STRUCTURE OF THE REDONDO CREEK AREA, BACA PROJECT, NEW MEXICO: IMPLICATIONS CONCERNING THE NATURE OF PERMEABILITY/PRODUCTION AND RECOMMENDATIONS FOR FUTURE DRILLING

Summary and Recommendations

Permeability and productivity of wells in the Redondo Creek development area depend on the ability to intersect open throughgoing fractures. Experience has proven the permeability to be highly heterogenous and probably anisotropic. Recent detailed field mapping combined with stratigraphy and static temperature profiles of wells in the development area provide the basis for interpreting the nature of the producing permeability/fracture system. This provides a foundation for planning future producing wells and redrilling selected nonproducers.

Fractures in this area include joints formed during cooling of the volcanic units and numerous major extensional faults associated with resurgent doming. Cooling joints have linear to curvilinear trends, dip shallowly, and are locally abundant. Their variable density and orientation, lack of continuity, and the dramatic decrease in joint density towards the base of cooling units within the Bandelier Tuff (Smith and Bailey, 1966), in concert, suggest that the permeability required for economic

production is not related to these structures.

Shallow and steeply-dipping normal faults are the two major fault orientations which have been recognized in the Redondo Creek area. Shallow-dipping structures are characterized by irregular surface trends, dip separation movement of less than 300 ft., and dips of less than 40°. The trace of these low angle fault zones project above the top of the geothermal reservoir (depth assumed to be greater than ≈ 3000 ft. below surface datum) indicating that they have no effect on production.

Steeply-dipping fault zones are typified by linear surface traces, dips of 60° to 70°, and dip separation movement of up to ~ 1800 ft. They commonly contain abundant surficial thermal manifestations. The projection of steeply-dipping faults through well courses coincides with zones of total lost circulation and isothermal static temperature profiles or abrupt temperature reversals. These features indicate that the steeply-dipping faults are undoubtedly producing, permeable conduits. All producing wells (Baca #'s 4, 6, 10, 11, 13, and 15) intersect or closely approach (within ~ 100 m) steeply-dipping fault zones below the casing point whereas nonproducers do not. Therefore, we conclude that permeability and production are controlled by major, through-going, steeply-dipping faults.

Should be shown on maps

NEED ALL T - LOGS

Future wells should be targeted towards the intersection of the base of the Bandelier Tuff with steeply-dipping fault zones and/or towards the intersection of faults with opposite vergence (as shown on the attached map).

Rationale for base of
the Bandelier described in
this report?

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Introduction

The variable productivity of wells in the Redondo Creek development area is directly related to the density, orientation, and nature of structure-controlled permeability encountered in each well. Structures which may act as permeable conduits consist largely of thermally produced joints/fractures and fault zones. These features are primarily the result of the complex Miocene to Recent volcanic-structural evolution of the Jemez Mountains which is summarized in Table 1 (a more complete discussion will be presented in a companion report by Behrman and Knapp, 1980).

Need this report!

In general, the area surrounding Redondo Creek comprises a resurgent dome which developed within the Valles Caldera probably in response to the rise of an underlying magma chamber. Extension associated with doming resulted in brittle failure of the rocks overlying the magma chamber and the development of the Redondo Creek Graben. Faults which define the graben contain a very large component of dip separation movement.

Shallow faults should be assoc. w/ graben formation.

These structures have been recognized during detailed field mapping of the Redondo Creek area and dip orientation determined from stratigraphic and temperature data from development wells. In addition, joint and fracture orientation and density data were collected at over 80 localities to determine the dominant trend/dip and regime associated with joint formation. The aim of this report is to integrate aspects of jointing and faulting with well productivity to determine the most significant structural

TABLE

SUMMARY OF THE LATE TERTIARY GEOLOGIC EVOLUTION OF THE JEMEZ MOUNTAINS

Age (m.y.b.p.)	Volcanic Events	Structural Events
15.0 to 10.0		Normal faulting associated with Rio Grande Rift formation. Deposition of Santa Fe Formation within graben.
10.0 to 2.1	Widespread extrusion of precaldera basaltic to rhyodacitic rocks of the older Keres Group (Paliza Canyon Andesite and related rocks) and the younger Polvadera Group (Tschicoma Formation and related rocks).	Continued extensional tectonics and intra-rift deposition.
1.4±		Emplacement of a silicic magma chamber and possible formation of an incipient fracture system.
1.4±	Ash flow eruptions of Otowi (lower) Member of Bandelier Tuff.	Simultaneous collapse of magma chamber along ring fracture system forming Toledo Caldera.
1.4 to 1.05±	Extrusion of Cerro Toledo and Cerro Rubio Rhyolite domes.	Deposition of Caldera Fill (0) within Toledo Caldera. Renewed silicic magma activity and possible development of a second fracture system.
1.05±	Ash flow eruptions of Tshirege (upper) Member of Bandelier Tuff.	Simultaneous collapse along younger ring fracture system forming Valles Caldera.
1.05 to 0.9±		Infilling of Valles Caldera (landsliding, fluvial deposition) forming Caldera Fill (1).
1.0 to 0.9	Extrusion of Deer Canyon and Redondo Creek Members of the Valles Rhyolite.	Continued intra-caldera deposition forming Caldera Fill (2).
0.9 to ?	Possible extrusion of older flows of Valle Grande Member of Valles Rhyolite along younger ring fracture system.	Emplacement of additional silicic magma and concommitant resurgent doming in the central portion of the Valles Caldera. Extension associated with doming results in the development of steeply-dipping normal faults which define the Redondo Creek Graben. Low-angle faulting occurs adjacent to unstable slopes formed by movement on steeply-dipping faults.
0.9 to 0.1	Continued extrusion of Valle Grande Member and subsequent members of Valles Rhyolite along younger ring fracture system.	Possible continued resurgence of the southwestern part of the dome.

contributor to permeability. Our interpretation of the structural control of permeability is the basis for developing a model for the location and orientation of future wells.

The geology of the Redondo Creek area is shown in Figure 1 with the stratigraphy subdivided into: (1) Bandelier Tuff; (2) Caldera Fill (1); (3) Deer Canyon Rhyolite; (4) Redondo Creek Rhyolite; (5) Caldera Fill (2). Lateral variations as well as age relationships of these strata are summarized in Figure 2.

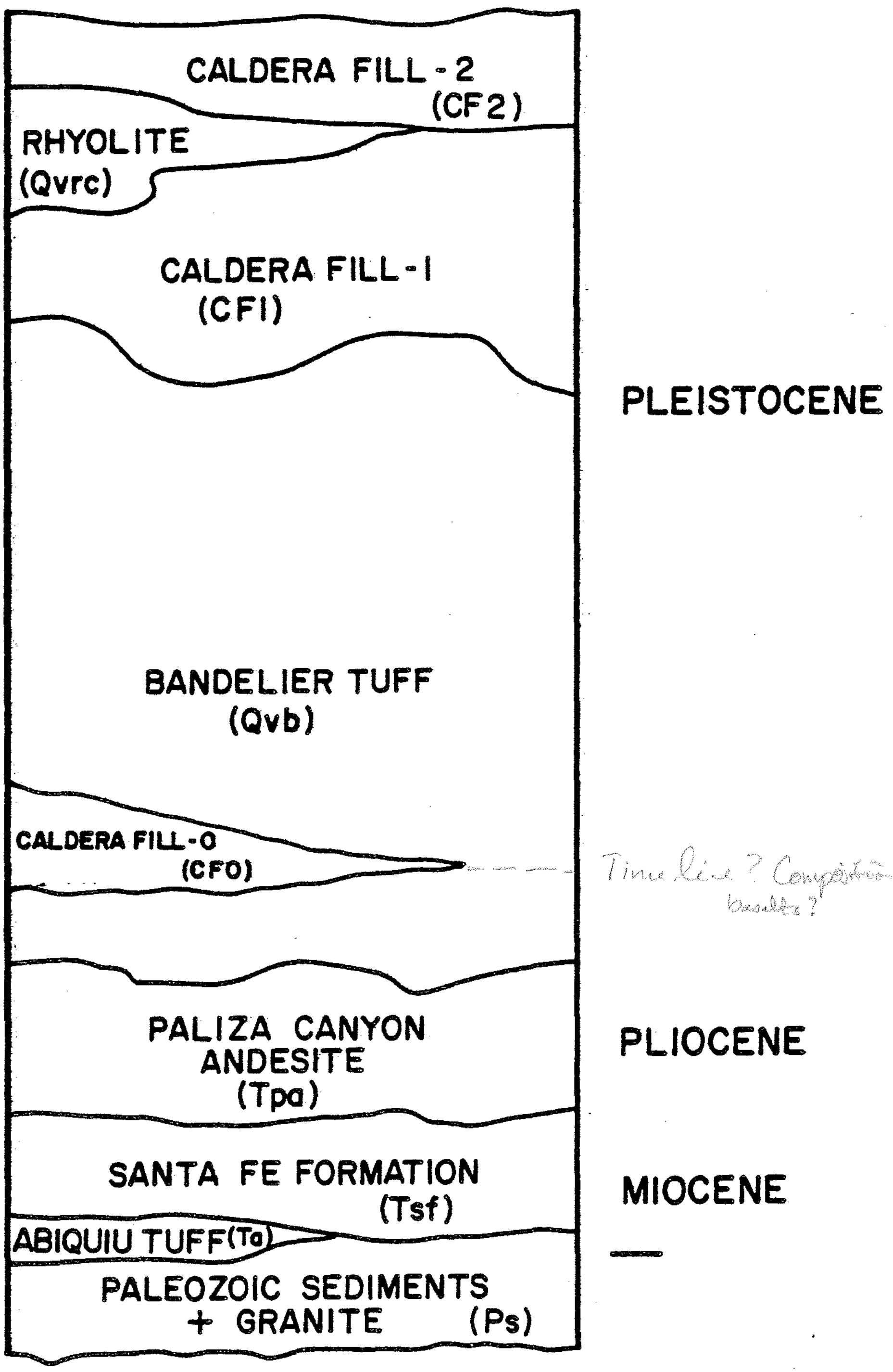
Structure

Joints

Joint orientations and abundances (number of fractures per 10 ft. interval) were measured for all fracture sets at 83 localities within the Redondo Creek development area. As the production interval is located within or below the Bandelier Tuff, the data discussed in this section only pertain to measurements on outcrops of Bandelier Tuff. Owing to the inherently poor exposure of Bandelier Tuff in the southeast part of the graben, most of the structural data are from localities northwest of Redondo Creek.

Joints in the Bandelier Tuff are characterized by linear to curved surface trends and an absence of lateral continuity

FIGURE 2 BACA STRATIGRAPHIC SECTION



Time line? Composition? ie. basaltic?

beyond 10 to approximately 40 ft. along strike. Local permeability is documented by the presence of iron staining on some of these surficial structures. Joint orientations, shown on a contoured plot of poles to planes on a lower hemisphere stereonet projection (Figure 3), display a marked anisotropy. In a regional scale, the number of low-angle joint sets is greater, but locally steeply-dipping structures dominate. Both joint sets are usually present at the same locality.

Steeply-dipping joints have variable orientations, but are generally typified by a N50-80°E strike and a 70° to 90° dip. Joint abundance commonly ranges from 3 to 10 per 10 ft. interval. Similar structures have been recognized by Smith and Bailey (1966) in Bandelier Tuff outside of the Valles Caldera and are interpreted to be thermally produced by contraction of the tuff during cooling. In addition, Smith and Bailey documented a dramatic decrease in joint density towards the base of a cooling unit. If these are cooling joints, then they should occur only sporadically throughout the Bandelier Tuff and, in general, decrease in density towards the base of the Bandelier Tuff (which is the producing interval). This suggests that steeply-dipping joints probably (?) have little effect on production. - unless they are genetically related to faulting.

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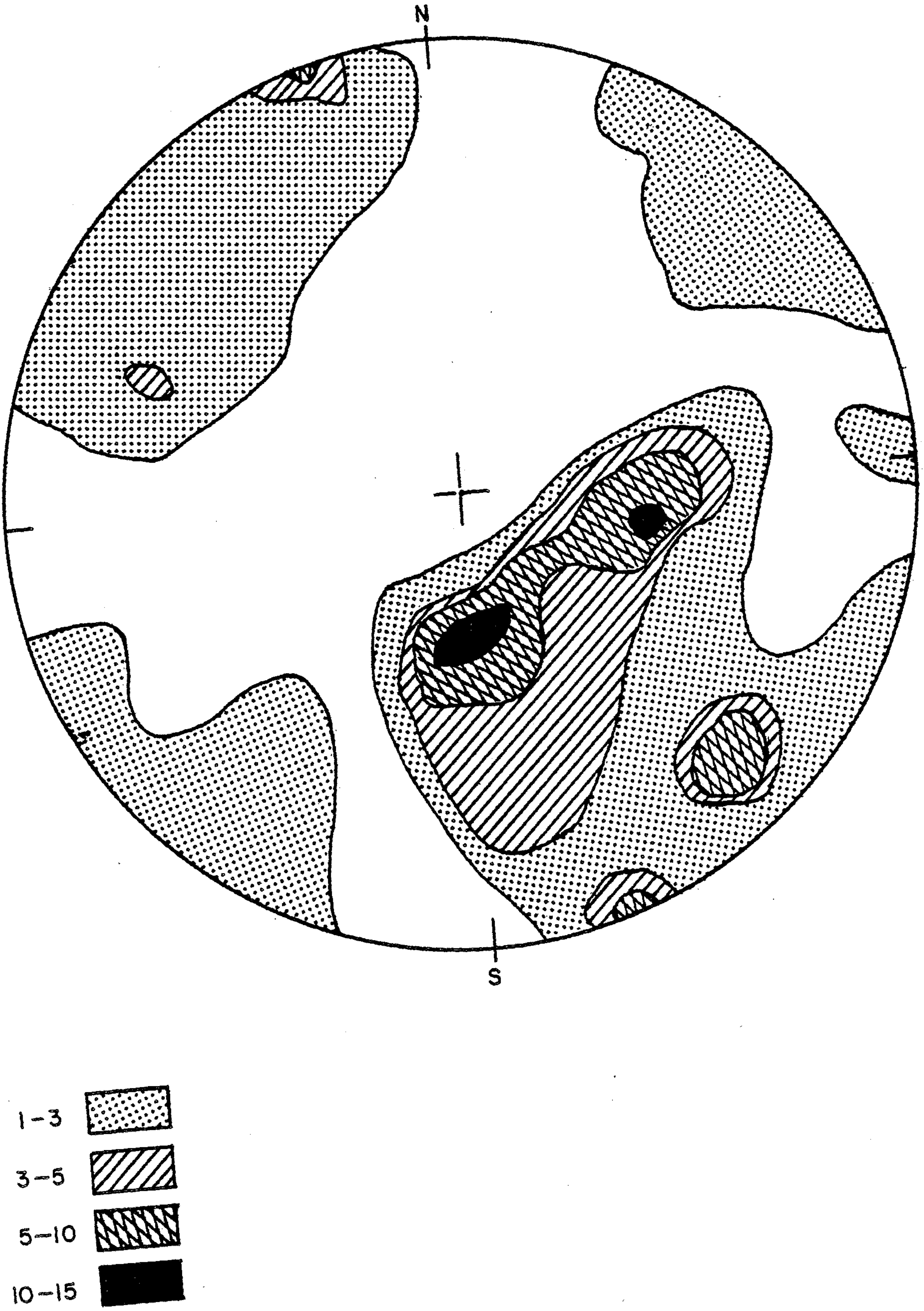
Shallow-dipping joints are characterized by a northeasterly strike and a 30± 10° dip (Figure 3) which roughly coincide

Figure 3. Density of Poles to Fracture Planes Measured in the Bandelier Tuff. Poles are projected to the lower hemisphere, and density is in the units of percent abundance - number of fractures per 10' - per 1% of total stereonet area. The more densely patterned areas depict the more abundant fracture orientations. The fractures predominantly strike northeasterly and dip westwardly 30° ± 10°. This orientation parallels the orientation of the northwestern side of the resurgent dome. Fracture abundances were measured at 72 stations.


N
S
1-3
3-5
5-10
10-15

with the structure contours of the northwest limb of the resurgent dome. Within this broad north-east trending joint pattern, there are minor but a significant number of joints which have north-south and east-west strikes (Figure 3). Neither of these minor joint orientations correspond to geomorphic features within the development area, but the broad northeasterly trend approximately parallels Redondo Creek. The abundance of these structures ranges from approximately 7 to greater than 40 per 10 ft. interval. The origin of the shallow-dipping joints is probably related to either thermal contraction or resurgent doming. If they are thermal contraction features, then fractures of similar orientation should exist throughout the Bandelier Tuff. These structures have been recognized in core from the Alamo Canyon #1 well, but are not abundant. Alternatively, if these structures are the result of unroofing associated with resurgent doming, then they are probably restricted to the upper portions of the Bandelier Tuff. The parallel orientations of fractures and dome structure are consistent with this hypothesis. The equivocal nature of this preliminary data preclude determining the significance of shallow-dipping joints to production permeability.

In conclusion, the variable density and orientation, lack of continuity, and decrease in joint density towards the base of cooling units within the Bandelier Tuff suggest that the permeability required for economic production is not related to joints. The presence of some steam entries and minor lost circulation zones which apparently are not related to fault zones indicate that joints may contribute a variable but minor amount to production.

Fault Zones

The Redondo Creek development area is situated within a complex graben structure which is approximately symmetrical about Redondo Creek (e.g., faults northwest of the creek dip to the southeast whereas those southeast of Redondo Creek dip to the northwest). Detailed field mapping (Fig. 1) has revealed the presence of two distinct structural styles, low-angle and high-angle fault zones. The existence of both fault orientations is confirmed in development wells by abnormal variations in thicknesses of stratigraphic sections and the coincidence of lost circulation zones and perturbations in static temperature profiles with projections of fault zones.

The chronology of faulting is summarized as follows:

1. Movement on steeply-dipping northeast striking graben faults and northwest trending cross faults.
2. Movement on low-angle faults.
3. Displacement on steeply-dipping faults within and southeast of Redondo Creek.

where data is sparse

The relative age of low-angle faults is determined by the observation that they cut some steeply-dipping faults and that they are symmetric about the graben axis - Redondo Creek. However, a steeply-dipping fault F(3), whose surface trace coincides with Redondo Creek, cuts all low angle fault zones as well as high-angle structures northwest of Redondo Creek. This indicates that the youngest fault movement in this area is associated with reactivation of steeply-dipping structures within and southeast of Redondo Creek. Since steeply-dipping faults southeast of Redondo Creek apparently are the youngest structures in this area, we show those faults, F(3) through F(9), cutting all other faults in Figures 6 through 14.

direction
reactivati

Shallow-Dipping Faults

All shallow-dipping fault zones are characterized by curvilinear surface trends (Figures 1 and 4), dip toward Redondo Creek (Figures 6 through 14), and commonly contain less than 400 ft. of dip separation. The intersection of the surface trace of individual fault zones with equal elevation contours geometrically define the dip of each structure. Dips calculated by geometric methods range from ~ 30° to 45°. In addition, the thickness of lithologies encountered in Baca #'s 17 and 15 (Figures 9 and 11) compared with measured surface dips and thicknesses require the presence of shallow-dipping (~ 30° to 40°) structure. A dip of 40° on these structures (as shown on all cross-sections) yields the "best fit" of surface geology with stratigraphy encountered in Baca #'s 17 and 15. As the strike and dip of individual faults vary, it seems likely that these structures define irregularly curved surfaces.

The projection of these fault zones reach a maximum depth of less than 2000 ft. below surface datum which indicates that they do not enter the production interval (located approximately 3000 ft. below surface datum). Therefore, low-angle structures are not production targets. It should also be noted that many low-angle faults define lineaments on air photographs which indicates that lineament mapping alone is insufficient geologic criteria for well targeting.

Low-angle structures are mechanically significant to the geothermal development of this area because Baca 17 failed during production tests where a shallow-dipping fault intersected the well course (Fig. 8). This does not indicate that casing failure on Baca 17 was the result of fault movement, but sloughing of the fault contact combined with a lack of returns while cementing the casing may have provided an environment that localized buckling when stressed. Careful cement jobs are a requirement in wells which penetrate these structures.

Steeply-Dipping Faults

All steeply-dipping fault zones are characterized by linear surface traces (Fig. 5), northeast trends, and dips which range from 65° to 80°. Locally, these faults contain up to 1800 ft. of dip separation. As these structures appear to be important to production (permeability), features which define dip and amount of movement are discussed individually. These faults have been labeled F(0) to F(8) in Figures 1 and 5.

Several west to northwest trending steeply-dipping fault zones are also present in the development area (Fig. 5A), but are not discussed owing to their minimal displacement and inability to define their surface trends. It should be noted that most of the offset on these faults can be explained by pure dip slip movement. The significance of these structures to production is unknown.

F(0)

F(0) parallels the eastern edge of Redondo Border and, to the south, probably continues into Mormon Canyon (Fig. 1). This fault zone demarcates the northwestern limit of the Redondo Creek graben. As F(0) is cut by several west-northwest trending fault zones, displacement on this structure probably occurred early in evolution of the graben structure. Movement consists of an apparent dip separation of $\approx$ 1200 to 1600 ft.

which is calculated from the correlation of the projected base of Caldera Fill (1) west of Redondo Border with exposures adjacent to Baca 15 and Baca 17. The dip on this fault has been determined from the lithologies encountered in Baca 16 and lost circulation data from Baca 17. In Baca 16, the absence of Caldera Fill (1) which is present in all surrounding areas can only be accounted for by tectonic removal and defines the intersection of F(0) with the Baca 16 well course. This well lithology data, together with the mapped surface trace of F(0), require a dip of ~ 65°. A zone of complete lost circulation and a temperature reversal (rig survey) in Baca 17 coincide with the projection of a 70° dip on F(0). These data indicate that the dip on F(0) may vary slightly but is bracketed between 65° to 75°.

F(1)

F(1) traverses the southern part of the development area and is truncated by F(3) near Baca 6 (Fig. 1). The determination of the amount of displacement is uncertain due to the presence of adjacent west-northwest trending cross faults with an unknown amount of movement but can be bracketed between 500 to ~ 1200 ft. assuming pure dip slip movement and projecting the Bandelier Tuff-Caldera Fill (1) contact over Redondo Border.

As F(1) separates Bandelier Tuff on the northwest from younger strata on the southeast, this fault must dip towards the southeast. However, the dip angle is equivocal. The relative linearity of this fault zone suggests that the dip is greater than ~ 60°. A dip of 70° correlates with a zone of lost circulation in Baca 12, but steeper dips also fit the observed geology. Since steeper dips on F(1) do not fit the lost circulation data in Baca 12, and because F(1) has an identical orientation and apparent movement as F(0) (which has a 70° dip), we show a dip of 70° on F(1) in Figures 12 through 15. It should be noted that very steep dips are not typical of faults in graben/extensional tectonic regimes.

F(2)

F(2) parallels and contains a similar sense of displacement as both F(1) and F(2) which suggest that all three of these faults originated during the same phase of graben formation. Offset sections of the base of Caldera Fill (1) document an apparent throw of ~ 400 ft. (southeast side down) on F(2). As with F(1), the dip on F(2) is uncertain, but we presume its similarities with F(0) and F(1) require that F(2) has a dip of ~ 70°. F(2) is also truncated by F(3).

F(3)

F(3) is present along the entire length of the Redondo Creek development area and demarcates the northwestern limit of northwest dipping fault zones. As this structure cuts both low-angle and high-angle faults, the youngest movement in this region probably occurred along F(3). In the southern part of the development area, this fault consists of a single strand, but north of Baca 11 F(3) splits into at least three segments: F'(3), F''(3), and F'''(3). The juxtaposition of younger strata against older rocks to the southeast indicates that F(3) dips towards the northwest (assuming major movement consists of dip slip displacement). There are no unequivocal data which define the dip on F(3), but linear surface expression of this structure is suggestive of a relatively steep dip. A dip of ~ 80° satisfies all surface and well geologic constraints, and the projection of an 80° dip coincides with zones of lost circulation and/or temperature reversals on Baca 6, Baca 10, and Baca 18. A dip of 70° on F(3) would result in a discontinuity in the structure contours of the base of the Bandelier Tuff between Baca 17 original, Baca 17 redrill, and Baca 16, but this is not observed. The relatively gentle dip on the base of the Bandelier Tuff between Baca 17-Baca 16 could only result if the dip on F(3) is approximately 75° or greater. Therefore, a dip of ~ 80° on F(3) (as shown in all cross-sections) provides a "best fit" of all geologic and well constraints.

The amount of displacement on F(3) can be calculated from the sum of the apparent dip separation offsets on F'(3), F''(3), and

F'''(3), and by the apparent dip separation of the base of Caldera Fill (1) near Baca 10 (Fig. 1). Using these methods, this fault contains an apparent throw of ~ 400 ft.

F(4), F(5), F(6), and F(7)

F(4), F(5), F(6), and F(7) comprise a series of east-northeasterly trending structures which parallel segmented F(3) around a large section of Redondo Creek Rhyolite in the northeastern part of the development area. All of these faults are cut by F(3).

Apparent offset on F(4) is in the opposite direction compared with the sense of motion which characterizes most structures south of Redondo Creek, whereas F(5), F(6), and F(7), in general, are typified by north-side-down apparent movement. The anomalous south-side-down apparent displacement on F(4) precludes uniquely determining dip orientation or even the style of movement. A southerly dip orientation indicates that this structure defines the edge of a minor graben within the flank of the larger Redondo Creek graben, while a northerly dip requires that reverse movement dominates. For structural simplicity we show a northwesterly steep dip (reverse fault model) on F(4) in Figures 7 and 8. Although the orientation of F(4) is uncertain, the apparent offset of the base of Caldera Fill (1) geometrically requires an apparent throw of ~ 350 ft.

F(5) splays into two segments, F'(5) and F''(5), which have different apparent movement directions but contain a composite north-side-down movement of ~ 100 ft. This net apparent movement suggests that F(5) dips to the north. The exact dip on F(5) is unknown, but a steep dip (~ 70°) is presumed due to its linearity and the documented steep dip on bounding structures.

F(6) also splays into a composite fault zone, F'(6), F''(6), and F'''(6), which contain a cumulative north-side-down type of movement. The apparent throw on F(6) is ~ 250 ft. The direction of apparent movement indicates that F(6) dips to the north, and its similarities with F(5) suggest that this structure is also characterized by a steep dip (as shown in Figures 6, 7, and 8).

F(7) does not split into a complex fault zone but contains the north-side-down apparent movement which typifies adjacent structures. The apparent movement direction suggests that F(7) also dips to the north. Analogies with F(5) and F(6) suggest that F(7) probably has a dip of ~ 70°. As the Redondo Creek Rhyolite south of this fault has been removed by erosion, the apparent dip separation movement can only be determined as greater than 150 ft.

F(8) and F(9)

F(8) and F(9) are major fault zones which define the southeastern flank of the Redondo Creek graben. In effect, these structures are mirror images of F(0) and F(1). F(8) consists of a single fault north of Baca 4, but south of this well it splits into two fault zones: F'(8) and F''(8). A temperature reversal and corresponding zone of complete lost circulation in Baca 5A are expressions of the intersection of F'(8) in the well course. The depth of F'(8) in Baca 5A, combined with the mapped surface trace of this fault, bracket the dip on this structure between ~ 70°-75°. As there are no other data which define dip angle, a dip of 75° for F(8), F'(8), and F''(8) is shown in Figures 7 through 12. Apparent dip separation movements on F'(8) and F''(8) of ~ 800 ft. and ~ 1000 ft., respectively, are calculated from offset of the base of Caldera Fill (1). Therefore, the F(8) segment contains ~ 1800 ft. of apparent throw.

F(9) crops out outside of the development area but is defined by an abrupt break in slope below Redondo Peak. This structure probably separates Caldera Fill (1) from Bandelier Tuff and likely accounts for over 800 ft. of apparent dip separation movement. Similarities with F(8) suggest that a steep dip angle characterizes F(9). The projection of the intersection of this structure with the base of the Bandelier Tuff is shown in Figure 15.

Structures Intersected by the Development Wells

Evaluations of the structure encountered in each well are based on geologic cross-sections through each well that are constrained by mapped surface geology (Fig. 1) and well lithologies. These cross-sections illustrate the consistent orientation of fault zones, two styles of faulting, and the importance of faults to production. As cross-sections of wells in the northeastern part of the production area depict critical constraints on fault orientations, the following discussion commences with Baca 16 (e.g., A-A' on Fig. 1). All cross-sections are drawn so that the reader is facing towards the northeast.

Baca 16

Baca 16 penetrated Caldera Fill (2), Redondo Creek Rhyolite, Bandelier Tuff, Paliza Canyon Andesite, and Santa Fe Formation (Fig. 6). The absence of Caldera Fill (1) below the Redondo Creek Rhyolite, together with the presence of Caldera Fill (1) in all adjacent wells and the close proximity of F(0), indicate that Baca 16 crossed F(0) at an elevation of 8742 ft. above sea level. The location of the intersection of F(0) with Baca 16, combined with the approximate surface trace of fault, unequivocally determines the dip on F(0) between 65° to 70°. Lost circulation was encountered above and below the casing point. A zone of complete lost circulation above the casing point may correspond to the intersection of an adjacent northwest trending cross-fault

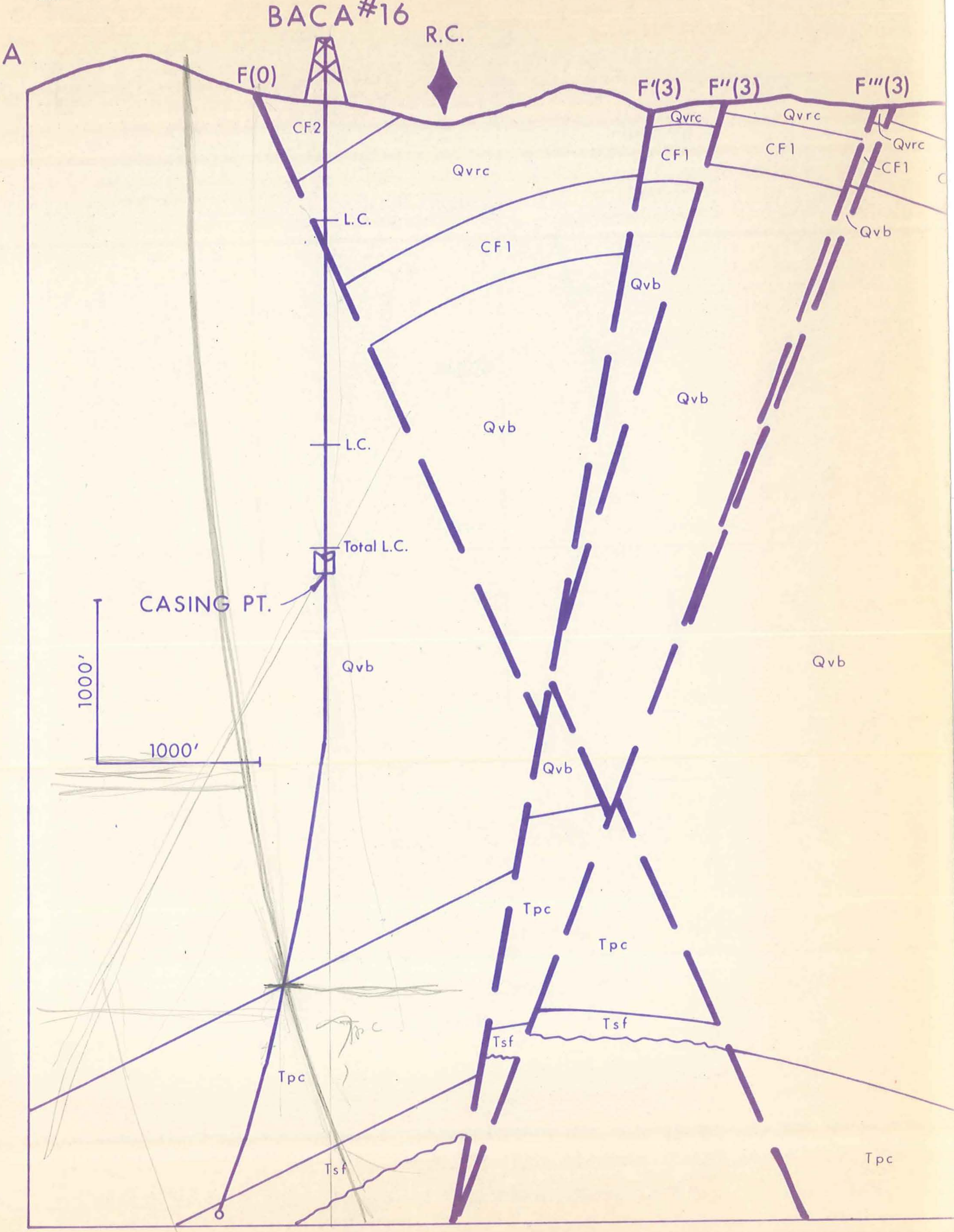
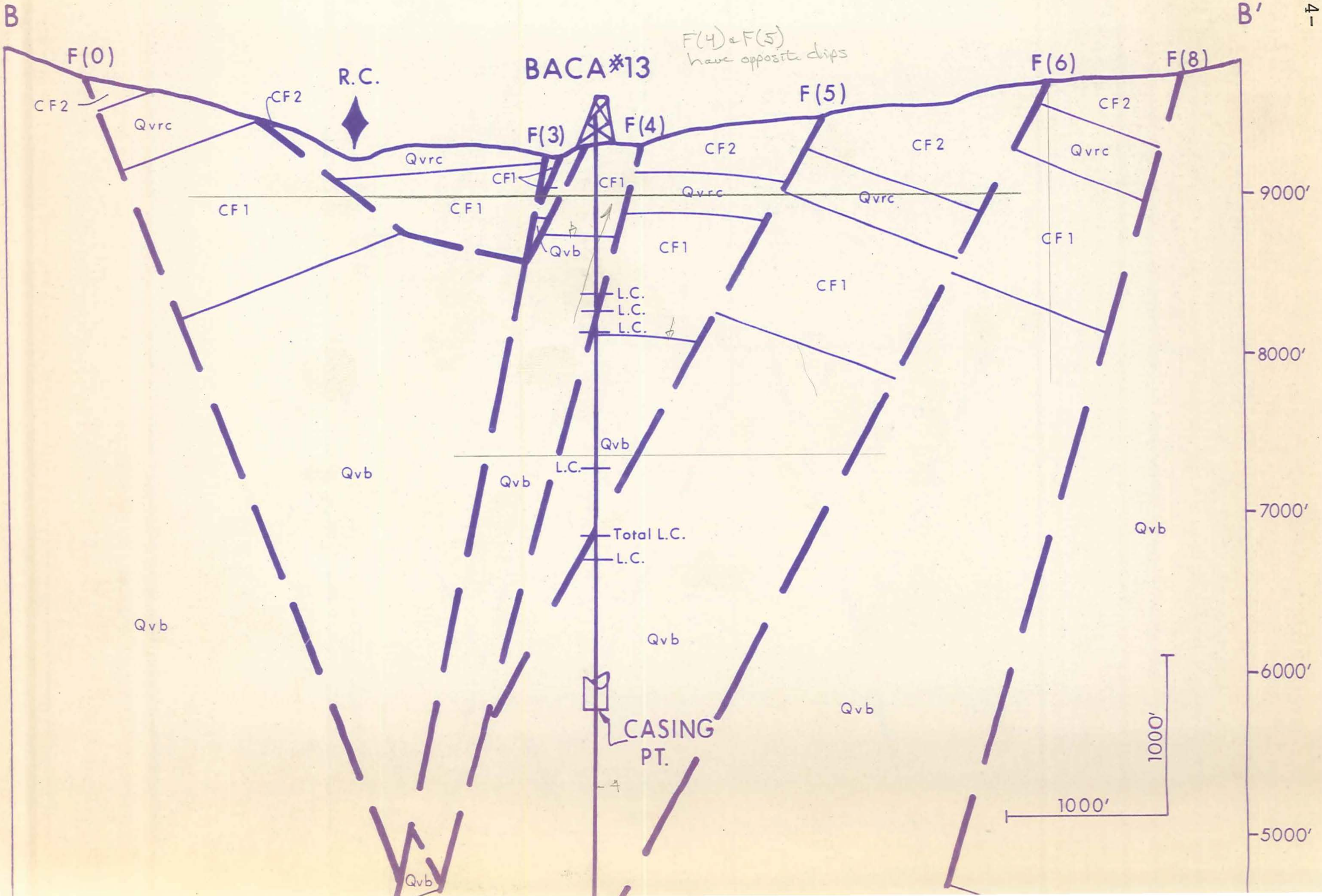


FIGURE 6. Cross Section through Baca 16; A-A' on Figure 1.

with the well course. The remaining lost circulation zones in the Bandelier Tuff probably correspond to areas characterized by a high density of cooling joints. Despite the presence of lost circulation below the casing point, this well did not produce. We interpret the lack of productivity in Baca 16 to the absence of steeply-dipping faults intersecting the well trend below the casing point. The high temperatures recorded in Baca 16 indicate that additional wells should be drilled in this area but targeted towards the intersection of F(0) with the base of the Bandelier Tuff.

Baca 13

A cross-section through Baca 13 (Fig. 7) depicts the two distinct fault orientations (low-angle and high-angle structures), as well as the lithologies encountered in this well. The projected flattening of the low-angle fault in Fig. 7 is the result of the curvature of this structure into the plane of the cross-section. Several zones of lost circulation in the upper portion of this well appear to correspond to the projections of F(4) and F(5). Below the casing point Baca 13 intersected F(6) and F(0). The intersection of F(6) in the well course also corresponds to a zone of lost circulation. An additional zone of lost circulation which was encountered below the casing point cannot be related to fault zones and may be the result of high joint density.



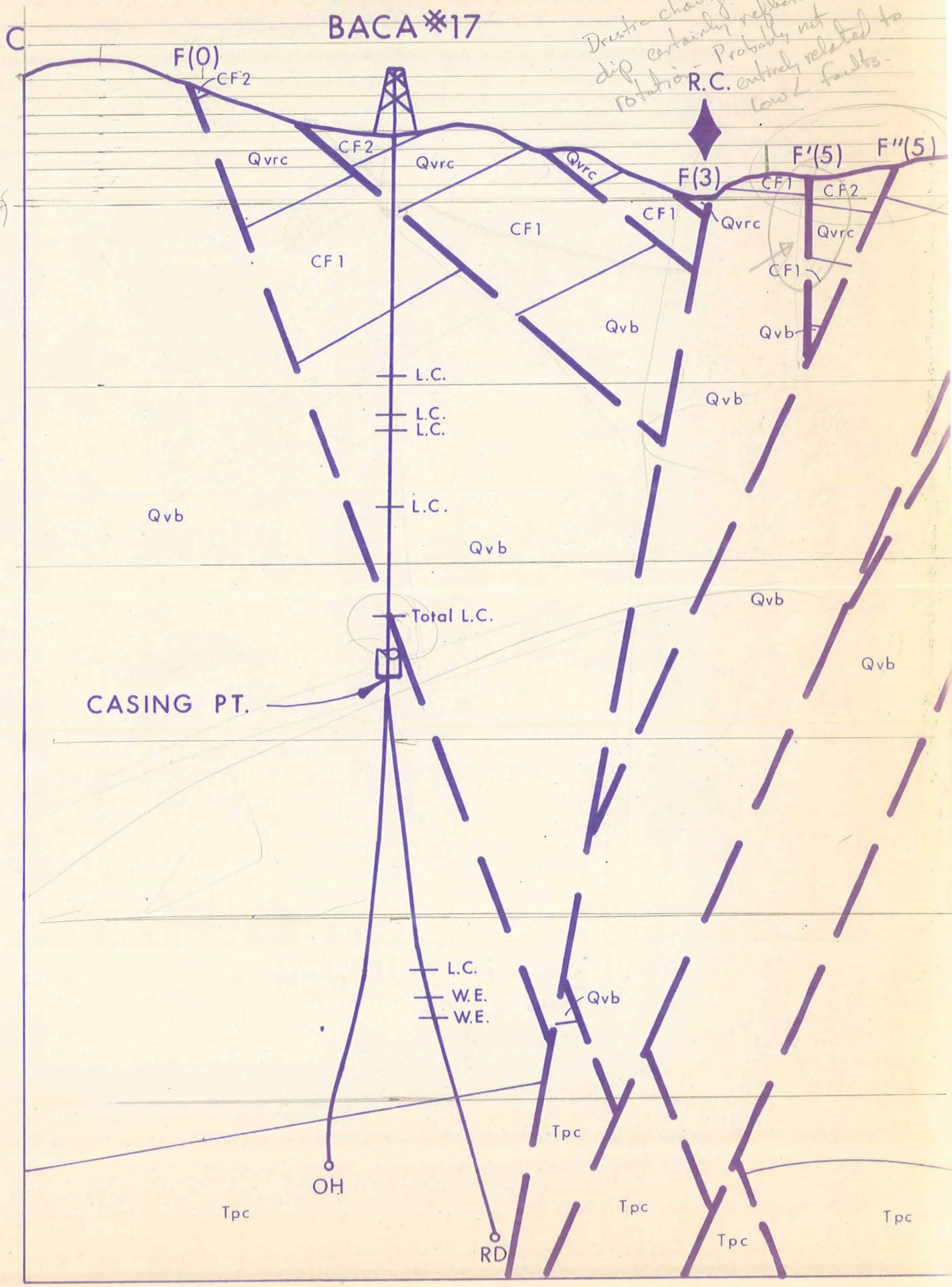
F(4) & F(5) have opposite dips

We interpret the moderate productivity of this well to the intersection of F(6) and F(0) with the well course.

Baca 17

The geology and structure of the area surrounding Baca 17 is shown in Figure 8. This well traversed a section of Caldera Fill (2), Redondo Creek Rhyolite, Caldera Fill (1), Bandelier Tuff, and Paliza Canyon Andesite. Dips of strata in Caldera Fill (2), surface contacts, and constraints on fault dip require that the contact between Redondo Creek Rhyolite and Caldera Fill (1) coincide with the projection of a low-angle fault. Although this fault has no production significance, its projection in the Baca 17 well course coincides with the point of casing failure. A zone of total lost circulation from 2642 to 3003 corresponds to the projected intersection of F(0) with Baca 17 assuming a 70° dip on F(0). These data confirm earlier conclusions (Baca 16, Fig. 7) on the orientation of F(0).

Below the casing point Baca 17 original trended away from F(0) and F(3), did not intersect steeply-dipping structures, and was tight. The redrill on this well trended towards F(3) but apparently did not intersect this fault (it should be noted that the dips on individual fault zones are oriented identically in each cross-section, whereas in reality they may curve). The very close approach (~ 100 m) of Baca 17 redrill to F(3) or the



Drastic change in dip certainly reflects rotation - Probably not entirely related to low∠ faults.

FIGURE 8. Cross Section through Baca 17; C-C' on Figure 1.

intersection of F(3) with this well if actual dip is several degrees less than is shown in Figure 9 probably accounts for its good productivity. A lost circulation zone and water entries in the lower part of this well do not correspond to recognized faults and may reflect locally high joint density.

Baca 11 and Baca 4

As directional data are not available on either of these wells, all interpretations of Baca 11 and Baca 4 are considered tentative. Preferred well locations (those which "best fit" the geology of adjacent areas) are shown on Figure 9. Above the casing point Baca 11 penetrated two low-angle faults and below crosses F(3), F'''(6), and possibly F(0). Lost circulation zones above and below the casing point appear to be related to the close approach and intersection of F(3) with the well course. The excellent productivity of this well is probably the result of intersecting several steeply-dipping structures below the casing point.

Baca 4 traversed F'''(6) and a westerly trending cross-fault above the casing point. Fractures and water and steam entries above the casing point do not correlate with faulting and probably reflect jointing in the Bandelier Tuff. The intersection of F(8) with the well course occurs below the casing point and corresponds to a steam entry zone. The good productivity

15, 19

Many structures not identified.

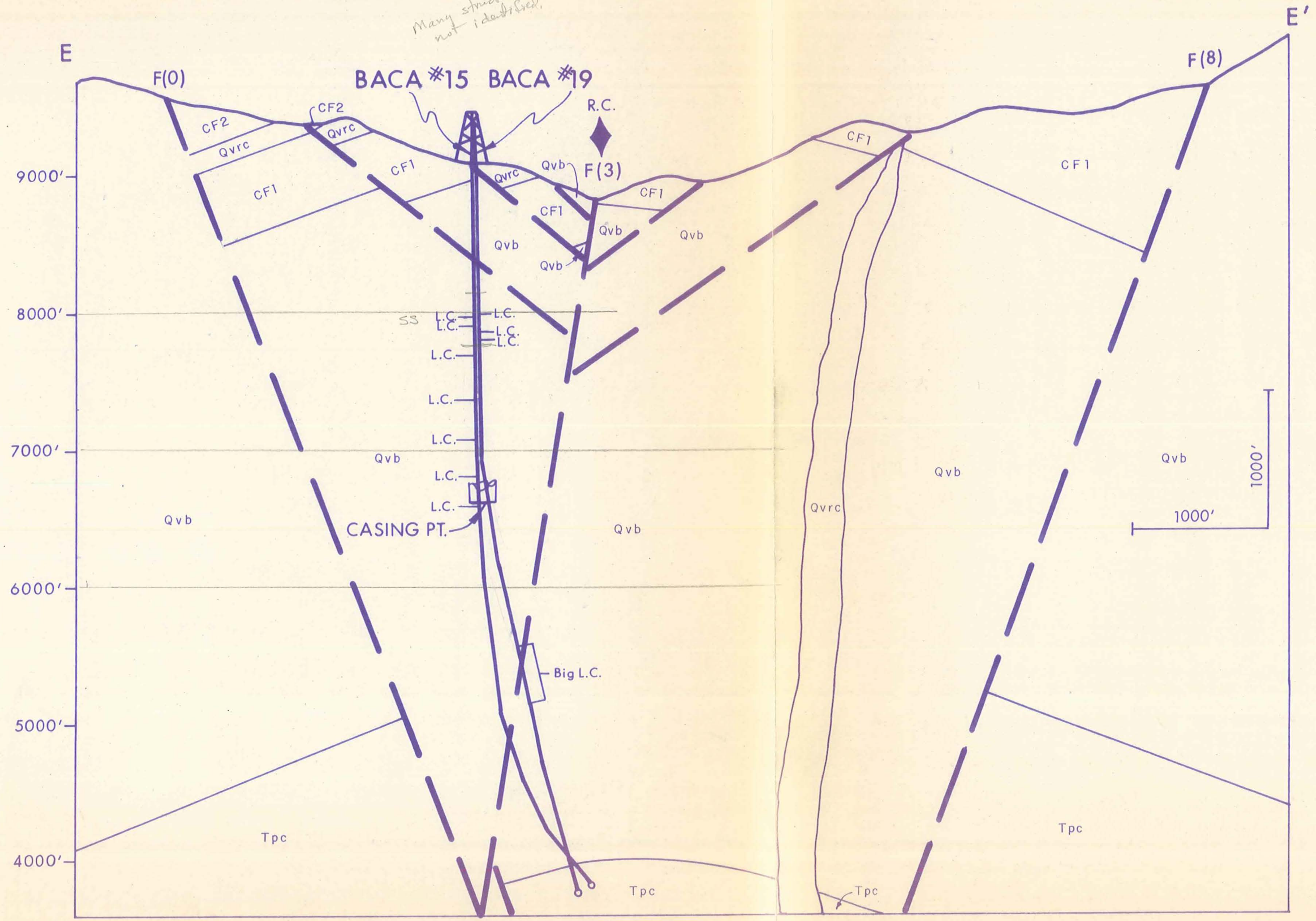


FIGURE 10. Cross Section through Baca 15 and 19; E-E' on Figure 1.

of this well is probably related to the intersection with F(8) below the casing point.

Baca 15

The unexpectedly thin sections of Redondo Creek Rhyolite and Caldera Fill (1) in Baca 15 compared with thicknesses measured in immediately surrounding areas require the presence of low-angle normal fault zones in the upper portion of this well (as shown in Figure 10). The symmetry of these low-angle structures around Redondo Creek is also shown in Figure 10. Zones of lost circulation above the casing point cannot be correlated with fault zones and appear to be related to jointing in the Bandelier Tuff. One steeply-dipping fault, F(3), was intersected below the casing point. Zones of lost circulation were not recognized due to the use of areated water as the drilling medium. Baca 15 is a good producer.

Baca 6

Baca 6 penetrated a steeply-dipping fault, F(1), as well as several shallow-dipping structures in the upper 1500 ft. of the well (Figure 11). Below the casing point this well intersected F(3) and continued down or adjacent to this fault zone for the length of this well (including remedial). Baca 6 is a good producer.

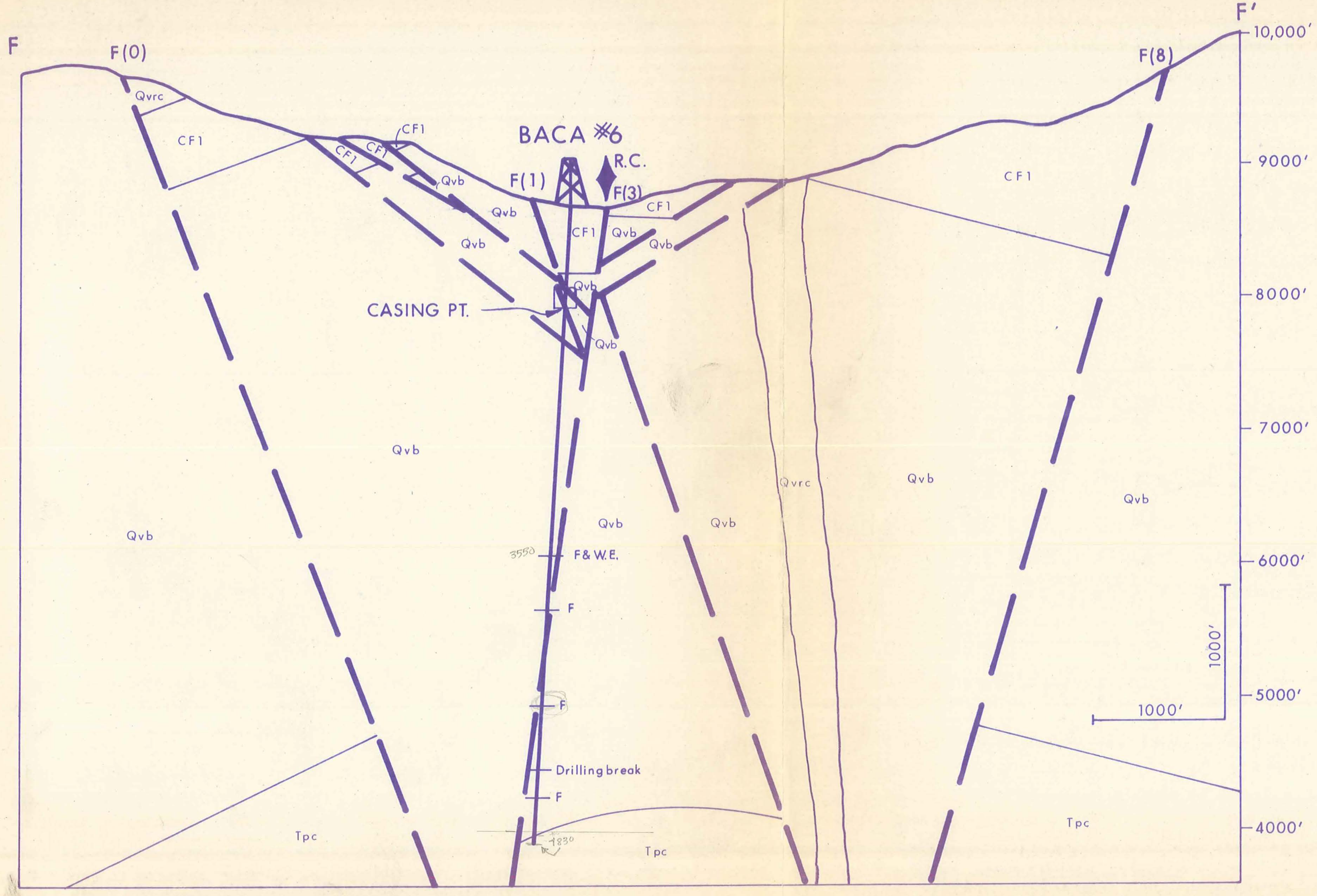


FIGURE 11. Cross Section through Baca 6; F-F' on Figure 1.

Baca 10 and Baca 18

The relationship between fault zones and production is graphically depicted in a cross-section through Baca 10 and Baca 18 (Figure 12). Baca 10 intersected all steeply-dipping fault zones above the casing point. Although this well flowed during initial production tests, attempts to gain production after the 7" liner was set were unsuccessful. The Baca 10 casing was perforated between 5700 to 4600 ft. elevations where there was an isothermal static temperature profile and several steam and water entries. This isothermal zone bounds the projected intersection of Baca 10 with F(3). Fair to poor production was obtained after perforation of the casing.

Baca 18 original also penetrated F(1) above the casing point and crossed F(3) below the casing point but was lost due to mechanical problems. Baca 18 redrill trended away from and did not intersect F(3) which probably accounts for its lack of productivity.

It should be noted that the apparent reverse offset on the base of the Bandelier Tuff is the result of projecting contacts which have a considerable dip across significant lateral distances.

Baca 14, Baca 9, and Baca 5A

The probable well locations of Baca 9 and Baca 5A along with the projection of the trace of Baca 14 are shown in Figure 13.

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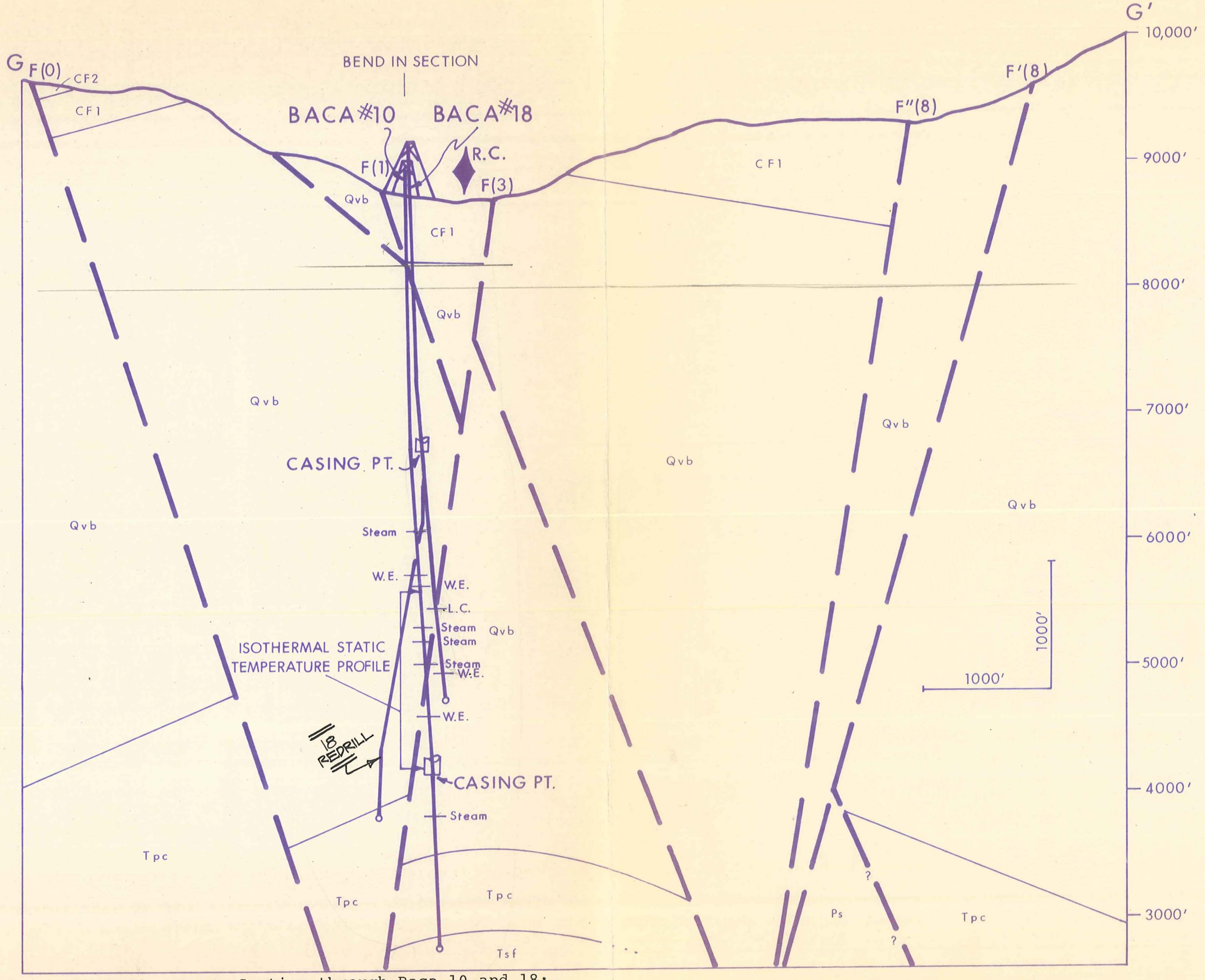

FIGURE 12. Cross Section through Baca 10 and 18; G-G' on Figure 1.

9,5A,14

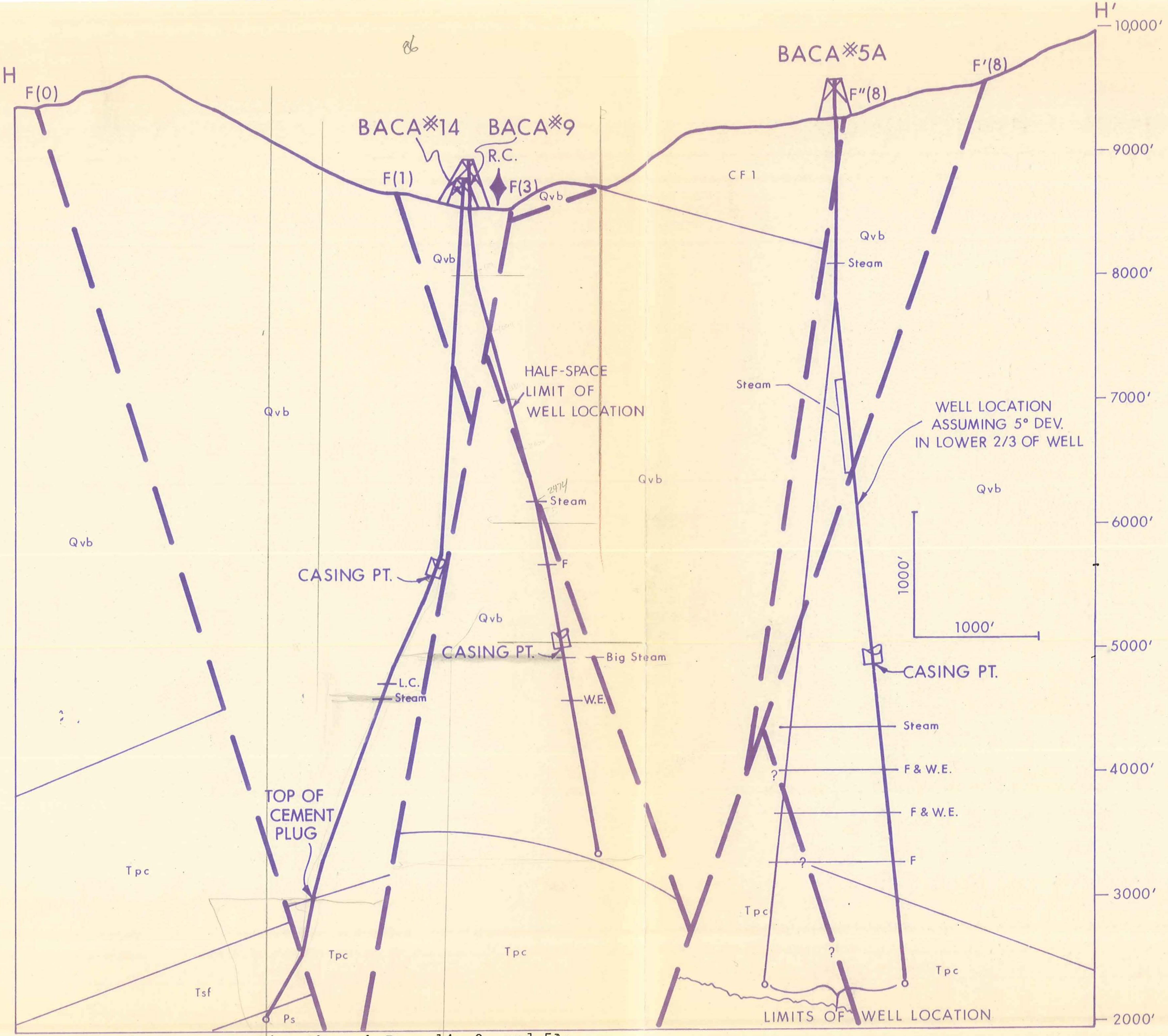

FIGURE 13. Cross Section through Baca 14, 9, and 5A; H-H' on Figure 1.

The geology of this cross-section depicts the "probable" Baca 9 and Baca 5A well locations that fit the structural-stratigraphic constraints in Baca 14 and adjacent areas.

Below the casing point, Baca 14 intersects F(0) at the base of the Paliza Canyon Andesite (this accounts for the very thin section of andesite). During production tests, the Santa Fe Formation flowed into the well requiring that a plug be set to the base of the Bandelier Tuff (thus, F(0) was blocked from the producing interval). Baca 14 did not produce fluids after the plug was set, which suggests that the zone of lost circulation and a steam entry below the casing point probably reflect the local presence of a high density of cooling joints in the Bandelier Tuff.

A large steam zone and sloughing (which resulted in mechanical failure) probably correspond to the intersection of F(1) (as shown in Figure 13) or possibly F(3) with the Baca 9 well course. Baca 9 redrill was cased below the fault intersection and is not a producer. Steam and water entries below the casing point are likely related to jointing in the Bandelier Tuff.

Baca 5A cuts several steeply-dipping faults F''(8) and F'(8), in the upper portion of this well. A large steam entry and a temperature reversal characterize the location of F'(8) in the

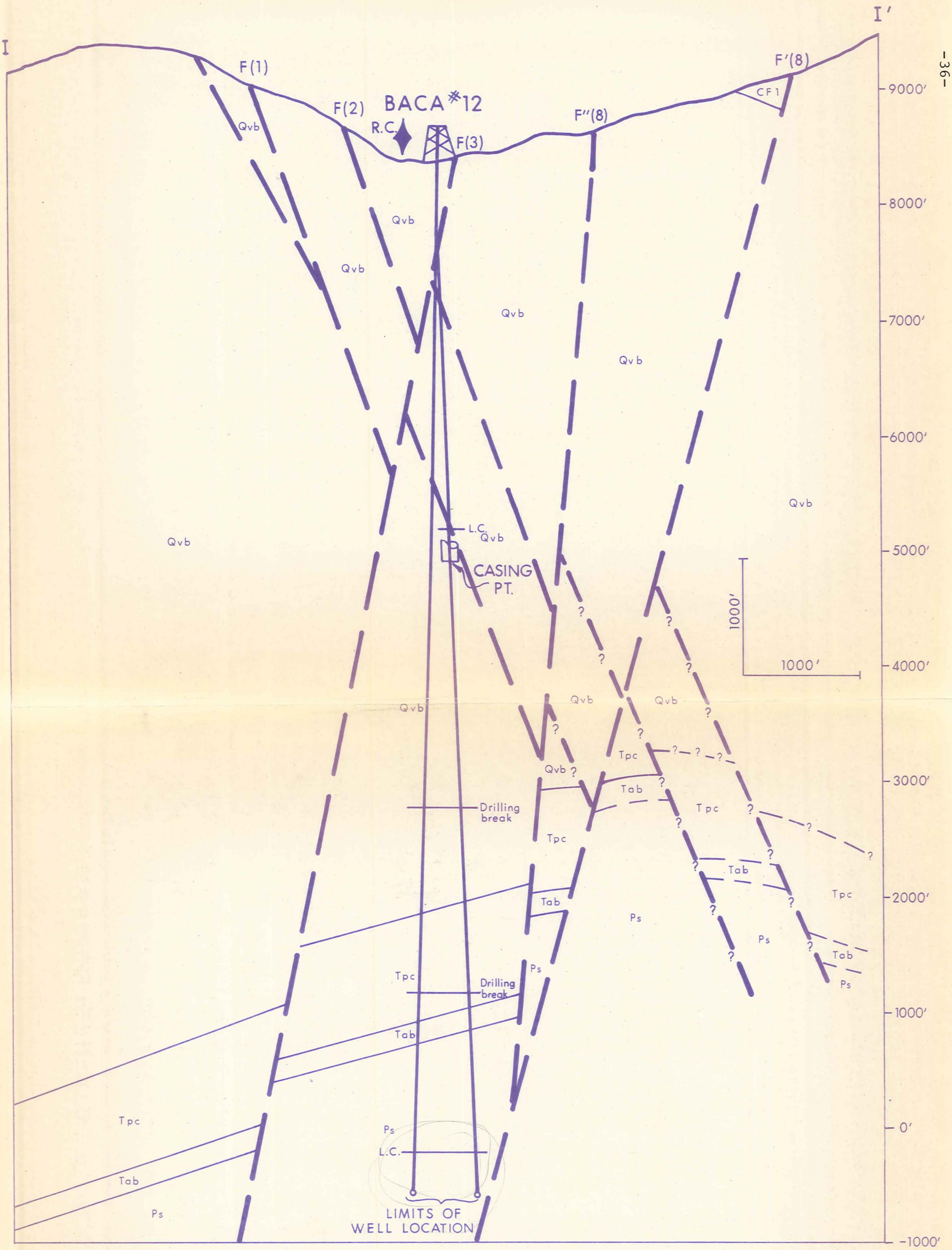

FIGURE 14. Cross Section through Baca 12; I-I' on Figure 1.

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well course. Below the casing point Baca 5A did not penetrate any fault zones and would not produce fluids due to the temperature reversal in the upper portion of this well.

Baca 12

All steeply-dipping fault zones crossed the Baca 12 well course above the casing point (Figure 14). A zone of lost circulation and associated temperature reversal probably coincide with the intersection of F(1) with Baca 12. This well did not cross any fault zones below the casing point and is a nonproducer.

It is important to note that approximately 50 to 125 barrels of fluid per hour were lost to the formation while drilling the lower 2600 ft. of this well, which suggests that lost circulation data may not be directly correlative to well producibility.

Conclusions

Temperature, lithologic, lost circulation, and production data from wells in the Redondo Creek development area, combined with surface geologic mapping, provide a consistent picture of the importance of structure to permeability. Shallow-dipping fault zones do not intersect the production interval, and cooling joints apparently do not have the lateral continuity or density to provide economic production. All producing wells intersect or closely approach (~ 100 m) steeply-dipping fault zones, whereas nonproducers do not. This suggests that these high-angle structures provide the permeability required for production. Steeply-dipping faults, which were commonly encountered in producing wells or contain documented permeability (inferred from the occurrence of total lost circulation), include F(0), F(3), and F(8). Therefore, future wells should be targeted towards the intersection steeply-dipping fault zones with the base of the Bandelier Tuff. As poorly consolidated fine-grained sediments appear to be characterized by high permeabilities but flow into the well (e.g., Santa Fe Formation), attention should be given to testing the producibility of coarser sediments such as Caldera Fill (0).

Recommendations for Future Drilling

As noted previously, the heterogeneous permeability in the Redondo Creek development area can only be accounted for by the presence of local structure. Geologic and well constraints set forth in this report suggest that permeability (and production) is directly related to steeply-dipping fault zones. All producers (Baca #'s 4, 6, 10, 11, 13, 15, and 17) either penetrated or closely approached (≈ 100 m) steeply-dipping fault zones below the casing point, while nonproducers did not. Therefore, all future wells should be targeted toward high-angle faults.

Since the Paliza Canyon Andesite is altered to a clay-mineral assemblage which apparently (?) has little permeability and the Santa Fe Formation lacks the induration required to withstand production (e.g., this formation flows into the well with the fluids), the lowermost sections of the Bandelier Tuff probably constitute the reservoir for this geothermal system. Permian sediments and the granitic basement have possible, but as yet unknown potential as reservoir rocks. Thus, future wells should be directed towards the intersection of steeply-dipping faults with the base of the Bandelier Tuff.

A contour map of the base of the Bandelier Tuff (constrained by the thicknesses of the tuff encountered in the development wells) along with the projected intersection of F(0), F(3), and F(8) with the base of the tuff (Figure 15) provide the required interpretive data base to target future activity.

Recommendations for future wells are subdivided into: (1) redrills and (2) future wells.

Redrills

The following nonproducing wells contain a geologic environment favorable for a redrill:

1. Baca 5A. Although somewhat cool, the abundant lost circulation (permeability) and relatively high

temperature associated with F'(8) suggest that a redrill from ~ 8300 ft. (elevation) which was directed to the northwest (intersection of F'(8) with F''(8) in Figure 13) would yield a producing well.

2. Baca 10. The presence of an isothermal static temperature profile horizon which is suggestive of convecting (permeable) zone, and the close spatial association of a producing well (Baca 18), together indicate that Baca 10 should be plugged to ~ 6800 ft. (elevation) and redrilled towards the projection of F(3) in Figure 12.
3. Baca 14. The close approach of Baca 14 to F(3) near the casing point, combined with the apparent producibility of F(3), suggests that this well should be plugged to near the casing point and redrilled (vertically) towards F(3) (Figure 13).
4. Baca 16. The high temperatures encountered in Baca 16 and the presence of adjacent steeply-dipping structures suggest that a redrill of this well is warranted. F(0) was crossed at a very shallow level, but this fault could be penetrated again or even F(3) could be intersected if Baca 16 were plugged to ~ 7500 ft. (elevation) and the redrill targeted to the southeast at a 30° deviation from vertical (Figure 6).

Future Wells

A contour map of the base of the Bandelier Tuff, along with projected locations of F(0), F(3), and F(8) at this horizon (Figure 15), provide the framework for selecting future drilling locations. Future wells should be targeted either slightly updip of the projected locations of fault zones or towards the intersection of fault zones of opposite vergence. Since these two types of targets cannot be intersected from all sections of the Redondo Creek development area, this region has been subdivided into domains. These domains are shown in Figure 16 and are discussed below on the order of those considered to have the highest (Domain 1) to the lowest (Domain 5) potential. It should be noted that these domains are targets at the base of the Bandelier Tuff and not surface locations. Directional drilling at moderate angles from vertical (20° to 30°) may necessitate adjustments of the domain boundaries.

Domain 1. This area has the highest potential and encompasses the intersection of F(3) with F(0) at or above the base of the Bandelier Tuff. Wells drilled in Domain 1 will intersect either one or both of these faults. The intersection of F(3) with F(0) occurs at the base of the Bandelier Tuff only in the southern half of this domain, while in the northern section, the fault zone intersection occurs above the base of the tuff. The highest permeability in the entire development area will likely be associated with this fault zone intersection. Wells drilled in the southern part of Domain 1 should initially be targeted towards this intersection and subsequent wells aimed slightly updip of either F(0) or F(3). The F(3)-F(0) intersection in the northern part of this domain is located ~ 500 to 1000 ft. above the base of the Bandelier Tuff which suggests that the fault zone intersection is a potential target, but that zones downdip of the projected intersection of either F(3) or F(0) with the base of the Bandelier Tuff are the deepest targets (Figures 6 and 16).

Domain 2. Domain 2 areas encompass the projected intersections of F(0), F(3), and F(8) with the base of the Bandelier Tuff. Wells in this domain should trend perpendicular to the structure, dip in the opposite orientation as the fault to be intersected, and be targeted updip of the steeply-dipping faults. This domain is interpreted to have less potential than Domain 1 only because of the absence of steeply-dipping fault zone intersections.

Domain 3. This area contains several steeply-dipping structures, F(4) through F(7) along with numerous smaller faults of unknown potential. The uncertainty of the dip angle on faults in this domain preclude determining target locations. However, the productivity of Baca 13 indicates that Domain 3 contains good potential. As most of the faults in this area trend east-west and probably dip to the north, directional wells in this region should have a north-south strike (perpendicular to structure) and plunge to the south.

Domain 4. This domain consists of two areas which have uncertain to poor potential. The area of Domain 4 situated south of Baca 15 contains steeply-dipping fault zones, but the projection of F(0) and F(3), as well as the intersection of these faults, are located below the base of the Bandelier Tuff. Production from below the base of the Bandelier Tuff is commonly poor. The other Domain 4 area parallels the projection of F(9). Wells in this area will intersect F(9), but the producibility of this structure has not been tested yet. In addition, the dip angle on F(9), as well as its exact location, are currently unknown which indicate that the location of this part of Domain 4 is speculative at best.

Domain 5. Domain 5 consists of at least three areas which are all characterized by an absence of steeply-dipping faults near the base of the Bandelier Tuff. Wells in all of these areas are nonproducers (Baca #'s 5A, 12, and 16). Domain 5 appears to have the poorest potential for locating permeability (production) in the entire development area.