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Forced Folding and Basin and Range Geothermal Systems

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ABSTRACT

Forced or drape folds occur where near-surface rocks deform by bending or folding over the top of faults. These folds can also form around corners or reentrants in complexly shaped uplifted or downdropped blocks and can completely conceal the underlying fault or block.

In the vicinity of three geothermal fields in Nevada, Dixie Valley, Beowawe, and Desert Peak, there is evidence for this structural style which can be recognized by bedding dipping into the valleys or grabens. At Dixie Valley the offset on the Stillwater fault is so great that there is no indication of forced folding in the immediate vicinity of the reservoir but it is possible that some evidence could be buried beneath the valley floor. At Beowawe, forced folding has been recognized in local areas where the topography undergoes sharp changes in strike. At Desert Peak, the faulting is completely concealed by folds which overlie a sawtooth shaped uplift.

INTRODUCTION

In the Basin and Range province heat has proven relatively easy to locate, and many thermal anomalies and reservoirs of varying character have been discovered. Unfortunately, further exploration and ongoing development of these reservoirs, continues to result in an uncomfortably high percentage of dry legs and holes, even in areas which appear to have been extensively drilled and studied.

If the geothermal industry is to be a competitive supplier of electricity, it must reduce costs and even the successful drilling costs represent a sizable percentage of the overall cost of a geothermal project. One obvious way to reduce costs is to drill a higher percentage of successful wells through a better understanding of the geologic structures which create and maintain permeability. However, it is an infinitely complicated, time consuming, and site-specific process to act on this simple statement. Most geothermal wildcat exploratory wells in the Basin and Range province were sited on geologic models, that with today's hindsight, are easy to criticize. Locating successful wells in the Basin and Range province has been as much a matter of perseverance and/or luck by deep-pocketed energy companies as geologic skill and insight.

At three of the existing Basin and Range geothermal developments, Dixie Valley, Beowawe, and Desert Peak, a common structural style of forced folding has been hypothesized or recognized to widely varying degrees. An understanding and recognition of the occurrence of this common structural style represents only a first step in one aspect of the quest for a greater understanding of where permeability is, or is not, located.

FOLD TERMINOLOGY

Many differing types of folds have been recognized and categorized with extensive terminology. Perhaps the broadest or simplest classification is that of "free" and "forced" folds. A free fold is one in which the mechanical properties of the folded rocks themselves, such as ductility, thickness, hardness, etc., control the overall character of the folding, such as size, shape or geometry, distance between axes, etc. The classic concept would be folding in a shallow, compressional environment where trains of symmetrical anticlines and synclines are present. Generally the axes of these folds are straight and strikes can be confidently projected. An example of a free fold in the Basin and Range province is the Virgin anticline near Saint George, Utah.

A forced fold is one in which the shape of the fold is forced on the folded rocks. These occur commonly in areas of vertical tectonics where deeper and firmer "forcing members" either rise or drop, somewhat analogous to movement of a vertical piston. These folds have axes which may sharply change strike and, almost never, does the fold appear symmetrical. These forced folds have commonly been called drape folds because they appear to be draping over underlying features. Most, if not all, monoclines, such as the spectacular Waterpocket fold in Capital Reef National Park in south central Utah, are forced (drape) folds.

FORCED FOLDING

Folds are most easily recognized in layered ductile sedimentary rocks. In the western United States classical Tertiary free and forced folds are exceptionally well developed and exposed in the Colorado Plateau and the Foreland Province in Wyoming and eastern Utah.

The simplest forced fold to visualize is a monocline. Figure 1 shows an east-west cross section through a part of Rattlesnake Mountain located west of Cody, Wyoming. This section shows the fold is highly asymmetrical, even locally overturned, and due to the exceptional exposure, is divisible into four recognizable blocks which are defined by minor subsidiary faults or splays off the main near-vertical fault. The character of these blocks is highly dependent upon the stratigraphy and physical characteristics of the folded rocks and the degree of bending which, to a large extent, is controlled by the amount of offset on the fault moving the forcing member. All four blocks can only locally be recognized even in this classic example. With a differing stratigraphy and fault geometry, it is possible that no individual blocks could be clearly defined. The forcing member in this fold is Precambrian metamorphic rock.

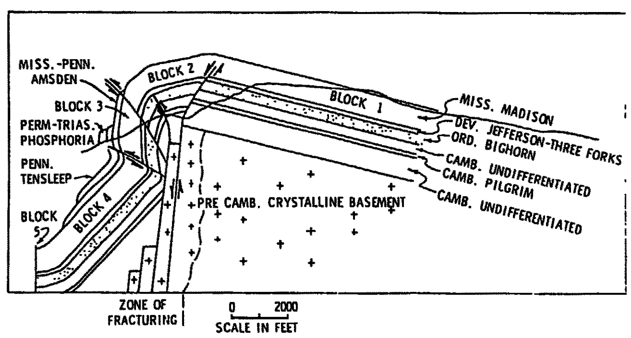

Figure 1. Controlled cross section through the Rattlesnake Mountain forced fold (Stearns and Stearns).

A key point from Figure 1 is that the zone of fracturing along the (in this case) near-vertical normal fault, is not at the point where a Basin and Range geologist might tend to draw a fault trace on a map, that is, at the point where bedrock is in contact with alluvium. The fault trace at this elevation, would be located some distance back inside of the uplifted block in map view.

The geometry of forced folds becomes much more interesting in the vicinity of edges and corners of the forcing members as the folds wrap or drape around corners and bends or over subsidiary blocks (Fig. 2). Strikes of forced fold axes can show even 180° changes in strike over relatively short distances. There is an infinite number of combinations of overall geology, geometry, and stratigraphy that allows each forced fold to be unique in detail. The details of the structure determine where permeability may be localized or enhanced.

One possible subsurface complication of forced folding is shown on Figure 3 where portions of the fold may be moved down along normal faults . Recognizing a feature like this completely buried beneath Quaternary grabens from geophysical data or a few drill holes would be a challenge.

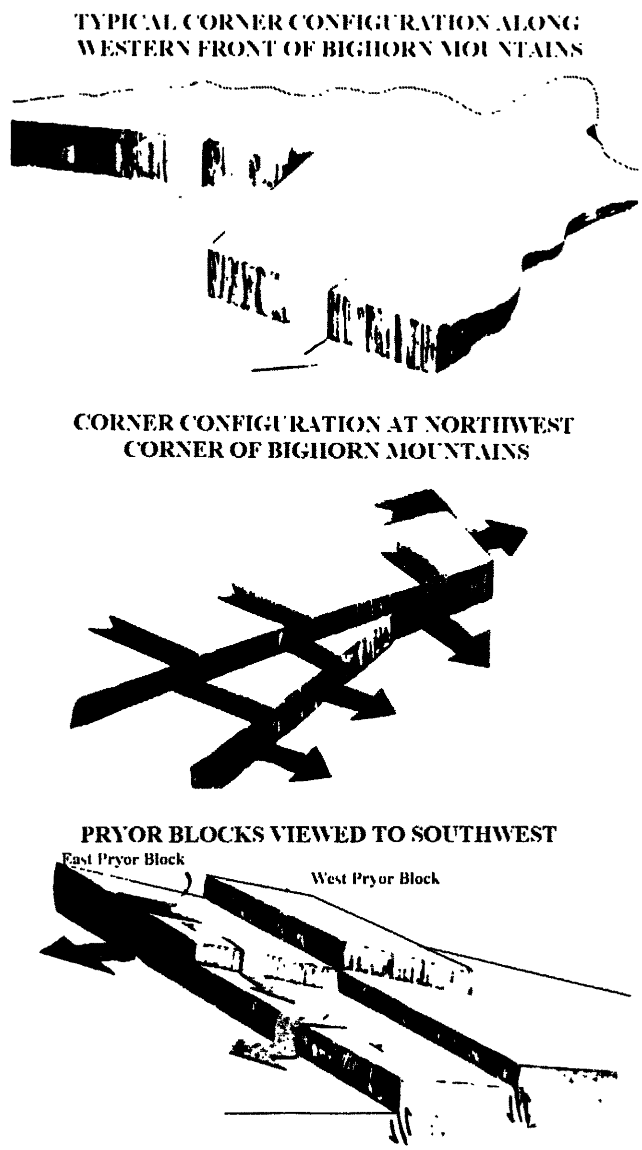

Figure 2. Examples of forced folds wrapping around blocks with complicated geometry (Stearns).

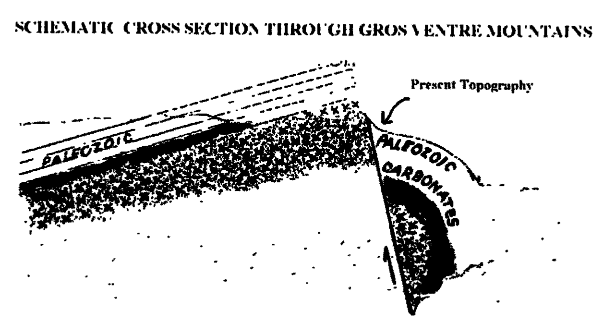

Figure 3. Example of possible subsurface structural complications resulting from forced folding (Stearns).

DIXIE VALLEY

The Dixie Valley geothermal field is, in many aspects, the classic Basin and Range geothermal reservoir developed along an active major range-front fault. The reservoir rocks are well exposed on the east face of the Stillwater Range. The produced reservoir consists of a fractured zone associated with a straight NE-SW segment of the Stillwater normal fault which separates the Stillwater Range from Dixie Valley (Waibel, 1987) .

Permeability in the reservoir consists of a network of fractures in hard rocks of the Jurassic Humboldt Lopolith (a metamorphosed ophiolite) a short distance above a Tertiary granitic intrusive. The Stillwater fault, or narrow fault zone, is the contact between the lopolith and the granitic intrusive and, in the vicinity of the geothermal reservoir has a consistent 52 to 54 degree dip. The fault has no measurable change in dip between depths of 6,000' and 10,000'. The subsurface strike of the fault is parallel to the surface trace of the fault. This is probably the most thoroughly drilled and documented segment of a major normal fault in the Basin and Range province to depths of 10,000'. The vertical offset on the Stillwater fault at the geothermal field is about 11,100' based on the offset on the top of 13 to 17 my Table Mountain basalts.

Incompetent or ductile layers above forcing members can obviously drape or thin only so far before further movement will result in breakage and offset of beds. At this point, the fold or drape becomes discontinuous, and recognizing the eroded structure becomes more difficult. The 11,100' of offset at the Dixie Valley geothermal reservoir has apparently removed any surficial evidence of forced folding that might have once been present.

To the north and south of the geothermal field the amount of offset on the Stillwater fault decreases and there are possible hints of forced folding still exposed. About 10 miles north of the field and just north of the Sou Hills, Figure 4 shows Triassic Star Peak Group carbonate beds dipping into the valley. This area has apparently not yet been mapped in detail. There is no obvious recent fault scarp at the base of the range here to verify the position of a range-front fault. This may be indicating that the Stillwater fault in this area has not actually broken through the folded rocks to create a surface rupture as it has further south. If so, the fault actually may lie some distance into the bedrock.

To the south of the geothermal field there is a large and exceptionally well exposed "syncline" composed of Tertiary volcanic rocks with the axis extending up White Rock Canyon (Hudson and Geissman, 1987 Fig. 4). There are no mapped or recognized anticlines to either side of this "syncline" and the folded Tertiary rocks, although rotated on a vertical axis by at least 25 ° in a counter clockwise direction during their deposition, have not been more recently subjected to regional compression. Hudson and Geissman (1987) briefly attribute this syncline to "differential tectonic tilting of different structural blocks". In the absence of more complete analysis, it is also possible that this "syncline", which is located near the intersection of two major normal faults (Speed, 1976), is a forced fold with the much harder rocks of the underlying Humboldt Lopolith presumably being the forcing member.

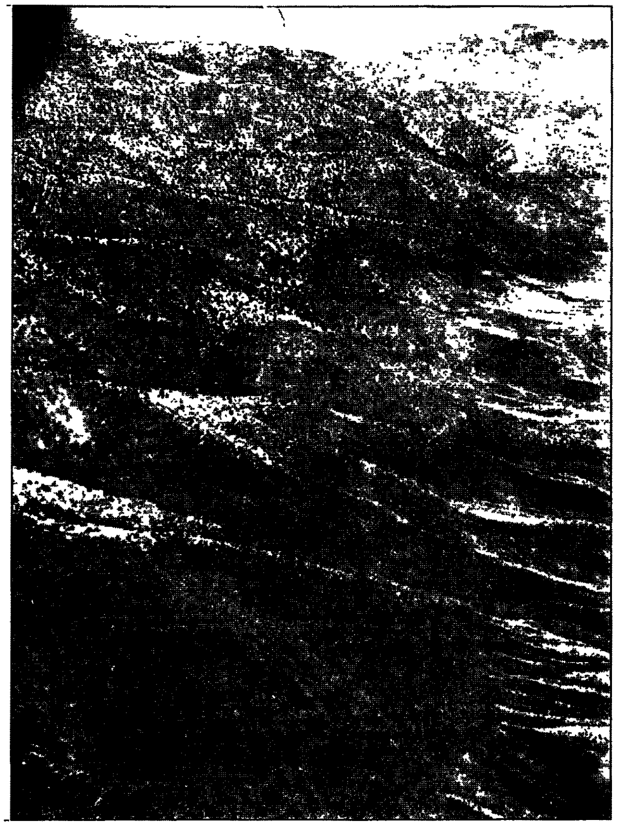

Figure 4. Photograph of possible forced fold along the Stillwater fault north of the Sou Hills in T 26 N, R 37 E.

Evidence for forced folding near the Dixie Valley geothermal field is meager and has not been further investigated. This geothermal field has been developed without benefit of a forced fold geologic model. It is possible that forced folding developed in the early stages of movement on the Stillwater fault but this evidence has been either buried beneath alluvium or lost to erosion as movement on the fault increased. If part of a forced fold has been downthrown into the valley as shown on Figure 3, it has not yet been recognized.

BEOWAWE

The Beowawe reservoir is a fracture network associated with the normal Malpais fault zone where it cuts across a mid Miocene graben filled with Miocene volcanic rocks. Production has been encountered in both the Miocene volcanic rocks and the underlying Ordovician Valmy formation. Published geologic maps of the Beowawe area (Zoback (1979), Smith et. al (1979), Sibbett (1983), Layman (1984), and White (1992)) show complicated fault patterns with multiple intersecting, and parallel faults defining the Malpais fault zone (Fig. 5). However, direct evidence for the individual mapped faults is, at best, tenuous. There are no recent scarps documenting these faults which often are simply mapped near contacts between bedrock and alluvium. Faults with no surface expression are inferred from geophysical surveys. Others have been hypothesized to explain reservoir interference testing results or to assign individual fluid entry points in wells to planes parallel to the Malpais escarpment.

Cross sections across the Malpais fault zone show the bedded Miocene volcanic rocks dipping away from the fault (valley) toward the southeast. No cross sections published prior to 1984 show indications of the volcanic rocks dipping northwest toward Whirlwind Valley. This is inconsistent with the maps showing strata dipping into the valley in the "horst block" immediately west of the sinter terrace and a few miles southwest at Horse Heaven where the Malpais fault sharply bends toward the south (Fig. 5 and, Sibbett, 1983). These inconsistencies were noted by Suneson (1983) in an unpublished report in which he was the first to identify the "monocline" associated with the Malpais fault and was the first to use the terms "forced" and "drape folding" to describe the local structure.

The directly measured offset on the Miocene rocks by the Malpais fault, in the vicinity of the production wells, is about 1,200'. Additional offset associated with the folding increases the total offset to 1,900' to 2,500' (Suneson, 1983). This is one-tenth to one-fifth of the offset on the Stillwater fault at Dixie Valley. This smaller offset has resulted in the local preservation of surficial features immediately southwest of changes in strike of the Malpais fault which suggest folding of the hard brittle volcanic rocks displaced by the Malpais fault.

A Suneson cross section through the west end of the silica terrace area at Beowawe (Fig. 6) clearly shows the "monocline" being broken by four more or less parallel faults of 300' to 900' displacement with a total combined throw of 1,900'. Suneson noted that most fault traces cannot be mapped geologically, but did (reluctantly ?) accept many of the surface traces shown on Figure 5 as concealed faults and integrated them into Figure 6. An alternative interpretation of Figure 6 is that the west end of the terrace area has broken into several blocks similar to those shown on Figure 1 and in the area of greatest flexure the brittle rocks were extensively fractured and eroded leaving only rather subtle hints of the overall structure.

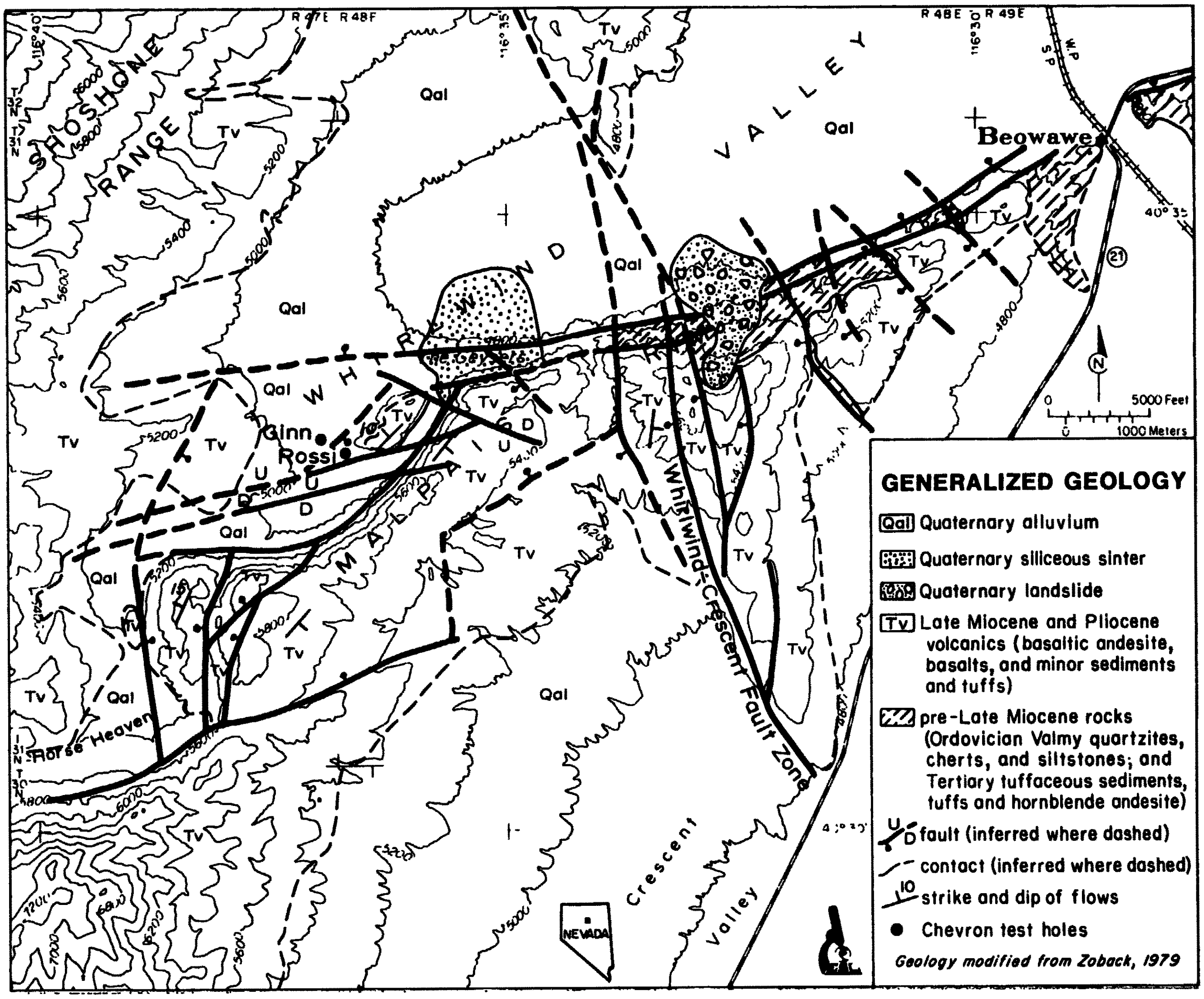

Figure 5. Representative published geologic map of the Beowawe geothermal field area (Smith et. al 1979).

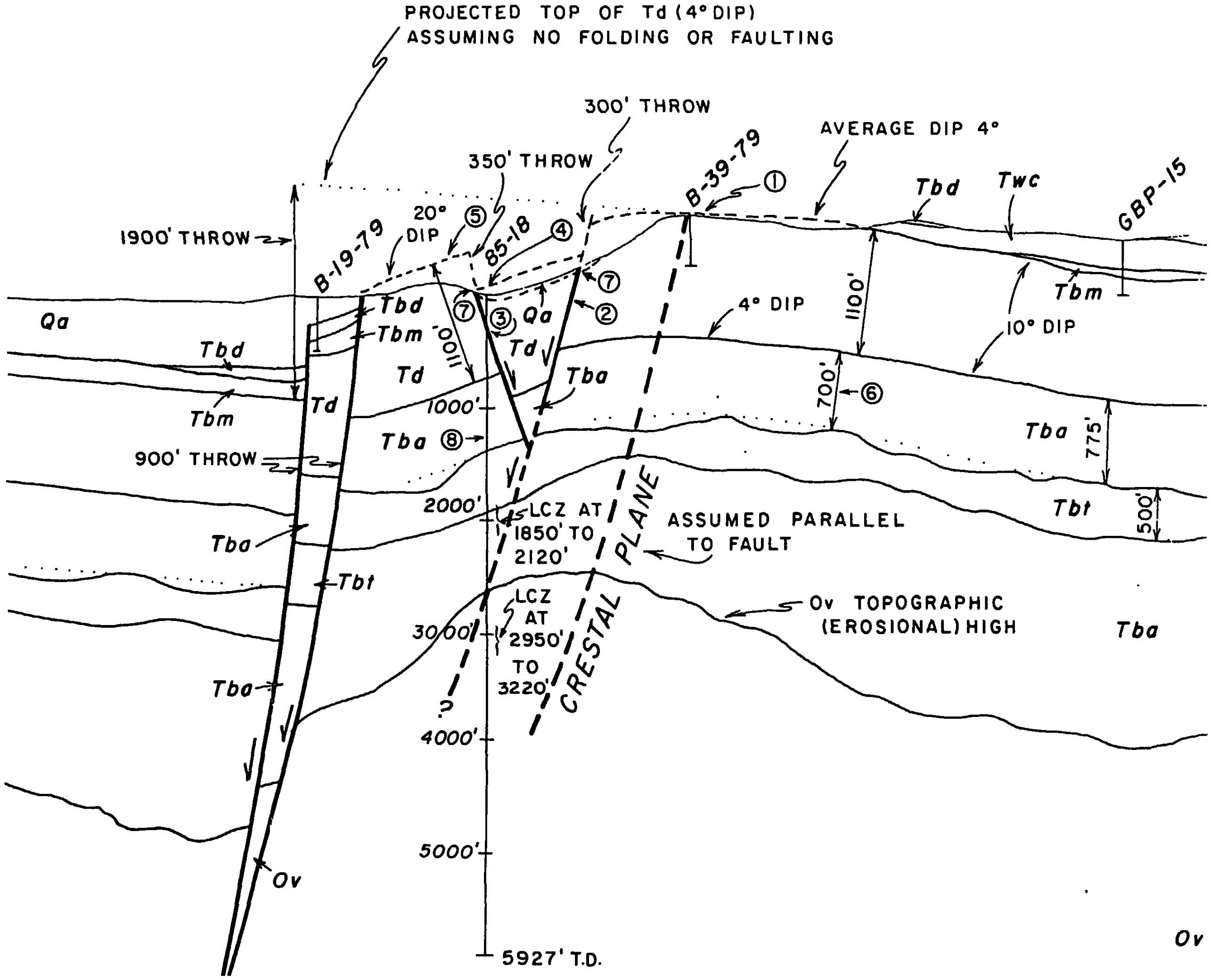

Figure 6. Portion of Suneson (1983) cross section D-D' through well 85-18 in the Beowawe geothermal field. This section suggests four distinct faults and shows the crestal plane of the monocline. An alternative section could just as easily show one main fault near the crestal plane and the other faults may be subsidiary features as shown on Figure 1.

Instead of three or four faults for which there is little or no solid evidence, there may be one dominant fault which does not crop out at the surface but lies somewhere beneath the crest of the monocline. Where the Malpais fault is relatively straight, there is no remaining surface evidence of the monocline so it is unknown if the folding is continuous between Horse Heaven and the silica terrace.

At Horse Heaven there is a major bend in the axis of the Malpais scarp where a more complete forced-fold wrapping around the corner of a block can be much more clearly identified (Figs. 5 and 7).

Suneson has proposed a relay fault interpretation to explain the overall structure at Beowawe wherein the Malpais fault zone is composed of a series of en echelon curved faults along strike. The forced folds develop at bends where throw is transferred from one fault to another. As these faults are not exposed, it is difficult to be certain whether there is one or multiple faults

Figure 7. Photograph of Whirlwind Valley and the Malpais Rim looking east-northeast. The Horse Heaven forced fold is the rounded portion of the escarpment. The power plant is visible in the upper left and just behind and to the right of the plant is the isolated hill which is a remnant of the forced fold shown in Figure 6. The silica terrace is hidden from view.

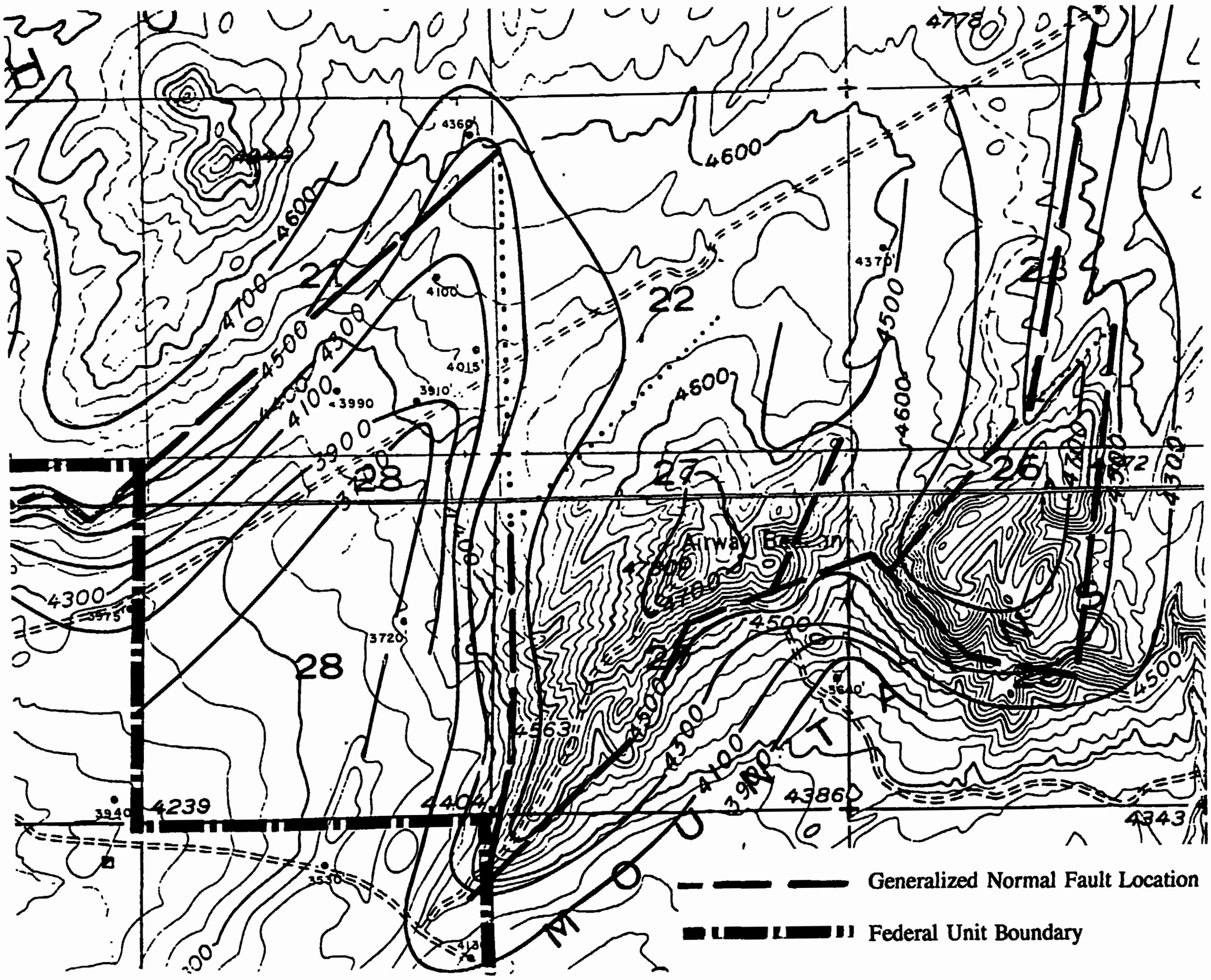

Figure 8. Map showing the elevation of the Truckee-Chloropagus contact at the Desert Peak geothermal field. This map is based upon both surface exposures from Figure 9 and drillhole data as shown by the individual data points on the map.

making up the Malpais fault zone. Detailed discussion of this topic is beyond the scope of this paper, but it is an understanding of details like these that ultimately will increase the success rate in finding permeability. Layman (1984) has presented the most thorough, published interpretation on the location of permeability at Beowawe.

At Beowawe the primary implication of forced folding is that the actual Malpais fault, as defined by the zone of maximum movement or offset, may not actually intersect the surface at the base of the Malpais Rim and, therefore, calculations of the dip of the fault may be incorrect: - being calculated as steeper than it really is. Incorrect or inconsistent dip calculations have even resulted in past working hypotheses that there were actually two parallel and completely separated faults in the area.

The question of dip becomes quite important when wells, such as well 85-18 (Fig. 6) are located close to the bottom of the Malpais Rim. Shifting the fault a relatively short distance beneath the upthrown block has a substantial reduction on the calculated dip. Another problem in calculating fault dips at Beowawe is that dips can reasonably be expected to change as the strike of the fault varies. Unfortunately, the Malpais fault in the vicinity of the Beowawe geothermal field is not straight for any distance so there is no known "baseline" on which to develop a precise local model of fault strike vs dip.

In summary, the Beowawe area is a case where 1,200' to 2,500' of offset has created recognizable forced folding only near obvious topographical bends in the Malpais Rim. It is not known if the folds are continuous between the bends as surficial evidence is lacking. Future detailed subsurface work may shed further light on this question but, until a more refined interpretation becomes available, the explorationist should be aware that there is a definite possibility that the Malpais fault does not intersect the surface at the base of the Malpais rim. The degree or recognizable extent of folding at Beowawe is intermediate between that at Dixie Valley and Desert Peak.

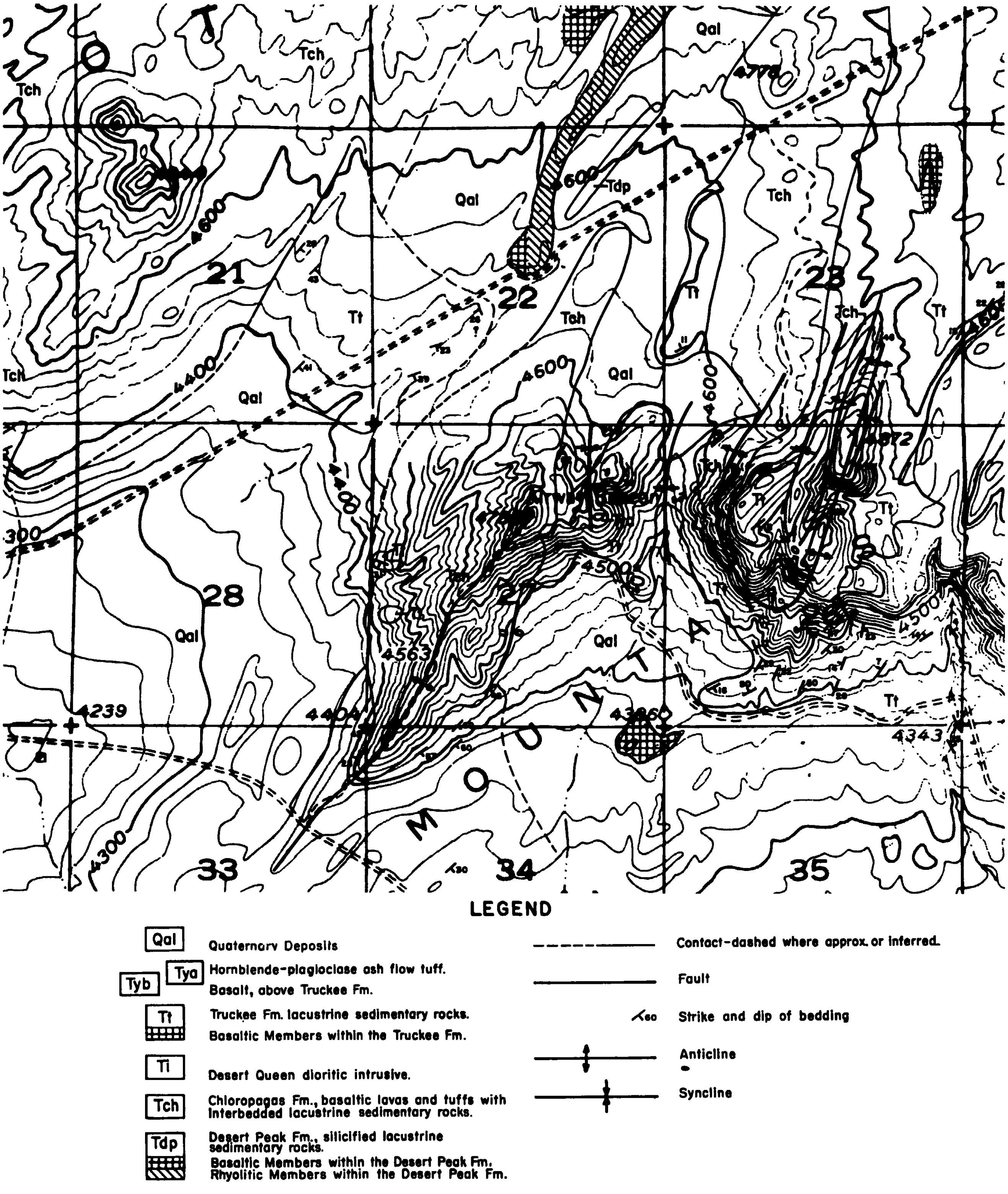

Figure 9. A portion of an unpublished geologic map of the Northern Hot Springs Mountains by the author. The production wells supplying the Desert Peak power plant are located in the southeast quarter of section 21.

DESERT PEAK

At Desert Peak, Nevada the topography in the vicinity of the geothermal field is subdued, generally covered with a thin veneer of sand, and there is no obvious linear structure which has been recognized as creating and controlling permeability. Drilling results and geologic remapping since 1980 have resulted in an updated geological model of the Desert Peak area which greatly simplifies the interpretation of Benoit et al. (1982). Desert Peak now appears to be a case where forced folds have completely concealed structures, presumably normal faults, which, in turn, control the permeability.

The generalized stratigraphy at Desert Peak, from top to bottom, consists of a thin veneer of windblown sand and Quaternary alluvium (generally tens of feet thick but up to a couple hundred feet) overlying lacustrine sediments of the 600' to 700' thick Pliocene Truckee Formation. The Truckee Formation overlays the Mio-Pliocene Chloropagus Formation which consists of up to 2,900' of primarily rubbly basaltic to andesitic flows and agglomerates. Beneath the Chloropagus there is a series of Miocene and Oligocene silicious tuffs and lava flows which overlie metamorphosed Mesozoic sedimentary and igneous rocks.

In determining the structure in the area, the most accessible contact in the vicinity of the geothermal field is the Truckee-Chloropagus, both from surface mapping and shallow drillhole data. A simple and well constrained plot of this contact versus elevation (Fig. 8) shows a sinuous pattern of anticlines and synclines plunging toward the SSW with a structural relief of a little more than 1,000'. This pattern of an apparently meandering zone of high gradient was also a dominant feature on the Bouguer gravity map of the area (Benoit et al., 1982 Plate 14). Only after post 1980 drilling was the linkage between the gravity pattern and the structure recognized.

A portion of the most recent and unpublished geological map of the area (Fig. 9) offers further insight into the structural style of the area. In the northern part of section 26 and the south central part of section 23 there are some beautifully exposed asymmetric folds which are interpreted to be forced folds. The main fold axis has a 180 degree change in direction as it wraps around a small (1/4 mi^2) topographically high block. This small area can serve as a model for the larger area by knowledge of the old adage that small folds on the flanks of larger folds often mimic the larger folds.

The overall picture that emerges from the gravity, unpublished temperature data, and both surface and subsurface geology at Desert Peak is one of uplift along the north side of a sinuous or sawtooth-shapped boundary. Within this zone there are a series of southward plunging anticlines (or antiforms)and synclines. These plunging folds are interpreted to be forced folds draping over and wrapping around the edges of a sawtooth-shaped uplift. In the reentrants such as the NE 1/4 of section 21 and the SE 1/4 of section 27, the deformation in the Truckee formation is so extensive that consistent or mappable bedding can not be found. It is in these reentrants where bedding is impacted by deformation from two directions and is extremely contorted.

The topographic offset across the uplift at Desert Peak is relatively small, not exceeding 600', while the structural offset is on the order of 1,000'. Presumably, this offset reflects the magnitude of the offset on buried normal faults, and the relatively small offset also explains why the folds in these relatively soft rocks are so beautifully developed and preserved. Folding has been able to accommodate all of the fault offset.

It is also important to note that there is only one small fault shown intersecting or breaking through to the surface on Figure 9, which is in marked comparison with plate 13 in Benoit et al. (1982) where numerous located, concealed, and inferred faults were shown. A forced fold model does create the problem of trying to accurately locate the fault(s) at depth, especially where it crosses thicker formations that may not be completely offset by the fault(s). Generalized fault locations are shown on Figure 8. An additional complication at Desert Peak, where the production wells in the SE 1/4 of Section 21 are located between two converging normal faults, is in determining which of the faults is responsible for the permeability.

In summary, the normal faulting, which must be present at Desert Peak, is completely obscured by overlying forced folds which have draped over and wrapped around corners and edges of an uplifted block with a sawtooth-shaped southern edge. The folds can be a useful tool in generally locating the fault locations, but they do make it more of a challenge to understand the faulting and its associated permeability, especially in the reentrant regions such as the NE 1/4 of Section 21. Obviously, much additional interpretation is needed to understand and accurately predict the location of permeability at Desert Peak.

CONCLUSIONS

A comparison of the Dixie Valley, Beowawe, and Desert Peak geothermal fields indicates that forced folding may be commonly associated with the normal faulting that plays a dominant role in the creation of geothermal reservoirs in the Basin and Range province. In these areas the rocks exposed in the uplifted ranges locally dip toward the valleys and this relationship is common in the Basin and Range province. The degree to which the folds develop and mask the faults depends upon the local stratigraphy and the amount of offset on the fault. The smaller the offset, and the more plastic the near surface rock, the more likely that the folds will be intact and not allow the fault to penetrate completely to the surface where it could leave a recognizable scarp.

Recognizing this structural style should aid both the explorationist and developer in developing geologic models that predict the location of subsurface permeability with a greater degree of accuracy. Even though forced folding in Tertiary volcanic rocks has been recognized at Beowawe and Desert Peak, there remains much detailed work to be performed to truly understand the almost infinite possible relationships between structure, stratigraphy, and permeability.

Future geothermal exploration in the Basin and Range province should be conducted with the knowledge that forced folding may be common throughout the province, even in rocks that may appear too brittle or hard to fold. Where bedrock dips into or beneath the valleys it may be erroneous to presume that normal faults separate the bedrock and alluvium. Lastly, even the total absence of indications of forced folding on the surface does not mean that remnants of such folding are not buried beneath the alluvium.

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