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FRACTURE PATTERN OF THE ZUNI UPLIFT

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By
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GEOLOGY AND MINERALOGY

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ABSTRACT

The objectives of this study have been to determine the nature of the major fracture pattern of the Zuni uplift; to analyze this pattern for evidence of the mode of origin of the uplift; and to compare the fracturing in the ore areas with that elsewhere on the uplift to see whether diagnostic features exist that might make it possible to indicate other favorable areas.

The general procedure followed was to measure samples of the jointing at numerous points distributed areally and stratigraphically over the entire Zuni uplift; to plot these together with observed and compiled fault orientations; and then to compare the resulting fracture pattern with those of several smaller uplifts of known origin. Folds of two types of origin were studied: long, narrow anticlines typical of belts ascribed to horizontal compression, and broad domings demonstrably produced by materials injected at depth. Of two anticlines studied, taken to have been formed by horizontal compression, one is a fold in the Marathon region, West Texas, and the other, a fold of the Appalachian folded belt near Maysville, West Virginia. In both, the most continuous fracturing strikes at an angle of about 75° with the fold axis. Only one example of the second type was studied in the field, a laccolithic structure, the Maze Arch in the Henry Mountains, Utah. Its fracture pattern was compared with several structures described in the literature. All these structures, "passively" domed by the rise of masses from below, are characterized by having the most continuous fractures parallel to their long axes.

A comparison of these contrasting patterns leads to the conclusion that the Zuni uplift bears stronger relationships to the second group than to the first. This

suggests that it is the result of doming of the rocks over masses rising from beneath, rather than the result of folding by lateral compression. Other characteristics of the overall uplift support this judgment, such as the parallelism of the fractures in the sedimentary flanks with those in the crystalline core; the prominent horsting in the crystalline core; and the various structures that indicate deep-seated fracturing below the sedimentary rocks on the flanks (such as large faults, monoclines, and volcanic phenomena). All these require that the doming was produced by large horsts in the basement crystallines rising differentially. The age of this doming is mainly Tertiary, but it is possible that movements of these horsts have occurred as early as pre-Pennsylvanian and Permian time and may have continued until the present, impressing similar joint directions recurrently.

The general area over which most of the ore has been found is a prominently faulted part of the uplift, characterized further by associated volcanic phenomena. The jointing there follows essentially two main directions, either one or both of which may be present at any one point and at least one of which has the direction of the major fractures in corresponding parts of the crystalline core. The line of outcrops of the Jurassic-Cretaceous formations along this northeast flank displays several large "scallops". These are structural features due to the combined effects of flexing and faulting. That they are not merely erosional features is demonstrated by structural contours drawn upon the Entrada sandstone for a portion of that flank. Most of the deposits known elsewhere on the uplift lie upon or near to major monoclines or faults.

The structural setting of the main ore body suggests the possibility that the ore is related to fracturing. Faults are prevalent in the ore area, and jointing seems to be especially dense near the faults. The abundant fluorite which is associated with some of the ore in the Todilto limestone suggests a possible

connection with the occurrence of fluorspar, in economic amounts, in veins on faults within the crystalline core, although the so-far barren Permian and Chinle interval separates the two regions areally. Some cutoff maps of the uranium ore bodies show well-defined elongations along the directions of the principal fracturing. There are also two general characteristics of the passively domed type of uplift which help explain the Zuni uplift as a favorable structure for uranium mineralization: Passive doming produces a lateral dilation of the sedimentary rocks which creates new open spaces; and it causes the structure to increase in severity with depth, affording easy access to deep sources of mineralization, if such were indeed responsible for the introduction of the ore.

The structural concept derived from the Zuni uplift applies to larger areas. The directions of several flexures and volcanic belts suggest that the major fracture zones extend beyond the limits of the uplift itself. These zones may extend as far as adjacent uplifts, including the large fractures along which fault blocks rose there, as did the fault blocks of the Zuni uplift. If so, they might be regarded as possible loci of mineralization. Considering still larger features, the whole Zuni uplift may be described as a unit of the "Zuni-Sacramento fractured belt", which extends southeastward toward the Sacramento uplift and the Guadalupe Mountains, and it may further be described as lying with its southeastern end at the intersection of this fracture belt with not only the Mount Taylor volcanic syncline, but with the more inclusive belt which trends from about Taos, New Mexico, (or even Trinidad, Colorado) to Globe, Arizona. Deep fracture belts of such dimensions, on the order of magnitude of the Colorado porphyry belt, may lie beneath the surface of the Colorado Plateau, evidencing themselves by monoclines, faults, and volcanic phenomena. They might be considered as the next larger loci of structures possibly favorable to mineralization.

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OBJECTIVES OF THE STUDY

The basic purpose of this study has been to determine the major fracture pattern of the Zuni uplift as a whole and to analyze the results for their bearing upon the origin of the uplift. It was hoped that this fracture information might afford a verdict upon whether the uplift had formed as a horizontally-compressed fold or whether it had arisen through passive doming of the rocks by masses rising from below them. Beyond these fundamental objectives was the intention of examining especially closely the fracture pattern of that part of the northeast flank of the uplift where most of the uranium ore has so far been found, to determine whether it has any structural peculiarities which might prove of use in considering ore possibilities elsewhere.

This report is the outcome of five months of field work, four of which were spent in the vicinity of Grants, New Mexico, and one of which was divided between the Marathon region of West Texas and the Henry Mountains, Utah. In addition one week of independent work outside of the contract was spent at Maysville Gap, West Virginia.

PROCEDURES AND DATA

General Plan

The general plan was to determine the principal characteristics of the fracture pattern of the Zuni uplift and then to compare that pattern with the fracturing found on several smaller anticlines whose mode of origin is reasonably certain. It was thus hoped that something about the origin of the Zuni uplift might be learned by analogy with those of the smaller structures with which it shares structural features that are believed to be diagnostic. The smaller structures of known origin selected for this purpose represent two general types: (1) anticlines formed by lateral compression, and (2) anticlines domed up passively by the rise of masses from below them. From theretical considerations, it was expected that the first group would

exhibit predominantly fracturing transverse to the fold axis while the second would show longitudinal fractures predominating. This criterion, or whatever other criteria would be found in its stead were to be applied to the Zuni uplift, as an approach toward understanding its origin. Then the other structural characteristics of the uplift were to be considered for any additional light they might provide.

Specific Procedures and Data

The following structures were studied in the field as examples of smaller anticlines of known origin: for the laterally compressed type, one anticline in the Woods Hollow Mountains of the Marathon folded belt, west Texas, and a part of the Wills Mountain anticline in the folded Appalachians of northeastern West Virginia (a study done independently of this contract); and for the passively domed type, one laccolithic dome, Maze Arch, in the Henry Mountains of Utah. The data for these and for the Zuni uplift are presented on the attached maps, and the procedures and data will be described with reference to the individual maps.

Maps of the Zuni Uplift

Ground Samples of Jointing, Zuni Uplift, New Mexico:

This map gives the most general picture of the Zuni uplift. On it are included as many of the major faults as could be compiled from other sources, in addition to those which were observed in the field, in the course of the joint measurements. Faults in the pre-Cambrian are taken entirely from the map of that region made by E. N. Goddard, et al (1951), and faults of part of the northeast flank are from maps by the U.S. Atomic Energy Commission geologists, Grants, New Mexico. Geological contacts, shown only where they could be confidently identified, were transferred by pantograph from controlled serial mosaics. Beyond these features, the map represents essentially a plot of the joint data. It cannot be regarded as a complete indication of the jointing which will be found in any given part of the

uplift, but instead merely summarizes the joints which were found at approximately one hundred and twenty-five points distributed areally and stratigraphically over the uplift. At each such point, the procedure was to find an outcrop completely exposing a statistically significant number of joints. Where jointing is complicated, especially in the crystalline rocks, this meant eighty to one hundred and fifty joints; in the sedimentary rocks, where the joint pattern is very regular and the joints are exposed on broad flat surfaces, as few as thirty joints proved to be adequate. At each point, all joints within the selected area were measured, so as not to bias that aspect of the sampling. The area comprising all measured joints at an individual locality varied from about 75 square feet to about 10,000 square feet, according to the joint density. The measurements were later plotted stereographically and the mean directions of the maxima were determined and entered upon the map. For approximately one-third of these joint localities, sketch maps of the jointing were made on the spot, providing an important record that is available, though not here reproduced.

One further characteristic of the jointing is noted on the map: the "relative continuity" of the various joint sets. Where the joints of one set commonly terminate against the joints of a second set, the first is labelled the less continuous and is represented on the map by a shorter strike line. At some localities, especially on horizontal surfaces, this relationship is immediately obvious. In others, especially in cliff exposures, it was necessary to adopt the method of recording which of two joints terminates against the other. An entry would be made, e.g., that "9 stops 7", meaning that the seventh joint measured terminates against the ninth joint measured. If, upon plotting these points, it became evident that one set nearly always terminates against another, then it was identified as the less continuous in the symbol entered on the map. Where no systematic difference in continuity can be clearly recognized in two sets of joints, the strike symbols are drawn equally long on the map. At such points the possibility exists that differences in continuity exist but could not be detected in the sample studied.

An exception to the above symbolism is made in the pre-Cambrian area, where the relative lengths of the strike lines stand for the relative strengths of the maxima in the point plots, for the reason that relative continuity could not be readily detected in the crystalline rocks.

The number of joints measured was usually thirty in the sedimentary rocks. Larger samples there, where the pattern is generally a very simple one of two or three joint sets, seemed much less desirable than a larger number of samples which could be secured with the time saved. In fact, at the conclusion of the study it is felt that where the joints are simple and well exposed, measurement may be less desirable than summaries by inspection, considering the many more localities which could be so treated. For the purposes of this project, though, it was felt that the sampling should be on as firm a basis as circumstances allowed. since the project was undertaken in order to define and test principles, not to apply principles which had already been well established.

Faults and Joints of a Part of the Northeast Rim of the Zuni Uplift, New Mexico:

This map gives more detailed information about one part of the uplift (K-15 to T-11 on previous map), showing more completely the faults which have been mapped by the U.S. Atomic Energy Commission geologists at Grants and showing also three additional types of information: (1) joint orientations taken entirely from low altitude aerial photographs; (2) structural contours for a part of the Todilto bench; and (3) locations of most of the uranium deposits now known in that area.

That jointing is well displayed in some of the low altitude aerial photographs provided originally for use in trace element investigations being carried out at Grants by Mr. Perry Narton of the U.S. Geological Survey was pointed out to the writer by Mr. Narton, and it developed that a wealth of information could be obtained by inspection of all of the photographs available. Previously, it had been found that the mosaics give no direct information of this kind and that the regular altitude stereoscopic pairs gave only a little. These low altitude photographs, however,

intended to be used for the identification of individual trees, furnish much more extensive and accurate sampling than could be accomplished in the field in any reasonable time. Many joints, in some cases many hundreds, can be seen over continuous areas, and so summaries can be made of samples very much larger than could be obtained on the ground. Furthermore, the length of individual fractures can be observed in some cases, and some impressions of jointing densities can be gained. Thus, the map compiled from these photographs provides fracture data of great reliability and usefulness. Fortunately, almost all of the joints in this area dip steeply, so that the strike itself is significant.

One importance of this map to the present study is that it provides a thorough check upon the validity of the ground sampling methods used for the map previously described. A comparison of the two gives one considerable confidence in the general trend of the jointing over a considerable area; individual points cannot be taken as decisive, and the local continuity is sometimes at odds with the more general continuity so accurately shown by the aerial photographs, but the general trend and the most common continuity shown on the overall map give a fairly correct impression. Thus it is thought that the map first discussed offers quite a useful picture of the uplift as a whole.

Because individual fractures can be observed for great distances on some of the low altitude air photographs, the present map also gives a valuable test of the validity of "relative continuity", and shows it to be a real and valuable characteristic. In many places, the aerial photographs show hundreds of joints of one set, with individual joints running actually for miles, and over these areas there may be almost no visible second set, even though the exposure is very nearly complete. In such places, what other joints may occur may run for only a few feet, merely dividing the segment between two adjacent joints of the more continuous set, and this may be especially true near the cliff fronts, where joint blocks have begun to pull away. At other points, less common, two sets may be seen of nearly equal continuity. What-

ever the significance of the relative continuity criterion may be, it is at least very real and it constitutes a striking difference between the several joint sets which may be observed at a given point, a difference which deserves recording as a prime characteristic of the jointing there.

Measuring the density of jointing on the ground would be a difficult process requiring careful technique. In some cases, the low altitude aerial photographs are an easy source of information on this problem. No systematic study was given this matter, but it was evident in the inspection of the aerial photographs for the preparation of the present map that there are pronounced differences in density from place to place. The impression is that the jointing is dense in the vicinity of the major faults and less dense elsewhere. This map, however, is not intended to imply anything about densities. The symbols are merely shown wherever the photographs reveal them with sufficient certainty.

This variation in the density of jointing is best shown in the Entrada formation, a very thick aeolian sandstone. In places it has a prominent major joint every few tens of feet, while in other places, stretches of hundreds of feet are free of any joints visible on the photographs. In the thinner sandstones, by contrast, the difference is less obvious, and the reason is presumably that, because the jointing is fairly dense in even the least fractured places, the density elsewhere either is a little greater or contrasts less prominently. That the density of the jointing increases with decreasing thickness of bedding became obvious early in the study, and whatever roles other factors such as lithology, cross-bedding, etc., play, thickness is a very important variable.

The common parallelism between faults and joints is well shown on this map and will be discussed in the interpretation.

If the fracture pattern is to be considered in relation to the form of the uplift, then detailed information about the shape is useful. The structural contours

drawn for a part of one rim have been constructed for that general purpose and for the specific purpose of investigating one of the large "scallops" in the outcrop pattern of the Jurassic-Cretaceous rim, in this case the one between Haystack Mountain (Q-13, on the first map) and the San Mateo fault (S-12). Subsurface information furnished the control for the solid contours, while the dashed connections follow the topography fairly closely, since that is a good indication of the attitude in this area. The contours can be seen to swing around with the outline of the "scallop".

The location of the ore bodies has been supplied by the Grants office of the U.S. Atomic Energy Commission and is presented on this map to allow comparison with the information concerning the shape of the structure and the fracture pattern. The shapes of the larger ore-rich areas are only roughly indicative of their accurate shapes as shown on the large-scale cutoff maps from which they were taken.

Maps of Smaller Uplifts of Known Origin

Laterally Compressed Folds:

Fold in Marathon Region, Texas -- 3 Maps: The "Topographic and Geologic Map of an Anticline in the Woods Hollow Mountains, Marathon, Texas" is a modified enlargement of a small part of Philip B. King's map of that area (1937). The faults other than the two largest in the southwest end of the fold were added by the writer as a result of his field observations, as details were too small to be shown on the scale of King's map. "Attitude of Beds, Anticline in Woods Hollow Mountains, Marathon, Texas" is included to give a clearer picture of the shape of the fold in the absence of a structural contour map. The data shown on the map bearing the title, "Faults and Joints; Anticline in Woods Hollow Mountains, Marathon, Texas", were obtained by the same ground sampling methods described for the overall map of the Zuni uplift. Again, it is a record of the measurements made, not a representation of the fracture orientations at any given point. The most continuous set of joints can be seen to parallel in general the direction of the faults and to intersect the axis of the

fold at about seventy-five degrees, in one direction only. Almost all of the measurements were made in the Caballos novaculite, a very closely fractured unit, which, however, has some five to ten foot-thick ledges with joints of that stratigraphic penetration. As on the Zuni map, nothing is implied about joint density in this representation. But it seemed in the field to be true that the densest and the most pronounced jointing was in the highest and the most deformed parts and that there also the orientation was most uniform.

Fold in Central Appalachians, West Virginia -- 2 Maps: A part of Wills Mountain Anticline at Maysville Gap, West Virginia, was selected because it is doubly-plunging, a condition necessary for the criterion to be tested, and because the outcrops are sufficiently large to allow study in at least a part of the fold, where the White Medina forms high cliffs above Maysville Gap. The doubly-plunging part shown is only a small part, a local culmination, of Wills Mountain anticline, a fold which continues for many miles in both directions. In this case, at least twenty joints were taken for each sample; otherwise, the procedure was the same as described for the overall Zuni uplift map.

The map entitled, "Joint Measurements, Wills Mountain Anticline, Maysville Gap, West Virginia", represents the joints as found, while the other map, "Joint Measurements Rotated to Position of Horizontal Bedding", gives the same information, but with the effect of the dip of the beds removed by rotation of the beds into the horizontal by graphical methods. The direction of the contours across the space of the gap -- where the lines are dashed -- is not clear, but on either side of it they are accurate. The contours drawn on the top of the White Medina sandstone are not continued farther out on the flanks. because the flanks are too steep for them to be effective; instead strike lines on the Helderberg-Oriskany have been indicated. While the most continuous set in the White Medina intersects the axis at about 70 degrees, the four localities lying on either side, measured along the Helderberg-

Oriskany escarpment have the most continuous set intersecting the strike line at twenty degrees or less, after rotation. Whether the results obtained by such a rotation back to the original horizontal position correspond to anything real remains to be seen. The results are here presented for whatever they may be worth.

One characteristic of the density of the jointing was apparent in the field, the very marked increase in density toward the crest of the fold. For several hundred feet above the bottom of the gap, the orientations are less pronounced and the jointing is relatively sparse, while above that, the density increases to almost a sheetiness along the highest part of the fold.

Passively Domed Anticlines:

Maze Arch, Henry Mountains, Utah. Fractures and Sketch Structural Contours on Top of the Kayenta Formation: Maze Arch was chosen as a dome almost certainly distended by the intrusion of igneous matter. When structural contours had been constructed, by identifying geological contacts on aerial photographs, transferring them to the recently available U.S. Geological Survey topographic map, and computing elevations from dips and stratigraphic thicknesses, it became clear that the dome is elongated northwestward in the direction of Mt. Ellen, a principal center of radiating laccolithic tongues, as shown by Charles B. Hunt's study of the area (1952). Thus it appears that Maze Arch is very likely a dome above a linguiform intrusion whose source was the Mt. Ellen stock.

In the field, joints were measured principally along the Morrison escarpment east and northeast of the dome. Samples of only ten joints were taken at a number of points and the directions at others were determined by inspection, in order to treat as many joints as possible in the short time available. Later, it proved possible to recognize jointing in some of the thicker beds from the aerial photographs, jointing which is too widely spaced to be measured by the regular methods in the field. Even those joints on the map which were taken directly from the air photographs do not tell much directly about jointing densities, because they lie in

several different beds, from the Kayenta through the Carmel, according to the beds outcropping at given points.

The reference on the map to joint sets filled with mineral matter pertains to certain structures in sandstones of the Morrison which weather so as to leave protruding joint fillings of sand and calcite. These structures usually appear in conjugate pairs and often show shear displacement along both sets.

It is not known whether this rather strikingly longitudinal pattern is restricted to the dome itself or whether it is more widespread.

Discussion of Two Other Domes from the Literature: The only other structure in this category which was visited was Mt. Ellsworth, also in the Henry Mountains. There the beds are so thick that almost no measurable joint localities were found on the side visited (west). This structure, originally chosen for the purpose, was accordingly abandoned for the thinner Morrison sandstones of Maze Arch. However, a sketch structural contour map of the Henry Mountains by Charles B. Hunt (1952) shows not only faults, but also swarms of joints on the Mt. Ellsworth-Mt. Holmes dome, especially on the east side. From it, the impression of a dominantly longitudinal pattern is also gained. In this case, direction of fracturing is almost at right angles to the regional jointing off the dome, to the southeast.

There can be little doubt that salt domes are passively uparched structures. For the purposes of this discussion, the structure of the Hawkins field, Wood County, Texas, serves very well, since it is a dome which is not only elongate (the criterion being tested breaks down for circular domes), but for which there is also available a great deal of subsurface control (Parker and McDowell, 1951). Its fracture (fault) pattern is less decisive than the two examples just described, but it still looks as if the dominant trend of the faults was essentially parallel to the axis of the uplift (i.e., longitudinal).

One experimental example might be added: the model of the Azores structure made by Hans Cloos. Its shape is much like Maze Arch, and the fracturing is also very similar, with longitudinal fractures dominating the picture (H. Cloos, 1939).

EVALUATION OF RESULTS

Interpretation of Data

It is thought that, with certain important qualifications, the data presented largely verify the predicted difference in the fracture patterns of laterally compressed and passively domed types of anticlines. Before applying this distinction to the Zuni uplift, it is advisable to mention briefly the theoretical reason for expecting this difference.

Theoretical Grounds for Prediction of Patterns:

In a laterally compressed fold, two given points on opposite limbs approach each other during the folding. In an anticline domed by masses rising from below, this is not true; instead, the arc length between two points on opposite limbs must stretch to some value greater than the original linear distance between them. This stretching is greatest in the direction of least radius of curvature and so the first-formed fractures may relate to that direction; in the case of tensional failure, this would result in early fractures at right angles to the direction of the least radius of curvature. Thus, if the first-formed fractures become the most continuous set, then a pattern with that set essentially longitudinal to the anticlinal axis would result. In the case of the laterally compressed fold, on the other hand, opposite points approach each other so that up to a certain point no increase in the arc length between them need take place. In that case stretching incurred at first only in a longitudinal direction, giving rise to tension fractures essentially at right angles to the fold axis.

Evidently the second case includes many possible relationships, depending upon the relative magnitudes of the two quantities discussed above, one the measure of the

approach of opposite points toward each other, and the other the measure of the change in length of a line between the two points measured along the surface of the bedding. In the first case, on the other hand, the first quantity is everywhere nil. This suggests that the fracture pattern of the passively domed type of uplift can be predicted with considerable confidence, while the pattern of a laterally compressed fold may include a range of special cases which are more difficult to foresee; this, in fact, seems to be the case in the smaller uplifts studied, inasmuch as the passively domed structures have rather decisively longitudinal fracture patterns, while the laterally compressed folds show several characteristics which are not readily explained, even though their overall pattern is within twenty degrees of the transverse direction first expected.

It is possible to develop this approach more fully by actually plotting the variation of the above two quantities as functions of direction in respect to the fold axis, measuring the second quantity and assuming the function of the first, each for an increment of the fold surface. Their difference can then be plotted, giving a third quantity which is an expression of the actual stretching incurred along each direction through the increment. It is hoped that it may become possible to predict from this the fracture pattern. A comparison with the real fracture pattern then gives a test of the assumptions involved. (This development is being carried out, but is omitted here as not of immediate importance to this report.)

In addition to the assumption of a function for the first quantity, there is implicit in all of this the assumption that the fracture pattern can be explained wholly by the present shape of the uplift. This certainly is not always true. It is, for instance, possible that faults affect the region around them, quite independently from the regional curvature of the bedding surfaces near them; or, the fracturing may be a result of transmitted stresses so that the regional shape of the surrounding structure is a companion effect to the fracturing and not its cause; or, again, the fractures may be the result of some deformation different, more extensive than, or

distinct from, merely the fold on which they are found, e.g., in the case of the epeirogenic uplift of a folded belt, long after the individual folds had been formed. A few observations bearing upon these possibilities may be recalled from the discussion of the data.

In respect to the first alternative mentioned in the preceding paragraph: The impression that the joint densities increase near faults on the detailed map of a flank of the Zuni uplift, and the parallelism of the joints and faults on the same map, suggest that the faults there may have had some such effect, although other equally reasonable interpretations are possible. It is, for instance, quite possible that heavily jointed areas were utilized in differential movements that produced the faults which appeared later in the deformational process. The other alternatives seem to be somewhat at odds with the overall map of the Zuni uplift, upon which the fracture pattern can be seen to vary from place to place in close relationship to the uplift itself. Similarly, the suggestions of denser jointing in the more deformed parts of the Marathon fold, the Appalachian fold, and the laccolithic dome seem also to relate jointing directly to the uplifts themselves. All in all, these considerations require much future study for their proper assessment, and they are listed here only as necessary qualifications.

The question arises, how large an increment of structure should be treated in the above type of analysis? It appears from the Maze Arch map, as well as several other maps in the literature, that the fracture pattern is sometimes constant over all or most of the uplift, rather than being different from point to point. This shows conspicuously on the map giving detail of one flank of the Zuni uplift where the joints maintain a nearly constant attitude across the "scallop" in the structural contours, which is the opposite of what would be expected if there were a point-to-point determination of the fracture pattern by the details of shape on the structure. Apparently the areal increment treated statistically must be quite large, in some

cases, nearly as large as the entire uplift, and as large as considerable parts of it in others.

Test of Predicted Criterion:

With that indication of the theoretical reasoning which led to the predicted difference in fracture patterns, the discussion of the facts will be resumed. It appears from the smaller uplifts of known origin that the passively domed uplifts are indeed characterized by longitudinal fracturing, and, in this respect the prediction was upheld. The folded uplifts, however, supported the prediction that the pattern would be transverse to the axis of laterally compressed folds, only to the extent of a seventy or seventy-five degree angle with the fold axes. In the case of the Appalachian fold, the dominance of longitudinal joints (rotated) on the Helderberg-Oriskany flanks in the pattern obtained by rotation appears at first abnormal, if we accept it as real. But at that stratigraphic level the anticline is not doubly plunging; as is shown by the straight strike lines of these beds. There is, accordingly, no reason to expect cross-joints to be well developed. This, in fact, had been anticipated originally. We may say, therefore, that with the above qualifications, the criterion has stood the test afforded by the structures studied.

Application of Criterion to the Zuni Uplift:

The Fracture Pattern: The most continuous sets of joints in the Zuni uplift are most generally longitudinal, if the direction of the uplift along different parts of its length is carefully considered. The statement does not fit a number of points, especially in the vicinity of some of the faults, but it has considerable validity in the overall picture. We may, accordingly, conclude that the Zuni uplift resembles the passively domed structures more nearly than it resembles those which arose from lateral compression.

The most striking single characteristic of the overall fracture pattern, as depicted on the map of the whole Zuni uplift, is the strong parallelism between the

faults in the crystalline core and the form of the uplift. The outcrop patterns near the crystalline core follow the boundary faults of the crystallines closely, and even the stratigraphically higher beds of the flanks parallel the boundary faults with considerable fidelity. In fact, the railroad, sensitively following directions of low and constant grade, traces out a line which is very nearly a strike line and which follows the directions of the crystalline faulting at the same time, illustrating the close correspondence between the crystalline faulting and the form of the uplift as a whole.

The form of the whole uplift has a conspicuous parallelism also to large faults and monoclines in the sedimentary flanks, structures which must be faults in the crystalline rock below those points. The general trend of these monoclines and large faults is either parallel to those in the corresponding part of the crystalline outcrop, as in the cases of the main northwest - and west northwest - striking faults, or the faults are actually continuous, as is true of some of the northeast-striking faults which pass from the crystalline area into the sedimentary flank. When this fact is combined with the conspicuously flat top of the Zuni uplift, the impression grows that its fundamental pattern is that of a group of blocks bounded by faults raised differentially above its surroundings.

That the major fractures are deep-seated is proven by the various volcanic phenomena, including lines of cinder cones (J-2 to N-6), various lava flows, e.g., the one associated with the cinder cone El Tintero (Q-12), and older phenomena such as the volcanic necks in the area where pumice is now being mined (T-10, although the necks are not specifically indicated).

The uplift has the peculiarity of rising fairly steeply over narrow monoclines and yet dipping only very gently elsewhere. A traverse across the uplift near its northwest end shows this well: the dip is very steep, up to eighty degrees, for the brief space of the Nutria monocline, and then it leads very gently in the opposite direction for fifteen miles across the width of the uplift, until the twenty degree

dips of the Coolidge monocline on the northeast flank are encountered for another brief space (see Rapaport et al, 1952, figure on page 10). This very flat topped shape is not the picture which is conveyed by the remark, often made, that the Zuni uplift is "very assymetrical to the northwest". In other parts of the uplift, **monoclines** occupy various other positions, so that the flat-topped form does not **apply everywhere**; but in each case the block-like behavior is clearly seen.

Horsting as Doming Mechanism: All these lines of evidence of deep fracturing and faulting support thus the conclusion that the doming is the result of differential movement of fault blocks in the basement crystallines, which had risen along fractures from below the sediments, shaping them into the Zuni uplift. Thus the uplift might be pictured as a sort of horst complex, draped with sedimentary rocks. The writer had already formulated this concept when the map of the main crystalline area made by E. N. Goddard et al in the course of an investigation of the Zuni fluorspar deposits became available. On it Goddard characterizes the core as comprising three major fault blocks, within each of which there are numerous less persistent faults. His map of that structure, incorporated into the overall map of the Zuni uplift, gives thus a graphic picture of the horsting in the crystallines where those rocks are exposed in outcrop. Extrapolating beyond the outcrop, we may conclude that the fracture pattern of the crystalline rocks beneath the sediments, outside of the crystalline areas, is much the same, and that the whole horst complex can be visualized in these terms.

In earlier reports of the present project, the writer had postulated a rough gridwork of basement fractures of essentially constant direction over the whole uplift, interpreting the westward swerve of the axis at the north end of the main crystalline area (J-10 to N-9) as a jog along one of the northeastward fracture zones, before the northwestward trend resumes beyond. However, Goddard's map shows that, instead, the northwesterly structures actually change their direction,

bending west-northwesterly for that interval. This picture is more satisfactory, especially when the major structures in the immediately adjacent sedimentary rocks are seen to swing similarly. The "swayback" appearance of the map outline of the Zuni uplift reflects this swing in the basement trends.

The resumption of the northwest trend beyond the north end of the main crystalline area is shown not only by the trend of the sedimentary structures beyond, but also by the joint measurements taken in two small crystalline areas to the northwest, (I-10, and F-12 to E-13), which show strong and consistent northwest trends. That they may be taken as indications of the major faulting in the crystalline rocks is established by the quite dependable parallelism of the joint orientations in the main crystalline area with the faults mapped there by Goddard. Here again, this is not true of every single locality, but the overall agreement is good. It is interesting to note in passing that where this structural relation exists such joint sampling offers a quick means of detecting the main trends of such a terraine; for a few points sampled give information about extensive areas.

The cause of this large swerve in the basement trends is certainly not known, but it should be remarked that the primary foliation of the crystalline rocks is followed conspicuously in some places, especially where that foliation is pronounced and steeply dipping, e.g., at K-10. Areas mapped by Goddard as meta-rhyolite have especially strong foliation. Goddard shows the crystalline area to be quite complicated and made up of a number of rock types, mapped as hornblende gneiss and quartzite, gneissic granite, gneissic aplite, and meta-rhyolite. It seems likely that the fracturing, whatever its age or ages, has followed certain of the strong primary trends in several of these rocks.

The group of faults that lies in general west and northwest of the town of Bluewater (P-11) is enigmatic to the writer. The faults roughly radiate from the northeast corner of the main crystalline area, as Clay T. Smith has indicated in

conversation. Smith has made the further point that the point of maximum displacement along at least some of these faults lies some distance out from the crystalline area, i.e., the displacement does not simply increase toward the core. It would seem that these faults are a consequence of the swerve in the trend of the axis, but no further explanation is here offered.

Timing of the fracturing is a very difficult problem about which this study has little to offer. It is possible that some of the basement fracturing may have had its origin early, even before the oldest sediments were deposited, especially since the coarse Permian (and Pennsylvanian) basal conglomerates suggest that the crystalline area stood high in late Paleozoic time. It is also clear that very recent volcanism has gone on in parts of the uplift, for pottery fragments considered to be one thousand years old have been found in the McCarty's lava flow and the most faulted flanks show deeply incised river meanders which suggest some upward movements during the lives of the present streams. It can only be concluded that the main lines of failure have remained about the same throughout whatever period of deformation has produced the jointing in the various beds, in view of the consistency of this jointing. It is surmised that the movement has been a sort of recurrent jostling among the major basement horsts. Of course, the great part of the deformation is post-Dakota and pre-Tertiary volcanics, the first being tilted and the second not. Other deformations must have been very slight, since the most severe of these, a pre-Dakota tilting which produced a truncation of underlying beds, is hardly perceptible over the uplift. It may be that whatever slight movements there were prior to the full development of the present uplift, impressed on the rocks joint patterns quite similar to those produced by the main disturbance, because the major units involved in it remained the same.

Nature of the Ore-bearing Flank: The ore-bearing flank of the Zuni uplift may now be considered in its relationship to the structure as a whole. It is apparent, first of all, that it is a heavily faulted part of the uplift, probably

the most faulted part. Detailed mapping may eventually show considerable faulting in the southwest part of the uplift also, but the southeast half of the northeast flank will probably still be seen to be the most highly faulted. This faulting, in combination with the sort of gentle flexing shown by the structural contours in the detailed map of part of the northeast flank is responsible for the "scallops" in the trend of the Jurassic-Cretaceous outcrops. Haystack Mountain (Q-13) lies structurally low on one of these. Its very position as a butte indicates that the capping Dakota sandstone is somewhat abnormally low, causing it to outcrop farther updip than does the Dakota rim to the east and south. The map shows how the faults to the northeast of it combine to drop down the quadrant in which it lies. Other parts of the area shown on this map can be seen to be prominently faulted, and farther southeast (T-12 to T-8) the faulting is still more severe, though partly obscured by volcanics.

Volcanics increasingly characterize the ore flank from as far northwest as El Tintero (Q-12) toward the southeast, where the pumice mining area (T-10) is rich in volcanic phenomena. Structure in the Chinle strike valley is almost entirely covered, but the flows at least indicate fissures, and the presence of El Tintero within close view of Haystack Mountain demonstrates the existence of some volcanic channels there.

Implications of the Interpretation

Implications Concerning the Zuni Uplift Itself:

So far, no positive causal relationship between an individual uranium deposit and an individual fault has been established, to the writer's knowledge, and the origin of the ore remains in doubt. It is possible that the ore depositing agents reached the rocks in the Zuni region by travelling upward along fractures. In that case, a tangible relation should exist between the fracture pattern and the ore deposits. What are the facts?

(1) It appears that faulting characterizes the ore-rich areas in a general way, regardless of the lack of known relationships of ore to specific faults. The better prospects recorded to date away from the area shown on the detailed map of part of the ore flank lie also at places of intensified structure. Those nearest to Gallup lie on a severe monocline, which must pass into large basement faults below. Those northeast of Grants are located very near a major fault and volcanic zone. The prospects known so far in areas of little structure are not promising.

(2) Volcanism also seems to go with much of the ore, though only in a general way. Volcanic phenomena demonstrate that the fractures involved are able to carry fluids.

(3) Of more direct interest is the association of fluorite with the uranium minerals in the Grants area, where locally up to 40% of the Todilto limestone is replaced by fluorite. The commercial fluorspar deposits within the crystalline area lie in veins, i.e., in fractures that served as channels and sites of deposition there. But there seems to be no uranium associated with the fluorite and there is no known physical continuity between the two areas, the so-far barren Permian and Triassic flank lying between them. But the strike of the fluorite veins fits into the fracture pattern and the lack of horizontal continuity with the joints near the uranium concentration cannot be taken as proof against a common origin.

(4) Several of the cut-off maps of the individual uranium ore bodies in the Grants region which were shown to the writer are definitely elongated in the principal fracture directions of their particular locality. While this does not prove a hydrothermal origin of the ore, it at least testifies to the uranium-carrying capacity of the joints.

Two aspects of the interpretation of the fracture pattern given above may help to explain why the Zuni uplift as a whole was favorable for ore deposition. One is that its structures increase in severity downward, e.g., a uniform dip at a high

stratigraphic level passes downward into a monocline at a lower level and the monocline in turn passes downward into a basement fault. This is inherent in the general nature of the uplift, as here interpreted, and can be seen, in a manner of speaking, by observing the way in which faults dominate the crystalline core while monoclines and lower dips characterize the outer flanks. It should be visualized as the upward decreasing effects of the movement of crystalline horsts at depth. If, then, it should be true that the source of the ore lay somewhere below the present position of the ore bodies, then it may have been important that the Zuni uplift has a type of structure which facilitates access to greater depths.

The second consideration is that the passive doming of the Zuni uplift resulted in a dilation of the rocks in all directions parallel to the bedding (though perhaps a bulk decrease in volume, due to the vertical forces). This dilation, probably accomplished mainly by the appearance of joints, could have afforded numerous new spaces available for the passage of fluids.

Both of these considerations apply, of course, to most of the Colorado Plateau structures, in view of the common presence of monoclines and horsts.

Implications Concerning Regions Beyond the Zuni Uplift:

If the main lines of fracturing are to be regarded as loci of favorable structure, it is important to note that they extend beyond the uplift itself. Their general strike reappears in structures beyond the limits of the Zuni uplift. One gains the impression that deep fracture zones in the basement rocks control a larger pattern, and that the Zuni uplift itself is only one element of high horsting along them. Thus there is the possibility that some of the northwesterly fracture zones along which the horsting occurred (and individual fractures associated with them) may extend into the Lucero uplift, and also into the Chuska Mountains and the north end of the Defiance monocline, and that some of the northeasterly trending fractures may extend toward the Jemez Springs and Nacimiento areas. At the same time, the "swayback"

in the axis of the Zuni uplift itself shows how sharply the trends may vary from a previous direction. Whatever relationship prevails between the Zuni and adjacent uplifts, the analogy between them at least leads us to suspect the presence of large fracture zones.

On the next larger order of magnitude, the Zuni uplift as a whole lies along a large structural trend which has been referred to in the literature as the "Zuni-Sacramento lineament", extending southeastward toward the Sacramento uplift and the Guadalupe Mountains, and intersecting a number of uplifts along its length. Furthermore, the southern end of the Zuni uplift lies at the intersection of this trend with the Mt. Taylor volcanic syncline and its considerable volcanic and structural features farther to the northeast. It does appear, thus, that the Zuni uplift may owe its existence to its position at the intersection of major trends of long and deep-seated fracture zones. This leads to the conclusion that ore prospects should be sought elsewhere along these trends, especially at their intersections with any similar structural trends.

This direction of thought brings one to the largest size structures of the region, deep-seated zones on the order of magnitude of the Colorado porphyry belt, the elongate zone several hundred miles long and at places fifty miles wide which embraces the Tertiary intrusions and also the principal mining areas of Colorado (Spurr, 1908). Whatever else may be true of the trend, it must be a locus of deep fractures along which intrusive material and ore fluids have been able to rise. When the two lineaments at whose intersection the Zuni uplift lies are followed beyond it, the northwesterly one appears to be headed toward Lukachukai; where it intersects the southwesternmost tip of the Colorado tertiary belt, and from there to proceed past the south end of the Monument uplift to the Circle Cliffs uplift (Waterpocket monocline). Such a hypothetical belt would be parallel to the prominent trends of the La Sal Mountains and the Uncompahgre uplift, which itself

is a member of a similar trend intersecting the Colorado porphyry belt near Ouray, Colorado. The other lineament spoken of can be projected northeastward into a zone of striking volcanism which includes the Jemez Springs volcanic area, the Taos region, and, eventually, the volcanic region in the general vicinity of Trinidad, Colorado. Southwesterly, this lineament might be carried toward Globe, Arizona. These and several other such zones, defined by monoclines, faulting, volcanism, and demarcations between typical Colorado Plateau structure and the more severe structure and volcanism of the Great Basin deserve study as the very large loci of deep-seated fracture belts which afford possibilities of movement, fluid transport, and mineralization.

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ATTITUDE OF BEDS. ANTICLINE IN WOODS
HOLLOW MOUNTAINS, MARATHON, TEXAS

Joint Measurements
Wills Mountain Anticline, Maysville Gap
West Virginia

Sketch Structural Contours on top of
White Medina Sandstone
(Silurian)

EACH JOINT SYMBOL SUMMARIZES 20 OR MORE
JOINTS MEASURED AT THAT POINT

E.G. - ONE SET STRIKING N35W AND
DIPPING 85°, AND A SECOND SET (LESS
CONTINUOUS) STRIKING N15E AND
DIPPING 85° S.E.

1/2 Mile
SCALE