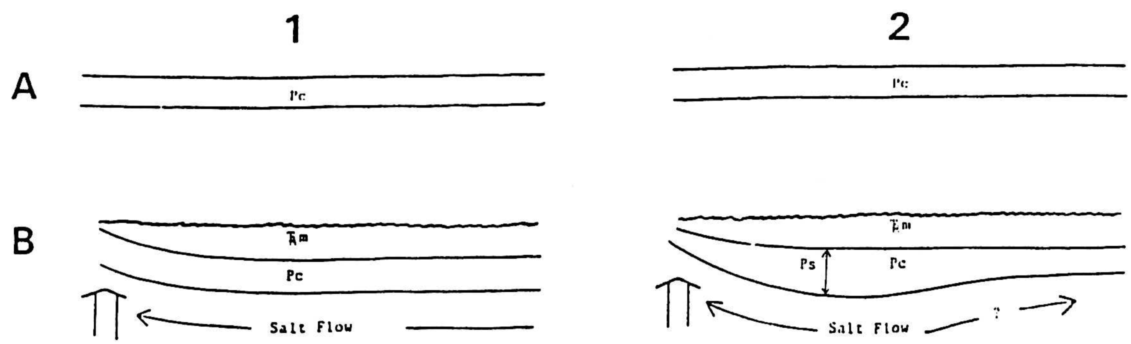
Relationship to Regional Structure

According to Hite (1961, 1975), the northeast-trending surface lineaments in the Paradox basin are the surface expression of deep-seated shear zones or wrench (strike slip) faults. Hite has suggested that the northeast-trending lineaments display left slip of 3-5 mi as determined from offset adjacent to the Uncompahgre uplift. The Cottonwood graben is the fault-swarm of the Cottonwood lineament. There may exist pre-Pennsylvanian left-lateral faulting on the Cottonwood lineament and other northeast-trending lineaments, such as the Roberts or Colorado lineaments, but there is no evidence in the field that any near-surface post-Pennsylvanian left-lateral faulting has occurred. It is unlikely that basement faulting propagated up section through the thick, ductile Paradox evaporites.

Genesis and Evolution

A schematic diagram of the growth history (fig. 15) of the Cottonwood graben suggests that the bowed shape of the graben could have been produced by drag folding and/or unequal dissolution of salt beneath the graben during graben collapse (model 1, fig. 15) or during pre-graben deformation associated with the growth of the salt-cored anticline (model 2, fig. 15).

The shape of the bowed graben suggests that salt flowed from below the Cottonwood graben into the crest of the Fisher Valley anticline as salt was being actively dissolved from the salt-cored Fisher Valley anticline (fig. 15). The shape of the graben indicates that a thick salt sequence may have been removed from beneath the present structural low. The structural low corresponds to the area in the graben that has undergone the greatest amount of structural downthrow (1 mi northeast of the southwest end of the graben). Salt structures, including anticlines, pillows, and diapirs, often have rim synclines (geometric term) and peripheral sinks (genetic term) adjacent to the main salt mass. These peripheral structures may be associated with slightly thinned salt sections, and commonly with secondarily thickened salt sections adjacent (outboard) to thinned sections (Trusheim, 1960; Seni and Jackson, 1983). It is possible that a thickened section existed (prior to dissolution) outboard of the main salt mass, near the location of greatest structural offset. Lack of exposed Cutler and Moenkopi strata prevented the recognition of thinned or thickened stratigraphic sections in the floor of Cottonwood graben.



Ps - peripheral sink
ss - subsurface
Gf - present graben floor geometry
Pg - pre-graben floor geometry
—— - formation contacts

Figure 15. Schematic growth diagram of Cottonwood graben. Models 1 and 2 start with undeformed strata (stage A) and end with the same graben floor shape (stage E) Model 1 illustrates deformation at the southwest end of the graben and formation of the bowed shape of the graben floor could have been two discrete events. This model does not require the development of a peripheral sink or a thickened section, which was not observed in the exposed Moenkopi strata. Model 2 generates graben geometry during growth of the salt core at the southwest end of the graben.

A. Undeformed strata prior to upward growth of the salt-cored anticline at the southwest end of Cottonwood graben. Top line represents pre-Wingate surface.
B. Upturned strata at the southwest end of the graben. Model 1 illustrates local deformation at the southwest end of the graben; Model 2 shows deformation, formation of a peripheral sink, a thickened section, and bowed surface.
C. Continued deformation and upturning of strata at the southwest end of the graben. Bowed graben floor develops in Model 2.
D. Regional tilting of area adjacent to Fisher Valley anticline; most likely related to formation of Sagers Wash syncline.
E. Graben formation; development of bowed graben floor in model 1 due to drag folding.

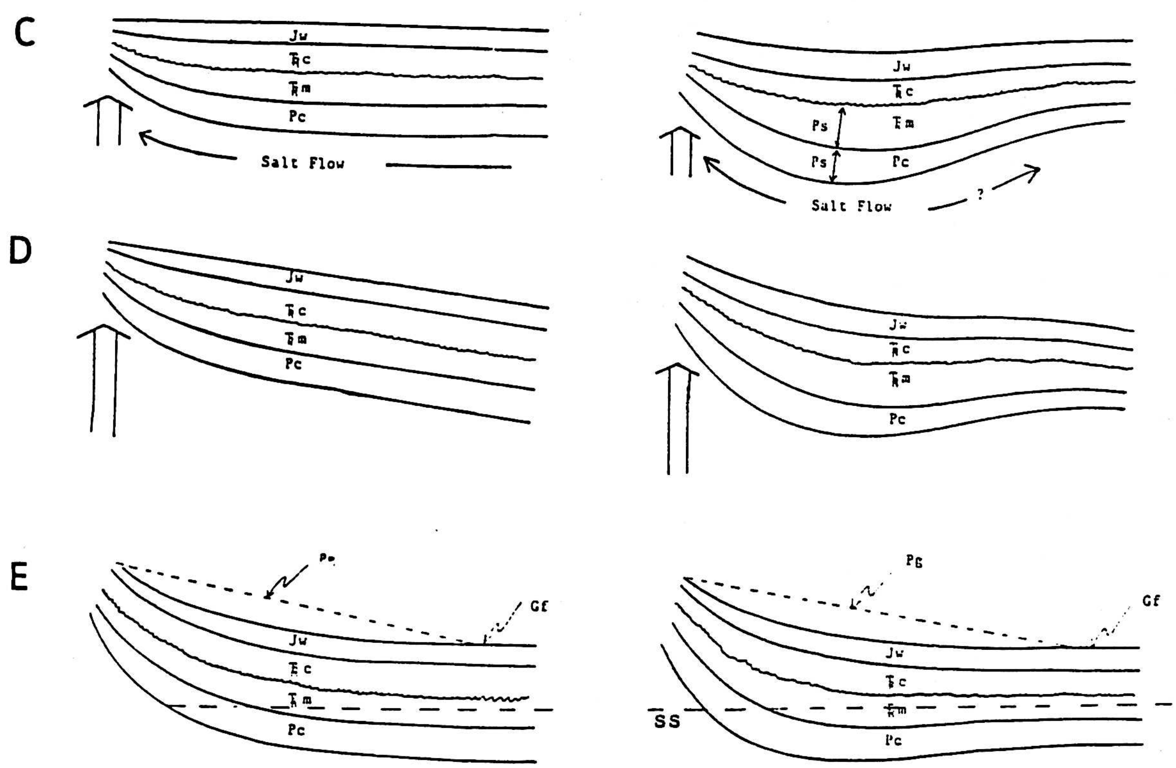


Figure 15. continued

It is probable that graben configuration was caused by deformation associated with salt movement, dissolution, and collapse. During collapse of the graben, a structurally positive area at the southwest end of the graben prevented downfolding of Mesozoic rocks. Goydas (1988) suggested that a anomalously thick salt section or diapir (informally named the Cottonwood diapir) existed at this location during the Jurassic. Even though rapid dissolution of the salt core may have occurred during collapse of the Fisher Valley anticline, part of the anomalously thick section may have remained as a structural high during collapse of the Cottonwood graben. Anomalous sedimentological variations in Moenkopi and Chinle strata exposed near this location indicate local, strongly developed, Triassic halokinetic deformation (see section on unconformities and sedimentologic variations).

A northeast-trending zone of extension developed on the northeast limb of the Fisher Valley anticline where curvature of the fold axis was greatest, and is coincident with the trend of Cottonwood graben and may have contributed to its growth. The graben also coincides with subtle arching of post-Paradox strata (cross-section C-C', plate 3; structure contour map, plate 1) suggesting that a thickened salt-section may have existed beneath the arch prior to graben formation. Similar arching has been explained by Stokes (1948), Cater (1955), Shoemaker and others (1958), Baars and Stevenson (1981), and Doelling and others (1988) as a result of salt flow into the core of folds. Hite (1961, 1975) suggested that left-lateral basement faults (reactivated during the Mesozoic) underlie the graben. Slip on these faults may have accentuated the northeast-trending zone of extension.

Some of the features associated with the Cottonwood graben, are similar to those found associated with the Fisher Valley anticline. Therefore, the Cottonwood graben may represent a small-scale, immature, model for Fisher Valley collapse.

Hite (1961, 1975) suggested that faulting associated with graben formation occurs only where salt is thin or absent. Results of my investigation suggest faulting occurred where salt was initially thick, but that salt thickness may have been severely reduced during periods of dissolution and collapse. Factors controlling the areal distribution of faulting are: 1) thinning of evaporites at the northeast end of the structure, and 2) an updip limit to evaporite flow to the southwest. U. S. Geological Survey aeromagnetic maps compiled by Joesting and Byerly (1958), and Case and Joesting, (1972) indicate anomalously thick salt deposits on the crest of the Fisher Valley anticline, specifically in the Onion Creek diapir region and adjacent to the southwest end of the Cottonwood graben, the location of the inferred Cottonwood diapir (Goydas, 1988). Graben-bounding faults terminate beneath Fisher Valley where a structural high (salt core) prevented downfaulting.

FOLDS ADJACENT TO THE ONION CREEK DIAPIR

Local Structure

In the western part of the study area, north of the Onion Creek diapir, several west-northwest-trending folds occur in the Cutler Formation adjacent to the diapir (fig. 16). The axis of a tight

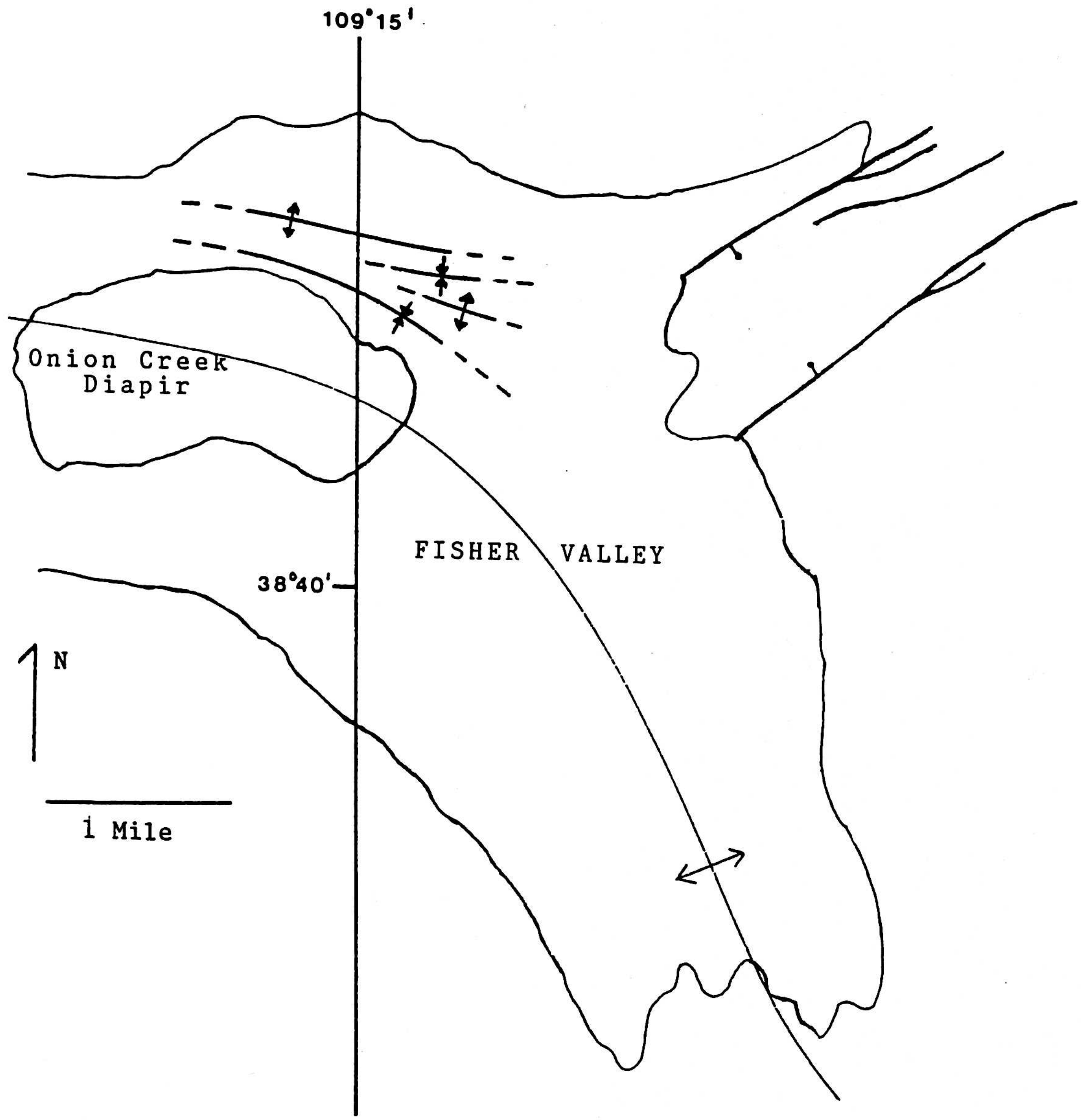


Figure 16. Map of folds in Cutler strata adjacent to the Onion Creek diapir.

northwest-verging syncline plunges 5° with a strike of S60°E. The steep limb of the structure is adjacent to the fault contact between the Cutler Formation and the Onion Creek diapir (Paradox Formation). Three open folds (two anticlines and one syncline) of lesser amplitude are present to the north.

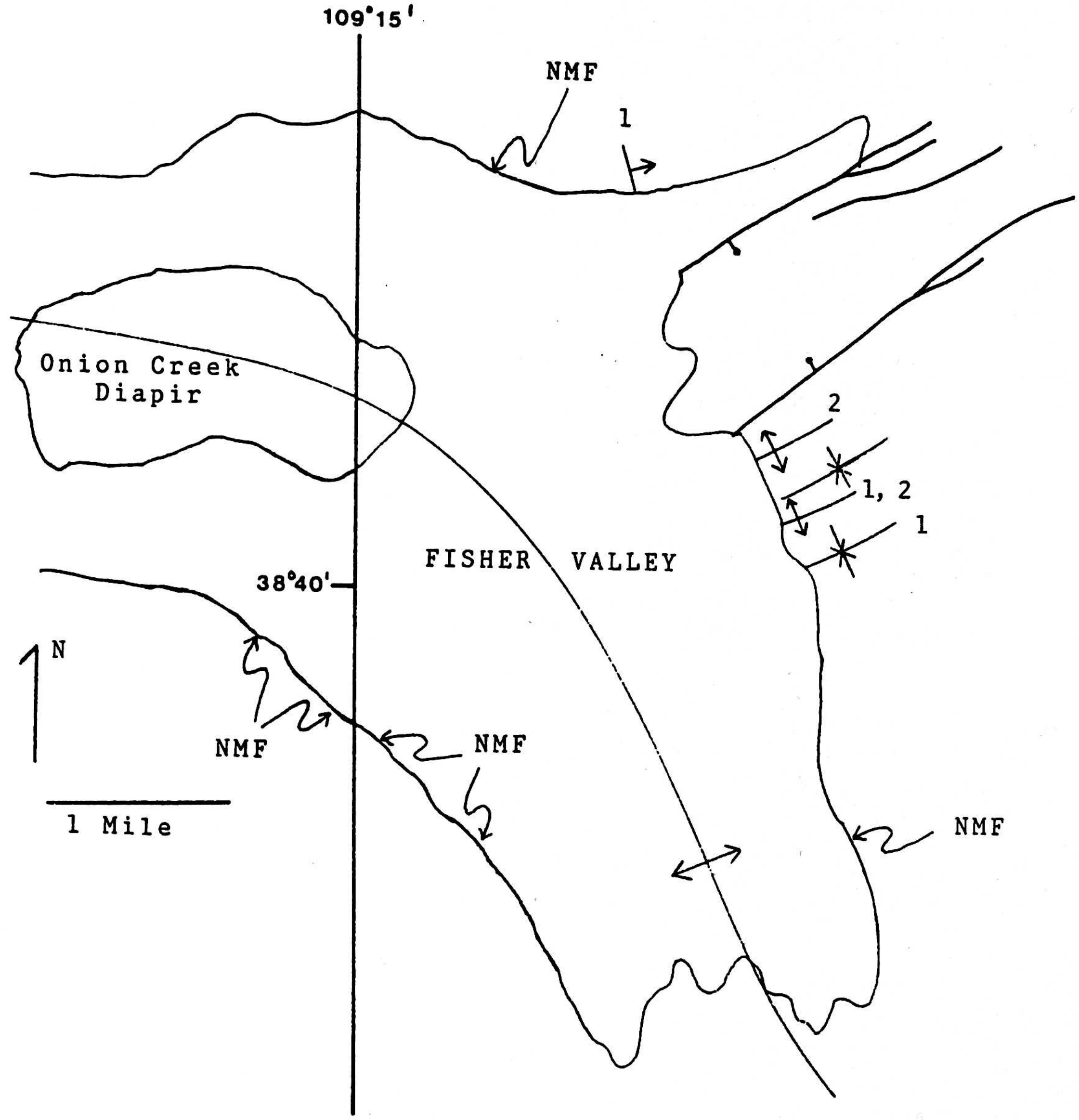
Genesis

These folds are probably related to halokinetic deformation caused by salt flowage into the diapir. The syncline appears to be a drag fold associated with the rising diapir, although the folds away from the diapir appear symmetrical and are possibly due to local compressional stress associated with a rising, expanding diapir. Doelling (1983, 1988) suggested that tight synclines form by collapse of rock units adjacent to the main salt mass following dissolution of underlying salt by water percolating downward from surface drainageways. Such a scenario requires contemporaneous non-dissolution and non-deformation of the relatively erodible, ductile main salt mass. This processes of collapse of rock units adjacent to the diapir could not have resulted in the shortening observed in the tight syncline. An alternative interpretation is that diapiric movement of salt caused folding in competent beds adjacent to the salt mass.

INTRAFORMATIONAL MOENKOPI FOLDS

Local Structure

Intraformational folding within the Moenkopi adjacent to the crest of the Fisher Valley anticline, indicates Early Triassic (Moenkopi time) deformation. More than nine (five of mappable size) small anticlines, subdued syncline pairs, and monoclines radiate outward from the western and central portion of the Fisher Valley intrusive salt mass (fig. 17). Four similar structures exist along the southern margin of Onion Creek in the adjoining Professor Valley quadrangle. Well developed examples of these anticlines are found adjacent to the Cottonwood graben near the arcuate bend in the axis of the Fisher Valley anticline. Intraformational folds' axes are up to 3000 ft long, with amplitudes up to approximately 150 ft. Most of the structures were formed during deposition of the upper Moenkopi (fig. 6). Lower Moenkopi beds are folded with little or no thickness changes across the structures. Upper Moenkopi beds are folded, but also thinned over the anticlinal crests. Structures die out upward through the Moenkopi section, and generally the top of the Moenkopi is conformable with the overlying horizontal Chinle Formation, although a few of the anticlinal crests are truncated by Chinle strata. Three of the folds, including the monocline flexure on the north wall of Fisher Valley, north of the mouth of Cottonwood graben, involved lower Chinle strata (fig. 17). Four (two of mappable size) of the anticlines with smaller interlimb angles have undergone minor brittle deformation. Displacement of less than 8 ft occurs in subvertical normal faults, which parallel the



1 - folds involve lower Chinle strata
2 - folds involve brittle deformation
NMF - non-mapped folds

Figure 17. Orientation of Moenkopi folds in the escarpments that bound Fisher Valley.

axial planes of the folds. These faults appear to be restricted to the lower Moenkopi, although they may continue down-section through the unexposed Cutler Formation. Few exposed sections of Cutler strata that lie beneath the folds are undeformed.

Genesis

Shoemaker (1956b) suggested that the Moenkopi anticlines in Fisher Valley originated by lateral sliding of the Moenkopi Formation over hills on the pre-Moenkopi surface. For such a scenario to work, Moenkopi rheologies would have been much different than those of the underlying Cutler and overlying Chinle Formations, and slide directions should have been normal to strike of the flank of the Fisher Valley anticline. Therefore, if the anticlines formed by sliding, their axes would have developed concentrically about the salt core. The observed pattern, however, is radial. A few of the folds which are restricted to the upper Moenkopi do not appear to be localized by preexisting topography as suggested by Shoemaker (1956b).

I suggest the alternative hypothesis, that the folds in the Moenkopi formed during pulses (expansion and contraction) in the growth of a very irregularly shaped salt mass. The consistent northeast-trend of most of the anticlines in Fisher Valley (all of the mapped anticlines that are located on the east wall of the valley), and their proximity to the northeast-tending Cottonwood graben suggests that these structures may be fault related at depth. Pre-Pennsylvanian basement faults, which were reactivated during the Permian and Early Triassic, or salt-tectonic faults (formed during salt dissolution) cutting most or all of the Permian section, could have precipitated the upward flow of salt and consequent deformation of overlying Moenkopi strata. If these faults exist they may represent an early manifestation of northeast-trending faults that constrained the location and orientation of Tertiary collapse of the Cottonwood graben. Anticlines in the Moenkopi exposed in the Professor Valley quadrangle trend northward and may also represent radial faulting away from the Onion Creek salt mass.

JOINTS

Style of Jointing

Master joints (those clearly visible on aerial photographs) in the Slickrock and Moab Members of the Entrada Sandstone (San Rafael Group) have been widened and sculptured by weathering processes. Joints within the Slickrock are generally single planar features. The Moab Tongue displays sets or zones of joints that are not traceable into the underlying Slickrock or overlying Tidwell. Joints on Sevenmile Mesa are oriented in two distinct directions N80^{o}W (dominant joint set) and N8^{o}E (secondary joint set). These joint orientations were recorded in beds at similar stratigraphic levels that dip less than 4 degrees. Dips of the west-northwest-trending joints average 80^{o}NE, while dips on the north-trending joints average 66 - 76^{o} NW. Joints display only opening displacement with no recognizable shear displacement. No dip-slip component of motion was detected though right-lateral movement (less than

2 ft ? of displacement was estimated using trough cross-beds as reference) was detected on Blue Chief Mesa (NE1/4, SE1/4, sec. 6, T. 24 S., R. 25 E.).

Rocks of the Wingate Sandstone and Kayenta Formation are fractured by two joint sets in the vicinity of the Cottonwood graben. Single planar joints are dominent in these rocks although discontinous joint arrays are evident in the Kayenta. Analysis of the strike of joints in the center of the graben structure show two distinct sub-orthogonal joint sets with orientations of N45°E and N50° W with an average dip of greater than 80°.

Genesis

Cumulative joint data from Seven Mile Mesa indicate that the dominant joint set parallels the axis of the Fisher Valley anticline, whereas the secondary joint set trends normal to the axis. Joint data from the Cottonwood graben area display two equally common joint sets. One set is parallel to the trend of the Fisher Valley anticline; the other is normal to the axis of the anticline (parallel to the trend of the Cottonwood graben). Fractures subparallel to the Fisher Valley anticlinal axis are interpreted as having formed as a result of extension normal to the crest, thus suggesting a genetic link between folding and fracturing. Those fractures that are normal to the anticlinal axis are poorly developed outside the Cottonwood graben area suggesting a link to graben formation. It is possible that the northeast-trending joints (parallel to the trend of the Cottonwood graben) formed contemporaneously with faulting in the graben. An alternative hypothesis is that those joints normal to the anticline axis pre-date formation of the graben. Different orientations of joints in the Fisher Valley area reflect the curvature of the northeast limb of the Fisher Valley anticline. Secondary joints are consistently oriented normal to the anticlinal axis and are most strongly developed near the greatest amount of curvature on the northeast limb of the anticline, near Cottonwood graben. Therefore, the graben may be coincident with this prexisting joint system.

Relationship to Regional Trends

Kelley and Clinton (1960, p. 63) suggested that orthogonal joints in the Paradox basin may be the result of Late Permian flow of evaporites following Cutler deposition. Joint patterns surrounding diapiric salt masses are easily explained by the Kelley and Clinton model, which allows for local changes in principal stress trajectories. Price (1974) developed an idealized stress model that predicts the conditions under which orthogonal tensile fractures may form parallel to the major and minor axes of a sedimentary basin that is either subsiding and compacting or being subjected to uplift and active erosion. "Knotted" or radial joint sets are attributed to local stress reorientations due to the effect of basement topography or syndepositional faulting. More recently workers have suggested that joint patterns and styles are controlled by a suite of variables. Nelson and Stearns (1975), have suggested that susceptibility of any stratum to fracturing is dominantly controlled by lithology and primary sedimentary structures as well as temperature, effective confining pressures, and strain rate. Dyer (1983), in his study of jointing in

Arches National Park, documented that lithologic contrasts between the Moab and Slickrock Members of the Entrada Sandstone strongly influence the presence or absence of jointing and the jointing style that ultimately develops.

Joint orientations in the Fisher Valley area can be attributed to either Kelley and Clinton's or Price's hypotheses, although: 1) the joint sets are recognized in rocks as young as Late Jurassic and therefore are not solely the result of early (Late Permian) movement of evaporites, and 2) rock type plays a role in controlling the distribution of joints (eg. Wingate/Kayenta, Slickrock/Moab Tongue styles of jointing).

HALOKINETIC HISTORY OF THE FISHER VALLEY AREA

Unconformities and Sedimentologic Features

The Fisher Valley anticline formed during the Pennsylvanian through Late Triassic. Interformational unconformities between the Cutler/Moenkopi, Moenkopi/Chinle, and Chinle/Wingate, and intraformational unconformities within the Cutler, Moenkopi, Chinle, and Wingate Formations are locally observable in the escarpments of the valley (nearest to the collapsed crest of the anticline). These unconformities are interpreted to represent periods of relatively rapid salt deformation. Intraformational unconformities within the Cutler are individually subtle but cumulatively noticeable. The basal part of the Cutler Formation, where exposed outside the quadrangle, dips 30 to 40 degrees away from the anticline. In the adjacent Professor Valley quadrangle, basal Cutler beds dip as much as 80 degrees adjacent to the Onion Creek diapir, with the upper bedding planes of the Cutler dipping 20 degrees away from the axis.

The interformational unconformity between the Cutler and Moenkopi is generally less than a 4-degree angular discordance. Intraformational unconformities within the Moenkopi are subtle (individually unmeasurable), but reflect that the top of the formation has a lower dip (5 degrees) than the base of the formation. The interformational unconformity between the Moenkopi and Chinle, which is generally 2 -3 degrees on the eastern, western, and northern escarpments surrounding Fisher Valley, is absent in exposures at the southern end of Fisher Valley. Intraformational unconformities within the Chinle and the interformational unconformity between the Chinle and Wingate Formations are subtle, but evident in the escarpments that surround the northern half of Fisher Valley, and absent in the southern half of the valley. Absence of upper Moenkopi through Wingate unconformities near the southern end of Fisher Valley indicates a lack of halokinetic deformation in this area and suggests a thin salt section. Those areas most strongly affected by halokinetic deformation are assumed to be located above thick salt sections. Therefore, areal distribution of syn-depositional deformation and sedimentologic variations induced by salt deformation can be used to delineate the elliptical shape of the salt core that underlies Fisher Valley. The inferred shape corresponds to the regional aeromagnetic maps constructed by Joesting and Case (1972).

Thinning of the Cutler, Moenkopi, and Chinle Formations is evident along the flanks of the anticline. Basal Cutler strata are in fault contact with the Paradox evaporites, which comprise the Onion Creek diapir. Removal of the crestal region of the anticline and renewed salt movement has obscured original (Cutler time) stratigraphic/structural relationships, but angular discordance between units is used to infer syndepositional thinning in the fold crest. Thickness trends, inferred from scattered well logs, and from publications (Baars, 1962, 1975; Cater, 1970) indicate thickened sections peripheral to the northeast side of the anticline. These thickness trends cannot be used to suggest syndepositional deformation associated with a rising salt mass because the Cutler regionally thickens toward the northeast.

Thickness changes within the Moenkopi, adjacent to the anticline crest, are well illustrated in the northwest escarpment that rims the Cottonwood graben. The Moenkopi in this outcrop, radically thickens to form a "monocline-like" structure (plate 1); more than 45 ft of vertical aggradation has occurred in less than 0.2 mi (down dip direction) away from the crest of the Fisher Valley anticline, into the neighboring Sagers Wash syncline. There is no evidence to indicate that the thickened Cutler and Moenkopi sections are local lens-shaped bodies. Thickness trends presumably continue (increase thickness less rapidly) away from the anticline. Therefore, it is suggested that peripheral sinks in the Paradox evaporites, did not materialize during growth of the salt structure or did not manifest themselves up through the buried Cutler Formation. Thickness changes in the southwest flank of the anticline could not be identified because outcrops of Moenkopi, normal to the axis of the anticline do not exist in the quadrangle.

Thinning of the Chinle Formation toward the crest of the anticline is evident but more subtle than thickness changes in the underlying Moenkopi.

In the northeast dipping flank of the anticline the Chinle is approximately 325 ft thick, and it thins to approximately 295 ft in the escarpments that bound the collapsed crest of the anticline.

Sedimentological variations, including subtle facies changes and changes in stratification (bedforms) exist within the Moenkopi and Chinle Formations adjacent to the crest of the anticline. Coarse sand grains in the Chinle, and lenticular silt deposits (deposits that are anomalous to the formation) within the Moenkopi Formation indicate changing or locally anomalous depositional environments adjacent to the anticlinal crest. Asymmetric lenses of medium-grained, cross-bedded sandstone, atypical in the Moenkopi Formation, are found peripheral to the crest of the anticline.

No recognizable unconformities exist within or at the contacts of the Wingate Sandstone or Kayenta Formations near the crest of the anticline. This suggests a relatively quiescent period of deposition. Homogeneity of Wingate thickness across the anticline, which has been used to document regional and local syn-depositional deformation (Nation and Blakely, 1988), corroborates the absence of deformation during deposition of the Wingate. Deformation in younger Mesozoic rocks was not detected because exposures in the crestal region of the anticline are lacking; the dipslopes on the flanks of the structure are composed dominantly of Kayenta strata.

Development of the Fisher Valley Anticline and Associated Diapirs

The halokinetic and sedimentological features in the Fisher Valley area, can be linked to particular stages in the development of the salt structure. Doelling (1988) proposed four chronologic periods in the development of salt structures in the Arches National Park region: 1) a period of most active salt movement (300-225 m.y.); 2) a period of localized salt movement (225-100 m.y.); 3) a period of deep cover (100-10 m.y.); and 4) a period of dissolution (10 m.y. - present) (fig. 18). Salt tectonic events in the Fisher Valley area can be loosely assigned to these periods.

A series of three schematic diagrams (figs. 19, 20, 21) and accompanying schematic cross-sections (fig. 22) illustrate the growth of the Fisher Valley anticline and areas of positive structural relief. Figure 19 (fig. 22, stage A and B) illustrates the growth of the main salt core that underlies Fisher Valley and the location and incipient growth characteristics of the Onion Creek and Cottonwood diapirs. The kidney-shaped core of the anticline was undoubtedly emplaced by the Late Permian. Simultaneous existence of the Onion Creek and Cottonwood diapirs during the Pennsylvanian and Permian is speculative.

Figure 20 (fig. 22, stage C and D) illustrates active vertical growth of the Cottonwood diapir during the Late Triassic through Middle(?) Jurassic. Sedimentologic evidence in the escarpments at the southwest end of Cottonwood graben indicate anomalous syn-depositional deformation. Interformational unconformities (Cutler/Moenkopi, Moenkopi/Chinle, Chinle/Wingate and numerous intraformational unconformities, facies

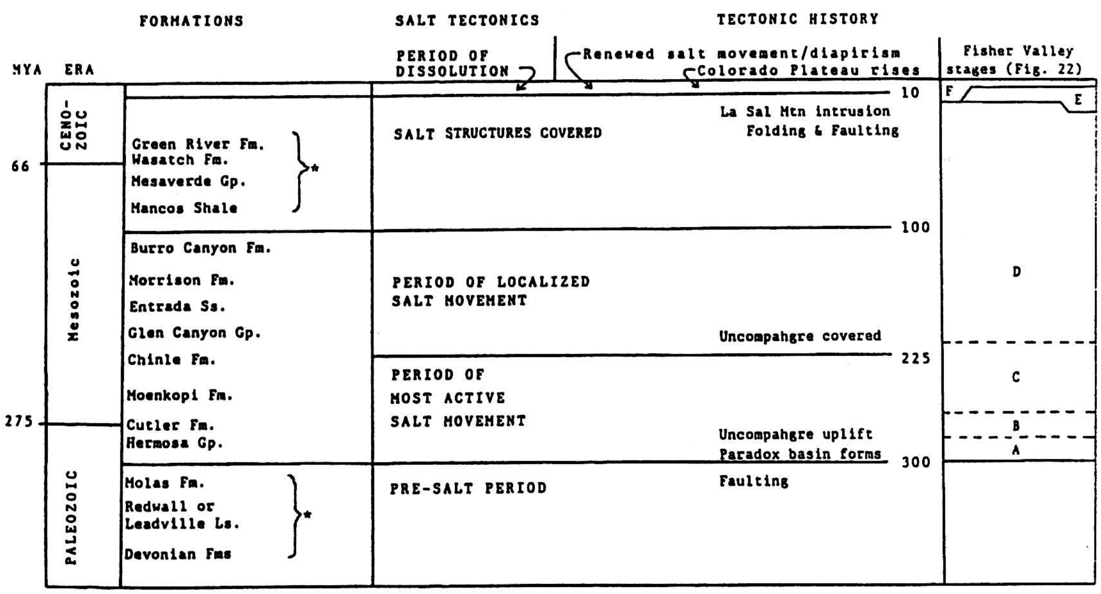


Figure 18. Periods of halokinetic deformation and regional tectonism (modified after Doelling, 1988).
* formations not exposed in the Fisher Valley area.

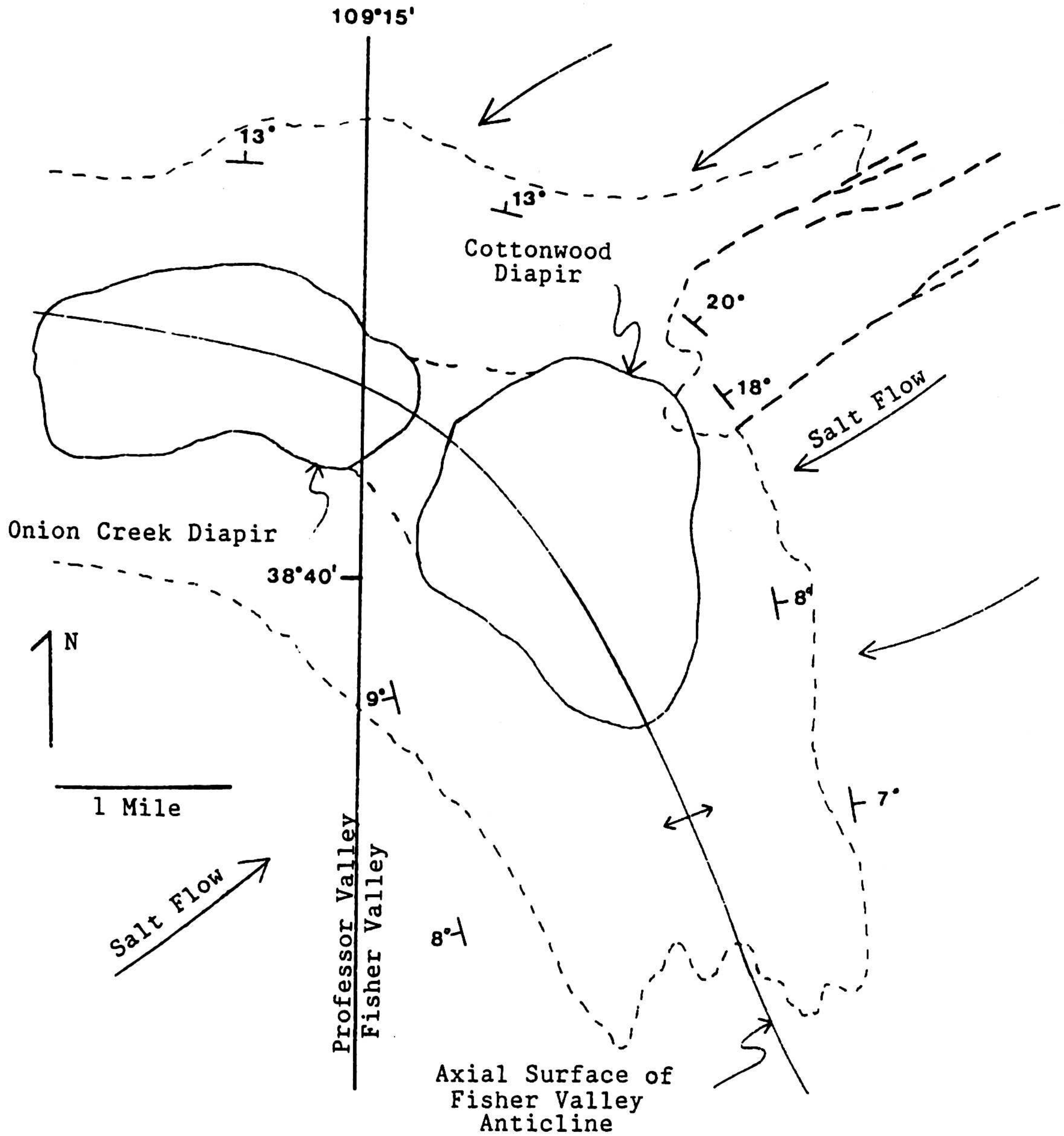


Figure 19. Locations of Onion Creek diapir and inferred Cottonwood diapir during initial formation (Late Pennsylvanian - Early Triassic). Schematic diagram illustrates the inferred location of those salt masses that were structurally positive in comparison to the remainder of the salt cored anticline; these masses were most likely nonpiercement structures.

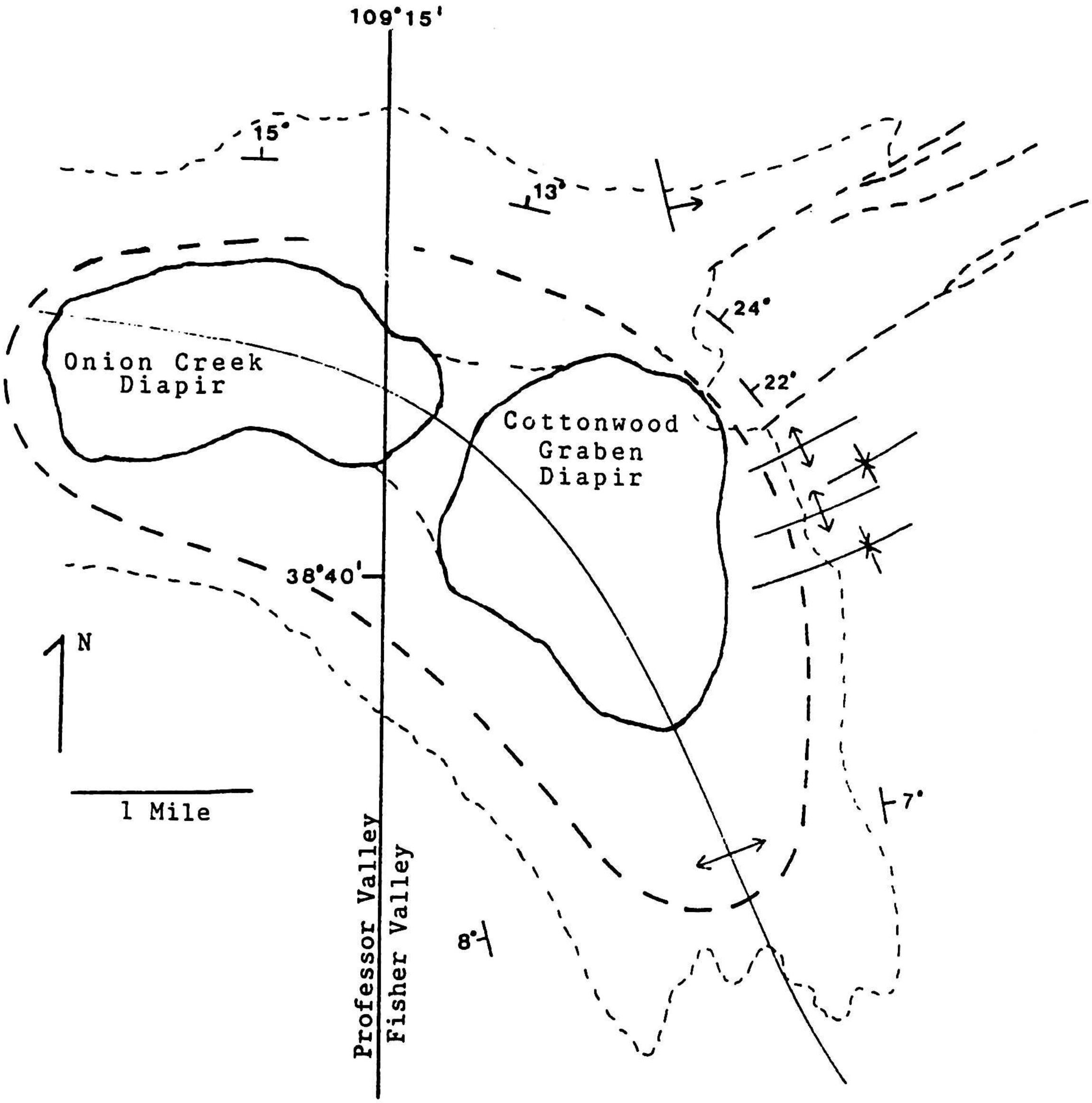


Figure 20. Location of Onion Creek diapir and inferred Cottonwood diapir during Triassic through Jurassic active upward movement. The Onion Creek - Fisher Valley anticline is underlain by three separate salt masses - - the Onion Creek diapir, the inferred Cottonwood diapir, and the structurally less prominent core that underlies Fisher Valley (heavy dashed line). Field evidence indicates that the salt diapirs may have been piercement structures. Fold axes represent structures formed during this phase of upward salt movement.

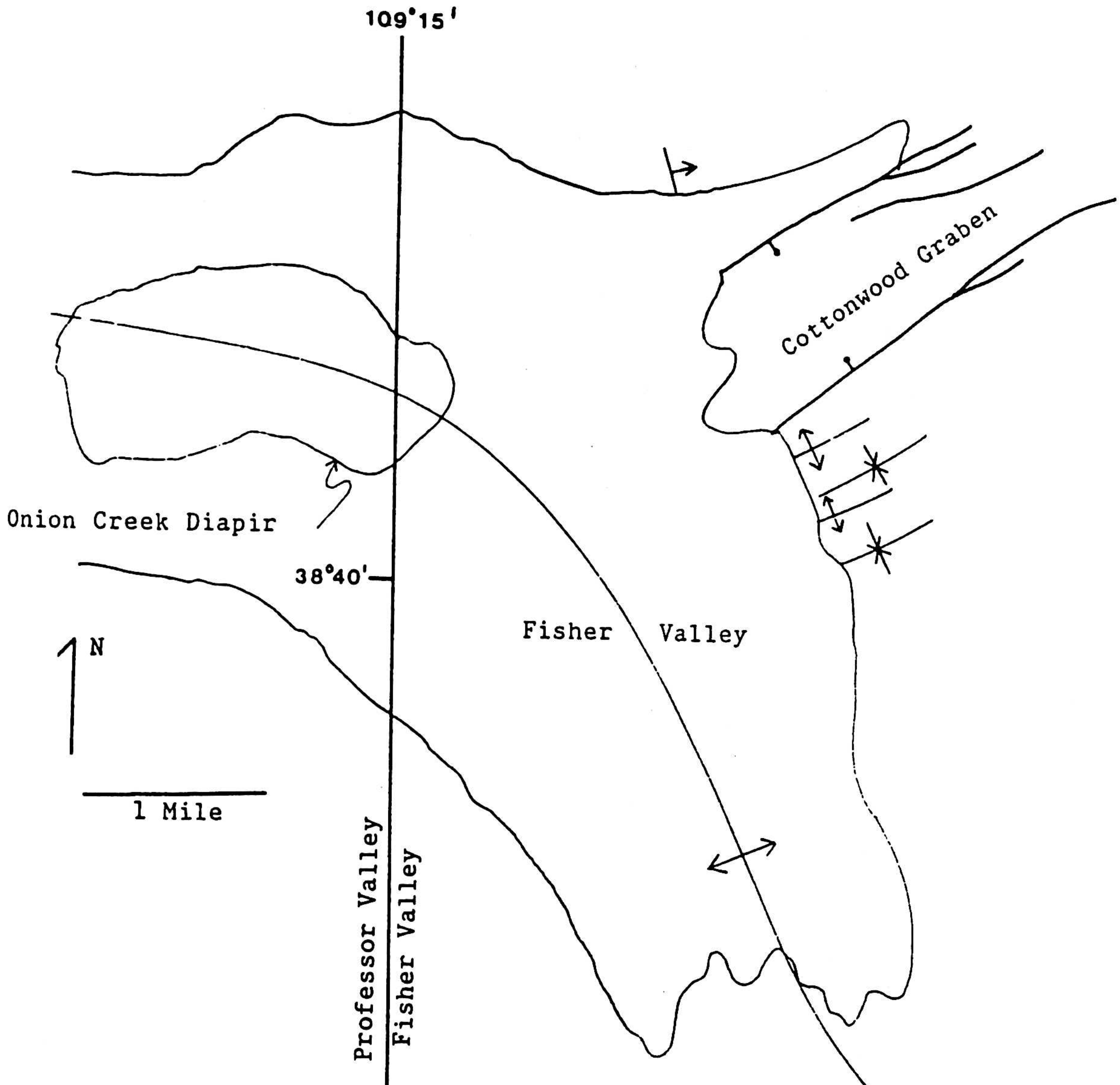


Figure 21. Location of Onion Creek diapir during dissolution of the Cottonwood diapir, collapse of Fisher Valley, and associated collapse of the Cottonwood graben. Quaternary eolian sand, alluvium, and colluvium blanket Fisher Valley. The Onion Creek diapir remains exposed at the surface and has been active throughout the Quaternary.

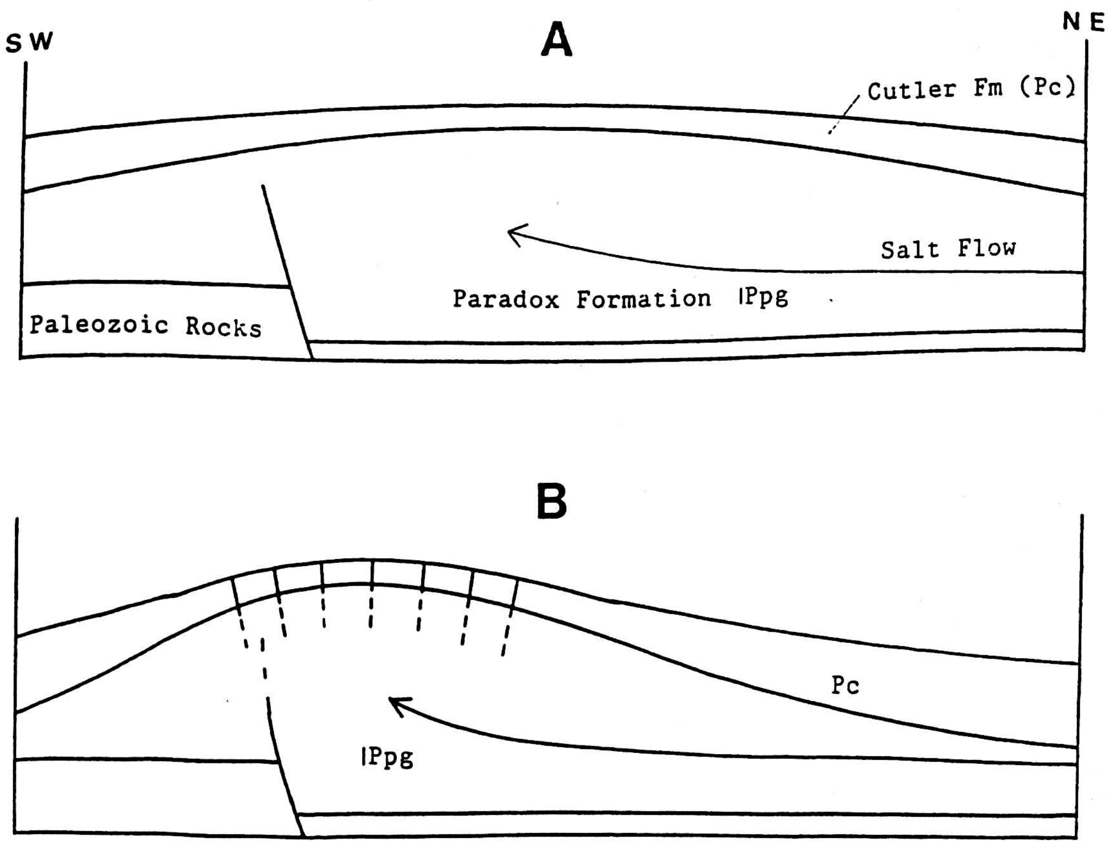


Figure 22. Suggested sequential growth and dissolution of the Cottonwood diapir.

A - Initial growth of the Fisher Valley anticline (Late Pennsylvanian - Early Permian)
B - Continued salt flow into the anticline core - - Permian strata truncated against the salt core (Permian)
C - Initial stages of the diapir - - Moenkopi strata truncated and deformed adjacent to the diapir (Middle Triassic)
D - Continued growth and culmination of the diapir - - Chinle strata truncated and deformed adjacent to the diapir - - Wingate strata cover the stagnant diapir (Late Triassic - Early Jurassic)
E - Dissolution of the diapir and related collapse of the overburden - - formation of Fisher Valley (early Tertiary)
F - Collapse of the Cottonwood graben - Right half of diagram illustrates longitudinal cross-section of the Cottonwood graben - - development of the present geomorphic state (middle ? Tertiary)

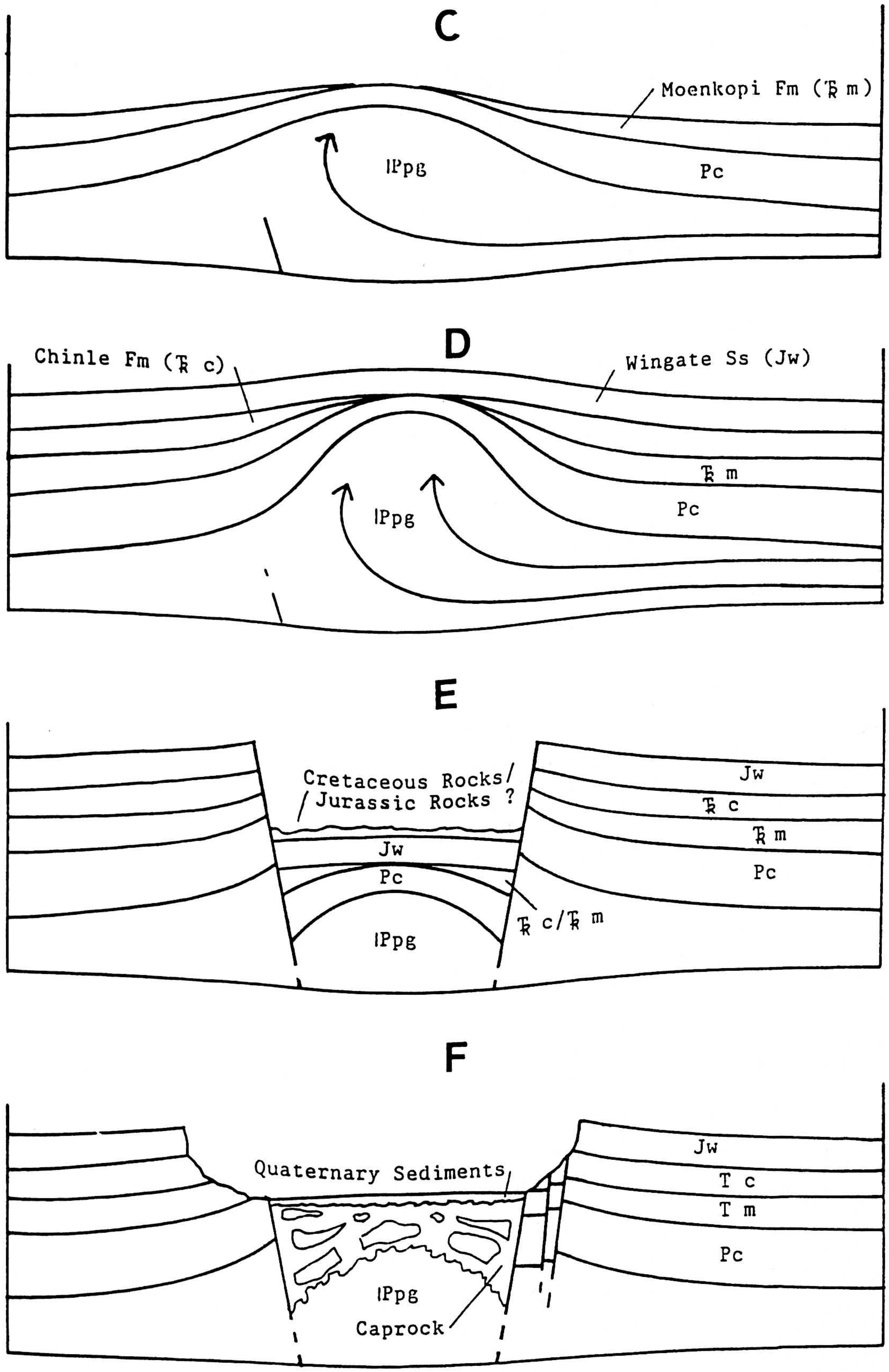


Figure 22. continued

changes, and syn-depositional folding of the Moenkopi and lower Chinle Formations adjacent to the present mouth of the Cottonwood graben indicate local salt deformation. Nowhere else along the trend of the anticline are such sedimentologic features so well developed and with such great magnitude. The southern escarpments of Fisher Valley, which lie closer to the crest of the anticline than any of the escarpments farther north, expose no sedimentologic evidence approaching the magnitude of the angular discordances and depositional thinning that exist farther north. Sedimentologic evidence in the escarpments north and south of the Onion Creek diapir suggest a period of quiesecence in the growth of the diapir during the Jurassic. During this phase in the development of the salt structures beneath Fisher Valley, salt-flow may have been locally diverted away from the Onion Creek diapir and into the growing Cottonwoood diapir. These structural positives were undoubtedly buried during the Early Cretaceous.

Figure 21 (fig. 22, stage E and F) illustrates the collapse of Fisher Valley, Cottonwood diapir and the related Cottonwood graben, during the Cenozoic (see Cottonwood graben description), and continued growth of the Onion Creek diapir during the Pliocene through Quaternary. Collapse of the structures was controlled by dissolution of salt which was facilitated by active erosion and rémoval of confining layers, canyon cutting, and incision by the Colorado River, which transects the anticline trend, and by active ground-water circulation along collapse-induced fractures. The inferred Cottonwood diapir is not exposed. Colman (1983), Colman and Hawkins (1985) and Colman and others (1987) have documented several pulses of diapiric salt movement within the Onion Creek salt mass between 2.5

m.y. ago and 250,000 years B.P.. This stage of halokinetic history withi Fisher Valley corresponds to Doelling's (1988) late Cenozoic period of dissolution and renewed salt movement.

ECONOMIC GEOLOGY

URANIUM-VANADIUM DEPOSITS

Carnotite was first mined in the Colorado Plateau adjacent to west Paradox Valley (Coffin, 1954). The search for radium for the treatment of cancer pushed for research in the extraction of radium and vanadium from carnotite ores. Carnotite mining ensued about 1910 in western Colorado on Blue Creek, Outlaw, and Tenderfoot mesas (Chew, 1983). Claims on Polar Mesa were not staked until 1914. The relatively late start of mining on the mesa was due to inaccessibilty and lack of water. Beaver Creek, which heads in the La Sal Mountains, had been diverted to Fisher Creek for ranching and irrigation (D.L. Taylor, 1987, personal communication). Little water remained on North Beaver and Polar Mesas. Drinking water was packed in from springs on the east and west sides of Polar Mesa, and stock were served from dirt tanks (Dane, 1935).

Keystone Metals Reduction Company developed many of the claims on Polar Mesa. Ore was hand sorted and sacked and sent to the Keystone Metals Reduction Company pilot mill on the south end of Polar Mesa (Chew, 1983). The majority of the concentrate was packed by mule across Cottonwood Canyon and onto Sevenmile Mesa, to a subcamp 5 mi southeast of Dewey, and then by wagon to Cisco (D.L. Taylor, 1987, personal communications; Dane, 1935). Some of the ore may have been shipped to Castleton, Utah. Mining on the mesa and throughout the Colorado Plateau slowed after 1921. Decline in production of radium was brought about by the discovery of extremely rich ore in the Belgian Congo; some shipments contained 60% U_3O_8. The Belgian monopoly pegged the price of uranium at $70 per ton in 1923 and forced all producers except the U.S. Radium company off the market by 1925 (Coffin, 1954). Operations were resumed on Polar Mesa in 1937 by Habro mines (Emerson and Smith, 1944). Significant amounts of radium were mined from 1942 - 1944 under contracts by the Metals Reserve Corporation, a government agency formed to aquire vanadium for steel production during World War II (Goodknight and Daub, 1983). The firmer price for vanadium, improved roads, and transportation made lower-grade ore more profitable than 25 years earlier. From June 1942 until February 1944, 7600 tons, averaging 2% V_2O_5, were shipped from Polar Mesa to the Metals Reserve Company stock piles (Emerson and Smith, 1944). After World War II, in 1948, mining resumed with incentives offered by the U.S. Atomic Energy Commission (AEC). The AEC program lasted until 1971 but development on Polar Mesa was essentially complete by the mid-1950s. Mining on Polar Mesa continued into the late-1970s (Chew, 1983).

The U.S. Department of Energy (DOE) records indicate that during 1948-1970, during the Atomic Energy Commission's procurement program, the mines on Polar Mesa are credited with producing 183,000 tons of ore averaging .31% U_3O_8 and 1.487% V_2O_5. DOE records indicate that since 1948 the Gateway mining district, which consists of mines on Moon, Blue, Outlaw, Calamity, Flat Top, Tenderfoot, John Brown, Beaver, and Polar

Mesas, produced 2,711,786 tons of ore that averaged 0.29% U_3O_8 and 0.94% V_2O_5.

Uranium deposits on Polar Mesa are located in the Salt Wash Member of the Morrison Formation. The major ore body is a bed of massive cross-bedded, fine to medium-grained, yellow-gray to brown sandstone ranging in thickness from 9 - 66 ft. This major uranium bed, which is called the "Pay Off Sand" on Polar Mesa (Eicher and Bivens, 1955), is located about 20 - 30 ft below the Salt Wash - Brushy Basin contact. The lowest known mineralized zone is about 75 ft above the Salt Wash - Tidwell contact.

Ore bodies are generally tabular-flat, or stratified, 3 - 6 ft thick, and their occurrence is controlled by lithology. Bedding and the lateral continuity of the channel sandstone are controlling factors in ore-body size. Mineralogy of these ore bodies includes carnotite, tyuyamunite, uraninite, coffinite, corvusite, montrosite, hewetite, vanoxite, pascoite, and rossite. These minerals are generally aphanitic to fine-grained crystals (H.H. Doelling, 1987, personal communication). Mines on Polar Mesa, mapped on figure 23, and listed in table 1, are generally open stope, room and pillar. Many of the mines tunnel into the soft mudstone underlying the ore-bearing sandstone. The rock mass in the mines is generally self-supporting, needing timber only for chutes and raises.

HYDROCARBONS

The Fisher Valley quadrangle is located in the Paradox fold and fault belt where petroleum occurrences are widespread but exploration in the immediate region has been limited. Production has been acquired from salt

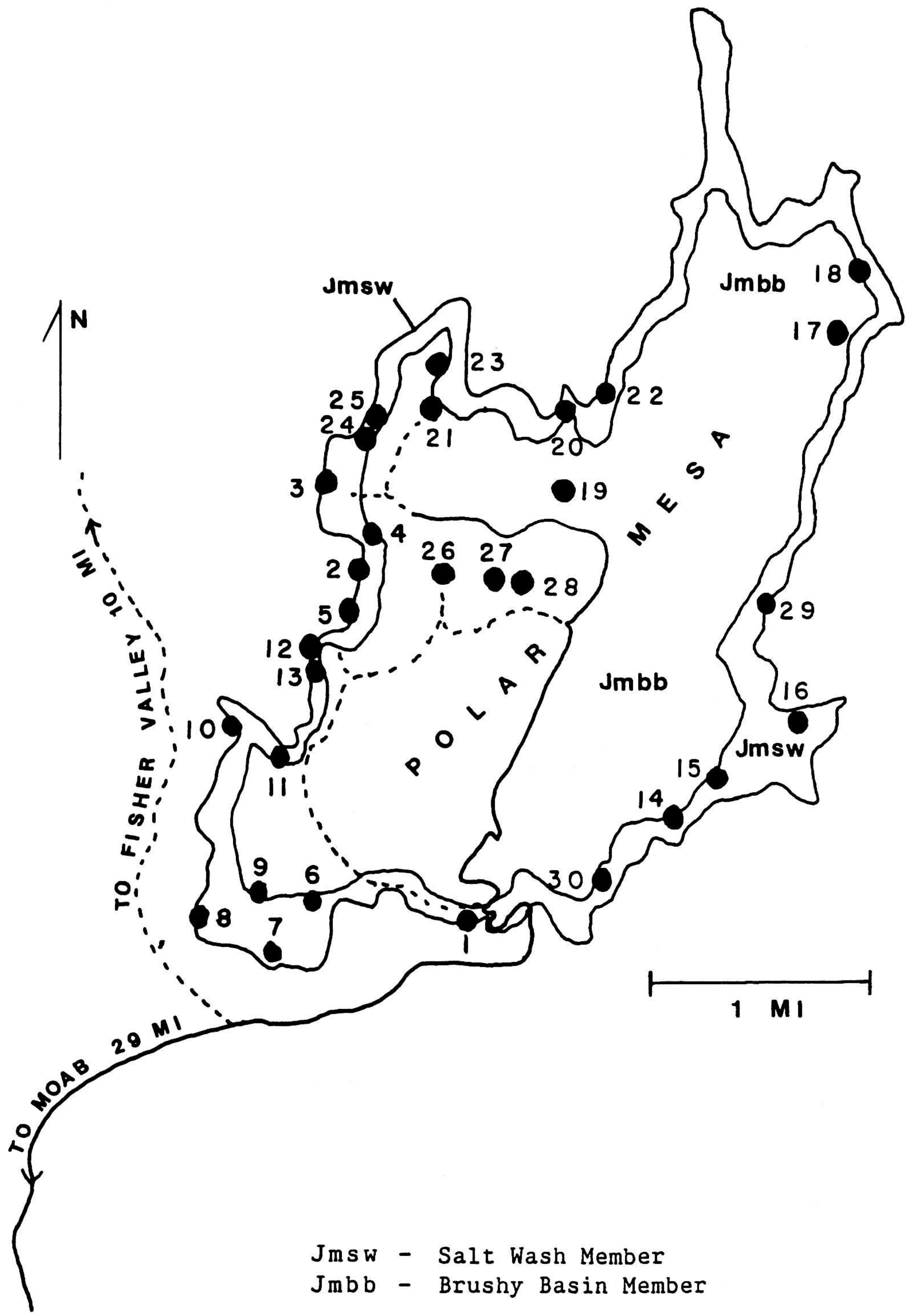


Figure 23. Location map of uranium - vanadium mines on Polar Mesa. Numbers correspond to mine names listed in Table 1.

TABLE 1. Polar Mesa uranium/vanadium mine-claim names and location numbers for accompanying map (Figure 24).

Map Location	Mine Name
1	Polar King
2	Unamed
3	Elva M Group
4	Effie F MIne
5	Thompson C
6	Polar #2
7	Polar No. 3
8	Pinto Jack
9	Polar No. 7
10	Vivian
11	Emma
12	Foster
13	New Armstrong
14	Freeport
15	Yellow Jacket
16	Avis
17	Jumbo
18	Pittsburg
19	Petrified Tree No. 9
20	Louise A and Louise A No. 2
21	Mineral Polar 22
22	Helen F
23	Rimrock
24	Mary No. 3
25	Captain Jack
26	F. W. #3
27	Unknown
28	Unknown
29	Dotsy Mine
30	Earl Mine

intrusion, structural, and structural/stratigraphic traps (Clem and Brown, 1984). The primary productive zones are the Leadville Formation, the Cane Creek zone of the Alkali Gulch Member of the Paradox Formation, the Akah Member of the Paradox Formation, the Ouray Formation, and the McCraken Member of the Elbert Formation. The source for petroleum in the region is the organic-rich shale beds of the Paradox Formation. The region south of the Fisher Valley quadrangle, in San Juan, Emery, Wayne, Garfield, and Kane Counties, has seen exploration activity during the last few years (Krivanek, 1981). North of the quadrangle, in northeastern Grand County, which is the most prolific area for oil and gas in the county, production has been realized from structural, salt intrusion, structural/stratigraphic, and stratigraphic traps (Young, 1983). Petroleum reserves in this area are generated in the Paradox Formation, Mancos Shale, and Green River Formation. Production is reported from sandstone beds in the Mancos Shale, Dakota, Cedar Mountain, Morrison, and Entrada Formations (Young, 1983).

Locally within the Fisher Valley field area, wells have been drilled unsuccessfully. North of the escarpment that bounds Fisher Valley, on Sevenmile mesa, two dry holes were drilled. West of the field area, on the western edge of the Onion Creek diapir, two wells were drilled, but no production was reported.

CONCLUSIONS

The following conclusions can be drawn from this study.

1) Salt flow within the Fisher Valley quadrangle was most active during Permian through Late Triassic. Salt cores that compose the Fisher Valley salt-cored anticline were well-defined structures by Permian (Cutler) time. Mapping of intraformational uncomformities within the Cutler and Moenkopi Formations help outline the kidney-shaped main salt core that undoubtedly existed beneath the Fisher Valley anticline during the Permian through Triassic.

2) Structural positives, including the Onion Creek diapir and inferred Cottonwood diapir, formed as a result of local salt movement into the anticlinal crest.

3) The eroded diapir at the mouth of the Cottonwood graben (Cottonwood diapir) was most active during the Late Triassic with dissolution and collapse during the Tertiary and Quaternary.

4) The Onion Creek diapir was active during the Permian through Quaternary with the exception of a period of quiescence or stagnation during the Jurassic.

5) Several features are coincident with the location of the inferred Cottonwood diapir and may have contributed to its growth: 1) The inferred position of the diapir coincides with the location where curvature of the Fisher Valley anticline axis was greatest; 2) Hite (1961, 1975) suggested that left-lateral basement faults underlie the arcuate bend in the anticlinal trend (the location of the inferred diapir). Slip on these faults may have cut the Paradox

evaporites and may have accentuated salt flow. Mapping of intraformational and interformational unconformities and anomalous sedimentologic features suggests that the region at the southwest end of Cottonwood graben was deformed more strongly than other areas along the anticlinal crest.

6) The geometry of the Cottonwood graben (its "hinge-like" shape and bowed floor) are the result of dissolution and collapse of a wedge-shaped salt mass. Orientation of the graben may have been constrained by: 1) a subtle thickened salt section that existed beneath the graben; 2) left-lateral basement faults (reactivated during the Mesozoic) that underlie the graben; and 3) a northeast-trending zone of extension that developed on the northeast limb of the Fisher Valley anticline where curvature of the fold axis was greatest.

7) Faulting of post-Paradox strata occurs where Paradox salt was initially thick. Faults bounding Fisher Valley and the Cottonwood graben are located above paleo salt highs.

8) There is no evidence in the field area to support the hypothesis of latest Cretaceous to early Eocene Laramide deformation. Fold geometry in the Fisher Valley area was probably controlled by salt flow into anticlinal regions from adjacent subsiding basins (synclines) during the Cretaceous through Tertiary.

9) The study of salt-induced sedimentologic variations in rocks adjacent to the Fisher Valley anticline results in an incomplete reconstruction of the structural history for the following reasons. 1) No strata remain over the main salt-cored anticlinal axis in the

quadrangle preventing the analysis of those rocks which presumably were deformed more intensly than rocks in flanking regions. This "missing" sequence of rocks has prevented the interpretation of the halokinetic deformation over the crest of the anticline and has limited the interpretation of the halokinetic history of the anticline and the quadrangle in general. 2) Exposures of units in the escarpments that bound Fisher Valley are not good for the study of sedimentologic variations because they lack 3-D perspective. 3) Post-Glen Canyon strata are restricted to the high mesas which are located several miles off the anticlinal crest.

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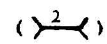
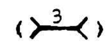
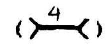
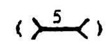
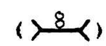
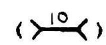
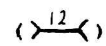
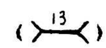
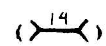
Appendix 1

Map Location of Measured Stratigraphic Sections

Measured Section	Section Number	Map Symbol
Cutler Formation*		
Moenkopi Formation	#1	
Chinle Formation	#2	
Wingate Sandstone	#3	
Kayenta Formation	#4	
Navajo Sandstone	#5	
Dewey Bridge Member	#6	
Dewey Bridge Member	#7	
Slickrock Member	#8	
Moab Tongue	#9	
Tidwell Member	#10	
Tidwell Member	#11	
Salt Wash Member	#12	
Brushy Basin Member	#13	
Burro Canyon Formation	#14	

* Location of Cutler measured section is outside the map area. See measured section description for location.

Measured section of Cutler Formation
sections 15, 22, T. 24 S., R. 25 E.
Located in Cottonwood Canyon,
Professor Valley quadrangle
Measured by Mark Jensen and
Richard Stancliffe, [6/10-12/80]

1) Arkose, grayish-red-purple (5RP 4/2) and dark reddish-brown (10R 3/4) bands; very fine to medium-grained, subangular, poorly-sorted, equant; massive; calcareous, well cemented; cross-stratified, calcite vein fillings; weathers same color as fresh; forms smooth rounded cliff, well exposed.

524.3'

2) Arkose, grayish-red-purple (5Rp 4/2) and moderate reddish-brown (10R 6/6); mostly very fine to medium-grained with occasional grains to 1 cm in diameter; subangular, poorly-sorted, equant grains; calcareous, moderately to well cemented, platy to massive; weathers same color as fresh, forms earthy steps and slopes, poorly exposed (90% covered).

311.9'

3) Conglomerate, grayish-red-purple (5RP 4/2); clasts to 7cm, subangular to subrounded, poorly-sorted, and equant; large mica flakes; some calcite cement. moderately indurated; massive bed, some cross-straification, weathers same as fresh., forms well exposed rough cliff.

6.6'

4) Arkose, like unit 2, but forms well exposed rough ledge or cliff,

122.2'

5) Interbedded arkose and conglomerate, grayish-red-purple (5RP 4/2); fine-grained to 7cm, subangular to subrounded, poorly-sorted, equant grains; some large mica flakes and gravel sized pieces of feldspar; calcareous, moderately cemented, massive, cross-stratified throughout, alternating fine to coarse-grained laminae; weathers to the same color as fresh, forms rough rounded ledge.

42.9'

6) Sandy siltstone, pale reddish-brown (10R 5/4); mica grains to fine-grained size, calcareous, poorly-indurated; fissile to thin bedded; weathers same color as fresh and moderate reddish-orange (10R 6/6) and moderate reddish-brown (10R 4/6), bleached spots and bands of pale green (10G 6/2), forms earthy recess, poorly exposed

15.2'

7) Interbedded arkose and conglomerate, like unit 5.

9.0'

8) Arkose, like unit 2 except predominantly grayish-red-purple (5RP 4/2) grading to pale reddish-purple (5RP 6/2); forms rough ledge or cliff, well exposed.

254.5'

9) Covered slope, possibly underlain by a more friable arkose.

12.0'

10) Arkose, banded pale reddish-purple (5RP 6/2) and moderate reddish-brown (10R 4/6); very fine to medium-grained, subangular, poorly-sorted, and equant grains; calcareous, moderately to well cemented; platy to massive; weathers same color as fresh, some reddish-orange staining, forms rough ledge.

18.7'

11) Covered slope, like unit 9.

10.5'

12) Interbedded arkose and conglomerate, like unit 5 except fresh color is pale red-purple (5RP 6/2), contains no cross-stratification; forms rough steps, poorly exposed.

8.9'

13) Arkose, pale reddish-purple (5RP 6/2); very fine-grained, rounded, well-sorted, equant grains; micaceous with muscovite and biotite present; calcareous, moderately cemented; platy- to medium-bedded; exhibits worm burrows parallel to bedding; weathers same color as fresh, light gray (N7) bleached spots, some manganese oxide staining, forms rough steps;
....16.0' above base of unit color changes to moderate reddish-orange(10R 6/6)
....10.0' below top of unit grain size increases, has calcite veinlets; some massive beds.

57.6'

14) Arkose, like unit 13, except is moderate reddish-orange (10R 6/6) and contains no worm burrows.

114.6'

15) Arkose, like unit 13, except contains no worm burrows and has pale reddish-purple (5RP 6/2) bands that average 3 feet in thickness and pale reddish-brown (10R 5/4) bands which average 8 feet in thickness; platy to massive

114.6'

16) Interbedded arkose and conglomerate, like unit 5.

7.3'

17) Arkose, like unit 15.

31.5'

18) Interbedded arkose and conglomerate, like unit 5.

35.6'

19) Covered slope, like unit 9.

35.9'

20) Arkose, like unit 15.

117.1'

21) Conglomeratic arkose, pale red-purple (5RP 6/2); fine grained to cobbly, subangular to subround, poorly-sorted, equant grains; contains large mica flakes; cross-stratified; weathers same color as fresh, forms rough rounded ledge, well exposed

22.7'

22) Arkose, like unit 15.

65.5'

23) Arkose, moderate reddish-brown (10R 4/6); very fine-grained, rounded, well-sorted, equant grains, muscovite and biotite mica; calcareous, moderately cemented; platy to massive; weathers to moderate reddish-orange (10R 6/6), some manganese oxide staining; forms rough step or ledge; other fresh colors include pale purple (5RP 6/2) and pale red-brown (10R 5/4) and moderate red (5R 4/6).

121.6'

24) Sandy siltstone, like unit 6, except color is grayish-red (10R 4/2) and weathers moderate reddish-brown (10R 4/6), non-calcareous cement, micaceous.

3.1

25) Arkose, like unit 23 except contains some rip-up clasts and some medium-grained laminae.

125.6'

26) Interbedded arkose and conglomerate, like unit 5, except color is pale red purple.

1.2'

27) Arkose, like unit 23.

244.4'

28) Interbedded arkose and conglomerate, like unit 26.

22.8'

29) Arkose, like unit 23.

125.7'

30) Conglomeratic arkose, like unit 21.

4.6'

31) Arkose, like unit 13, except pale reddish-brown (10R 5/4); and contains no worm burrows.

11.1'

32) Covered slope, appears to be underlain by a micaceous arkose, apparently very friable.

20.1'

33) Interbedded arkose and conglomerate, like unit 26, ...25 feet above base of unit color becomes grayish-red (10R 4/2); moderately exposed.

133.6'

34) Covered slope, probably underlain by micaceous arkose.

34.3'

35) Arkose, pale reddish-brown (10R 5/4); very fine to fine-grained, subangular, well-sorted, equant grains; muscovite and biotite mica present; calcareous, moderately cemented; platy to medium-bedded; some small scale cross-stratification; worm burrows present, weathers same color as fresh; some manganese oxide staining; forms rough steps, poorly exposed.

139.3'

36) Covered slope, pale reddish-brown (10R 5/4); underlain by micaceous sandstone or arkose, platy.

42.1'

37) Interbedded arkose and conglomerate, like unit 5 except fresh color is pale blue (5B 6/2).

53.7'

38) Arkose, like unit 13 except color is pale reddish-brown (10R 5/4).

19.0'

39) Covered slope, white (N9), grayish-orange (10YR 7/4), pale red (5R 6/2). light blue gray (5B 7/1) and pale reddish-brown (10R 5/4); sandstone grades upsection into arkose.

46.4'

Total measured thickness of the Cutler Formation 3048.5'

Measured section of Moenkopi Formation
by M. Goydas, [6/21/87]
SE1/4, SE1/4 sec. 6, and SW1/4, SW1/4 sec. 5 T. 25 S., R. 25 E.
section #1

Upper Moenkopi

Parriot Member

10) Mudstone, grayish-red-purple (5RP 4/1), to dark reddish-brown (10R 3/4), to dusty-purple (5PR 2/2); sand grains are distributed throughout; calcareous, moderately-poorly cemented; thinly to massively bedded; weathers same as fresh, forms earthy slope, poorly exposed.

9.0'

9) Sandstone to conlomeratic sandstone, moderate reddish-orange (10R 6/8) locally bleached light gray (N7), fine to medium-grained, subrounded to rounded, poorly-sorted. Thickly laminated to thinnly bedded; coarse sand and pebble conglomeratic sandstone lenses; lenses display fining upward sequence; scour and fill features, ripple marks, climbing ripples and small-scale trough cross stratification evident; very calcareous, moderately well cemented. Forms rough slope.
.... 11' above base: Sandstone, moderate-reddish-orange (10R 6/8), fine to medium grained, subrounded, moderately-sorted: calcareous, moderately well-cemented; micaceous, thinly laminated to thinly bedded; sand bodies are generally lenticular displaying basal, coarse sand to pebble size lag deposits: grains up to 5/16" in diameter. Fining upwards sequence is evident in many of the lenticular sands. Small-scale tabular-planar and trough cross-stratification present. Tabular sets non-plunging, and less than 1.5 feet thick; foreset strata thinly to thickly laminated, straight and dip at low angles (less than 20°). Trough sets are slightly-plunging and lenticular; foreset strata are thickly laminated, concave upward, dip at low angles (less than 24°) and are tangential to and angular to lower bounding surfaces. Forms well-exposed earthy slope.

31.6'

Sewemup Member

8) Interbedded sandstone, siltstone and mudstone. Sandstone: moderate reddish-orange (10R 6/8), very fine-grained (Vfl), subrounded to well-rounded, well-sorted, equant grains; calcareous, poorly - moderately cemented; micaceous; thinly laminated to massively bedded, cross beds to 3' in height, ripple marked on planar horizontal bedding surfaces; weathers light brown (5YR 5/6),

forms earthy slope, poorly exposed (exposed as blocky ledges in runoff ditches). Siltstone: moderate-reddish-orange (10R 8/6) to grayish-red (10R 4/2), calcareous and poorly to moderately cemented, thinly laminated to thickly bedded, ripple marks present but not as abundant as in unit 4, bleached zones of light-gray (N7) to very-pale-green (10G 8/2), weathers moderate-reddish-brown (10R 4/6) to light-brown (5YR 6/4), forms poorly-exposed slope. Mudstone: dark-reddish-brown (10R 3/4), calcareous and poorly cemented, bleached zones of very pale green (10G 8/2), to light gray (N7); weathers same as fresh, forms earthy slope, poorly exposed.
....94'-139' above base of unit siltstone is dominant rock type.
....139'-140 above base of unit (in siltstone) there are several lenses composed of sand to pebble size grains (<1/2"); grains very well rounded and poorly-sorted.

140.6'

Total measured thickness of the upper Moenkopi 181.0'

Lower Moenkopi

Ali Baba Member

7) Interbedded sandstone and siltstone: Sandstone: moderate reddish-brown (10R 4/6), very fine grained (Vfl), feldspathic, subangular to subrounded, well-sorted, micaceous, thinly laminated, small-scale tabular-planar cross-bedding in sets up to 2" high, bands of crossbeds up to 1' thick; sets are non-plunging, foresets are thinly bedded, straight and dip at low angles; horizontal laminae exhibit ripple marks. Siltstone: same composition as sandstone but finer-grained; cross-stratification less noticeable than in the sandstone, thin horizontal laminations ubiquitous, light gray (N7) bleached zones prominent; weathers same as fresh; sandstones form ledges in slope-forming siltstone, both well exposed.

125.7'

6) Silstone, moderate reddish-orange (10R 6/8), very micaceous, calcareous, well cemented, fissile, ripple-marked, thin moderate reddish-brown (10R 4/6) laminae abundant; weathers gray moderate reddish-orange (10R 6/6), forms poorly-exposed slope between units 5 and 7., poorly exposed.

5.5'

5) Sandstone, moderate reddish-orange (10R 6/6), very fine-grained well rounded grains, equant grains, well-sorted, calcareous, well cemented, platy; thinly laminated to thickly bedded, ripple-marked; weathers moderate-reddish-brown (10R 3/4), stains dark reddish-brown (10R 32/4) to moderate brown (5YR 3/4); jointing is ubiquitous throughout unit; forms well-exposed blocky cliff.

11.2'

4) Interbedded sandstone and siltstone: Sandstone: moderate reddish-brown (10R 4/6), fine-grained (fl), subangular to subrounded, well-sorted, sphericity of grains increases upward, very micaceous, thinly laminated to thinly bedded, trough and tabular cross-beds are of minor significance; weathers same as fresh. Siltstone: moderate reddish- brown (10R 4/6), calcareous, moderately well cemented, very micaceous, thinly laminated, ripple-marked; weathers grayish-red (10R 4/2), sandstone forms blocky steps in slope-forming siltstone; sandstone steps very well exposed; siltstone moderately exposed.

66.7'

3) Sandstone (very fine grained) interbedded with sandstone (coarse grained). Sandstone: moderate reddish-brown, very fine-grained (Vfl), subangular to rounded grains, equant grains, very well-sorted; calcareous, well cemented, thinly laminated to thinly bedded sandstone: pale red (10R 6/2), coarse grained, subrounded to well rounded, moderately-sorted; calcareous, well cemented; thickly laminated to thinly bedded.
Both sandstones horizontally bedded and cross-bedded; cross-beds well developed in coarser sandstone.
....14' above base of unit is lenticular, cross-bedded, fine-grained sandstone unit; represents clean channel sand deposit. Both fine and coarse grained sandstones weather same as fresh, fine-grained sandstone stained dark reddish-brown (10R 3/4); unit forms blocky-cliff, very well exposed.

18.1'

Tenderfoot Member

2) Mudstone, moderate reddish-brown (10R 4/6), calcareous, poorly cemented, thinly bedded, with bleached zones of very light gray (N8), to pale green (10G 8/2) mudstone; weathers grayish-red (10R 4/2) and forms poorly-exposed earthy slope.

14.2'

1) Silty sandstone, moderate-reddish-brown (10R 4/6), very fine-grained (Vfl), subrounded to well rounded, equant grains, well-sorted, micaceous along bedding planes; calcareous, poorly cemented, thin to massive bedding; lenses of reworked Cutler gravel and cobbles; Coarse (1/5") quartz grains distributed throughout, laminae of coarse grains (very well rounded) also exists; bleached very light gray (N8) zones abundant; weathers same as fresh, forms well rounded cliff, well exposed.
....15' above base of unit very fine-grained particles become dominant grain size, fining upward sequence continues to top of unit.

92.1'

Total measured thickness of the lower Moenkopi 333.5'

Total measured thickness of the Moenkopi 514.0'

Measured section of Chinle Formation
by M. Goydas [6/17/87]
SW1/4, SW1/4, sec. 30, T. 24 S., R. 25 E.
section #2

8) Sandstone, moderate-reddish-brown (10YR 4/6) very fine-grained angular to subrounded, well-sorted; thinly laminated at base, grading upward into a more thickly bedded unit; calcite-cemented, well cemented; scour and fill structures abundant throughout lower 8', tabular and trough cross-beds, in sets up to 2' present in the upper 1/2 of unit; tabular sets non-plunging; individual foresets thinly to thickly laminated, straight to weakly concave up and dip at low angles; trough sets are lenticular and slightly-plunging; foresets thinly laminated and strongly concave up; weathers same as fresh; lower 4/5 of unit forms poorly-exposed slope, upper 4' forms well-exposed cliff; upper few feet of unit transitional (but not conformable) with the overlying Wingate; contact with overlying Wingate Formation sharp, and locally angular unconformity exists.

24.8'

7) Sandstone - Siltstone, moderate-reddish-orange (10R 6/6) very fine-grained, well-sorted, angular to subrounded; thinly to thickly laminated; minor ripple laminations; less micaceous and carbonaceous than underlying unit (6). Calcite cement, well cemented; weathers same as fresh unit forms earthy slope, poorly exposed.

98.4'

6) Sandstone, moderate reddish-brown (10YR 6/6), fine-grained, subrounded grains, very well-sorted; thinly laminated to thickly bedded; calcite cement, very well cemented; weathers same as fresh, forms blocky cliff, and very well exposed.

7.9'

5) Sandstone, moderate reddish-brown (10YR 6/6) fine-grained, subrounded to well rounded grains, well-sorted; indistinctly bedded, locally thinly to thickly bedded.
....28' above base of unit there is light gray (N7) to moderate reddish-orange (10YR 6/6), 2'-thick calcareous sandstone; unit as a whole weathers same as fresh, forms blocky ledges and earthy slopes, and poorly exposed (in runoff ditches).

34.9'

4) Gritstone, moderate reddish-brown (10R 4/6) fine-grained to pebble-size particles (<0.1" - 1.5"), subangular to very well rounded grains;
thinly to thickly bedded (lenticular); calcite cement, poorly cemented, friable; reperesents channel lag deposits and is

locally restricted unit; weathers same as fresh with minor light gray (N7) staining; forms blocky step and locally moderately well exposed.

1.5'

3) Siltstone - Sandstone, moderate reddish-brown (10R 6/6), very fine-grained, very well-sorted, angular to subrounded; calcareous and well cemented; micaceous debris constitutes less than 2% of the bulk rock composition and is less dominant than in the underlying unit (2).

....14.9' above base of unit there is light gray (N7), 1.1' thick calcarenite.

....20.7' above base of unit is an identical 6" thick calcarenite.

The calcarenite beds are thinly laminated, lenticular, not laterally continuous, with terrigenous silt and clay, weathers same as fresh.

Entire unit weathers same as fresh, forms earthy slope and poorly exposed.

48.5'

2) Interbedded sanstone and siltstone; Sandstone: moderate-reddish-brown (10R 4/6), very fine-grained, subangular to subrounded, well-sorted, calcareous, moderately well cemented and micaceous; small scale (less than 3.0') trough cross-stratification; trough sets lenticular, generally less than 2 feet thick; foresets thickly laminated, strongly concave up; coarse grains often concentrated at base of trough sets; contains lenses and bands (inches to tens of inches thick and greater than 6 feet wide) of coarse-grained rock consisting of quartz and carbonate clasts; coarse grains are angular to very well rounded and poorly sorted; lenses and bands more resistant than surrounding sandstone; sandstone unit weathers same as fresh, forms earthy slope and locally moderately well exposed. Siltstone: moderate reddish brown (10R 4/6), thin to thickly bedded, calcareous, poorly cemented and micaceous; siltstone unit weathers same as fresh, forms earthy-slope and locally poorly exposed.

....41' above base of unit light gray (N7) calcareous bed (0.5' thick) is evident.

....45' above base of unit an identical bed to that found at the 41'interval exist; both beds situated within siltstone and poorly exposed. Sandstone/siltstone package is less calcareous toward top of unit; unit forms earthy slope and moderately well exposed.

72.0'

1) Limestone to limestone-grain sandstone (calcarenite), very light grey (N8); unit ranges in composition from dense limestone containing minor amount of pale reddish-brown siltstone clasts, to sandstone composed of coarse grains to granules of limestone and siltstone in very calcareous matrix; base of

unit is clean limestone, becomes quartz rich (40%) in upper 1/2 of unit; quartz grains very fine-grained, subangular to subrounded and well-sorted; presence of stained quartz darkens upper section of unit reddish-light-grey (N8); structureless in lower 5 feet, thin laminations abundant in the upper part of unit and more prominent in weathered surfaces; calcite spar cement present in void spaces and fills vertical stylolites; unit weathers moderate-brown (5YR 4/4) and forms blocky-ledge well exposed locally. Unit may correspond to basal gritstone of the Chinle Formation found farther west (Stewart and Wilson, 1960).

9.5'

Total thickness of the Chinle Formation 294.4'

Measured section of Wingate Sandstone
by M. Goydas, [6/23/87]
SW1/4, NW1/4, sec. 30, T. 24 S., R. 25 E.
section #3

8) Sandstone, moderate-orange-pink (10R 7/4) to moderate reddish-orange (10R 6/6), fine-grained, subrounded to rounded, equant grains, well-sorted, minor black accessory grains (magnetite), calcareous, well cemented, thinly to massively bedded with sweeping trough and wedge-planar cross-beds in sets up to 7' thick, sets nonplunging(?), foresets thickly laminated to thinly bedded, straight to weakly concave upward, dip at moderate angles (10-20 degrees), in places tangential to lower bounding surface; weathers moderate reddish-brown (10R 6/6) to pale red (5R 6/2), manganese oxide staining; smooth as sheer cliff, very well exposed.
....upper 80' measured by triangulation due to inaccessability along cliff face.

105.1'

7) Silty sandstone, moderate reddish-brown (10R 4/6), very fine-grained to fine-grained, subrounded to rounded, well-sorted, calcite cement, well cemented, feldspathic; thinly laminated, trough and tabular planar cross-beds in sets up to o.7' thick are abundant toward top of unit; weathers same as fresh, forms sheer cliff, very well exposed.

10.3'

6) Sandstone, moderate orange-pink (10R 7/4) to moderate reddish-pink (10R 6/6), fine-grained, subrounded to rounded, equant grains, well- sorted, minor black accessory grains (magnetite), calcite cement, well cemented, massive with sweeping trough and wedge-planar cross-beds in sets up to 4' thick, wedge cross-sets may actually be truncated trough sets; sets non-plunging, foresets dip at high angles (> 15 degrees); weathers moderate reddish-brown (10R 6/6) to pale red (5R 6/2), manganese oxide staining, forms a smooth sheer cliff, very well exposed.

143.0'

5) Silty sandstone, moderate reddish-brown (10R 4/6), very fine-grained to fine-grained, subangular to subrounded, well-sorted, feldspathic, thinly to thickly laminated, no noticeable cross-beds, ... 0.025'-0.2' dark reddish-brown (10R3/4) bed separates units 4 and 5; bed similar in composition and texture to Chinle, bed fills troughs at top of unit 5, top of unit 4 is bounded by similar less prominent band; unit weathers same as fresh, forms a recessed concave-cliff, well exposed.

8.7'

4) Silty sandstone, moderate reddish-brown (10R 4/6), very fine-grained to fine-grained, subrounded to rounded, well-sorted,

feldspathic, calcite cement, well cemented, thinly laminated; weathers same as fresh, stains tannish-purple, forms earthy-recess, well exposed.

2.4'

3) Sandstone, moderate reddish-orange (10R 6/6), very fine-grained subrounded to well rounded, well-sorted, calcite cement, well cemented, slightly feldspathic, thin horizontal laminations interrupted by wedge-planar crossbeds in sets up to 2.0' high, foresets thinly-bedded, straight and dip at moderate angles (10-20 degrees); weathers same as fresh; forms a sheer cliff with locally rounded top (in fault-shattered region), very well exposed.

17.9'

2) Sandstone, moderate reddish-orange (10R 6/6), very fine-grained subrounded to well rounded, well-sorted, calcite cement, well cemented, feldspathic (<15%), massive bedding interrupted by small-scale sweeping trough cross-beds in sets up to 0.7' high, foresets strongly concave upward dipping at varying angles (5-30 degrees); weathers same as fresh, forms sheer cliff, very well exposed.

24.7'

1) Sandstone, moderate reddish-orange (10R 6/6), very fine-grained subrounded to well rounded, well-sorted, feldspathic (<10%); thinly laminated at base grading upward into a massively-bedded unit, weathers same as fresh, dark brown to black manganese oxide staining, forms sheer cliff; sharp angular unconformity with underlying Chinle; composition and texture appears gradational between two formations.

2.2'

Total measured thickness of the Wingate Formation 315.3'

Measured section of Kayenta Formation
by M. Goydas [6/28/87]
NW1/4, sec. 28, T. 24 S., R. 25 E.
section #4

5) Sandstone, very light-gray (N8), very fine-grained (Vfu), angular to rounded, very well-sorted; calcite cement, moderately cemented, lenses of friable material, thinly laminated to thickly bedded.
....from the base of the unit to 9'5" is thinly laminated.
....9'5" from the base to 19'8" from the base is massively bedded.
....19'8" from the base to the top of the unit is thinly laminated and trough and wedge-planar cross-beds are abundant. Intraformational unconformities line the base of large trough cross-beds; cross-sets are large-scale, up to 5 feet thick and non-plunging; foresets are thinly-bedded, concave upward and dip at low angles.

33.1

4) Sandstone, moderate orange-pink (10R 7/4), very fine-grained to fine-grained (Vfu-fl), subangular to well rounded, well-sorted, slightly micaceous, calcite cement, well cemented; thickly bedded, no recognizable cross-bedding, round blebs (clusters) of light gray (N8), medium-grained, well rounded quartz grains, "clusters" <5% of total rock volume; weathers moderate reddish-orange (10R 6/6), forms an earthy-slope that is poorly exposed.

9.9'

3) Sandstone, moderate reddish-orange (10R 6/6), fine-grained to medium-grained, (fu-ml), subangular to rounded, moderately-sorted; slightly micaceous, calcite cement, moderately well cemented, lenses of friable material; base of unit (lower 1/3 of unit), contains horizontal laminations (1/16"-1/4") of dark reddish-brown (10R 3/4) sand-sized particles, above this the unit is banded with 1"-3" zones that are thinly laminated within zones that are massively bedded and 1'- 2' thick; unit becomes more massively bedded up section and thinly laminated zones are less abundant; weathers moderate reddish-orange (10R 6/6), forms a step-like cliff and is well exposed.

118.8'

2) Silty sandstone, grayish orange-pink (5Yr 7/2), fine-grained to medium-grained, (fu-ml), subangular to rounded, moderately-sorted, micaceous, silt-sized particles sprinkled throughout, thinly to thickly laminated, color laminations 1/16"-1/4", are moderate reddish-brown (10R 3/4), calcite cement, moderately well-cemented; wedge-planar cross-beds up to 1'8" thick, foresets are thinly laminated, straight and dip at low angles; bulk of

unit is horizontally bedded; weathers moderate reddish-brown (10R 3/4), forms a blocky-cliff that is well exposed (locally fissile beds form an earthy slope).

20.1'

1) Sandstone, grayish orange-pink (5YR 7/2) to moderate orange-pink (10R 7/4), fine-grained to medium-grained (fu-ml), subangular to subrounded, moderately well-sorted; calcite cement, moderately cemented; thinly to thickly laminated, laminations,1/16"-1/8", of dark reddish-brown (10R 3/4) silty material are present; minor wedge-planar cross-beds in sets up to 2", foresets are thinly cross-bedded, straight, dip at low angles, cross-sets are vertically stacked thick; sprinkled with opaques and chlorite (<1%); unit becomes more moderate reddish-pink up section and weathers darker up section; weathers light brownish-gray (5TR 6/1) to moderate orange-pink (10R 7/2); forms step-like cliff (locally fissile) that is well exposed.

35.6'

Total measured thickness of the Kayenta 217.4'

Measured section of Navajo Formation (incomplete)
by M. Goydas [7/6/87]
SW1/4, NW1/4, sec. 30, T. 25 S., R 25 E.
section #5

4) Sandstone, moderate orange-pink (5YR 8/4) to moderate reddish-orange (10R 6/6), fine grained, subrounded to well rounded, very well-sorted, equant grains: sprinkled with opaques, angular rod shaped accessory grains (<<1%), zones of abundant opaques (up to 15% opaques), zones are less than 1' thick; unit is thinnly laminated to massively bedded. Sweeping crossbeds up to 15' in amplitude; medium - to large-scale trough sets, sets are slightly plunging; foreset strata are thickly laminated to thinnly bedded, concave upward and dip up to 30°; weathers moderate orange-pink (19R 7/4) to pale red (10R 6/2), forms smooth rounded cliff, very well exposed, incomplete section

155.6'

3) Sandstone, reddish-brown (10R 3/4), fine-grained, subangular to subrounded, very well-sorted, equant grains, calcareous, thinnly bedded; beds (1/2" - 4" thick) of very light gray (N8) sandstone (lithology and texture is identical to main body of the unit), no recognizable cross bedding; weathers same as fresh, forms recess, well exposed.

1.7'

2) Sandstone, very pale-orange (10R 8/2) to moderate orange-pink (5YR 8/4), fine grained, subrounded to well rounded, very well-sorted, equant grains; 60-70% of the grains are polished, 20% frosted; shericity and the amount of polished grains increases upwards, dark accessory minerals (<1%); thinnly laminated to thickly bedded, rare thin color laminations (iron stained grains and opaques), cement is most likely a mixture of SiO_2 and $CaCO_3$; wedge-planar cosets up to 2' in height; unit weathers light gray (N8) to moderate reddish-orange (10R 6/6), forms rounded-step and ledge (locally smooth cliff), very well xposed.

42.2'

1) Sandstone, very-light gray (N8), fine-grained, subangular, very well rounded, very well-sorted, 20% of the grains are polished, a small population of the larger grains are frosted; calcareous, moderately-cemented, locally friable; minor dark grains (opaques) <<1%, angular chert fragments <<1%, unit is speckled with olive-brown (5YR 5/6) lenses (lenses of dark grains), base of unit is thinnly laminated, top is massively bedded, top beds are truncated by wedge-shaped crossbeds of unit 2; unit is transitional with the underlying Kayenta Formation, the upper 56' of the unit is similar in composition

to the underlying Kayenta but its bed forms (large trough and wedge-planar cross-beds) are more like the overlying Navajo. This unit appears to be reworked Kayenta material, weathers same as fresh, forms a rough slope and is moderately well exposed; weathers ligt grey (N7) to moderate reddish-orange (10R 6/6), reddish-brown staining, weathers as a rounded step, well exposed.

64.9'

Total measured (incomplete) thickness of the Navajo Formation 264.4'

Measured section of Dewey Bridge Member of the Entrada Sandstone
by M. Goydas [6/23/87]
SW1/4, sec. 34, T. 24 S., R. 25 E.
section #6

4) Covered slope; from float and hand-dug trenches unit appears similar to underlying sandstone.

2.0'

3) Sandstone, moderate-reddish-orange (10R 6/6), very fine-grained, subangular to subrounded, well-sorted; a fining upward sequence evident, but subtle (as a result the top of the unit is very well-sorted); rare laminae of dark reddish-brown (10R 4/6) silt interstratified; unit is sprinkled with opaque minerals, with some zones containing as much as 8-10% (visual estimate); forms rounded- cliff, poorly exposed.

11.7'

2) Sandstone, moderate-reddish-brown (10R 4/6), very fine-grained, subangular to subrounded, well-sorted; calcite cement, well cemented; opaque minerals and chert fragments evident (more abundant than in unit 2 but less abundant than in unit 4); thinly laminated to thinly bedded; weathers same as fresh, forms an earthy slope between unit 2 and 4, very poorly exposed.

8.6'

1) Sandstone, moderate-reddish-brown (10R 4/6), very fine- to medium-grained, subangular to subrounded, moderately sorted; dominant fine grains with sparse medium grains throughout, chert fragments (0.05"-0.3"), abundance of opaque minerals present in upper half; massively bedded; calcite cement, well cemented; weathers same as fresh, stains pale-reddish brown (10R 4/6), bleaching causes grayish-pink (5R 8/2) color zones, forms poorly- exposed rough slope.

26.7'

Total measured thickness of the Dewey Bridge Member 49.0'

Measured section of Dewey Bridge Member of Entrada Sandstone
by M. Goydas, [6/29/87]
SE1/4, sec. 6, T. 24 S., R. 25 E.
section #7

4) Sandstone, light gray (N8), very fine-grained to fine-grained subangular to subrounded, well-sorted: trace of opaque minerals, calcareous, well cemented; thinly to thickly bedded, convoluted bedding, weathers moderate yellowish-brown (10YR 4/2) to brownish-gray (5YR 4/1); well exposed, forms blocky-step.

3.0'

3) Limestone, grayish-purple (5RP 4/2), argillaceous, slightly recrystallized, algal sparite, terrigenous sand grains are abundant toward the top of the unit: thinly laminated, convoluted laminations, displays flaggy to platty parting, soft sediment compaction and deformation are noticeable, moderately well exposed, forms a earthy-slope with random blocky-steps.

0.8'- 1.3'

2) Sandstone, very light-grey (N8), fine-grained to medium-grained angular to well rounded, well-sorted; calcareous, moderately well cemented (not as well cemented as unit 4), 10% of the grains are frosted, <1% polished,; yellow limonite staining speckled throuhgout; thinly to thickly bedded; weathers same as fresh; well exposed forms step-like ledge.

2.6'

1) Sandstone, moderate reddish-orange (10R 6/6), to dark reddish-brown (10 R 3/4). fine-grained to medium-grained, (fl- ml), subangular to very well rounded, coarse grains sprinkled throughout, poorly-sorted; calcareous, thickly to massively bedded; coarse grains very well rounded, (60% - 80 % frosted, 20% - 30% polished); unit fines upward, top 1/3 of unit fine-grained with rare coarse grains; weathers moderate reddish-orange at base and dark reddish-brown at top; top 1'2" of the unit mottled; top contact is very undulatory with crest to trough amplitude height as much as 15', formation thins to less than 6' in sec. 4, T. 24 S., R. 25 E.; at this location units 2, 3, and 4 are absent. Poorly exposed and forms an earthy-slope.

6.0'- 32.0'

Total measured (maximum) thickness of Dewey Bridge 38.9'

Total measured (minimum) thickness of Dewey Bridge 6.0'

Measured section of the Slickrock Member of the Entrada Sandstone
by M. Goydas [7/8/87]
SW1/4, sec. 34, T. 24 S., R. 25 E.
section #8

4) Sandstone, yellowish-light gray (N7), medium grained, subrounded to well rounded, well-sorted, equant grains, small number of grains frosted, subtle fining upward sequence evident; black accessory grains distributed throughout; massively-bedded, large-scale wedge-planar and trough cross-beds evident, but faint on weathered surfaces, wedge sets non-plunging, up to 10'high, foresets generally thickly laminated, straight to weakly concave upward, dip up to 22°; trough sets non-plunging to slightly plunging, up to 12' high, foresets thickly laminated, concave upward, tangential to lower bounding surfaces, dip up to 26°; limonite staining (yellow) noticeable on horizontal laminations;
....upper 52' measured by triangulation due to inaccessibility along the cliff face; very well exposed as smooth rounded cliff.

82.1'

3) Sandstone, very light gray (N7), medium grained with few coarse grains distributed throughout, subangular to very well rounded, well-sorted, few of larger grains frosted, opaque minerals evident throughout, poorly-cemented; cross-stratification evident in lower part (poorly preserved on weathered surfaces), wedge-planar and trough cross-beds appear to be dominant cross-stratification; remainder of the unit (upper part) horizontally-bedded; opaque minerals concentrated in horizontal laminae that display strong limonite staining
....at 6', 7' and 8' above the base of unit are 0.1' thick, moderate reddish-brown (10R 4/6) very poorly cemented and friable sandstones, composition of poorly cemented sands appears identical to surrounding sandstone, unit weathers same as fresh (except those laminae stained yellow), very well exposed in convex cliff.

54.5

2) Sandstone, moderate reddish-brown (10R 6/6), fine grained, subangular to well rounded, well-sorted; wedge-planar and trough cross-beds dominant; cross-bed sets generally small- to medium-scale, non-plunging, foresets thickly laminated, straight to weakly concave upward, dip at low angles, foreset strata can be traced laterally more than 40', coarse sand locally found in lens-shaped deposits at base of trough cross-beds; unit weathers same as fresh, very well exposed in a concave-shaped cliff.
....39.5' above base of unit is a 4' thick bed of grayish-orange (10R 6/6) sandstone, appears lithologically identical

to surrounding sandstone; weathers light gray (N7) to pale red (10R 6/2)
....53' above base of unit is a 10' thick bed of interbedded moderate reddish-orange (10R 6/6) sandstone and grayish-orange (10YR 6/6) sandstone; bed is lithologically identical to surrounding sandstone.

109.0'

1) Sandstone, pale yellowish-orange (10YR 8/6), fine grained, subrounded to rounded, well-sorted; poorly to moderately cemented, friable; weathers same as fresh, forms recess below well cemented unit (2); locally unit is not found (NW1/4, sec. 21, T. 24 S., R. 25 E.); may represent local lens-shaped deposit on hummocky Dewey Bridge surface.

8.1'

Total measured thickness of the Slickrock Member 253.7'

Measured section of Moab Member (Tongue) of Entrada Sandstone
by M. Goydas, [623/87]
NW1/4, sec. 21, T. 24 S., R. 25 E.
section #9

1) Sandstone, very light-gray (N8) to grayish-orange (10YR 7/4), medium-grained, subrounded to rounded, well-sorted; massively bedded, cross-stratification evident, small-scale low angle wedge-planar and trough cross-stratification dominant type of cross-stratification, wedge-planar sets less than 2.5' high, non-plunging, foresets thinly bedded, straight (some slightly concave upward), dip less than 22°, trough sets less than 3.0' high, generally non-plunging (some cross sets plunge a few degrees), foresets thinly-bedded, concave up, (not as curved as trough foresets in Navajo Sandstone) generally longer than foresets in planar sets with dip up to 25°, cross-beds commonly truncated by horizontal bedding planes; top 3.0' of unit thinly (horizontally) bedded; well-cemented, probably mixture of silica and calcite cement, calcite fills minor fractures and joints; surface of outcrop dotted with large rounded weathering (solution) pits; unit weathers pale yellowish-brown (10YR 6/2), locally limonite-stained (yellow), very well exposed in a rounded, pitted cliff. 38.2'

Total measured thickness of the Moab Member 38.2'

Measured section of the Tidwell Member of the Morrison Formation
by M. Goydas, [6/25/87]
NE1/4, sec. 11, T. 25 S., R 25 E.
section #10

6) Interbedded sandstone, limestone and sandy siltstone. Sandstone: reddish- light-gray (N8), fine-grained, subangular to subrounded, well-sorted, very well cemented (calcite); thinly laminated to thinly bedded; weathers moderate-reddish-orange (10R 6/6). Limestone: light gray (N8), aphanitic, thinly laminated (terrigenous laminations); weathers pale moderate-reddish-orange (10R 6/6). Siltstone: moderate reddish-brown (10R 4/6) coarse siltstone to sandy siltstone, slightly micaceous, calcareous; thinly laminated to thinly bedded; weathers same as fresh. Total unit composed of approximately 50% sandstone, 35% limestone, and 15% siltstone. Base of unit (sandstone) forms step-like blocks and well exposed; limestone and sandstone outcrops form step-like ledges. Siltstone forms smooth-slope and poorly exposed. Contact with overlying Salt Wash conformable, gradational, hard to discern.

49.1'

5) Limestone interbedded with sandstone. Limestone: light-gray (N8), aphanitic; thinly laminated (some laminations appear algal (stromatolitic), others are clearly terriginous films); beds 5" to 2' thick; weathers same as fresh though locally stained moderate reddish-orange (10R 6/6). Sandstone: moderate reddish-orange (10R 6/6), fine-grained, subangular to subrounded, well-sorted; occurs as thin stringers in dominant limestone; weathers same as fresh. Unit forms rough ledges and well exposed, though locally covered by debris from overlying unit.

8.0'

4) Sandstone, moderate reddish-orange (10R 6/6), fine- to medium-grained, subangular to subrounded, moderately sorted; mica flakes sprinkled throughout; base massively bedded, very micaceous; upper 3/4's cleaner sandstone, thickly laminated to thinly bedded; weathers same as fresh though yellow (limonite) staining evident locally; base forms a "pillow-like" exposure; upper 3/4's forms moderately well exposed blocky cliff.

13.0'

3) Covered slope; from float debris and hand-dug trenches lithology appears to be interbedded sandstone and siltstone: Sandstone; identical to unit 2. Siltstone: dark-reddish-brown (10R 32/4); moderately well cemented, calcareous. Siltstone appears more abundant toward top of the unit. Unit forms an earthy-slope.

5.6'

2) Sandstone, very light-gray (N8), fine-grained, subrounded to well rounded, well-sorted; indistinctly bedded, strong surface weathering masks stratification; base poorly cemented (calcite) and friable, becomes better cemented up section; opaque minerals sprinkled throughout; yellow (limonite) staining is evident but local, several bands (3"-6" thick) iron stained moderate reddish-brown (10R4/6); base (friable zone) weathers same as fresh, remainder of unit weathers moderate-reddish-orange(10R 6/6), forms poorly exposed blocky surface. exposed.

12.3'

1) Sandy siltstone, moderate reddish-brown (10R 4/6), indistinctly bedded (masked by very strong surface weathering); poorly to moderately cemented (calcite); weathers same as fresh with bands and lenses of very-pale-green (10G 8/2); bedded nodular calcareous lenses weather from base; lenses consist of: medium-grained, subangular to subrounded, well-sorted sand grains floating (matrix supported) in aphanitc carbonate matrix; clean spar calcite fills fractures in lenses. Unit weathers same as fresh, forms very poorly exposed earthy-slope; contact with underlying Moab Member sharp.

23.1'

Total measured thickness of the Tidwell Member 111.1'

Measured section of Tidwell Member of the Morrison Formation
by M. Goydas, [6/23/87]
NW1/4, sec. 21, T. 24 S., R. 25 E.
section #11

5) Covered slope; from float unit appears to be sandy siltstone, moderate-reddish-brown (10R 4/6), weathers same as fresh, sharp contact with overlying Salt Wash Member.

47.0'

4) Sandstone interbedded with siltstone. Sandstone: (lower 1.5') yellowish-gray (5Y 8/1), fine-grained, subangular to subrounded, well-sorted, equant grains; grades up into clean sandstone, (upper 8.9') Light-gray (N7), fine- to medium-grained, subangular to subrounded, moderately well-sorted, very few accessory minerals, fewer dark grains than in unit 4: base massively bedded, grades up into thickly laminated to thinly bedded sandstone; calcite cemented, moderate to poorly cemented. Siltstone: moderate-reddish-brown (10R 4/6), calcite cemented, calcite vein fillings, occurs as bands within sandstone; weathers same as fresh; Sandstone well exposed as blocky step-like cliff (base well exposed, top less well exposed), siltstone forms poorly-exposed slope.

10.3'

3) Siltstone, moderate-reddish-brown (10R 4/6), thick to massively bedded?, strong surface weathering tends to mask stratification, very calcareous, very poorly cemented, calcite vein fillings, weathers same as fresh, very poorly exposed as earthy slope.

2.3'

2) Sandstone, yellowish-gray (5Y 8/1), to moderate yellowish-brown (10R 5/4), very fine- to fine-grained, subangular to subrounded, moderately well-sorted; stratification masked by severe surface weathering; silt stringers in thin laminations, dark opaque accessory minerals sprinkled throughout, calcareous, weathers moderate yellowish-brown (10R 4/6), well exposed as a blocky step-like cliff.

2.9'

1) Siltstone, moderate-reddish-brown (10R 4/6), sprinkled with fine-grained sand, calcareous, moderately well cemented, calcite vein fillings, weathers same as fresh, very poorly exposed as earthy-slope.

29.1'

Total measured thickness of the Tidwell member 91.6'

Measured section of Salt Wash Member of the Morisson Formation
by M. Goydas, [6/30/87]
NE1/4, sec. 11 and S1/2, sec. 2, T. 25 S., R. 25 E.
section #12

13) Sandstone, very light-gray (N8), medium-grained, subangular to well rounded, well-sorted; fines upward into silty fine-grained sandstone, some mica flakes, calcareous, poorly to moderately cemented, well developed cross-stratification, small-scale trough, wedge-planar and minor tabular-planar cross-beds, weathers very light-gray (N7) to moderate orange-pink (10R 7/4), minor black (N1) staining (Mg oxide), minor yellow staining (limonite); contact gradational with overlying Brushy Basin; well exposed.

24.0

12) Covered slope, appears to be interstratified sandstone, similar to unit 3 with siltstone similar to unit 10.

22.0'

11) Sandstone, grayish-pink (5R 8/2), very fine-grained, subangular to very well rounded, well-sorted, massively bedded, cross-stratification lacking, calcareous, well cemented, weathers same as fresh, well exposed as cliff.

3.5'

10) Siltstone, moderate reddish-brown (10R 4/6) to dark reddish-brown (10R 3/4) interbedded with light greenish-gray (5G 8/1) siltstone beds, 2-6" thick; both units thickly bedded; calcareous, moderately cemented; weathers same as fresh, poorly exposed on earthy-slope.

15.4'

9) Sandstone, very light-gray (N8), very fine- to fine-grained, subangular to very well rounded, well-sorted; calcite cement, well cemented; scour and fill features ubiquitous at base, small-scale, wedge-planar and trough cross-beds evident near top; cross-sets non- to slightly-plunging; foresets thickly laminated to thinly bedded, weakly concave upward, variable dip; horizontal bounding surfaces not evident, cross-sets often stacked, minor carbonaceous debris fills base of scour surfaces; weathers moderate reddish-orange (10R 6/6); well exposed in blocky-cliff.

16.8'

8) Interbedded sandstone, siltstone and mudstone, Sandstone: light gray (N8), fine-grained, subangular to subrounded, well-sorted; calcite cement, well-cemented; massive bedded to indistinct bedding with lenticular cross-bedded units; accessory minerals increase upward, successive sandstone beds thin upward, (1-3' thick, 5-8" at top); weathers same as fresh. Siltstone; moderate

reddish-brown (10R 4/6) minor sand grains sprinkled throughout, unit fines upward, sand grains rare, becomes mudstone, weathers same as fresh. Mudstone: moderate reddish-brown, bedding indistinct; soft calcareous nodules (2-3" thick, 4-7" long) are evident in upper part; mudstone dominant rock type in upper part of section, weathers same as fresh.

23.8'

7) Sandstone, very-light-gray (N8), very fine- to fine-grained, subangular to very well rounded, well-sorted; calcite cement, well cemented; scour and fill features present in lower part of section; well developed trough cross-beds and wedge-planar cross-beds found in middle to upper part of section; thin lenses of moderate reddish-brown siltstone; siltstones thinly laminated with pinch and swell structures, lenses undoubtedly fill troughs in underlying sandstone; weathers moderate reddish-orange (10R 6/6), well exposed in blocky-cliff.

14.9'

6) Interbedded sandstone, siltstone and mudstone, Sandstone: light gray (N8), fine- to medium-grained, subangular to subrounded, well-sorted; calcite cement, well cemented, massive to indistinctly bedded, beds thin upward (2-3' thick at base, 6-8" at top), weathers same as fresh. Siltstone: moderate reddish-brown (10R 4/6), minor sand grains, opaque minerals sprinkled throughout, minor soft sedimentation deformation (?), becomes silty mudstone upward. Mudstone: moderate reddish-brown (10R 4/6), bedding indistinct, minor sand grains and black accessory grains evident near base, weathers same as fresh. Upper 1' very calcareous, gritstone, conglomerate (probably locally derived) with pebbles up to 1" in diameter, directly below unit (7), sandstone units form well exposed ledges in a siltstone-mudstone slope.

38.4'

5) Boulder-covered slope, from float it appears unit may be similar to unit 3.

10.1'

4) Sandstone, grayish-orange pink (5YR 7/2), very fine- to medium-grained, subangular to well rounded, poorly-sorted; calcite cement, moderately well-cemented; not as friable as underlying unit (3); thinly laminated to thinly bedded, thin siltstone laminations (<0.1") moderate reddish-brown, silty, micaceous, moderately indurated, weathers same as fresh, well exposed as rounded steps.

7.0'

3) Sandstone, lower 10' moderate reddish-brown (10R 4/6), remainder very light-gray (N8); color gradational; fine- to medium-grained, subangular to subrounded, well-sorted; thin color laminations (moderate red-brown and light gray) present in lower 1/3; well

developed cross-stratification, small scale wedge-planar and trough cross-beds evident throughout upper 2/3's of section, medium-scale (up to 5'), well developed, well exposed trough cross-beds scattered throughout, cross-sets generally non-plunging, lenticular, foresets thinly bedded, concave upward with variable dip; horizontal bounding surfaces evident. Siltstone lenses (6-13" thick and 5-65" long) moderate reddish-brown (5YR 4/4) found at base of large trough crossets, generally thick bedded, silt lenses restricted to thinly bedded sandstones; above silt lenses sandstones tend to be thinly-bedded (horizontal); unit weathers pale moderate-orange-pink (10R 7/4) to light gray (N8); well exposed in blocky-cliff with rounded tops.

34.1'

2) Slope covered, from float, bottom 1/2 of unit appears to be siltstone, moderate reddish-brown (10R 4/6), upper 1/2 appears to be sandstone, very light gray (N8), fine-grained, subangular to well rounded; calcite-cemented, poorly cemented, very poorly to non-exposed

32.0'

1) Sandstone, very light gray (N8), medium-grained, subangular to well rounded, well-sorted; minor mica flakes and opaque minerals abundant, carbonate minerals less abundant; calcite-cemented, poorly to moderately well cemented, often friable; well developed cross-stratification, trough and wedge-planar cross-beds in sets up to 2' high, sets generally non-plunging, lenticular, foresets thinly bedded, weathers very light-gray (N7) to moderate orange-pink (10R 7/4); black (N1) staining (Mg oxide); clean sharp contact with underlying Tidwell Member of Morrison, well exposed as blocky-ledges with rounded tops.

11.1'

Total measured thickness of Salt Wash Member 252.9'

Measured section of Brushy Basin Member of the Morrison Formation
by M. Goydas, [6/30/87]
SE1/4, sec. 3, T. 25 S., R. 25 E.
section #13

11) Sandstone, dark yellowish-orange (10YR 6/6) to blue-white (5B 9/1) fine- to medium-grained, subrounded to very well rounded, moderately well-sorted; thinly to thickly laminated; contains pebbles and reworked mudstone clasts; calcareous, moderately cemented; beds (1/4"-3/4") of highly indurated sandstone; weathers light-brown (5YR 6/6) moderate-brown (5YR 3/4) very poorly exposed as an earthy-slope.

12.1'

10) Boulder-covered slope appears the same as unit 6.

43.7'

9) Covered slope, appears to be silty sandstone, moderate reddish-orange; fine-grained, subrounded to rounded, well-sorted.

16.1'

8) Conglomerate interstratified with coarse sandstone, grayish-red (5R 4/2) to dusky-red (5R 3/4) to moderate-brown (5YR 3/4), well rounded red, green, brown, pink quartzite, chert pebbles to 0.3', average size 0.45"; conglomerate bands 0.25'-0.7' thick; Coarse sandstone: moderate brown (5YR 3/4), coarse-grained, well rounded, poorly-sorted; thickly laminated with fine-grained pebbles (1/8-1/4") (very well-rounded); sandstones tend to be thinly laminated; low angle trough and wedge-planar cross-beds, sets small scale, non-plunging, foresets thinly bedded, straight to weakly concave upward, dip at low angles; fining upward sequence evident; top grades overlying siltstone unit; weathers dark reddish-brown (10R 4/6) to pale yellowish- orange (10YR 8/6); also occurs as float more than 700 feet below on Navajo ledges; well exposed as rounded cliff.

11.7'

7) Covered slope, from float appears to be sandy siltstone, moderate reddish-brown (10R 4/6).

58.0'

6) Boulder-covered slope, from float appears to be sandy mudstone, pale purple (5R 6/2), sand grains fine-grained, subangular to well-rounded, well-sorted, equant grains; calcareous, moderately cemented; thickly laminated to massively bedded; not feldspathic, no opaque minerals; weathers moderate reddish-orange (10R 6/6) stains medium-gray (N5).

184.9'

5) Covered slope, from float appears same as unit 4.

25.0'

4) Sandstone, very-light-gray (N8), fine-grained, subangular to rounded, well-sorted, equant grains, feldspar grains, thin laminations of opaque minerals, minor reworked mudstones; weathers light gray (N7), upper 1' stains dark gray (N3), very poorly exposed.

4.8'

3) Covered slope, from float appears to silty mudstone interstratified with sandstone similar to unit 2.

35.9'

2) Sandstone, very light-gray (N8), fine-grained, subangular to rounded, well-sorted, equant grains, minor opaque minerals and feldspar, reworked mudstone clasts, clasts angular, up to 0.2" in diameter, clasts light gray (N7); unit weathers grayish-orange-pink (10R 6/2) to pale red (10R 6/2), poorly exposed as step (blocky ledge) in earthy slope.

1.7'

1) Sandy siltstone to mudstone, moderate reddish-brown (10R 4/6) to grayish-purple (5P 8/2) beds of very light gray (N8) to very pale green (10G 8/2); calcareous, moderately cemented; feldspar and minor opaque minerals (<5%); some beds friable and poorly indurated; weathers same as fresh, very poorly exposed as earth slope.

14.5'

Total measured thickness of the Brushy Basin Member 408.4'

Measured section of Burro Canyon Formation
by M. Goydas [6/26/87]
SE1/4, sec. 3, T. 25 S., R. 25 E.
section #14

1) Sandstone, pale yellowish-orange (10YR 8/2) to light greenish-gray (5G 8/1), fine-grained, subrounded to wellrounded, well-sorted, equant grains; feldspathic (as much as 10% ? of rock), angular chert fragments sprinkled throughout; calcareous, well-cemented, thinly to massively bedded, cross-stratification abundant, small-scale, low angle wedge-planar and trough cross-stratification dominant, planar and trough sets slightly plunging, less than 1.6 feet high, planar and trough foresets thinly bedded, slightly concave to concave upward, (trough foresets are generally concave upward and commonly tangential to lower bounding surfaces), dip at low angles (less than 22°); upper surface weathers into a hummocky surface, with 0.7'-1.0'(diameter) pitted holes, lower contact (with Brushy Basin) sharp; unit weathers moderate-orange-pink (10R 7/4) to moderate-reddish-brown (10R 4/6), toward base, limonite (yellow) staining occurs in thin laminations, unit very well exposed in a rough, jointed cliff above slope-forming Brushy Basin Member, very well exposed.

56.6'

Total measured thickness of the Burro Canyon Formation 56.6'

STRATIGRAPHY, STRUCTURE, AND HALOKINETIC HISTORY OF FISHER VALLEY QUADRANGLE, GRAND COUNTY, UTAH

by

Michael J. Goydas

B. S., Queens College, City University of New York, 1986

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

Kansas State University
Manhattan, Kansas

1989

ABSTRACT

This report is based on detailed geologic mapping of the Fisher Valley quadrangle (1:24,000) on the northeast edge of the Paradox Basin fold and fault belt, east-central Utah. Fisher Valley is the collapsed crest of a long northwest-trending anticline cored by salt of the Pennslyvanian Paradox Formation. Surrounding uplands consist of eolian, fluvial, lacustrine, and shallow marine sedimentary rocks of Permian through Cretaceous age. Pliocene and Quaternary units are the only rocks deposited since the Early Cretaceous that have not been subsequently eroded.

Initial growth of the Fisher Valley anticline at the end of the Pennsylvanian was caused by lateral flowage of salt of the Paradox Formation from areas adjacent to the anticline. Contemporaneous deformation and movement of the evaporites along the anticlinal crest resulted in local thinning of Permian through Jurassic clastic sediments over the rising salt. Sagers Wash syncline and other so-called folded syncline pairs in the region are post-Early Cretaceous features. These structures may not be related to Laramide deformation as others have suggested but may be due to local contemporaneous sediment loading and salt flowage away from syncline basinal areas. Salt may have flowed into anticlinal regions where active dissolution, salt removal, and collapse were occurring and may also be responsible for the growth of local salt diapirs.

Evidence for halokinesis within the Fisher Valley quadrangle includes: 1) interformational unconformities in Mesozoic rocks

(Cutler/Moenkopi, Moenkopi/Chinle, Chinle/Wingate), 2) numerous intraformational unconformities, and 3) syn-depositional folding (lower Moenkopi and Chinle Formations). In addition, dissolution on a regional scale is inferred to have been responsible for the formation of the Cottonwood graben, near the center of the quadrangle. Abundant evidence suggests prolonged upward movement and dissolution of a previously unrecognized salt diapir (here informally termed the Cottonwood diapir) within the Fisher Valley quadrangle. The Cottonwood diapir is covered by collapsed and faulted rocks of overlying formations and thick eolian and alluvial Quaternary sediments.

The Cottonwood diapir is considered analogous to the Onion Creek salt diapir, which is situated 3 mi northwest on the same anticlinal crest. The main difference between these two salt masses is their Cenozoic history. The Onion Creek diapir has been active throughout the Quaternary with upward movement as recent as 250,000 yr B.P.. However, upward movement of the Cottonwood diapir was continuous throughout the Triassic and Jurassic ?, with subsequent dissolution and collapse during the Cenozoic.

Collapse of Fisher Valley and the Cottonwood graben was controlled by dissolution of Paradox Formation salt. Dissolution was facilitated by erosion and removal of confining layers, canyon cutting, ground-water circulation along collapse-induced fractures, and incision of the Colorado River, which crosses the anticline.

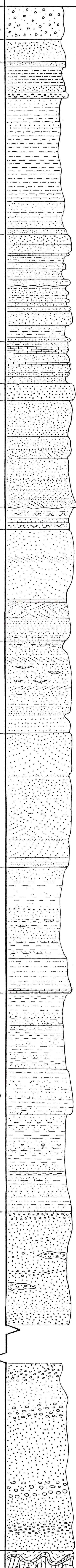
GEOLOGIC MAP OF THE FISHER VALLEY QUADRANGLE
GRAND COUNTY, UTAH
by
MICHAEL J. GOYDAS

Plate I

Plate 2

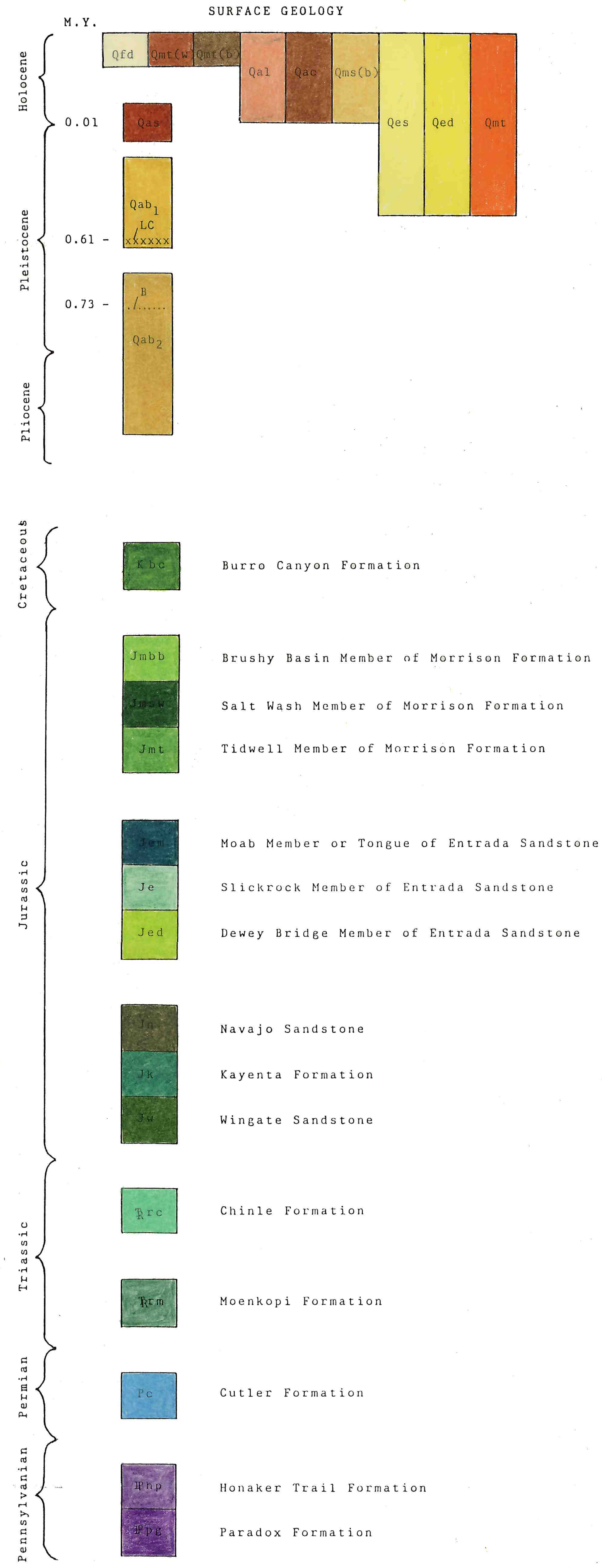
FORMATION		SYMBOL	THICKNESS feet (meters)
Unconsolidated deposits		Q	0-508 (0-155)
Burro Canyon		Kbc	56 (17)
MORRISON FORMATION	Brushy Basin Member	Jmbb	408 (124)
	Salt Wash Member	Jmsw	252 (77)
	Tidwell Member	Jmt	111 (34)
ENTRADA SANDSTONE	Moab Tongue	Jem	38 (12)
	Slickrock Member	Je	254 (77)
	Dewey Bridge Member	Jed	49 (15)
Navajo Sandstone		Jn	264 (80)
Kayenta Formation		Jk	217 (66)
Wingate Sandstone		Jw	315 (96)
Chinle Formation		₮c	294 (90)
Moenkopi Formation		₮m	514 (157)
Cutler Formation		Pc	3048 (929)
Paradox Formation		IPpg	150 (46)

LITHOLOGY



C O R R E L A T I O N   O F   M A P   U N I T S

SURFACE GEOLOGY



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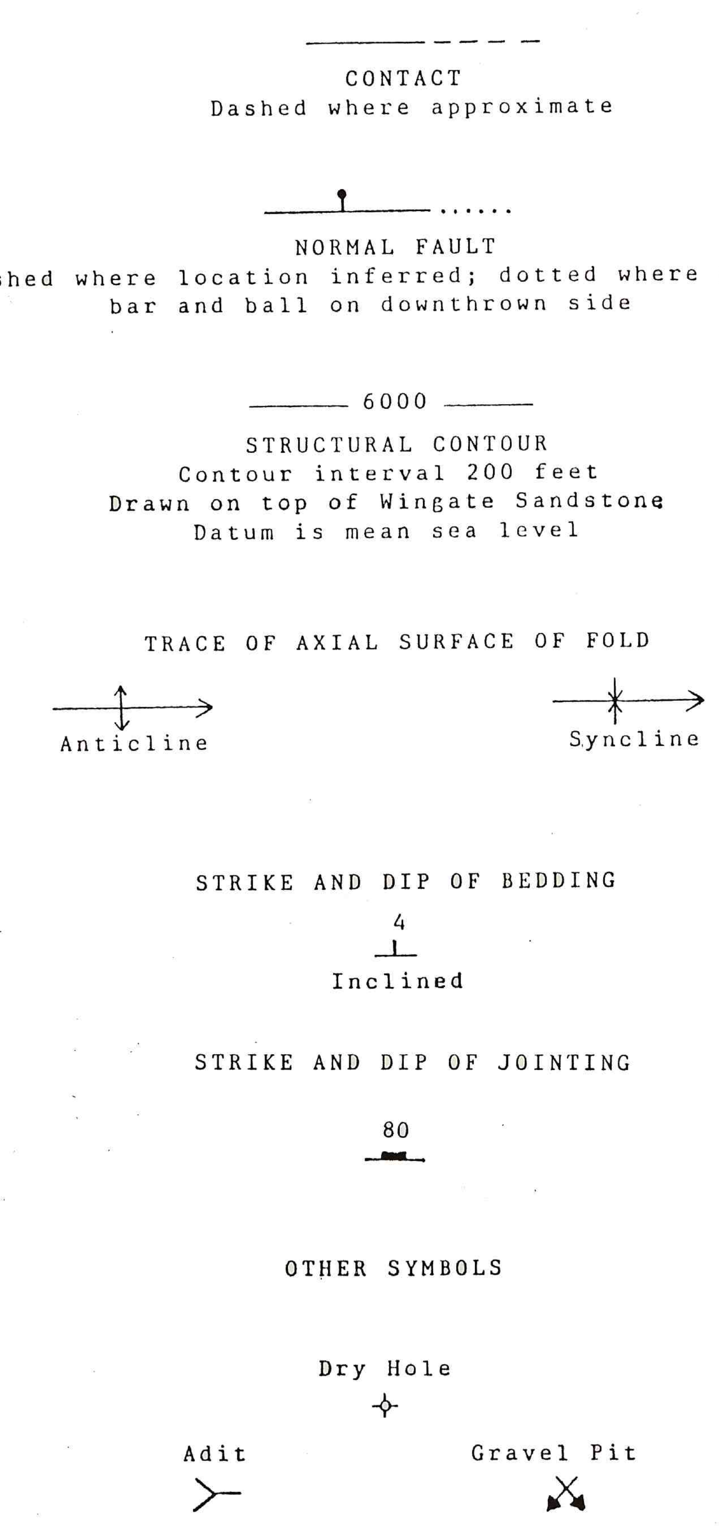

CONTACT
Dashed where approximate

NORMAL FAULT
Dashed where location inferred; dotted where covered; bar and ball on downthrown side

6000

STRUCTURAL CONTOUR
Contour interval 200 feet
Drawn on top of Wingate Sandstone
Datum is mean sea level

TRACE OF AXIAL SURFACE OF FOLD

Anticline   Syncline

STRIKE AND DIP OF BEDDING

4

Inclined

STRIKE AND DIP OF JOINTING

80

OTHER SYMBOLS

Dry Hole

Adit   Gravel Pit

D E S C R I P T I O N   O F   M A P   U N I T S

Surface Geology

Qfd — Man-made fill-
Mine dump debris, restricted to Polar Mesa

Qmt(w) — Talus deposits-Mostly rockfall boulders and smaller angular fragments of Wingate material lying on Chinle and Moenkopi slopes.

Qmt(b) — Talus deposits-Mostly rockfall boulders of Brushy Basin material lying on Salt Wash and Tidwell slopes and Navajo bench.

Qal — Alluvium-Thickly to thinly bedded, fine to coarse sand, and minor subangular to subround gravel mixed with varying amounts of colluvial and eolian deposits (2-25 ft thick).

Qac — Colluvium-Angular, poorly sorted slope deposits mixed with varying amounts of alluvial and eolian deposits.

Qms(b) — Landslide deposit-Poorly sorted debris deposited by mass movement on slopes. Primarily involves Brushy Basin material.

Qmt — Talus deposit-Rockfall blocks, boulders, and smaller angular fragments lying on slope immediately below the parent outcrop. Mapped only where 90% of underlying unit is covered.

Qas — Alluvial sand-Thickly to thinly bedded, silt and fine to coarse sand, contains laminated beds with carbonaceous debris.

Qes — Eolian sand sheet deposit-Unstratified, non-indurated fine sand and coarse silt. Mantles floor of Fisher Valley and caps dipslopes (1-30 ft thick).

Qed — Eolian sand dune deposit--Unstratified, non-indurated fine sand in dune morphology. Restricted to the edge of bluffs near Onion Creek.

Qab_1 — Upper basin-fill deposit-Massive to medium-bedded, moderately indurated sand, minor lenses of fine to medium, matrix- and clast-supported subangular to subround gravel. Unit contains considerable cross-bedded fluvial sand and gravel and massive eolian sand. Angular unconformity separates upper and lower basin-fill units. Lava Creek ash occurs locally at the base of the unit.

LC — Lava Creek Ash-Very light gray to white ash fall deposit as much as 3.5 ft thick, 0.61 m.y. old (Izett,1981)

Qab_2 — Lower basin-fill deposit-Thickly to thinly bedded, fine to coarse sand, strongly indurated. Toward edges of basin unit is composed predominantly of subround matrix-supported gravel. Unit contains at least three buried soils, the Bishop ash, and several angular unconformities.

B — Bishop Ash-White to reddish-gray ash fall and flow deposit. Basal part of unit is massive ash fall deposit, upper part of unit consists of thinly cross-bedded ash flow deposit. Occurs locally about 85 ft below the top of lower basin-fill unit (Qab1) as much as 5.5 ft thick, 0.73 m.y. old (Izett, 1981).

Kbc — Burro Canyon Formation-Pale yellowish-orange to greenish-gray, cliff-forming, cross-bedded, fine-grained quartzose sandstone.

Jmbb — Brushy Basin Member of Morrison Formation-Purple reddish-gray variegated slope-forming mudstone and muddy siltstone with thin ledges of sandstone and conglomeratic sandstone containing varicolored chert.

Jmsw — Salt Wash Member of Morrison Formation-Very light gray to grayish-pink, ledge forming, very fine- to medium-grained, cross-bedded lenticular sandstone interbedded with moderate reddish-brown slope-forming mudstone and siltstone.

Jmt — Tidwell Member of Morrison Formation-Moderate reddish-brown to light gray slope forming silty mudstone interbedded with light yellowish-gray slope-forming fine-grained sandstone and light gray ledge-forming limestone.

Jem — Moab Member or Tongue-Very light gray, rounded cliff-forming, medium-grained quartzose sandstone.

Je — Slickrock Member of Morrison Formation-Reddish-orange to light yellowish gray, rounded cliff-forming fine-grained, cross-bedded quartzose sandstone, massive often covered with self-derived Holocene sand.

Jed — Dewey Bridge Member of Morrison Formation-Moderate reddish-orange, slope-forming, horizontally bedded fine-grained sandstone with local light gray limestone beds. Exhibits contorted bedding which affects the lower part of the Slickrock Member above. Formerly known as Carmel Formation (0-49 ft thick).

Jn — Navajo Sandstone-Yellowish-gray, cliff-forming fine- to medium-grained, cross-bedded eolian quartzose sandstones. Forms domes and rounded knolls on Kayenta Dipslopes. Contains local thin, hard, gray chert bearing limestone beds.

Jk — Kayenta Formation-Grayish-red ledge-forming fine- to medium-grained, irregularly bedded sandstone with subordinate intraformational conglomerate and siltstone units. Forms thick step like ledges between the more massive Navajo and Wingate Formations.

Jw — Wingate Sandstone-Moderate reddish-orange, massive cliff-forming, fine-grained, very well-sorted cross-bedded eolian quartz sandstone.

₮c — Chinle Formation-Moderate reddish orange, slope-forming, very fine-grained sandstone to siltstone with a basal gray discontinuous limestone bed. Exhibits local angular unconformities (294-315 ft thick).

₮m — Moenkopi Formation-Brown, slope-forming thinly laminated siltstone, very fine- to fine-grained sandstone and minor conglomerate lenses. Sandstones are ripple-marked. Exhibits local angular unconformities (510-555 ft thick).

Pc — Cutler Formation-Pale reddish-purple, fine- to medium-grained arkosic sandstone and pale reddish-brown granule- to cobble-conglomerate. Exhibits local angular unconformities.

IPhp — Honaker Trail Formation-Not exposed in Fisher Valley

IPpg — Paradox Formation-Mostly light gray contorted gypsum with interbeds of black silty shale, light brownish-gray sandstone and limestone.

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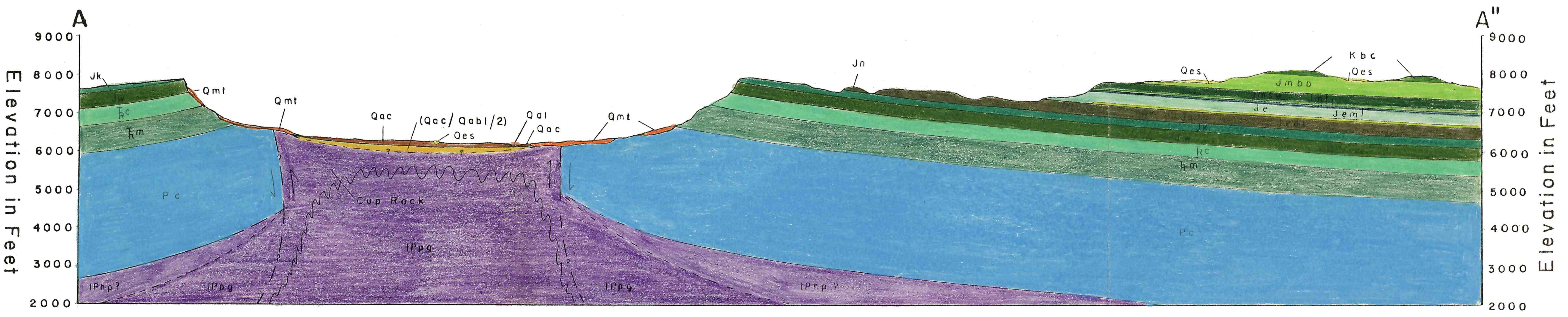
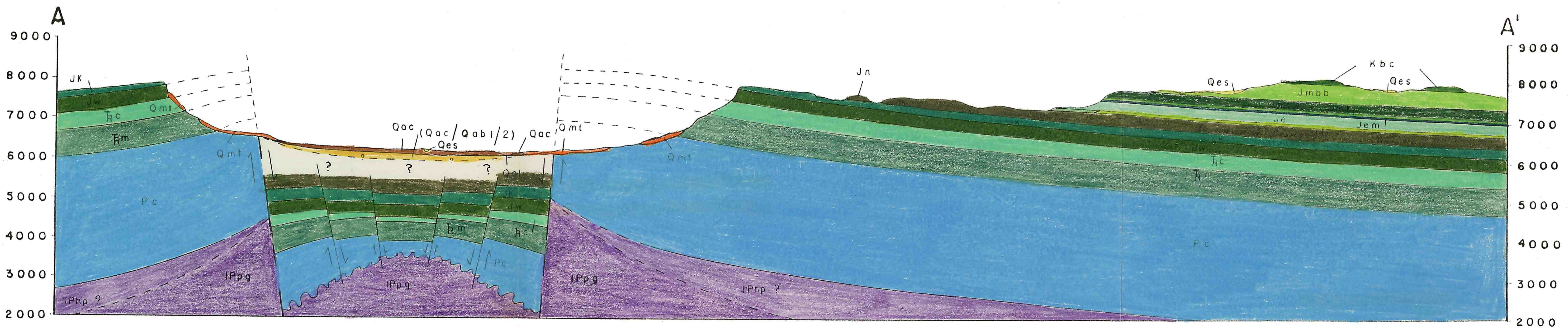
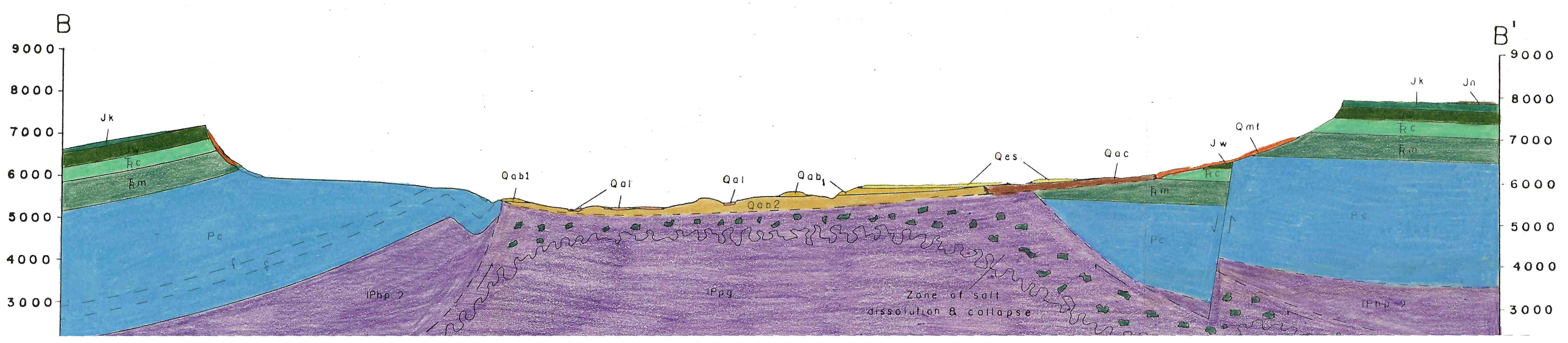
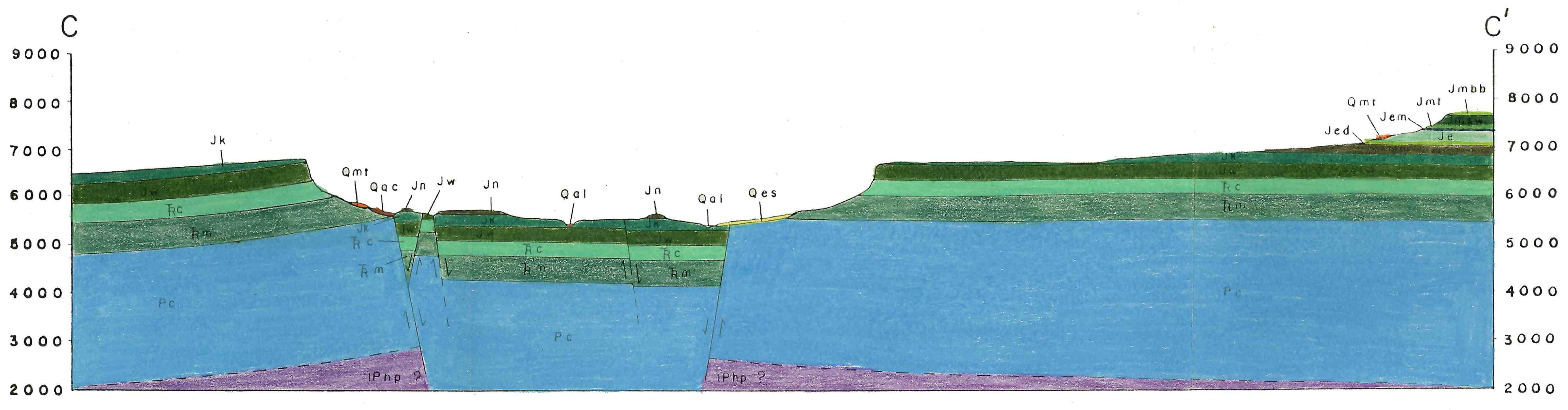
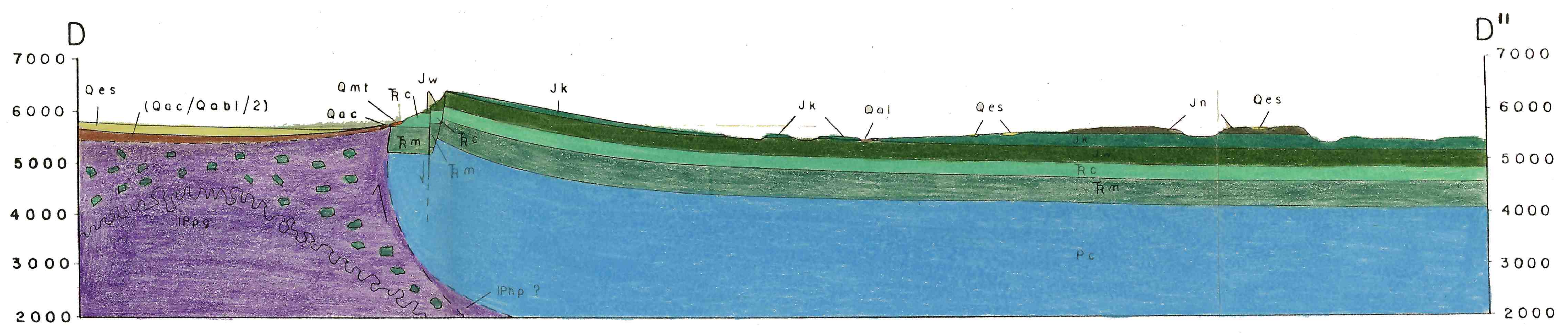
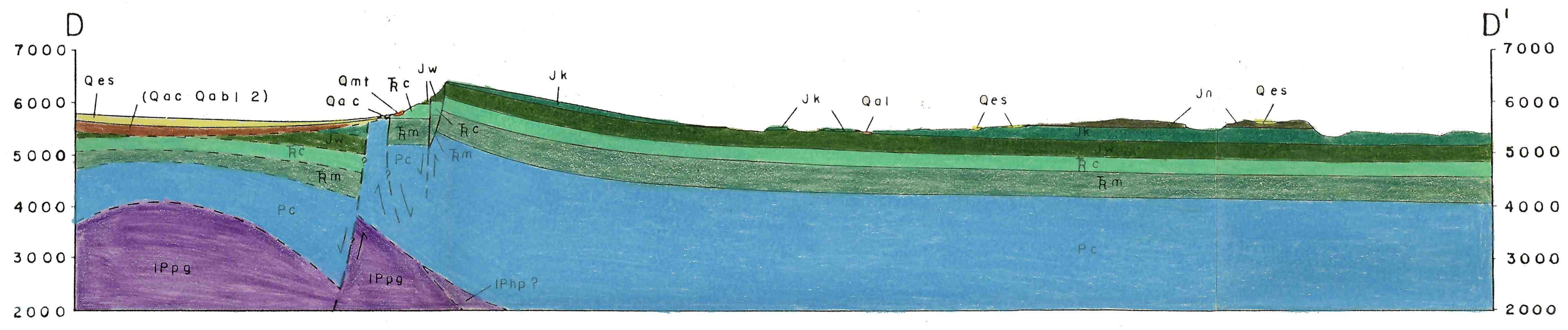




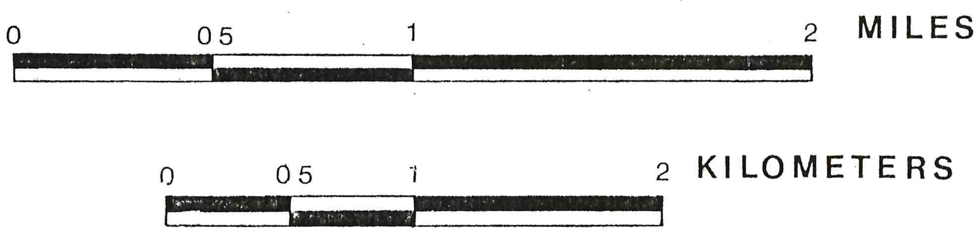








SCALE



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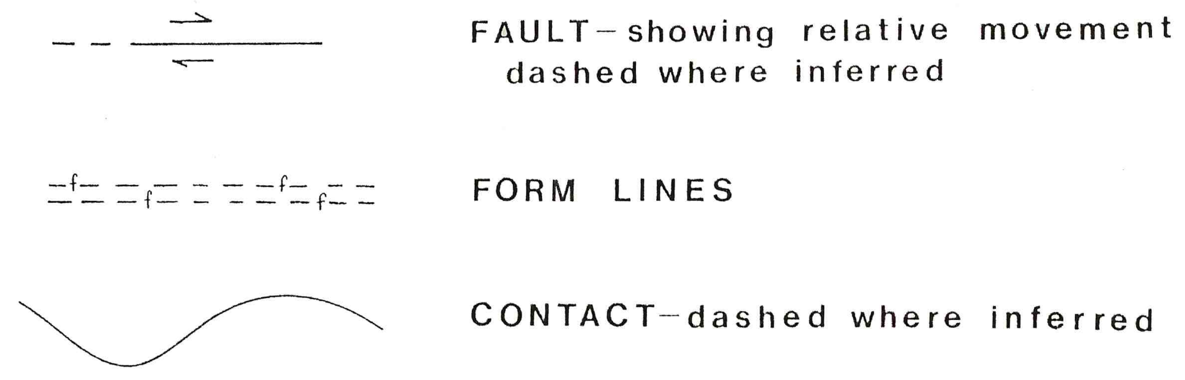

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