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

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ABSTRACT

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

INTRODUCTION

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

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

GEOLOGIC SETTING

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

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

METHODS AND PROCEDURES

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

Samples from the high-level clay alteration

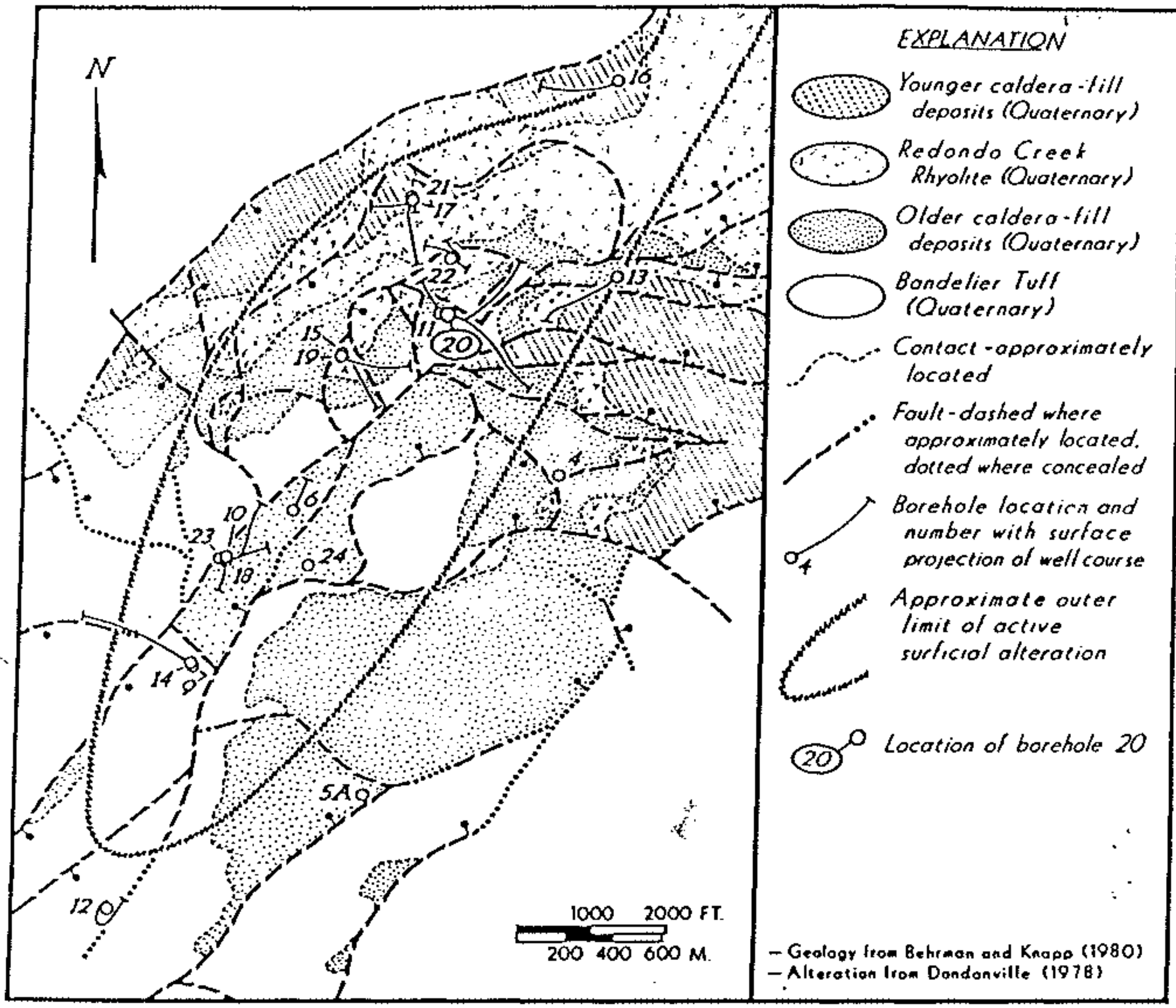

Figure 1. Geologic map of the Redondo Creek area, showing the location of Union Oil Company boreholes, including No. 20, the subject of this study.

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

STRATIGRAPHY

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

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

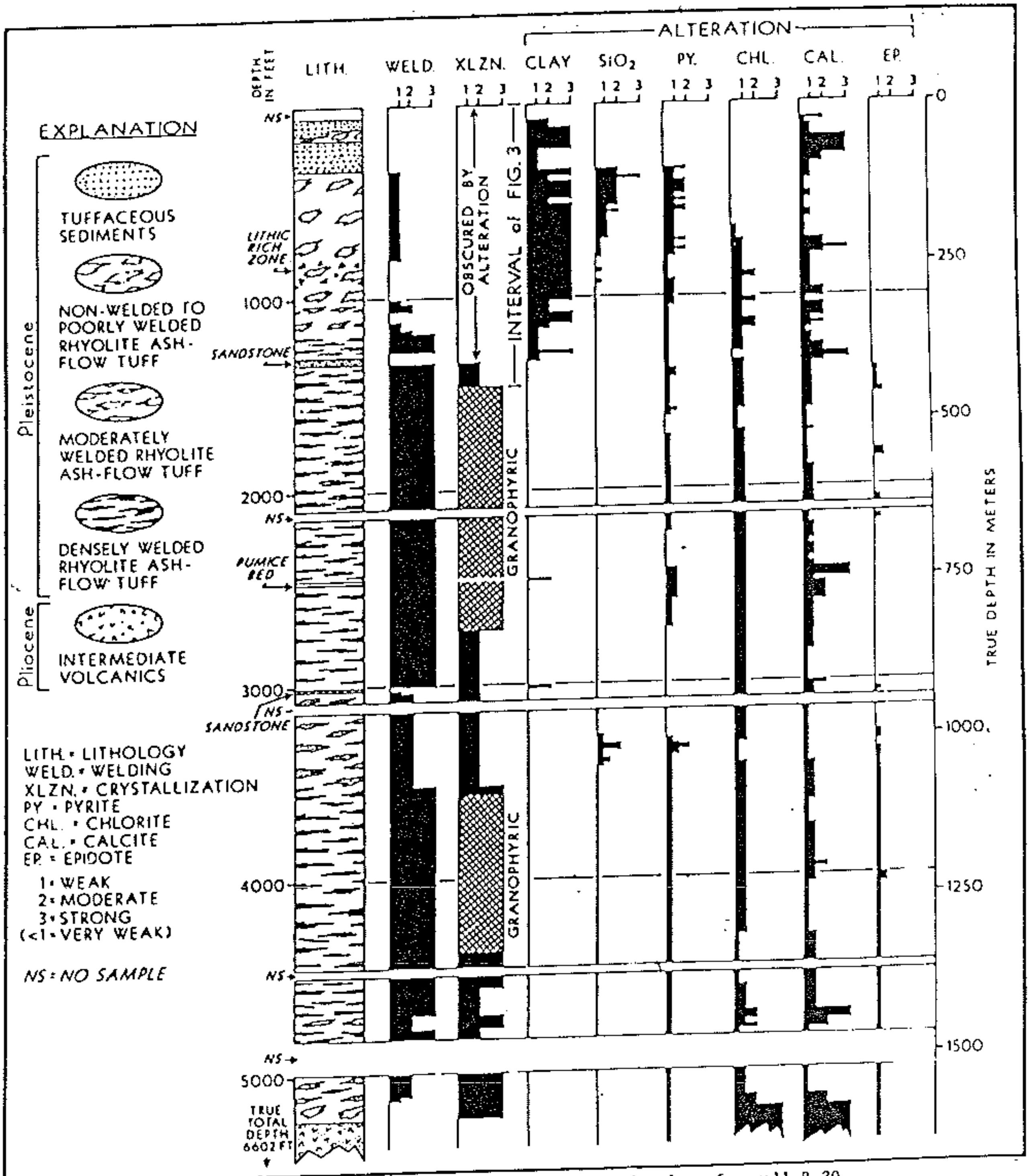

Figure 2. Generalized lithologic and hydrothermal alteration logs for well B-20.

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

The lower (Otowi) interval, from 3018 ft to

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

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

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

HYDROTHERMAL ALTERATION

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

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

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

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

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

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

DISCUSSION AND CONCLUSIONS

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

High level intense clay alteration in B-20

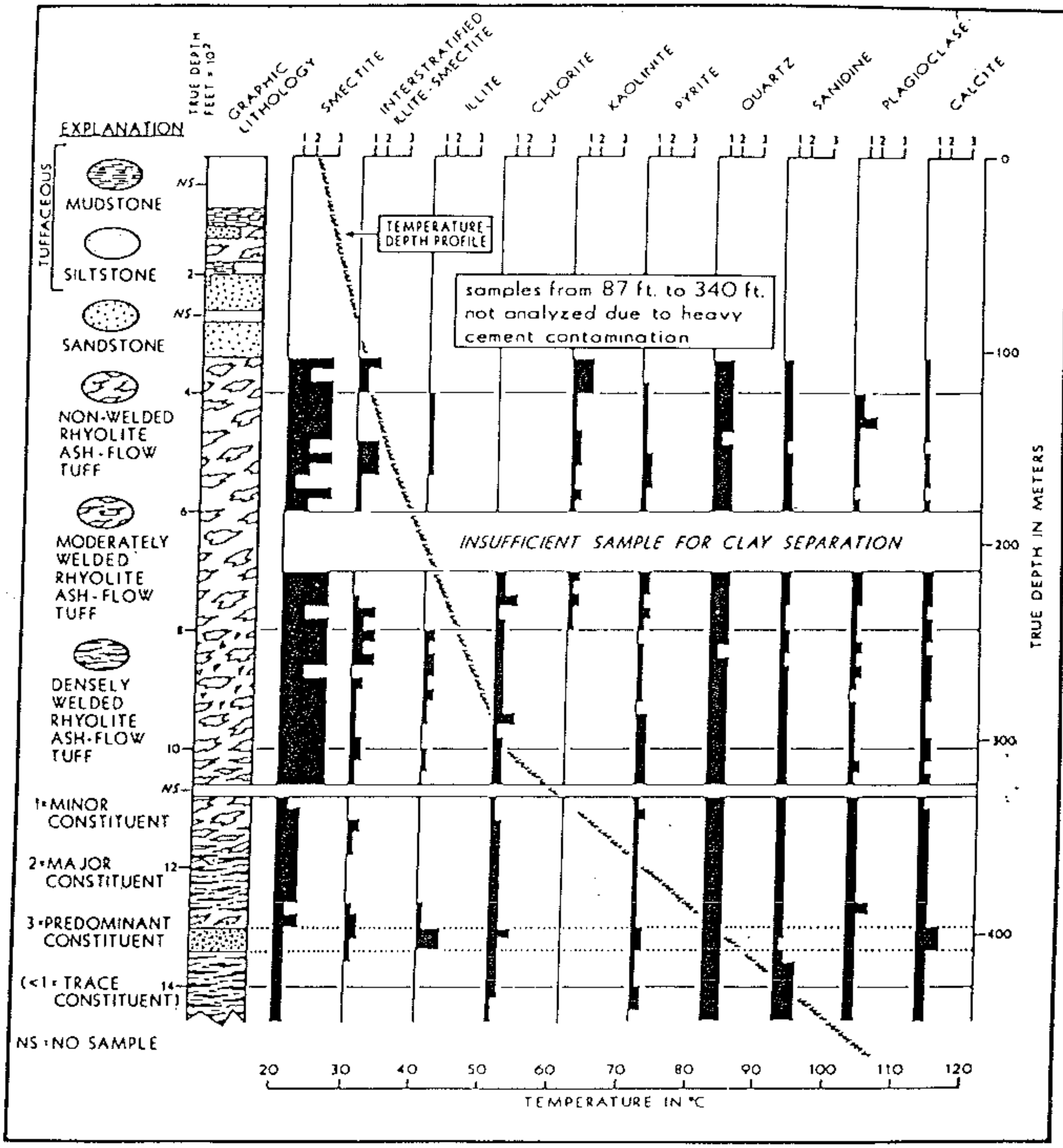

Figure 3. Detailed mineralogy of the high-level clay alteration zone in well B-20, as determined by X-ray diffraction.

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

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

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REFERENCES

Behrman, P.G., and Knapp, R.B., 1980, Structure of the Redondo Creek area, Baca project, New Mexico--implications concerning the nature of permeability and production and recommendations for future drilling: Union Oil Co., Geoth. Div., Internal Rept.

Crowe, B.M., Linn, G.W., and Heiken, G., 1978, Stratigraphy of the Bandelier Tuff in the Pajarito Plateau--Applications to waste management: Los Alamos Sci. Lab. Rept. LA-7225-MS.

Doell, R.R., Dalrymple, G.B., Smith, R.L., and Bailey, R.A., 1968, Paleomagnetism, potassium-argon ages and geology of the rhyolites and associated rocks at the Valles Caldera, New Mexico in Coats, R.R., Hay, R.L., and Anderson, C.A., eds., Studies in volcanology: Geol. Soc. America Mem. 116, p. 211-248.

Dondanville, R.F., 1978, Geologic characteristics of the Valles Caldera geothermal system, New Mexico: Geoth. Resources Council, Trans., vol. 2, p. 157-160.

Grant, M.A., and Garg, S.K., 1981, Baca geothermal demonstration project--interpretation of downhole data from the Baca geothermal field: Systems, science and software, Topical Rept. No. DOE/ET/27163-12.

Hartz, J.D., 1976, Geothermal reservoir evaluation of the Redondo Creek area, Sandoval County, New Mexico: Union Oil Co., Geoth. Div., Internal Rept.

Hower, J., 1981, X-ray identification of mixed-layer clay minerals, in Longstaffe, F.J., ed., Short course in clays and the resource geologist: Calgary, Mineralogical Assoc. Canada Short Course Handbook, vol. 7, p. 39-59.

Hulen, J.B., and Nielson, D.L., 1982, Stratigraphic permeability in the Baca geothermal system, Redondo Creek area, Valles Caldera, New Mexico: Geoth. Resources Council, Trans., vol. 6, p. 27-30.

Muffler, L.J.P., and White, D.E., 1969, Active metamorphism of Upper Cenozoic sediments in the Salton Sea geothermal field and the Salton Trough, southeastern California: Geol. Soc. America Bull., vol. 80, p. 157-182.

Schoen, R., White, D.E., and Hemley, J.J., 1974, Argillization by descending acid at Steamboat Springs, Nevada: Clays and Clay Minerals, vol. 22, p. 1-21.

Smith, R.L., 1960, Zones and zonal variations in welded ash flows: U.S. Geol. Survey Prof. Paper 354-F.

Smith, R.L., and Bailey, R.A., 1968, Resurgent cauldrons in Coats, R.R., Hay, R.L., and Anderson, C.A., eds., Studies in volcanology: Geol. Soc. America mem. 116, p. 613-662.

Steiner, A., 1968, Clay minerals in hydrothermally altered rocks at Wairakei, New Zealand: Clays and Clay Minerals, vol. 16, p. 193-212.