TM-123

UNITED STATES ATOMIC ENERGY COMMISSION
GRAND JUNCTION OPERATIONS OFFICE
GEOLOGIC BRANCH

FRACTURING IN THE SAN RAFAEL SWELL, EMERY COUNTY, UTAH

by

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May 15, 1957

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ABSTRACT

A ground check of faults and joints in the San Rafael Swell was made, supplemented by use of photogeologic maps, aerial observations in some areas, and study of lineations on aerial photographs. Fault and joint trends, direction of fault displacements, and in some instances the amount of displacement, were mapped.

Normal gravity faults, grabens and horsts are predominant, and appear to be divisible into five areal sectors of distinctive characteristics. Some fault traces can be followed up through the stratigraphic section through the Carmel formation and into the Entrada sandstone. Major faults displacing the Cretaceous formations south of Green River, Utah, do not appear to be related to any major fault system in the San Rafael Swell, though a few cut into the beds on the flank of the Swell. There is at present only limited evidence of local horizontal thrust faulting.

Most joints are normal to the bedding, but in the steeply-dipping east flank there are also a few nearly vertical joints, oblique to the tilted bedding. The major joint trends along the east flank do not appear to be related to the general form of the Swell.

Ore bodies in the Swell are both offset by faults and found along faults. Ore bodies at Temple Mountain are elongate along major fracture trends.

INTRODUCTION

Purpose and Scope of the Fracture Study

This study of fractures inthe San Rafael Swell was started in conjunction with the study of the structure of the Colorado Plateau by V. C. Kelley, under contract with the Atomic Energy Commission. Faults and joints, as observed on the ground, were plotted on aerial photograph mosaics. Additional prominent lineations, appearing on the photographic mosaics, were added to the map to indicate probable other fractures, or extensions of faults observed on the ground. Later the scope of the study was expanded to determine the relation of fractures to the known ore bodies. Time was sufficient for only a brief field examination of a large percentage of the faults, and a smaller percentage of the joints.

Location

The San Rafael Swell is a breached anticline in southeastern Utah (fig. 1), bounded on the east by the Green River and San Rafael River deserts, on the south by the Henry Mountains basin, on the west by Castle Valley, and on the north by the Book Cliffs.

The area within the high cliffs of the breached anticline is approximately 60 miles long and 30 miles wide, but the structural influence of the uplift extends much farther outward.

Accessibility

The breached central portion of the San Rafael Swell is accessible by traveling 4 miles west from Green River, Utah, on U. S. Highway No. 6-50, thence south 32 miles on Utah State Highway No. 24 to the Temple Mountain turnoff, then turning right (west) and traveling 7 miles to South Temple Wash, along which the access road crosses the easterly dipping outcrops on the east flank of the Swell. From South Temple Wash a large part of the interior of the Swell is accessible over mine access and grazing service roads. The interior is also accessible from the north through Buckhorn Wash from the Castledale-Woodside Dome road, and in dry weather it is accessible from the south through the Muddy River Canyon from Utah State Highway No. 24 between Hanksville and Torrey. Many washes and canyons provide access to roadless areas. The east flank can be reached from Utah State Highway No. 24 over mine access and grazing service roads, the south flank is accessible from a mine access road that follows the curve of the Swell, limited access to the southern nose and the western flank may be found over primitive roads, and the northern nose may be reached from the Castledale-Woodside road. Four wheel drive vehicles and reserve supplies are necessary to provide against road hazards and seasonal conditions.

Physiography

The San Rafael Swell is a breached anticline with many washes and canyons, some developed along faults but others exhibiting dendritic erosion patterns. Remnants of the Triassic Moenkopi, Chinle and Wingate formations form steep sided buttes and mesas (fig. 2). Wide flats and valleys, many developed on the Sinbad limestone member of the Moenkopi formation, occupy the crest of the Swell. The flanks of the Swell are cut by sheer-walled canyons that expose formations from the Jurassic San Rafael group down through the section to the Permian Coconino sandstone.

The Black Box Canyon of the San Rafael Swell, in which the Pennsylvanian Hermosa limestone is exposed, is 1,500 feet deep.

STRATIGRAPHY

Sedimentary rocks exposed in the Swell range from the Pennsylvanian Hermosa formation to the Lower Cretaceous Cedar Mountain formation. The formations included in the fracture study are described and illustrated in figure 3.

GENERAL STRUCTURE

The San Rafael Swell is an asymmetrical, breached anticline trending N 60 E through the southern two-thirds of its length and N 15 E through the northern one-third. The general structure is shown on figure 2, which is reduced from U. S. Geological Survey photogeologic maps, with minor corrections. The folding and uplift is evident for several miles outward from the cliffs formed by the breached crest of the anticline. The anticline dies out to the north beneath the gently dipping Cretaceous formations in the Book Cliffs. The steeply dipping beds on the eastern flank disappear beneath eroded Jurassic beds in the San Rafael and Green River deserts. The dipping beds on the southern nose can be traced to the edge of the Henry Mountains Basin. The western flank dips gently toward the Wasatch Plateau. The Farnham and Woodside domes and other minor structures are found on the flanks.

The axial trend of the anticline is not continuous throughout its length (fig. 2). The dominant trend is approximately N 15 E with segments of the axis lying en echelon to the south and west from the northernmost segment. In the northern half of the Swell the axis lies nearer the steep eastern flank and trends N 15 E, approximately parallel to the eastern flank. In the southern half the axis makes a 55 degree turn to the southwest and then turns 55 degrees to the southeast to resume the N 15 E trend. This portion of the axial trace is indefinitely located on the U. S. Geological Survey photogeologic maps. Another segment continues the axis, beginning west of the northern segment, down the southern nose of the fold on a N 5 E trend. Several minor folds lie along the crest and the western flank, some parallel and others transverse to the axial trend. A few minor folds lie parallel to the strike of the beds on the eastern flank.

STRUCTURAL HISTORY

The San Rafael Swell is believed to have been formed by a combination of vertical uplift due to shifts in the basement rocks, and horizontal compressional forces caused by readjustment of the earth's crust. Spieker (1954) has concluded that a number of similar structures in south central Utah were formed during the same period. In a summary of diastrophic history of the Wasatch Plateau, he has listed a series of crustal movements beginning in the late Jurassic and continuing sporadically through the Tertiary into the Pleistocene of the Quaternary, showing movement was present over a long period in south central Utah (Spieker, 1949).

The largest fault at Tomsich Mountain was traced west into the Tertiary beds and its trace was followed by aerial reconnaissance into the Jurassic Entrada sandstone and into the Curtis formation where it appears to terminate. Other faults in the main part of the Swell cannot be traced higher in the section than the Carmel or Curtis formations. Faults that displace Jurassic and Cretaceous beds east of the San Rafael Swell do not appear to be related to any major fault system cutting across the anticline. Some younger faults do displace the folded flanks of the Swell. The age of the major faults in the San Rafael Swell appears to be pre-late Curtis and definitely pre-Summerville. A study of the Tertiary dikes and terrace gravels may give some indication of the age of some of the faults west of the San Rafael Swell.

Young (1955) described a disconformity between the Price River and Black Hawk formations in the Book Cliffs to the north, and Abbott and Liscomb (1956) described a thinning of the Price River and Black Hawk formations which indicates that uplift of the Swell continued for a long period or was resumed in the late Cretaceous time. Hunt (1953) dates the formation of the Henry Mountain Basin to the south as late Cretaceous, by the deposition of the Wasatch formation across a portion of the Water Pocket Fold near Thousand Lake Mountain.

FAULTS

Faults in the San Rafael Swell appear to be divisible into five sectors, distinguished by different angular relationships (see sectors I through V, fig. 2). Figure 4 is a map of faults and joints as verified by ground checking and traced from plotting on airphoto mosaics; this was prepared as a sampling check on airphoto interpretations, and there was no attempt to plot all faults or joints.

None of the faults in the San Rafael Swell are continuous across the structure; they are discontinuous, bifurcating and sinuous, often forming fault zones and terminating in them. Few faults extend through the upturned flanks; most die out in the massive Wingate and Navajo sandstones on the flanks of the anticline.

Faults have been traced vertically, by aerial reconnaissance and field investigation, upward from the lower formations through the Carmel and into the Entrada. Large faults seen outside the Swell cannot be traced across or very far into the Swell.

Configuration of faults is controlled by lithology. Those in the Coconino, Wingate, and Navajo sandstones are continuous vertically and horizontally, and are generally open and smooth faced. Slickensides found on or near the faults indicate that movement has occurred, but very few examples remain in place to show the direction of apparent movement. Faults in the Moenkopi and Chinle formations are often seen as faulted zones rather than individual faults, and they die out horizontally and vertically within relatively short distances. They are sinuous, curved, bifurcating and discontinuous, in the interbedded siltstones and mudstones which appear to have had a dampening effect on the faulting.

Fault fillings vary from place to place. In the Coconino sandstone in the west-central sector, and in the Moss Back member in Rod's Valley, Boulder Canyon, in Mexican Bend area, near Calf Mesa, and in Straight Wash, exceptional concentrations of iron staining were observed. At Calf Mesa, the Mexican Bend area, and in Straight Wash iron sulphates were found. The sulphates at Calf Mesa are weathering products of sulphides in the Moss Back and Moenkopi, in a fault zone. Other faults may also have sulphide fillings in unweathered portions. In Mexican Springs Wash, in the mesa north of Sinbad well, in Vanadium King No. 1 mine, and mines on the Calyx Bench at Temple Mountain, faults contain asphalt. Faults along the eastern flank, from Boulder Canyon to the San Rafael River Canyon, contain quartz and calcite. Gypsum is quite common and is especially noticeable in Little Wild Horse Creek Canyon, southeast of the Swell (fig. 2), where fracture fillings of alabaster 10 to 12 inches thick are found. Barite and pyrite have been found in a few faults.

Sector I - Southwest

In sector I, the southwestern end of the Swell, faults are normal, vertical to high-angle, and form irregular graben and horst blocks. Parallel sets of faults are scarce. The major faults trend N 60 W to N 80 W, with two minor trends N 50 E to N 60 E and N 25 W to N 35 W. Most of the faults are sinuous, curved and discontinuous. An angular relationship exists between the intersecting faults; the bisectrices of a majority of the acute angles formed trend between N 40 W and N 70 W, or between N 50 E and N 75 E. Some are hinge or rotational faults, and the amount of displacement varies along the majority of them. The displacement of the faults ranges from a few feet, to approximately 300 feet along the major fault north of Tomsich Mountain. Evidence of horizontal movement was not found on the segments of the majority of the faults observed, though slickensides were found on the float near the faults. One fault, described under sector II but which extends into sector I northeast of Boulder Canyon, shows some evidence of horizontal movement. In a fault zone in Boulder Canyon a number of small faults a few inches to a few feet apart have displacements of a fraction of an inch to a few inches (fig. 5-A). These faults trend approximately N 70 E, parallel to the strike of the beds. Each fault was displaced in the down dip direction, and they are numerous enough to be equivalent to a much larger displacement along a single fault. Numerous joints between the faults, and also the fault openings are filled with calcite and quartz.

A few questionable low angle fractures were observed in the Moenkopi formation in Red's Canyon.

Curved and straight normal faults almost completely surround the Delta mine, forming a huge down-dropped block in which is found the only major non-asphaltic uraniferous ore body in the San Rafael Swell.

A few dark greenish gray, fine-grained dikes are found in the breached area of sector I, and there are numerous dikes on the southwest flank trending from N 25 W to N-S.

One of the collapses reported by W. S. Keys and R. L. White (1956) shown as No. 8 on figure 2, is about 3 miles north of Tomisch Mountain and has about 700 feet of displacement. Whether this, and other collapse structures, are independent features, or integral products of the formation of the Swell, is not known, but they are distinctive structural features of the San Rafael Swell.

Sector II - Southeast

Most faults in sector II, the southeastern part of the Swell, are roughly parallel, high angle, normal faults that form a number of horsts and grabens. These faults trend within 20 degrees of east-west, and are perpendicular to the trend of the southern segment of the anticlinal axis and oblique to the strike of the beds in the southeastern flank. Displacement was measured on a few of the faults.

Dip slip varies from a few feet to 300 feet or more; strike slip varies from a few feet near the flank of the Swell to a hundred feet or more near the crest. No strike slip was found on the majority of the faults observed, but the continuous fault which can be traced northeastward from the Delta mine across Boulder Canyon nearly to Chute Canyon has a horizontal component of displacement shown in slickenside striations, which dip 45 to 70 degrees west. Feather joints or gash fractures trending approximately E-W, found along the fault show some displacement and indicate eastward movement of the north side. The majority of the faults are downthrown to the south, forming a series of step faults. A large proportion of the faults in this sector are seen in the Moenkopi formation, and are discontinuous vertically and horizontally. A large fault often ends in a faulted zone, and another fault begins in the same fault zone and continues on the same trend but with opposite displacement, thus forming hinge or rotational faults.

The Temple Mountain collapse and seven other collapses lie in the major east-west fault system.

Sector III - West Central

Most faults in sector III, the west central part of the Swell, are parallel unlike the majority of faults in other sectors, and trend N 30 E to N 40 E parallel to the regional strike of the western flank and roughly parallel to the axis. A few trend between N 45 W and N 90 W. All faults are normal, vertical to high angle, and continuous horizontally and vertically. In the Wingate and Navajo sandstones the faults are open, but the surfaces are usually obscured or destroyed by erosion. Most faults are dropped down to the east; however, a few grabens and horsts were found. No horizontal movement was observed, but only a few faults in the deep canyons were investigated in this sector.

Several small springs flowing from a fault in Eagle Canyon give off a strong H_2S odor, and in Mexican Springs Wash, tar and water flow from a fault.

A small asymmetric fold transverse to the strike of bedding and anticlinal axis near Swazys Flat becomes a fault to the east in sector IV.

Sector IV - East Central

Faults in sector IV, the east-central sector, have an acute angular relation to each other and to the axis. The most numerous faults form a rude radiating westward pattern, varying in trend from almost due west in the southern part, to about N 40 W in the northern part. There are less numerous faults trending between north and N 60 E. There are several cross-faults trending N 60 W to N 65 W. The bisectrices of the acute angles of a number of intersecting faults in this area are as follows: N 15 W, N 70 W, N 80 W, N 75 E, N 50 E, N 45 E, N 35 E, and N 5 E. All the faults are normal, and vertical to high angle faults. The displacement of the faults in this sector varies from a few feet to a hundred and fifty feet. At Tan Seep a suggestion of offset was noted on the photogeologic map, but the faults could not be identified during the field investigation. No evidence of horizontal movement was found on the portions of the faults accessible in the washes and canyons. Formations younger than the Coconino sandstone are missing in this sector and a large proportion of the outcrop is Coconino. The Coconino is a poorly-cemented, highly cross-stratified, eolian sandstone and since reference bedding planes are few, fault movement and displacement may exist but not be discernible in the mass of lineations along the eroded cross-stratification planes. This sector has some of the most steeply folded beds, from Iron Wash north to the San Rafael River Canyon, and west to the anticlinal crest; and a scarcity of faults is found on the photogeologic maps in an area that would be expected to produce more. Movement along bedding planes is present though only a few small drag folds were found in the canyons cutting the steeply folded area. The upper beds moved down dip in relation to the lower beds. Numerous small (gash?) fractures and some brecciation are found along bedding planes. Calcite and quartz fill the fractures and outline the breccia fragments.

Sector V - North

Most of the faults in sector V, the northern end of the Swell, are roughly parallel, trend N 45 W, and are nearly perpendicular to the anticlinal axis. They are normal, vertical to high angle faults, forming several grabens and horsts. The average displacement is not great, varying from a few feet to approximately one hundred feet. No horizontal movement was observed along the faults investigated. Several pressure ridges trending roughly northeastward were observed in the Moenkopi formation southwest of Calf Mesa.

JOINTS

Two types of joints were noted: those formed during consolidation, and tectonic joints. Joints verified by ground observation are shown on figure 4.

The joints formed during consolidation were observed in the Moenkopi formation. They are sinuous, curved and discontinuous vertically and horizontally. Rough polygonal patterns similar to patterns of desiccation cracks were noted in a siltstone of the Moenkopi formation northeast of Shinarump Mesa. Many of the joints are closed, and open joints close downward. Joints prominent in the fine-grained sandstones terminate at the contacts with the mudstone and siltstones above and below. Many joints in mudstone are filled with coarser sandstone and siltstone. A number of joints or cleavages found in the gray-green mudstone below the Moss Back member of the Chinle formation have slickensides and may have formed by compaction during consolidation. However, some of the fractures may have been caused by movement along the bedding planes. Charles Hawley, of the U. S. Geological Survey, has reported what appears to be bedding shear at the Green Dragon No. 3 mine (personal communication, 1956).

Tectonic joints were found as joint sets near faults, oblique, parallel and perpendicular to the fault planes (figs. 4, 6 and 7), the result of vertical stress during faulting, relief of pressure, and slumping. Joint sets along several faults are oriented at an acute angle to the fault plane. Slickensides and the oblique orientation of joints on opposite sides of the faults seem to indicate that horizontal movement has occurred, as oblique strike-dip-slip movement. Sufficient statistical work to find the amount of movement was not completed. Many of the slickensided joints have no displacement, although several small faults with a few inches or a few feet displacement were found among the joints.

Tension, extension, and shear joints are also found. Strike of joints plotted on figures 6, 7 and 8 taken from field measurements, shows joints parallel and perpendicular to the strike of beds, and some oblique to the strike. However, faults complicate the joint picture and a more detailed study of relative ages would be necessary to determine those related to faulting and folding.

The dip of joints is easily noted and a large majority are normal to the bedding planes; where the beds are nearly horizontal most joints are nearly vertical, but on the steep east flank most joints are normal to the bedding planes, although a few are vertical even there. In the steeply dipping beds in the canyons between Straight Wash and Black Dragon Wash the majority of the joints are normal to the bedding planes. At a few places along the southern, western and northern flanks of the Swell, joints with a lower angle of dip are found (fig. 5-B). The best developed sets are found in the

Buckhorn Wash area. Parallel sets strike N 40 W; one set dips 25 to 45 degrees NE, and the other set dips 25 to 45 degrees SW. As the joint trends are parallel, and angularity is to a vertical plane, they are probably oblique joints caused by vertical forces, although it is possible they are shear joints caused by horizontal forces.

The tectonic joints are open, and can usually be traced vertically through a lithologic unit, but they often terminate against mudstone beds. Tectonic joints observed near normal faults in sector II often exhibit slickensides on joint surfaces although no evidence of vertical or horizontal displacement was found. Some of the open, persistent joints in faulted areas in the Moenkopi formation have a visible color alteration in the area immediately adjacent to the fracture. Fresh, broken surfaces reveal a hematite rich zone 1/4 to 1/2 inch in thickness.

The number of joints in the different lithologies appears to be controlled by density and thickness. The Moenkopi formation has a wide variation of lithologies; the lower siltstones are very consistent in grain size and the spacing of joints varies from 10 to 25 feet; the Sinbad member, a dense, thin-bedded, sandy limestone, has regular joints spaced from 1/2 to 1 foot apart in the thinner beds, and at increasing intervals in the thicker beds. The Moss Back member of the Chinle, a conglomerate and sandstone stream deposit of varying densities and grain size, has irregular joints spaced 5 to 25 feet apart; the overlying finer-grained part of the Chinle has joints spaced very closely in thin dense beds, and much more widely in thicker beds. The thick, homogenous Wingate sandstone is an example of the thicker-bedded formations and has joints spaced from 25 to 100 feet or more.

A number of minerals are found in the joints: pyrite, marcasite, fibrous goethite, earthy limonite, calcite, siderite, dolomite, barite, celestite, and quartz, primary and secondary vanadium and uranium minerals, and secondary copper, arsenic and cobalt minerals. Time did not permit tabulation of an areal distribution of joint fillings; however, a number of concentrations of limonite, pyrite, dolomite, jasper, iron sulphates, cobalt and asphalt were noted. Additional work would be necessary to determine whether any relationship exists between these concentrations, the age of fracturing, and the introduction of mineralizing solutions.

In the Kayenta and Carmel formations, joint relationships in the dark reddish-brown rocks seem to indicate two ages of jointing, or two ages of mineralization. One set of fractures terminates against the other. The more persistent fractures exhibit a light gray to white color alteration; the other joint set, which terminates against the first, appears to have once been altered to light gray but has since altered again to a light- to dark-reddish-brown.

Relative age of fractures near the collapse on North Temple Mountain may be indicated by one set of open vertical fractures and one set of healed joints dipping approximately 50° north. These are located at the head of a small wash north of the collapse in the lowest of several downwarped Chinle sandstone beds.

EVIDENCE OF HORIZONTAL AND VERTICAL MOVEMENTS

The evidence of horizontal movement along the faults on the crest of the San Rafael Swell is meager; time did not permit walking out all major faults and only sections were examined. A fault trending N 80 E paralleling the cliffs southwest of Chute Canyon has slickensides indicating an oblique dip-strike movement. In the shatter zone feather joints and short faults trending N 55 W, with a few inches to a few feet displacement, indicate that the north or upthrown block moved east relative to the downthrown block. Displacement of one fault by another was not observed in the field or on aerial photographs. The discontinuity and sinuosity of faults in the Moenkopi and Chinle formations, and the large number of fault zones, suggests a gradual readjustment rather than any large single movement along faults. Horizontal movement in the area affected by the uplift has been reported by Peterson (1954), who discovered several thrust faults, one with a displacement of 700 feet, in drilling Farnham Dome on the northwest nose of the Swell. The direction of movement is approximately S 60 E.

A reverse fault having a displacement of 100 feet or more was observed in the cliffs north of the Castledale-Woodside road west of Buckhorn Wash. Undulating patterns of outcrop, as seen on airphotos, and several low angle fractures with slickensides observed at Red Seep, suggest horizontal thrust fault movement in the Jurassic formations along the western flank of the Swell, south of the San Rafael River. The discontinuity and southwestward offsetting of the axis of the Swell may be due to horizontal movement, but may also be explained by irregular vertical uplift.

There is little doubt that there has been vertical uplift beneath the San Rafael Swell. Oil wells drilled on the crest have encountered Precambrian rocks (figs. 9, 10, and 11). There are approximately

3,500 feet of sedimentary rocks from the Salt Wash-Summerville contact down to the Coconino-Hermosa contact. Thickness of the formations as reported by Baker (1946) were used to construct figure 12 and to compute the figure of 3,500 feet. Over 4,000 feet of relief at the base of the Coconino has resulted from the uplift. Some relief existed on the Precambrian surface during Mississippian deposition (figs. 9, 10 and 11).

EXPLANATION OF FRACTURES

The fractures of the San Rafael Swell may then be explained as products of the uplift and horizontal movement. The faults in sectors I, II, and V are extension faults caused by the elongation of the beds along the length of the anticline during uplift, and the numerous grabens and horsts were formed by the relaxation of horizontal pressure or a withdrawal of magma that caused the uplift, resulting in a collapsed structure. The parallel faults in sector III are tension faults, and those in sector IV are tension and shear faults resulting from the horizontal compression and collapse. The best example of shear faults previously described is the long continuous fault, in sectors I and II, which parallels the Wingate cliffs from the Delta mine northeast toward Chute Canyon.

This explanation of fracturing in the San Rafael Swell is apparently a valid one, but several questions arise that will require a more detailed study. One question concerns the high angle to vertical dip of the faults - are these consistent with the interpretation of tension and extension faults known elsewhere? What is the relation to fracturing of the numerous dikes in sector I? Is there a thrust in the steeply dipping beds on the eastern flank as indicated in figure 12?

RELATION OF FRACTURES TO URANIUM DEPOSITS

The role of fractures in emplacement of uranium ore is uncertain because of conflicting opinions on the causes of precipitation. The elongation of the ore bodies at Temple Mountain is along the two major fracture trends. A few faults in the Vanadium King No. 1 mine at Temple Mountain contain uraniferous asphaltic ore; some faults in the Temple Mountain collapse zone contain ore; barren faults in the Lopez mine, Dirty Devil No. 6 mine, and Vanadium King No. 1 mine displace ore. No ore has been found in faults cutting the Moenkopi or Coconino formations, although uranium minerals, primary and secondary, have been found in the Coconino sandstone, the Kaibab limestone, and the Moenkopi formation in the Temple Mountain collapse (Keys and White, 1956), and in the Monitor Butte and the Moss Back members of the Chinle, the upper Chinle, and the Wingate sandstone. Though no generalization as to the role of fractures in controlling ore on the Swell should be made from this limited number of occurrences, possible fracture control cannot be ignored. Clark and Million (1956) report that younger faults found in the mines of the Four Corners Uranium Co. mining area, southwest of Green River on the northeast flank of the Swell, cut and displace the ore bodies in the Salt Wash. Thus, there may be two ages of faulting relative to the ore deposition.

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