FAULT AND JOINT GEOMETRY AT RAFT RIVER GEOHERMAL AREA, IDAHO

by

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ABSTRACT

Raft River geothermal reservoir is formed by fractures in sedimentary strata of the Miocene and Pliocene Salt Lake Formation. The fracturing is most intense at the base of the Salt Lake Formation, along a decollement that dips eastward at less than 5° on top of metamorphosed Precambrian and Lower Paleozoic rocks.

Core taken from less than 200 m above the decollement contains two sets of normal faults. The major set of faults dips between 50° and 70° . These faults occur as conjugate pairs that are bisected by vertical extension fractures. The second set of faults dips 10° to 20° and may parallel part of the basal decollement or reflect the presence of listric normal faults in the upper plate.

Surface joints form two suborthogonal sets that dip vertically. East-northeast-striking joints are most frequent on the limbs of the Jim Sage anticline, a large fold that is associated with the geothermal field. The north-trending joint set is prominent in the fold's hinge. Surface joint intensity decreases in proximity to known faults, indicating that surface joint intensity mapping may be useful for locating the surface traces of faults in the reservoir.

INTRODUCTION

Raft River thermal area is located on the eastern flank of the Jim Sage Mountains of southwestern Idaho (Fig. 1). The geothermal reservoir is controlled by fractures near the base of the Miocene and Pliocene Salt Lake Formation which consists of tuffaceous sandstone, shale and rhyolitic volcanic rock (Williams and others, 1976; Mabey and others, 1978; Covington, 1980).

The Salt Lake Formation is faulted over Precambrian metamorphic rocks along an eastward-dipping decollement that dips less than 5° (Fig. 2; Mabey and others, 1978; Covington, 1980). This decollement forms part of an extensive Tertiary dislocation surface that extends into the adjacent metamorphic core complexes in the Raft River and Albion mountain ranges (Compton and others, 1977; Miller, 1980; Armstrong, 1980).

Numerous north-trending faults are exposed in Pleistocene deposits along the eastern flank of the Jim Sage Mountains (Fig. 1). According to Covington (1980), these faults have listric geometries and merge into the gently dipping decollement at the base of the Salt Lake Formation (Fig. 2). The orientations of the listric faults indicate east-west extension in the Salt Lake Formation, and this is consistent with eastward displacement of the rocks above the decollement. Mabey and others (1978) suggest that up to 3 km of eastward movement may have occurred along the decollement since deposition of the Salt Lake Formation which began about 10 m.y. ago.

A set of east-trending normal faults occurs along the southern border of the geothermal area (Fig. 1). Mabey and others (1978) speculate that these faults may form part of an extensive structural lineament that extends westward into Nevada. However, the history and regional extent of the east-trending faults is poorly documented. Precambrian basement to the west has not been affected by faulting along this eastward trend (Compton and others,

FIGURE 1. Geologic map of the Raft River thermal area (after Williams and others, 1974). Joint study domains for Figure 4 and joint intensity measurement sites for Figure 5 are shown on the map.

FIGURE 2. Schematic east-west cross section through Raft River thermal area (after Covington, 1980). The position of the section can be located on Figure 1 by finding the position of drill hole RRGE#1.

1977). Covington (1980) infers a narrow, highly fractured zone with an east-northeast trend in the metamorphic rocks beneath the Salt Lake Formation in part of the geothermal field.

SURFACE FRACTURE ANALYSIS

The Jim Sage Mountains are formed by a large, open anticline that contains abundant lava flows and domes in its central part (Williams and others, 1976). The fold hinge trends a few degrees west of north and the limbs dip up to 25° (Fig. 3). Joints occur in two, sub-orthogonal sets that dip vertically (Fig. 4). One set is usually more prominent than the other in any given area, and the orientation of the prominent set changes between the limb and hinge region of the fold. The prominent joint set in the limbs strikes east to east-northeast (Domains I and III, Fig. 4), perpendicular to the prominent set in the hinge region (Domain II, Fig. 4). The orientations of joints in the limbs group into a smaller angular range when the limbs are rotated back to horizontal about the fold axis (Fig. 4, rotated composite stereoplot). This suggests that the joints may have formed either prior to, or during, the early stages of folding and were then rotated about the hinge along with the bedding.

The prominent joint set in the hinge region of the anticline strikes northward and the joints are perpendicular to bedding (Fig. 4). Presumably, this joint set is more closely spaced in the hinge area as the result of localized extension perpendicular to the hinge during folding. This means that Domain III is located above the fold's neutral surface.

Joint orientations were also measured in outcrops of Salt Lake Formation located just south of the Jim Sage anticline on the southern side of the zone of east-trending faults (Fig. 1). The bedding dips gently towards the west and the terrane is cut by several normal faults. The joint orientations are

JIM SAGE ANTICLINE

FIGURE 3. Bedding and fold hinge orientations for the Jim Sage anticline (Fig. 1). Data are plotted on a lower hemisphere, stereographic projection. The number of bedding poles, $n=31$.

JIM SAGE ANTICLINE - JOINT ORIENTATIONS

FIGURE 4. Joint orientations in the Raft River thermal area and adjacent terrane. Structural domains are located on Figure 1 and the number of individual joint measurements in each domain is indicated on the Figure by "n." The "rotated composite" joint diagram is discussed in the text. Data are plotted on lower hemisphere projections and contoured in percent/one percent area.

similar to those in the Jim Sage anticline and the prominent joint set strikes east-northeast, as in Domains I and II to the north.

We recorded the spacing between joint planes at each measurement site and converted this information into average fracture intensities using the method of Wheeler and Dixon (1980). Fracture intensities were then plotted against distance to the nearest mapped fault to see if an increase in fracture intensity could be used to predict the surface trace of major faults in the geothermal reservoir (Fig. 5). The data indicate that there is a significant correlation between decreasing fracture intensity and distance to a fault. Therefore, joint spacing or "intensity" may be a useful criterion for finding faults at the surface in the Salt Lake Formation. In many terranes there is a significant increase in fracture intensity adjacent to faults (Wheeler and Dixon, 1980), just the opposite situation than that observed in the Salt Lake Formation. However, Pohn (1981) finds that joint intensity systematically decreased near faults in Paleozoic rocks of the Allegheny Plateau in New York and Pennsylvania and is able to locate several major faults by identifying areas of abnormally low joint intensity.

SUBSURFACE FRACTURE SYSTEM

Only 70 metres of core have been recovered from the Raft River geothermal site, although total exploratory and production drilling have amounted to about 12.5 km. We estimate that only about 14 m of the recovered core can be oriented with the aid of dipmeter logs. Consequently, it is not possible to make a thorough study of reservoir structure with the available core.

Visual inspection of the core reveals that there is an abrupt increase in fracturing near the base of the Salt Lake Formation. Indeed, the highly fractured nature of the rocks across the contact between the Salt Lake Formation and metamorphic rocks has led Mabey and others (1978) and Covington

FIGURE. 5. Joint intensity versus distance to nearest mapped fault. The symbols by each data point are used to locate the measurement site on Figure 1. The median intensity value for each site is plotted as a dot while the upper and lower bounds represent the first and third quartiles calculated from the joint spacing measurements (Wheeler and Dixon, 1980). Note the general decrease in joint intensity with decreasing distance to a fault.

(1980) to suggest that the contact was a low-angle normal fault.

Two well-preserved and coherent core sections were selected for a study of the mesoscopic fracture geometry in the Salt Lake Formation near the decollement. The rocks in both core sections were tuffaceous sandstones with thin siltstone laminations. One core section was 50 cm in length and obtained from only 18 metres above the decollement in well RRGE#1. The second core was 350 cm long and came from 180 metres above the decollement in well RRGP#5. The core axes were essentially vertical; borehole surveys indicated that neither well deviated more than 5° from vertical. Separated pieces of each core section could be easily realigned using bedding plane attitudes.

The cores contained numerous normal faults and extension joints (Fig. 6). In Figure 7 we have compiled a histogram of fault dip angles and compared the number of faults in each dip interval with the number expected in each interval if the population had random dips. The solid dots in the figure represent the expected number of faults that should be observed in each interval if a randomly dipping fault population was present in the core (Stearns and Friedman, 1972). The histogram of the actual fault data suggests a non-random, bi-modal dip distribution, with the prominent set of faults dipping between 50° and 70° and the other, subordinate set dipping 10° to 30°. Notably, the slip directions on both the high and low-angle faults were the same. It was difficult to tell if movement occurred simultaneously on both fault sets, although the amount of alteration on the fault planes was similar, suggesting that the high and low-angle faults could have evolved during the same time interval.

The steeply dipping faults form conjugate fault pairs (Fig. 6) and are bisected by vertical extension fractures that are commonly filled with calcite. The conjugate faults and vertical extension fractures indicate that,

- Poles to bedding
- Poles to faults
- ▽ Poles to extension fractures

FIGURE 6. Fault and extension fracture orientations in core samples from drill holes RRGE#1 and RRGP#5. The core samples were oriented with respect to each other using bedding attitudes. The north arrow on the stereoplot is arbitrary because the core was not oriented. Data are plotted on a lower hemisphere projection.

FIGURE 7. Histogram of dip angles for mesoscopic faults in drill core from RRGE#1 and RRGP#5. The solid dots indicate the number of faults that would be expected in each dip interval if the fault population was random (Stearns and Friedman, 1972).

the maximum principal compressive stress was vertical at the time of their formation.

The faults that dip 10° to 30° are not parallel to bedding, indicating that bedding was not a plane of weakness along which the low-angle faults nucleated. There are two simple interpretations for the low-angle fault set: the faults may sub-parallel the decollement at the base of the Salt Lake Formation or, alternatively, could reflect the geometry of gently dipping portions of listric normal faults that cut the upper plate rocks. We don't believe that either of these alternatives should be preferred given the small amount of core available for study.

DISCUSSION

The analysis of surface jointing provided little information about the geometry of faulting in the geothermal reservoir near the base of the Salt Lake Formation. Presumably, one of the surface sets aligns with the calcite-filled extension joints that bisect the steeply dipping conjugate faults in the core samples. We suspect that this set would be the north-striking one at the surface because the two wells from which core was taken are located over 2 km from the nearest east-striking normal faults but are adjacent to north-striking faults (Fig. 1).

The decrease in joint intensity near faults could provide a useful method for locating the surface traces of faults in the geothermal reservoir. Pohn (1981) used joint intensity contour mapping to locate several major thrust faults and transcurrent faults in the Allegheny Plateau of New York and Pennsylvania. Contour mapping could be applied at the Raft River site or other areas where one can document that the surface joint intensity decreases towards faults. Extreme caution is advised, however, because joint intensity often increases, rather than decreases, in the vicinity of faults (Wheeler and

Dixon, 1980).

Pohn (1981) suggests two hypotheses to explain the observed relationship between faulting and joint intensity in the Allegheny Plateau. One possibility is that faulting releases residual stress in the rocks adjacent to the fault and therefore inhibits jointing. A second possibility is that the number of joint sets increases near faults even though the joint intensity of a given set decreases. Pohn's (1981) work did not adequately test this second hypothesis, but our results from the Raft River area do not support it. We have included all of the joint sets in the intensity calculations and still found a significant decrease in joint intensity near faults.

The Salt Lake Formation is poorly indurated and friable at the surface but is more indurated at depth due to several episodes of fracturing and cementation by calcite and silica cement (Batzle and Simmons, 1976; Covington, 1980). Perhaps the poorly indurated rock at the surface behaved anelastically to stress concentrations adjacent to faults, while the faulting itself relieved residual stresses in the manner suggested by Pohn (1981). This process would explain the joint intensity distribution near faults at the surface and still be consistent with elastic behavior of indurated rocks at depth where intensive jointing and faulting occurred in the base of the formation above the gently dipping decollement.

Several types of geological evidence point to the presence of a major decollement at the base of the Salt Lake Formation. The geothermal site is located only 15 km north of the Raft River Mountains and 25 km east of the Albion Mountains (Fig. 1). These mountains are metamorphic core complexes and the Precambrian rocks in the Raft River geothermal field are associated with major, Tertiary dislocation surfaces in both mountain ranges (Armstrong, 1968; Compton and others, 1977; Miller, 1980). Furthermore, mapping by Compton

(1975) and Todd (1980) has demonstrated that the Salt Lake Formation was involved in low-angle normal faulting at several localities in the Raft River Mountains.

The abrupt increase of fracturing in core obtained near the base of the Salt Lake Formation further suggests the presence of a low-angle decollement (Mabey and others, 1978; Covington, 1980). Significantly, brittle disruption in the base of low-angle fault plates is a characteristic style of deformation in metamorphic core complexes in the western United States (Coney, 1980). The presence of faults dipping less than 45° in the two core sections is a more subtle, but apparently significant type of evidence for the presence of either a basal decollement or listric normal faults near the base of the Salt Lake Formation.

CONCLUSIONS

Three sets of mesoscopic faults are present in the core sections from drill holes RRGE#1 and RRG#5. Two of the sets form a conjugate fault pair and dip between 50° and 70° . These conjugate faults are intersected by vertical extension fractures. The second fault set dips between 10° and 20° , forming a gently dipping set of faults. Presumably, this latter fault set developed sub-parallel to either the decollement at the base of the Salt Lake Formation or to gently dipping parts of listric normal faults.

The surface joint system in the Salt Lake Formation is formed by two suborthogonal sets of extension joints. East-northeast-striking joints are most prominently developed on the limbs of the Jim Sage anticline while the north-striking set is prominent in the fold's hinge. Joint intensity mapping may provide information on the surface positions of major faults and we encourage the use of joint intensity mapping in geothermal areas. However, interpretation of joint intensity maps requires that the relationship between

joint intensity and faulting be empirically determined for each site until a general theory relating the intensity of jointing to proximity of faults is developed. We suggest that the degree of induration of the rock at the time of faulting places a primary control on the joint intensity distribution due to the bulk anelasticity of poorly indurated material.

The hypothesis that a decollement occurs at the base of the Salt Lake Formation is supported by several types of geological evidence (Mabey and others, 1978; Covington, 1980). The metamorphosed Precambrian and lower Paleozoic rocks below the Salt Lake Formation occur at the stratigraphic level of major, low-angle faults exposed in the adjacent Raft River and Albion mountains. Also, there is an abrupt increase in fracturing of the Salt Lake Formation near its base that can be readily observed in drill core (Mabey and others, 1978; Covington, 1980). Finally, low-angle normal faults are present in core sections obtained from less than 200 m above the contact of the Salt Lake Formation and metamorphic rocks.

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