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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.

Fig. 3 near here

Table 1 near here

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 micrograпophyric 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 ℓ = 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.

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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.

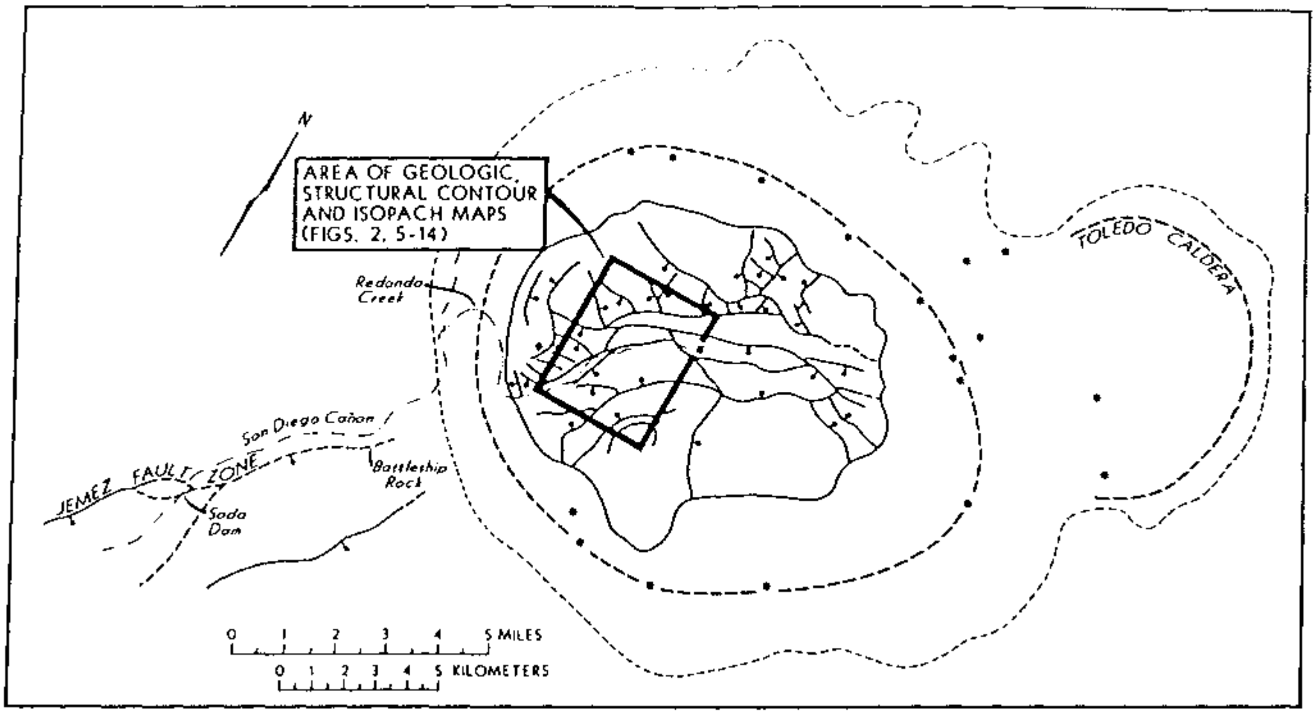
N
AREA OF GEOLOGIC, STRUCTURAL CONTOUR AND ISOPACH MAPS (FIGS. 2, 5-14)
Redondo Creek
TOLEDO CALDERA
San Diego Cañon
JEMEZ FAULT ZONE
Battleship Rock
Soda Dam
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

Fig 1

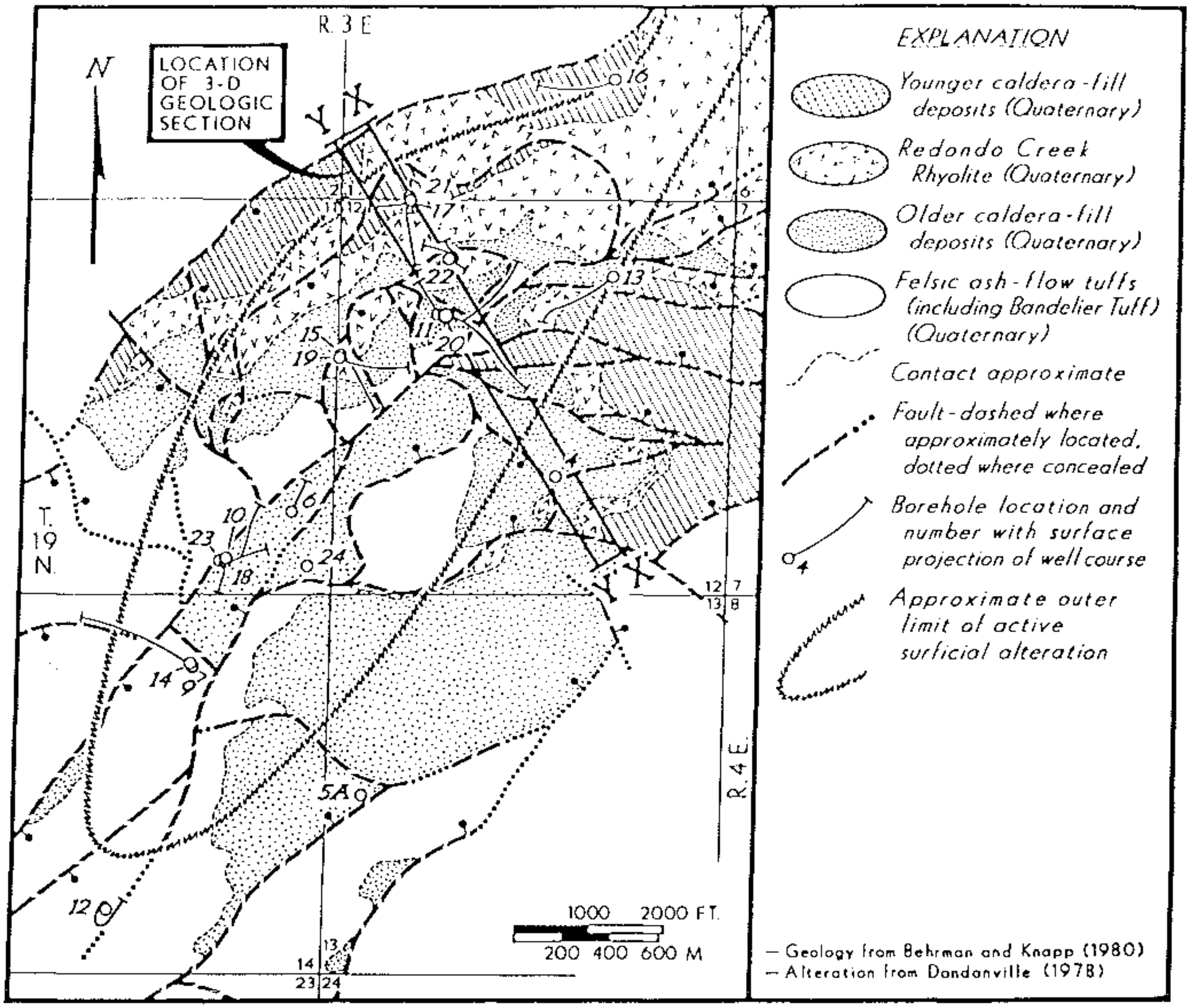
LOCATION OF 3-D GEOLOGIC SECTION
N
R. 3 E.
R. 4 E.
T. 19 N.
EXPLANATION
Younger caldera-fill deposits (Quaternary)
Redondo Creek Rhyolite (Quaternary)
Older caldera-fill deposits (Quaternary)
Felsic ash-flow tuffs (including Bandelier Tuff) (Quaternary)
Contact approximate
Fault-dashed where approximately located, dotted where concealed
Borehole location and number with surface projection of well course
Approximate outer limit of active surficial alteration
1000 2000 FT.
200 400 600 M
— Geology from Behrman and Knapp (1980)
— Alteration from Dondanville (1978)

Fig 2

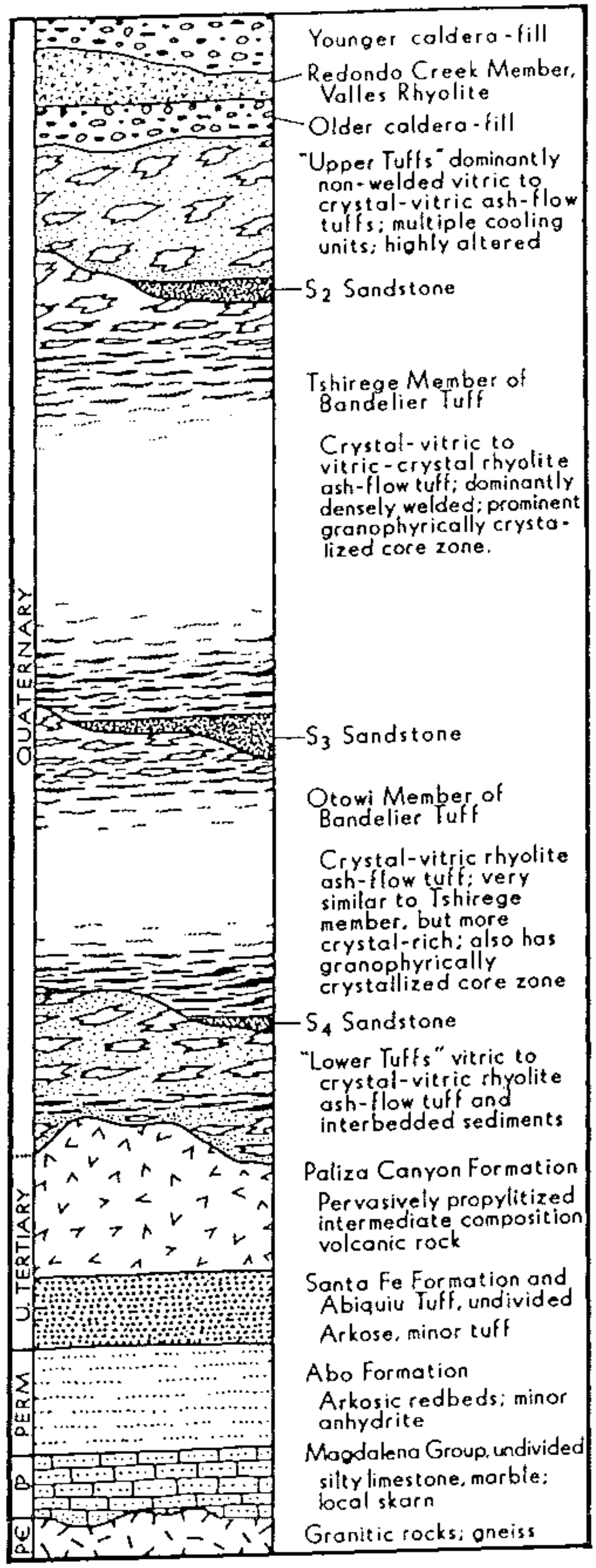
QUATERNARY
U. TERTIARY
PERM
P
PЄ
Younger caldera-fill
Redondo Creek Member, Valles Rhyolite
Older caldera-fill
"Upper Tuffs" dominantly non-welded vitric to crystal-vitric ash-flow tuffs; multiple cooling units; highly altered
S2 Sandstone
Tshirege Member of Bandelier Tuff
Crystal-vitric to vitric-crystal rhyolite ash-flow tuff; dominantly densely welded; prominent granophyrically crysta-lized 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

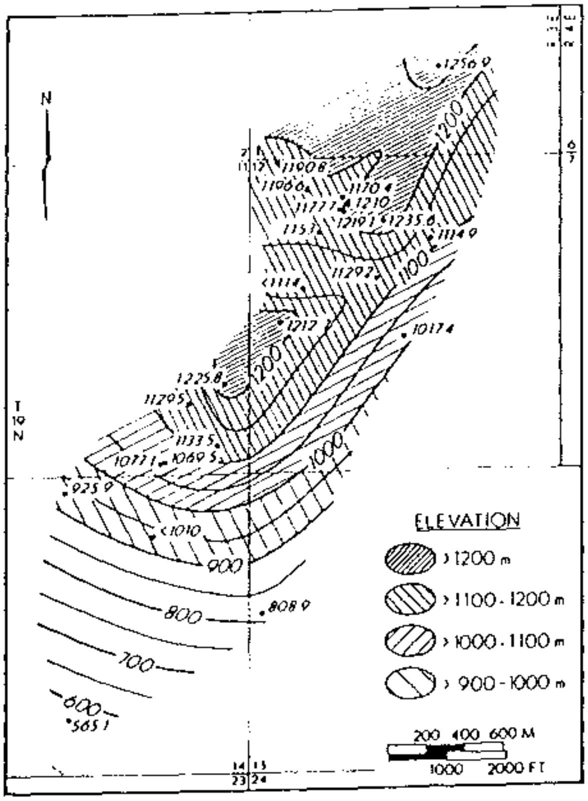

Fig 4

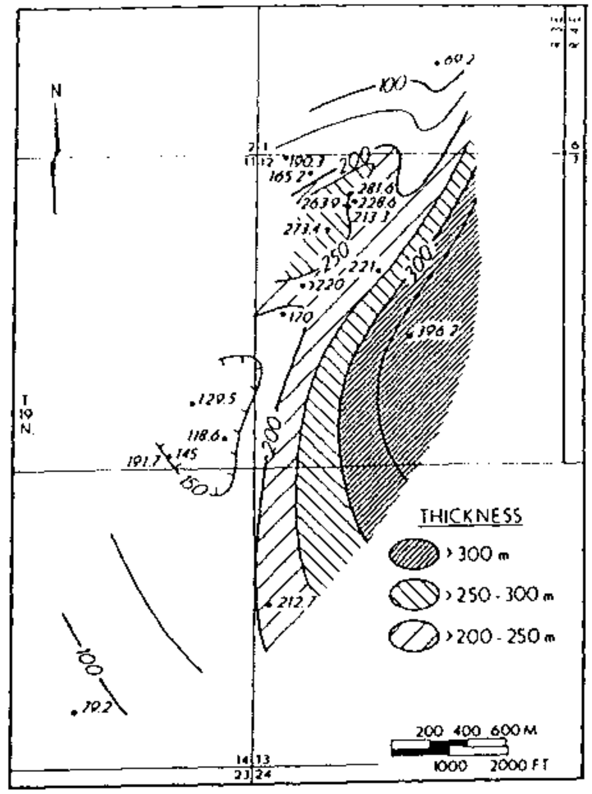

Fig 5

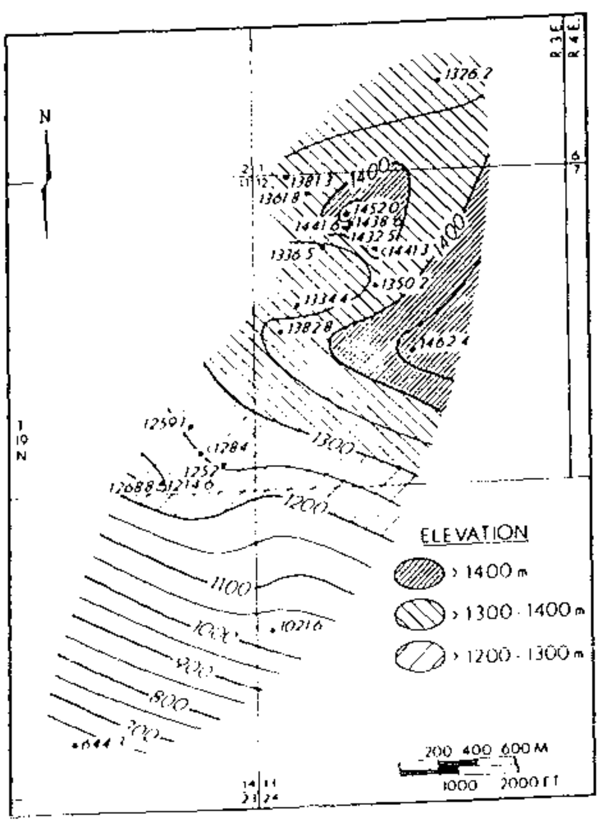

Fig 6

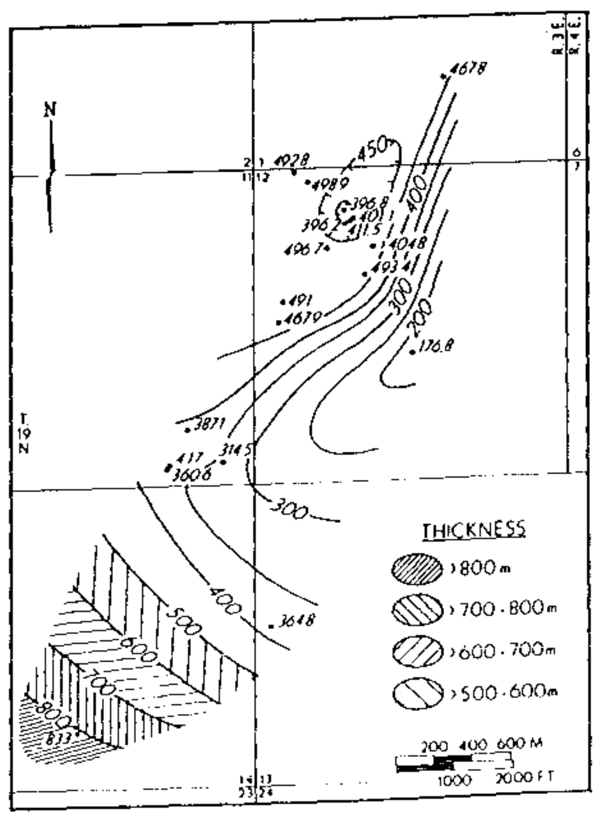

Fig 7

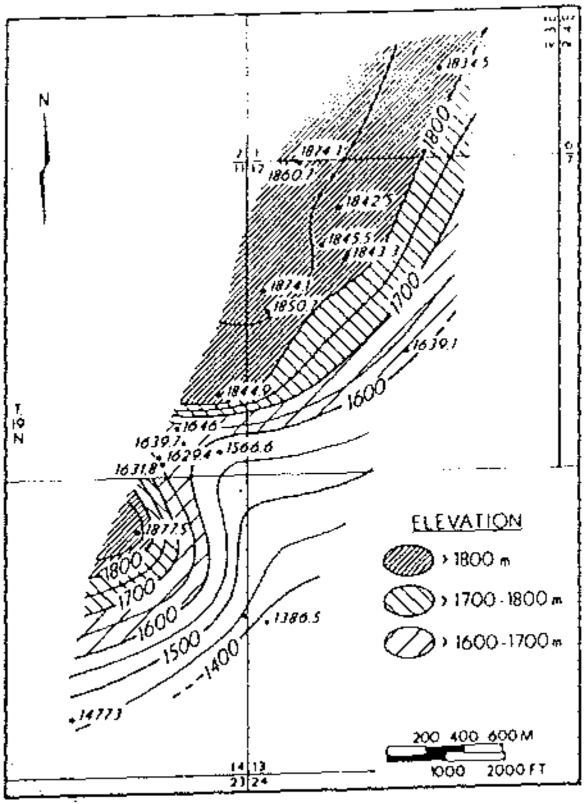

Fig 8

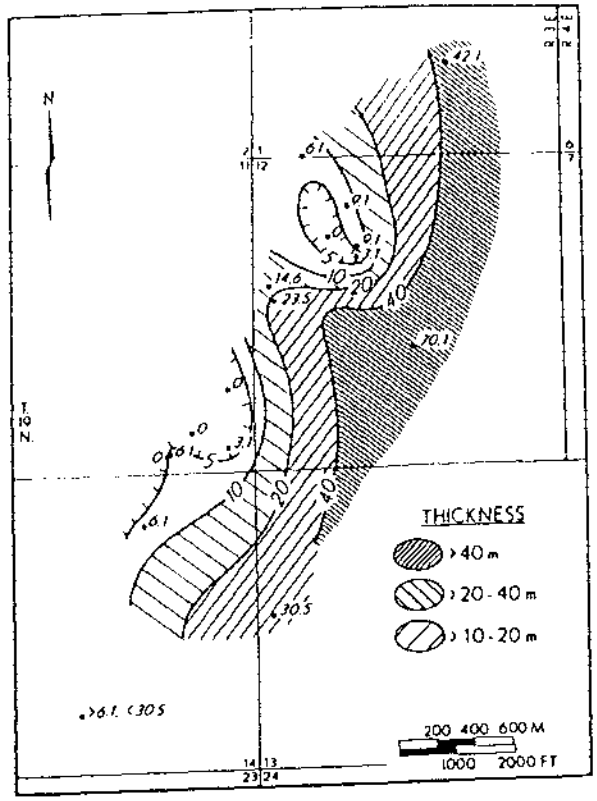

Fig 9

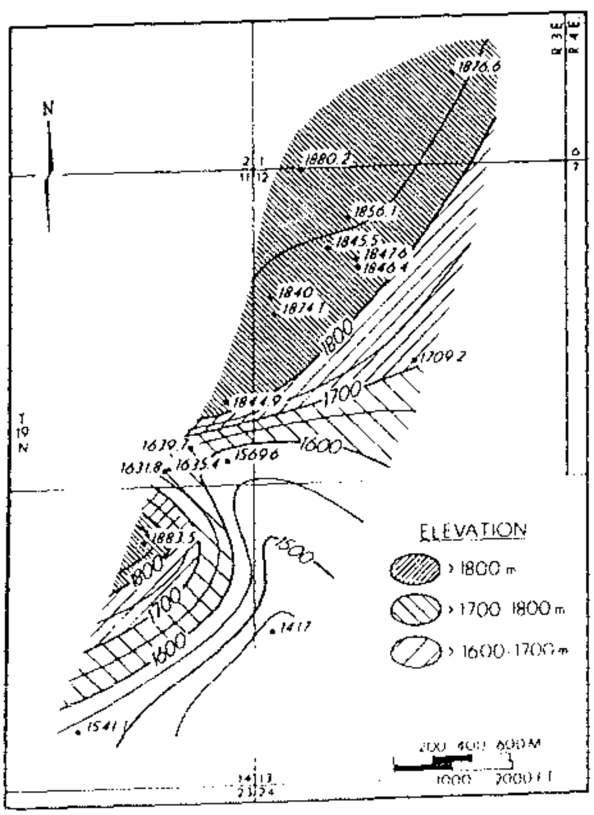

Fig 10

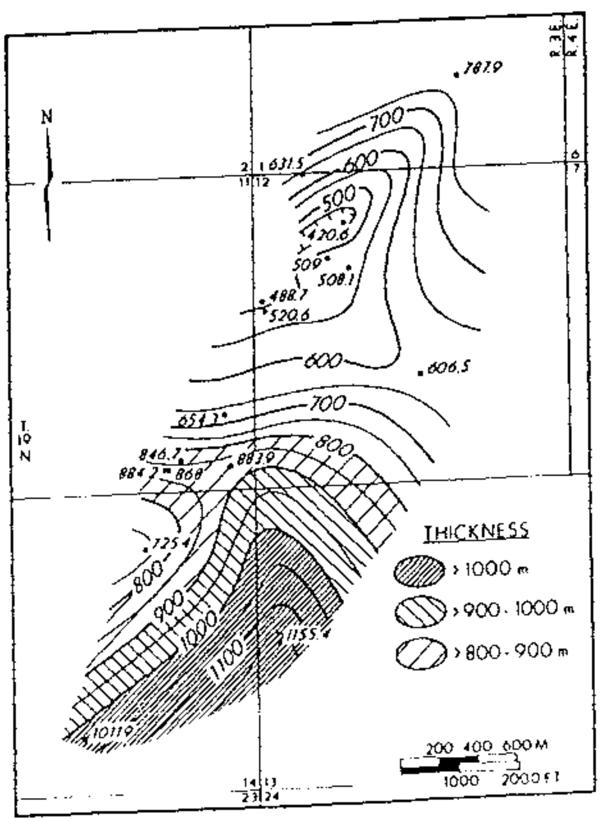

Fig 11

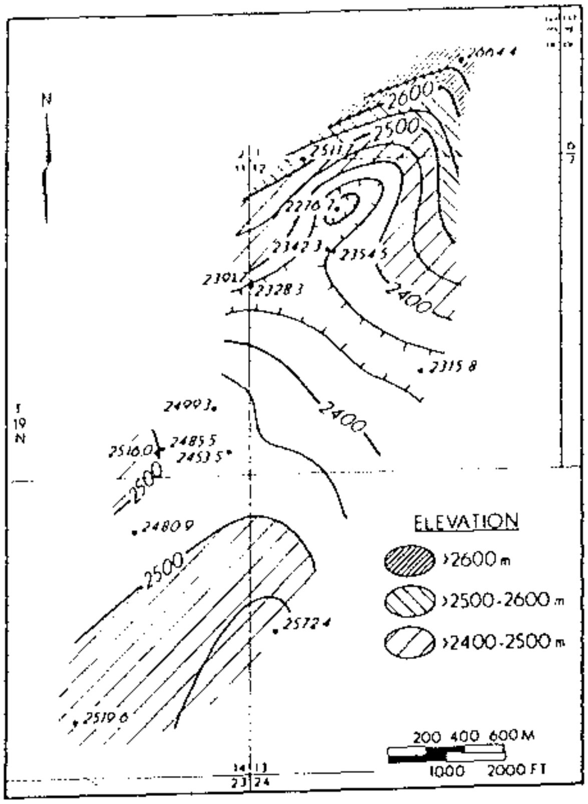

Fig 12

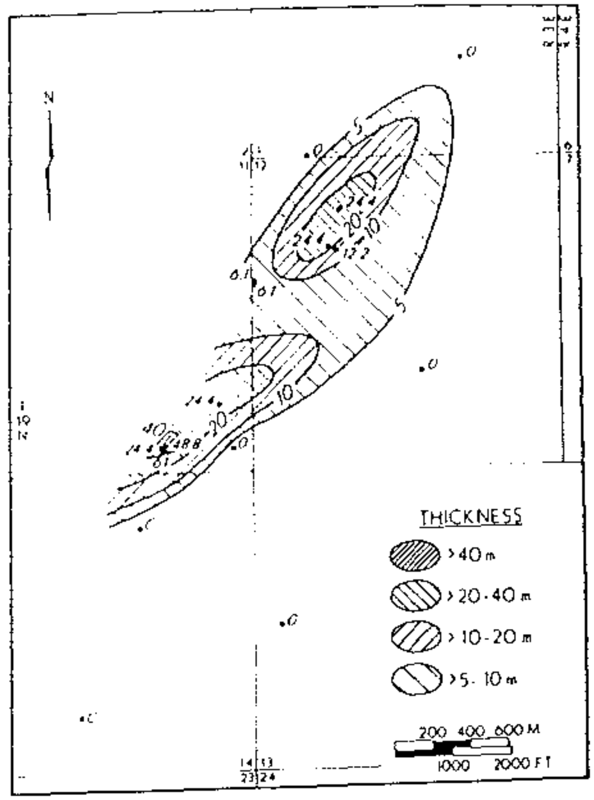

Fig 13

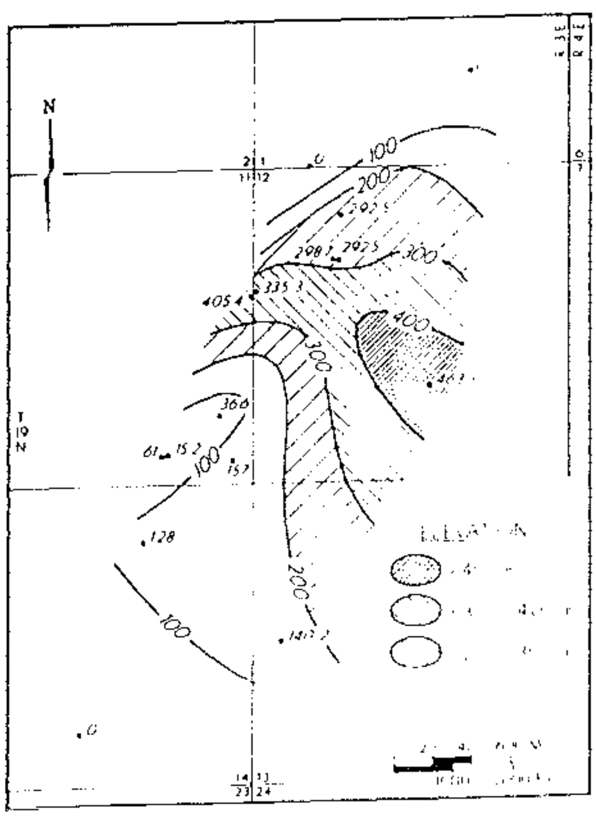

Fig 14

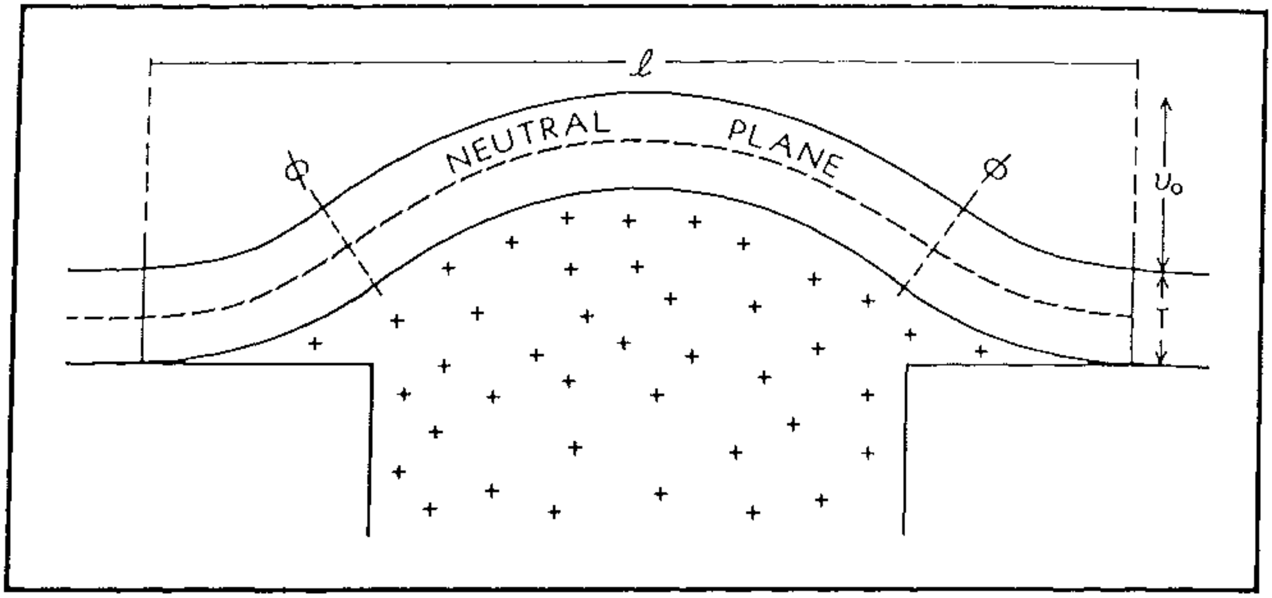

Fig 15

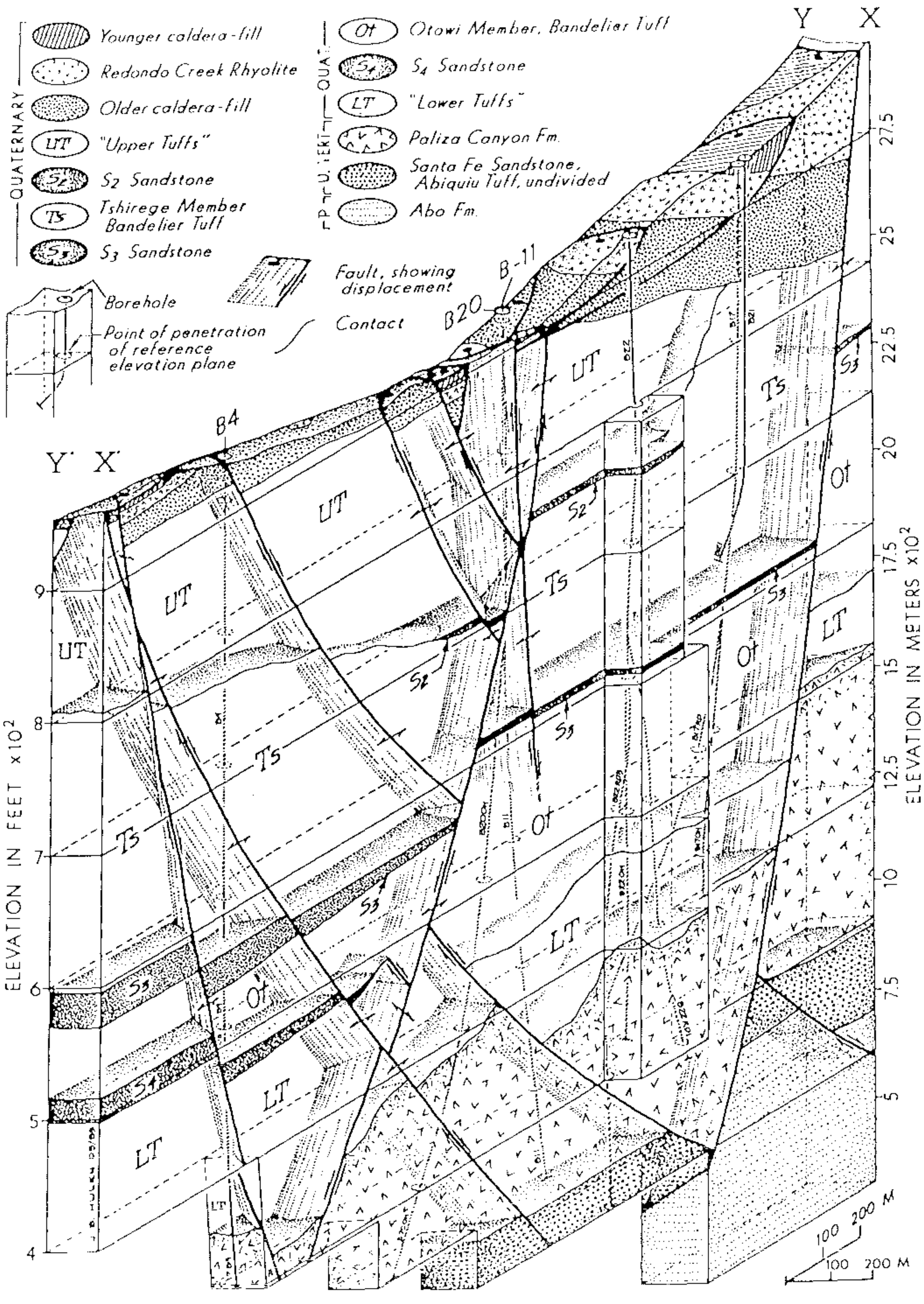
Y X
Y' X'
QUATERNARY
Younger caldera-fill
Redondo Creek Rhyolite
Older caldera-fill
"Upper Tuffs"
S2 Sandstone
Tshirege Member Bandelier Tuff
S3 Sandstone
Otowi Member, Bandelier Tuff
S4 Sandstone
"Lower Tuffs"
Paliza Canyon Fm.
Santa Fe Sandstone, Abiquiu Tuff, undivided
Abo Fm.
Borehole
Point of penetration of reference elevation plane
Fault, showing displacement
Contact
B-11
B20
B4
UT
Ts
Ot
LT
ELEVATION IN FEET x10²
ELEVATION IN METERS x10²
100 200 M
100 200 M

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	