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HYDROTHERMAL ALTERATION IN WELL BACA 22, BACA GEOTHERMAL AREA, VALLES CALDERA, NEW MEXICO

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January 1984

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price Code: A03

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Baca Geothermal Area, Valles Caldera,
New Mexico

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[*] This work was originally a Masters of Science thesis for the Department of Geology and Geophysics, University of California, Berkeley.

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Division of Engineering, Mathematics, and Geosciences, U. S. Department of Energy, under U. S. Department of Energy contract No. DE-AC03-76SF00098.

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Acknowledgements

The Union Oil Company of California, and the University of Utah Research Institute, generously provided drill cuttings. Steve Flexser critically read this report and suggested changes. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Division of Engineering, Mathematics, and Geosciences, U. S. Department of Energy, under U. S. Department of Energy Contract No. DE-AC03-76SF00098.

Hydrothermal Alteration in Well Baca 22, Baca Geothermal Area, Valles Caldera, New Mexico

Dennis James Fox

Introduction

The Baca geothermal area is located in the Valles caldera in the Jemez Mountains of north-central New Mexico. Union Geothermal Company drilled a number of exploration wells to supply steam for a proposed electric generating plant. Drill cuttings from one of these wells, Baca 22 (see Figure 1), were studied with a petrographic microscope and by x-ray diffraction to determine the nature of the original rocks and of the hydrothermal alteration. The hydrothermal alteration will be used to determine the temperatures of alteration which can then be compared with borehole temperatures to determine if the mineral assemblages are compatible with present day temperatures. It will be shown that there is evidence indicating that the upper 2000 feet of borehole is cooler now than it has been in the past.

Sample sizes were limited in this study (usually less than 5 grams). In most cases, one quarter of the sample was used to make the thin section while the remainder was reserved for x-ray analysis. Samples were mounted in epoxy and cut to a thickness of 30 microns for petrographic study. X-ray diffraction patterns were obtained using a Debye-Scherrer camera and Fekα radiation.

The Valles caldera is considered a promising area for geothermal development for several reasons. The recency, magnitude, and duration of volcanic activity in the Jemez Mountains combined with the surficial rock alteration and numerous hot springs and fumaroles all suggest a large heat source located at a shallow depth—presumably the same magma chamber which

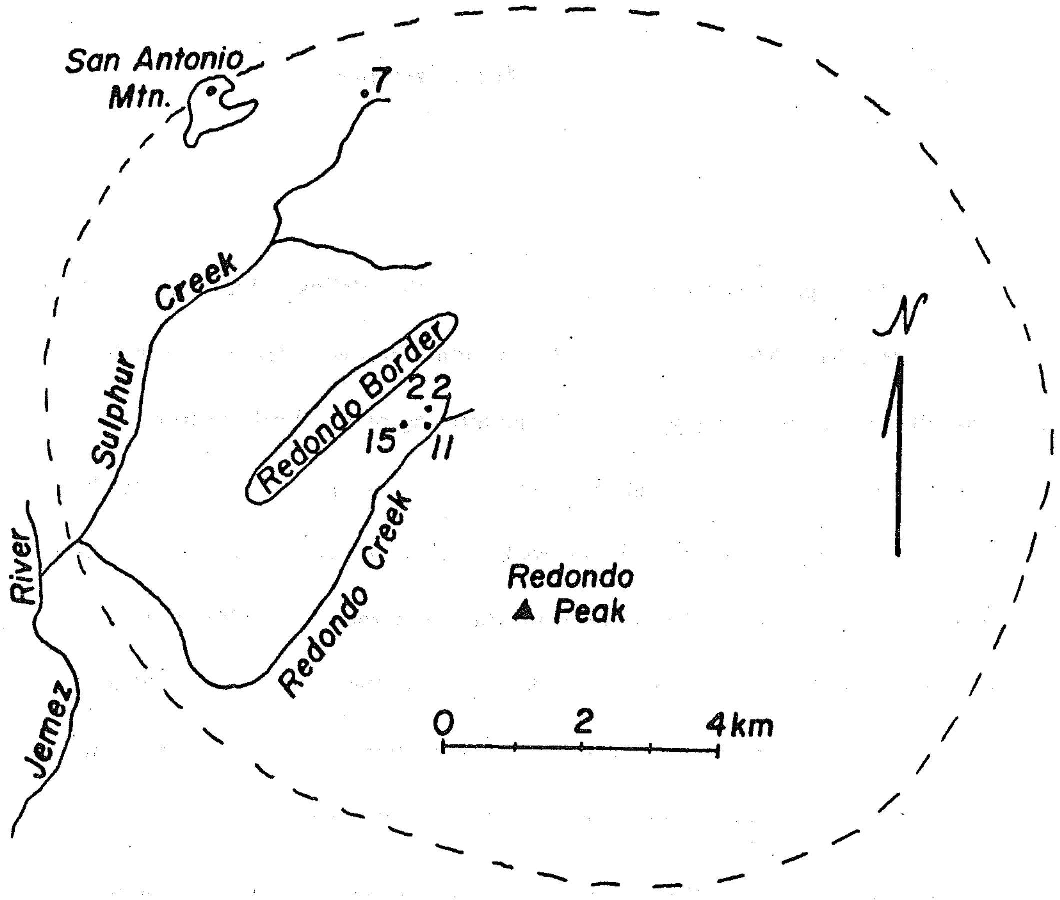

Figure 1. Location map. The location of four wells in the Baca geothermal area are shown. The broken circle indicates the approximate location of the ring fracture system of the latest caldera.

produced the voluminous volcanic rocks. Recent flow testing by Union Geothermal Company did not produce the large amounts of steam which were expected. Thus, this area has a low potential for generating electricity. However, low temperature geothermal resources are being investigated for use in space heating and Hot Dry Rock research is being conducted by the Los Alamos National Laboratory (Laughlin, 1981).

The Jemez Mountains are composed of late Miocene to Pleistocene volcanic rocks overlying older sedimentary rocks of the middle Miocene to upper Pliocene Santa Fe Group, the Abo Formation of Permian age, and the Carboniferous age Magdelina Group which rests on Precambrian granite. Volcanism began with the eruption of the Keres Group over 9 million years ago (m.y.a.) (Bailey et al., 1969). The Keres Group comprises the basalts of Chamisa Mesa, the Canovas Canyon Rhyolite, the Paliza Canyon Formation, and the Bearhead Rhyolite-Peralta Tuff Member. The basalts and rhyolites were erupted from numerous centers over a wide area. A thick sequence of andesite tuffs, flows, and breccias form coalesced composite cones overlying the earlier basaltic shields (Ross et al., 1961). Between 7.4 and 2.0 m.y.a. the Lobato Basalt, the Tshicoma Formation, and the El Rechuelos Rhyolite were erupted to form the Polvadera Group which overlies the andesites of the Keres Group (Bailey et al., 1969). The Tewa Group represents the latest stage of volcanism in the Jemez Mountains. This group is composed of the Bandelier Tuff, the Cerro Toledo Rhyolite, the Cerro Rubio Quartz Latite, and the Valles Rhyolite (Bailey et al., 1969). The volcanic rocks penetrated by Baca 22 are the Paliza Canyon Formation, the Bandelier Tuff, and the Valles Rhyolite.

The Toledo caldera, which is truncated by the north-east rim of the Valles caldera, was formed 1.4 m.y.a. during the eruption of the lower member (Otowi Member) of the Bandelier Tuff (Doell et al., 1968). The Valles caldera was formed during the eruption of the upper member (Tshirege Member) 1.1 m.y.a. (Doell et al., 1968). The Valles caldera was occupied by a lake soon after subsidence which persisted until near the end of the late rhyolite stage of volcanism (~0.5 m.y.a.). The lake was drained by headward erosion of the Jemez River and San Antonio Creek (Ross et al., 1961). The caldera floor was locally buried by more than 2000 feet of caldera fill before formation of a resurgent dome. Many of the post-caldera rhyolites erupted between 1.1 and 0.4 m.y.a. flowed into the lake (Doell et al., 1968). The source of these post-caldera lavas is presumed to be the same magma chamber which produced the Bandelier Tuff. Figure 2 shows a columnar section of Baca 22 and two adjacent wells.

Determination of Sample Depth and Temperature

Samples from Baca 22 were taken at 20 foot intervals with depth measured along the wellbore. The nature of the samples (drill cuttings) lends a measure of uncertainty to the results. At the time of sample collection no correction is made for travel time from bit to surface so a sample from a specified interval will not necessarily contain cuttings representing or exclusively from that entire interval.

Corrections to vertical depth can usually be accomplished with a dip-log which measures inclination within the wellbore. Dip-logs are available for Baca 22 for the original hole and the first two redrills but not for redrill 3 which was the source of all samples below 2700 feet for this study. The dip-log for the original hole (which was the source of all samples above 2700 feet) showed that a measured depth of 2528 feet corresponded to a vertical depth of 2523 feet. The error (5 feet) is less than the sample interval so it is considered negligible in this study. Errors within redrill 3 are not available so these depths are given as depth along wellbore.

Temperatures were obtained from a pressure/temperature gradient survey conducted in redrill 2. No temperature data are available below 5900 feet.

All of the photomicrographs shown in this paper have a sample number such as [1065A335]. "1065" is the U.C. Berkeley Geology Department collection number, "A" refers to Baca 22, and "335" refers to the depth interval of the sample. This number is obtained by

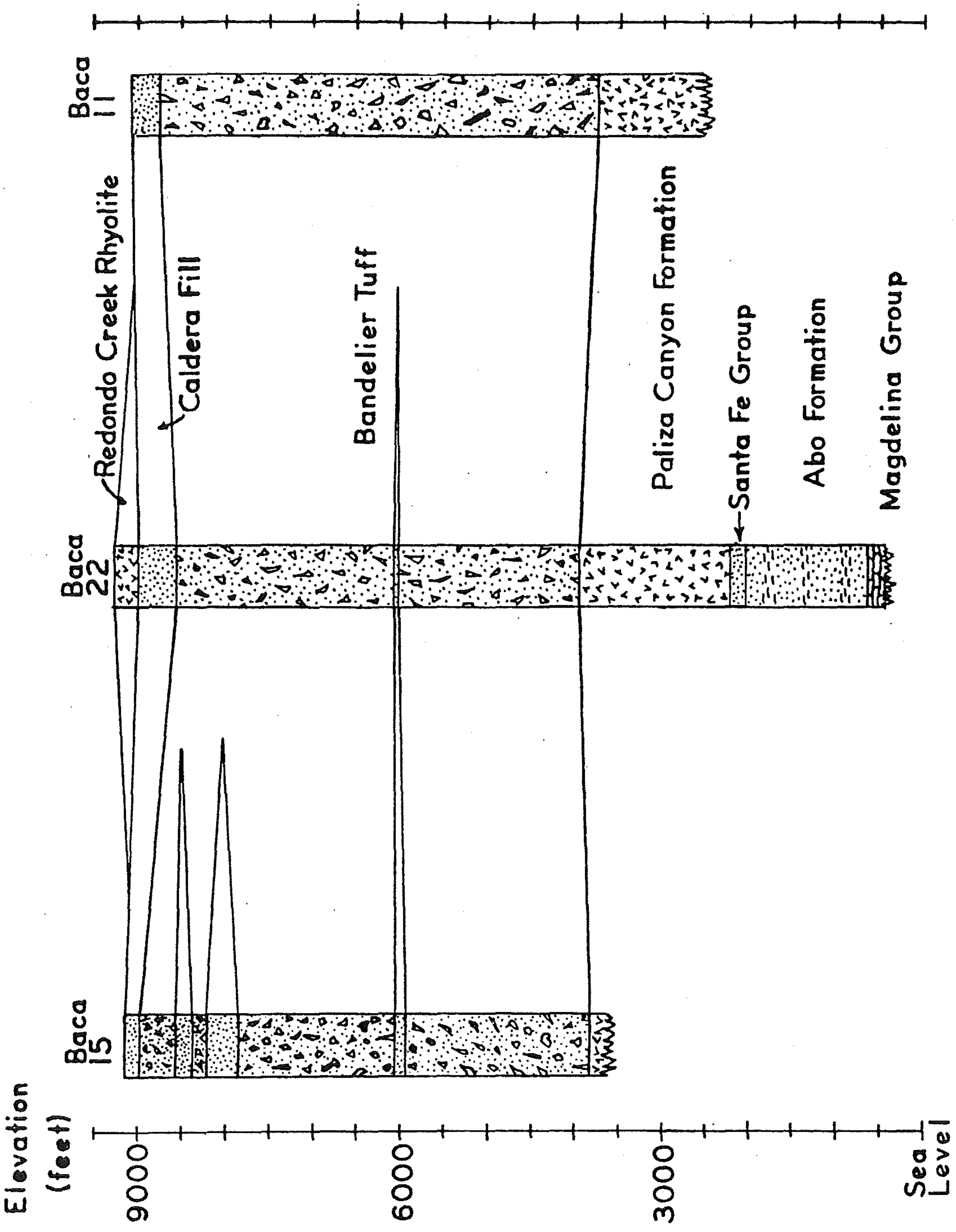

Figure 2. Baca 22 local stratigraphy. Columnar sections of Baca 22, Baca 15, and Baca 11 are shown here. Locations for these three wells are shown in Figure 1.

averaging the upper and lower limits of the sample interval and dividing the average by 10. Therefore, 335 would refer to the sample interval from 3340 to 3360 feet.

Petrographic and X-ray Analysis

Redondo Creek Rhyolite

The Redondo Creek Rhyolite is the uppermost unit penetrated by Baca 22. This 250 foot thick member of the Valles Rhyolite is readily distinguishable from all other members by the presence of plagioclase phenocrysts mantled with sanidine, large biotite phenocrysts, and by the absence of quartz phenocrysts (Bailey et al., 1969). The groundmass is primarily fresh clear glass with numerous areas of spherulitic devitrification which are most evident around phenocrysts. A typical sample of this rock is shown in Figure 3.

Alteration within the Redondo Creek Rhyolite is limited to about 1% of the glass and comprises opal and a green phyllosilicate. Smectite is thought to be the most likely composition of this phyllosilicate based on its color and depth of occurrence and on the composition of the original glass. The opal forms spheres similar to those described by Honda and Muffler (1970). As shown in Figure 4, the alteration is confined to fractures and the width of the zone is on the order of 50 microns. Orpiment and realgar were precipitated in trace amounts below 110 feet.

Caldera Fill

Below the Redondo Creek Rhyolite is Caldera Fill about 450 feet thick consisting of fine sand and silt sized particles of quartz, plagioclase, microcline, granitic rock fragments, and minor magnetite. Calcite cement is common and is accompanied by illite in the matrix of some samples. The illite was identified by x-ray diffraction and appears to be of both sedimentary and hydrothermal origin. The illite in the matrix shows no evidence of having grown in place

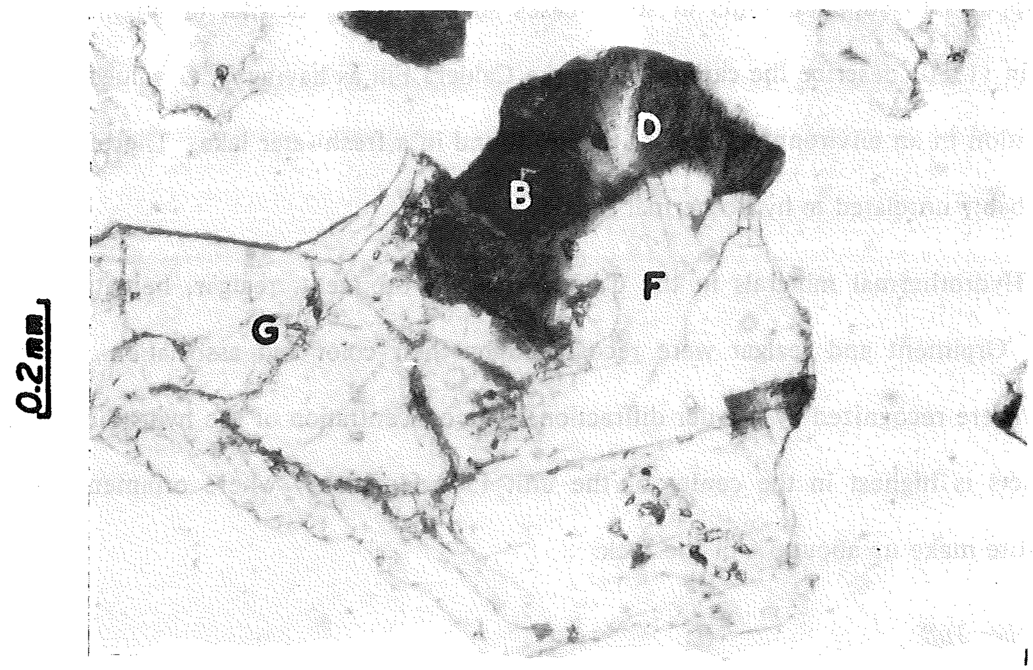

Figure 3. Redondo Creek Rhyolite. G-glass, B-biotite, D-devitrified glass, F-feldspar. Plane polarized light. [1065A010]

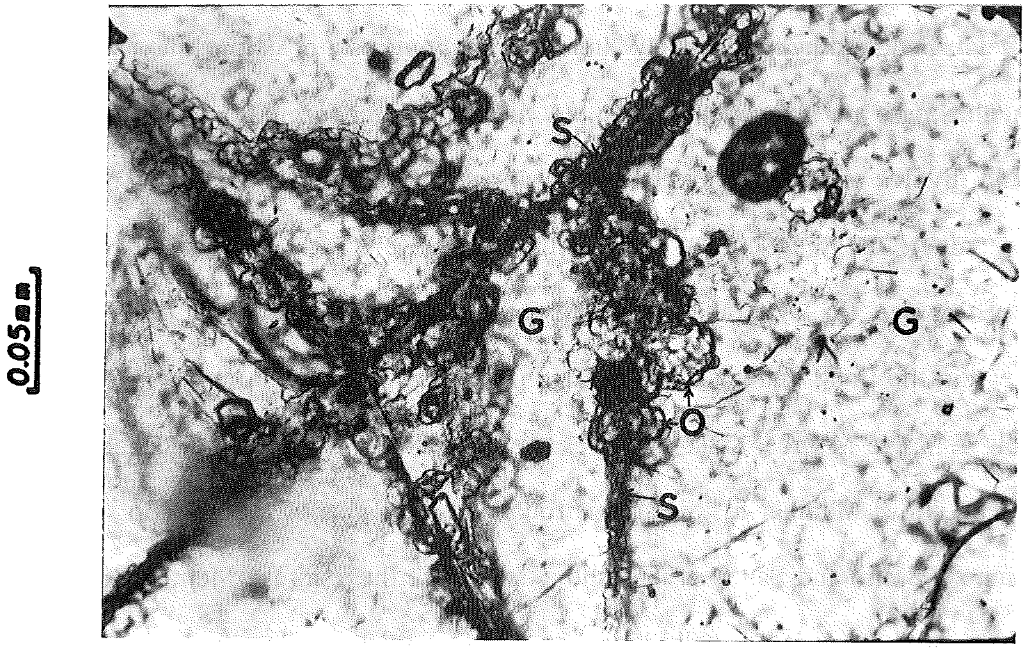

Figure 4. Opal and smectite in the Redondo Creek Rhyolite. The spherical alteration of the glass (G) is opal (O) and the darker alteration is smectite (S). Plane polarized light. [1065A010]

and appears to support grains in some cases so is probably detrital in origin. Lambert and Epstein (1980) describe the carbonates in the Caldera Fill as having $\delta^{18}O$ values which indicate deposition in an environment similar to that found in a freshwater lake. Therefore, the calcite is probably unrelated to hydrothermal activity.

Hydrothermal minerals in the Caldera Fill are orpiment, realgar, hematite, pyrite, and illite. Orpiment and realgar were recognized by their color and association. Hematite and pyrite were recognized by powder diffraction. The concentration of the hydrothermal alteration products is highest in the center of the unit (500 feet deep) where orpiment, realgar, and hematite make up about 3% of the rock.

Bandelier Tuff

Underlying the Caldera Fill is the Bandelier Tuff of rhyolite composition. The combined thickness of the two members is approximately 4700 feet in Baca 22. The tuff is densely welded, devitrified, and hydrothermally altered throughout most of its thickness. Ignimbrites of this great thickness are not widely known. A mechanism for forming a deposit of this magnitude would involve eruption of vast amounts of ash during the foundering of the roof of the magma chamber. Ponding of ash flows within the developing caldera could easily produce deposits of this size. Bailey et al. (1976) describe a similar thickness of ash flows (1000 to 1500 meters) within the Long Valley caldera in California. The bulk of the Bandelier Tuff in Baca 22 is probably Tshirege Member since it was erupted concurrent with the subsidence of the Valles caldera. The Otowi Member in this area is found on the flanks of the volcano so it should be much thinner. Smith and Bailey (1966) show that where the Tshirege Member is found on the flanks of the volcano, it is normally less than 600 feet thick and locally attains a thickness of 800 feet where it has filled in former valleys.

The primary minerals of the Bandelier Tuff are quartz, plagioclase, sanidine, pyroxene, minor magnetite, and minor lithic fragments. The anorthite content of the plagioclase was not determined due to the highly altered state of the phenocrysts. The pyroxene phenocrysts are totally replaced by chlorite, sphene, and epidote. Thin sections of the Tshirege Member borrowed from Fraser Goff of the Los Alamos National Laboratory contain pigeonite which exhibits the same crystal habit as the chlorite pseudomorphs in the Baca 22 samples. Smith and Bailey (1966) also noted hypersthene, fayalite, and anorthoclase at various levels in the Tshirege Member. Above 1400 feet the devitrified groundmass (probably containing cristobalite and alkali feldspar) retains its axiolitic and spherulitic texture. Below this point to a depth of 3000 feet the devitrified groundmass has been recrystallized to a clear featureless mosaic of fine-grained quartz and albite.

A layer of fine sandstone is located between 3190 and 3240 feet. The grains are made up of quartz, microcline, plagioclase, and sanidine. The sandstone is cemented by quartz overgrowths, calcite, and phyllosilicate. The sand is well sorted, subangular, well indurated and is mineralogically and texturally similar to the Caldera Fill.

Above and below the sandstone, between 3000 and 3400 feet, the rhyolite tuff is only partly (or locally) recrystallized as shown in Figure 5. The welding and devitrification textures are well preserved here although x-ray diffraction patterns indicate that some of the groundmass has been recrystallized to quartz and albite. Below 3400 feet the recrystallization texture appears again and continues throughout the remainder of the formation.

Hydrothermal alteration within the Bandelier Tuff has been quite extensive. In addition to the recrystallized groundmass discussed above, pyrite, illite, and hematite which were present in the Caldera Fill, continue into this formation. The hematite is not found below 1000 feet but pyrite continues to be present throughout the total depth of the hole with the exception of the interval between 2850 and 3150 feet. Calcite is commonly present as a replacement of plagioclase phenocrysts and groundmass. Illite replaces feldspar in minor (less than 5%) amounts throughout much of this formation.

Albitization of plagioclase begins at 700 feet and continues to the base of the Bandelier Tuff. A lower refractive index, higher birefringence, and a clouded appearance in plane light all make this replacement readily recognizable. Figure 6 shows a typical Bandelier Tuff plagioclase phenocryst which is partially albitized. The absence of polysynthetic twinning in the albite is

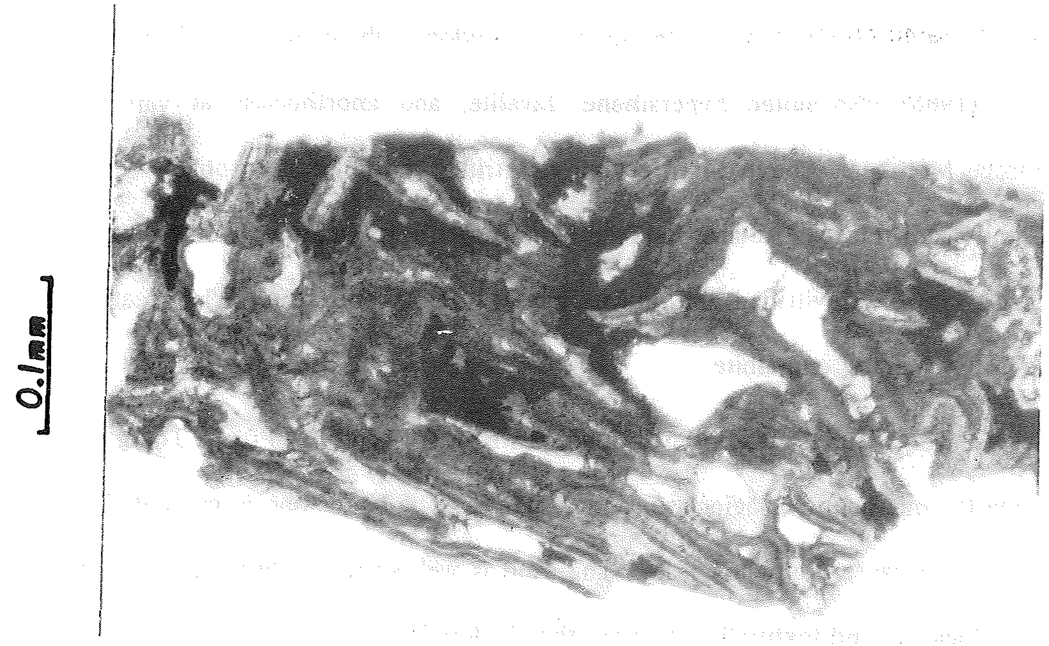

Figure 5. Welded-tuff texture in the Bandelier Tuff. This sample is from the interval between 3000 and 3400 feet where the groundmass has not been recrystallized. Plane polarized light. [1065A315]

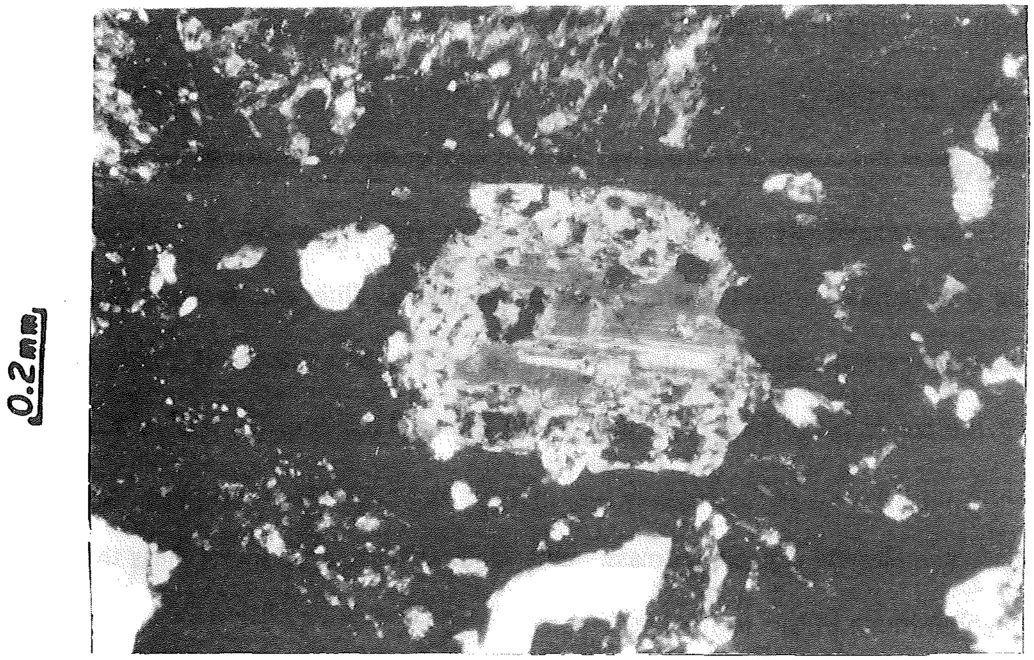

Figure 6. Albitized plagioclase in the Bandelier Tuff. This phenocryst of twinned plagioclase rimmed by untwinned albite demonstrates the loss of twinning and higher birefringence of the albitized plagioclase. Crossed nicols. [1065A075]

unusual in albitization of plagioclase. Usually, the twinning in the original phenocryst will continue into the albite. Twinning continues from the plagioclase into the replacement albite in only a few samples of the Bandelier Tuff. In these cases the albite is relatively clear and free of inclusions. The untwinned secondary albite is much cloudier and frequently contains inclusions. It is not known if this difference is caused by differing modes of albitization, differing temperatures, differences in original phenocryst composition, or some other factor.

In addition, albite begins to replace sanidine at a depth of 1300 feet. Figure 7 demonstrates that this albite is readily distinguishable from albitized plagioclase by the presence of chessboard-twinning (Callegari and De Pieri, 1967). As discussed above, albite and quartz occur as recrystallization products of the devitrified glass. This hydrothermal alteration gives the groundmass a finely crystalline texture in crossed nicols as shown in Figure 8. Although the recrystallization generally eliminates the devitrification texture, it does not completely remove the welded-tuff texture which can still be seen in plane light.

Chlorite first appears in the sample from 1100 feet. As shown in Figure 9, the most common habit of the chlorite is as pseudomorphs after pyroxene although it also occurs in the recrystallized groundmass. At depths in excess of 1700 feet, sphene occurs as numerous, brown, fine grained crystals grouped together into clusters. Epidote commonly occurs below 3400 feet with chlorite as prismatic crystals arranged in a radial pattern.

Paliza Canyon Formation

Three dacitic rocks in the 1300 foot thick Paliza Canyon Formation have been dated at 8.5, 8.8, and 9.1 million years old (Bailey et al., 1969). Andesite and dacite flows appear to be the dominant rock type in the Baca 22 samples. The mineralogy of the Paliza Canyon is dominated by zoned and twinned plagioclase with compositions determined by the Michel-Lévy technique of An_{24} to An_{55} with the most common anorthite content about An_{33}. Pyroxene is wholly altered throughout this formation. Magnetite is common and apatite can be found as small euhedral crystals.

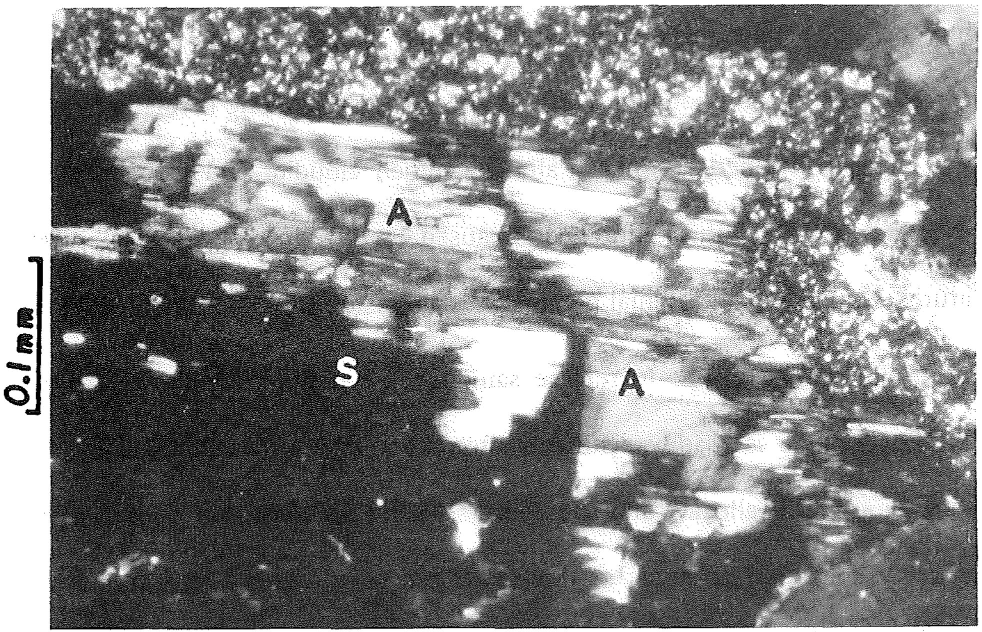

Figure 7. Albitized sanidine in the Bandelier Tuff. This photomicrograph shows the sanidine (S) being replaced by albite (A) which displays chessboard-twinning. Crossed nicols. [1065A381]

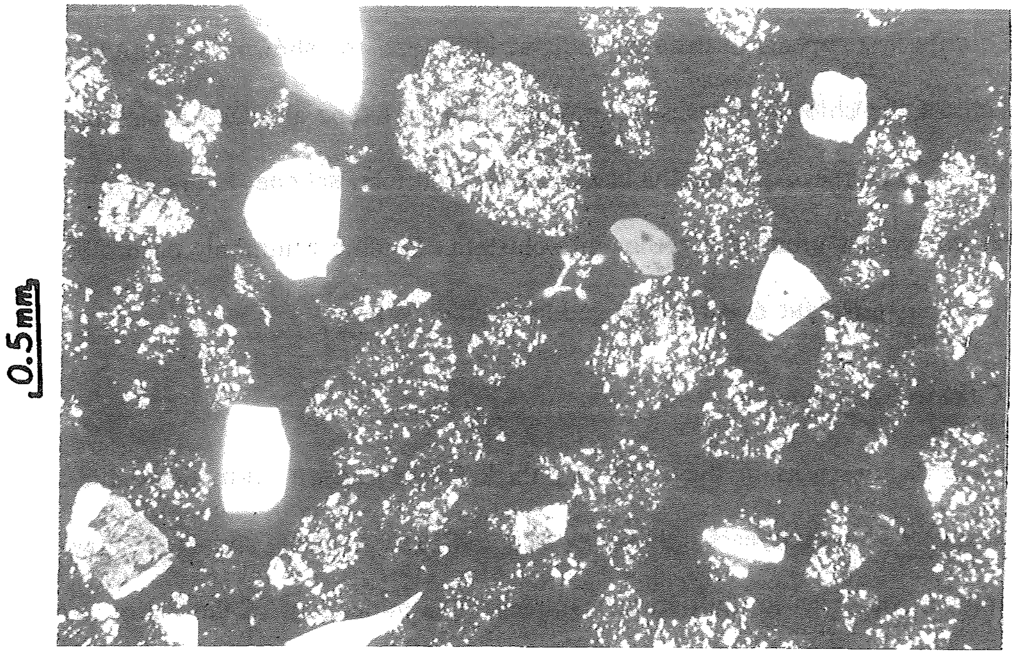

Figure 8. Recrystallized groundmass in the Bandelier Tuff. The groundmass is recrystallized to quartz and albite. Crossed nicols. [1065A533]

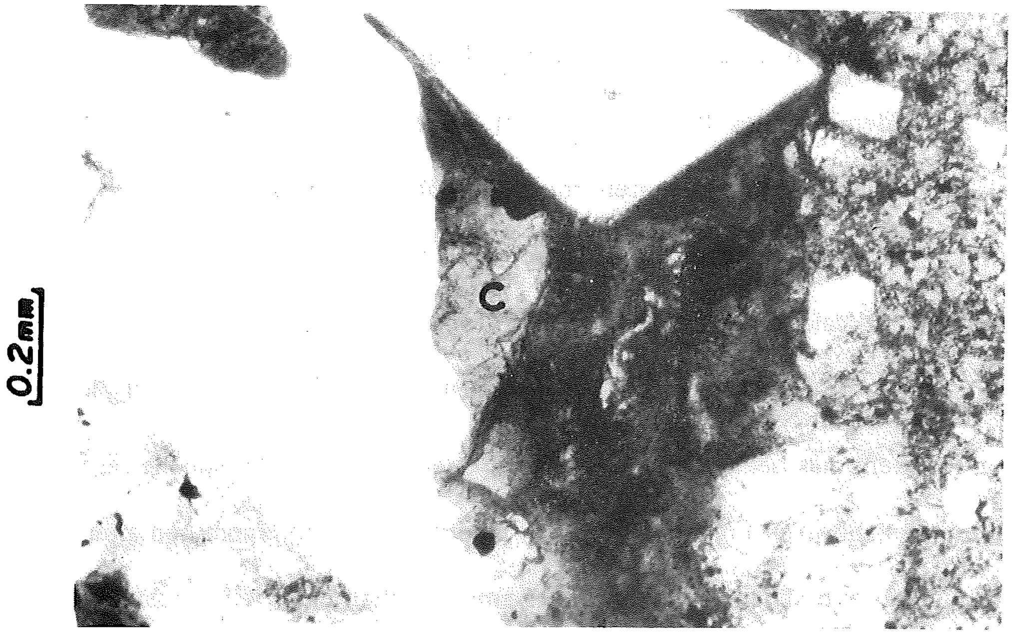

Figure 9. Chlorite after pyroxene in the Bandelier Tuff. This sample shows a pseudomorph of chlorite (C) after pyroxene. Plane polarized light. [1065A315]

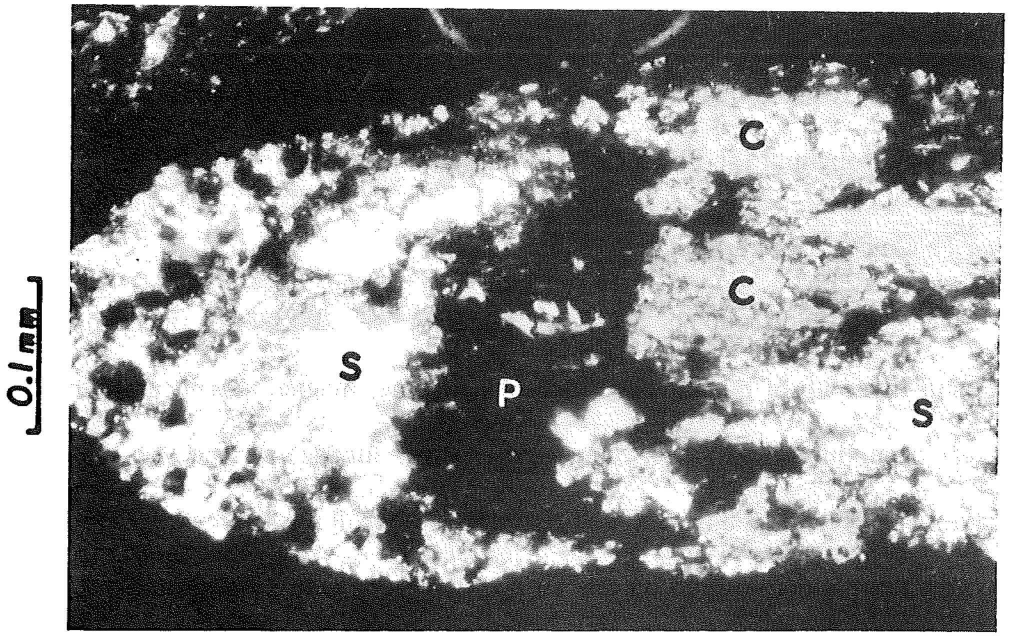

Figure 10. Calcite and sericite replacing plagioclase in the Paliza Canyon Formation. C-calcite, S-sericite, P-plagioclase. Crossed nicols. [1065A573]

Hydrothermal alteration in the Paliza Canyon includes sericite which is an extensive alteration product of plagioclase replacing half or more of some phenocrysts in many samples. Figure 10 demonstrates the large size of some of the sericite crystals. Calcite commonly replaces plagioclase although rarely more than about 15% of a phenocryst. Epidote is another common alteration product of plagioclase but in most samples its abundance is minor compared to sericite and calcite. However, a sample from 6270 feet (Figure 11) is unusual in that it contains much more epidote than sericite and calcite as alteration products of plagioclase.

Pyroxene has been completely altered to chlorite, epidote, sphene, and quartz in this formation. As shown in Figures 12 and 13, chlorite is the more common alteration product. Epidote, quartz, and sphene occur in lesser amounts than chlorite in most cases. Figure 14 illustrates that some of the chlorite replacements (after hypersthene?) are rimmed by quartz.

Much of the groundmass of the Paliza Canyon Formation has the same appearance as the recrystallized groundmass in the Bandelier Tuff. X-ray diffraction and oil immersion has shown this groundmass to be quartz and albite. Sphene clusters are common and pyrite continues to be present throughout the Paliza Canyon Formation.

Santa Fe Group

The Santa Fe Group, of Miocene age, comprises 200 feet of unconsolidated, well sorted fine sand made up of quartz, plagioclase, microcline, magnetite, and perthite. The quartz and feldspar occur in two varieties. One type is clear, subangular, and was probably deposited by stream. The second type is very well rounded, has small pits (percussion marks) in the surface, and has a faint hematite stain on the surface suggesting eolian transport.

Hydrothermal alteration is slight in these sediments. A minor amount of sericite (less than 1%) is seen in some of the plagioclase grains. Pyrite is present in trace amounts and epidote is found as small isolated crystals.

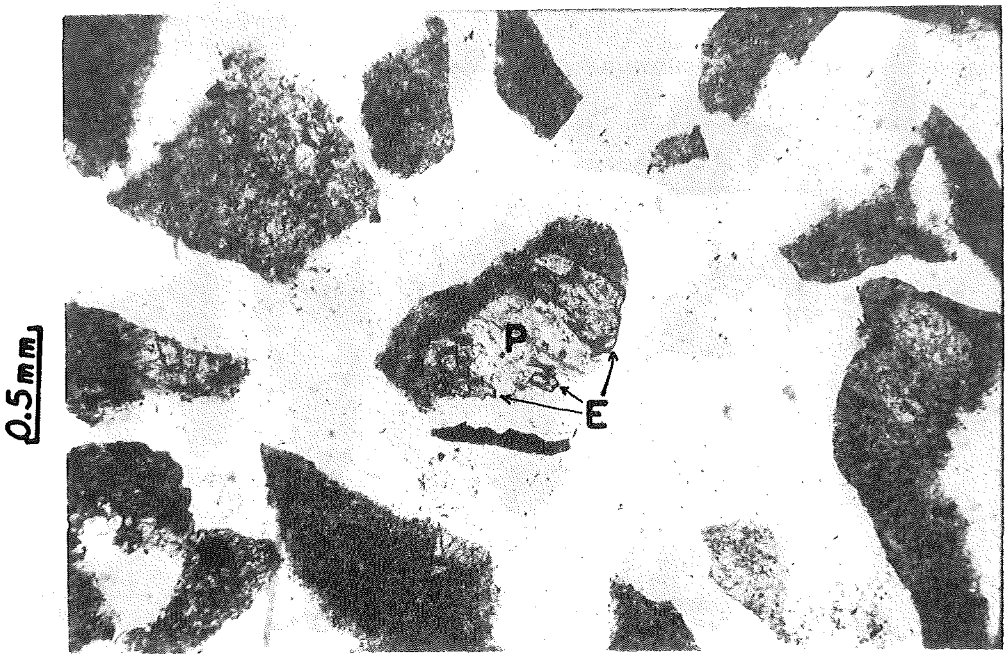

Figure 11. Epidote replacing plagioclase in the Paliza Canyon Formation. E-epidote, P-plagioclase. Plane polarized light. [1065A627]

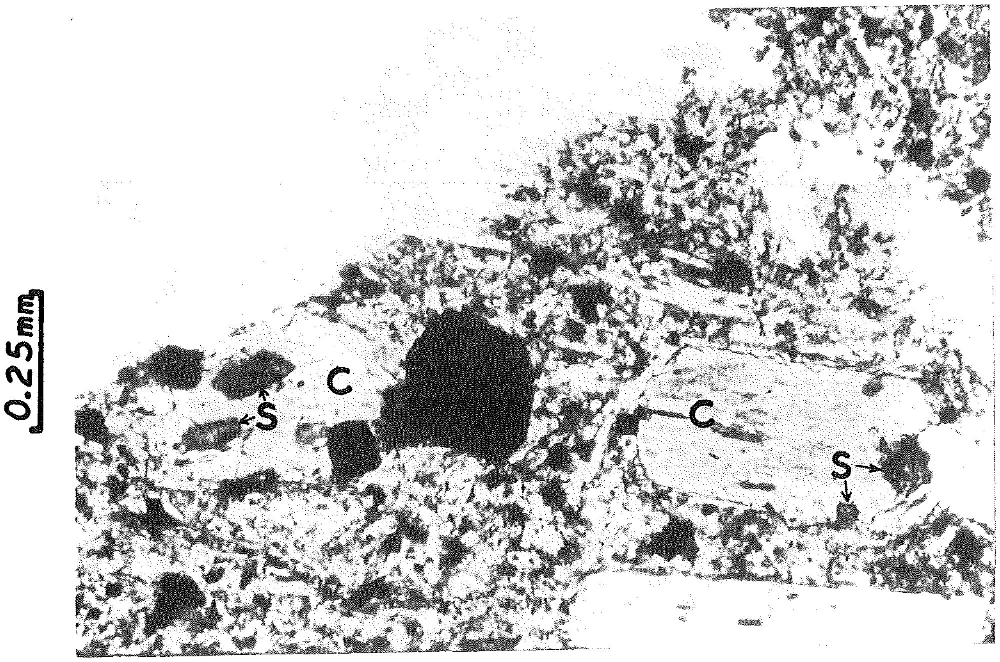

Figure 12. Chlorite and sphene after pyroxene in the Paliza Canyon Formation. S-sphene, C-chlorite. Plane polarized light. [1065A591]

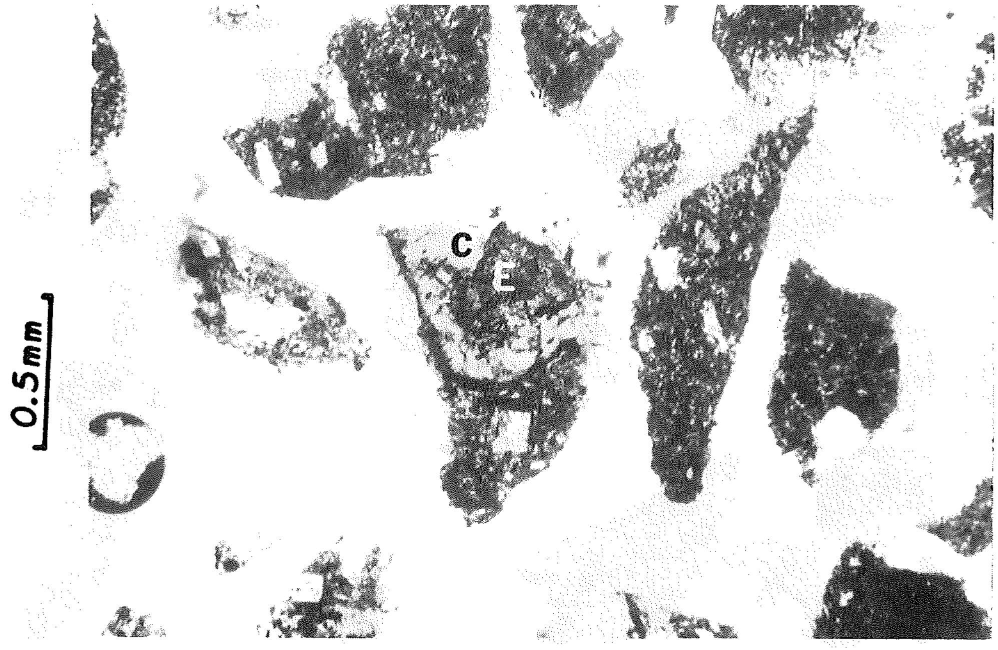

Figure 13. Chlorite and epidote after pyroxene in the Paliza Canyon Formation. C-chlorite, E-epidote. Plane polarized light. [1065A591]

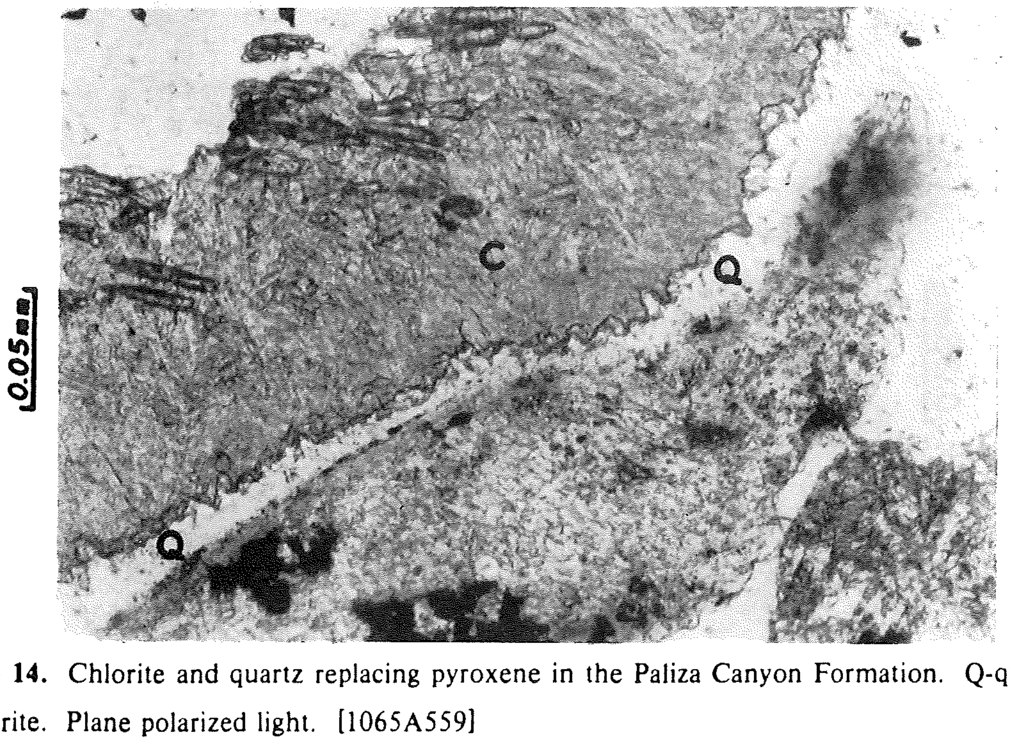

Figure 14. Chlorite and quartz replacing pyroxene in the Paliza Canyon Formation. Q-quartz, C-chlorite. Plane polarized light. [1065A559]

Abo Formation

The 1300(?) foot thick Abo Formation comprises calcite, epidote, and hematite cemented fine grained sandstones and siltstones of Permian age. The sand consists of subangular to subrounded well sorted quartz and feldspar grains. Hydrothermal alteration includes sericite replacing plagioclase in trace amounts and precipitation of minute subhedral to anhedral pyrite crystals and subhedral epidote crystals in the interstitial pore spaces.

Magdelina Group

One sample from the Magdelina Group has been studied. It comprises red argillite, brown mudstone with silt-sized quartz grains, and dense micritic limestone. Hydrothermal alteration has recrystallized some of the micrite to sparite and formed the zeolite wairakite.

Patterns of Hydrothermal Alteration

Opal and Green Phyllosilicate

Hydrothermal alteration of glass in the Redondo Creek Rhyolite is confined to fractures in the glass (see Figure 4). Alteration products comprise opal and a green phyllosilicate of undetermined composition, possibly smectite.

Sulfides and Oxides

Three sulfides and one oxide were precipitated in the rocks penetrated by Baca 22. Pyrite is found throughout the Baca 22 samples below 600 feet except for the interval between 2850 and 3150 feet. The pyrite occurs as minute cubic crystals (usually less than 0.5 mm) which are disseminated throughout the samples and exhibit no systematic relationship to any other mineral. Lambert and Epstein (1980) describe the occurrence of pyrite in Baca 7 below 3710 feet. Orpiment and realgar are two sulfides which are restricted to the upper portion of the well between 200 and 700 feet where they appear to have been precipitated in pores. Hematite was precipitated in pore spaces in the Caldera Fill and Bandelier Tuff between depths of 400 and 900 feet.

Illite and Sericite

Illite was detected with x-ray diffraction in the Caldera Fill and is visible in thin sections of the Caldera Fill and Bandelier Tuff. The illite in the Caldera Fill appears to be of sedimentary and hydrothermal origin. Hydrothermal illite has replaced feldspar grains which were present in the sandstones and siltstones. In the Bandelier Tuff the illite is most evident in the replacement of feldspar phenocrysts (see Figure 15) but is also present in minor amounts in the groundmass. Lambert and Epstein (1980) found kaolinite in the groundmass of Baca 7 but none was detected here.

A clear birefringent phyllosilicate occurs as a replacement of plagioclase in the Paliza Canyon Formation. The 2V was determined to be 32° using the method of Tobi (1956) which indicates that this mica is sericite (muscovite) as opposed to pyrophyllite (2V=53-60°) or illite (small 2V). Figure 10 shows the large crystal of sericite on which the axial angle measurement was made and illustrates the common association of sericite with calcite in the alteration of plagioclase.

It is not known at what point the illite grades into sericite or what structural types of muscovite these two minerals represent. Yoder and Eugster (1955) describe the range of compositions and structure types which are encompassed by these two mineral names.

Albite

Albite is formed from three different materials in the Baca 22 samples. Below 1300 feet the devitrified groundmass is altered from the original cristobalite and alkali feldspar to quartz, albite, and minor illite. The groundmass changes from the faintly birefringent dusty looking devitrified glass to a finely crystalline moderately birefringent clear aggregate of anhedral crys-

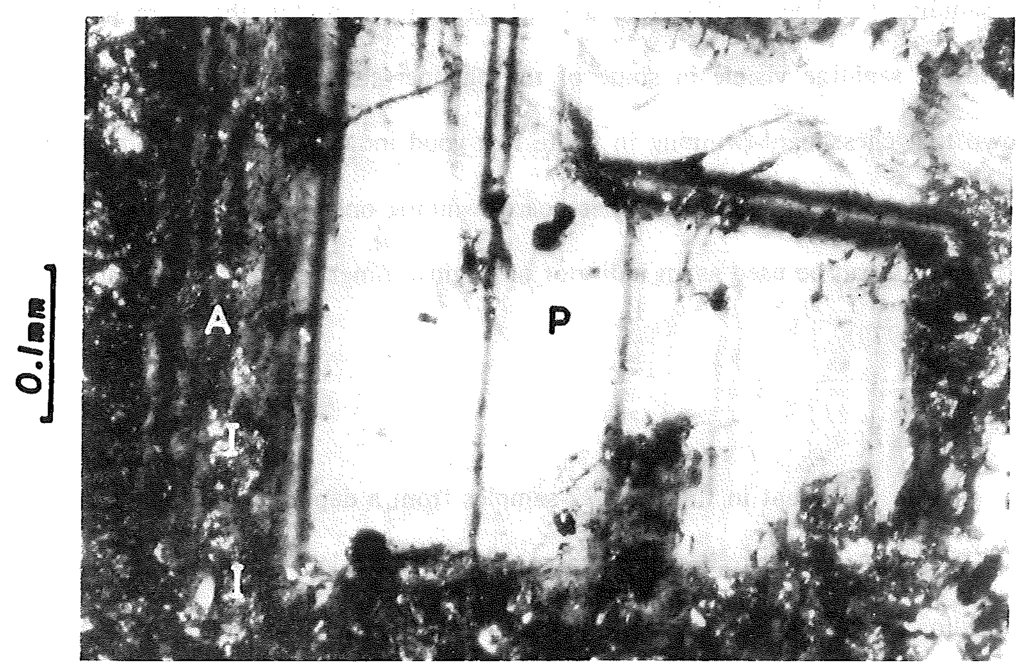

Figure 15. Illite replacing plagioclase in the Bandelier Tuff. The edges of this plagioclase phenocryst have been albitized and altered to illite. The albite retains the twinning present in the original phenocryst. A-albite, I-illite, P-plagioclase. Crossed nicols. [1065A089]

tals. This recrystallization does not disturb the welded-tuff texture or the glass shard outlines which can still be seen in the drill cuttings but it does eliminate the devitrification texture. Albitized plagioclase is first seen at 700 feet and is progressively farther advanced as one looks at deeper samples from the Bandelier Tuff.

Chessboard-twinned albite occurs as a replacement of sanidine in the Bandelier Tuff. Albite replaces sanidine below 1300 feet where some sanidine phenocrysts appear to be untouched and others appear to be completely replaced. Near the base of the Bandelier Tuff the sanidine has been replaced to a much greater extent but there are usually a few small patches of sanidine visible in some of the phenocrysts. Callegari and De Pieri (1967) have shown that chessboard-twinning in albite is a good indicator that the albite is more than 98% pure. It has been observed that chessboard-twinning only occurs in albite when it replaces K-feldspar so it can be used as an indicator of original mineralogy in a highly altered rock (Moore and Liou, 1979).

Calcite

Calcite is present in the Baca 22 samples from a depth of 300 feet to the bottom of the hole. Some of this calcite is sedimentary in origin (the calcite cement in the sandstones and the Magdelina Group limestones) while some is the product of hydrothermal activity. Hydrothermal calcite is found as a pore filling mineral and in the replacment of the groundmass and of plagioclase. Calcite is associated with albite, sphene, sericite, and illite as a replacement of plagioclase.

Quartz

Quartz formed by recrystallization under hydrothermal conditions was recognised through x-ray diffraction in the Paliza Canyon Formation and the Bandelier Tuff. The quartz occurs as an alteration product when the groundmass of these formations is recrystallized. Recrystallization takes place between 1300 and 6850 feet. Quartz also occurs with chlorite in the alteration of hypersthene.

Chlorite

Chlorite is found in most samples below 1100 feet as an alteration product of pyroxene and in minor amounts as a groundmass alteration. X-ray powder diffraction has yielded 001 and 002 reflections of 14.15å and 7.08å respectively. Optically, the chlorite occurs as fibrous radiating crystals with anomalous blue and green birefringence. The alteration of pyroxene to chlorite appears to involve little or no volume change. Both clino- and orthopyroxenes were altered to chlorite since both types of pyroxene were present in the Bandelier Tuff (discussed earlier) and the Paliza Canyon Formation. Two thin sections of fresh Paliza Canyon rocks on loan from the Los Alamos National Laboratory contain both clino- and orthopyroxenes. Unpublished microprobe data obtained from Jamie Gardner, a Ph. D. candidate at U. C. Davis, indicates that the pyroxene compositions within the Paliza Canyon Formation remain constant throughout all of the flows. These compositions are augite ($Ca_{45}Mg_{45}Fe_{10}$) and hypersthene ($Mg_{75}Fe_{25}$).

Sphene

Sphene occurs in the Bandelier Tuff (below 1500 feet) in and the Paliza Canyon Formation as minute brown anhedral crystals grouped into clusters. These clusters appear to form anywhere within the rock outside of the sanidine and quartz phenocrysts. The sphene is recognised by its very high relief which causes it to look white in reflected light, by its high birefringence, and by rare euhedra.

Epidote

Epidote first occurs in the Baca 22 samples below 3400 feet, primarily as a replacment of plagioclase and pyroxene. The epidote crystals occur in two habits. In the more common habit, the epidote occurs as prismatic to anhedral crystals in radial or aggregate form. More rarely, the epidote occurs as acicular crystals arranged in a radial pattern. Many of the larger crystals are zoned from a pleochroic yellow center to a colorless border. Figure 16 shows that epidote also occurs as a pore filling mineral in the Abo Formation.

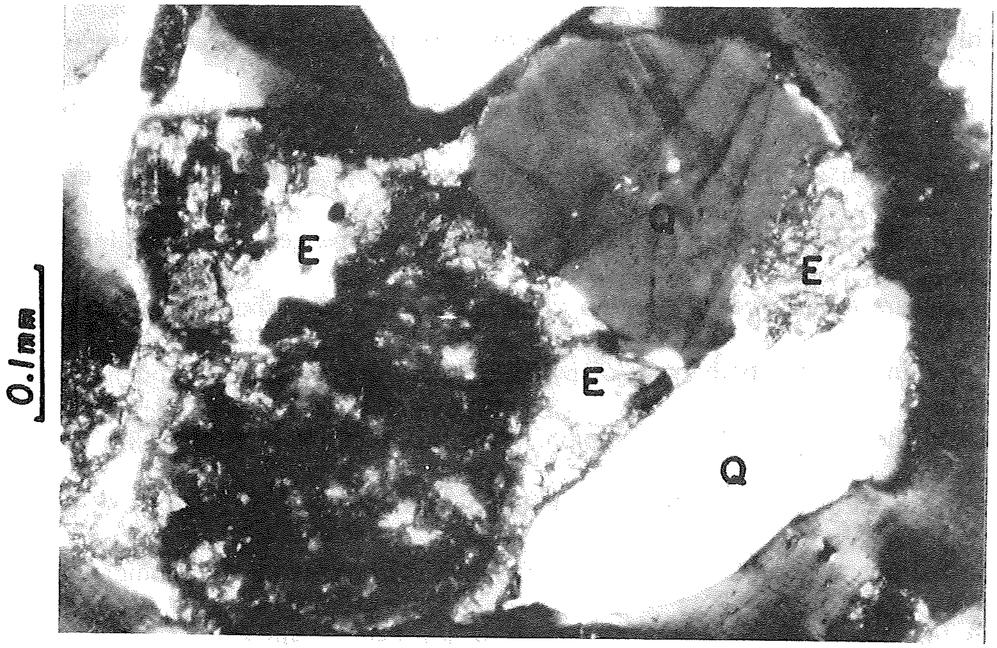

Figure 16. Epidote cement in the Abo Formation. The epidote appears to form a cement between the detrital grains. E-epidote, Q-quartz. Crossed nicols. [1065A817]

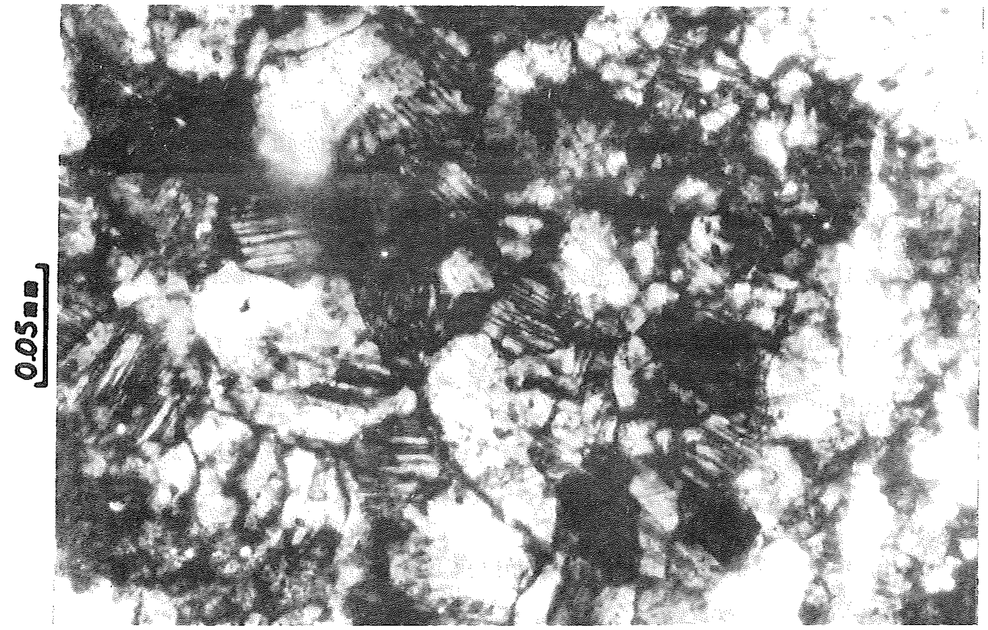

Figure 17. Wairakite in the Magdelina Group. The low birefringence and polysynthetic twinning make this zeolite easily recognizable. Crossed nicols. [1065A867]

Wairakite

Coarse-grained (0.35 mm) crystals of wairakite were seen in the one sample available from the Magdelina Group. The crystals occur in groups and were identified by their low birefringence and polysynthetic twinning (see Figure 17). The wairakite has formed primarily in the mudstone and to a lesser extent in the limestone.

Discussion of Alteration Conditions

Figure 18 shows the relationships of the different alteration products with each other, with lithology, and with depth along wellbore. There are minerals which appear only in specific lithologic types and minerals which occur independent of lithology. Orpiment, realgar, hematite, sericite, illite, pyrite, calcite, and epidote all seem to occur independent of lithology. Minerals which appear to be related to lithology include smectite and opal which occur only in the Redondo Creek Rhyolite. Cristobalite is a devitrification product in the Redondo Creek Rhyolite and the Bandelier Tuff. Chlorite and sphene occur only in the Bandelier Tuff and Paliza Canyon Formation. Hydrothermal quartz and albite were found primarily in the Bandelier Tuff and Paliza Canyon Formation where glass, devitrified glass, or fine grained groundmass was available for alteration.

Clays are relatively rare in the upper portion of this drillhole which contrasts with other hydrothermal areas such as Ohaki-Broadlands (Browne and Ellis, 1970), Wairakei (Steiner, 1977), and Yellowstone (Keith et al., 1978). The only clays detected in Baca 22 were the limited amounts of possible smectite in the Redondo Creek Rhyolite, the illite in the Caldera Fill and Bandelier Tuff, and the chlorite which is present in the deeper portions of the well.

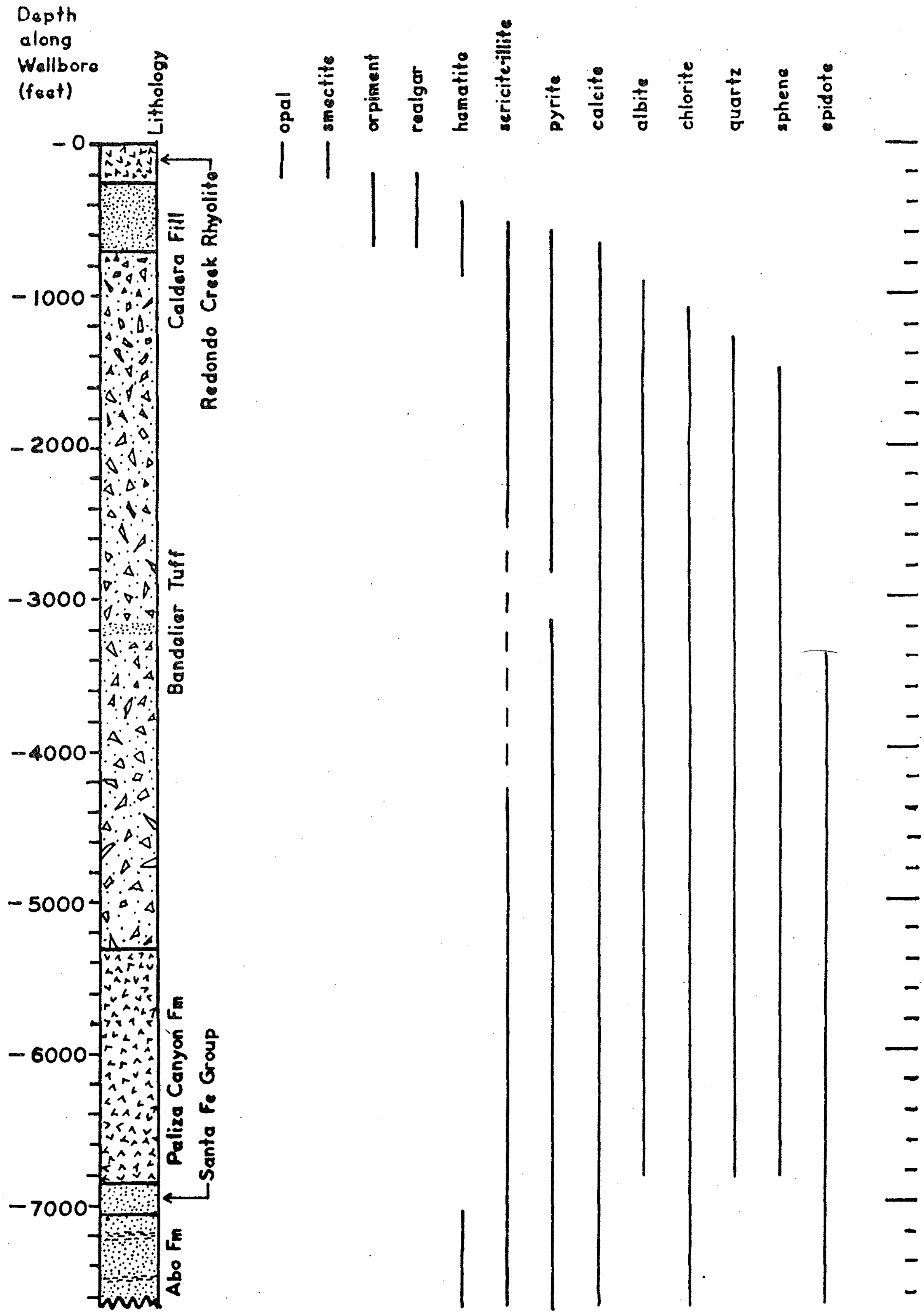

Figure 18. Occurrence of hydrothermal alteration minerals in Baca 22.

Two minerals in Baca 22 occur at temperatures significantly lower than is seen in other hydrothermal areas. These minerals are albite and chlorite.

Albite first occurs at a depth of 700 feet where the temperature is presently 75°C. Browne and Ellis (1970) noted that albite was first formed at temperatures near 120°C at Ohaki-Broadlands which is in agreement with temperatures reported by Iijima and Utada (1971) and Iijima (1975).

Chlorite generally forms at temperatures in excess of 120°C (Sigvaldason and White, 1962), (Honda and Muffler, 1970), (Keith et al., 1978), and (Cavarretta et al., 1982). In Baca 22 chlorite is seen at depths where the temperature is 100°C.

Figure 19 gives the downhole pressures and temperatures from Baca 22 redrill 2 which demonstrate the relationship between the water table depth and the temperature gradients due to the higher thermal conductivity of saturated rocks (Garg and Kassoy, 1981) and convection of fluids within the rocks. Until about 0.5 m.y.a. the Valles caldera contained a lake, below which the rocks were saturated. The presence of this water in the hydrothermal system may well have increased temperatures above the present water table so that the present placement of alteration minerals was more in keeping with other hydrothermal areas. The lowering of the water table to its present position would have lowered the conductivity and temperature of those rocks above the water table.

Another possibility explaining the occurrence of albite and chlorite at such low temperatures is given in Doell et al. (1968) who suggested that the caldera floor was buried by more than 2000 feet of caldera fill before the formation of the resurgent dome. This extra overburden, since thinned by erosion, may have insulated the rocks sufficiently to raise temperatures to the necessary levels to form albite and chlorite where we see them today. The formation of the resurgent dome also may have provided heat for the temperature increase.

Wairakite occurs in one sample near 8400 feet. Lambert and Epstein (1980) describe the initial occurrence of wairakite in Baca 7 at 4660 feet. The great difference in depth of occurrence can be attributed to the depth of the Magdelina Group rocks. The wairakite seen in

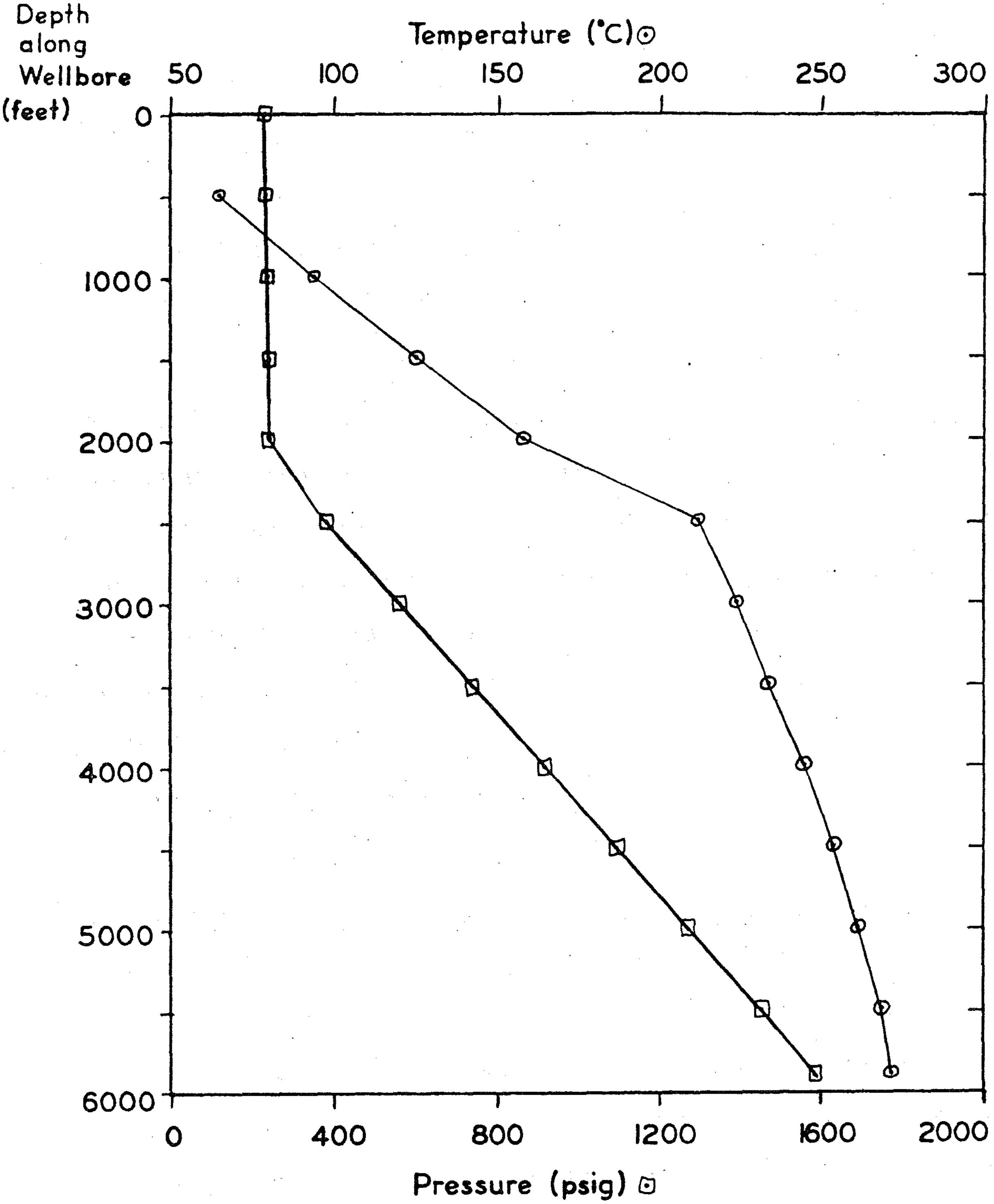

Figure 19. Temperature and pressure in Baca 22.

Baca 22 occurs within the Magdelina Group and the wairakite seen in Baca 7 occurs a short distance above the Magdelina Group.

With the exception of wairakite, zeolites are absent in the Baca 22 cuttings. This may be related to the cooling history of the Bandelier Tuff. Most of the tuff devitrified soon after emplacement and zeolites are not known to form from devitrified silicic glass.

Conclusions

1. The following minerals were formed in hydrothermal alteration of volcanic rocks: calcite, illite, quartz, chlorite, albite, epidote, sphene, opal, smectite, pyrite, orpiment, realgar, hematite, and sericite. Hydrothermal minerals formed in the sedimentary rocks are: calcite, illite, quartz, epidote, pyrite, orpiment, realgar, hematite, sericite, and wairakite.
2. Textural detail is lost in hydrothermal alteration of welded-tuff below a depth of 1400 feet.
3. Albite and chlorite are found at temperatures lower than usual for their formation in hydrothermal areas.
4. The draining of a lake in the caldera ~0.5 m.y.a. dropped the water table 2000 feet and consequently lowered the conductivity and the temperatures in the rocks above the present water table.
5. Albitization of sanidine and plagioclase phenocrysts is pervasive in the Bandelier Tuff but is absent in the Paliza Canyon Formation. The albitization of plagioclase is unusual here in that the polysynthetic twinning present in the original phenocryst is not retained in the pseudomorphic albite.

6. The Bandelier Tuff devitrified soon after emplacement which may account for the lack of hydrothermal zeolites such as are commonly found elsewhere in hydrothermal alteration of rhyolites.

7. Alteration reactions such as feldspar to illite; plagioclase to sericite, sphene, calcite, albite, and epidote; and sanidine to albite have not yet gone to completion.

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