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RESULTS OF DEEP DRILLING IN THE VALLES CALDERA, NEW MEXICO

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INTRODUCTION

The Valles caldera in New Mexico has been the site of extensive drilling for geothermal exploration and development by Union Oil Company, with the financial participation of the U. S. Department of Energy. The data base generated through this project represents one of the most extensive sets of subsurface information on young volcanic-hydrothermal systems which is currently in the public domain. The data includes subsurface lithologic samples, geophysical well logs, reservoir engineering information, and extensive surface geology and geophysics.

SLIDE 1
Index Map

The Valles caldera is located in New Mexico on the western margin of the Rio Grande Rift. Shown on this index map is the structural margin of the Valles caldera, the resurgent dome of the Valles, the Toledo caldera, and the Baca project area. The deep drilling I will be discussing was completed within the Baca project area.

The major episode of caldera development began about 1.4 million years ago with the eruption of the Otowi Member of the Bandelier Tuff and the formation of the Toledo caldera, only a portion of which remains exposed. At 1.1 million years the Valles caldera formed with the eruption of the Tshirege Member of the Bandelier Tuff.

SLIDE 2
Geologic Map

This is a generalized geologic map of the Baca project area showing the location and deviation of the drill holes we have studied.

In our studies of the Valles system, we have logged over 21,000 meters of lithologic samples. Although the holes were drilled for exploration and production purposes, we have been able to accumulate considerable information which is of interest to the scientific community. Our studies have included definition of the intra-caldera stratigraphy, formulation of structural models, and we are now involved in evaluating hydrothermal mineral zonation, defining fluid flow paths of the active hydrothermal system, and investigating similarities with epithermal, vein-type, precious metal systems.

STRATIGRAPHY

SLIDE 3
Strat. Column

In the past year our logging has allowed us to develop a consistent stratigraphic section within the caldera. Due to the youth of the structure, this stratigraphy has not been exposed within the caldera and is only partially developed outside the caldera. This is a composite stratigraphic section from that work.

Paliza Canyon Formation - sequence of basaltic and andesitic flows and pyroclastic rocks which formed prior to the development of the Valles caldera. These rocks were old enough that a rugged topography was developed by erosion prior to the eruption of the initial products of the Bandelier Tuff. Pervasive porphylitic alteration preceeded the development of the present day caldera structures.

Initial eruptions of the developing silicic volcanic center generated a series of ash-flows and associated sediments which form a sequence we have called Lower Tuffs. This unit is extremely variable and it is often not possible to correlate with certainty even between redrills of the same holes. This unit contains important fluid entries in a number of wells. Above this is the Otowi Member of the Bandelier Tuff which was emplaced during the formation of the Toledo caldera about 1.4 my ago. This unit shows the typical welding zonation, with a dense zone of graophyrically crystallized ash making up most of the unit. Following the emplacement and cooling of the Otowi Member, a period of erosion stripped the upper portion of the unit and deposited the S_3 Sandstone in stream channels. The Tshirege Member of the Bandelier Tuff was deposited about 1.1 my and accompanied the formation of the Valles caldera. It has also developed a cooling zonation similar to the Otowi with a thick granophyrically crystallized core region. A period of erosion again followed this eruption and the S_2 Sandstone was formed by streams draining the Baca project area. Note the position of the S_2 SS, we will be coming back to this in a moment. Subsequent smaller ash eruptions have formed a sequence of largely non-welded tuffs which we have designated the Upper Tuffs.

STRUCTURE

Following the formation of many calderas, including the Valles, continued magma pressure results in the formation of a central structural dome which is termed a resurgent dome.

SLIDE 4
Panorama

In the Valles, the resurgent dome is called the Redondo Dome, and is shown in this slide. The Baca project area is located entirely within this resurgent dome. As this slide

SLIDE 5
Geologic Map

shows the drilling is confined to the keystone graben of the resurgent dome within an area which is characterized by intense faulting. Since previous workers had emphasized a strong structural control on the system, and since much lower total permeabilities were found than had been expected, we have taken a look at the structural processes involved in dome formation.

SLIDE 6
Idealized Model

This is an idealized model of dome development which follows that presented by Johnson for the formation of the Henry Mts. in Utah. Within the domed strata there exists a neutral plane which separates areas of extension above and compression beneath. Thus, extensional faulting with relatively high permeability would be expected above the neutral plane; and relatively low permeability fracturing beneath the neutral plane.

SLIDE 7
S_2 Isopach

However, it is clear from some of our geologic relationships that the idealized model of dome formation is not entirely correct. This is an isopach map of the S_2 Sandstone which developed above the Tshirege Member shortly after the formation of the Valles caldera. This shows a stream channel system has developed along a northeast-southwest trend parallel to the Jemez Fault which geologic evidence shows was present long before the caldera eruptions. Thus the S_2 Sandstone channel formed along the Redondo Creek/Jemez fault trend very early in the development of the Redondo Dome. We believe that this represents an activation of the Jemez fault structures which would be present in the basement rocks at this time.

SLIDE 8
Dome Model
w/faults

Thus our idealized dome is modified somewhat and contains two different types of faults. 1. Shallow normal faults which are developed due to extension above the neutral plane, and 2. steep normal faults which are due to reactivation of basement structures of the Jemez fault trend.

SLIDE 9
3-D X-Sect.

We have combined our stratigraphic and structural information to develop an interpretive 3-D cross section of the Baca project area. This slide begins to show the complex interaction between stratigraphy and structure within the area.

HYDROTHERMAL SYSTEM

SLIDE 10
Baca 12

This is the wellhead of Baca-12, the deepest hole in the field with a depth of 3242 meters. There are a number of ways of using such a well to explore the physical and chemical processes which are taking place within an active hydrothermal system. Reservoir engineers tend to look at the results of flow and injection tests to define the gross permeability and productive capacity of the reservoir. Geologists tend to look at the variation of trace elements and alteration assemblages. The fact remains that the definition of fluid entires in boreholes are often not as straightforward as one would think. We have applied several approaches to the investigation of the hydrothermal fluid flow regime at the Valles caldera; hydrothermal mineral zonation and a review of the existing reservoir engineering data.

Measured temperatures within the Baca geothermal field have been measured up to 341°C in Baca-12. The fluids are sodium chloride brines with salinities of about 7000 ppm TDS,. The

SLIDE 11
T Contours

fluids are derived from the heating of meteoric waters (Goff and Grigsby, Trainer). The variation of temperatures within the geothermal zone can be seen by looking at this slice map of temperatures at 1200 meters elevation. The highest temperatures are centered around Baca well #4, and trend east-west and then to the northeast. The temperatures drop off toward the southwestern portion of the explored field.

The fluid flow which produces this temperature distribution is controlled by both stratigraphic units (non-welded tuffs and tuffaceous sediments) and faults and fractures which cut the welded tuff portions of the stratigraphy.

SLIDE 12
Granophyric
zone

The densely welded tuffs, which make up the bulk of the stratigraphic section, are largely primarily devitrified as shown in this slide. These rocks are essentially impermeable until fractured, and thus show little hydrothermal alteration except in fracture zones. In contrast, this is an electron photomicrograph of the S_3 sand. Note here the detrital grains within mass of hydrothermal illite and chlorite. This rock has little permeability at this time due to self sealing by hydrothermal alteration. Ash and non-welded ash-flows have also served as stratigraphic fluid conduits. This SEM photo shows a former pumice bed from Baca-17 which has been altered largely to illite but still preserves the textural character of the pumice.

SLIDE 13
Bridging illite
from S_3

SLIDE 14
Detail of 13

SLIDE 15
Pumice

SLIDE 16
Detail of 15

Although confined to stratigraphic interbeds and faults and fractures, the hydrothermal alteration zonation shows consistent relationships throughout the Baca field. This slide documents in cross section the zonation which we have determined through XRD and microscope evaluation of the subsurface samples. The upper portion of the holes contains an argillic alteration which affects the non- to poorly-welded Upper Tuffs as well as the overlying caldera-fill sediments and the Redondo Creek Rhyolite. This argillic zone is characterized by smectite, mixed layer illite-smectite, illite, kaolinite, quartz, and pyrite.

SLIDE 17
Alteration
zonation

Beneath the argillic zone, propylitic alteration is widespread and pervasive at Baca. The propylitization is very weak in the mostly impermeable Bandelier Tuff, weak to moderate in the Lower Tuffs, and generally strong in the Paliza Canyon Formation, (where it may be older than the active geothermal system). Chlorite, calcite, illite, albite and epidote are the key alteration mienrals in this zone. Epidote is relatively rare in the felsic Bandelier Tuff and Lower Tuffs, but common and abundant in the intermediate-composition Paliza Canyon. Phengitic illite is relatively enriched in the Lower Tuffs.

Most of the major thermal fluid entries are associated with phyllic alteration. This alteration is characterized by partial to complete destruction of the rock to form illite + pyrite + quartz + calcite + chlorite. The zones of alteration are restricted to zones of structural and stratigraphic permeability.

The Lower Tuffs are characterized by chlorite + illite + albite assemblages. This alteration is much more intense than in the overlying Bandelier Tuff, largely because of non- to poorly-welded ash-flow tuffs, tuffs, and sediment within the interval. These rocks had considerable primary permeability, but in some holes, this permeability has been effectively sealed by hydrothermal alteration. The actual character and controls of present fluid entries within the Lower Tuffs are open to speculation. We do however correlate an increase in temperature with an increase in thickness of the Lower Tuffs, and the Lower Tuffs remain one of the principal target horizons for geothermal drilling. Therefore, we suspect that stratigraphically-controlled permeability is an important component, but realize that faulting may provide important controls also.

As with other high-temperature hydrothermal systems, alteration is a key to the identification of fluid flow systems and, specifically, fluid entries into geothermal wells. However, we realize that these fluid flow systems are dynamic, and it is helpful to be able to apply additional fluid flow data to the problem of system dynamics.

Our studies of the alteration are still in their preliminary stages, but it is apparent from these studies that isotherms have changed with time in the Baca system.

SLIDE 18
I/S Clays

This slide shows the distribution of illite-smectite clays in the Baca and some other active thermal systems, including geothermal systems and active diagenetic systems.

ON = Onikobe
CP = Cerro Prieto
W = Wairakei
GC = Gulf Coast Sediments

NS = North Sea Sediments
SH = Shale Diagenesis (Perry and Hower)

When available from the literature, we have plotted the ordering of the I/S clay as a function of temperature. The geothermal literature does not specify the ordering of I/S clays, but they are specified for diagenetic environments. The general transition from randomly interstratified to ordered is found between 75-100°C. In the Baca system ordered I/S clays are found at temperatures as low as 30°C. Suggesting that alteration assemblages document temperatures which reflect higher temperatures than are realized presently. The immediate explanation for this observation is that the system has cooled with time. However, an alternative explanation may be that the system has remained essentially fixed with time, and the apparent collapse of isotherms is a result of uplift of the resurgent dome. Our observation of cooling with time is in contrast to the oxygen isotope work of Lambert and Epstein who see no evidence for cooling with time.

Reservoir engineering data are also useful in interpreting the hydrothermal mineral zonation and the dynamics of the hydrothermal system. From the standpoint of alteration, well Baca 18 is not unique. However, it is the only well in the field which intersects the Lower Tuffs and upper portion of the Paliza Canyon and does not produce geothermal fluids from those intervals.

SLIDE 19
B-18 T

SLIDE 20
Spinner

The slide on your left shows a series of temperature measurements in B-18, and the slide on the right shows the results of two spinner surveys run in the well during injection. The comparison shows that the Lower Tuffs accepted no fluids during injection, and the results are confirmed by the series of temperature surveys run to document the thermal recovery of the well. Thus, even though the alteration assemblages in the Lower Tuff interval are the same as in other wells, the alteration has been intense enough to effectively seal all fluid pathways in this interval.

SLIDE 21
Metal Deposits

There are many similarities between the active Baca geothermal system and fossil hydrothermal metal systems. Many of these correlations are shown on this slide which is patterned after a similar table by White and Heropoulos. The key difference is that pyrite is the only sulfide species found in the deep portion of the holes, although it is often rich in silver running up to 2 oz/ton. In addition, the fluids presently circulating within the Baca system are at the dilute end of the salinity ranges which are thought to be responsible for the deposition of hydrothermal metal deposits.

We anticipate that our ultimate model of the Baca geothermal system will allow us to tie together the systematics of the active hydrothermal system with the structural evolution of the Valles caldera. We may summarize our present results as follows.

SLIDE 22
Dome Model w/
faults

Returning to our modified idealized model of the Redondo Dome, we have the steep reactivated Jemez faults and the listric extensional faults. We feel that the steep reactivated faults control the ascent of fluids through the area beneath the neutral plane which is under compression. Fluids rising above the neutral plane are then able to flow out through permeable horizons which are intersected by the steep faults. Shallow faults which do not intersect these principal reactivated faults have no way of acquiring fluids.

SLIDE 23
Index

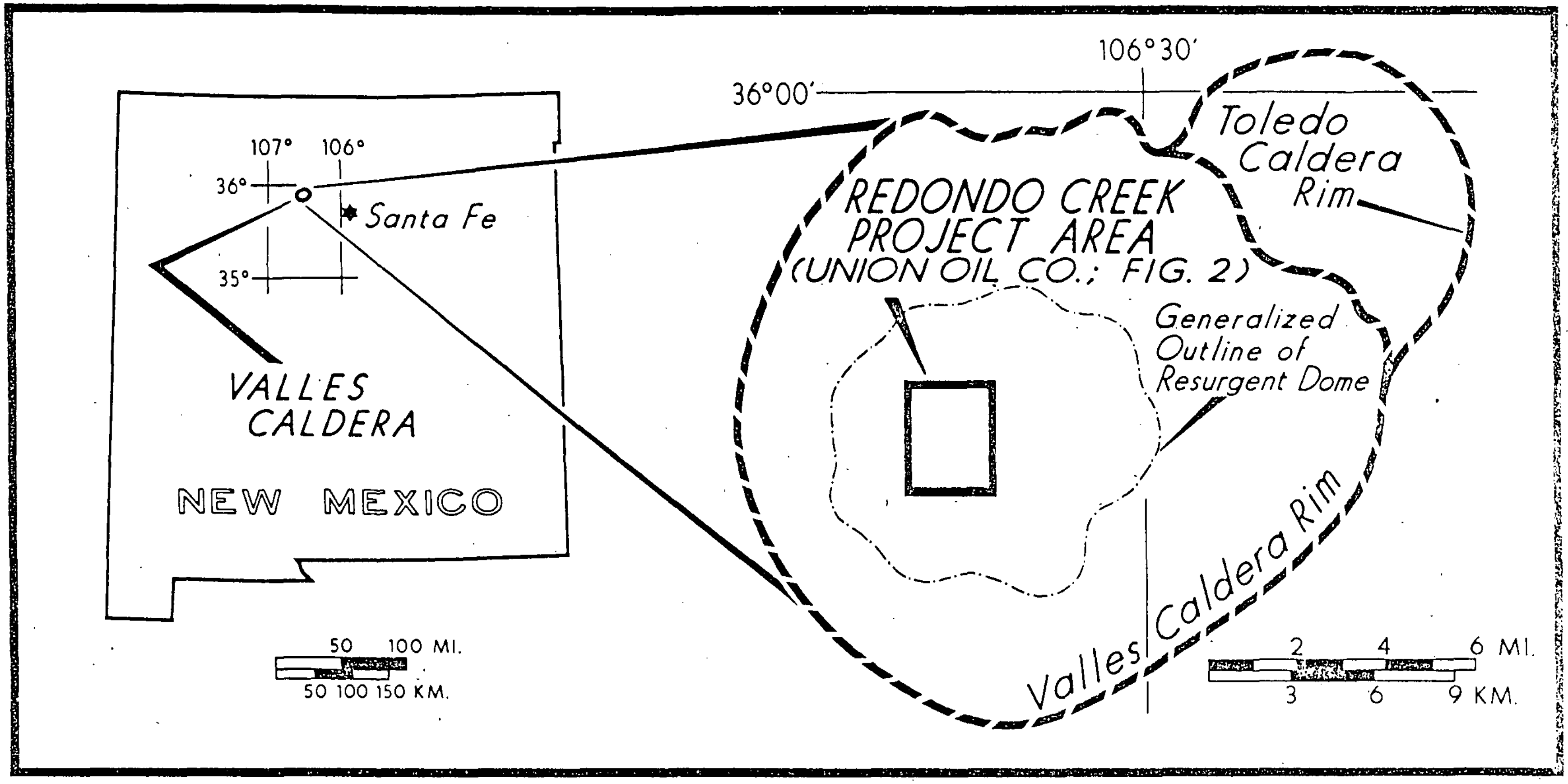
Now we'll look at this concept in terms of a cross section of the reservoir.

SLIDE 24
Fluid Flow
X-Sect

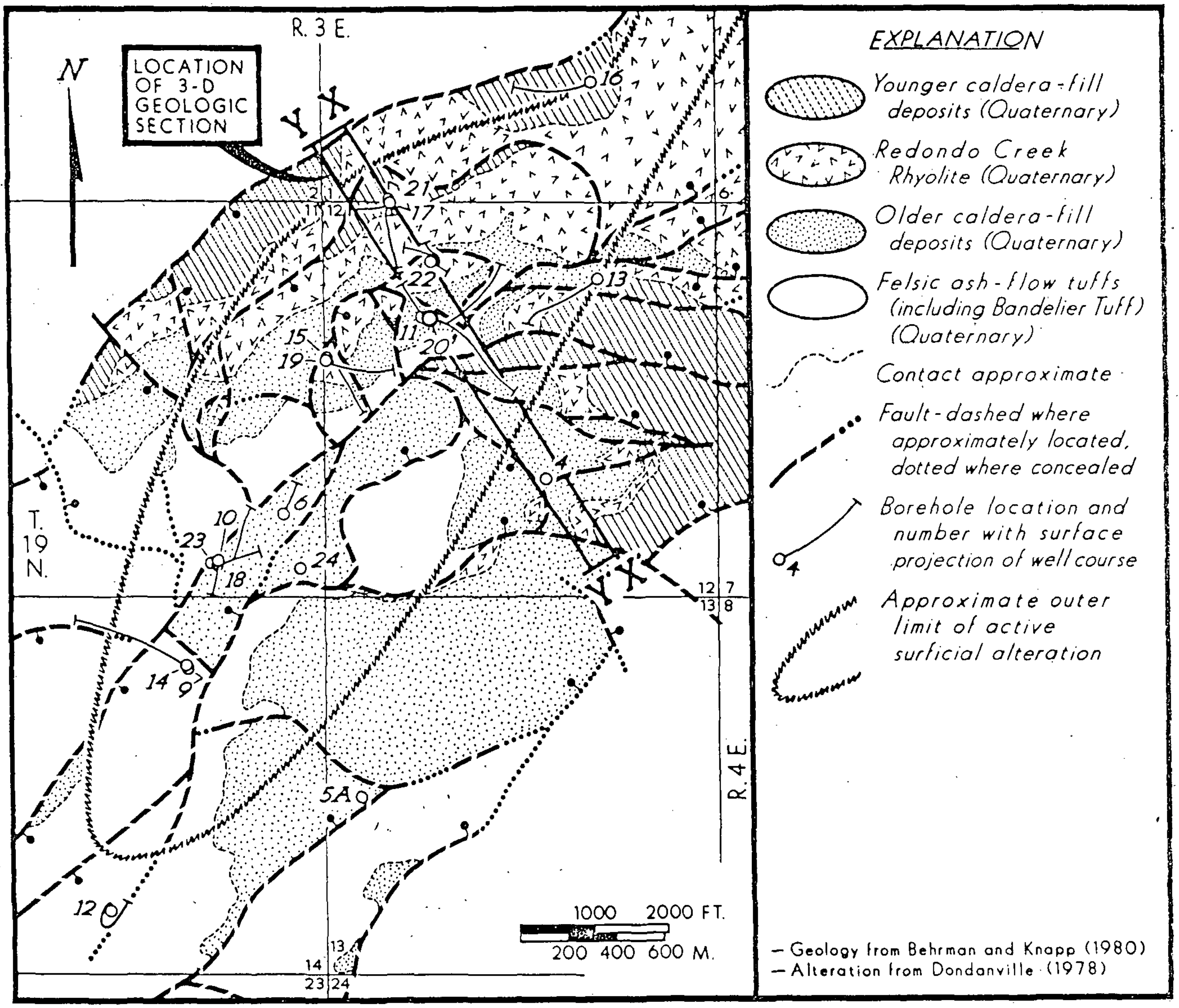
Here we have superimposed production zones upon a geologic cross section constructed from our logging. We have also superimposed isotherms on the diagram. Fluids move from depth along major fault zones and are distributed into shallow faults and stratigraphic intervals. Faults which have been developed during doming and do not intersect the faults controlling major upflow zones do not carry fluids, do not show hydrothermal alteration, and serve as lost circulation zones during drilling.

With time, permeability along the zones of fluid flow is reduced due to hydrothermal alteration. This sealing is particularly effective in non-welded ash and volcaniclastic beds. In contrast fault and fracture zones can have their permeability renewed by subsequent movement along those zones.

Although the fluids at Baca are of low salinity, clear parallels exist between this active hydrothermal convection system and precious metal vein systems in similar settings.

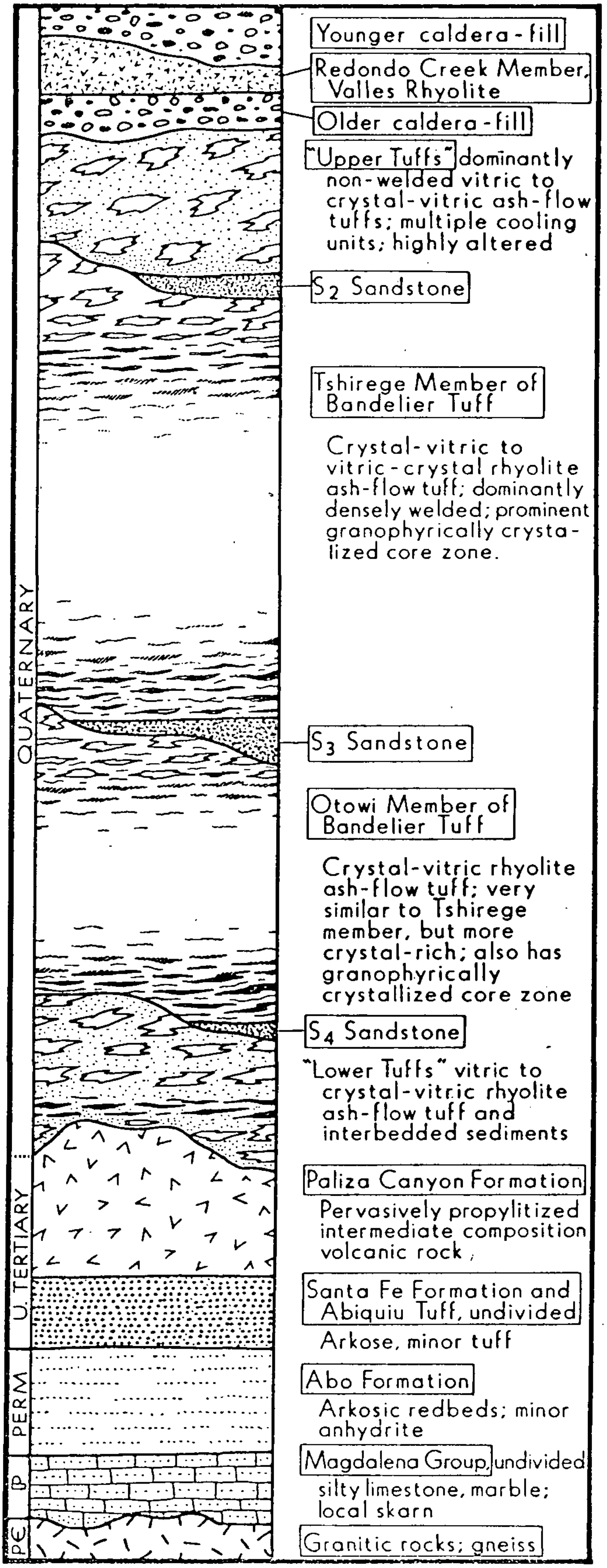

107°
106°
36°
35°
Santa Fe
VALLES CALDERA
NEW MEXICO
50 100 MI.
50 100 150 KM.
106°30′
36°00′
Toledo Caldera Rim
REDONDO CREEK PROJECT AREA (UNION OIL CO.; FIG. 2)
Generalized Outline of Resurgent Dome
Valles Caldera Rim
2 4 6 MI.
3 6 9 KM.

SLIDE 1



– Geology from Behrman and Knapp (1980)
– Alteration from Dondanville (1978)

SLIDE 2



Younger caldera-fill

Redondo Creek Member, Valles Rhyolite

Older caldera-fill

"Upper Tuffs" dominantly non-welded vitric to crystal-vitric ash-flow tuffs; multiple cooling units; highly altered

S_2 Sandstone

Tshirege Member of Bandelier Tuff

Crystal-vitric to vitric-crystal rhyolite ash-flow tuff; dominantly densely welded; prominent granophyrically crystalized core zone.

S_3 Sandstone

Otowi Member of Bandelier Tuff

Crystal-vitric rhyolite ash-flow tuff; very similar to Tshirege member, but more crystal-rich; also has granophyrically crystallized core zone

S_4 Sandstone

"Lower Tuffs" vitric to crystal-vitric rhyolite ash-flow tuff and interbedded sediments

Paliza Canyon Formation

Pervasively propylitized intermediate composition volcanic rock

Santa Fe Formation and Abiquiu Tuff, undivided

Arkose, minor tuff

Abo Formation

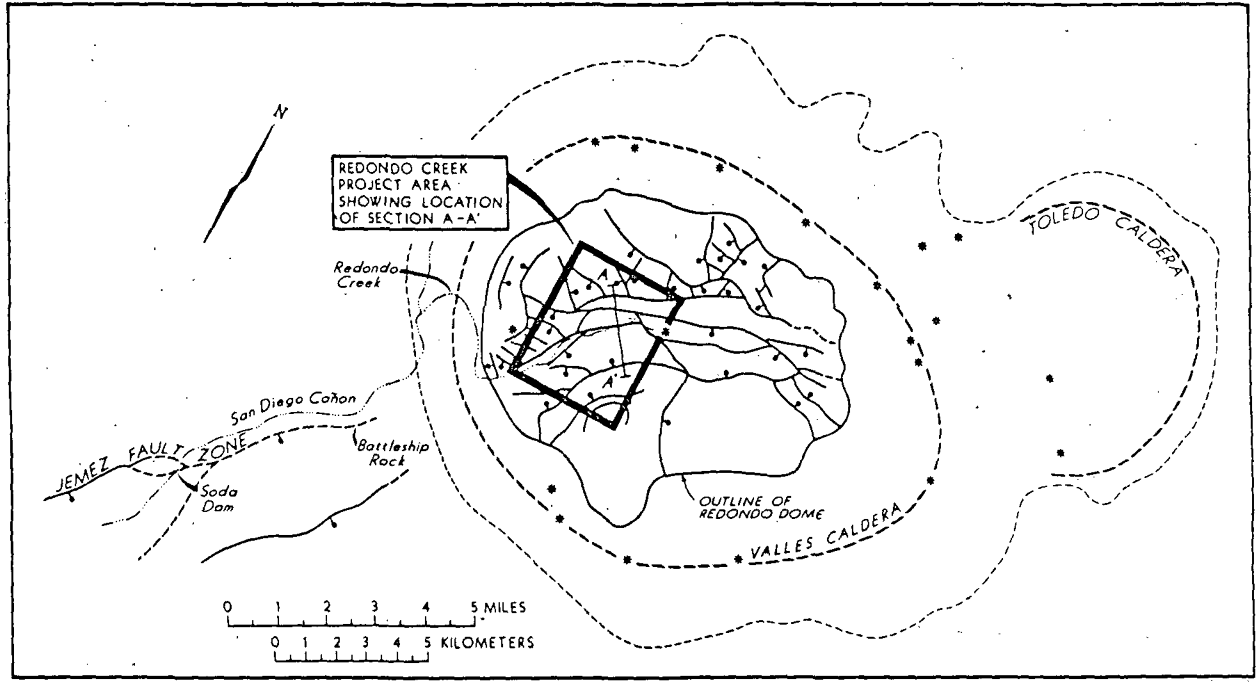
Arkosic redbeds; minor anhydrite

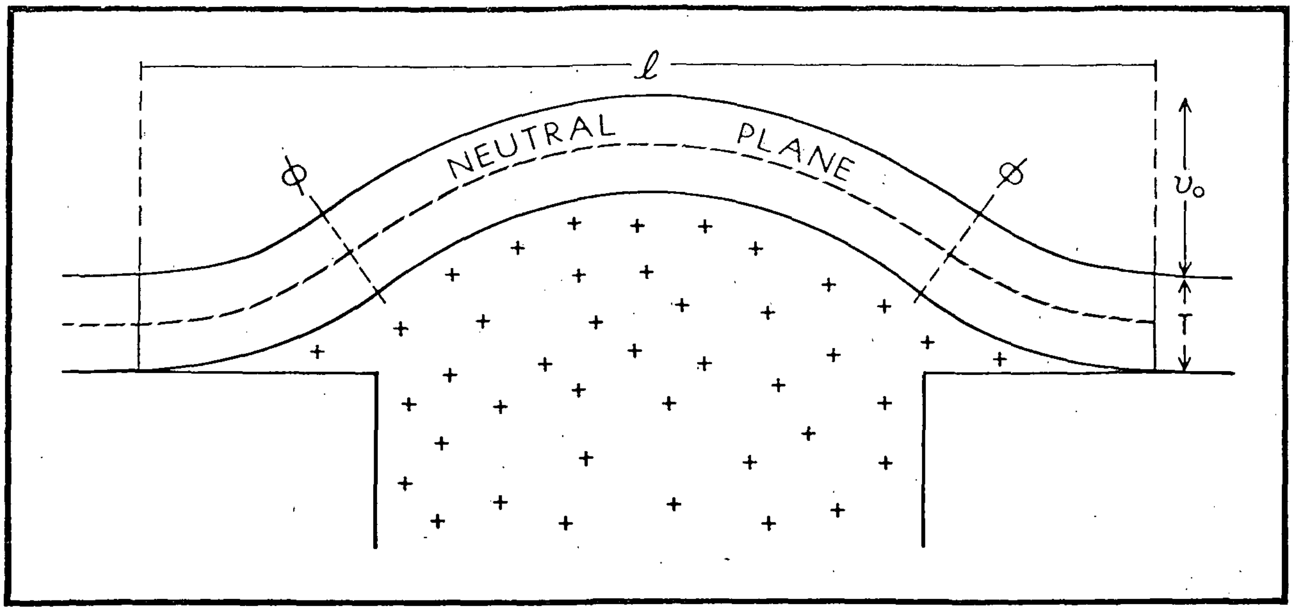
Magdalena Group, undivided

silty limestone, marble; local skarn

Granitic rocks; gneiss

SLIDE 4- Redondo Dome as viewed from Valle Grande


N
REDONDO CREEK PROJECT AREA SHOWING LOCATION OF SECTION A-A'
A
A'
Redondo Creek
San Diego Cañon
JEMEZ FAULT ZONE
Battleship Rock
Soda Dam
TOLEDO CALDERA
VALLES CALDERA
OUTLINE OF REDONDO DOME
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS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NEUTRAL PLANE
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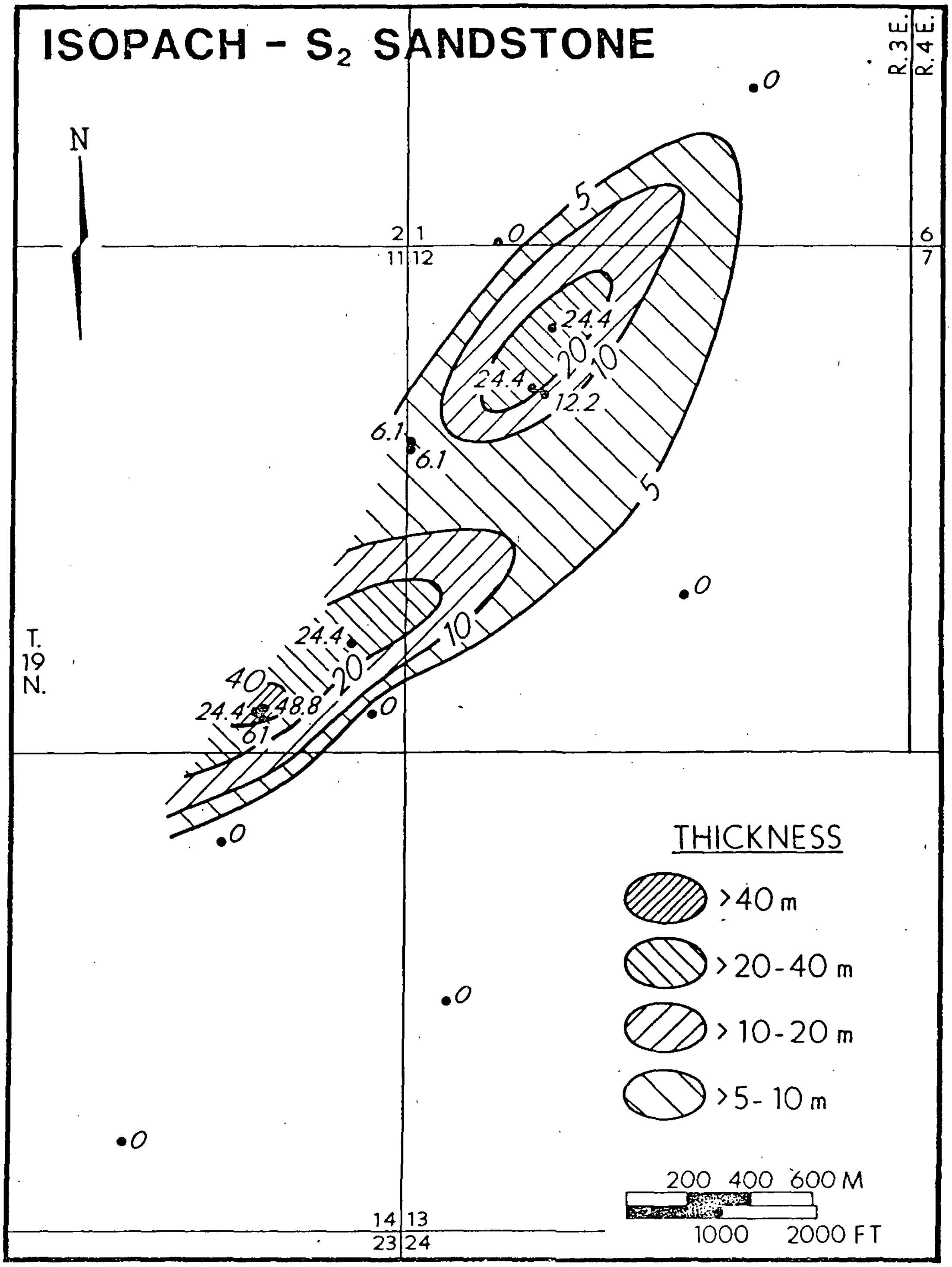
SLIDE 7


ISOPACH - S₂ SANDSTONE
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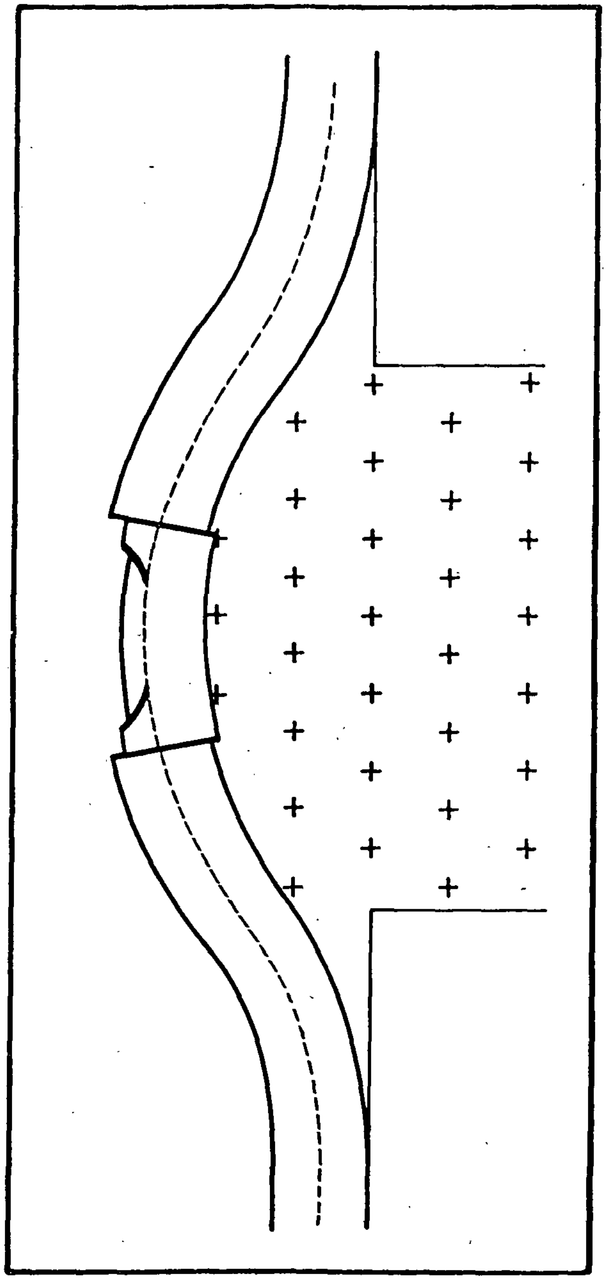
R.3E.
R.4E.
T. 19 N.
2 1
11 12
6
7
14 13
23 24
0
5
10
20
40
24.4
12.2
6.1
48.8
61
THICKNESS
>40 m
>20-40 m
>10-20 m
>5-10 m
200 400 600 M
1000 2000 FT

SLIDE 8



SLIDE 9

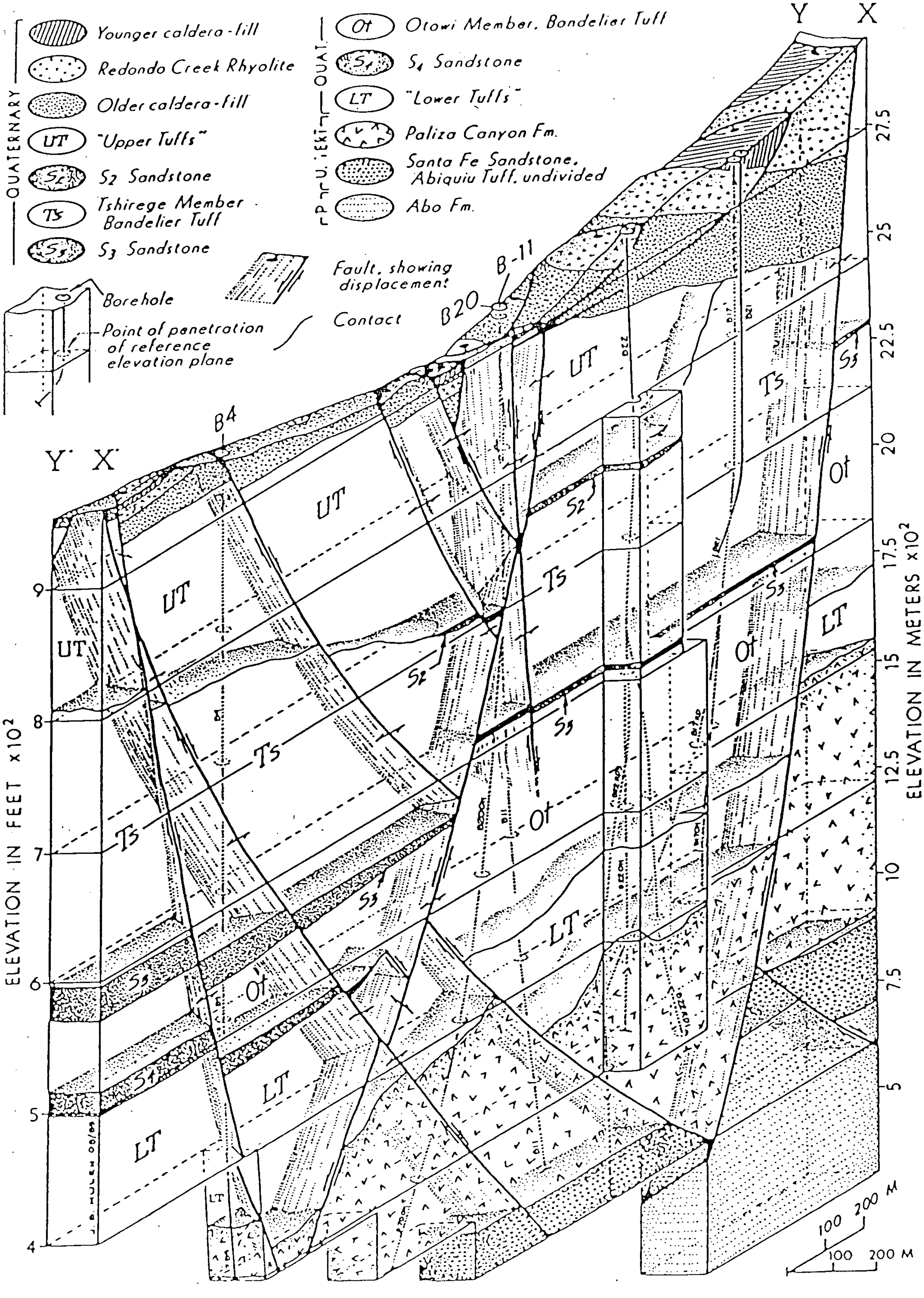
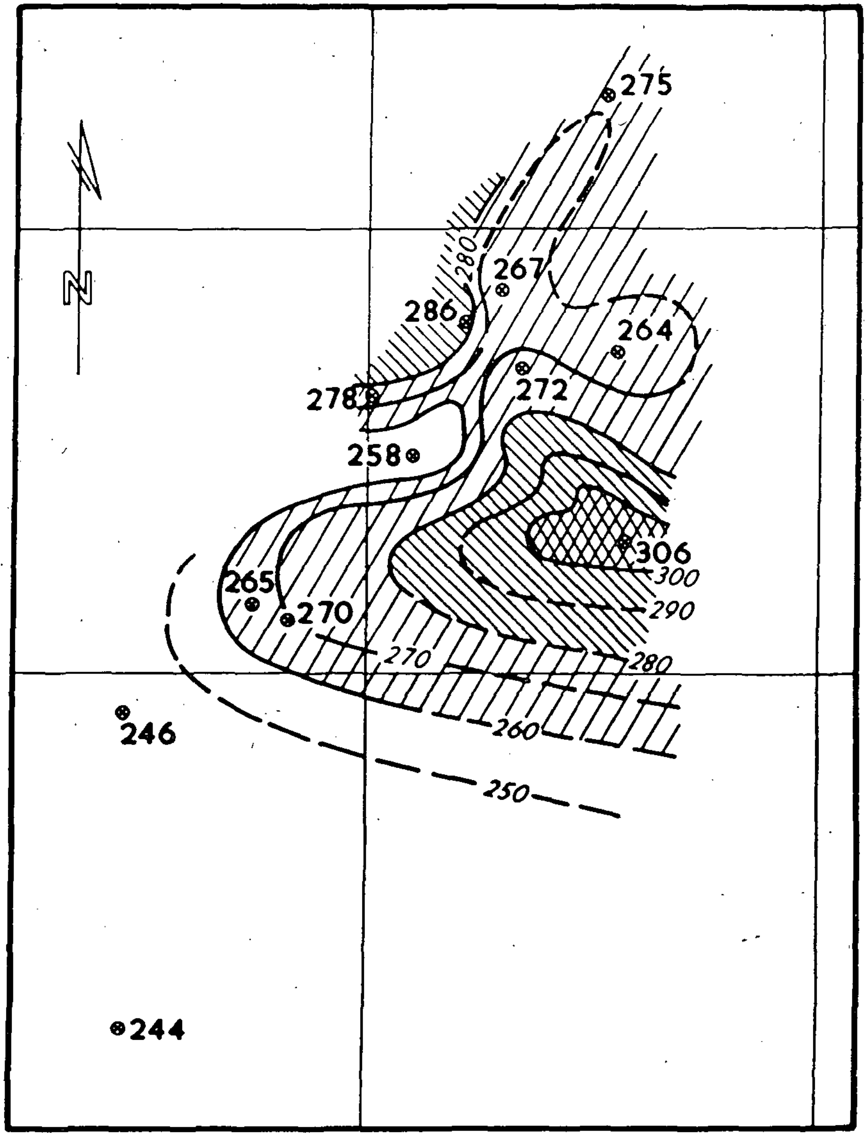


FIG. 15

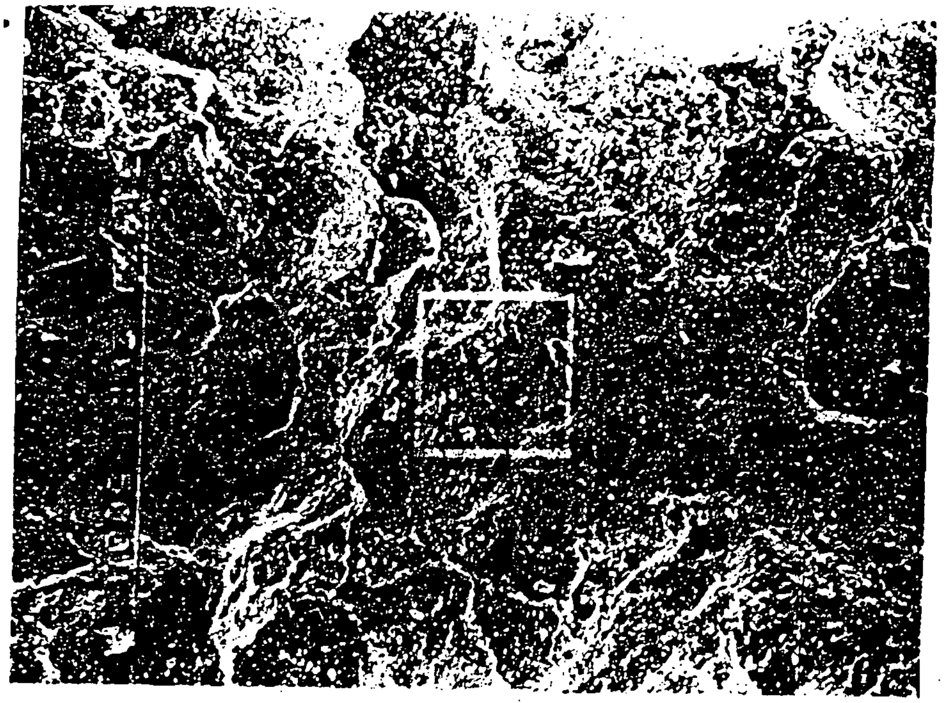
SLIDE 10- Photograph of the well head of Baca-12

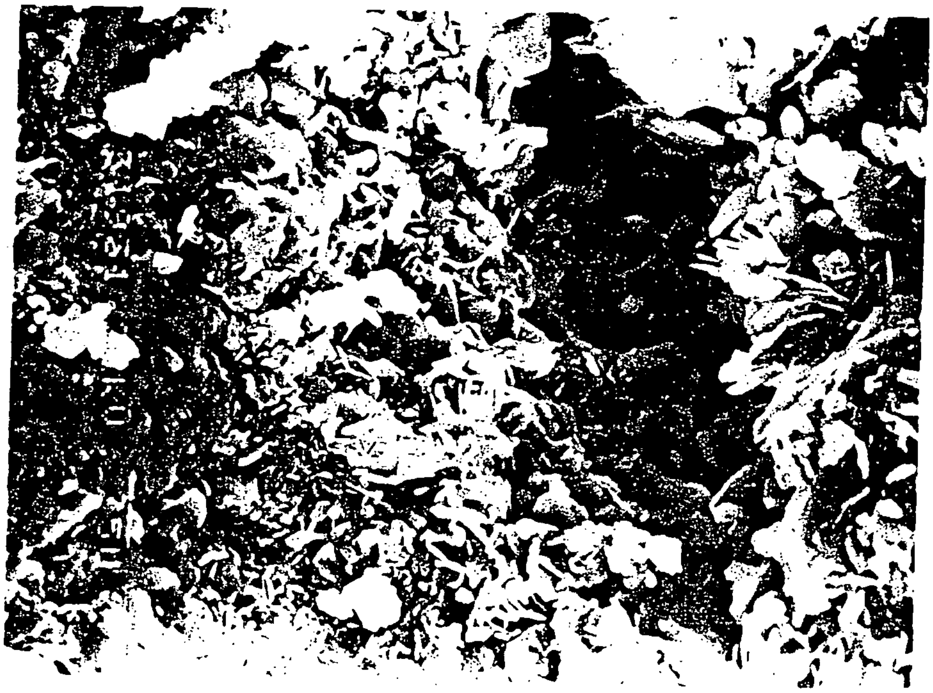
Temp. at 1200m elev.[°C]



SLIDE 12-Photomicrograh of granophyric crstallization from Baca-17

SLIDE 13





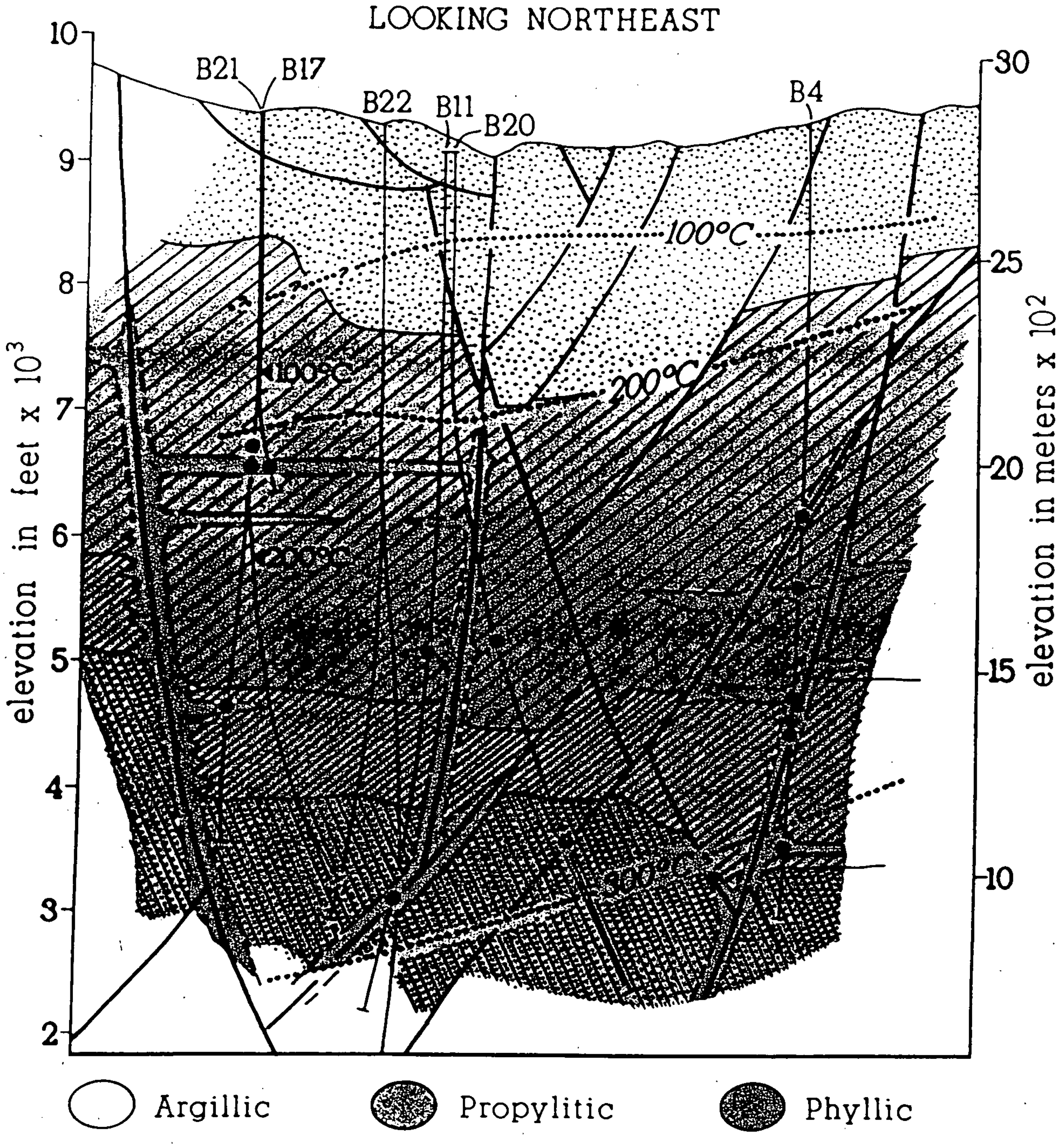
SLIDE 14

SLIDE 15

A

SLIDE 16

E


LOOKING NORTHEAST
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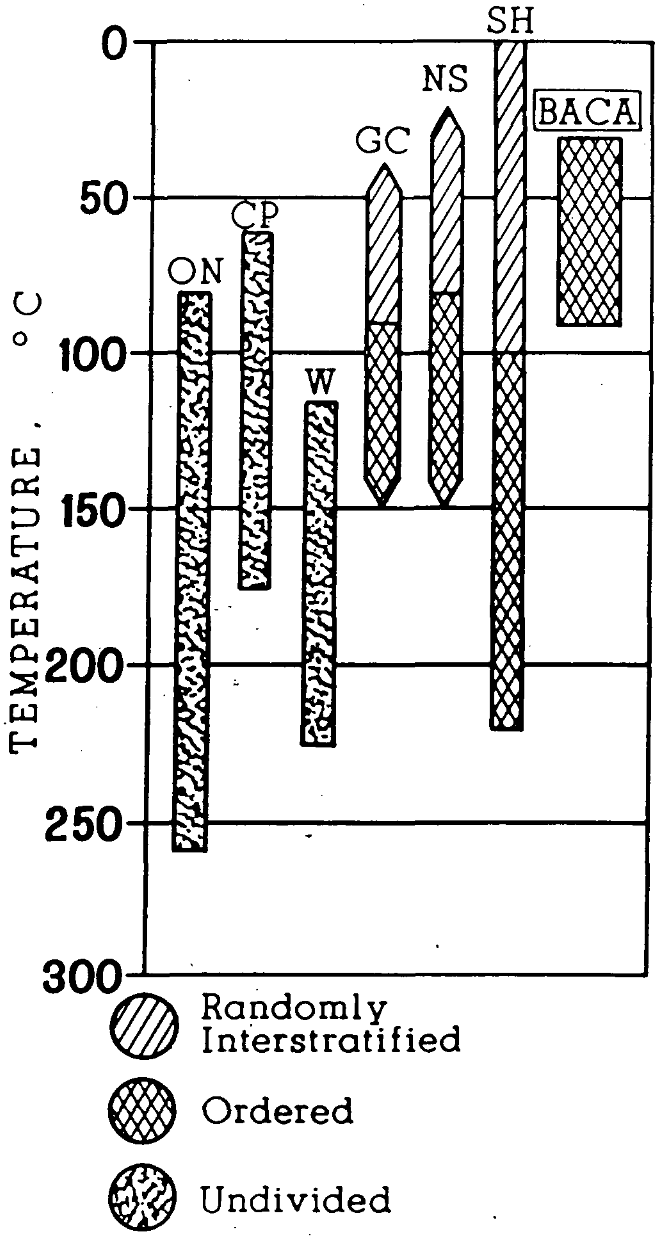
B17
B22
B11
B20
B4
100°C
150°C
200°C
200°C
300°C
elevation in feet x 10^3
10
9
8
7
6
5
4
3
2
elevation in meters x 10^2
30
25
20
15
10
Argillic
Propylitic
Phyllic


SH
NS
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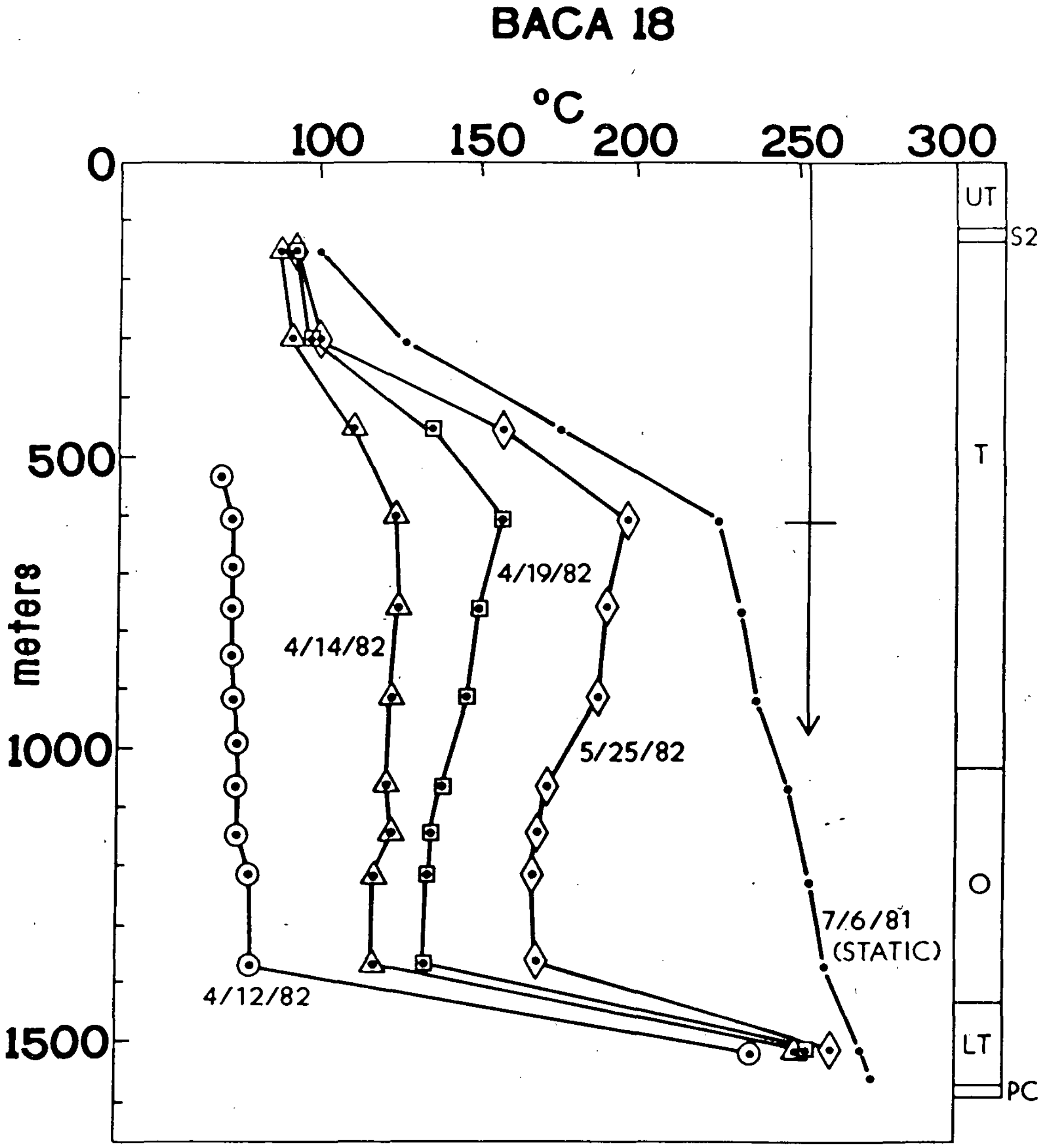
250
300
TEMPERATURE, °C
Randomly Interstratified
Ordered
Undivided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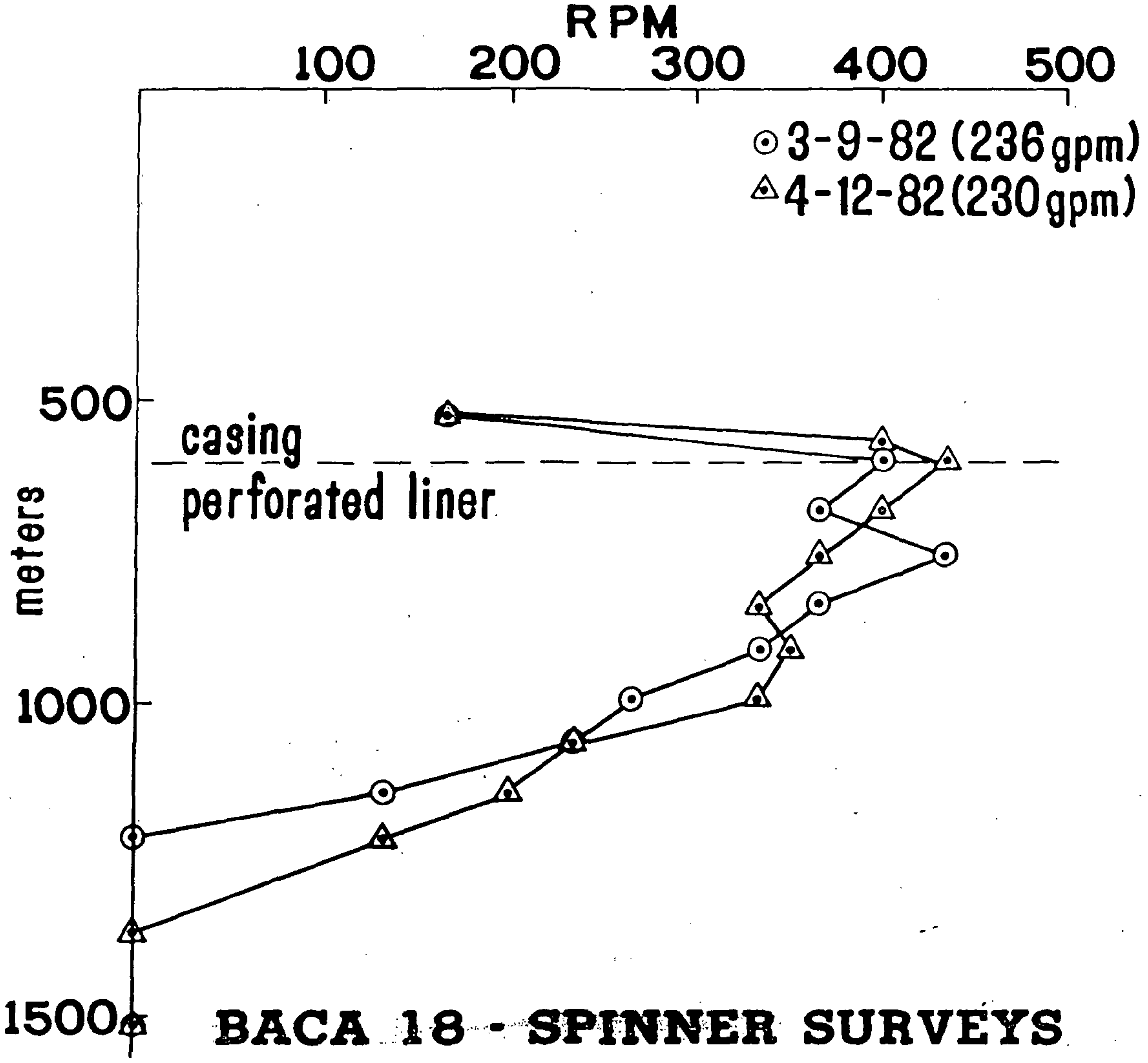
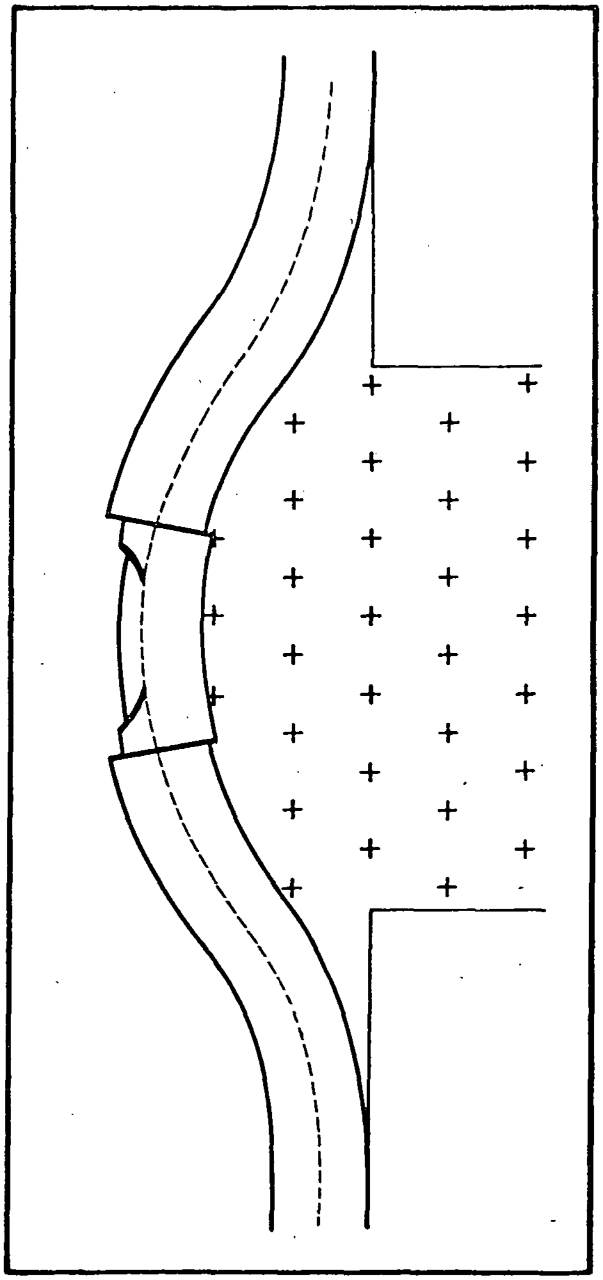
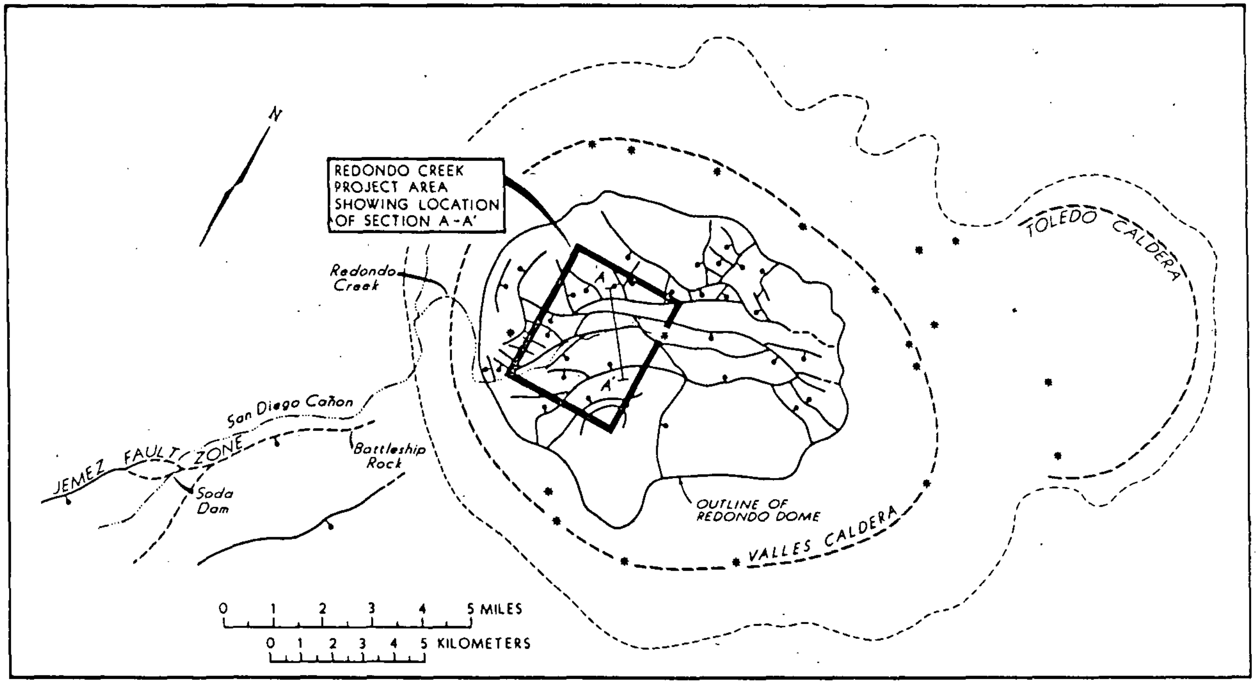


BACA 18 - SPINNER SURVEYS

	SILVER/BASE METAL DEPOSITS	BACA
● Host Rocks/Tectonic Setting	Felsic ash flow tuffs, complexly faulted	Same
● Ore	Ag, Ag-bearing sulfosalts and sulfides	None; Ag-rich PYRITIC ZONES
● Temperature	190-270°C	20-341°C
● Heat Source	Felsic magma chamber	Felsic magma chamber
● Water	NaCl; 40-120 x 10^3 ppm TDS	NaCl; 5200-7300 ppm TDS
● Geochemical Zoning	Hg, As, Sb above ore zone	Data incomplete; Hg ENRICHED AT HIGH LEVELS
● Hydrothermal Alteration	Widespread propylitization; Phyllic alteration of vein envelopes; ARGILLIC "CAP" WITH ILLITE-SMECTITE	Pervasive propylitization Phyllic alteration in FAULT ZONES AND PERMEABLE STRATA; ARGILLIC "CAP" WITH ILLITE-SMECTITE

SLIDE 22

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REDONDO CREEK PROJECT AREA SHOWING LOCATION OF SECTION A-A'
Redondo Creek
A
A'
TOLEDO CALDERA
San Diego Cañon
JEMEZ FAULT ZONE
Battleship Rock
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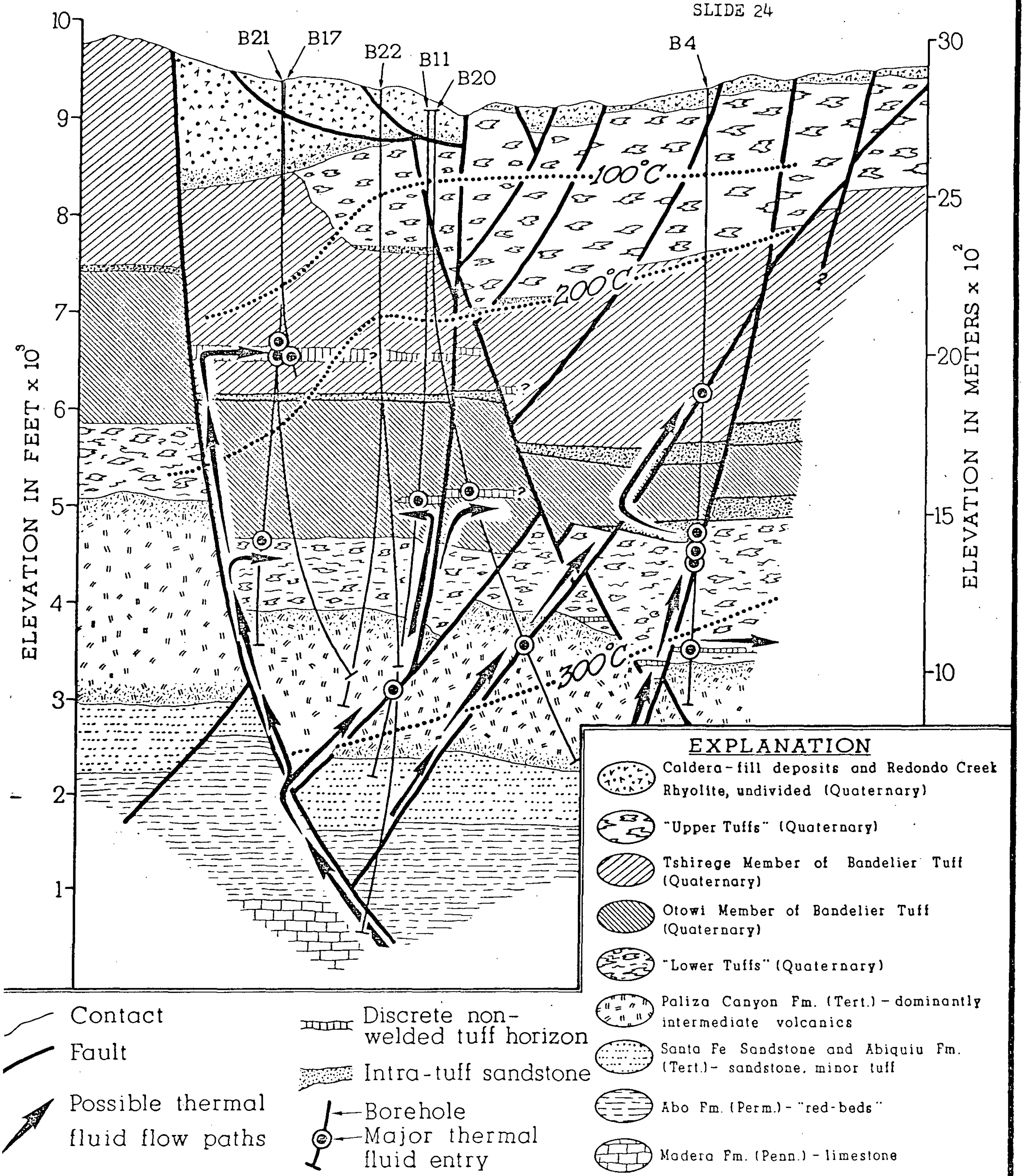
OUTLINE OF REDONDO DOME
VALLES CALDERA
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS



Data from Union Geothermal (1973 - 1981), Berhrman and Knapp (1980) and Grant and Garg (1981). Interpretation by J.B Hulen and D.L. Nielson

INTERNAL GEOLOGY AND EVOLUTION OF THE REDONDO DOME, VALLES CALDERA, NEW MEXICO

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ABSTRACT

Deep geothermal drilling in the resurgent Redondo Dome of the Valles caldera has allowed us to develop a consistent intra-caldera stratigraphic data base which differs in a number of respects from the stratigraphy established by exposures outside the caldera. Above the Pliocene Paliza Canyon Formation, felsic ash-flows and sediments form a complex sequence of undetermined age that we call the Lower Tuffs. An erosional interval separates these rocks from the overlying Otowi Member of the Bandelier Tuff. Another period of erosion, during which a widespread blanket of arkose was deposited, separates the Otowi from the overlying Tshirege Member of the Bandelier Tuff. Both the Otowi and Tshirege Members, with maximum thicknesses of 833 m and 1155 m respectively, are substantially thicker within the caldera than outside. Both are largely densely welded with distinctive granophyrically crystallized cores. Resurgent doming was initiated following the emplacement of the Tshirege Member. Streams draining the uplifting dome were localized along the present Redondo Creek trend. These scoured into the Tshirege locally depositing sands and gravels. Subsequent volcanic activity resulted in the formation of at least three additional ash-flow tuff cooling units prior to deposition of caldera fill and the eruption of the Redondo Creek Member of the Valles Rhyolite. Modeling of resurgent dome formation suggests that the causative magma body is located at a depth of about 4700 meters. The deepest drilling reaches 3242 m and bottoms in Precambrian granite without intersecting the magma which produced the resurgent doming. Our analysis suggests that the faults associated with the Jemez Lineament influenced the location of the faults bounding the apical graben. These faults were active early in the uplift history of the dome and account for many of the structural differences between idealized dome development and reality.

INTRODUCTION

In this study we present the results of detailed logging of subsurface samples from wells drilled by Union Oil Company (UOC) in a portion of the resurgent Redondo Dome in the Valles caldera (Fig. 1). This drilling was part of a geothermal exploration and development program within what is termed the Baca project area (Goldstein et al., 1982). The samples we report on here constitute a very detailed subsurface sampling of the stratigraphy of this area. From this stratigraphic data, we can infer the structure and draw conclusions concerning the structural evolution of the Valles caldera in general and the Redondo Dome in particular. Previous work (Hulen and Nielson, 1982) was based upon the synthesis of lithologic logs constructed by a number of Union geologists. We believe the present study provides a more consistent evaluation of the complex geology of this area. Work is in progress on the igneous and hydrothermal geochemistry as well as the zonation of hydrothermal alteration phases (Hulen and Nielson, 1983).

Fig. 1 near here

The location of the Baca Project area is shown on Fig. 1. This area of detailed deep drilling is located within the resurgent Redondo Dome, and most of the drilling is located between the faults which bound the apical graben of the resurgent dome. Figure 2 shows details of the geology along with the locations and deviations of the wells studied as part of this project.

Fig. 2 near here

GEOLOGIC BACKGROUND

The Valles caldera formed at the intersection between the Rio Grande Rift zone and the northeast trending Jemez Lineament. The Jemez Lineament is a broad zone which includes the Jemez fault which is exposed to the southeast of the caldera in San Diego Cañon (Fig. 1). This fault has been mapped in detail by Goff and Kron (1980) as an enechelon series of nearly vertical faults. Offsets indicate that the Jemez fault has been active for some time as evidenced by the greater offset on units which are older than the Bandelier Tuff as contrasted with the younger rocks. In addition, Tertiary sediments thin dramatically to the west of the fault (F. Goff, personal communication, 1983). Where the fault can be clearly observed at Soda Dam, very high angle offset of about 280 meters can be documented on the Madera Limestone (Goff and Kron, 1980). The Jemez fault is covered by the rhyolites of the moat of the caldera in the vicinity of Battleship Rock. However, within the caldera the apical graben of the resurgent dome is aligned with the Jemez fault suggesting the influence of this older structure in the development of the fault pattern observed on the Redondo Dome (Fig. 1). Goff et al. (1981) have concluded that the hot spring activity observed in the San Diego Cañon area represents leakage from the hydrothermal system of the Valles caldera which has been mixed with shallow meteoric waters. Thus they argue for a hydrologic connection of this area with the high temperature hydrothermal resevoir within the caldera.

The geology of the Valles caldera is largely known from the work of R. L. Smith and his coworkers (Smith and Bailey, 1968; Smith et al., 1970; Doell et al., 1968). Heiken and Goff (1983) have summarized the evolution of the caldera and discussed the thermal energy of the system. Caldera formation began about 1.4 million years ago with the eruption of the Otowi Member of the Bandelier Tuff. About 300 km^3 of material was erupted at this time to form the Toledo caldera. About 1.1 million years ago, an eruption comparable to that of the Toledo caldera formed the Valles caldera with the emplacement of the Tshirege Member of the Bandelier Tuff. Subsequent rhyolitic activity has resulted in extrusion of domes in the moat area of the Valles caldera. Rhyolite and ash flow tuff eruptions continued until 100,000 years ago.

The stratigraphic relationships of the two members of the Bandelier Tuff, as exposed in the Pajarito Plateau outside the caldera, have been discussed by Crowe et al. (1978). They have used the nomenclature of Griggs (1964) as modified slightly by Bailey et al. (1969). The formation of the Toledo caldera was initiated with a Plinean airfall which formed the Guaje Pumice, considered the basal portion of the Otowi Member of the Bandelier Tuff. Above this the principal volume of the Otowi was deposited as a basal surge followed by two flow units which subsequently cooled as a simple cooling unit. The upper contact of the Otowi shows reworking of the tuff and some soil development. The formation of the Valles caldera, after an approximate 300,000 year hiatus (Doell et al., 1968), was again heralded by a Plinean airfall which formed the Tsankawi Pumice. Above this the ash flows of the Tshirege Member form a multiple flow composite ash flow sheet with three clearly recognized cooling units.

Smith and Bailey (1968) describe the continued evolution of the Valles as follows. Following the collapse of the Valles caldera, a caldera lake formed in the depression. During this time the Deer Canyon Member of the Valles Rhyolite (Smith et al., 1970) erupted forming rhyolite flows and pyroclastics. This activity plus landslides from the topographic margin of the caldera resulted in the deposition of approximately 600 m of fill over the subsided cauldron block. In the late stages of lacustrine deposition, the Redondo Dome was formed, developing about 900 meters of structural relief. During the formation of the dome, the Redondo Creek Member of the Valles

Rhyolite (Smith et al., 1970) was erupted from the northwest portion of the ring fracture zone and from within the longitudinal graben near the center of the uplifted dome. In the ring fracture zone the Redondo Creek Member is locally interbedded with lake beds which thin against the Redondo Dome. Faulting and dips in these rocks indicate that the growth of the dome continued after the emplacement of the Redondo Creek Member. Near the end of this stage of development the caldera was breached on the southwest, allowing the caldera lake to drain through San Diego Cañon.

The Valle Grande Member of the Valles Rhyolite (Smith et. al., 1970) was emplaced in the ring fracture system periferal to the Redondo Dome. There is no evidence that the Redondo Dome continued to grow following the eruption of these late rhyolitic rocks. Since that time, hot spring and sulfataric activity have characterized the only surficial evidence of magmatic activity in the Valles caldera.

Behrman and Knapp (1980) have integrated the results of field mapping, well logging, production and static temperature data to form an exploration model of the hydrothermal system in the Baca Project area. They emphasize the predominant importance of faulting and fracturing in providing the controls on the geothermal reservoir. They also point out the importance of steeply dipping fault zones in contrast with shallow dipping zones which we interpret as resulting from extension in the upper portions of the Redondo Dome or from mass movement in areas of steep topography. The conclusions presented here will not agree in detail with Behrman and Knapp's evaluations, but we do agree with the fundamental importance in the steep throughgoing faults maintaining a significant control on the flow paths of hydrothermal solutions in the Redondo Dome.

LITHOLOGY AND STRATIGRAPHY WITHIN THE REDONDO DOME

During the Baca Project UOC drilled over 42,000 meters of hole. Of this total we were able to log samples representing over 21,000 meters. For the remainder of the holes, copies of well logs done by UOC geologists were available, and we were able to interpret most of the logs in a fashion which agreed with our conclusions from the holes for which we have cuttings and core. The cuttings samples were generally available on 6 meter intervals, although some were sampled at 3 m intervals. These samples were washed and dried and then mounted on chipboards for logging under the binocular microscope. In addition, selected intervals were thin sectioned for examination under the petrographic microscope. Selected portions of the holes were also chemically analyzed and mineralogical determinations made by X-ray diffraction techniques. There are, of course, limits on the data which can be acquired from cuttings samples. No orientation data can be acquired and one must be aware of the possibility of fractionation within the borehole and contamination by sloughing from above. In addition, drilling additives and drill steel can lead to chemical and mineralogical contamination (Hulen and Sibbett, in press).

Several of the holes with very complete stratigraphic sections have enabled us to understand the stratigraphy and extrapolate to holes where the stratigraphic section is not as clearly defined. Figure 3 is a schematic stratigraphic column of the units encountered in the Baca drill holes. The thicknesses, tops, and bottoms of the units are listed in Table 1.

<ins>Fig. 3 near here</ins>

<ins>Table 1 near here</ins>

The focus of this paper is on stratigraphy and structural disruption of the Bandelier Tuff and associated felsic tuffs and sediments. These tuffs were deposited on a deeply incised erosional surface developed on the Pliocene Paliza Canyon Formation, which therefore will be briefly characterized to provide a geologic setting for the caldera-related events to follow.

The Paliza Canyon Formation

The Pliocene Paliza Canyon Formation, as penetrated by Union boreholes in the Redondo Creek area, is a highly variable sequence of mostly intermediate-composition porphyritic flows, tuffs, breccias, volcanic siltstones and sandstones, and probably subvolcanic intrusive rocks.

A distinctive feature of the Paliza Canyon is its nearly pervasive propylitic alteration. All units within the formation have been at least partially converted to one or more minerals of the assemblage chlorite-calcite-albite-epidote-quartz-pyrite-hematite. In some wells, virtually none of the original rock-forming minerals remain intact. Veinlets of calcite-quartz-epidote-chlorite are also commonly encountered in the Paliza Canyon cuttings.

In striking contrast with all but the uppermost overlying ash-flow tuffs, which have been affected by near-surface acid sulfate leaching, alteration in the Paliza Canyon Formation is not confined to fracture zones or permeable tuffs and sediments. This relationship strongly suggests that much of the propylitic alteration in the Paliza Canyon pre-dates the overlying units.

The Lower Tuffs

A complex sequence of generally thin felsic ash-flow tuff cooling units and interbedded tuffaceous sedimentary rocks, herein informally designated the Lower Tuffs, rests unconformably on the Paliza Canyon Formation in the Redondo Creek area. Individual ash-flow sheets, cooling units and sandstone beds within this sequence presently cannot be correlated with confidence between boreholes. Preliminary work suggests that these units may have accumulated as overlapping lenses, blankets and channel deposits of limited local extent. The common presence of thin (up to 12.2 m) volcaniclastic sandstone beds throughout the Lower Tuff sequence suggests that ash-flow eruption during their emplacement was frequently interrupted by erosional intervals. Very thin (less than a few meters) apparent sandstones, it should be noted, could actually be surge deposits since the two rock types could be confused for one another in drill cuttings.

The Lower Tuffs in the Redondo Creek area range in aggregate thickness from 69.2 to 396.2 meters, and in the northern half of the project area clearly occupy depressions in the Paliza Canyon erosional surface. This surface is overlain locally by up to 6 meters of coarse sandstone and possibly conglomerate; larger cobbles and boulders would be destroyed during the production of cuttings. Grains of propylitized andesite porphyry are common in this basal sediment, as are uncollapsed, highly rounded pumice lapilli.

Individual ash-flow cooling units in the Lower Tuffs are typically less than 100 meters and commonly less than 50 meters in thickness. Welding of these cooling units is quite variable. In boreholes B-22 and B-23, for example, the Lower Tuffs are predominantly densely welded, with the lowest cooling unit densely welded to its base. In borehole B-17, the basal cooling unit is densely welded immediately above the Paliza Canyon Formation, but becomes progressively less welded upward to become completely non-welded in its upper 30 meters. The Lower Tuffs are predominantly devitrified, particularly in more highly welded portions, although irregular wispy patches of dense black obsidian are locally common. Vapor-phase crystallization is apparently rare, but locally present in the basal and upper portions of individual cooling units.

Phenocrysts in the Lower Tuffs range from less than five percent to as much as 40 percent of the rock, depending on the individual unit and its degree of welding. Microperthite phenocrysts are dominant. These are subhedral to euhedral or broken, up to four mm in length, and typically form stubby laths to roughly equant grains. XRD reveals these microperthite crystals to consist of albite and monoclinic potassium feldspar. A few phenocrysts in the Lower Tuffs are essentially discrete albite, with scattered, irregular potassium feldspar inclusions. Quartz phenocrysts, accounting for up to 10% of the more densely welded portions of the Lower Tuffs, are anhedral to euhedral, commonly rounded and embayed, frequently broken, and average about 2 mm in diameter. Former mafic phenocyrsts, forming less than 0.5% of these tuffs, are completely altered to chlorite-calcite-magnetite±sphene±epidote aggregates. These aggregates, up to 1.5 mm in length or diameter, vary from irregular, roughly equant grains to crude lath shaped masses. No diagnostic amphibole or pyroxene cross-sections were observed in thin section. Disseminated, discrete anhedral to subhedral equant magnetite grains, scattered throughout the Lower Tuff sequence, are typically less than 0.3 mm in diameter and make up about 0.3% of the total volume of these rocks. The magnetite is usually fresh, but is locally altered to pyrite and/or maroon submetallic hematite.

Angular lithic fragments, up to at least 10 mm in diameter, are locally common in the Lower Tuffs, in certain horizons forming up to 10% of the total rock volume. Most are derived from older welded ash-flow tuffs similar in character to the tuffs in which they are embedded. Other less abundant lithic fragments are porphyritic, intermediate-composition volcanics, quartzite and granite gneiss, all of which can be correlated with Pre-Quaternary rocks penetrated beneath the Lower Tuffs in the Redondo Creek boreholes.

X-ray diffraction shows the groundmass of representative Lower Tuff samples to consist of quartz, monoclinic potassium feldspar and variable amounts of albite, illustrating that devitrification of these rocks is complete.

There are no dates on these samples, but it is possible, based on their stratigraphic position, that they may be equivalent to the 3.6 to 3.1 million year old tuffs described by Self and Goff (this volume) which are exposed in San Diego Cañon beneath the Otowi Member of the Bandelier Tuff. Alternatively, they may represent activity associated with the El Rechuelos Rhyolite which has been dated at 2.0 m.y. (Bailey and Smith, 1978).

The S_4 Sandstone

A thick accumulation (48.9 m) of probable arkose separates the Lower Tuffs from the overlying Otowi Member of the Bandelier Tuff in borehole B-4. This sandstone, "S_4", has not been recognized in the other Redondo Creek wells and therefore probably represents deposition in an isolated depression or channel.

Cuttings from the S_4 sandstone were not available for this study. As logged by R.F. Dondanville, of Union Oil Company, the S_4 is a friable to highly silicified, fine- to coarse-grained sandstone consisting dominantly of subrounded to euhedral crystals of quartz and feldspar with minor basalt. In addition to being silicified, the S_4 is also locally epidotized. This hydrothermal alteration, along with a pronounced increase in dry steam production in the S_4, indicates the unit to have been a major thermal fluid conduit.

Otowi Member of the Bandelier Tuff

The Lower Tuffs and S_4 are overlain in sequence, throughout the Redondo Creek area, by two extremely thick ash-flow tuff cooling units. On the basis of composition, distinctive welding and crystallization characteristics, inferred erosional history, and stratigraphic positions, we believe these tuffs correlate with the Otowi and Tshirege Members of the Bandelier Tuff as presently defined outside the Valles caldera (Griggs, 1964; Smith and Bailey, 1968; Doell et al., 1968; Crowe et al., 1973).

The Otowi Member, as penetrated in the Redondo Creek boreholes, ranges in thickness from 176.8 m (B-4) to 833 m (B-12), and averages well over 400 m in thickness (Table 1). In contrast, the Otowi outside the Valles caldera seldom exceeds 100 m (Crowe et al., 1973). The Otowi in the Baca Project area also is characterized by a densely welded, granophyrically crystallized core, whereas outside the caldera, the Otowi is typically non-welded to partially welded and commonly not crystallized. The relationship between the known Otowi outside the caldera and the intra-caldera Otowi thus bears out the predictions of Smith (1960) who deduced that cooling units would not only thicken dramatically toward and within their source area calderas, but, where so thickened, would also develop the dense granophyric cores such as observed in the Otowi at Redondo Creek.

The Otowi Tuff as observed in drill cuttings with the binocular microscope, is a light- to medium-gray, felsic crystal-vitric to vitric-crystal ash-flow tuff. It is almostly entirely densely welded, though less so in its upper 100-200 m. The most distinctive feature of the Otowi in the Redondo Creek cuttings is its thick, granophyrically crystallized core, generally accounting for more than half its total thickness. In cuttings this granophyric core has a unique, translucent, sugary appearance. This characteristic, routinely logged by Union Oil Company geologists, enabled confident correlation of the Otowi (and the lithologically similar, overlying Tshirege Member) among boreholes logged by us and those logged by Union. Shards and eutaxitic texture are visible in cuttings only where the rock is not granophyrically crystallized.

Petrographically, the Otowi typically consists of 30-35 percent phenocrysts, rare lithic fragments and a few severely flattened pumice lapilli in a cryptocrystalline to very fine crystalline matrix aggregate of quartz, potassium feldspar and variable amounts of albite. X-ray diffraction of the groundmass revealed no cristobalite or tridymite.

Phenocrysts in the Otowi comprise quartz, microperthite, a completely altered former mafic mineral, and magnetite. Quartz phenocrysts (7-10%) are rounded or anhedral to subhedral, commonly broken, locally embayed, very clear of inclusions, and range in diameter up to 4 mm. Microperthite phenocrysts are subhedral or broken and up to 3 mm in diameter (averaging about 1 mm). These feldspars typically consist of variable amounts of albite, as highly irregular, optically continuous patches, irregularly distributed throughout a host sanidine. These albite patches are not usually connected by veinlets or stringers, nor are they typically concentrated around the periphery of the crystals in which they occur. Thus, they are probably formed by exsolution, rather than replacement. However, replacement stringers, veinlets and rims of albite are present in and around some of these feldspar phenocrysts, so albite in the Otowi (and throughout the felsic tuff sequence in the Redondo Creek area) is probably of dual origin.

Former mafic phenocrysts in the Otowi Member form about 0.5% of the rock. They are irregular to lath-shaped aggregates, up to one mm in length or diameter, consisting of light green chlorite, magnetite, calcite, sphene, and pyrite in variable proportions with a trace of euhedral zircon.

Unaltered solitary magnetite grains up to 0.5 mm in diameter, account for about 0.3% of the Otowi Member. They are uniformly disseminated throughout the Otowi and thus probably primary constituents of the rock.

The groundmass of the Otowi varies from cryptocrystalline to fine-crystalline, depending on degree of devitrification and granophyric crystallization. Components of the groundmass, as verified by XRD, are quartz, potassium feldspar and albite with minor chlorite. Well-developed micrographophyric intergrowths of quartz and potassium feldspar are common in the Otowi Member's granophyric core.

The S_3 Sandstone

The eroded upper surface of the Otowi Member in the Redondo Creek area is capped by an eastward-thickening wedge of arkose, separating the Otowi from the overlying Tshirege Member. This arkose, which we have designated S_3, reaches a maximum thickness of 70.1 m in borehole B-4 (Fig 3; Table 1). This attests to a significant erosional interval between the two Bandelier members and supports the 0.3 m.y. eruptive hiatus indicated by K-Ar dating (Doell et al., 1968) to have followed Otowi deposition.

The S_3 sandstone is lithologically heterogeneous. In borehole B-17, for example, it is a well sorted, fine-grained arkose, with 75% angular to subrounded quartz and feldspar grains embedded in a matrix of cryptocrystalline quartz with minor sericite, chlorite, calcite and pyrite. Quartz and feldspar grains are present in roughly equal proportions. Feldspars are dominated by sanidine but also include microperthite, albite and a trace of microcline. Other grains occuring in minor amounts in the S_3 sandstone of B-17 includes fine-crystalline, commonly granophyrically crystallized quartz-potassium feldspar intergrowths and andesite porphyry. In borehole B-22, the S_3 is much finer-grained forming a silty fine-grained sandstone. It also differs from its counterpart in B-17 in having a calcite-dominated matrix; grain mineralogy and proportions are about the same. In borehole B-4, logged by R.F. Dondanville of Union Oil Company, the S_3 is comparatively rich in shale and other lithic fragments as well as obvious bipyramidal quartz crystals. The S_3 in borehole 5A is logged by Dondanville as a basalt and sandstone zone.

Source for the S_3 sandstone is clearly in part the underlying Otowi Member. However, the S_3 also contains common sanidine devoid of the ubiquitous albite patches and stringers occuring in this mineral throughout these tuffs. These albite-free sanidine grains as well as microcline grains in the S_3 probably have different sources, the sanidine perhaps from the Cerro Toledo rhyolites, erupted in the Otowi-Tshirege hiatus, and the microcline from Precambrian granite or granite gneiss then exposed in the walls of the caldera.

Tshirege Member of the Bandelier Tuff

Above the Otowi Member and S_3 sandstone in the Redondo Creek wells is a thick, simple cooling unit of felsic ash-flow tuff, which we believe to be the Tshirege Member of the Bandelier Tuff. It is remarkably similar in appearance and petrography to the Otowi. This unit can be more fully described than the Otowi, since not only drill cuttings, but also 1.5 m of core (from borehole B-20) was available for study.

Thickness of the Tshirege at Redondo Creek varies from 420.6 m to 1155.4 m, the variation due in part to basal topography and in part to post Tshirege erosion. As with the Otowi, these thicknesses are much greater than corresponding Tshirege thicknesses outside the Valles caldera (Smith and Bailey, 1966 and Crowe et al., 1978).

At Redondo Creek, the Tshirege forms a simple cooling unit of felsic vitric-crystal to crystal-vitric tuff which is typically densely welded throughout except for thin local basal and uppermost zones of partial to no welding. Like the Otowi, this unit has a dense, sugary-appearing granophyric core zone. Densely welded zones above and beneath the granophyric zone are moderately to completely devitrified, but not granophyrically crystallized.

The Redondo Creek Tshirege contains slightly fewer phenocrysts, at about 27%, than the underlying Otowi, with an average of about 32%. Size, mineralogy, morphology, and relative percentages of phenocrysts in the two units, however, are very similar. Microperthite phenocrysts, at 20-25%, are the most abundant. These feldspars, like those in the Otowi, also appear locally to be partly replaced with albite. Quartz, at 3-5%, is also present, as are 0.3% calcite-chlorite-sphene-magnetite±epidote aggregates apparently holes (Fig. 2). In addition, we once again see the gradient toward the east and southeast which reflects the influence of both resurgent doming and the northeast trending faulting along Redondo Creek.

Figure 11 is an isopach of the Tshirege Member and shows thicknesses ranging from 1155 meters to 420 meters near the central portion of the resurgent dome. In order to interpret this, we must also consider the structural contour map drawn on the top of the Tshirege (Fig. 12).

Figs. 12 and 13 near here

The pattern of Figure 12 is one of a broad trough developed along the Redondo Creek trend. Overlaying the Tshirege member isopach map on the structural contour map, it can be seen that thin portions of the Tshirege coincide with the structural contour lows. We interpret this as representing erosion of the Tshirege by a stream system which followed the path of the present Redondo Creek. As we will point out later, this erosion must have taken place during the initial stages of uplift of the Redondo Dome. The structural contour map drawn on the base of the Tshirege (Fig. 10) shows a general gradient to the SE roughly corresponding with thickening of the Unit (Fig. 11).

Figure 13 is an isopach of what we have termed the "S_2 sandstone". This sand was deposited on top of the Tshirege in a channel system that closely follows the trend of the present Redondo Creek. This deposition also follows the lows on Figure 12 supporting the hypothesis that the thinning of the Tshirege Member shown in Figure 11 is a consequence of erosion rather than deposition.

Figure 14 is an isopach map of the Upper Tuffs. These rocks range from 0 to 463 m in thickness, with the thickest portions found in B-4. The thicker portions are offset to the southeast of the channels which formed the S_2 sands. Much of the present thickness of this unit may be a function of erosion and mass wasting. To the east of this area Tshirege Member has been mapped on the surface by Smith et al. (1970), so we feel that the apparent thickening of the Upper Tuffs to the east and southeast does not continue.

Fig. 14 near here

Three-Dimensional Geologic Cross Section

Because most of Union's deep Redondo Creek geothermal wells are variably directed and inclined, standard two-dimensional geologic cross-sections have proven inadequate as a means of interpreting and portraying the complex stratigraphy and structure penetrated. Three-dimensional cross-sections, as exemplified by Figure 15, more clearly depict the subsurface geology of the Baca project area, particularly where boreholes traverse several structural blocks.

The distinctive S_2 and S_3 intra-tuff sandstones and the thick, laterally continuous granophyric core zones of the Otowi and Tshirege Members of the Bandelier Tuffs, provide excellent constraints on subsurface stratigraphic correlation among the Union boreholes. Because the stratigraphy is well-defined, structural disruption (further evidenced by zones of lost circulation and alteration in boreholes) can be much more accurately characterized. Thus we believe that Figure 15, while not a unique interpretation, closely approximates the subsurface geology of the western portion of the Redondo resurgent dome.

Figure 15 is oriented roughly perpendicular to the northeasterly-trending replacing former mafics, as well as 0.3% disseminated, unaltered magnetite grains. Angular lithic fragments visible in core from 793-794.5 m in borehole B-20 form 1-2% of the rock, and range in diameter up to at least 15 mm. These lithics are mostly of older welded felsic ash-flow tuffs, but also include intermediate composition volcanic rocks, granite gneiss and quartzite.

The groundmass of the Tshirege is nearly all devitrified to quartz and potassium feldspar with minor albite. As with the Otowi groundmass, no other silica minerals were detected by XRD. A little glass remains in upper and basal non-welded zones. The granophyric core of the unit is fine-crystalline and contains abundant, though not ubiquitous, micrographophyric quartz-potassium feldspar intergrowths.

The S_2 Sandstone

The Tshirege Member appears to have been deeply eroded in the Redondo Creek area. This erosion, to be further discussed later in this paper, is indicated by the pronounced irregularity of the unit's upper surface and by the local deposition upon it of another locally thick sandstone, which we have termed S_2.

The S_2 sandstone, where present, varies from 6.1 to 48.8 m in thickness and occupies a northeast trending trough developed on the Tshirege, and may in fact be a stream- or river-deposited sediment. The S_2 sandstone varies from a poorly sorted silty fine-grained arkose to a fine-grained carbonate sandstone consisting of angular to subrounded calcite grains embedded in a matrix of illite, interstratified illite-smectite, calcite and powdery hematite. This hematite is a common distinctive feature of S_2, staining the unit bright brick red to maroon.

The Upper Tuffs

Deposition of the S_2 sandstone in the Redondo Creek area was followed by emplacement of a complex sequence of dominantly non-welded to poorly welded felsic ash-flow tuffs which presently aggregate a maximum thickness of 463.3 m (in B-4). This tuff sequence, because of its lack of welding and hence high porosity, as well as its high-level position above the active Baca geothermal system, has been intensely argillized throughout the Redondo Creek project area. Documented in detail for borehole B-20 (Hulen and Nielson, 1983), this alteration obscures or obliterates much of the mineralogic and textural evidence that might otherwise allow correlation of individual ash-flow sheets or cooling units among the Redondo Creek boreholes. At this stage of our investigations, such correlation would be unacceptably tentative. For this paper, we will simply refer to the entire sequence as the "Upper Tuffs", and document certain of its more obvious characteristics.

The Upper Tuff sequence is best developed in borehole B-22. In this well, it forms three cooling units, from the lowest upward 42.7 m, 36.6 m and 213.2 m in thickness. The two thin lower, apparently simple cooling units are densely welded in their interiors, grading downward and upward through moderately welded to poorly welded or non-welded zones. Hydrothermal alteration prevents confident identification of original devitrification or vapor-phase crystallization. The upper cooling unit is almost all non-welded, and because of the corresponding high porosity, it is pervasively altered to various combinations of clay, chalcedony and opal, calcite, chlorite and pyrite. The groundmass is most affected by this alteration, phenocrysts commonly remain partially unaltered.

In borehole B-20, only two cooling units can be recognized at present.

The lower, simple cooling unit resting on the S_2 sandstone is 67.1 m thick, has 6.1 m basal and 12.2 m upper non-welded zones and a densely welded core 30.5 m thick. The 225.4 m thick accumulation of highly altered tuff above the basal cooling unit, upon further detailed investigation, may be separable into two or more additional cooling units. Intense argillization presently prevents such a subdivision. Clay mineralogy in the Upper Tuffs in B-20 shows a distinct downward zoning, from kaolinite-rich, through smectite-rich to smectite-poor and chlorite-bearing intervals.

Phenocrysts in the Upper Tuffs generally account for less than 10% of the non-welded intervals, but locally form up to 30% of more densely welded zones. Those spared by alteration comprise microperthite identical to that occurring in underlying units, quartz and local biotite. Of the entire felsic tuff sequence penetrated by the Redondo Creek wells, only the Upper Tuffs apparently contain sanidine free of albite inclusions. A bulk X-ray diffractogram of a sample of the Upper Tuffs from 182.8-189 m in borehole B-19 showed anorthoclase to be the only feldspar present. Diffractograms of the entire Upper Tuff sequence in B-20, by contrast, revealed no anorthoclase, only sanidine and albite.

Lithic fragments are locally very abundant in the Upper Tuffs. Between 243.9 and 286.5 meters in borehole B-20, lithic fragments account for 15-20% of the non-welded tuff penetrated. They are angular, up to at least 10 mm in diameter, and consist primarily of dense, gray, flinty-appearing massive felsic volcanic rocks; siltstone and sandstone lithic fragments are locally present. In borehole B-19, lithic fragments form an average 15-20% of the poorly-welded to non-welded tuffs between 176.7 meters and 396.2 m. If the lithic-rich zones in the Upper Tuffs in these two boreholes represent the same cooling unit or individual ash-flow sheet, considerable erosion is indicated for the pre-lithic-rich tuffs of B-19.

The stratigraphic position of the Upper Tuffs (Fig. 3) suggests that they are part of the Deer Canyon Member of the Valles Rhyolite of Smith et al. (1970).

STRATIGRAPHIC AND STRUCTURAL SYNTHESIS

Isopach and Structural Contour Maps

Compilation of the lithologic logs both from holes logged by ourselves and those logged by UOC geologists has resulted in a reasonably consistent data base from which isopach and structural contour maps can be drawn. This data is summarized in Table 1 and the isopach and structural contour maps are shown in Figures 4 to 14.

Figs. 4 to 7 near here

A structural contour map drawn on top of the Paliza Canyon Formation (Fig. 4) appears to define the geometry of the resurgent dome. But it must be remembered that this is the eroded upper surface of the Paliza Canyon which also has a regional dip to the west. The formation is not present in B-8 which is located about 2 1/2 km WNW of B-16. It is probable that much of the northeast trend of the structural contour map is influenced by normal faulting along the Redondo Creek trend.

The volcanic sequence we have designated as the Lower Tuffs comprises up to five ash flow tuff cooling zones with associated sediments and tuffs. The isopach map of these rocks is shown in Figure 5. The sequence is heterogeneous enough that it is not possible at this time to correlate from hole to hole with any degree of confidence. The isopach of the Lower Tuffs

(Fig. 5) shows that these tuffs range in thickness from about 70 meters in B-16 to nearly 400 meters thick in B-4. This suggests an increase in thickness to the east of the project area. This thickening may represent the caldera or series of nested calderas that were the sources of the Lower Tuff sequence.

A unit we have designated the "S_4 sandstone" is only found in B-4 where it is 48 m thick. Although it is of limited extent, it is important in demonstrating considerable erosion between the time the Lower Tuffs were deposited and the eruption of the Otowi Member. In addition, its presence only in B-4 suggests that the same depositional basin existed to the east of the area that was responsible for the thick accumulation of the Lower Tuffs.

The structural contour map of the base of the Otowi (Fig. 6) shows the general configuration of the resurgent dome, with the elevation rising from B-12 in the southwestern portion of the area to somewhat of a plateau in the central and northern portions of the area.

An isopach of the Otowi Member of the Bandelier Tuff is shown in Figure 7. Within the area of our sample the unit reaches a thickness of 833 meters in B-12 and thins to about 177 meters in B-4. This thinning corresponds to highs in the structural contour map of the base of the formation (Fig. 6). One interpretation of this is that the Otowi was deposited over topographic highs which existed in the vicinity of B-4 and B-11 and B-20. The data unfortunately gives us little indication of the location of the Toledo caldera in this area. However, it is clear through comparison with Figures 5 and 7 that areas which were depositional basins during the formation of the Lower Tuffs had become topographic highs prior to the deposition of the Otowi Member.

Figs. 8 to 11 near here

Figure 8 is a structural contour map on the top of the Otowi Member. As we have already shown, the top of the Otowi is an erosional surface where much of the non- and partially-welded upper portions of the unit have been removed by erosion. The form of Figure 8 again seems to reflect the resurgent doming and is strongly influenced by the northeast-trending structural grain of the Redondo Creek area. The low in the southeast corner of section 11 may represent the influence of a northwest-trending zone that Behrman and Knapp (1980) mapped as "F_7" faults. This trend will be evident through the structural contour maps of the Tshirege Member.

The "S_3 sandstone" marks an erosional and depositional interval which postdated the formation of the Otowi Member and was terminated by the formation of the Valles caldera and the deposition of the Tshirege Member of the Bandelier Tuff. This is one of the more important stratigraphic markers in the subsurface; and, as seen in the isopach of Figure 9, it is not present in all of the wells. Figure 9 shows a depositional basin on the eastern side of the area with eroded highs on the west. The data also suggest the formation of channels in the vicinity of B-15 and B-19. It may represent sedimentation into a depression created by the formation of the Toledo caldera; or, it may suggest that the Jemez fault zone was active following Otowi time developing down-dropped areas to the east.

A structural contour map drawn on the base of the Tshirege Member of the Bandelier Tuff is shown in Figure 10. The map pattern is quite similar to that shown by the top of the Otowi (Fig. 8). This similarity includes a relative low in the vicinity of B-10, B-23, and B-18. This may represent the influence of faulting along an east-west fault, shown to the south of these

Jemez fault zone and to the apical graben of the Redondo dome. Displacement in the graben is greatest along the northeastern margin, where the graben-bounding fault shows an apparent offset of about 500 meters. The southwestern graben-bounding fault, by contrast, shows a throw of less than 100 meters.

The Upper Tertiary Santa Fe sandstone and Abiqui Tuff (also predominantly sandstone), apparently deposited disconformably on underlying Permian Abo redbeds, seem to be roughly horizontal overall and to have an uneroded, horizontal upper surface in the area of Figure 15. By comparison, the overlying Pliocene Paliza Canyon Formation varies greatly in thickness and is deeply eroded, apparently, as suggested by Union's R.F. Dondanville (pers. comm., 1982), forming a landscape of high hills and steep-walled canyons on which succeeding felsic ash-flows were emplaced.

The Lower Tuffs, deposited immediately above the Paliza Canyon, thicken southwestward (see also Fig. 5). The Otowi Member of the Bandelier Tuff, however, becomes thicker to the northeast. This relationship, and the configuration of overlying units, suggests that the Lower Tuffs and underlying rocks were downdropped to the northeast prior to Otowi deposition along the normal fault originating at an elevation of about 1500 meters between boreholes B-4 and B-20. This hypothetical fault coincides with major lost-circulation zones in boreholes B-20, B-11 and B-22-RD3.

The S_3 sandstone is a key marker horizon in the Redondo Creek area. Its occurrence in the Union boreholes tightly restricts possible subsurface structural interpretations. For example, Behrman and Knapp (1980) show the major normal fault at the northeastern end of the 3-D section as passing through boreholes B-17 and B-21 at an elevation of about 2100 m. The lateral continuity of S_3 beneath this point in B-17, B-22 and B-20 (Figure 15), however, suggests that this fault passes through the section several hundred meters further northeast, and that consequently it is much more steeply inclined than the first interpretation would indicate.

The S_2 sandstone is interpreted on Fig. 15 (and on Fig. 13) to be a channel-fill, probable fluvial deposit of local extent deposited on the hilly topography eroded into the Tshirege Member of the Bandelier Tuff. Additional evidence for this erosion is the position of the Tshirege itself in B-17 and B-21 relative to B-20 and B-22. In the latter two holes, the top of Tshirege was intersected, respectively, at 2355 and 2277 meters elevation, whereas in B-17 and B-21, the eroded, granophyrically crystallized core of the Tshirege is immediately overlain by caldera fill at an elevation of 2500 meters.

The configuration of units above the Upper Tuffs on Figure 15 relies heavily on geologic mapping by Behrman and Knapp (1980) as well as on our own lithologic logging. These near-surface rocks, caldera-fill sediments and the Redondo Creek rhyolite, commonly are apparently disrupted by low-angle faults, particularly toward the northeast, where the rocks reach an aggregate thickness of about 500 meters.

Major stratigraphic units in the portion of the Redondo Creek area intersected by Figure 15 are surprisingly flat-laying considering their occurrence on a major resurgent dome. This horizontality, however, is probably a function of the position of the cross-section near the apparent center of the dome. Here, strata elsewhere inclined on the flanks of the dome would locally be nearly horizontal.

STRUCTURAL DEVELOPMENT

The process of resurgent doming is generally initiated soon after caldera collapse. The presence of extrusive volcanic rocks, generally rhyolites, which are contemporaneous with the doming in many calderas (Smith and Bailey, 1968; Steven and Lipman, 1976; Bailey et al., 1976) suggests that upward pressure from the underlying magma body is responsible for the doming. This conclusion is supported at the Valles (Smith and Bailey, 1968) by the spacial and temporal association of the Redondo Creek Member of the Valles Rhyolite with doming and structure developed during doming. The process may continue for some time as evidenced by the continued uplift of the resurgent domes of the Yellowstone caldera (Smith and Braile, 1982). Smith and Bailey (1968) have also noted that the process of resurgent doming is confined to calderas which are at least 16 km in diameter. In that publication they also emphasized the paucity of data on the depth to magma and discussed the conclusion that resurgent cauldrons have a ratio of thickness of the roof rocks to diameter of less than 1. In other words, the thinner the roof, the more susceptible the structure is to the doming process.

Steven et al. (this volume) have remarked on the variety of structural styles within the Marysvale volcanic field where erosion has exposed sections through the roof zones of a number of calderas facilitating three dimensional observation. They argue that a more critical consideration in controling resurgence may be the strength of the roof in which thickness is a major element. In the Monroe Peak caldera they feel that collapse resulted in the destruction of the structural integrity of the roof such that renewed magma pressure was relieved by surface flows rather than by resurgent doming.

One of the results of this study which was surprising to us was that the deep drilling failed to intersect any plutonic bodies which could be considered the cause of the resurgent doming. In order to investigate this phenomena and establish a framework for the interpretation of our subsurface relationships, we have modeled the dome using the methods outlined by Johnson (1970). We do not intend that this be a precise mathematical model of the evolution of the Redondo Dome. Johnson's analysis is based on studies of laccoliths in the Henry Mountains of Utah and on mechanical considerations of the bending of a plate in response to magmatic pressure from beneath. His solution for doming a circular plate is

$$\ell = \left[\frac{v_0 T}{k_1(p - \gamma T)}\right]^{1/4}$$

where v_0 is amplitude of the dome, ℓ = diameter, T = overburden thickness, γ = unit weight of strata, p = magma pressure, and k_1 is a constant (Fig. 16).

Fig. 16 near here

Thus the diameter of a dome is related to the depth to the causative magma body. This relationship was found to be the case in the study of the Henry Mountains where smaller domes were characterized by shallower overburden thicknesses. Since this analysis is based upon magma pressure ($p - \gamma T$) the nature of the magmatic source shouldn't matter, and the analysis should be equally applicable to describing resurgent doming as the formation of laccoliths. By assuming that magma pressure is constant, and demonstrating that the mean ratio of the amplitude to the diameter (v_0/ℓ) of the uplift in the Henry mountains is .14, Johnson demonstrated that $\ell = 2.3T$.

To rationalize using this approximation in our study, we measured the v_0/ℓ for a number of resurgent domes following the schematic shown in Figure 16. This process was quite subjective both from the aspect of our measurements on published cross sections, and most likely from the standpoint of the various authors not having access to subsurface data in the construction of their cross-sections. Using Smith et al.'s (1970) cross-section of the Valles, we calculate v_0/ℓ = .12. A cross-section of the Sour Creek Dome from Yellowstone National Park (Christensen and Blank, 1975) shows v_0/ℓ = .14. And, a cross-section of the resurgent dome from the Long Valley caldera (Bailey et al., 1976) demonstrates v_0/ℓ = .15. Given the nature of the data we were using these results were surprisingly consistent. They not only suggest that Johnson's model for the development of laccoliths may not be a bad representation for the formation of resurgent domes, it also suggests that the processes involved are similar; lifting of roof rocks in response to the presence of the underlying magma body.

When applied to the Redondo Dome with an estimated diameter of 10,900 m, this approximates the thickness of overburden at about 4,739 m. The deepest drilling in the Redondo Dome is B-12 which is 3242 m deep and bottoms in Precambrian granite without intersecting intrusive rocks which can be related to the formation of the Redondo dome.

Note on Figure 16 that approximately half way through the overburden is a surface defined as the neutral plane which suffers neither extension nor compression in the folding process (Johnson, 1980). Above the neutral plane the rocks undergo extensional strain, and beneath the neutral plane, rocks are subjected to compressional stresses. Under this type of analysis, the complex zones of extensional faulting which characterize resurgent domes would be listric in character, flattening and disappearing at the neutral plane. Beneath the neutral plane, fracturing would be characterized by conjugate shears. Along the margins of the dome, the radius of curvature and thus the stress regimes would be reversed with compression above the neutral plane and extension beneath the neutral plane.

Our idealized model for the development of the Redondo Dome conflicts to some extent with our cross section based on the detailed analysis of the subsurface data (Fig. 15). It is apparent that the principal faults bounding the apical graben of the Redondo Dome were activated soon after the initiation of dome growth and continued to subside during dome growth. This is evidenced by the channeling of the Tshirege Member along the Redondo Creek trend and subsequent filling of this depositional low by the S_2 sands and probably also the Upper Tuffs. It is also apparent from Figure 15 that the faults bounding this graben structure are nearly vertical and not listric as our idealized model would predict. We propose that the evidence is best explained by activation of steep basement structures associated with the Jemez fault zone. This has resulted in a lagging of the apical graben area from the first uplift of the resurgent dome. This depression would guide the course of streams resulting in the erosional thinning of the Tshirege member. This would also explain the deposition of the S_2 sand which thickens to the southwest, toward San Diego Cañon. Subsequent to S_2 sand deposition in a fluvial environment, ash and ash-flow tuffs which we call the Upper Tuffs were deposited in the Redondo Creek Canyon as at least three cooling units. Following this, members of the Valles Rhyolite and additional caldera fill were deposited in the canyon. The dome was still growing after this time, and this continued growth and resultant topographic instability resulted in the shallow listric faulting observed along Redondo Creek.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1. Map of the Valles caldera and vicinity from Smith et al. (1970) with modifications from Goff and Kron (1980). The topographic margin of the Valles and Toledo calderas are shown in the light dashed lines and the structural margins in the heavy dashed line. The Redondo Dome is marked with the solid line. The Baca Project area is shown in the heavy solid line. Stars represent the vents of the Valles Rhyolite.

Figure 2. Detailed map of the Baca Project area showing the locations and deviations of drillholes modified from Behrman and Knapp (1980) and Dondanville (1978). YX-Y'X' is the location of the three-dimensional geologic cross-section of Figure 15.

Figure 3. Composite stratigraphic column from the Baca Project area. Thickness of units are listed in Table 1.

Figure 4. Structural contour map drawn on the top of the Paliza Canyon Formation.

Figure 5. Isopach map of the "Lower Tuffs".

Figure 6. Structural contour map on the base of the Otowi Member of the Bandelier Tuff.

Figure 7. Isopach map of the Otowi Member of the Bandelier Tuff.

Figure 8. Structural contour map drawn on the top of the Otowi Member.

Figure 9. Isopach map of the "S_3 sandstone".

Figure 10. Structural contour map drawn on the base of the Tshirege Member of the Bandelier Tuff.

Figure 11. Isopach map of the Tshirege Member.

Figure 12. Structural contour map drawn on the top of the Tshirege Member.

Figure 13. Isopach map of the "S_2 sandstone".

Figure 14. Isopach map of the "Upper Tuffs".

Figure 15. Three-dimensional geologic cross-section of the Redondo Creek area. Location of this section is shown in Figure 2.

Figure 16. Idealized model of a resurgent dome modified from Johnson (1970). See text for explanation.

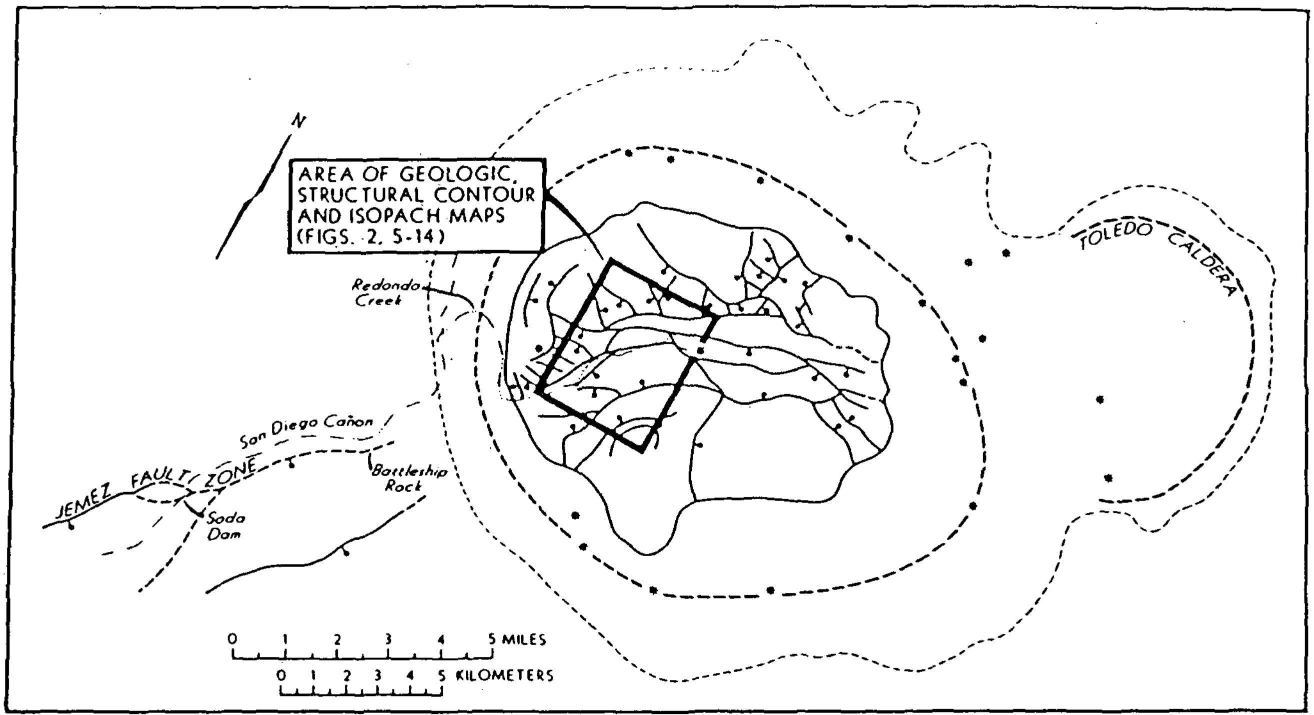

N
AREA OF GEOLOGIC, STRUCTURAL CONTOUR AND ISOPACH MAPS (FIGS. 2, 5-14)
Redondo Creek
San Diego Cañon
JEMEZ FAULT ZONE
Soda Dam
Battleship Rock
TOLEDO CALDERA
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

Fig 1

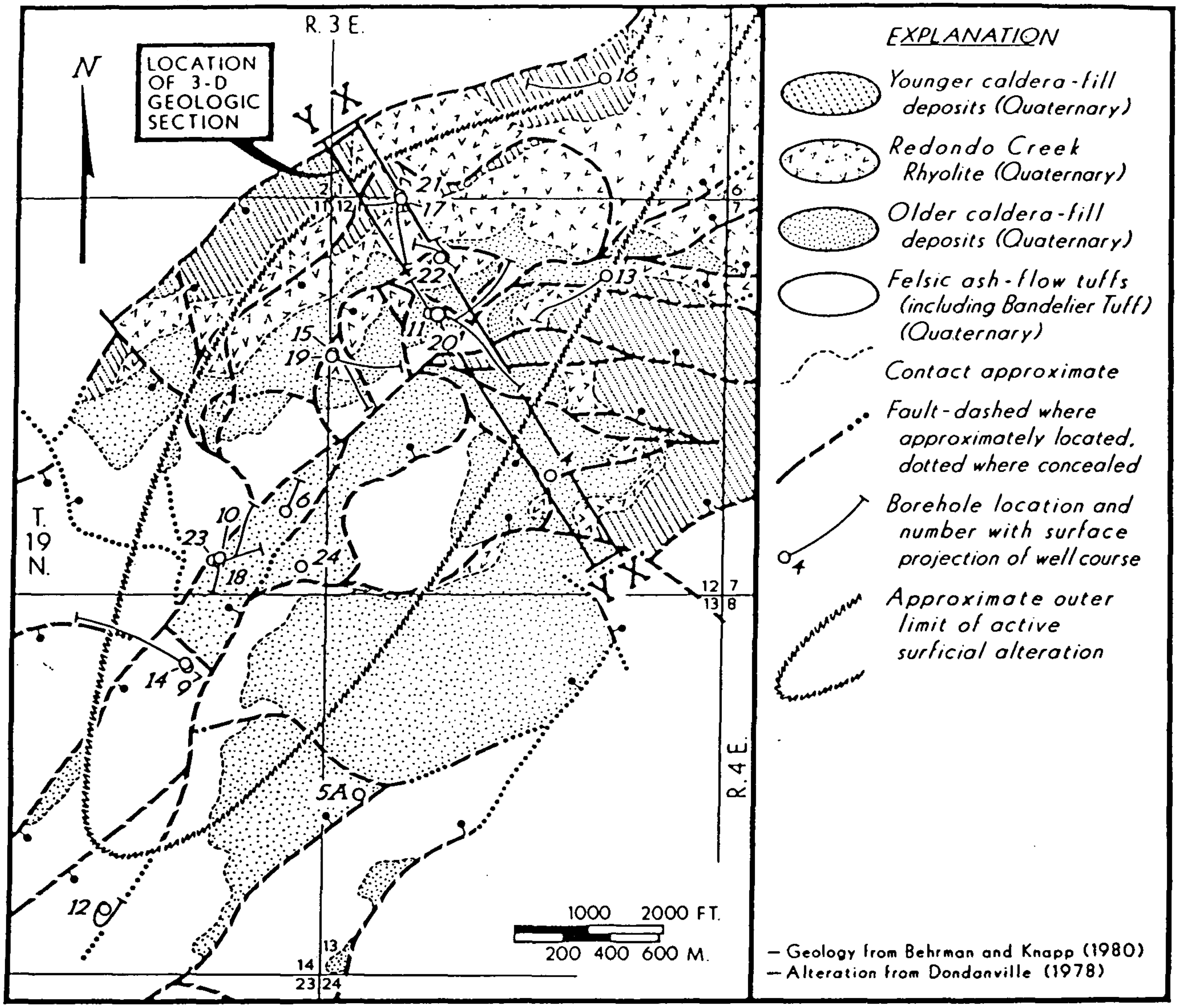

R. 3 E.
N
LOCATION OF 3-D GEOLOGIC SECTION
Y
X
21
17
22
11
20
15
19
16
13
6
10
23
18
24
14
9
12
5A
T. 19 N.
R. 4 E.
2 1
11 12
6
7
12 7
13 8
13
14
23 24
1000 2000 FT.
200 400 600 M.
EXPLANATION
Younger caldera-fill deposits (Quaternary)
Redondo Creek Rhyolite (Quaternary)
Older caldera-fill deposits (Quaternary)
Felsic ash-flow tuffs (including Bandelier Tuff) (Quaternary)
Contact approximate
Fault-dashed where approximately located, dotted where concealed
Borehole location and number with surface projection of well course
4
Approximate outer limit of active surficial alteration
— Geology from Behrman and Knapp (1980)
— Alteration from Dondanville (1978)

Fig 2

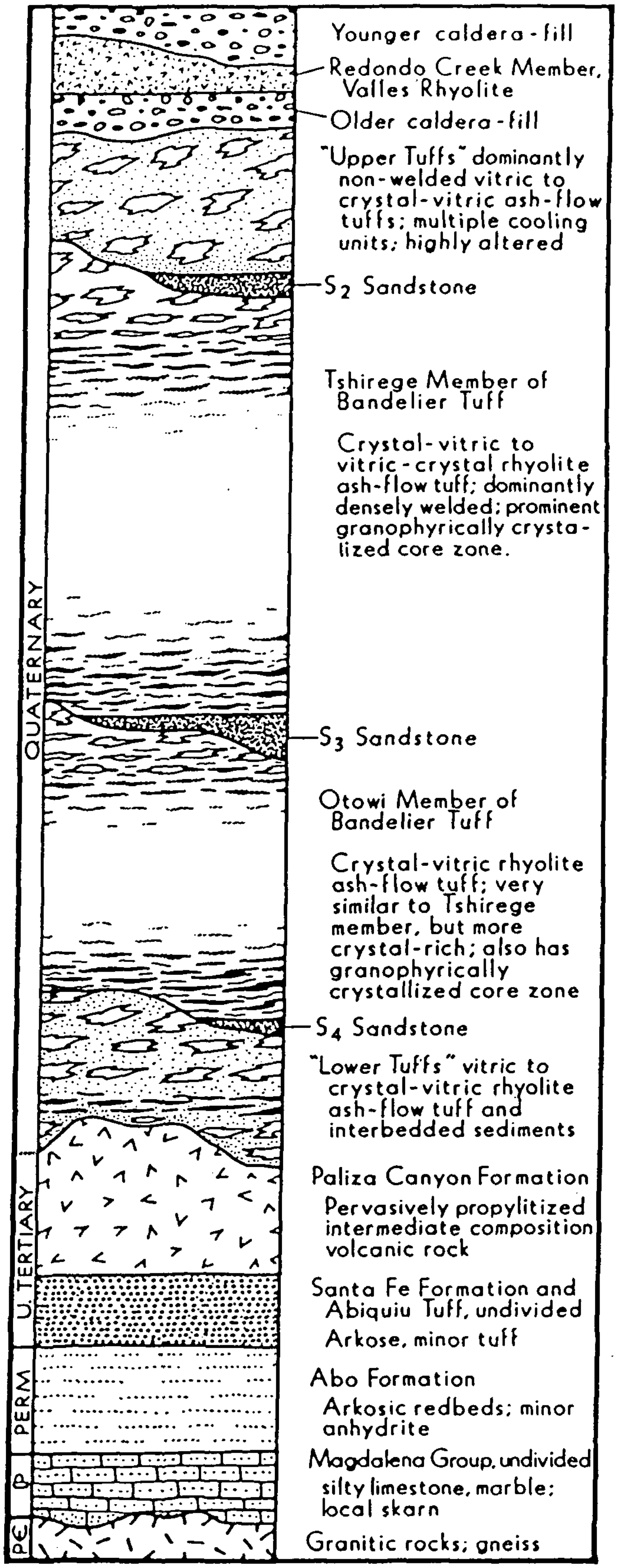

QUATERNARY
U. TERTIARY
PERM
P
P€
Younger caldera-fill
Redondo Creek Member, Valles Rhyolite
Older caldera-fill
"Upper Tuffs" dominantly non-welded vitric to crystal-vitric ash-flow tuffs; multiple cooling units; highly altered
S2 Sandstone
Tshirege Member of Bandelier Tuff
Crystal-vitric to vitric-crystal rhyolite ash-flow tuff; dominantly densely welded; prominent granophyrically crystalized core zone.
S3 Sandstone
Otowi Member of Bandelier Tuff
Crystal-vitric rhyolite ash-flow tuff; very similar to Tshirege member, but more crystal-rich; also has granophyrically crystallized core zone
S4 Sandstone
"Lower Tuffs" vitric to crystal-vitric rhyolite ash-flow tuff and interbedded sediments
Paliza Canyon Formation
Pervasively propylitized intermediate composition volcanic rock
Santa Fe Formation and Abiquiu Tuff, undivided
Arkose, minor tuff
Abo Formation
Arkosic redbeds; minor anhydrite
Magdalena Group, undivided
silty limestone, marble; local skarn
Granitic rocks; gneiss

Fig 3

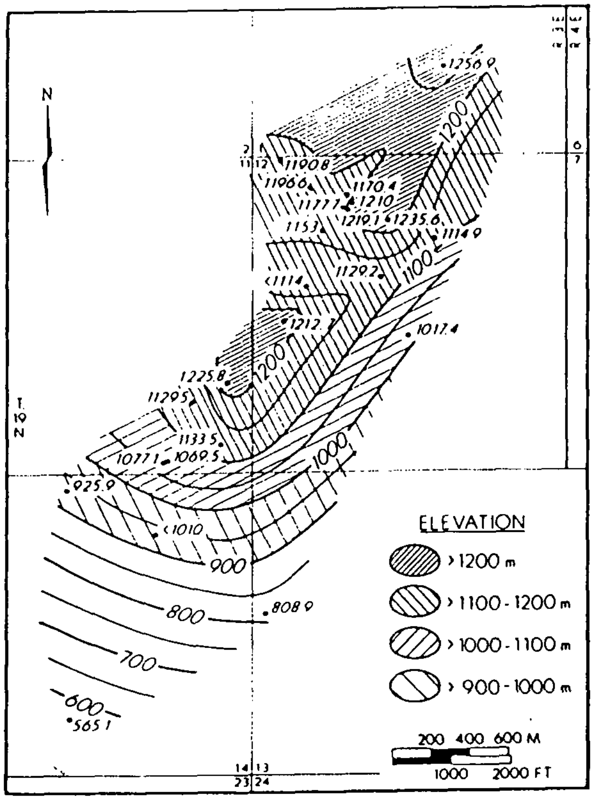


Fig 4

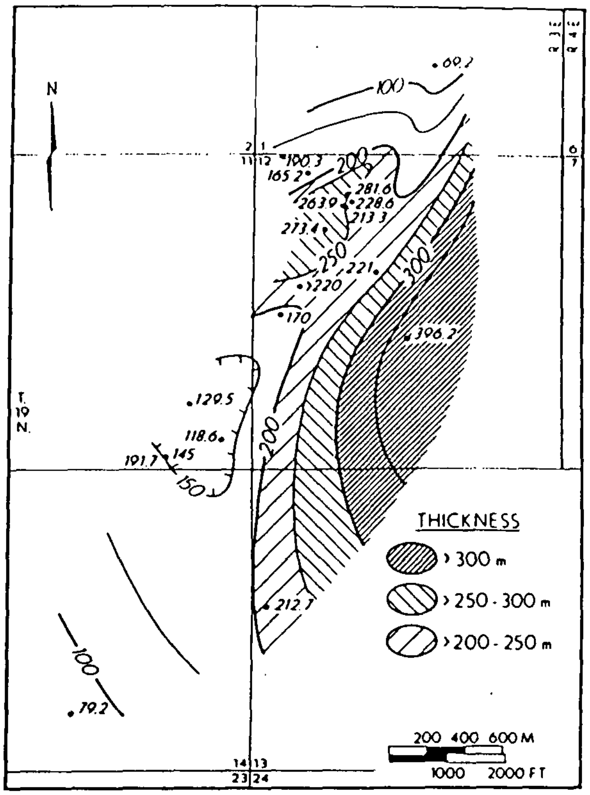


Fig 5

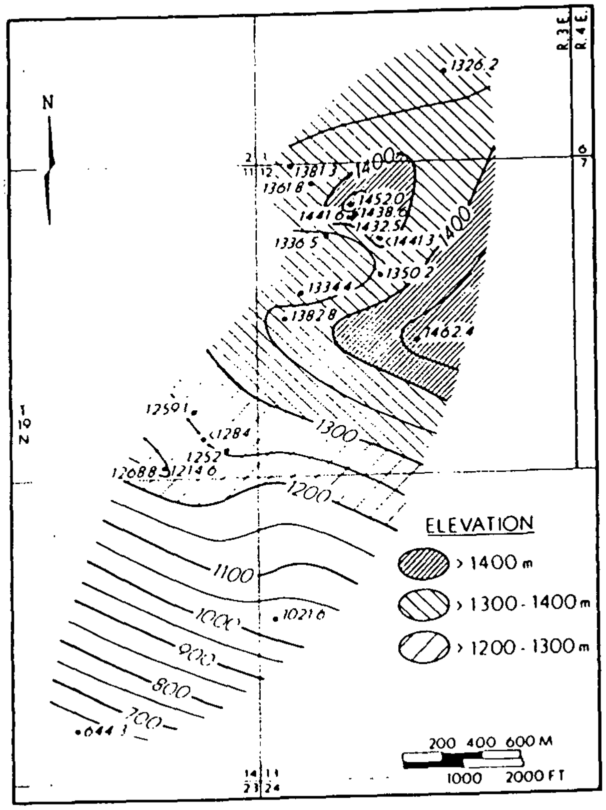


Fig 6

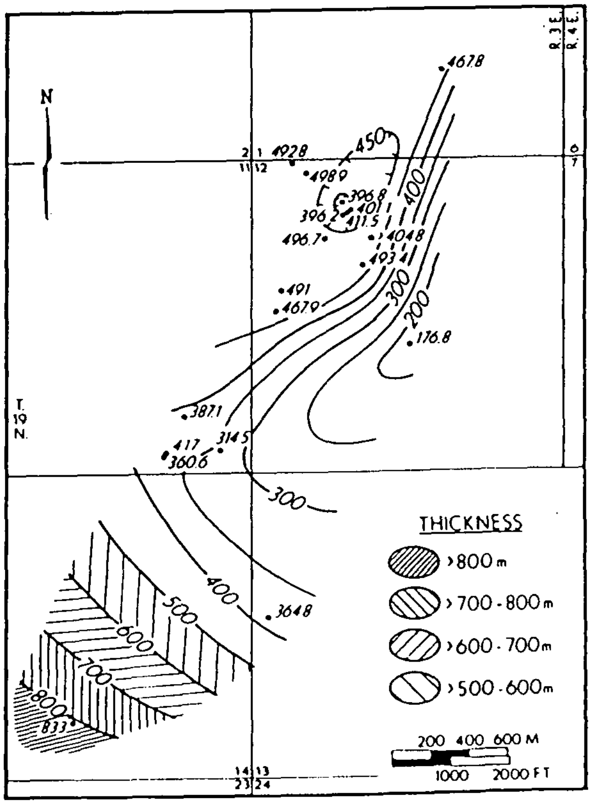


Fig 7

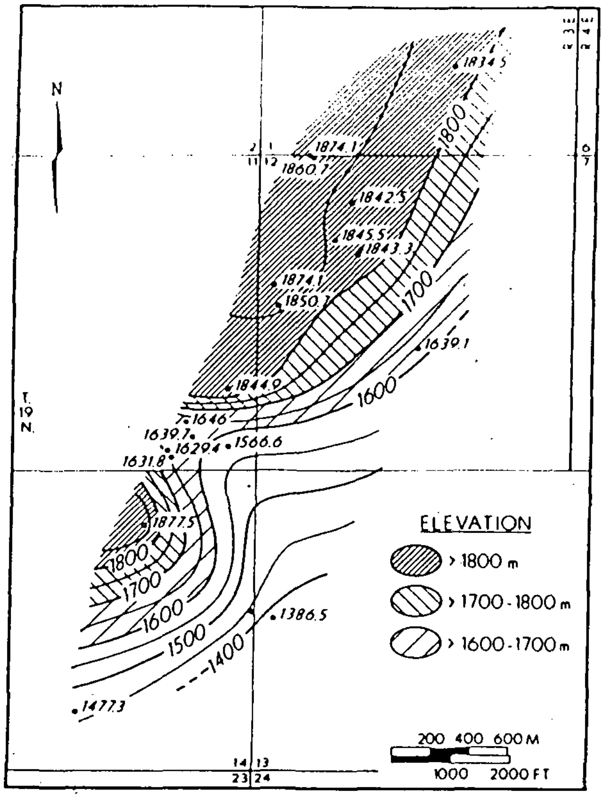


Fig 8

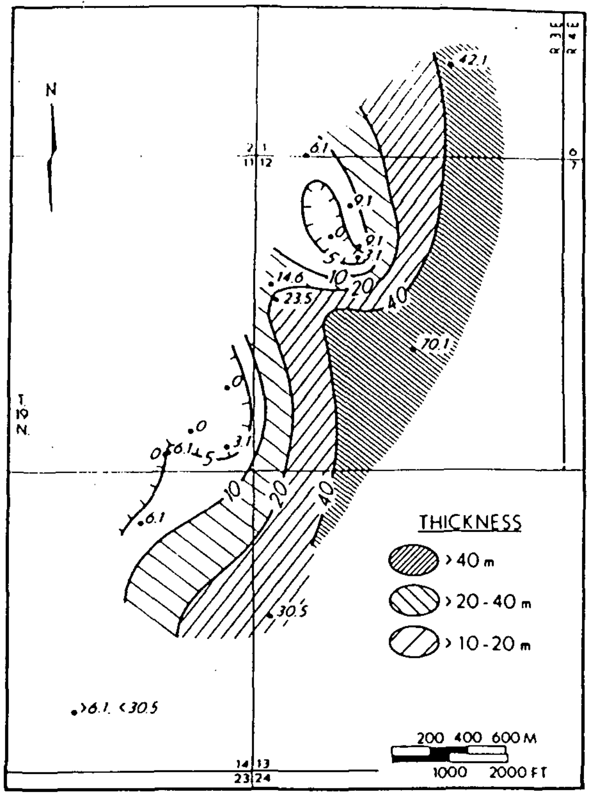


Fig 9

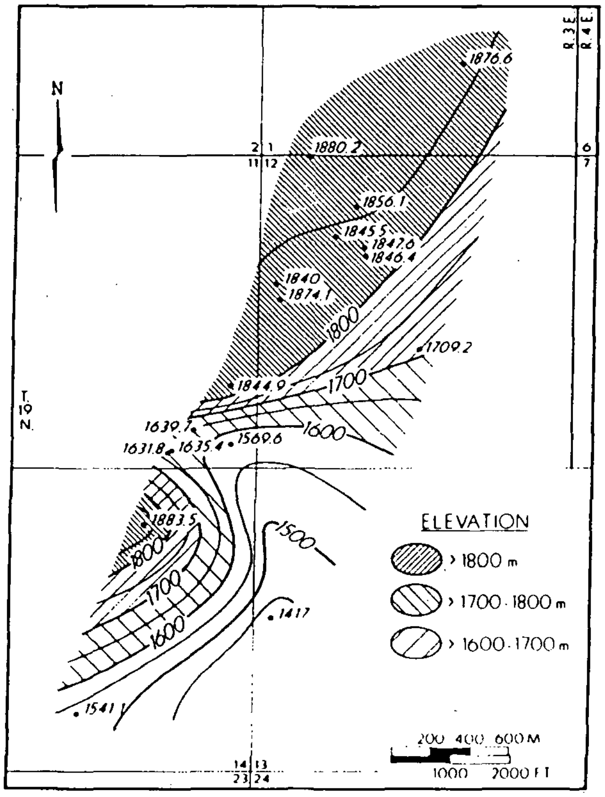


Fig 10

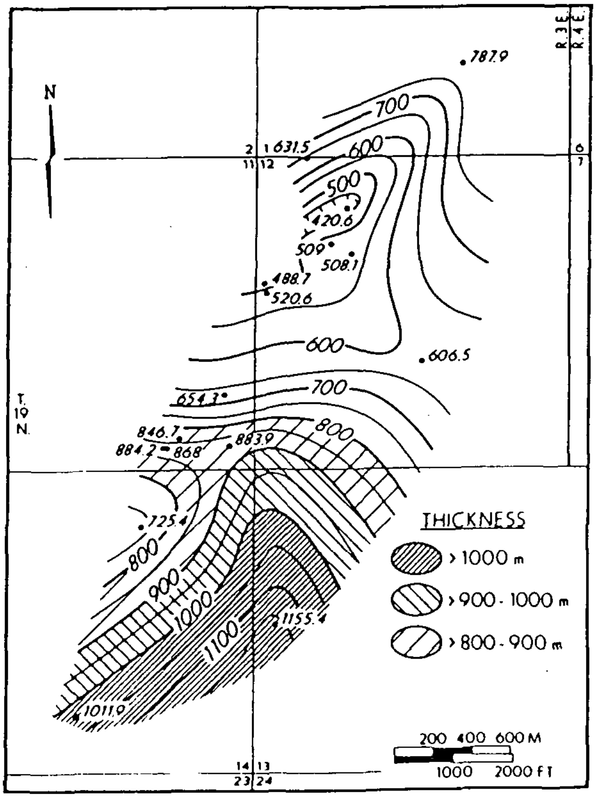


Fig 11

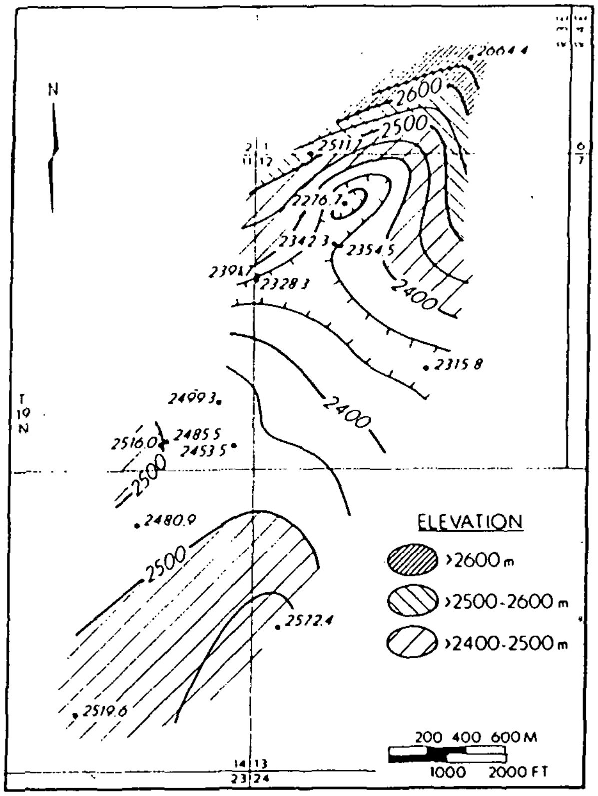


Fig 12

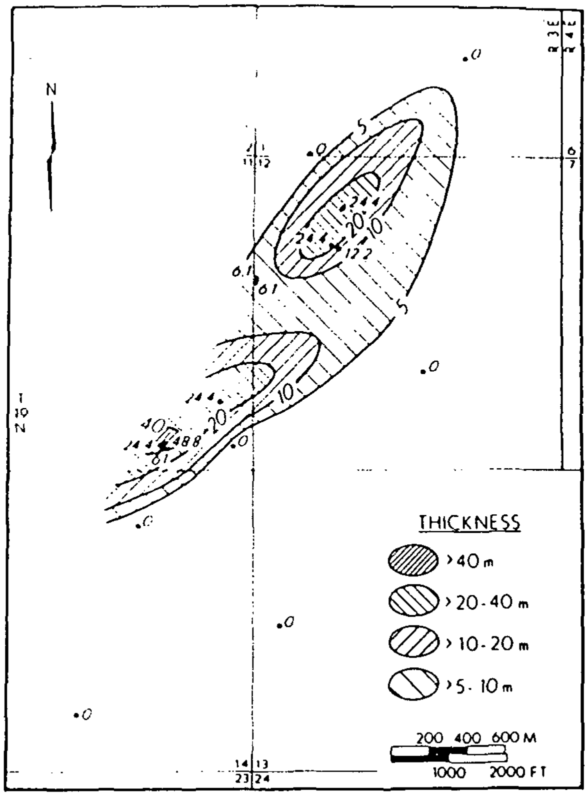


Fig 13

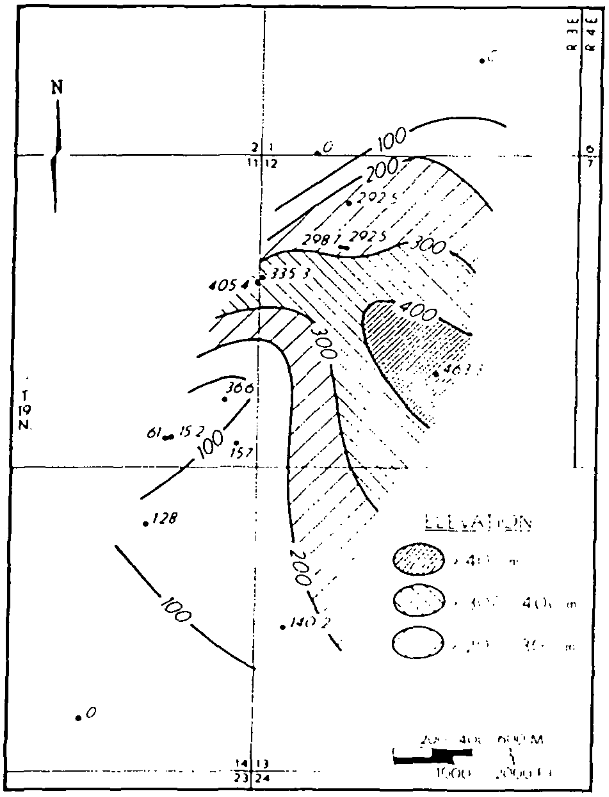


Fig 14

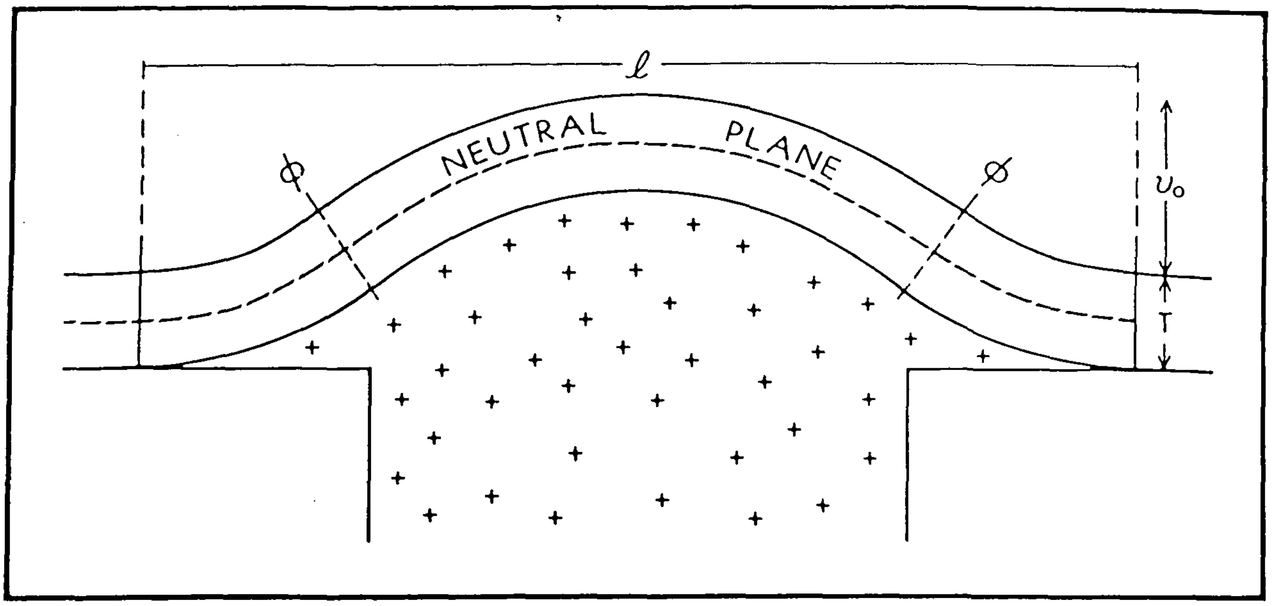
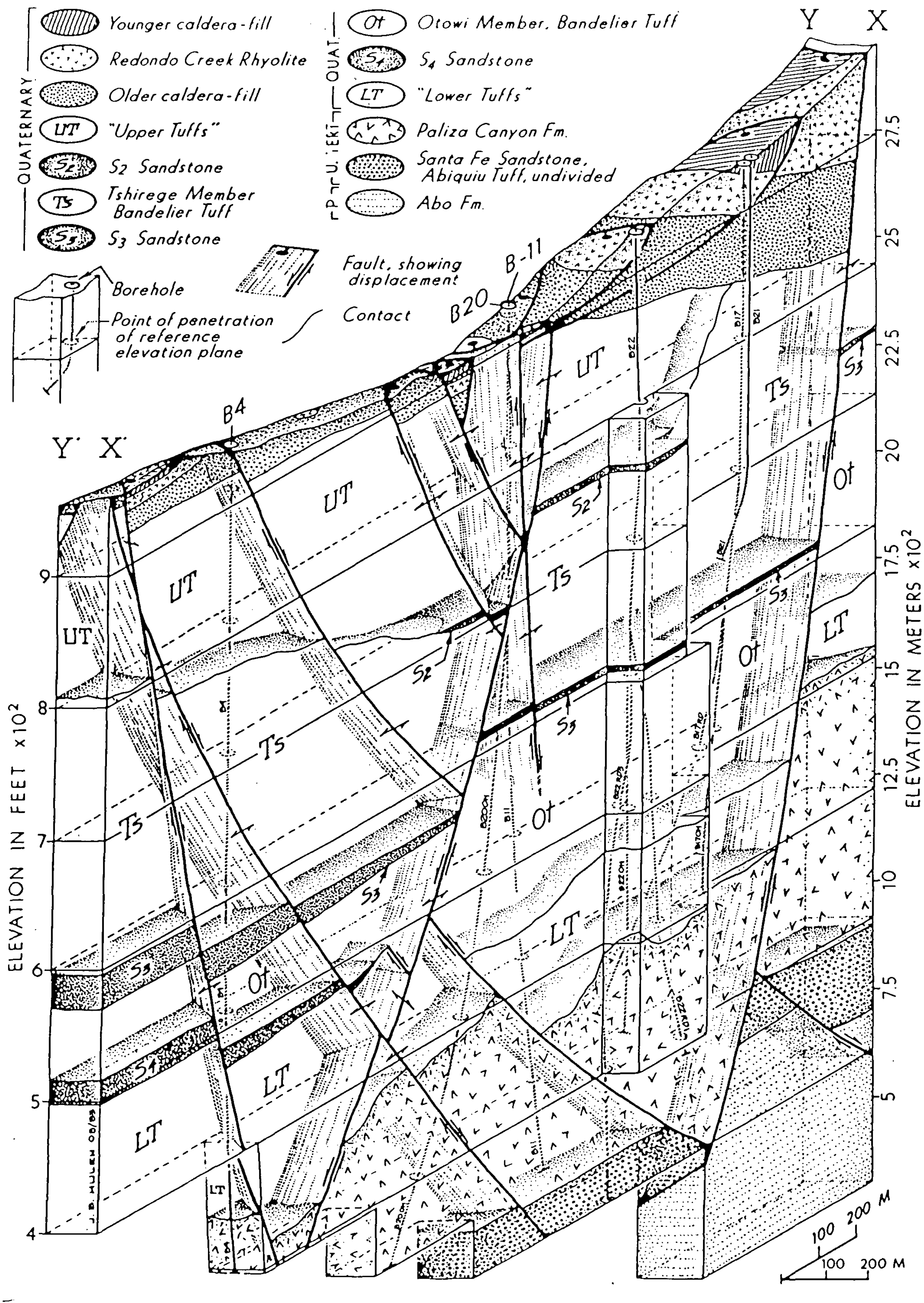


Fig 15


QUATERNARY
Younger caldera-fill
Redondo Creek Rhyolite
Older caldera-fill
UT "Upper Tuffs"
S2 S2 Sandstone
Ts Tshirege Member Bandelier Tuff
S3 S3 Sandstone
QUAT.
Ot Otowi Member, Bandelier Tuff
S4 S4 Sandstone
LT "Lower Tuffs"
U. TERT.
Paliza Canyon Fm.
Santa Fe Sandstone, Abiquiu Tuff, undivided
P
Abo Fm.
Borehole
Point of penetration of reference elevation plane
Fault, showing displacement
Contact
Y X
Y' X'
B4
B20
B-11
B22
B17
B21
UT
S2
Ts
S3
Ot
LT
S4
ELEVATION IN FEET x10²
4
5
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7
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9
ELEVATION IN METERS x10²
5
7.5
10
12.5
15
17.5
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22.5
25
27.5
100 200 M
100 200 M
J. B. HULEN 08/85

Fig. 16

TABLE CAPTIONS

Table 1. Stratigraphic data for wells in the Baca Project area. Data is in elevation (in meters) above sea level. (*Sequence probably includes Lower Tuffs)

TABLE 1

WELL	ELEVATION	UNIT	TOP EL	BOTTOM EL	THICKNESS
BACA 4	2840	UT	2779	2316	463
		T	2316	1709	607
		S_3	1709	1639	70
		O	1639	1462	177
		S_4	1462	1414	48
		LT	1414	1017	396
		PC	1017	925 TD	
BACA 5	2841	UT	2713	2573	140
		T	2573	1417	1156
		S_3	1417	1387	30
		O	1387	1022	365
		LT	1022	809	213
		PC	809	716 TD	
BACA 6	2562	UT	2560	2524	36
		S_2	2524	2499	25
		T	2499	1845	654
		O*	1845	1230?	
		PC	1230?	1212 TD	
BACA 9&9RD	2633	UT	2609	2481	128
		T	2481	1884	725
		S_3	1884	1878	6
		O	1878	1506	372
		LT	1506	1018 TD	
BACA 10	2662	UT	2568	2552	16
		S_2	2552	2504	48
		T	2504	1636	868
		S_3	1636	1629	7
		O	1629	1269	360
		LT	1269	1077	192
		PC	1077	862	215
		SF	862	840 TD	
BACA 11	2763	UT	2665	2367	298
		S_2	2367	2342	25
		T	2342	1846	496
		O	1846	1337	509
		LT	1337	1610	273
		PC	1610	1988	378
		SF	1988	2097 TD	
BACA 12	2569	T	2520	1508	1012
		S_3	1508	LCZ	6+
		O	LCZ	644	833(?)
		LT	644	565	79
		PC	565	263	302
BACA 17 RD	2853	S_3	1867	1861	6
		O	1861	1362	499
		LT	1362	1197	165
		PC	1197	979	218
BACA 18	2662	S_2	2547	2486	61
		T	2486	1640	846
		O	1640	1285 TD	
BACA 18 RD	2662	O	1646	1259	387
		LT	1259	1130	129
		PC	1130	1103 TD	
BACA 19	2779	UT	2740	2334	405
		S_2	2334	2328	6
		T	2328	1840	488
		S_3	1840	1825	15
		O	1825	1334	491
		LT	1334	1114	220
BACA 20	2763	UT	2659	2367	292
		S_2	2367	2355	12
		T	2355	1846	1667
		S_3	1846	1843	3
		O	1843	1350	493
		LT	1350	1129	221
		PC	1129	671 TD	
BACA 20 RD	2763	S_3	1848	1846	2
		O	1846	1441 TD	
BACA 21	2853	T	2502	1992 TD	
BACA 22	2826	UT	2594	2301	293
		S_2	2301	2277	24
		T	2277	1856	421
		S_3	1856	1850	6
		O	1850	1439	411
		LT	1439	1210	229
		PC	1210	994 TD	
BACA 22 RD1	2826	S_3	1858	1849	9
		O	1849	1452	397
		LT	1452	1170	282
		PC	1170	861 TD	
BACA 22 RD2	2826	S_3	1840	1834	6
		O	1834	1433	401
		LT	1433	1219	213
		PC	1219	999 TD	

WELL	ELEVATION	UNIT	TOP EL	BOTTOM EL	THICKNESS
		A	263	-238	501
		M	-238	-531	294
		PG	-532	-642 TD	
BACA 13	2832	PC	1115	401	714
		A	401	360 TD	
BACA 14	2623	PC	926	827	99
		SF	827	665	162
		A	665	629 TD	
BACA 15	2779	UT	2736	2401	335
		S_2	2401	2395	6
		T	2395	1874	521
		S_3	1874	1851	23
		O	1851	1383	468
		LT	1383	1213	170
		PC	1213	1161 TD	
BACA 16	2933	T	2665	1877	788
		S_3	1877	1835	42
		O	1835	1326	509
		LT	1326	1257	69
		PC	1257	887	370
		SF	887	852 TD	
BACA 170H	2853	T	2512	1880	632
		S_3	1880	1874	6
		O	1874	1381	493
		LT	1381	1191	190
		PC	1191	1108 TD	
BACA 22 RD3	2826	S_3	1850	1838	12
		O	1838	1442	396
		LT	1442	1178	264
		PC	1178	733	445
		SF	733	497	236
		A	497	235	262
		M	235	144 TD	
BACA 23	2662	UT	2601	2541	61
		S_2	2541	2516	24
		T	2516	1632	884
		O	1632	1215	417
		LT	1215	1070	145
		PC	1070	928 TD	
BACA 24	2664	UT	2611	2456	155
		S_2	NO SAMPLE		
		T	2454	1570	884
		S_3	1570	1567	3
		O	1567	1252	315
		LT	1252	1134	119
		PC	1134	990 TD	

STRATIGRAPHY OF THE BANDELIER TUFF AND CHARACTERIZATION OF HIGH-LEVEL CLAY ALTERATION IN BOREHOLE B-20, REDONDO CREEK AREA, VALLES CALDERA, NEW MEXICO

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ABSTRACT

Stratigraphy and alteration of borehole Baca-20 from the Redondo Creek area in the Valles Caldera have been investigated by binocular microscopic logging and X-ray diffraction techniques. Within the caldera, the Bandelier Tuff has thickened dramatically from documented exposures outside the caldera. The two principal members of the Bandelier, the Otowi and Tshirege, have been recognized in Baca-20. Additional ash-flow tuff cooling units have been delineated both below and above the Bandelier. The units above the Bandelier have undergone intense alteration with the formation of a variety of clay minerals, including pure Mg- or Ca-smectite, allevardite-ordered illite-smectite, kaolinite and illite. This alteration is apparently controlled largely by high original permeability of these rocks. The presence of the highly ordered illite-smectite suggests that higher temperatures than presently prevail existed during the alteration process.

INTRODUCTION

The high-temperature (up to 330°C; Dondanville, 1978), liquid-dominated Baca geothermal system, in the Redondo Creek area of the Valles Caldera, New Mexico (Fig. 1) is hosted primarily by the Pleistocene Bandelier Tuff and associated felsic tuffs and sediments. The Bandelier has been well studied outside the Valles Caldera (Smith and Bailey, 1968; Doell et al., 1968; Crowe et al., 1978) where it reportedly forms two distinct members--the lower (Otowi) and upper (Tshirege)--aggregating only a few hundred feet in average thickness. The thick (up to 6000 ft) sequence of Bandelier and associated felsic tuffs and sediments within the caldera, however, has not been fully characterized. One aim of this paper is to document the stratigraphy of this tuff sequence in borehole B-20, a 6824-ft geothermal well completed by Union Oil Company in 1980.

The upper portion of well B-20 demonstrates the development of intense clay mineral alteration (Fig. 2). Mineralogy and mineralogic zoning of this interval have been investigated by X-ray diffraction (XRD). This paper will present the results of this XRD investigation and its significance in definition of the Baca reservoir.

GEOLOGIC SETTING

For excellent discussions of the regional geologic setting of the Valles Caldera and vicinity, the reader is directed to the classic works of Smith and Bailey (1968) and Doell et al. (1968). According to these investigators, caldera formation began about 1.4 m.y. ago with eruption of about 300 km^3 of ejecta to form the Otowi Member of the Bandelier Tuff, with resultant subsidence of the Toledo Caldera. Following a 300,000 year erosional interval, a second eruption, of comparable size, formed the Tshirege Member and the Valles Caldera. Rhyolite domes, flows and tuffs subsequently were emplaced in the Caldera's moat area while upward pressure of magma caused resurgent doming. The Redondo Creek project area, site of well B-20 and other deep Union wells straddles the apical graben of the resurgent dome.

The geology of the Redondo Creek area has been mapped at the surface by Behrman and Knapp (1980) and interpreted in the subsurface by them and by Hulen and Nielson (1982). Above a deep basement of Pliocene volcanics and sediments, and underlying Paleozoic clastics and carbonates, the Bandelier Tuff and associated rocks locally reach a thickness of 6000 feet in this area. Hulen and Nielson (1982) demonstrated that thermal fluid flow in the Bandelier is controlled not only by faults and fractures, but by thin, permeable, intra-tuff sandstones and non-welded tuff beds.

METHODS AND PROCEDURES

Cuttings from borehole B-20, collected by Union at 20 ft intervals, were first thoroughly washed in warm water to remove drilling mud and lost circulation material, then mounted on chipboards at a scale of 1" = 10 ft. These boards allow observation of subtle textural and color gradations that might otherwise escape detection. The well was logged in detail for lithology, alteration and evidence of faulting /fracturing, using a conventional binocular microscope, occasionally supplemented by petrographic and XRD techniques. Results of this logging are presented in Figure 2. Depths shown are true vertical depths calculated from a downhole deviation survey.

Samples from the high-level clay alteration

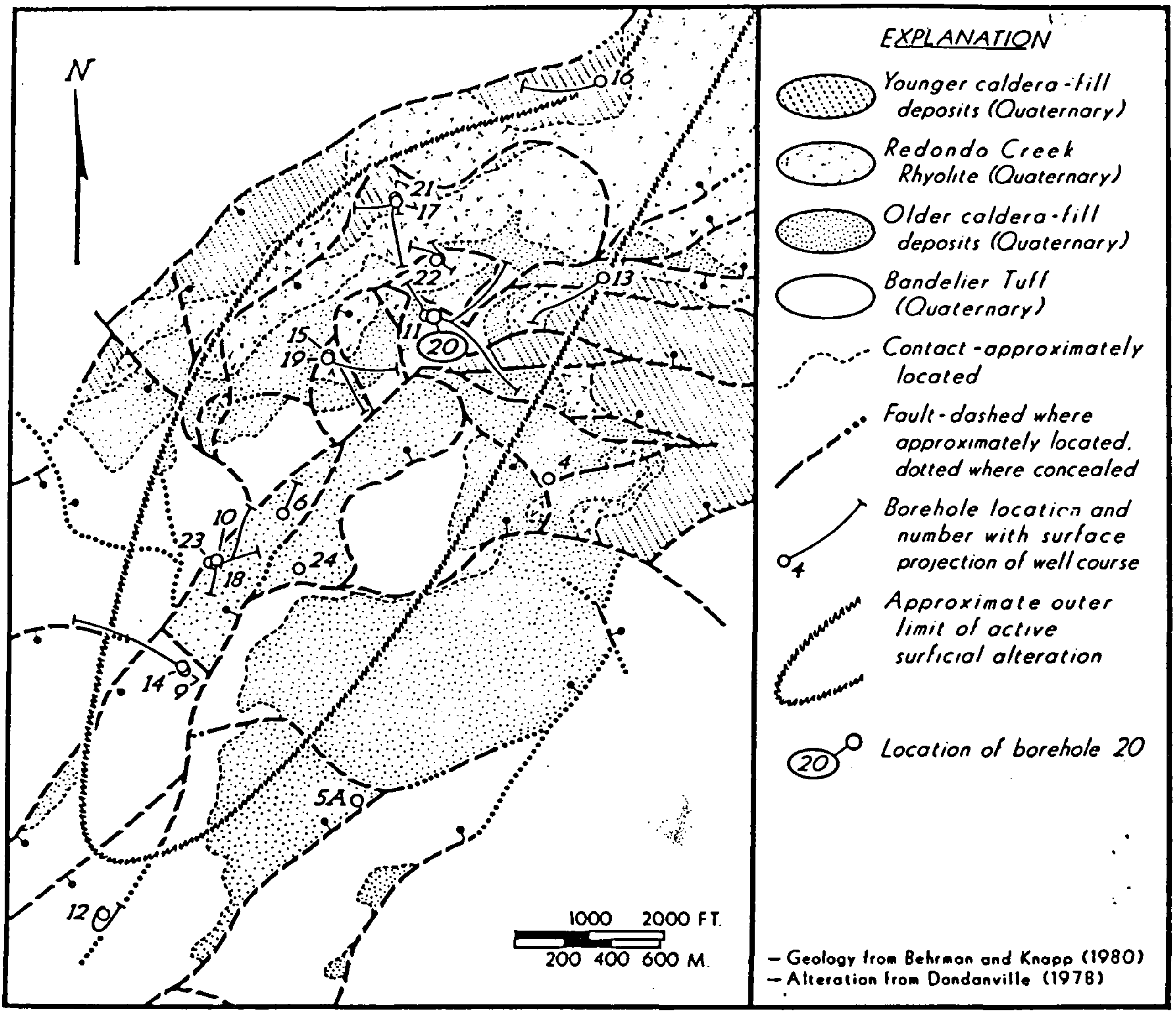

Figure 1. Geologic map of the Redondo Creek area, showing the location of Union Oil Company boreholes, including No. 20, the subject of this study.

zone in B-20 were lightly crushed, then sonically disaggregated in water. The 2-micron fraction then was decanted and concentrated by centrifugation. The resulting clay slurry was smeared on glass slides and X-rayed following air-drying, vapor glycolation, and heating to 250°C and 550°C, using a Phillips diffractometer with Ni-filtered Cu-Kα radiation. The distribution of layer silicates (and contaminants) thus detected is graphically displayed as Figure 3. Sediments and minor interbedded tuffs above 340 ft were not analyzed due to heavy borehole cement contamination.

STRATIGRAPHY

Below a surficial interval of "caldera-fill" tuffaceous sandstone, siltstone, mudstone and tuff to 340 ft depth, borehole B-20 penetrated primarily non-welded to (dominantly) densely welded felsic ash-flow tuff (Fig. 2), much of which can be attributed confidently to the Bandelier Tuff. Dominating this tuff sequence are two thick, moderately to densely welded intervals, each with a granophyrically crystallized core zone, and each capped by a thin tuffaceous arkosic sandstone. The upper of these two intervals, from 1340 ft to 3007 ft, we identify as the Tshirege Member of the Bandelier Tuff; the lower interval, from 3018 ft to roughly 4635 ft, we believe to be the Otowi Member.

The upper (Tshirege) interval is a densely welded, crystal-vitric felsic ash-flow tuff containing about 22-25% sanidine phenocrysts, 3-5% quartz phenocrysts, 0.3% disseminated magnetite, 0.5% disseminated chlorite and 1-3% lithic fragments embedded in a dense groundmass of quartz, K-feldspar and minor albite; XRD reveals no

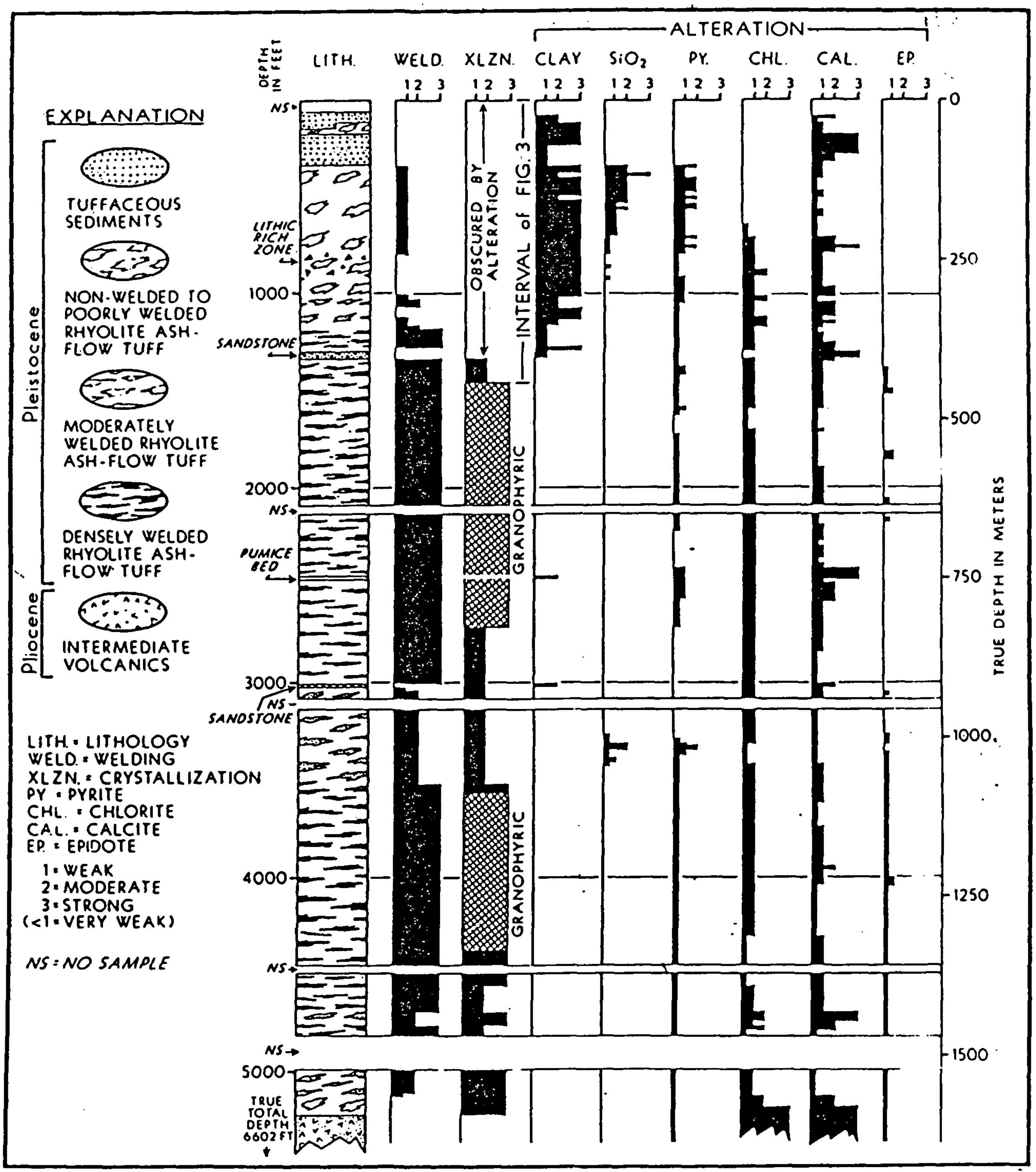

Figure 2. Generalized lithologic and hydrothermal alteration logs for well B-20.

detectable opal, cristobalite or tridymite. The groundmass in the granophyric core of the upper (Tshirege) interval, from 1460 ft to 2727 ft (Fig. 2) is a megascopically sugary-appearing aggregate of quartz, K-feldspar and variable albite, commonly showing granophyric texture in thin-section. A thin pumice bed, from about 2450-2465 ft, probably represents a minor cooling break in the Tshirege. The upper (Tshirege) interval is overlain by 40 ft (1300-1340 ft) of tuffaceous arkose, with abundant illite, clay and calcite as matrix constituents.

The lower (Otowi) interval, from 3018 ft to

4635 ft, is very similar to the upper (Tshirege) interval, from which it is separated by a second thin tuffaceous arkose (3003-3018 ft; Fig. 2). This interval, however, differs from the Tshirege in being only moderately welded to a depth of 3520 ft and in containing slightly more sanidine and quartz phenocrysts (total about 27-32%). The lower contact of this unit is tentatively placed at a subtle cooling break at about 4635 ft.

Below the lower (Otowi) interval, between depths of 4635 ft and 5230 ft (Fig. 2), non-welded to densely welded felsic ash-flow tuffs form at least two cooling units, at present poorly understood. These rocks, like those overlying them, also contain quartz and sanidine phenocrysts in highly variable amounts, in a mostly crystallized (quartz, K-feldspar, albite) matrix. We suspect they pre-date the Bandelier Tuff.

Above the Tshirege predominantly non-welded to poorly welded felsic ash-flow tuffs form multiple cooling units between 340 ft and 1300 ft (Fig. 2). They contain 5-15% sanidine phenocrysts and 3-5% quartz phenocrysts with variable lithic fragment content; hydrothermal alteration obscures any primary crystallization of these tuffs. Our data are incomplete at this time, but suggest that these tuffs may be genetically related to the formation of the Early Rhyolite of Smith and Bailey (1968).

HYDROTHERMAL ALTERATION

Beneath a high-level zone of intense clay alteration (Fig. 2) the tuffs and associated sediments penetrated in borehole B-20 (above 5230 ft) are generally only weakly hydrothermally altered. Intensity of alteration varies directly with the initial permeability. The high-level clay alteration zone, for example, occupies an interval of generally non-welded to poorly welded (and thus presumably permeable) ash-flow tuffs. By contrast, the densely welded and crystallized tuffs at lower depths have remained relatively fresh.

Principal alteration minerals detected during binocular microscopic logging (and confirmed by XRD) comprise various clays, silica (chalcedony), pyrite, chlorite, calcite and epidote. The clays are more fully described below. Chalcedony occurs as a pervasive flooding and as microveinlets above 1500 ft and as rare veinlets below this depth. Pyrite forms microveinlets and minute disseminated grains; microveinlets are much more common above 1500 ft. Chlorite forms sparsely disseminated grains and microveinlets (commonly with calcite and pyrite) throughout the well, and as a pervasive stain in the argillic zone between 630 ft and 1460 ft. Calcite occurs as groundmass flooding, plagioclase replacement, and as a matrix constituent in arkose. Epidote occurs primarily as minute disseminated grains and also as scattered, rare microveinlets. Chlorite and calcite increase dramatically in deep andesite, where these two minerals could reflect higher host rock reactivity and/or could predate the presently active geothermal system.

The high-level clay alteration zone, between 340 ft and 1460 ft (Fig. 2), was investigated in detail by X-ray diffraction. The layer silicates detected by this method display a distinct zoning (Fig. 3). Pure smectite is the predominant constituent to a depth of 1060 ft. The smectite yields a basal peak of 14-14.5A in the air-dried state, indicating magnesium or calcium to be the interlayer cation (Schoen et al., 1974).

Ordered, interstratified illite-smectite is another common constituent of the high-level argillic zone. The ordering is of the "allevardite" type (Hower, 1980) as indicated by prominent peaks at about 27A, 13.6A, 9A and 5.35A following vapor glycolation. The positions of these peaks indicate nearly perfect ordering with an illite content of about 65%.

Kaolinite is a major constituent of the argillic zone to a depth of 400 ft (Fig. 3) below which it gradually diminishes to disappear entirely at 800 ft. Its disappearance coincides with the appearance of chlorite, which persists to the base of the sampled interval at 1460 ft. Chlorite is distinguished from kaolinite by the presence of major peaks at 14.20A and 3.54A. The latter is clearly distinguishable from the 3.57A kaolinite peak at slow scanning speeds.

Other phases detected by XRD in the high-level argillic zone of B-20 include discrete illite, pyrite, quartz, sanidine, plagioclase and calcite. Illite, pyrite and kaolinite show no distinctive zoning characteristics, but are enriched in the tuffaceous sandstone between 1300 and 1340 feet (Fig. 3). Quartz is probably both an alteration product and a rock-forming constituent. Sanidine and albite likewise are probably original host rock minerals; albite could also be partially of replacement origin.

DISCUSSION AND CONCLUSIONS

Detailed logging of borehole B-20 has resulted in recognition of two distinctive, very thick felsic ash-flow tuff cooling units, both with granophyrically crystallized cores, which we have tentatively correlated with the Otowi and Tshirege Members of the Bandelier Tuff. The Otowi and Tshirege are both relatively thin outside the Valles-Toledo Caldera complex, seldom reaching more than a few hundred feet in aggregate thickness (Crowe et al., 1978; Dondanville, 1978). These units, however, according to the predictions of Smith (1960), could reasonably be expected not only to thicken dramatically within the caldera complex, but to develop the thick granophyrically crystallized cores observed in borehole B-20. Both units in B-20 are capped by sandstones, attesting to significant erosional intervals following welding and crystallization. Complex ash-flow tuff sequences above and below these two units in B-20 we believe to predate and post-date, respectively, the Bandelier Tuff as presently defined.

High level intense clay alteration in B-20

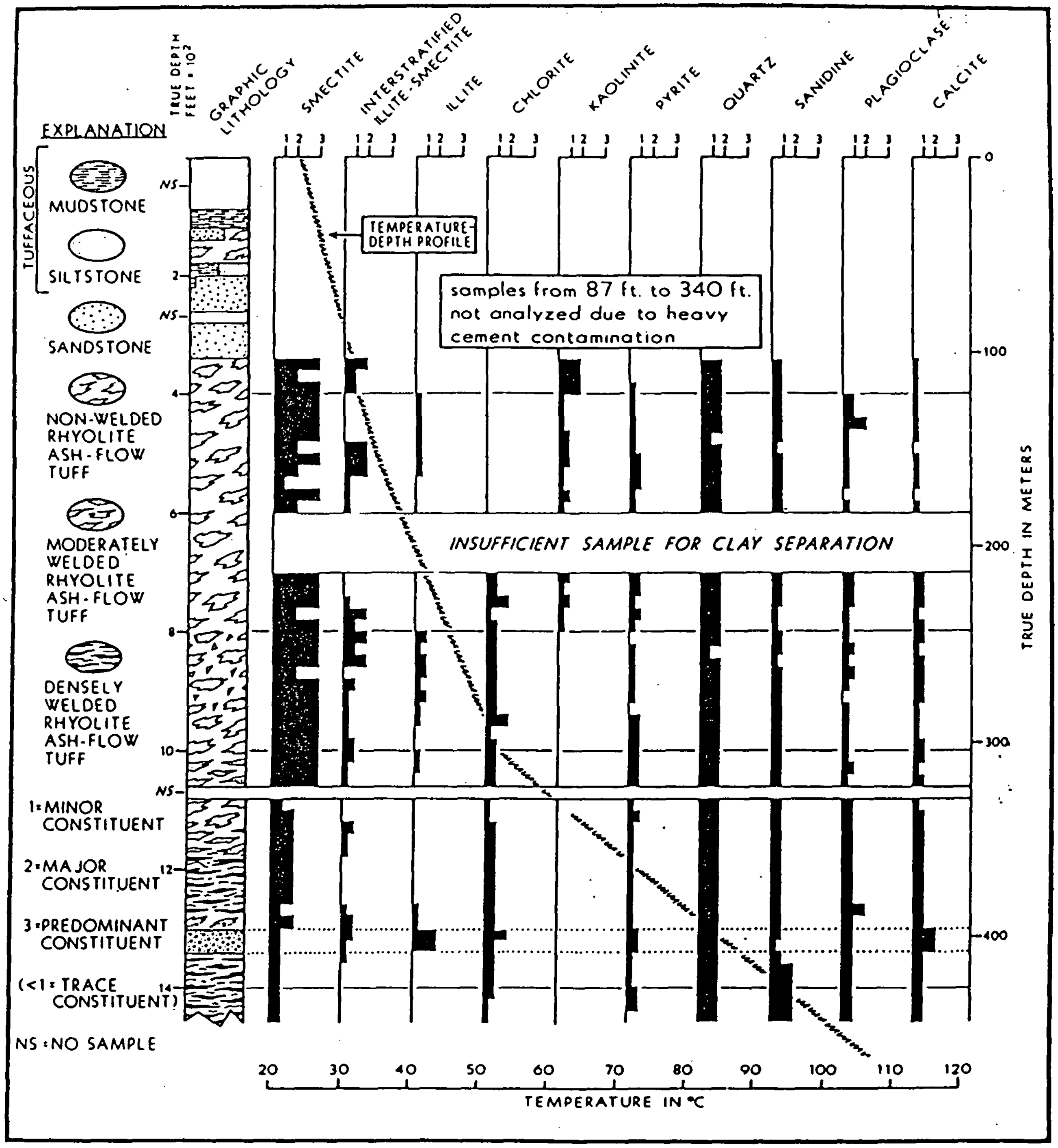

Figure 3. Detailed mineralogy of the high-level clay alteration zone in well B-20, as determined by X-ray diffraction.

probably reflects both the high permeability and relatively low temperatures prevailing in the upper portion of the borehole. The alteration shows a distinct downward zoning, from kaolinite-rich, through smectite-rich to smectite-poor and chlorite-bearing intervals. This zoning is in part temprature dependent, but could also indicate increasing pH with depth. Kaolinite disappears and chlorite appears between interpolated temperatures of about 38 and 41°C. This mineral, however, is known to be stable under highly acid conditions (Schoen et al., 1974), so its position in B-20 may reflect alteration under acid conditions created by oxidation of sulfides or ascending H_2S. Pure smectite of the type identified in B-20 also forms by such acid alteration (Schoen et al., 1974), but at somewhat higher pH's. Its minor presence at the base of the sampled interval, at a temperature of about 100°C, is consistent with its disappearance temperatures at other geothermal systems, including the Salton Sea (about 100°C; Muffler and White, 1969) and Wairakei (generally about 130°C (Steiner, 1968). Chlorite occurs throughout the borehole and requires further investigation for determination of its thermal significance. Mixed-layer, allevardite-ordered, illite-smectite is believed to form between temperatures of about 100°C and 175°C, yet it is found in B-20 at temperatures as low as about 30°C. This mixed-layer clay, therefore, we believe to be a relict phase formed when higher-temperatures prevailed at current depths. Pure illite in the argillic interval is also believed to be paleohydrothermal.

Hartz (1976) and Grant and Garg (1981) postulate the presence of a high-level caprock zone above the Baca geothermal reservoir, based on examination of equilibrium temperature profiles for the deep boreholes. It seems likely that the high-level clay zone penetrated in B-20 (and many other Baca boreholes) could effectively contribute to the formation of such a caprock.

ACKNOWLEDGEMENTS

Study of this well is part of ongoing stratigraphic, structural and alteration research at the Earth Science Laboratory/University of Utah Research Institute (UURI/ESL) on drill cuttings and core obtained through the courtesy of Union Oil Co. and funded by the U.S. Department of Energy, contract no. DE-AC07-80ID12079. Discussions with Mike Adams on interpretation of clay mineral x-ray diffractograms were extremely helpful in characterizing the clays of borehole B-20. The manuscript was prepared by Holly Baker. Illustrations were prepared by Connie Pixton.

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RESULTS OF DEEP DRILLING IN THE VALLES CALDERA, NEW MEXICO

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INTRODUCTION

The Valles caldera in New Mexico has been the site of extensive drilling for geothermal exploration and development by Union Oil Company, with the financial participation of the U. S. Department of Energy. The data base generated through this project represents one of the most extensive sets of subsurface information on young volcanic-hydrothermal systems which is currently in the public domain. The data includes subsurface lithologic samples, geophysical well logs, reservoir engineering information, and extensive surface geology and geophysics.

SLIDE 1
Index Map

The Valles caldera is located in New Mexico on the western margin of the Rio Grande Rift. Shown on this index map is the structural margin of the Valles caldera, the resurgent dome of the Valles, the Toledo caldera, and the Baca project area. The deep drilling I will be discussing was completed within the Baca project area.

The major episode of caldera development began about 1.4 million years ago with the eruption of the Otowi Member of the Bandelier Tuff and the formation of the Toledo caldera, only a portion of which remains exposed. At 1.1 million years the Valles caldera formed with the eruption of the Tshirege Member of the Bandelier Tuff.

SLIDE 2
Geologic Map

This is a generalized geologic map of the Baca project area showing the location and deviation of the drill holes we have studied.

In our studies of the Valles system, we have logged over 21,000 meters of lithologic samples. Although the holes were drilled for exploration and production purposes, we have been able to accumulate considerable information which is of interest to the scientific community. Our studies have included definition of the intra-caldera stratigraphy, formulation of structural models, and we are now involved in evaluating hydrothermal mineral zonation, defining fluid flow paths of the active hydrothermal system, and investigating similarities with epithermal, vein-type, precious metal systems.

STRATIGRAPHY

SLIDE 3
Strat. Column

In the past year our logging has allowed us to develop a consistent stratigraphic section within the caldera. Due to the youth of the structure, this stratigraphy has not been exposed within the caldera and is only partially developed outside the caldera. This is a composite stratigraphic section from that work.

Paliza Canyon Formation - sequence of basaltic and andesitic flows and pyroclastic rocks which formed prior to the development of the Valles caldera. These rocks were old enough that a rugged topography was developed by erosion prior to the eruption of the initial products of the Bandelier Tuff. Pervasive porphylitic alteration preceeded the development of the present day caldera structures.

Initial eruptions of the developing silicic volcanic center generated a series of ash-flows and associated sediments which form a sequence we have called Lower Tuffs. This unit is extremely variable and it is often not possible to correlate with certainty even between redrills of the same holes. This unit contains important fluid entries in a number of wells. Above this is the Otowi Member of the Bandelier Tuff which was emplaced during the formation of the Toledo caldera about 1.4 my ago. This unit shows the typical welding zonation, with a dense zone of graophyrically crystallized ash making up most of the unit. Following the emplacement and cooling of the Otowi Member, a period of erosion stripped the upper portion of the unit and deposited the S_3 Sandstone in stream channels. The Tshirege Member of the Bandelier Tuff was deposited about 1.1 my and accompanied the formation of the Valles caldera. It has also developed a cooling zonation similar to the Otowi with a thick granophyrically crystallized core region. A period of erosion again followed this eruption and the S_2 Sandstone was formed by streams draining the Baca project area. Note the position of the S_2 SS, we will be coming back to this in a moment. Subsequent smaller ash eruptions have formed a sequence of largely non-welded tuffs which we have designated the Upper Tuffs.

STRUCTURE

Following the formation of many calderas, including the Valles, continued magma pressure results in the formation of a central structural dome which is termed a resurgent dome.

SLIDE 4
Panorama

In the Valles, the resurgent dome is called the Redondo Dome, and is shown in this slide. The Baca project area is located entirely within this resurgent dome. As this slide

SLIDE 5
Geologic Map

shows the drilling is confined to the keystone graben of the resurgent dome within an area which is characterized by intense faulting. Since previous workers had emphasized a strong structural control on the system, and since much lower total permeabilities were found than had been expected, we have taken a look at the structural processes involved in dome formation.

SLIDE 6
Idealized Model

This is an idealized model of dome development which follows that presented by Johnson for the formation of the Henry Mts. in Utah. Within the domed strata there exists a neutral plane which separates areas of extension above and compression beneath. Thus, extensional faulting with relatively high permeability would be expected above the neutral plane; and relatively low permeability fracturing beneath the neutral plane.

SLIDE 7
S_2 Isopach

However, it is clear from some of our geologic relationships that the idealized model of dome formation is not entirely correct. This is an isopach map of the S_2 Sandstone which developed above the Tshirege Member shortly after the formation of the Valles caldera. This shows a stream channel system has developed along a northeast-southwest trend parallel to the Jemez Fault which geologic evidence shows was present long before the caldera eruptions. Thus the S_2 Sandstone channel formed along the Redondo Creek/Jemez fault trend very early in the development of the Redondo Dome. We believe that this represents an activation of the Jemez fault structures which would be present in the basement rocks at this time.

SLIDE 8
Dome Model
w/faults

Thus our idealized dome is modified somewhat and contains two different types of faults. 1. Shallow normal faults which are developed due to extension above the neutral plane, and 2. steep normal faults which are due to reactivation of basement structures of the Jemez fault trend.

SLIDE 9
3-D X-Sect.

We have combined our stratigraphic and structural information to develop an interpretive 3-D cross section of the Baca project area. This slide begins to show the complex interaction between stratigraphy and structure within the area.

HYDROTHERMAL SYSTEM

SLIDE 10
Baca 12

This is the wellhead of Baca-12, the deepest hole in the field with a depth of 3242 meters. There are a number of ways of using such a well to explore the physical and chemical processes which are taking place within an active hydrothermal system. Reservoir engineers tend to look at the results of flow and injection tests to define the gross permeability and productive capacity of the reservoir. Geologists tend to look at the variation of trace elements and alteration assemblages. The fact remains that the definition of fluid entires in boreholes are often not as straightforward as one would think. We have applied several approaches to the investigation of the hydrothermal fluid flow regime at the Valles caldera; hydrothermal mineral zonation and a review of the existing reservoir engineering data.

Measured temperatures within the Baca geothermal field have been measured up to 341°C in Baca-12. The fluids are sodium chloride brines with salinities of about 7000 ppm TDS,. The

SLIDE 11
T Contours

fluids are derived from the heating of meteoric waters (Goff and Grigsby, Trainer). The variation of temperatures within the geothermal zone can be seen by looking at this slice map of temperatures at 1200 meters elevation. The highest temperatures are centered around Baca well #4, and trend east-west and then to the northeast. The temperatures drop off toward the southwestern portion of the explored field.

The fluid flow which produces this temperature distribution is controlled by both stratigraphic units (non-welded tuffs and tuffaceous sediments) and faults and fractures which cut the welded tuff portions of the stratigraphy.

SLIDE 12
Granophyric
zone

The densely welded tuffs, which make up the bulk of the stratigraphic section, are largely primarily devitrified as shown in this slide. These rocks are essentially impermeable until fractured, and thus show little hydrothermal alteration except in fracture zones. In contrast, this is an electron photomicrograph of the S_3 sand. Note here the detrital grains within mass of hydrothermal illite and chlorite. This rock has little permeability at this time due to self sealing by hydrothermal alteration. Ash and non-welded ash-flows have also served as stratigraphic fluid conduits. This SEM photo shows a former pumice bed from Baca-17 which has been altered largely to illite but still preserves the textural character of the pumice.

SLIDE 13
Bridging illite
from S_3

SLIDE 14
Detail of 13

SLIDE 15
Pumice

SLIDE 16
Detail of 15

Although confined to stratigraphic interbeds and faults and fractures, the hydrothermal alteration zonation shows consistent relationships throughout the Baca field. This slide documents in cross section the zonation which we have determined through XRD and microscope evaluation of the subsurface samples. The upper portion of the holes contains an argillic alteration which affects the non- to poorly-welded Upper Tuffs as well as the overlying caldera-fill sediments and the Redondo Creek Rhyolite. This argillic zone is characterized by smectite, mixed layer illite-smectite, illite, kaolinite, quartz, and pyrite.

SLIDE 17
Alteration zonation

Beneath the argillic zone, propylitic alteration is widespread and pervasive at Baca. The propylitization is very weak in the mostly impermeable Bandelier Tuff, weak to moderate in the Lower Tuffs, and generally strong in the Paliza Canyon Formation, (where it may be older than the active geothermal system). Chlorite, calcite, illite, albite and epidote are the key alteration mienrals in this zone. Epidote is relatively rare in the felsic Bandelier Tuff and Lower Tuffs, but common and abundant in the intermediate-composition Paliza Canyon. Phengitic illite is relatively enriched in the Lower Tuffs.

Most of the major thermal fluid entries are associated with phyllic alteration. This alteration is characterized by partial to complete destruction of the rock to form illite + pyrite + quartz + calcite + chlorite. The zones of alteration are restricted to zones of structural and stratigraphic permeability.

The Lower Tuffs are characterized by chlorite + illite + albite assemblages. This alteration is much more intense than in the overlying Bandelier Tuff, largely because of non- to poorly-welded ash-flow tuffs, tuffs, and sediment within the interval. These rocks had considerable primary permeability, but in some holes, this permeability has been effectively sealed by hydrothermal alteration. The actual character and controls of present fluid entries within the Lower Tuffs are open to speculation. We do however correlate an increase in temperature with an increase in thickness of the Lower Tuffs, and the Lower Tuffs remain one of the principal target horizons for geothermal drilling. Therefore, we suspect that stratigraphically-controlled permeability is an important component, but realize that faulting may provide important controls also.

As with other high-temperature hydrothermal systems, alteration is a key to the identification of fluid flow systems and, specifically, fluid entries into geothermal wells. However, we realize that these fluid flow systems are dynamic, and it is helpful to be able to apply additional fluid flow data to the problem of system dynamics.

Our studies of the alteration are still in their preliminary stages, but it is apparent from these studies that isotherms have changed with time in the Baca system.

SLIDE 18
I/S Clays

This slide shows the distribution of illite-smectite clays in the Baca and some other active thermal systems, including geothermal systems and active diagenetic systems.

ON = Onikobe
CP = Cerro Prieto
W = Wairakei
GC = Gulf Coast Sediments

NS = North Sea Sediments
SH = Shale Diagenesis (Perry and Hower)

When available from the literature, we have plotted the ordering of the I/S clay as a function of temperature. The geothermal literature does not specify the ordering of I/S clays, but they are specified for diagenetic environments. The general transition from randomly interstratified to ordered is found between 75-100°C. In the Baca system ordered I/S clays are found at temperatures as low as 30°C. Suggesting that alteration assemblages document temperatures which reflect higher temperatures than are realized presently. The immediate explanation for this observation is that the system has cooled with time. However, an alternative explanation may be that the system has remained essentially fixed with time, and the apparent collapse of isotherms is a result of uplift of the resurgent dome. Our observation of cooling with time is in contrast to the oxygen isotope work of Lambert and Epstein who see no evidence for cooling with time.

Reservoir engineering data are also useful in interpreting the hydrothermal mineral zonation and the dynamics of the hydrothermal system. From the standpoint of alteration, well Baca 18 is not unique. However, it is the only well in the field which intersects the Lower Tuffs and upper portion of the Paliza Canyon and does not produce geothermal fluids from those intervals.

SLIDE 19
B-18 T

SLIDE 20
Spinner

The slide on your left shows a series of temperature measurements in B-18, and the slide on the right shows the results of two spinner surveys run in the well during injection. The comparison shows that the Lower Tuffs accepted no fluids during injection, and the results are confirmed by the series of temperature surveys run to document the thermal recovery of the well. Thus, even though the alteration assemblages in the Lower Tuff interval are the same as in other wells, the alteration has been intense enough to effectively seal all fluid pathways in this interval.

SLIDE 21
Metal Deposits

There are many similarities between the active Baca geothermal system and fossil hydrothermal metal systems. Many of these correlations are shown on this slide which is patterned after a similar table by White and Heropoulos. The key difference is that pyrite is the only sulfide species found in the deep portion of the holes, although it is often rich in silver running up to 2 oz/ton. In addition, the fluids presently circulating within the Baca system are at the dilute end of the salinity ranges which are thought to be responsible for the deposition of hydrothermal metal deposits.

We anticipate that our ultimate model of the Baca geothermal system will allow us to tie together the systematics of the active hydrothermal system with the structural evolution of the Valles caldera. We may summarize our present results as follows.

SLIDE 22
Dome Model w/
faults

Returning to our modified idealized model of the Redondo Dome, we have the steep reactivated Jemez faults and the listric extensional faults. We feel that the steep reactivated faults control the ascent of fluids through the area beneath the neutral plane which is under compression. Fluids rising above the neutral plane are then able to flow out through permeable horizons which are intersected by the steep faults. Shallow faults which do not intersect these principal reactivated faults have no way of acquiring fluids.

SLIDE 23
Index

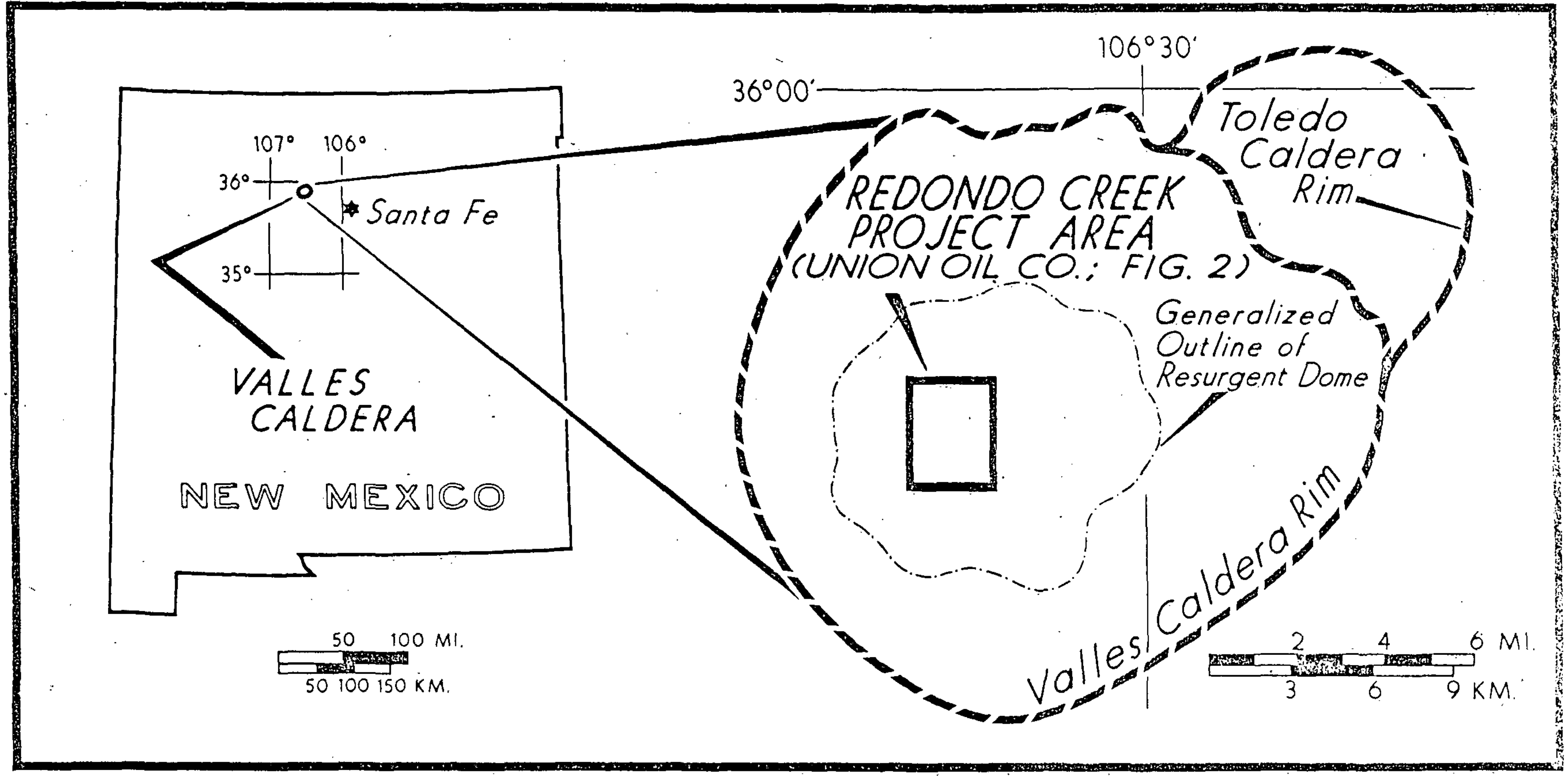
Now we'll look at this concept in terms of a cross section of the reservoir.

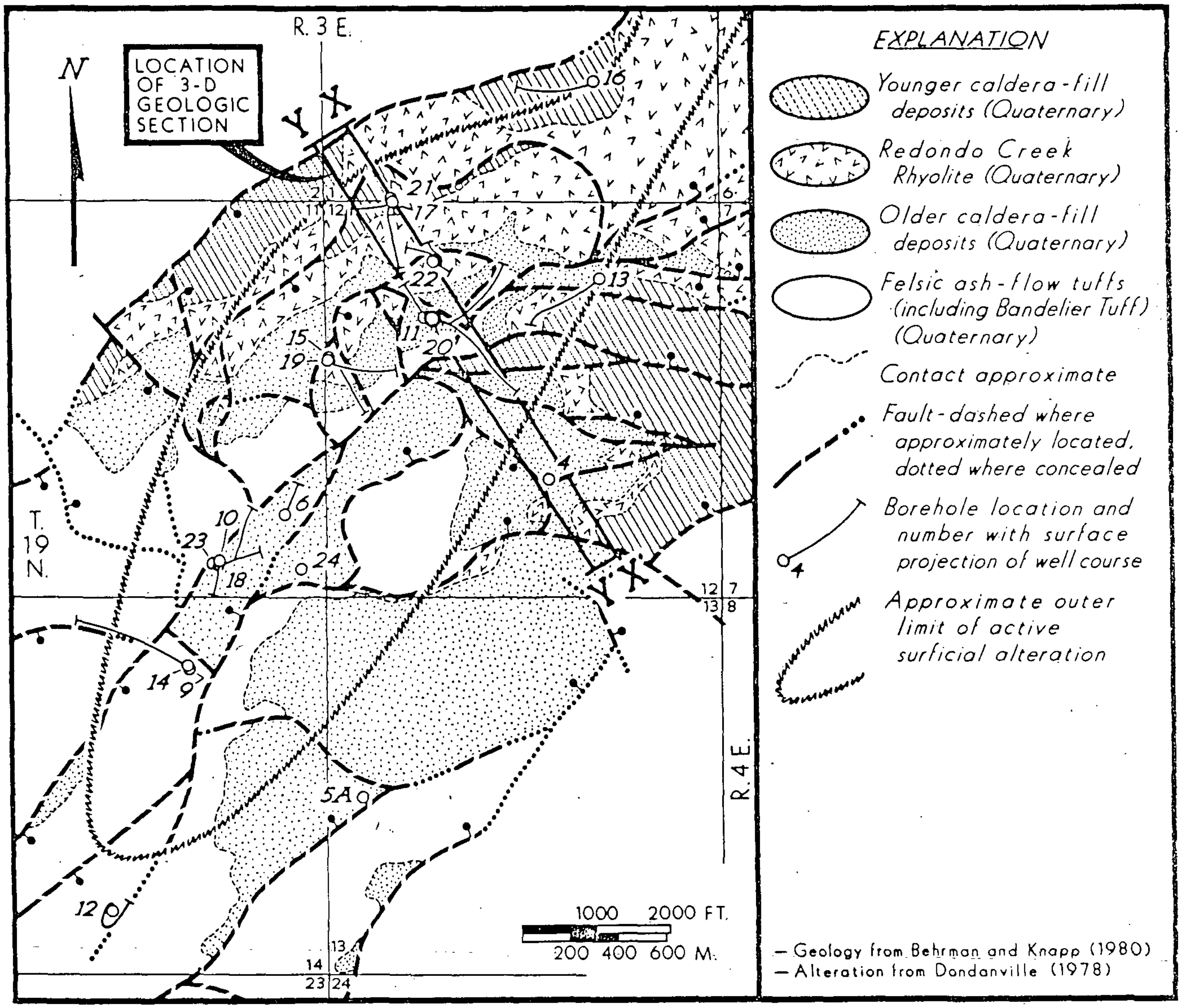
SLIDE 24
Fluid Flow
X-Sect

Here we have superimposed production zones upon a geologic cross section constructed from our logging. We have also superimposed isotherms on the diagram. Fluids move from depth along major fault zones and are distributed into shallow faults and stratigraphic intervals. Faults which have been developed during doming and do not intersect the faults controlling major upflow zones do not carry fluids, do not show hydrothermal alteration, and serve as lost circulation zones during drilling.

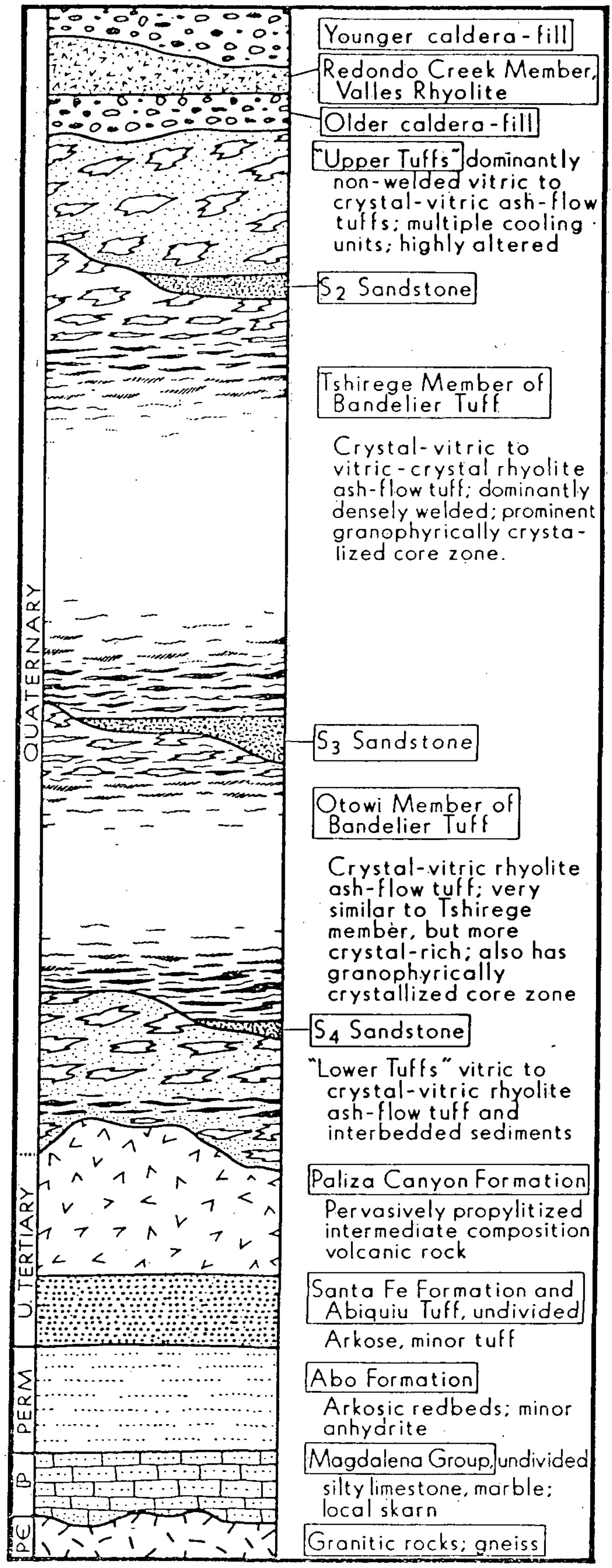
With time, permeability along the zones of fluid flow is reduced due to hydrothermal alteration. This sealing is particularly effective in non-welded ash and volcaniclastic beds. In contrast fault and fracture zones can have their permeability renewed by subsequent movement along those zones.

Although the fluids at Baca are of low salinity, clear parallels exist between this active hydrothermal convection system and precious metal vein systems in similar settings.


107°
106°
36°
35°
Santa Fe
VALLES CALDERA
NEW MEXICO
50 100 MI.
50 100 150 KM.
106°30′
36°00′
Toledo Caldera Rim
REDONDO CREEK PROJECT AREA (UNION OIL CO.; FIG. 2)
Generalized Outline of Resurgent Dome
Valles Caldera Rim
2 4 6 MI.
3 6 9 KM.



— Geology from Behrman and Knapp (1980)
— Alteration from Dondanville (1978)



Younger caldera-fill

Redondo Creek Member, Valles Rhyolite

Older caldera-fill

"Upper Tuffs" dominantly non-welded vitric to crystal-vitric ash-flow tuffs; multiple cooling units; highly altered

S_2 Sandstone

Tshirege Member of Bandelier Tuff

Crystal-vitric to vitric-crystal rhyolite ash-flow tuff; dominantly densely welded; prominent granophyrically crystalized core zone.

S_3 Sandstone

Otowi Member of Bandelier Tuff

Crystal-vitric rhyolite ash-flow tuff; very similar to Tshirege member, but more crystal-rich; also has granophyrically crystallized core zone

S_4 Sandstone

"Lower Tuffs" vitric to crystal-vitric rhyolite ash-flow tuff and interbedded sediments

Paliza Canyon Formation

Pervasively propylitized intermediate composition volcanic rock

Santa Fe Formation and Abiquiu Tuff, undivided

Arkose, minor tuff

Abo Formation

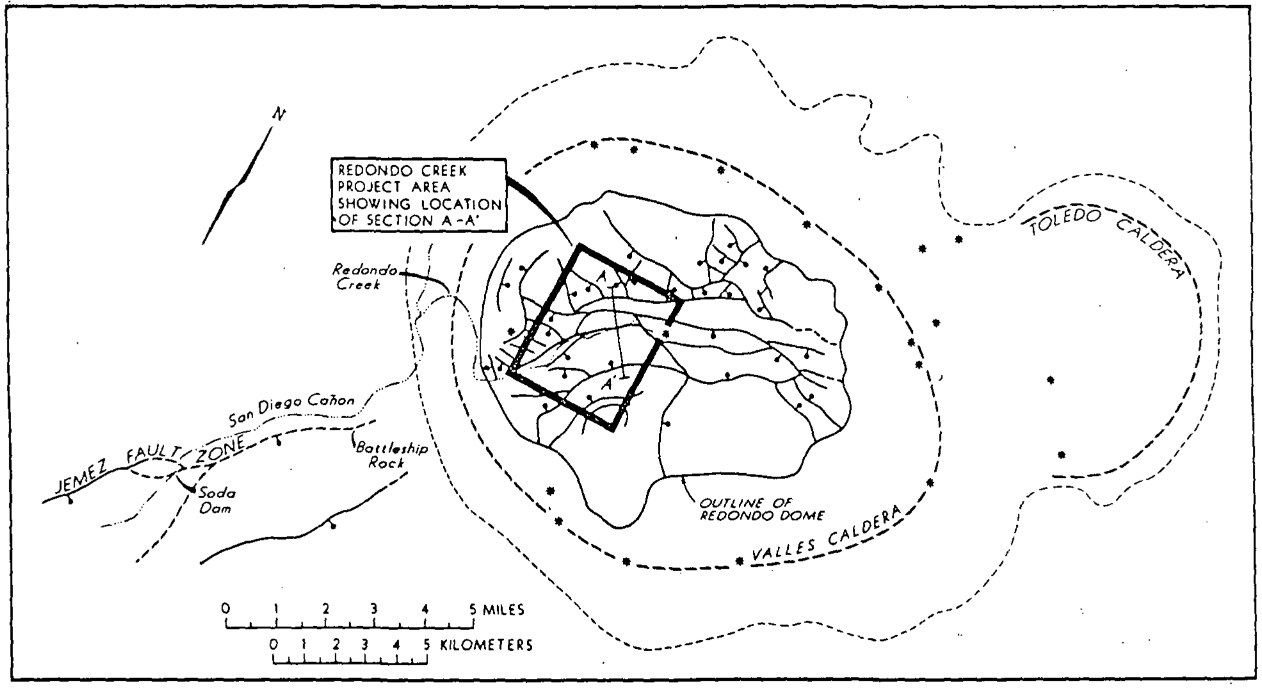
Arkosic redbeds; minor anhydrite

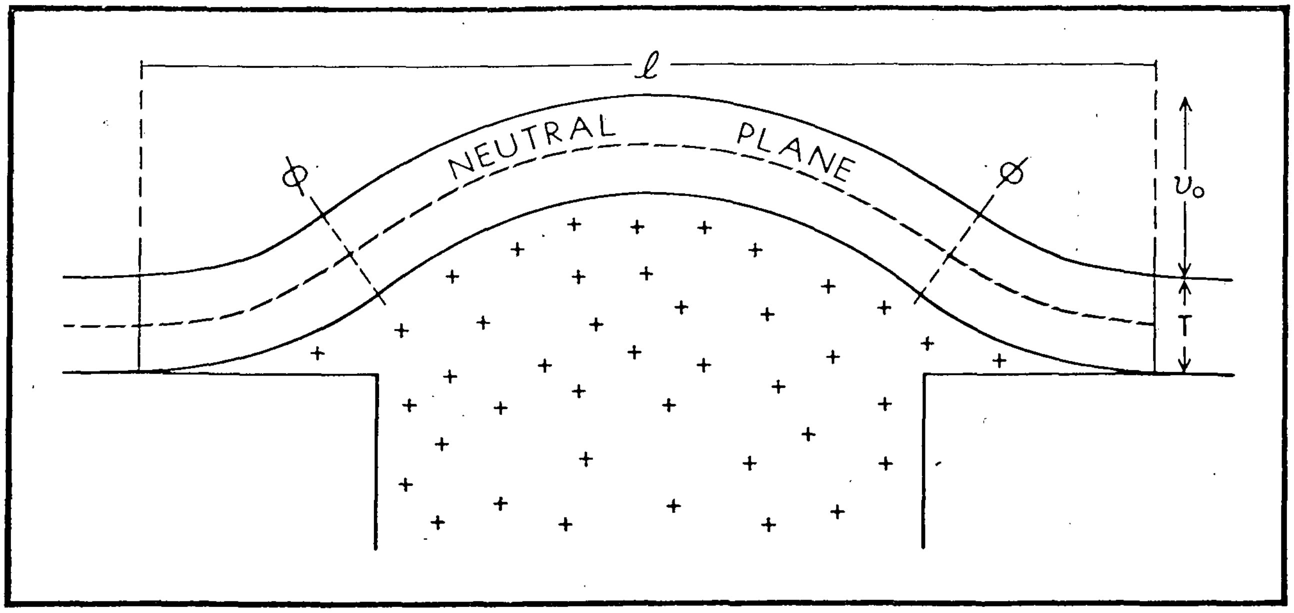
Magdalena Group, undivided

silty limestone, marble; local skarn

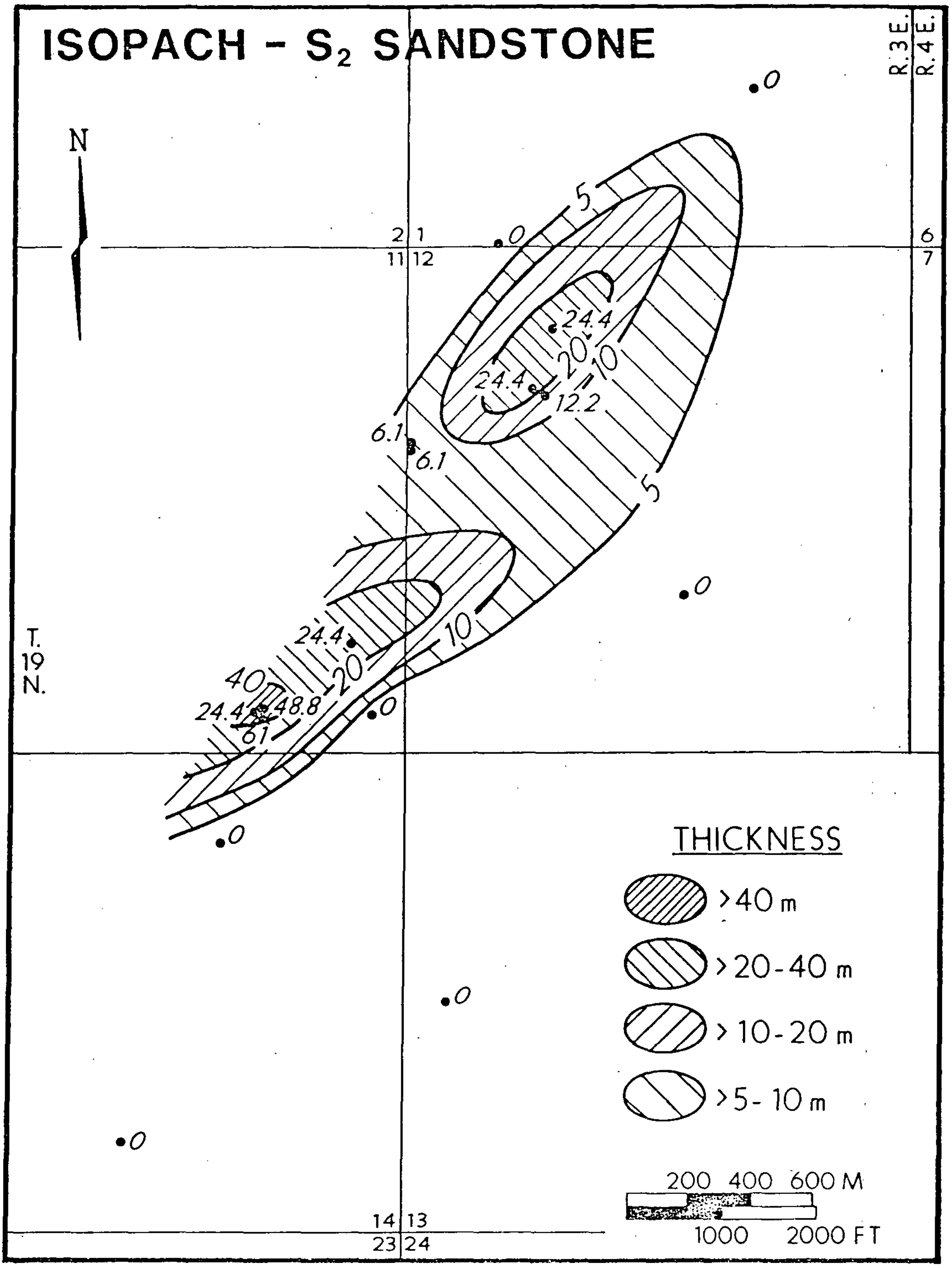
Granitic rocks; gneiss

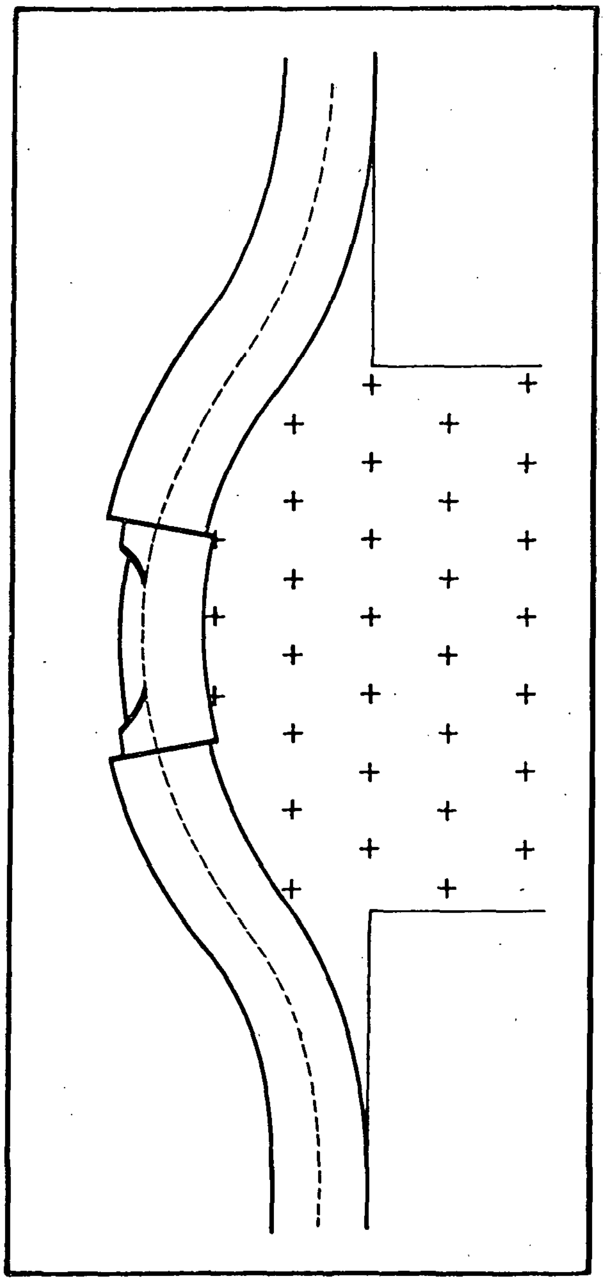
SLIDE 4- Redondo Dome as viewed from Valle Grande


N
REDONDO CREEK PROJECT AREA SHOWING LOCATION OF SECTION A-A'
Redondo Creek
A
A'
TOLEDO CALDERA
San Diego Cañon
JEMEZ FAULT ZONE
Battleship Rock
Soda Dam
OUTLINE OF REDONDO DOME
VALLES CALDERA
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS


ℓ
NEUTRAL PLANE
ϕ
ϕ
v_o
T

ISOPACH - S_2 SANDSTONE





SLIDE 9

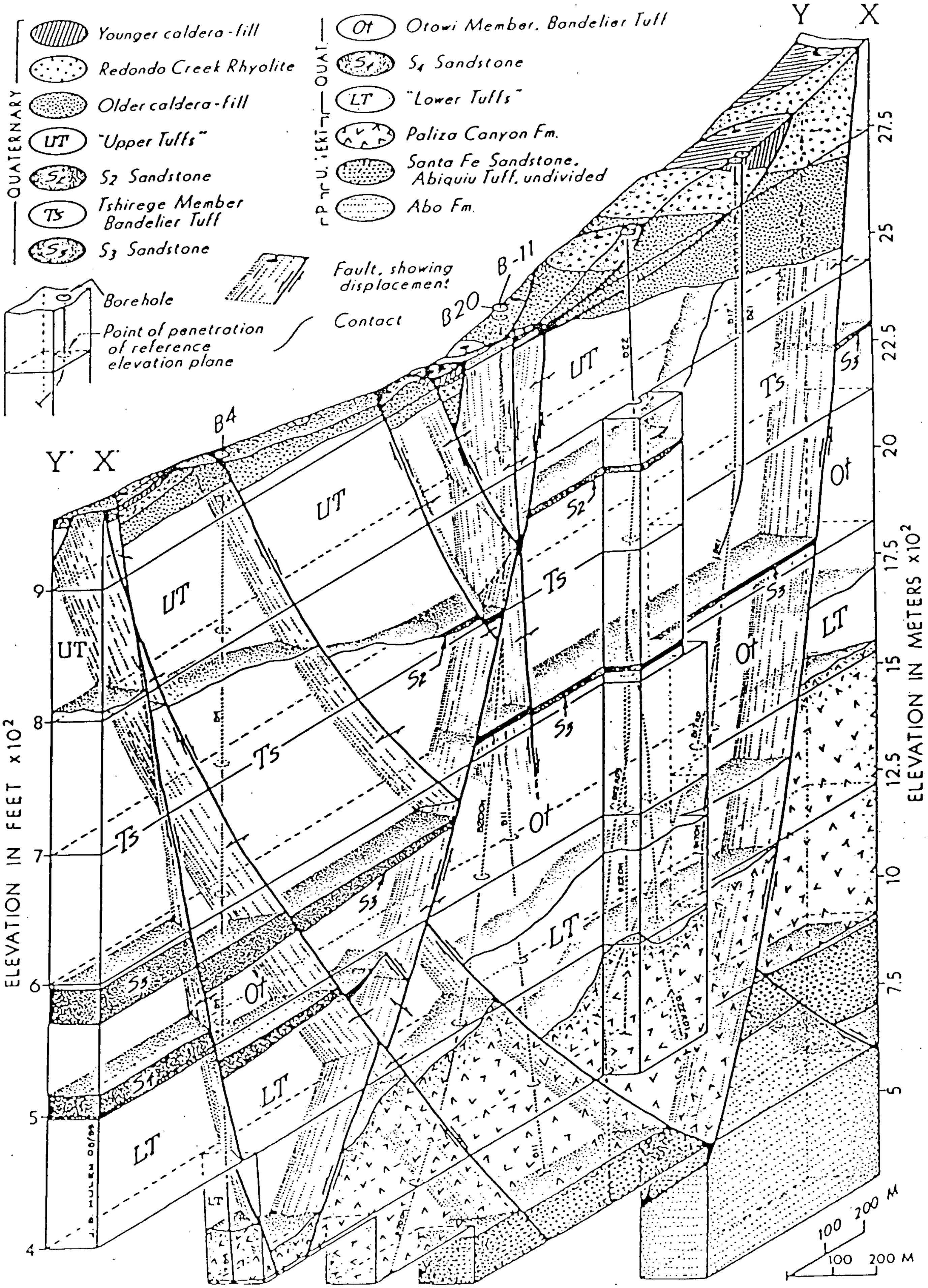
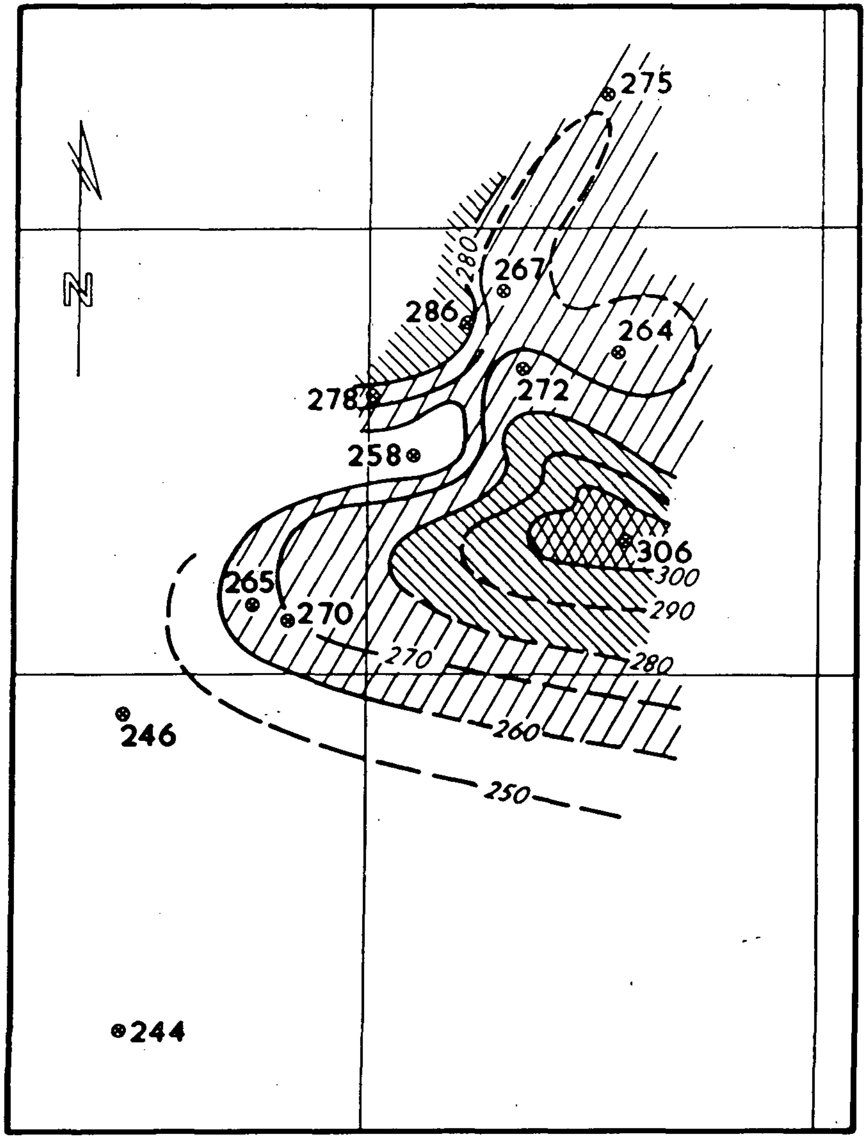


FIG. 15

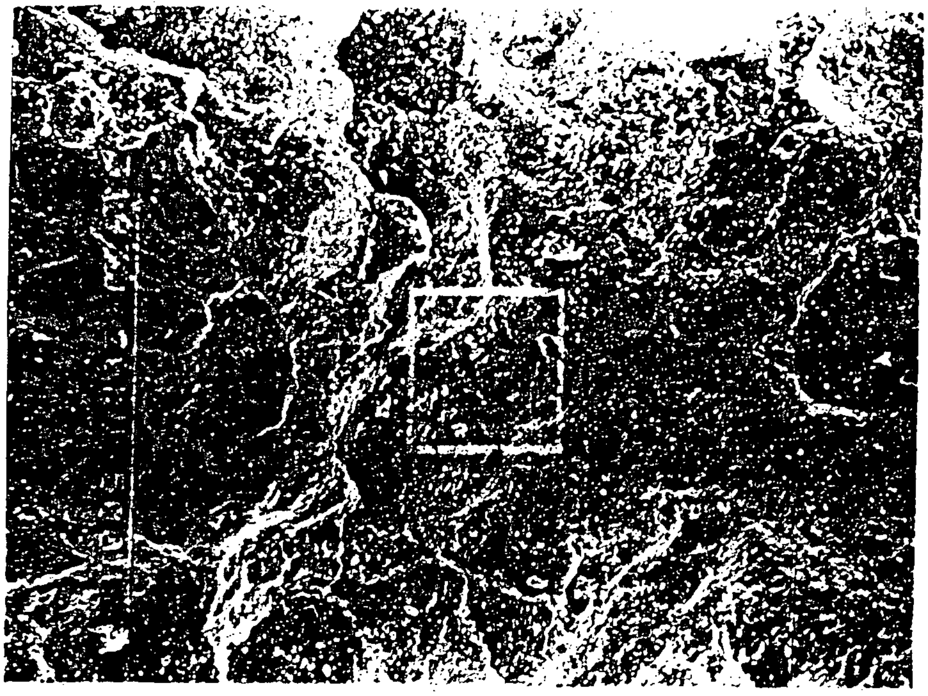
SLIDE 10- Photograph of the well head of Baca-12

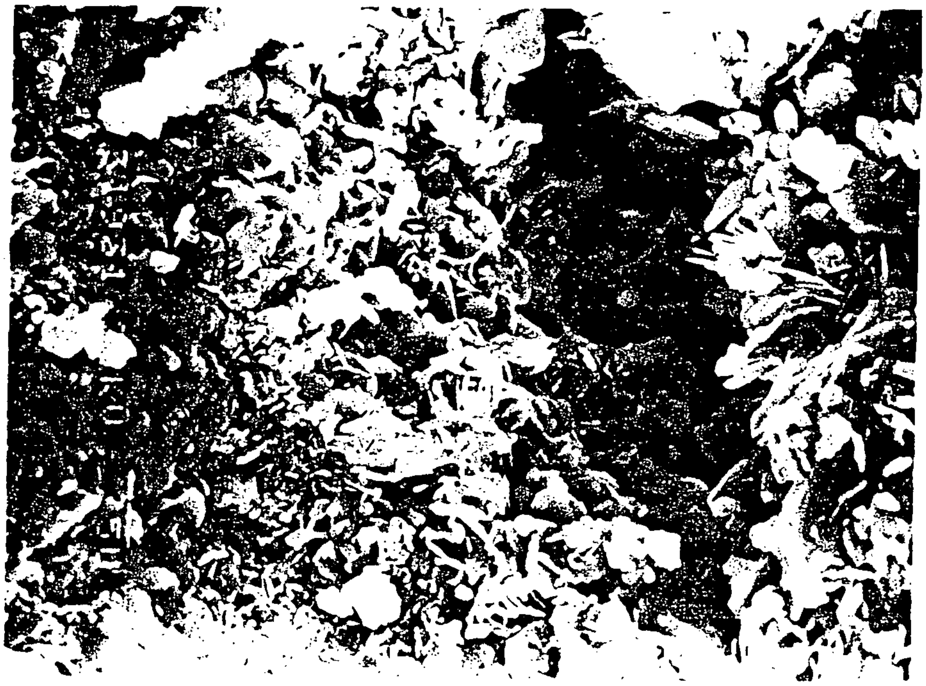
Temp. at 1200m elev.[°C]



SLIDE 12-Photomicrograh of granophyric crstallization from Baca-17

SLIDE 13





SLIDE 14

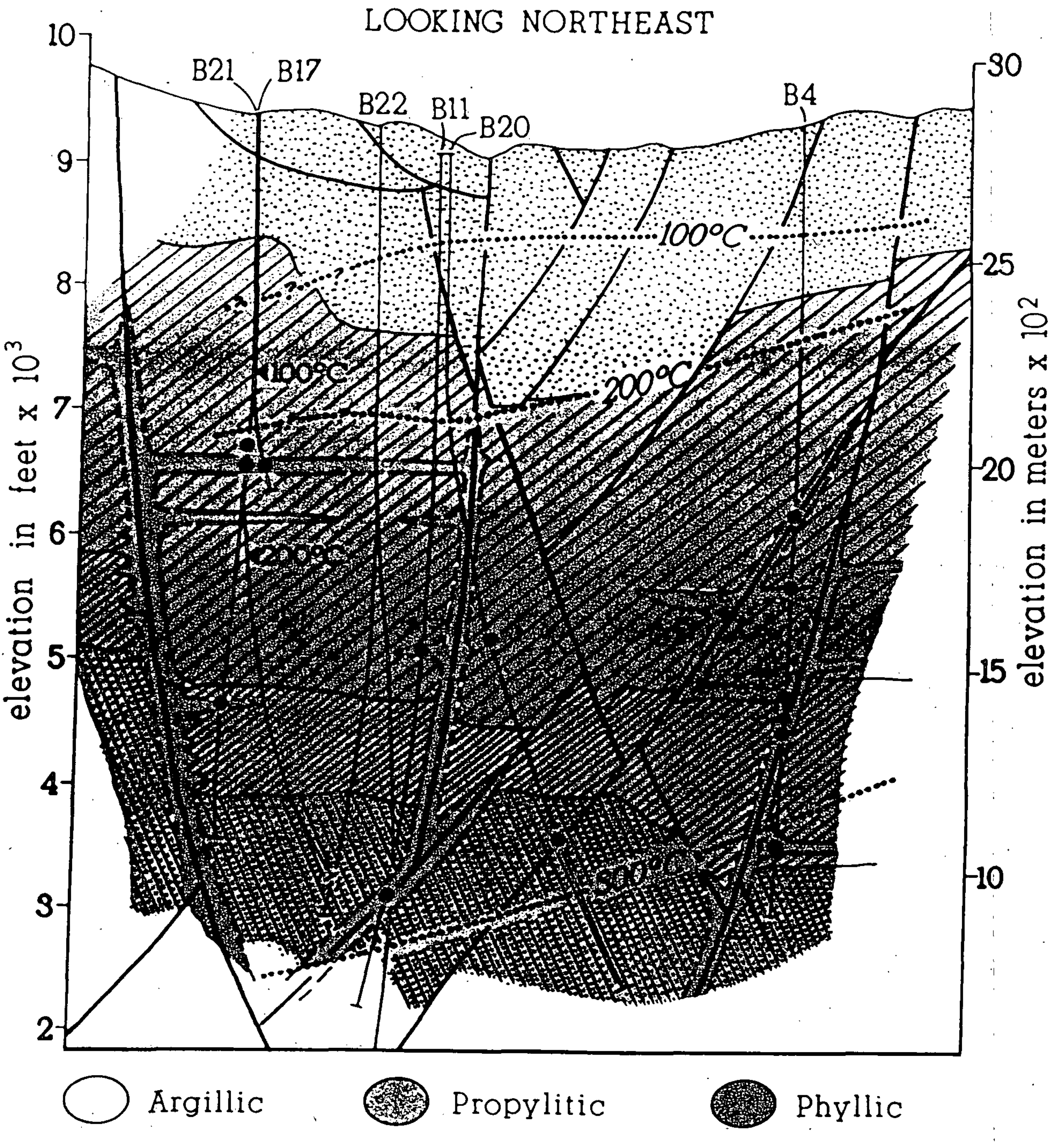
SLIDE 15

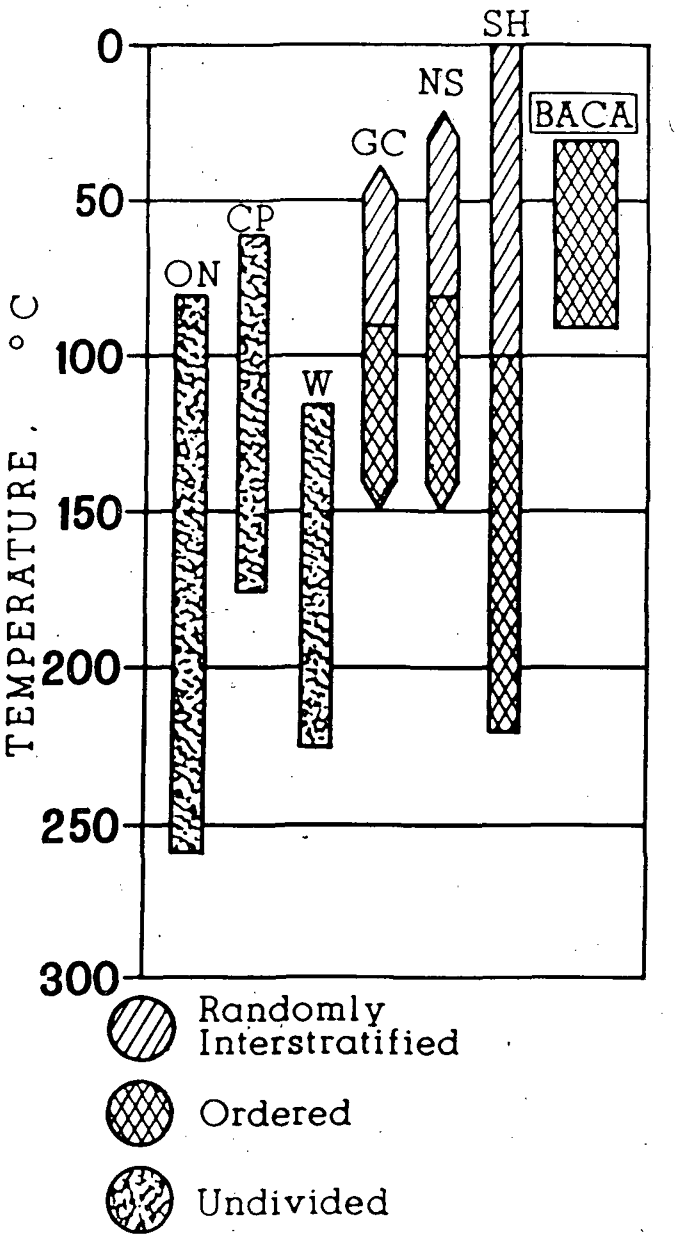

A

SLIDE 16

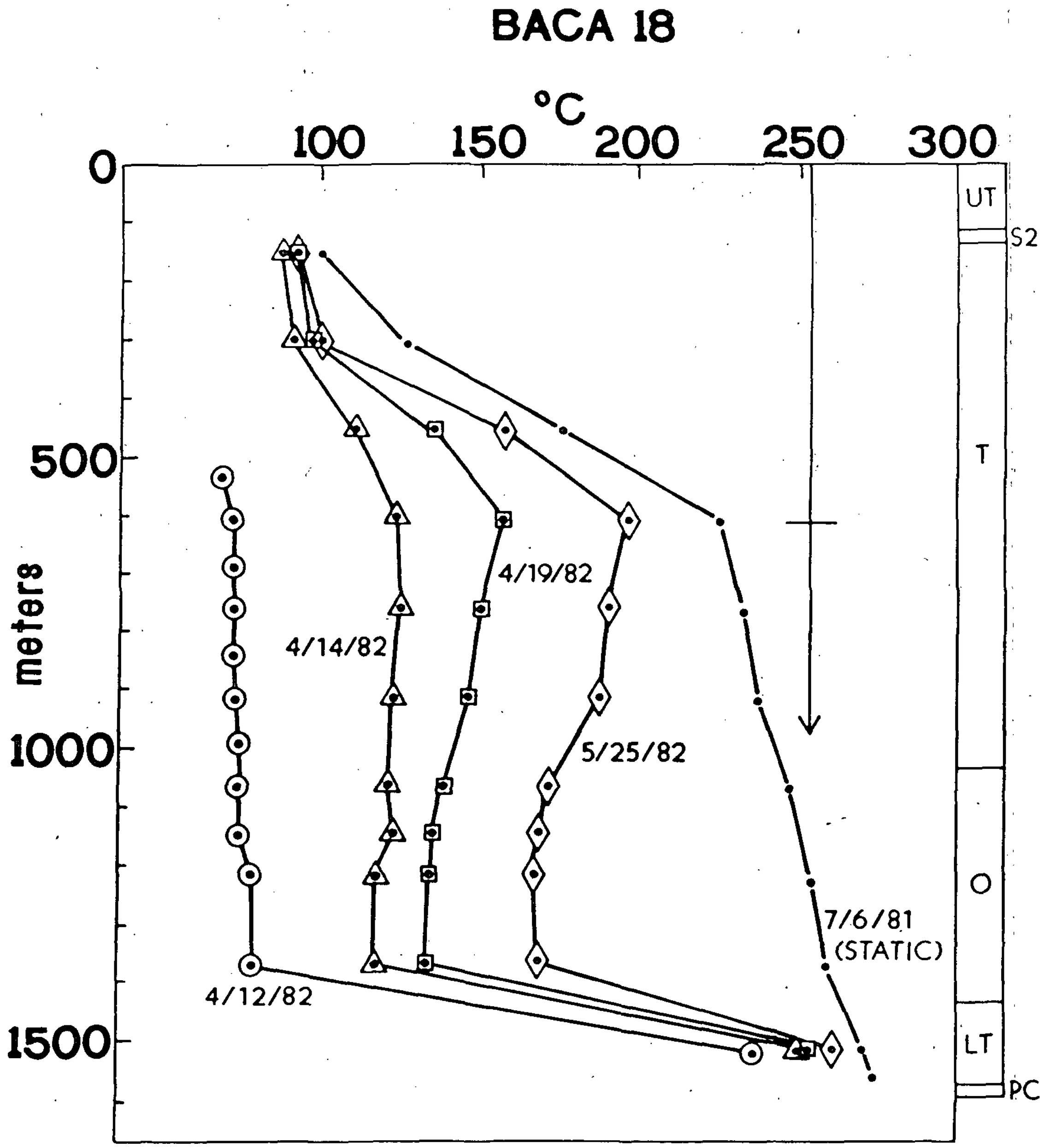
E

SLIDE 17


LOOKING NORTHEAST
B21
B17
B22
B11
B20
B4
100°C
200°C
100°C
200°C
300°C
elevation in feet x 10^3
10
9
8
7
6
5
4
3
2
elevation in meters x 10^2
30
25
20
15
10
Argillic
Propylitic
Phyllic


SH
NS
BACA
GC
CP
ON
W
0
50
100
150
200
250
300
TEMPERATURE, °C
Randomly Interstratified
Ordered
Undivided

SLIDE 19


BACA 18
°C
100
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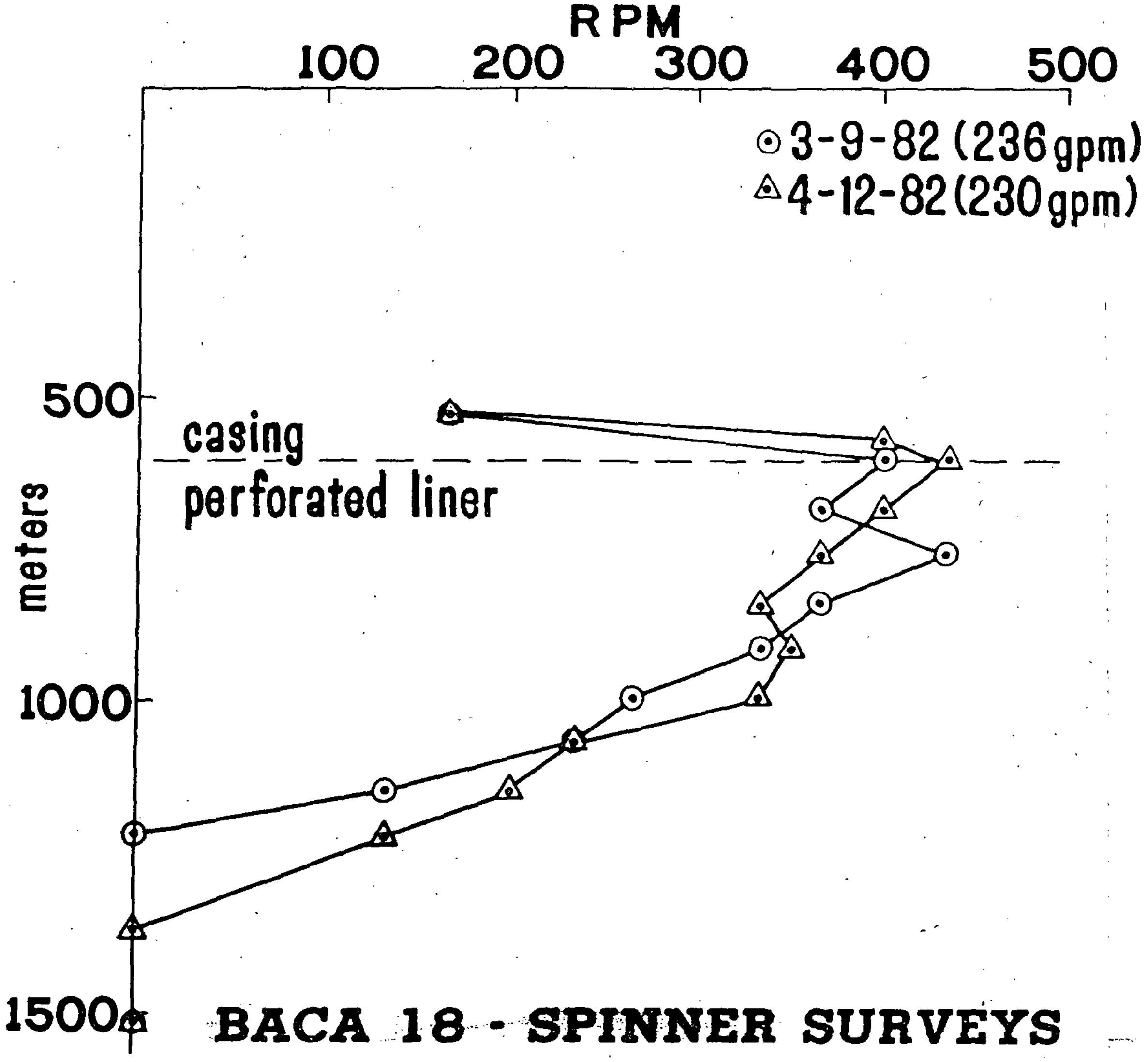
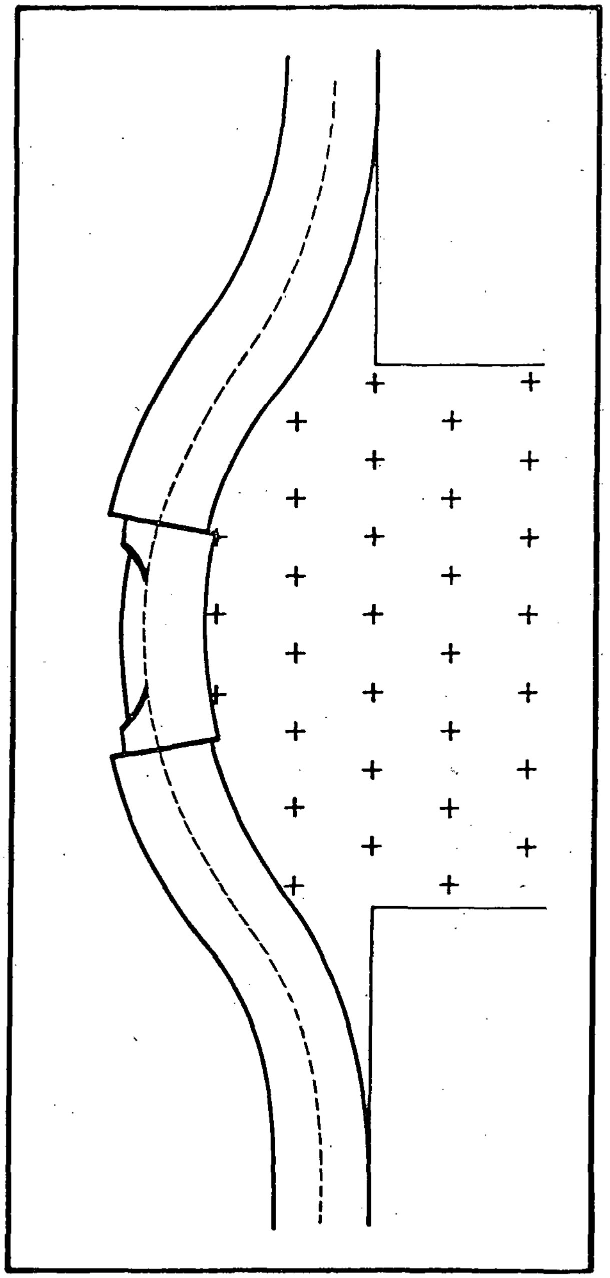
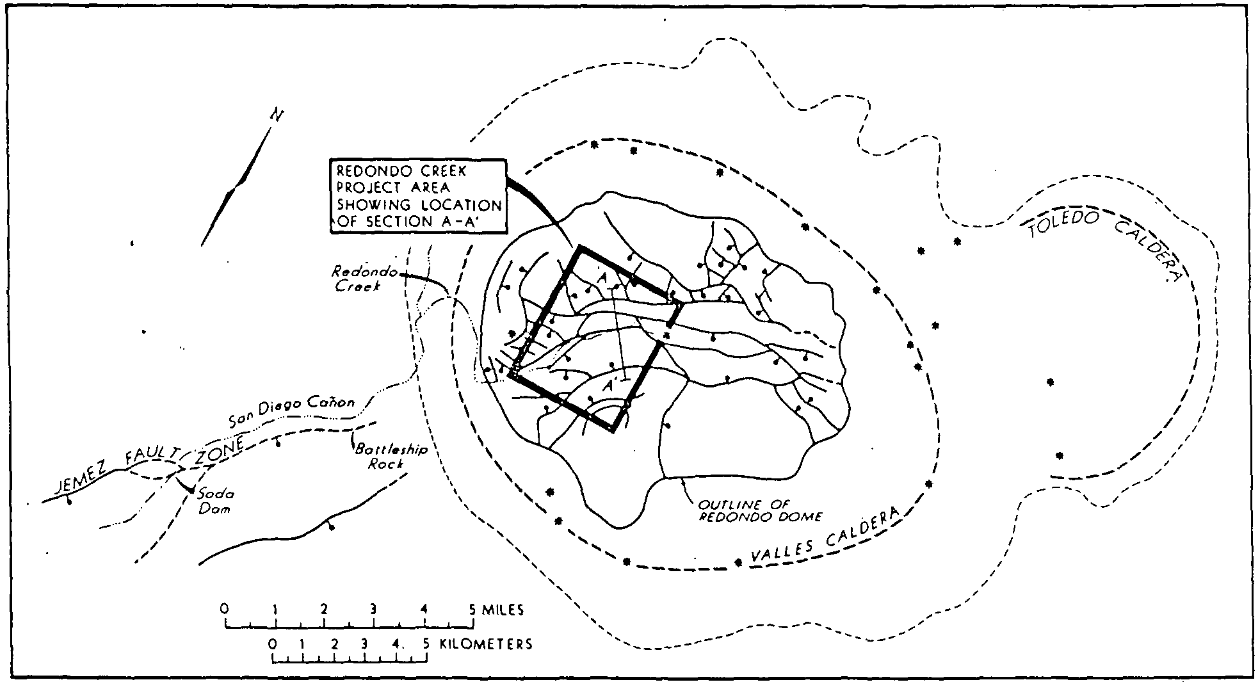


BACA 18 - SPINNER SURVEYS

	<u>SILVER/BASE METAL DEPOSITS</u>	<u>BACA</u>
● Host Rocks/Tectonic Setting	Felsic ash flow tuffs, complexly faulted	Same
● Ore	Ag, Ag-bearing sulfosalts and sulfides	None; Ag-rich pyritic zones
● Temperature	190-270°C	20-341°C
● Heat Source	Felsic magma chamber	Felsic magma chamber
● Water	NaCl; 40-120 x 10^3 ppm TDS	NaCl; 5200-7300 ppm TDS
● Geochemical Zoning	Hg, As, Sb above ore zone	Data incomplete; Hg enriched at high levels
● Hydrothermal Alteration	Widespread propylitization; Phyllic alteration of vein envelopes; Argillic "cap" with illite-smectite	Pervasive propylitization Phyllic alteration in fault zones and permeable strata; argillic "cap" with illite-smectite

SLIDE 22

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REDONDO CREEK PROJECT AREA SHOWING LOCATION OF SECTION A-A'
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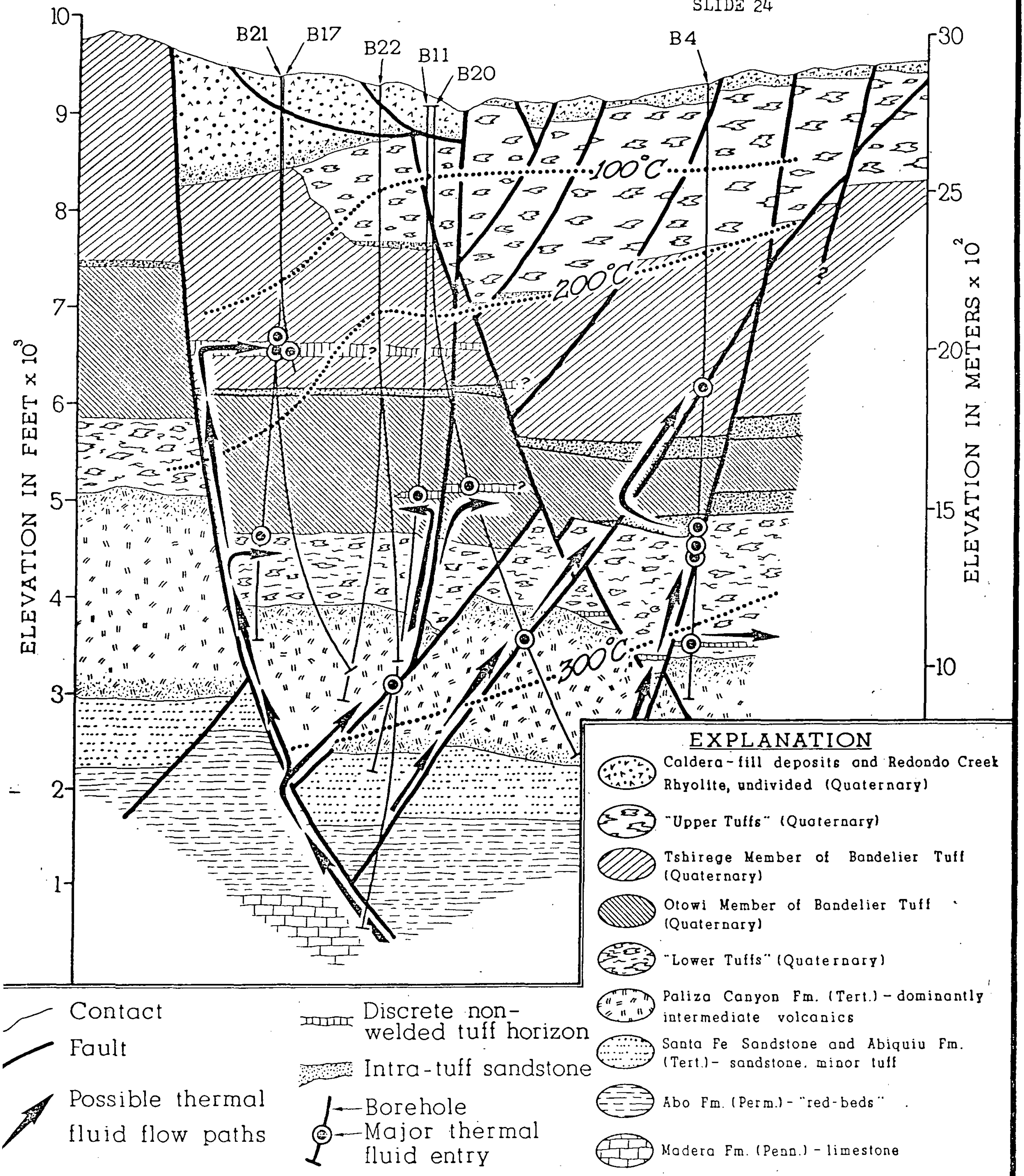
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS



Data from Union Geothermal (1973-1981), Berhrman and Knapp (1980) and Grant and Garg (1981). Interpretation by J.B Hulen and D.L. Nielson