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STRUCTURAL INTERPRETATION OF THE FRACTURES ASSOCIATED WITH THE BONITA FAULT

by

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INTRODUCTION

The Bonita fault is an isolated structural feature and from this fact stems its geological interest. The fault itself is nearly ideal in its geometry and fulfills every geologist's concept of a "typical" normal fault. The fault plane trends northeasterly, dips a uniform 55° to 60° west, and has a throw that ranges from 500 to 700 feet. The total system is replete with a smaller antithetical fault zone that results in a tilted graben block up to 1.5 miles wide. The Bonita fault proper forms a narrow zone and, therefore, most of the displacement is along a more-or-less planar surface. The antithetic fault zone, however, is wider, composed of numerous faults, and more discontinuous so that the dropped graben is not a single block, but rather a series of small disorganized blocks that come together to form a graben valley along the fault.

The fault is located in east-central New Mexico southeast of Tucumcari (Fig. 1). The only other major structural features in the entire region are the Mesa Rica, Newkirk, and Bell Arch anticlines. Not only are these features tens of miles away but even then they are extremely gentle; their flank dips seldom exceeds 5 degrees. The relatively small Mosquero monocline has a flank dip of about 20+ degrees, but it has an extent of not much more than 8 to 10 miles. Far to the north and northwest in northern New Mexico is the southern terminus of the Rocky Mountains which are rotated basement blocks and drape folds produced during Laramide tectonism. About an equal distance to the southwest are the well-known structural features of the Delaware Basin which are late Carboniferous in age. Because the Bonita fault displaces beds as young as Cretaceous it cannot be part of the Delaware system and, by negation rather than compelling positive evidence, it is assigned to Laramide deformation. It probably reflects the distal edges of the stress field produced during the formation of the colossal rotated basement blocks of the Southern Rockies.

Why then, if the structure is so undramatic, should the feature be studied at all? Certainly not to unravel a complicted structural history. Far from it; the reason for studying the fault is quite the opposite; it is an ideal opportunity to study normal faulting and simple extension of the uppermost crustal skin without other complicating factors. The fact that no large anticlines or local arching are associated with the Bonita fault eliminates even the necessity of subtracting bending-moment effects. The Bonita fault is a singular case of an isolated normal fault in mixed clastics and as such makes an ideal study area for secondary features such as fractures, gouge, and slickensides because even geologists would find it difficult to argue about the causative stress field.

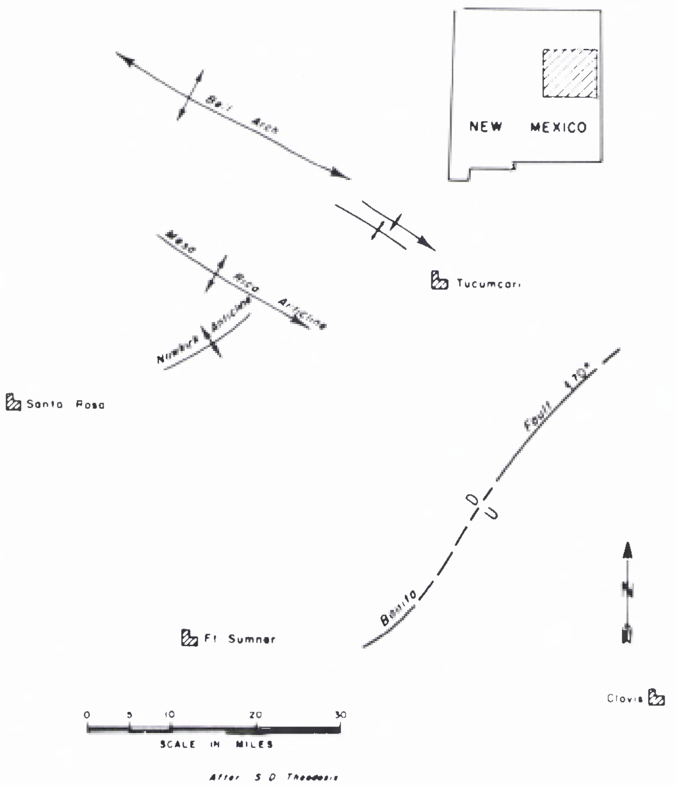

Figure 1. Location map of the Bonita fault area

PHYSICAL ENVIRONMENT OF DEFORMATION

Using the convention of P_1 P_2 P_3 for the three principal stresses and the Bonita fault geometry, it follows that overburden must have been the greatest principal stress (P_1) during faulting. The fault would also indicate that the intermediate principal stress (P_2) and the least principal stress (P_3) were horizontal, with P_2 paralleling the fault strike, and P_3 normal to it. At the present stage of erosion, nearly-horizontal rocks of Triassic age are in contact with the lower part of the Cretaceous section, therefore, the lithostatic load (due to burial alone) during deformation could not have exceeded a few thousand psi (pounds per square inch). The stratigraphic section involved, characterized by porous sandstone and shale, must have cropped out in the southern Rockies so there is no reason to assume an abnormal pore-pressure gradient. Therefore, the effective maximum principal stress probably never exceeded 2,000 to 3,000 psi. This means then that in order to rupture the rocks, even over long time periods, the least and intermediate principal stresses must have been close to the transition from compression to tension, and no matter what their sizes, their absolute value must have been low. Because the fault has a very consistent strike there must, however, have been a significant difference between P_2 and P_3. The very fact that under such mild stress conditions there was a distinct difference between P_2 and P_3 is in itself somewhat surprising, but, as will be discussed later, study of the minor features associated with the region indicate a rational explanation.

FRACTURES ASSOCIATED WITH THE BONITA FAULT

The most conspicuous secondary geologic feature associated with the Bonita fault system are the fractures. There are many ways in which fractures can be classified, and they will here be subdivided arbitrarily on the most general scale according to Stearns (1968) into regional orthogonal fracture systems and structurally related fracture systems. Regional orthogonal fractures are those that pervade an entire region independent of, or in the absence of, specific structural features. Each system is comprised of two fracture sets that form perpendicular to each other, and vertical with respect to bedding. Frequently there are two systems (four fracture sets) that pervade a particular area. There has been a great deal of speculation as to the cause of these fractures, but for the most part it remains just that—speculation. Price (1959) developed the idea that these systems are the result of regional uplift. This hypothesis, in my opinion, is the best offered, but so little is known about the sources of small regional stress differentials that the genesis of regional orthogonal fractures is still an open question.

In the area surrounding the Bonita fault there are two regional orthogonal fracture systems. The first of these contains one fracture set that strikes northeast (parallel to the fault system) and a fracture set that strikes northwest. The second system contains one fracture set that trends just west of north and another that trends just north of east. Even though at any particular outcrop all four sets may not be found, after studying many outcrops in the area the pattern becomes clear. For example, at a particular outcrop there may be one fracture set from each regional system. In this case the fractures would not be perpendicular to each other, but after measuring the fractures at tens of outcrops it becomes clear that there are four sets that form two perpendicular patterns. These fractures are characterized by sharp, clean breaks that, in places, cut several hundred feet of vertical section in a single plane. Though there can be a variation of up to 10° in the strike of a particular set between stations the strikes of individual fractures within a single outcrop is remarkably consistent.

The topography is such that outcrops are commonly continuous for 1,000 feet or more and even here the strikes of the individual sets is very consistent. Therefore, any changes in strike are gradual and occur over distances in excess of 1,000 feet. The rock material outside the fault zone then can be described as containing five planes that would impart a strength anisotropy and that are statistically homogeneous in their distribution throughout the rock mass. These five planes are the horizontal to subhorizontal bedding and the four regional fracture planes (see the right-hand side of Figure 2).

Near the fault planes the regional orthogonal fracture systems become statistically insignificant because of the large numbers of structurally related fractures that are developed in these zones (Fig. 2 and 3).

In using structurally related fractures in the field to gain a mechanical insight into structures, the first premise is that all fractures, shear and extension, form with a consistent and unique geometry relative to the principal stresses in the rock at the time of fracture. If this is correct, it follows that paleostress fields can be deduced from existing fracture geometries. It also follows from this premise that fracture types can be identified from geometry even in the absence of visible-movement criteria.

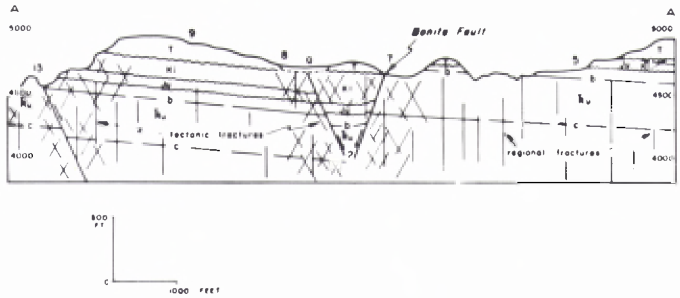

Figure 2. Schematic cross-section of the Bonita fault zone showing relationship of regional orthogonal and structurally related fracture systems.

The validity of this premise is supported by a large number of experiments carried out in many laboratories on numerous rock types. Further, it has been shown that, in general, the fracture geometry is unaffected by temperature, confining pressure, or pore pressure. There are two potential orientations of the shear fractures such that the fracture planes form an acute angle and an obtuse angle. For most rocks the acute angle is about 60°. This acute angle is bisected by $\sigma 1$. The obtuse angle is bisected by σ_3. The intersection of the planes defines the orientation of the intermediate principal stress, σ_2. The extension fracture forms normal to σ_3 and defines the σ_1 -σ_2 plane; that is, the extension fracture bisects the acute angle between the shear fractures.

This geometry of shear fractures is in accord with the Coulomb fracture condition which states that in a material the shear stress must exceed some constant initial cohesive shear resistance (τ_0) before shear fracture can take place. Further, it states shear rupture will occur on those planes where there is an optimum value to the ratio between the shear stress (τ) less the cohesive shear resistance and the normal stress (σ). In other words, shear rupture occurs where $(\tau\text{-}\tau_0)/\sigma$ is a maximum. There is no good detailed theory of fracture, and even the Coulomb condition is not intuitively appealing. Rather, shear fracture might be expected to occur along those planes where the shear stress is the highest, namely, at 45° to the

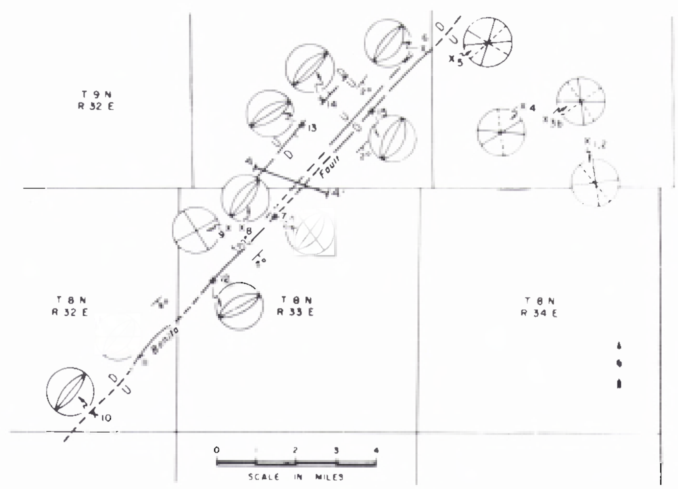

Figure 3. Map of the Bonita fault zone showing cross-section shown in Fig. 2 and lower hemisphere projection of centers of 6 percent or greater point maxima of fracture data at several stations along the fault. The centers are plotted as single planes.

maximum principal stress. The geologic literature is replete with examples of this assumption. That this assumption, namely, shear fracturing forms where the shear stress is highest, is erroneous is supported by hundreds of experiments by many workers.

The structurally related fractures form a complete conjugate system of two shear fractures and an extension fracture. Their combined geometry is such that the shear fractures form an acute angle of nearly 60° and an obtuse angle of 120°. The extension fracture bisects the acute angle. The strikes of all three fracture sets parallels the fault system. Therefore, either applying a Coulomb fracture condition or the vast amount of experimental work on fractures in rock by Handin and others (1957 and 1963), these fractures represent the same stress condition as does the fault system, namely, P_1 vertical, P_2 horizontal and parallel to the fault strike, P_3 horizontal and perpendicular to the fault. Figure 2 is schematic, but the data in Figure 3 is actual. The planes plotted in lower hemisphere projection in Figure 3 represent the centers of gravity of all 6 percent or greater point maxima of all the fractures measured at a given station. It can be seen that away from the fault the only significant fractures are the regional orthogonal systems, but near the fault these systems drop into "background noise" of less than 6 percent point maxima and the fractures associated with the faulting dominate.

Figure 4 is a photograph taken near the edge of the antithetic fault zone. The strong development of both the shear and extension fractures can be seen. Despite a vast amount of empirical data there still exists those who are reluctant to designate fracture type (shear or extension) on the basis of geometry alone in the absence of any offset information. The reluctance can be dispelled along the Bonita fault, where light and dark bedding laminations of certain standstones provide perfect small scale offset data. Figure 5 is a photograph of shear fractures in such a sandstone along the Bonita fault. The offset of the laminae indicate the same position of P_1 as does the overall geometry of the fracture system. These fractures could just as well have been designated as shear fractures by their geometry. It is also interesting to note that the small "faults" in Figure 5 formed without the rock ever totally losing cohesion (note that many of the darker bands are offset, but continuous).

Figure 4. Photograph along the Bonita fault zone showing shear (making 60° vertical angle) and extension (vertical) fractures associated with the fault.

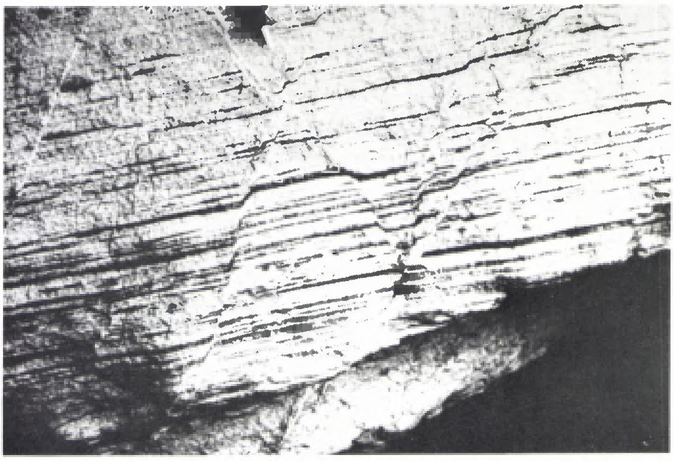

Figure 5. Photograph of small scale shear fractures in the Bonita fault zone showing small scale offset

As mentioned earlier it is difficult to imagine stress conditions during deformation of the Bonita fault in which the horizontal principal stresses (P_2 and P_3) were significantly different, yet the fault has a very regimented strike indicating a fixed P_2 - P_3 relationship. It should be noted however that the fault system parallels one of the regional orthogonal fracture systems. It is postulated therefore that the regional fractures were present before faulting and imparted a strength anisotropy to the flat-lying rocks that favored faulting to the northeast. This postulation is supported by unpublished experiments of Handin and Stearns. In the standard triaxial compression test of rocks $P_1 > P_2 = P_3$. That is even though the piston load exceeds the confining pressure all stress components around the circumference of the test specimen are equal. Therefore when shear fracturing (faulting) occurs there is no way to predict the azimuth of the fracture. However, if the specimen is precut along a vertical plane, the shear fracture always parallels the vertical cut in strike indicating that even though a new rupture occurs in a rock where $P_2 = P_3$ its orientation is controlled by the presence of a preexisting vertical plane of no cohesion. The Bonita fault area is not the only one in which simple normal faults parallel the regional fracture systems. This same case exists in the Uinta Basin of Utah. Here normal faults such as the Duchesne fault parallel one of the regional orthogonal fracture systems of the area.

CONCLUSIONS

Though the area around the Bonita fault is cut by several sets of regional fractures, in the fault zone those fractures associated with the faulting so dominate in numbers that their interpretation is uninfluenced by other systems. Therefore, such fractures can be used in the absence of other data to determine the stress condition that produced the faulting. With this knowledge the type and orientation of the fault can be determined because indeed, the shear fractures are miniature examples of the geologic feature in question.

ACKNOWLEDGMENTS

Much of the work reported here was part of a larger study of fractures in general undertaken while I was in the employ of Shell Development Company of Houston, Texas. Therefore, I am grateful for their release of these data. Further I was assisted in collection and interpreting much of the Bonita fault data by Messrs. W. Abbott, F. Conger, J. Beall, and S. Day who were, at the time, also employed by Shell Development. In other studies of the area after I joined Texas A&M I was ably assisted by Messrs. A. Brown and H. Swolfs. Mr. T. Engleder is currently studying gouge development along the Bonita fault zone. Dr. S. Theodosis first introduced me to the area and was most helpful in pointing out the local geology and outcrop occurrences.

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