Hydrothermal alteration in research drill hole Y-2, Lower Geyser Basin, Yellowstone National Park, Wyoming

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Abstract

Y-2, a U.S. Geological Survey research diamond-drill hole in Lower Geyser Basin, Yellowstone National Park, was drilled to a depth of 157.4 meters. The hole penetrated interbedded siliceous sinter and travertine to 10.2 m, glacial sediments of the Pinedale Glaciation interlayered with pumiceous tuff from 10.2 to 31.7 m, and rhyolitic lavas of the Elephant Back flow of the Central Plateau Member and the Mallard Lake Member of the Pleistocene Plateau Rhyolite from 31.7 to 157.4 m. Hydrothermal alteration is pervasive in most of the nearly continuous drill core. Rhyolitic glass has been extensively altered to clay and zeolite minerals (intermediate heulandite, clinoptilolite, mordenite, montmorillonite, mixed-layer illite-montmorillonite, and illite) in addition to quartz and adularia. Numerous veins, vugs, and fractures in the core contain these and other minerals: silica minerals (opal, β-cristobalite, α-cristobalite, and chalcedony), zeolites (analcime, wairakite, dachiardite, laumontite, and yugawaralite), carbonates (calcite and siderite), clay (kaolinite and chlorite), oxides (hematite, goethite, manganite, cryptomelane, pyrolusite, and groutite), and sulfides (pyrrhotite and pyrite) along with minor aegirine, fluorite, truscottite, and portlandite(?).

Interbedded travertine and siliceous sinter in the upper part of the drill core indicate that two distinct types of thermal water are responsible for precipitation of the surficial deposits, and further that the water regime has alternated between the two thermal waters more than once since the end of the Pinedale Glaciation (~10,000 years B.P.). Alternation of zones of calcium-rich and sodium- and potassium-rich hydrothermal minerals also suggests that the water chemistry in this drill hole varies with depth.

Introduction

Research hole Y-2 is one of 13 research diamond-drill holes put down by the U.S. Geological Survey at selected sites in hot-spring and geyser areas of Yellowstone National Park. The holes were drilled in 1967 and 1968 for the purpose of gathering detailed data on the shallow portion of a high-temperature geothermal system (White *et al.,* 1975). Similar hydrothermal-alteration studies of cores from other holes in Yellowstone have been reported by Honda and Muffler (1970), Bargar *et al.* (1973), Muffler and Bargar (1974), Honda and Sasaki (1977), Keith and Muffler (1978), Keith *et al.* (1978a, b).

The Y-2 drill hole is in Lower Geyser Basin (at an elevation of 2247 m) about 134 m east of Hot Lake (Fig. 1) near the southern margin of an area dotted by hot springs and geysers. Drilling of Y-2, using water as the circulating fluid, began on May 3, 1967,

and ended on June 6, 1967, at a depth of 157.4 m. Core recovery was by wireline method and averaged 78 percent.

The drill core was logged at the drill site by L. J. P. Muffler, A. H. Truesdell, and D. E. White. Approximately 330 pieces of core that are representative of coring intervals (usually 1.5 or 3.0 m) or contain unusual features such as veins, vugs, and fractures were selected for detailed laboratory study. This skeleton core was systematically studied by petrographic (31 thin sections), X-ray diffraction (more than 600 X-ray diffractograms), electron microprobe (20 polished thin sections), and scanning electron microscope (SEM) methods. Whole-rock chemical analyses, semiquantitative spectrographic analyses, and bulk- and powder-density measurements were obtained for 16 selected core samples.

Y-2 was plugged with cement and abandoned before reliable chemical analyses of the water could be
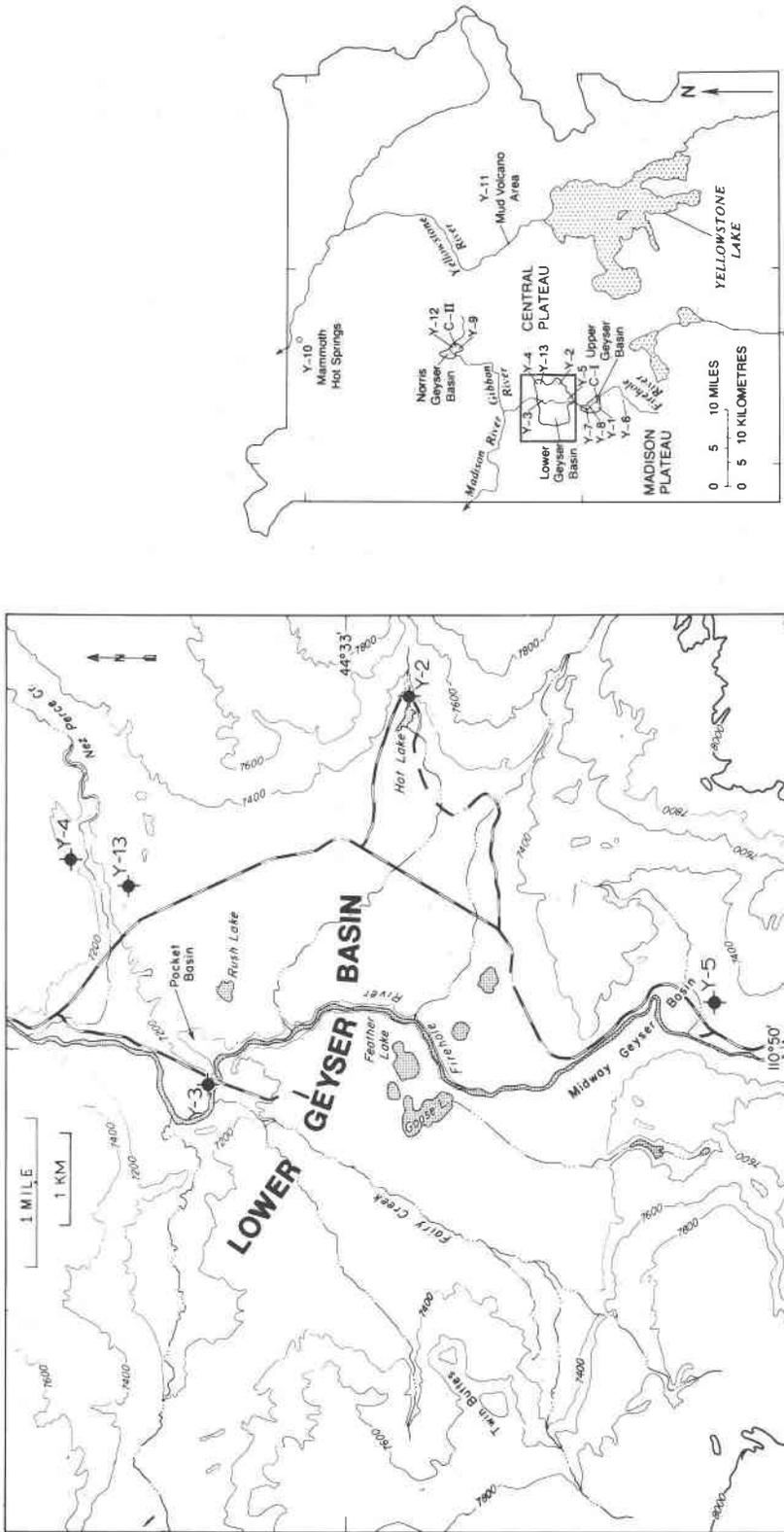
Fig. 1. Map of Lower Geyser Basin showing location of Y-2 and other research drill holes. Small index map shows location of major geothermal areas and sites of all research drill holes in Yellowstone National Park.

obtained. Chemical analyses of waters from nearby hot springs and geysers are reported in Allen and Day (1935), Rowe *et al.* (1973), Thompson *et al.* (1975), and Thompson and Yadav (1979). The chemical composition of these slightly alkaline dilute thermal waters is very similar to that of Steady Geyser (Table 1). Chemical geothermometers suggest that such water should come from an aquifer having a temperature of about 170°C (Fournier and Truesdell, 1970; White *et al.*, 1975; Fournier *et al.*, 1976). The maximum temperature recorded by White *et al.* during drilling of Y-2, however, was 203.1°C at the bottom (157.4 m) (Fig. 2). Water of this temperature would, according to Fournier and Rowe (1966), contain significantly more SiO_2 and would probably be similar in composition to that of Surprise Pool (see Table 1) (R.O. Fournier, U.S. Geological Survey, personal communication, 1979). The Y-2 drill hole thus apparently penetrates a shallow aquifer containing 170°C, low-silica, low-chloride water as well as a deeper, higher temperature aquifer having appreciably greater sodium, silica, and chloride values (Fournier *et al.*, 1976).

Stratigraphy

The Y-2 drill core penetrated sinter with interbedded travertine and detrital sediments (0–10.2 m), glacial sediments and tuff (10.2–31.7 m), and the Elephant Back flow of the Central Plateau Member (31.7–122.8 m) and the Mallard Lake Member (122.8–157.4 m) of the Plateau Rhyolite (Fig. 2).

Sinter, travertine, and detrital sediments

The upper 10.2 m of the Y-2 core consists primarily of sinter that is interbedded with travertine from 8.1 to 8.8 m and at 9.4 m and hydrothermally altered detrital sediments from 9.3 to 10.2 m. Some of the sinter occurs as primary amorphous opaline silica precipitated from discharging hot-spring waters. However, most of the sinter consists of fragments of weathered primary sinter cemented by later silica deposits and contains molds and silica casts of plant fragments.

Travertine was not unexpected in the upper part of Y-2 since two small calcareous aprons are currently being deposited near Steady (~ 81 m N44°W of Y-2) and Young Hopeful (~ 117 m N74°E of Y-2) Geysers (Allen and Day, 1935; White, 1955; R.O. Fournier, U.S. Geological Survey, unpub. geologic mapping, 1969). Allen and Day also describe two nearby old travertine terraces.

In addition to travertine, the sinter contains thin layers of interbedded brown-black manganese oxide. Manganese oxide is currently being deposited by a few hot springs in the Hot Lake area (Allen and Day, 1935; White, 1955).

Interbedded with sinter in the lower part of the interval are layers of detrital sediment (less than 4 cm thick) composed of subangular to subrounded, sand- to gravel-sized rhyolite and hydrothermally altered obsidian grains, probably glacial outwash material deposited during the Pinedale Glaciation about 50,000 to 10,000 years B.P. (Pierce *et al.*, 1976).

Glacial sediments and tuff

From 10.2 to 31.7 m, the core consists predominantly of fairly well indurated conglomerate and coarse-grained sandstone containing a few beds of finer grained sandstone and siltstone. These sediments are probably part of the kame deposits that partly encircle the drill-hole site, outwash from ice-marginal and melt-water streams during the Pinedale Glaciation (Waldrop and Pierce, 1975).

Subrounded to rounded, granule- to pebble-sized clasts of rhyolite, composed of quartz, sanidine, and α-cristobalite, are common in the glacial sediments, as are smaller detrital quartz and sanidine grains; plagioclase, pyroxene, and magnetite are rare. Most of the sediments are cemented by hydrothermal minerals; however, one of the freshest obsidian intervals (16.5 to 17.1 m) appears to be cemented by finely ground glass (amorphous to X-rays).

Friable tuff beds interrupt the interval at 19.8 to 25.0 m and 26.5 to 27.1 m. The tuff beds probably represent waning pyroclastic activity related to emplacement of the underlying Elephant Back flow of the Central Plateau Member of the Plateau Rhyolite. Originally composed of blocky to arcuate glass shards, these tuffs have been hydrothermally altered. Fine- to coarse-sand-size grains of rhyolite, hydrothermally altered obsidian, and phenocrysts of quartz and sanidine occur in the tuff beds.

Elephant Back flow of the Central Plateau Member

From 31.7 to 122.8 m, the drill hole penetrated the Elephant Back flow and related volcaniclastic rocks of the Central Plateau Member of the Plateau Rhyolite (Christiansen and Blank, 1974; White *et al.*, 1975). The Elephant Back flow has a K-Ar date of ~150,000 years B.P. (J. D. Obradovich and R. L. Christiansen, U.S. Geological Survey, unpub. data, 1973).

Most core samples of the Elephant Back flow (from 37.6 to 110.9 m) consist of rhyolite flow breccia
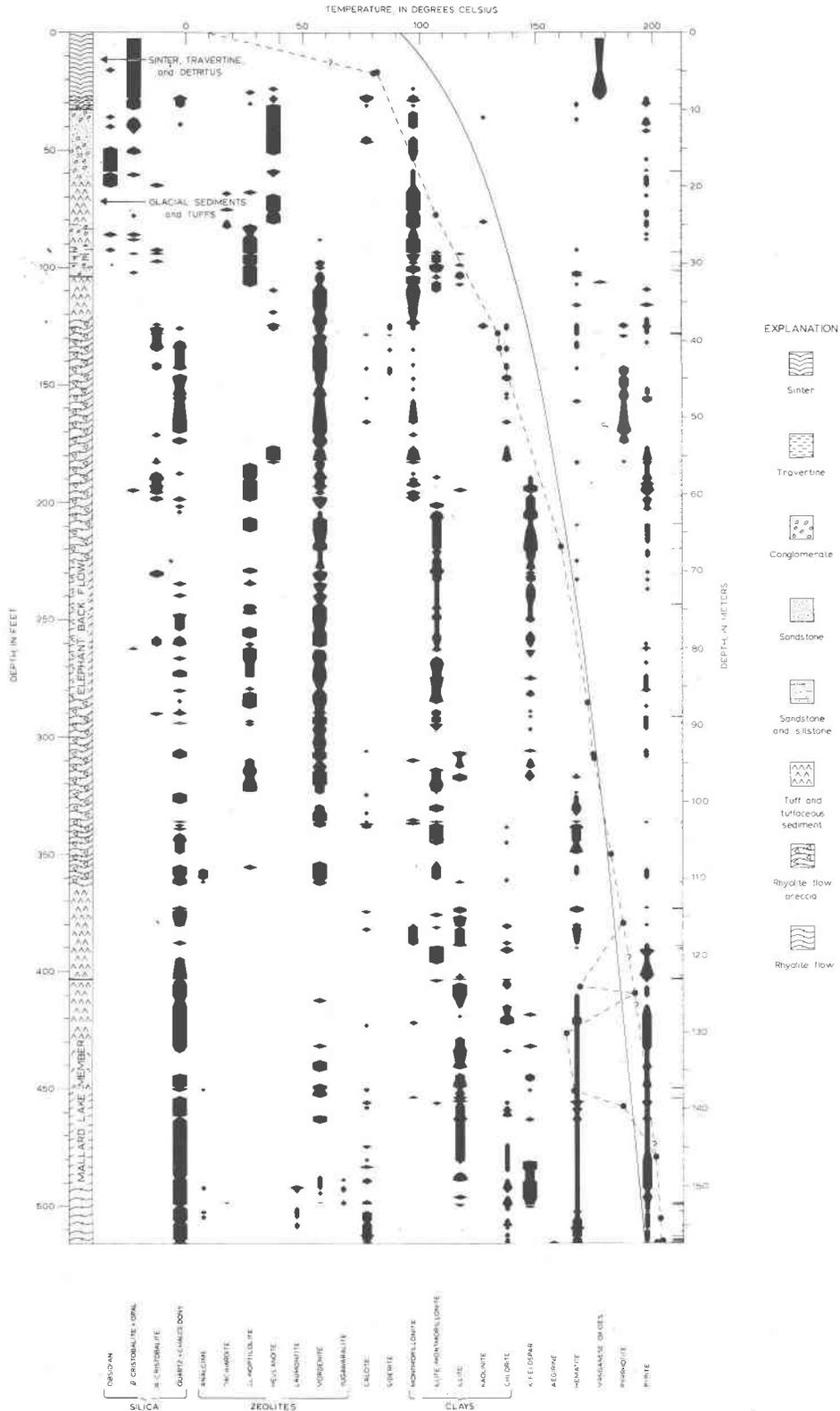
Fig. 2. Distribution of unaltered obsidian and hydrothermal alteration minerals in drill core from Y-2. Left column shows a generalized stratigraphic section of rock units penetrated by drill hole; lithologic boundaries marked with horizontal lines. Horizontal lines at right indicate distribution of samples studied. Width of mineral columns provides an estimate of relative abundance based on X-ray diffraction data and microscopic observation. Vertical continuity in mineral presence between samples studied assumed except where a mineral abundance becomes zero, in which case the zero point is arbitrarily placed 0.3 m from last occurrence of the mineral. Dashed curve connects bottom-hole temperature measurements obtained as drilling progressed. Queried dashed curve at top denotes uncertainty in temperature data, second queried dashed curve below 116 m shows temperature trend if temperature reversals are discounted. Solid

that is highly fractured and displays minor vesicularity and flow banding. Quartz and sanidine are the predominant magmatic minerals; plagioclase, magnetite, and pyroxene are minor constituents. Vapor-phase minerals (α-cristobalite, alkali feldspar, and tridymite) occur in numerous irregular cavities and patches in the upper 8 m of the interval. Perlitic and pumiceous textures evident throughout the interval indicate that much of the original rock was glassy. Fairly fresh glass remains at about 80 m. Some glass has been devitrified to intergrown α-cristobalite and alkali feldspar zones marked by spherulitic texture, but most of the remaining glass has been hydrothermally altered.

Two volcaniclastic sequences (from 31.7 to 37.6 m and from 110.9 to 122.8 m), included with the Elephant Back flow by Christiansen and Blank (1974), consist of pumice, vitric to crystal tuff (containing some rhyolite lithic fragments and altered glass grains that display remanent perlitic texture), and tuffaceous sediments. Magmatic minerals include quartz, sanidine and plagioclase in nearly equal amounts, and sparse magnetite. The tuffaceous sediments are composed of altered obsidian and pumice clasts, rhyolite fragments (to small cobble size), and detrital quartz, sanidine, and plagioclase grains. Bedded air-fall tuff separates the Elephant Back flow from the underlying Mallard Lake Member (R. L. Christiansen, U.S. Geological Survey, personal communication, 1980).

Mallard Lake Member

Between 122.8 m and the bottom of the drill hole at 157.4 m, the core penetrated the Mallard Lake Member of the Plateau Rhyolite (White et al., 1975) which has a K–Ar date of ~150,000 years B.P. (J. D. Obradovich and R. L. Christiansen, U.S. Geological Survey, unpub. data 1973).

In Y-2, the Mallard Lake Member consists primarily of vitrophyric, brecciated, or pumiceous rhyolitic lava and contains a few pumiceous tuff beds. Quartz, sanidine, and plagioclase are the predominant magmatic minerals; magnetite and pyroxene are minor constituents. Devitrification and vapor-phase minerals are rare, but hydrothermal alteration is extensive.

Hydrothermal-alteration mineralogy

The distribution of obsidian and hydrothermal alteration minerals with depth in the Y-2 drill core is given in Figure 2. Magmatic, devitrification, vapor-phase, and a few hydrothermal minerals that have only minor distribution are not shown.

Table 1. Chemical composition (in ppm) of thermal water in vicinity of Y-2 drill hole.[†]

	Surprise Pool[††]	Steady Geyser[†††]
Sample No.	75114	F7712
Date Collected	10/9/75	9/30/77
Temperature (°C)	95	95
pH	8.95	8.05
SiO_2	280	191
Fe	n.d.	<0.01
Mn	n.d.	0.1
Ca	0.47	9.5
Mg	0.14	0.043
Na	333	105
K	15	14
Li	3.6	0.3
Rb	0.1	n.d.
Cs	0.68	n.d.
HCO_3	194	171
CO_3	81	0
SO_4	25	25
Cl	313	61
F	24	10
B	3.1	0.5
Total	1273.09	587.453

[†] Analyses from Thompson and Yadav (1979).
[††] Located ∽1.4 km S 53°W of Y-2.
[†††] Located ∽81 m N 44°W of Y-2.
n.d.=not determined.

Obsidian

The glacial sediments were originally mainly black obsidian grains. Most of the obsidian has been hydrothermally altered to clinoptilolite, intermediate heulandite, and montmorillonite; some unaltered glass occurs at 11.0, 12.2, 15.1 to 19.8, 26.2, and 28.2 m.

Obsidian from 26.2 m is only slightly altered. Scanning electron microscope (SEM) and thin-section studies show that the obsidian grains are dotted by numerous shallow vesicles about 10 μ in diameter; several of these occur along hydration cracks (Fig. 3). Many of the vesicles are filled with rosettes of bladed clinoptilolite crystals and crudely spherical boxwork aggregates of montmorillonite crystals.

Silica minerals

Opal. The upper 10.2 m in Y-2 originally consisted primarily of amorphous opaline silica deposited in the form of minute coalescing spheres. Irregular blocky masses of very fragile white opal and clear
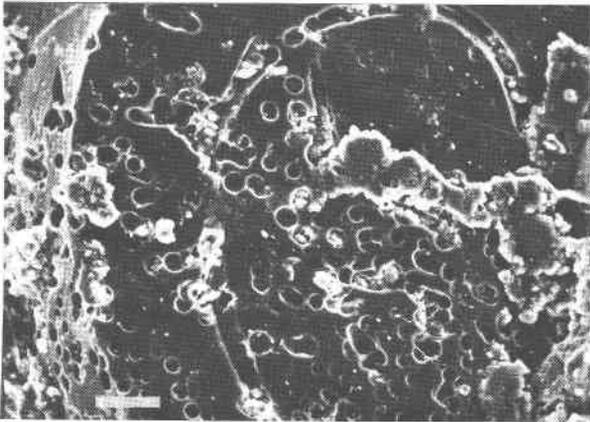
Fig. 3. Scanning electron micrograph of broken surface of obsidian grain from 26.2 m. Surface and interior of grain contain numerous shallow vesicles partly filled by clinoptilolite and montmorillonite. White bar at bottom left is 30 microns.

hyalite beads (refractive index, 1.45 to 1.46) fill open spaces in the porous sinter at 0.8 m. Secondary opal occurs as clear to white vein material from 7.3 to 8.8 m, as brownish mineralized fossil-plant fragments at 9.3 and 9.4 m, and as white horizontal layers in the bottom of a few cavities at 9.4 and 9.8 m. In addition, a solitary tiny (~16 μm-diameter) opal sphere was observed in SEM photos at 31.1 m.

β-cristobalite[1]. Honda and Muffler (1970) indicate that β-cristobalite probably originates through recrystallization of opal. According to X-ray diffraction studies, the opaline sinter in the upper 10.2 m of Y-2 is partly to completely replaced by β-cristobalite. β-cristobalite apparently replaces opal in vein or fracture fillings in a few widely scattered pieces of core from as deep as 80.0 m and occurs as yellowish- or brownish-cryptocrystalline cement in some of the glacial sediments (notably at 18.4 and 26.2 m).

At 9.8 m, several large cavities are lined by a clear to white druse of minute tabular heulandite crystals and later white, hollow, fragile, bladed to blocky β-cristobalite pseudomorphs (0.5 to 1 mm in size) that resemble the fragile blocky opal open-space fillings at 0.8 m. SEM micrographs show that the β-cristobalite typically consists of spherical aggregates of bladed crystals. Rounded clusters of spherical aggregates of bladed β-cristobalite crystals were found fill-

ing cavities at 26.8 m and on a bedding-plane parting in volcanic sandstone at 31.1 m.

α-cristobalite. Most of the α-cristobalite in Y-2 is a product of devitrification; however, mineralogic or textural association of several samples suggest a hydrothermal origin for some of the α-cristobalite. At 19.8 m, the glacial sediments are cemented by yellowish-cryptocrystalline α-cristobalite. Cryptocrystalline α-cristobalite also occurs as hard, thin, white, red or green fillings in veins, fractures, and cavities and as snowy white horizontally layered cavity fillings at several widely scattered locations in the upper three-fifths of the drill core. The α-cristobalite is commonly associated with chalcedony (observed in X-ray patterns) or with later pyrite and mordenite.

Hydrothermal α-cristobalite also occurs as hard gray colliform masses of blocky crystals lining cavities or fractures from as deep as 95.3 m in the core. When viewed with a SEM, the α-cristobalite appears as spherical aggregates of blocky crystals. Similar blocky crystals of α-cristobalite occur as a soft buff powdery cavity filling that partially coats mordenite fibers in a few pieces of core.

Chalcedony. Cryptocrystalline chalcedony fills cavities and veins, or lines fractures throughout the drill core. Clear, pink, white, and buff chalcedony vein or fracture (?) fillings in travertine at 8.4 to 8.8 m appear to have formed by replacement of calcite, as the filling consists in part of bladed pseudomorphs of chalcedony after calcite. Chalcedony forms a white crust lining cylindrical molds of plant fragments and other cavities in siliceous sinter from 9.3 and 9.4 m. One large cavity at 9.4 m is partly filled with a clear to white siliceous crust that is in part colliform and by X-ray diffraction was identified as chalcedony with some β-cristobalite. Colliform chalcedony persists in scattered cavity and fracture filling as deep as 89.6 m. Chalcedony also commonly occurs as white horizontally layered cavity fillings that appear to be an early hydrothermal deposit, usually associated with later tiny euhedral quartz prisms, mordenite fibers, or pyrite cubes. Presumably, open-space chalcedony was originally deposited as opal and later converted to a more stable silica phase.

Quartz. Tiny euhedral dipyramidal quartz crystals occur along with adularia as an alteration product of glassy rhyolite. Discrete hydrothermal quartz crystals or coalesced knobby crystal clusters fill cavities and line fractures and occasionally were deposited later than associated hydrothermal minerals. Crystal size ranges from a few microns to a few millimeters, and crystal habit varies from subhedral to euhedral pyra-

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[1] A complete gradation exists between X-ray amorphous opal, poorly ordered β-cristobalite, and well-ordered α-cristobalite (Murata and Larson, 1975). α-cristobalite is distinguished from β-cristobalite by a sharp major X-ray peak between 4.04 and 4.07Å along with several other minor peaks; β-cristobalite has a broad major peak between 4.07 and 4.11Å and a single minor peak near 2.50Å.

midal or diapyramidal prisms. Quartz may have been deposited in more than one generation, as the mineral appears to have formed both earlier and later than mordenite in the same sample.

Zeolite minerals

Heulandite-group. Clinoptilolite and intermediate heulandite type 2 (Alietti, 1972; Boles, 1972) are scattered throughout much of the upper 110 m of drill core. Intermediate heulandite is prevalent down to 24.5 m and between 33.4 and 55.8 m, whereas clinoptilolite is generally restricted to depths between 24.5 and 33.4 m and below 55.8 m (see Fig. 2). The two minerals are distinguished from one another by X-ray diffraction after heating at 450°C for 15 hours (Mumpton, 1960). Clinoptilolite displays little or no weakening in the intensity of the d(020) X-ray peak at ~9.0Å following the heat treatment, whereas intermediate heulandite is characterized by the formation of three peaks at about 8.9, 8.7, and 8.3Å (Alietti, 1972; Boles, 1972).

Intermediate heulandite and clinoptilolite commonly occur as cementing material for much of the glacial sediments and as a major alteration product of glass in the core along with montmorillonite or mixed-layer illite-montmorillonite. Clay is initially deposited along concentric shell-like hydration cracks in the glass, thus preserving the perlitic texture. The glass is then altered to clear euhedral zeolite crystals and later clay (Figs. 4 and 5). Intermediate heulandite and clinoptilolite crystals produced by alteration of glass typically display tabular or "tombstone" habits as shown in Figures 4 and 5 but occasionally may have a more blocky habit. Fairly fresh obsidian from 26.2 m contains rosettes of bladed clinoptilolite crystals and associated platey boxwork of montmorillonite crystals deposited along perlitic cracks and in shallow vesicles (Fig. 3).

Clear euhedral blocky or tabular clinoptilolite and intermediate heulandite crystals deposited by circulating thermal waters fill open-space cavities and fractures commonly in association with later mordenite. A few shallow-dipping fractures at 12.8, 15.1, 15.5, and 18.0 m are partially coated by intermediate heulandite crystals that appear to be pseudomorphous after bladed calcite.

Thirty-eight individual heulandite-group crystals from 12 samples (6 intermediate heulandites and 6 clinoptilolites) were analyzed with an ARL EMX electron microprobe using natural mineral standards (Table 2). Nearly all of the analyses have cation balance errors that exceed 10 percent. In analyzing zeo-
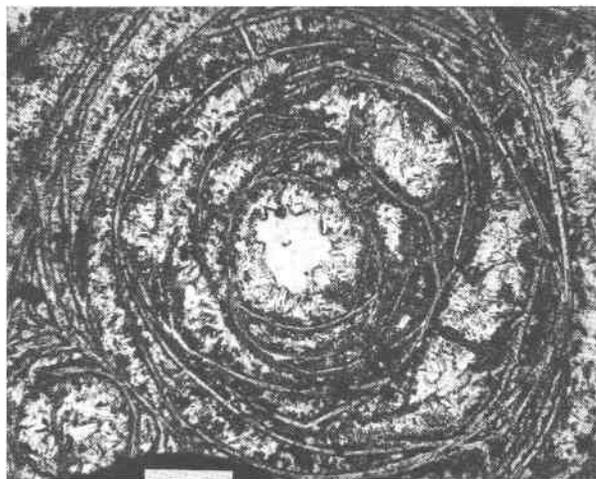
Fig. 4. Photomicrograph of altered glass from 14.2 m (plane light). Perlitic texture is preserved by deposition of montmorillonite along concentric shell-like hydration cracks. Subsequent alteration consists of deposition of clear, tabular, intermediate heulandite crystals oriented perpendicular to clay-filled hydration cracks. White bar at bottom left is 0.1 mm.

lite minerals, several factors such as volatilization of water and small crystal size frequently result in less than satisfactory chemical analyses (see discussion in Wise and Tschernich, 1976). Nonetheless, the analyses do provide a basis for division of the heulandite-group zeolites of Y-2 into two separate mineral species that are generally consistent with their thermal stabilities. A single exception is sample 24.2, which gives a definitive heating test for intermediate heu-
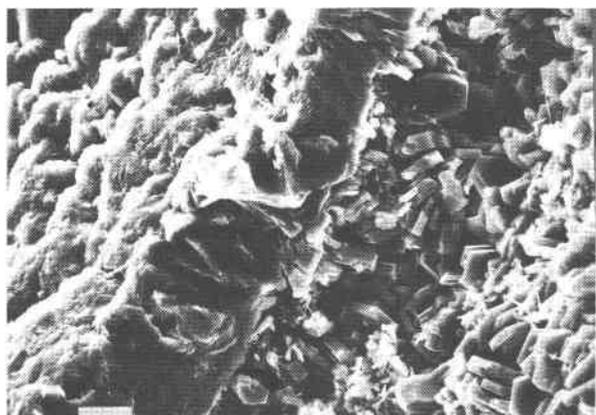
Fig. 5. Scanning electron micrograph of altered glass from 14.2 m. A montmorillonite-filled former hydration crack shown in left half of photo. Right half shows area between clay-filled hydration cracks in which tabular- or "tombstone"- shaped intermediate heulandite crystals are oriented perpendicular to remanent hydration cracks. Fibrous mordenite and clusters of montmorillonite platelets are later than the heulandite. White bar at bottom left is 10 microns. (After Bargar *et al.,* 1981.)

Table 2. Microprobe analyses of heulandite-group zeolites from Y-2 drill core.[†]

Sample no.[††]	7.3	10.5	12.8	14.2	18.0	20.7	24.2	31.7	32.5	54.3	108.4	108.8
Mineral [†††]	I	I	I	I	I	C	C	C	C	I	C	C
Number of analyses	2	4	3	2	3	2	7	5	2	4	2	2
					Weight Percent							
SiO_2	66.84	66.67	64.11	65.24	63.53	65.37	63.33	58.72	67.96	63.19	71.38	67.49
Al_2O_3	12.71	14.91	12.36	15.31	14.99	13.61	15.36	11.93	11.36	14.83	11.84	12.96
Fe_2O_3	n.d.	0.65	n.d.	0.73	0.60	n.d.	0.34	0.16	n.d.	0.54	0.00	0.17
CaO	4.40	4.59	4.34	5.02	5.08	2.61	2.84	1.96	2.50	4.87	1.67	1.63
Na_2O	0.31	0.47	0.18	0.44	0.45	1.41	2.30	1.95	1.40	0.16	4.55	4.05
K_2O	1.52	1.46	1.24	1.58	1.26	2.57	2.22	1.81	1.42	1.12	0.41	0.60
MnO	0.30	0.02	0.34	0.00	0.08	0.24	0.00	0.06	0.05	0.11	0.14	0.00
Total	86.08	88.77	82.57	88.32	85.99	85.81	86.39	76.59	85.14	84.82	89.99	86.90
					Numbers of ions on the basis of 72 oxygens							
Si	29.636	28.785	29.595	28.436	28.426	29.270	29.347	29.367	30.322	28.548	30.182	29.605
Al	6.643	7.591	6.724	7.866	7.891	7.184	8.102	7.050	5.976	7.893	5.903	6.701
Fe	n.d.	0.210	n.d.	0.240	0.202	n.d.	0.113	0.061	n.d.	0.182	0.001	0.055
Ca	2.091	2.127	2.116	2.344	2.419	1.248	1.362	1.048	1.195	2.356	0.757	0.767
Na	0.266	0.392	0.163	0.373	0.397	1.226	1.976	1.893	1.209	0.142	3.729	3.445
K	0.862	0.802	0.727	0.878	0.729	1.465	1.267	1.161	0.810	0.646	0.221	0.334
Mn	0.111	0.006	0.133	0.000	0.028	0.092	0.000	0.024	0.190	0.041	0.050	0.000
Si/Al	4.46	3.79	4.40	3.62	3.60	4.07	3.50	4.17	5.07	3.62	5.11	4.42

[†] Analyst: M. H. Beeson, U. S. Geological Survey.
[††] Sample numbers correspond to depth in meters.
[†††] C=clinoptilolite, I=intermediate heulandite.
  n.d.=not determined.

landite, although both groundmass and vesicle-filling crystals have the chemical composition of clinoptilolite. Presumably, the thermal behavior of this sample is influenced by the low Si/Al ratio (see Table 2) (Boles, 1972).

Separation of the Y-2 heulandite-group zeolites into two distinct chemical groups can be seen in a ternary diagram of Si/Al ratio, sum of divalent cations, and sum of monovalent cations (Fig. 6A). This plot offers virtually the same three-fold division of heulandite-group minerals as similar discrimination diagrams of Alietti (1967, 1972), except that the traditional heulandite field (more calcium-rich) is vacant because this mineral was not found in Y-2 core. A ternary plot of Ca, K, Na (Fig. 6B) displays the same separation of intermediate heulandite and clinoptilolite groups but also suggests a need for further subdivision because the deeper samples contain more sodium than potassium. Hawkins (1974) divided the heulandite-group minerals into five compositional subgroups (A–E), using multivariant statistical methods, according to discriminant functions based upon CaO content. Using Hawkins' classification, the sodium-rich clinoptilolites of Y-2 belong to an extreme member subgroup E (or traditional clinoptilolite); most of the clinoptilolites fall into intermediate subgroup D. All but one of the intermediate heulandite analyses (a subgroup B) fit into subgroup C. No subgroup A or traditional heulandite occurs in Y-2. Clinoptilolites from other Yellowstone drill holes (Fen-

ner, 1936; Honda and Muffler, 1970; Keith *et al.,* 1978b) fall into subgroup E, since they contain much less CaO than the Y-2 zeolites. Whereas calcium in clinoptilolites from other Yellowstone drill holes ranges from 0.1 to 0.7 mole percent, calcium in the Y-2 samples varies from 0.8 to 1.4 mole percent for clinoptilolite and from 2.0 to 2.6 mole percent for intermediate heulandite.

Mordenite. Mordenite is fairly abundant throughout most of Y-2 from 26.8 to 110.5 m but is present only sporadically in the lower ~45 m of drill core (see Fig. 2). Feathery mordenite fibers replace glass in altered rhyolite with preservation of the remanent perlitic texture. Mordenite also occurs as tiny (less than 4 μ diameter) clear delicate discrete needles, white spongy or cottony mats of interwoven long, thin fibrous crystals, or sprays of radiating white fibers that line cavities, fractures, or veins. Open-space mordenite is usually a late hydrothermal mineral that formed after most other zeolite, clay, and silica minerals but earlier than some quartz and α-cristobalite.

Seki (1973) equates an increasing difference between the d(060) and d(202) X-ray-diffraction peaks of mordenite with an increasing $Ca/(Ca+\frac{1}{2}(Na+K))$ ratio. He also defines calcium-rich mordenite as having a $Ca/(Ca+\frac{1}{2}(Na+K))$ ratio of 0.6 or greater. The $\Delta2\theta_{060-202}$ values for nine mordenite samples taken from 16.0 to 63.7 m in drill hole Y-1 showed a general increase with depth, which Seki interpreted as indicating that the $Ca/(Ca+\frac{1}{2}(Na+K))$ ratio should
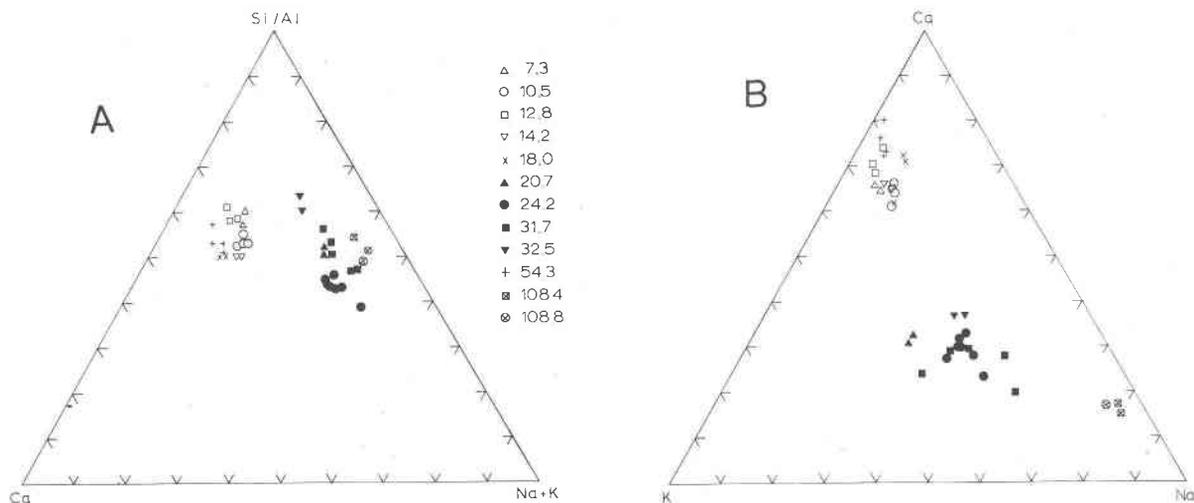
Fig. 6. (A) Ternary diagram of Si/Al-sum of divalent cations-sum of monovalent cations for heulandite-group zeolites from Y-2 drill core. Data from Table 2. Sum of divalent cations shown as Ca because no Mg, Ba, or Sr was found in any of the samples analyzed. (B) Ca–K–Na plot for heulandite-group zeolites from Y-2 drill core. Data from Table 2. Symbols same as in Figure 6(A).

become greater with increasing depth in this drill core. Average $Ca/(Ca+\frac{1}{2}(Na+K))$ ratios for 20 microprobe analyses of eleven mordenite samples from Y-2 ranged between 0.54 and 0.80 from 29.7 to 52.9 m and 0.43 and 0.52 from 64.6 to 109.7 m. The zone of calcium-rich mordenite is nearly coincident with the intermediate heulandite (calcium-rich) zone at 33.4 to 55.8 m; similarly, the sodium-potassium mordenite zone corresponds to the lower clinoptilolite (sodium- and potassium-rich) zone at 55.8 to 110.0 m.

Analcime-Wairakite. Core from Y-2 contains analcime between 108.9 and 110.9 m, at 137.3 m, and from 150.0 to 153.9 m. In the upper zone, analcime is found in cavities in association with mordenite and mixed-layer illite-montmorillonite or illite, in the lower zones, in cavities along with earlier chalcedony and quartz crystals and later bladed calcite.

An X-ray diffraction pattern of one of the samples (Y2-152.1) displays a peak at ~6.8Å. A second scan between ~3.6 and ~3.3Å at ¼°/minute, made to determine if wairakite or noncubic analcime were present, indicates that the d(400) peak at ~3.4Å is not a doublet and that the mineral should be analcime (Coombs, 1955). Yet, several microprobe analyses (Table 3) show that the mineral contains no K_2O, a little more than 3 percent Na_2O, and about 9 percent CaO and thus would appear to be a sodium-rich wairakite.

Dachiardite. In Y-2, dachiardite was found primarily in an altered pumiceous tuff zone from 20.7 to 25.1 m along with kaolinite, intermediate heulandite,

and sodium-rich montmorillonite. Dachiardite was also identified as clear blocky euhedral crystals lining a 45° fracture at 152.0 m in association with clear tabular yugawaralite crystals, fibrous mordenite, and earlier quartz crystals and bladed calcite.

An electron microprobe analysis (Table 3) for dachiardite from 20.7 m differs greatly from other published dachiardite chemical analyses (Berman, 1925; Gottardi, 1960; Alberti, 1975; Wise and Tschernich, 1978) and seems to reinforce Wise and

Table 3. Microprobe analyses for zeolites other than heulandite-group minerals from Y-2 drill core.[†]

Sample no.[††]	152.1	20.7	150.0
Mineral	Wairakite	Dachiardite	Yugawaralite
Number of analyses	5	2	2
	Weight Percent		
SiO_2	54.29	65.95	52.55
Al_2O_3	22.72	15.50	22.02
Fe_2O_3	0.11	0.24	0.00
CaO	8.96	2.96	11.01
Na_2O	3.34	1.63	0.43
K_2O	0.00	2.77	0.10
Total	89.42	89.05	86.11
	Numbers of ions on the basis of 72 oxygens		
Si	24.163	28.589	24.206
Al	11.934	7.920	11.954
Fe	0.036	0.079	0.000
Ca	4.280	1.376	5.435
Na	2.878	1.371	0.387
K	0.000	1.528	0.060
Si/Al	2.02	3.61	2.02

[†] Analyst: M. H. Beeson, U. S. Geological Survey.
[††] Sample numbers correspond to depth in meters.

Tschernich's conclusion that the Si/Al ratio and exchangeable cation content of dachiardite are indeed quite variable.

Erionite. Radiating bundles of white fibrous erionite crystals were identified from cavities in a single sample from 11.3 m in Y-2, where the temperature was probably about 90°C.

Laumontite. In Y-2, individual white-prismatic crystals of calcium-rich laumontite are found in association with earlier quartz crystals and calcite blades between 150.0 and 155.2 m, where the temperature measured during drilling was about 200°C.

Yugawaralite. In Y-2, yugawaralite is found as cavity or fracture fillings in association with earlier quartz and calcite crystals as well as other zeolite minerals (analcime, dachiardite, laumontite, and mordenite) in a zone from 149.0 to 152.2 m, where the temperature measured during drilling was about 200°C.

Chemical analyses by electron microprobe, Table 3, shows the yugawaralite to be quite low in SiO_2 and high in Al_2O_3 and CaO relative to other yugawaralite analyses (Eberlein *et al.*, 1971; Pongiluppi, 1977; Wise, 1978). Cation balance errors (4–7 percent) and comparison between replicate analyses are quite good.

Carbonate minerals

Calcite is sparsely distributed in the Y-2 drill core from about 8.4 to 14.2 m, 39.1 to 50.6 m, and below 93.3 m (see Fig. 2). In the upper zone, calcite occurs mainly as hot-spring travertine deposits, although some calcite was found in the groundmass of the glacial sediments and bladed crystals fill fractures and intergranular cavities. A few fractures and cavities in the second zone are lined by bladed calcite crystals. This zone overlaps with the sole occurrence of tiny (less than 0.5 mm) yellowish rhombohedral siderite crystals, sparsely distributed in a few cavities between 37.9 and 44.2 m. The temperature at which siderite was found ranged from about 130° to 140°C (Fig. 2) slightly higher than that at Broadlands, New Zealand (37° to 130°C; Browne and Ellis, 1970) and about the same as that at the Salton Sea geothermal area (135°C; Muffler and White, 1969).

The top of the lowest calcite zone is nearly coincident with the point at which the measured temperatures exceed the reference boiling-point curve (Fig. 2); however, wellhead water pressures indicate that boiling could not occur above 116 m (White *et al.*, 1975). In fact, owing to the uncertainty of the measured temperatures between 116 and 146 m (discussed in White *et al.*) the origin of the bladed calcite cavity, vein and fracture fillings above 146 m cannot be definitely attributed to loss of CO_2 upon boiling. Between 146 m and the bottom of the drill hole, calcite is more abundant and probably originates through boiling of the geothermal fluid.

Clay minerals

Montmorillonite. Montmorillonite is the principal clay mineral from 7.3 to 60.7 m (see Fig. 2). Brownish to greenish montmorillonite fills hydration cracks in rhyolitic glass, preserving the perlitic structure (see Figs. 4 and 5). The glass subsequently alters to euhedral zeolite crystals and clusters of montmorillonite platelets. Gray, brown, or green montmorillonite, in association with later tiny pyrite cubes and various zeolite minerals, lines a few cavities and fractures. The open-space deposits were undoubtedly precipitated from circulating thermal waters.

Detailed X-ray-diffraction studies of montmorillonite in drill core Y-2 reveal several fluctuations in exchangeable cations with depth. Basal (001) spacing of ~15.0Å from 7.3 to 18.4 m and 33.4 to 55.8 m that expands to ~17.4Å upon glycolation (Table 4) indicates that Ca^{2+} is the exchangeable cation (Grim, 1968). At intervening depths of 18.7 to 33.4 m and 57.3 to 60.7 m, a Na^+ exchangeable cation is evident in an (001) X-ray peak at ~12.4Å that expands to ~17.2Å after glycolation. Sodium is also the exchangeable ion in a few deeper montmorillonite samples (Fig. 2).

Vermiculite (?). A brown to green clay mineral, not shown in Figure 2, occurs as fracture fillings and whole-rock alteration in seven samples from 116.0 to 118.3 m, 128.6 m, and 138.4 to 139.0 m. the mineral is characterized by fairly sharp ~14.3Å basal (001) X-ray peaks (Table 4) and contracts to ~10.4Å after being heated to 400°C for 1 hour, similar to a calcium-rich montmorillonite. Because the clay consistently expands to less than 17Å (15.6Å) upon glycolation, it is tentatively classified here as vermiculite (Warshaw and Roy, 1961) although such criteria for distinguishing between vermiculite and montmorillonite may not be completely definitive (Walker, 1957).

Mixed-layer illite-montmorillonite. Mixed-layer illite-montmorillonite occurs in a narrow zone from 28.5 to 33.4 m and is the predominant clay mineral between 60.7 and 120.7 m. The greenish to brownish mixed-layer clay is similar in origin to montmorillonite in that it typically forms as an alteration

Table 4. Range and average values of basal (001) spacings for clay minerals from drill hole Y-2.[†][††]

Mineral		Number of samples	Treatment[†††]	Average (A)	Range (A)
Montmorillonite	Calcium-rich	50	Untreated	15.0	14.0-15.9
		"	Glycolated	17.4	17.0-18.2
		5	Heated	10.1	9.8-10.3
	Sodium-rich	62	Untreated	12.4	10.7-13.9
		"	Glycolated	17.2	16.5-18.0
		17	Heated	10.0	9.8-10.3
Vermiculite(?)		7	Untreated	14.3	13.9-14.7
		"	Glycolated	15.6	14.6-16.4
		1	Heated	10.4	---
Mixed-layer Illite-montmorillonite	(20-30% expandable)	24	Untreated	10.6	10.0-11.5
		"	Glycolated	12.5	11.5-13.2
		"	"	9.7	9.3-10.7
		1	Heated	10.1	---
	(100% expandable)	21	Untreated	11.3	10.2-13.0
		"	Glycolated	17.2	16.8-17.7
		"	"	9.9	9.4-10.2
		2	Heated	10.0	9.9-10.0
Illite(?)		17	Untreated	10.5	10.0-11.1
		"	Glycolated	10.0	9.9-10.4
		0	Heated	--	---

[†] Values determined by X-ray diffraction studies of whole rock or multicomponent samples.
[††] A few samples display good crystallinity in which X-ray peaks are sharp and well defined; most samples are poorly crystalline and are characterized by low, broad asymetrical peaks that are difficult to evaluate and undoubtedly result in some measurement errors.
[†††] Slurried samples on glass slides were X-rayed once from 3° to 37° (2θ) and a second time from 3° to 14° (2θ) after being placed in an atmosphere of ethelyene glycol at 60°C for 1 hour. Data include results of heating samples to 450°C for 15 hours during discrimination tests for clinoptilolite and intermediate heulandite.

product of glass or as a precipitate in vugs and fractures in the core.

X-ray diffraction data for randomly interstratified illite-montmorillonite are given in Table 4. In the upper zone, the basal (001) spacing occurs at ~11.3Å and splits into two peaks at ~17.2Å and ~9.9Å following treatment with ethylene glycol. Fully expandable illite-montmorillonite also occurs at 66.9 m and from 88.8 to 89.8 m. Randomly interstratified illite-montmorillonite of the lower zone typically displays a basal (001) spacing of ~10.6Å that splits into two peaks at ~12.5Å and ~9.7Å after glycolation. According to Figure 2 of Weaver (1956), this mixed-layer clay may contain about 20 to 30 percent expandable layers.

Illite. Green or red-brown illite was found in the Y-2 drill core in thinly laminated glacial and volcan-

iclastic sediments from 28.7 to 32.6 m, filling fractures at 59.4 m and from 93.4 to 96.7 m, and as fracture fillings and alteration of glass from 110.0 to 118.6 m and 120.7 to 152.1 m (see Fig. 2). The illite basal (001) spacing, although poorly defined, appears to occur at ~10.5Å and exhibits slight contraction to ~10Å after being glycolated (Table 4). As such, the mineral may actually be a mixed-layer illite-montmorillonite with less than 20 percent expandable layers (Weaver, 1956; Hower and Mowatt, 1966); it is called illite here because of the uncertainty of accurately measuring the low, broad, asymmetrical X-ray peaks.

Kaolinite. White or yellowish- to greenish-gray-stained kaolinite fills a few cavities at 11.0 and 24.5 m, where it may be an alteration product of detrital obsidian, since remanent perlitic structures are pre-

Table 5. Microprobe analyses of feldspars from Y-2 drill core.[†]

Sample no.[††] Mineral[†††]	116.0 Ab	138.8 Ab	157.1 Ab	157.2 Ab	157.2 P	66.1 Ad[††††]	75.6 Ad	157.1 Ad*	157.2 Ad	--- S**	--- D***
					Weight Percent						
SiO₂	67.00	67.61	67.51	67.81	63.19	67.58	66.76	64.09	63.56	65.80	67.81
Al₂O₃	21.58	20.87	20.17	20.01	22.66	18.63	19.11	18.98	18.48	19.33	19.84
Fe₂O₃	0.57	0.00	0.05	0.12	0.19	0.80	0.74	0.13	0.13	0.13	0.83
CaO	1.19	0.27	0.00	0.00	4.00	0.00	0.00	0.00	0.00	0.34	0.22
Na₂O	10.68	11.16	11.27	11.11	8.03	0.07	0.11	0.64	0.36	5.32	4.71
K₂O	0.03	0.07	0.29	0.70	1.63	13.48	15.05	14.66	14.62	8.08	8.22
MnO	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.03
Total	101.05	99.98	99.29	99.75	99.70	100.60	101.82	98.50	97.15	99.00	101.66
				Numbers of ions on the basis of 32 oxygens							
Si	11.624	11.805	11.879	11.900	11.248	12.171	12.009	11.933	11.991	11.922	11.941
Al	4.413	4.296	4.184	4.140	4.754	3.953	4.051	4.167	4.110	4.129	4.119
Fe	0.075	0.000	0.007	0.015	0.026	0.018	0.100	0.019	0.019	0.018	0.111
Ca	0.222	0.050	0.000	0.000	0.763	0.000	0.000	0.000	0.000	0.067	0.042
Na	3.593	3.778	3.846	3.779	2.772	0.024	0.039	0.232	0.132	1.869	1.608
K	0.007	0.016	0.064	0.156	0.369	3.096	3.455	3.481	3.518	1.867	1.848
Mn	0.000	0.000	0.000	0.000	0.000	0.007	0.007	0.000	0.000	0.000	0.004

[†] Analyst: M. H. Beeson, U. S. Geological Survey.
[††] Sample numbers correspond to depth in meters.
[†††] Ab=hydrothermal albite
  P=plagioclase phenocryst.
  Ad=hydrothermal adularia.
  S=sanidine.
  D=devitrification alkali feldspar.

[††††] Average of three analyses.
  *Average of two analyses
  **Average of two analyses from Mallard Lake Member.
  ***Average of four analyses from Elephant Back flow of Central
  Plateau Member.

served in some of the clay. A thin, almost transparent, coating of white to light greenish-brown and red-stained kaolinite lines 45° to 60° fractures at 37.9 and 38.1 m. Kaolinite is one of the earliest of several hydrothermal minerals that line the fractures, in approximate order of paragenesis, pyrrhotite, kaolinite, intermediate heulandite, α-cristobalite, pyrite, and mordenite.

Chlorite. Chlorite is restricted to two zones, 37.9 to 55.6 m and 103.2 m to the bottom of the drill hole, 157.4 m (Fig. 2). In both zones, chlorite is most com-

monly found filling tiny cavities in association with magnetite, hematite, and pyrite and is probably an alteration product of pyroxene. A few pieces of greenish tuff and rhyolite in the lower zone contain chlorite that appears to have formed during alteration of the glass. In both zones, several fractures and cavities (seen in SEM) are partly lined with light- to dark-green massive clay or spherical clusters of platey crystals of chlorite deposited directly from solution.

Feldspar minerals

Plagioclase was identified in several whole-rock X-ray diffractograms, particularly from samples of the Mallard Lake Member. Thin-section studies indicate that most of the plagioclase consists of magmatic phenocrysts; the chemical analysis of one phenocryst listed in Table 5 and plotted in Figure 7 has an oligoclase composition. Plagioclase also occurs in thin-section as clear euhedral crystals filling vesicles in several pieces of core at 103.3, 116.0, 138.8, and 150.0 m and as an overgrowth on a sanidine grain at 157.1 m. Chemical analyses of these plagioclase crystals show that they are nearly pure albite (Ab_{94}–Ab_{98}) in composition and are probably hydrothermal in origin, although the structural state has not been investigated.

Hydrothermal plagioclase in cores from thermal areas of New Zealand is reported by Browne and Ellis (1970) and Steiner (1977) to form by replacement of primary plagioclase phenocrysts. The few
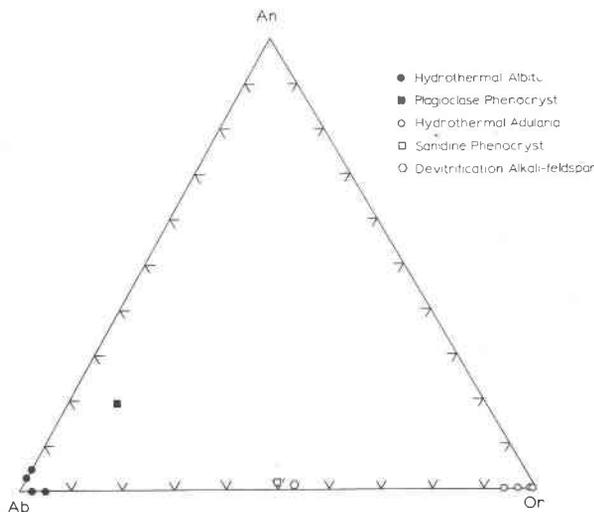
Fig. 7. An-Ab-Or ternary diagram for feldspar minerals encountered in Y-2 drill core. Data from Table 5.

occurrences of hydrothermal plagioclase in the Y-2 drill core mostly fill open spaces and thus appear to have been precipitated from solution.

Other feldspars in Y-2 are magmatic sanidine phenocrysts, devitrification alkali feldspar, vapor-phase alkali feldspar, and adularia. (Chemical analyses of three of these feldspar groups are given in Table 5 and are shown in Fig. 7). Sanidine and devitrification alkali feldspar compositions range between about Or_{49} and Or_{55} and are quite distinct from the nearly pure adularia (Or_{94}–Or_{99}) which is considered to be hydrothermal on the basis of its chemistry and mode of occurrence; its structural state was not determined.

A few fractures and cavities contain clear tabular crystals of adularia associated with later mordenite. Hydrothermal K-feldspar was observed in thin section as an overgrowth on sanidine (see also Keith *et al.*, 1978b, Fig. 10). In drill core Y-2, adularia occurs primarily as an alteration product of glass.

The two zones of hydrothermal K-feldspar, shown in Figure 2 at 57.8 to 96.9 m and 127.6 to 152.4 m, are based mostly on whole-rock X-ray diffraction studies. Diffraction patterns for adularia are quite distinct from diffractograms of the other three forms of alkali feldspar in Y-2, which display reflections characteristic of sanidine. The two adularia zones are nearly coincident with two potassium-rich zones revealed in whole-rock chemical analyses.

Aegirine

The bottom 13 cm of drill core contain prismatic to bladed, euhedral bright-green pleochroic hydrothermal aegirine crystals, along with later bladed chlorite crystal clusters deposited in cavities created by partial leaching of primary sanidine phenocrysts. Replicate microprobe analyses of aegirine from two samples (Table 6) range in composition between aegirine and aegirine-augite (Fig. 8).

Iron and manganese oxide minerals

Brown to black, massive to dendritic manganese oxides were precipitated in core between 0.8 and 8.5 m, in part contemporaneous with siliceous sinter; core from 7.3 m contains interbedded primary sinter and manganese oxide. Circulating thermal waters also deposited manganese minerals in cavities and along fractures in the porous sinter. X-ray-diffraction analysis of a manganese precipitate from 7.3 m indicates that the deposit is poorly crystalline but appears to be composed of cryptomelane and manganite. Thin-section and microprobe studies of the

Table 6. Microprobe analyses of hydrothermal aegirine from Y-2 drill core.[†]

Sample no. [††]	157.1	157.1	157.1	157.2	157.2
Weight Percent					
SiO_2	51.96	51.52	51.99	51.86	52.01
Al_2O_3	0.71	1.02	0.41	0.83	0.63
Fe_2O_3	31.23	31.87	31.95	33.35	32.92
MnO	0.88	0.74	0.74	0.32	0.35
CaO	5.14	8.22	2.12	1.97	1.43
Na_2O	9.94	9.21	12.74	12.71	13.03
K_2O	1.06	0.03	0.04	0.03	0.09
Total	100.92	102.61	99.99	101.07	100.46
Numbers of ions on the basis of 6 oxygens					
Si	1.986	1.942	1.999	1.975	1.990
Al	0.032	0.045	0.018	0.037	0.028
Fe	0.898	0.904	0.925	0.956	0.948
Mn	0.028	0.024	0.024	0.010	0.011
Ca	0.210	0.332	0.087	0.080	0.059
Na	0.736	0.673	0.950	0.939	0.967
K	0.051	0.001	0.002	0.001	0.004

[†] Analyst: M. H. Beeson, U. S. Geological Survey.
[††] Sample numbers correspond to depth in meters.

sample show the presence of two intergrown varieties of manganese oxide that have a considerable range in chemistry from grain to grain, the MnO_2 varying from 81.6 to 88.3 percent in one variety and from 71.1 to 92.3 percent in the other. Another manganese deposit at 7.8 m was identified in X-ray as well-crystallized pyrolusite.

At 32.5 m, two parallel subhorizontal fractures(?) are coated by ~1 mm of brown-black manganese oxide minerals: cryptomelane, manganite, and groutite. Core adjacent to the fractures is peppered with manganese oxide, which decreases in abundance away from the fractures.

The sample from 32.5 m contains a few greenish-brown clayey patches that constitute the only occurrence of goethite in the Y-2 drill core. The only other iron oxide identified (by X-ray) in the drill core is hematite, sparsely distributed throughout the upper three-fifths of the core, more abundant in the lower part, particularly in flow rocks of the Mallard Lake Member (see Fig. 2). Hematite commonly occurs as an alteration product of magnetite and fills tiny cavities in association with chlorite and pyrite suggesting that pyroxene may have been one of the original constituents. Several pieces of core scattered throughout the drill hole have varying degrees of red staining that presumably is hematite; a few pieces in the sedimentary or volcaniclastic sections, particularly at 113.9 m, appear to be cemented by hematite and clay. In fractured and brecciated zones hematite lines fractures later filled by mordenite, and coats vapor-phase minerals and chalcedony in a few cavities.
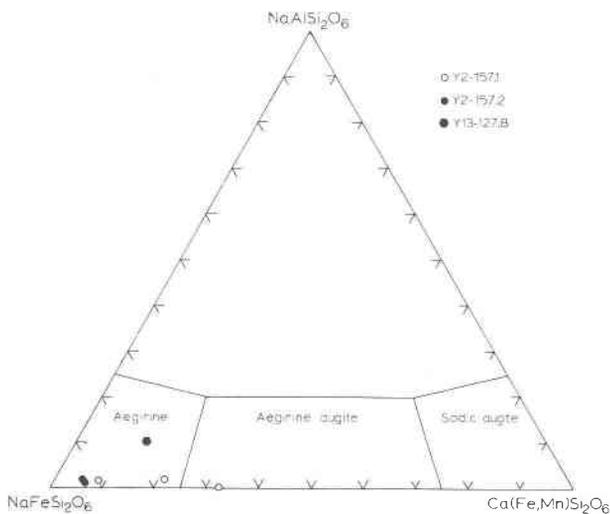
Fig. 8. $NaAlSi_2O_6$–$NaFeSi_2O_6$–$Ca(Fe,Mn)Si_2O_6$ ternary diagram showing variation in aegirine composition for two samples from drill core Y-2 (data from Table 6) and one sample from Y-13. Composition of aegirine from drill core Y-13 from T. E. C. Keith and M. H. Beeson (unpub. data, 1979).

Sulfide minerals

Tiny (generally less than 0.5 mm) euhedral cubic pyrite crystals are disseminated throughout much of the groundmass of the Y-2 drill core, becoming most abundant in the lavas of the Mallard Lake Member (see Fig. 2). Pyrite crystals commonly occur in association with chlorite, hematite, and partly altered(?) magnetite, which suggests that the pyrite is probably related to alteration of pyroxene and magnetite. Individual pyrite crystals or clusters of crystals that line cavities, veins, and fractures were deposited from circulating thermal waters. Pyrite appears to be an early hydrothermal mineral and may even be contemporaneous with chalcedony at 47.4 m.

Between 37.9 and 55.6 m, the core contains bronze tabular hexagonal pyrrhotite crystals that range in size from about 0.5 mm to ~5 mm, the only occurrence of pyrrhotite in all of the Yellowstone research drill cores. Pyrrhotite samples from 37.9 and 39.3 m display sharp, nearly symmetrical (102) peaks near 2.07Å and no observable (202) peaks when X-rayed at ¼°/minute, indicating that the pyrrhotite probably does not have a monoclinic component (Arnold, 1966). Pyrite is present in the core at this depth but is fairly sparse in the main pyrrhotite zone at 43.6 to 53.2 m (see Fig. 2). Pyrrhotite crystals are deposited in cavities on top of vapor-phase alkali feldspar and tridymite crystals or hydrothermal chalcedony and along fractures, usually later than chalcedony. Pyr-

rhotite platelets lining a fracture at 51.7 m appear to be both earlier and later than the thin chalcedony coating.

Browne and Ellis (1970) and Steiner (1977) found pyrrhotite in drill core from New Zealand thermal areas where temperatures ranged from about 152° to 268°C. In Y-2, the temperature range in which pyrrhotite occurs is about 130° to 152°C.

Summary and discussion

The Y-2 drill hole penetrated interbedded siliceous sinter and travertine, obsidian-rich glacial sediments of the Pinedale Glaciation, and glassy rhyolitic lava and related volcaniclastic rocks of the Elephant Back flow of the Central Plateau and Mallard Lake Members of the Pleistocene Plateau Rhyolite. Hydrothermal alteration is pervasive throughout most of the recovered core and consists essentially of (1) conversion of rhyolitic glass to several zeolite and clay minerals as well as to quartz and adularia, and (2) deposition of these minerals in vugs, veins and fractures along with several carbonate, oxide, sulfide and feldspar minerals.

Chemical analyses of the Yellowstone Plateau rhyolites (Boyd, 1961; Hamilton, 1963; R. L. Christiansen, unpub. data, 1974) all contain abundant sodium and potassium but little calcium or magnesium. Hydrothermal minerals containing sodium or potassium as the dominant cations are, as would be expected, plentiful in the drill core, and magnesian minerals are entirely absent. However, several calcium-rich hydrothermal minerals do occur in Y-2. Calcium enrichment appears to be produced by extraction of this element from the circulating thermal waters.

Reliable chemical analyses of water from Y-2 were not obtained prior to sealing of the drill hole. Chemical analyses of hot-spring water from the immediate vicinity of Y-2 show that the present travertine-depositing water (similar to Steady Geyser in Table 1) is much lower in silica and contains considerably more calcium than the higher silica, sodium, and chloride water (like that of Surprise Pool in Table 1) responsible for deposition of the more extensive siliceous sinter found in Y-2 (Fig. 2) and the surrounding area (see map of Waldrop and Pierce, 1975). Travertine interbedded with siliceous sinter in the upper part of the drill core suggests that the water regime precipitating the two kinds of surficial deposits has in the past alternated between the two types of water given in Table 1.

The distribution of several calcium-rich and sodium- and potassium-rich hydrothermal minerals

with depth in the Y-2 drill core is shown in Figure 9. From about 7 to 19 m, calcite, calcium-rich, montmorillonite, and intermediate heulandite (calcium-rich) are the predominant minerals. Sodium-and potassium-rich minerals (clinoptilolite, sodium-rich montmorillonite, mixed-layer illite-montmorillonite, and illite) are abundant between approximately 19 and 33 m; intermediate heulandite overlaps near the top and calcium-rich mordenite overlaps at the bottom of the zone. A second calcium-rich zone occurs between about 33 and 56 m, where there is a sharp break between calcium-rich and sodium- and potassium-rich minerals. Clinoptilolite was found down to a depth of about 109 m. Sodium-rich mordenite is abundant throughout the same depth range; below 109 m, it occurs sporadically to a depth of about 152 m. The sodium- and potassium-rich clay minerals are found throughout the interval from 56 to 152 m. Hydrothermal adularia occurs in two zones, from 58 to 97 m and from 127 to 152 m. Analcime was found in two general zones at about 109 to 111 m and 150 to 154 m.

Calcite occurs sporadically below 93 m, becoming fairly abundant below 152 m. Laumontite, a calcium zeolite mineral, was found between 150 and 155 m, yugawaralite between 149 and 152 m. Several other calcium-rich minerals were found near the same depth. The only occurrence of clear euhedral fluorite crystals in the drill core was at 155.2 m. One sample at 152 m contains wairakite. A hydrous calcium silicate mineral, truscottite, partially lines a few cavities in core from 149.2 m. A mineral occurring as a vesicle filling at 152.1 m that has replicate microprobe analyses indicating about 75 percent CaO was tentatively identified as portlandite(?). A gradual decline of hydrothermal sodium minerals near the bottom of the drill core and the presence of multifarious calcium minerals suggest that a third calcium-rich zone may occur near the base of Y-2.

The alternating zones of calcium-rich and sodium- and potassium-rich minerals in the drill core are not coincident with changes in lithology and thus do not appear to have resulted from differences in the composition of the starting materials. Factors that influence the distribution and kind of mineral assemblages present in hydrothermal systems in addition to rock and water composition, are permeability and porosity of the rocks, water temperature, confining pressure, and duration of hydrothermal alteration (Browne and Ellis, 1970).

Other than a reasonable speculation that hydrothermal alteration has occurred in this area since at
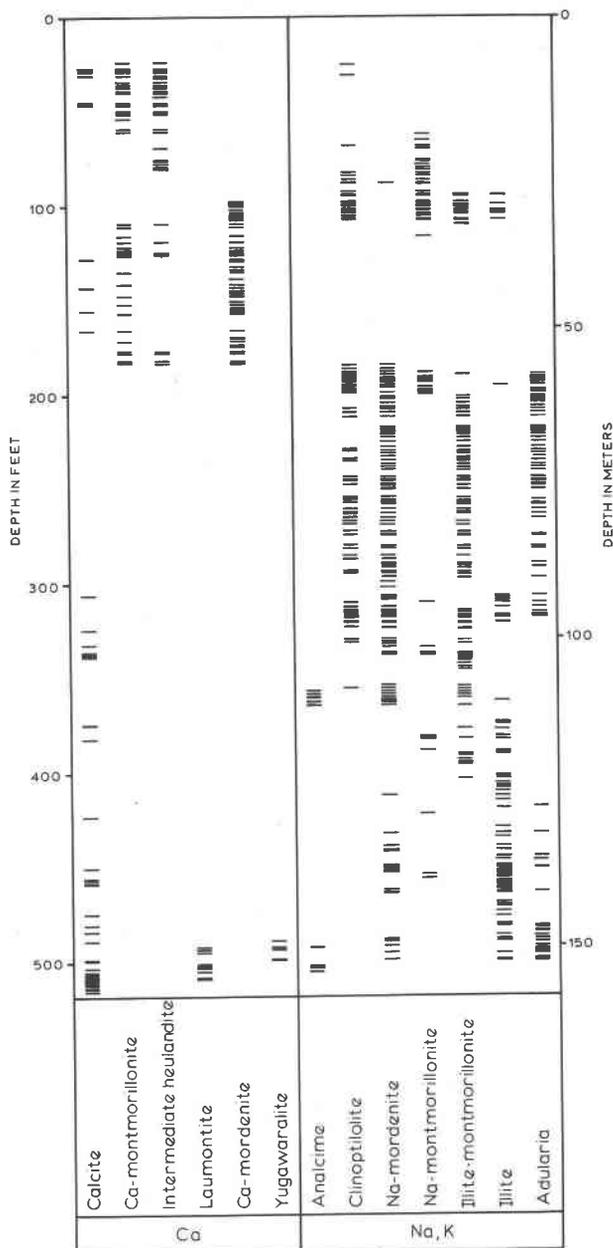
Fig. 9. Distribution of calcium-rich and sodium- and potassium-rich hydrothermal minerals in drill core Y-2

least 150,000 years B.P. (Eaton *et al.*, 1975; Fournier *et al.*, 1976), no information on the duration of hydrothermal activity is known.

According to drilling information of White *et al.* (1975), the wellhead fluid pressure is low in the upper 40 m and increases irregularly to the bottom of the hole. White *et al.* report a near-bottom fluid pressure of 16.4 kg/cm^2 at 148.7 m; however, they indicate that the actual bottom-hole pressure (at 157.4 m) may have been at least as much as 17.9 kg/cm^2. Such

pressures (less than 200 atmospheres) are, according to Browne and Ellis (1970), not likely to greatly influence the formation of hydrothermal mineral assemblages, although the distribution of bladed calcite is undoubtedly influenced by the depth at which boiling occurs (Browne and Ellis, 1970; Honda and Muffler, 1970; Keith et al., 1978b).

Calculated porosity, based on the difference between bulk- and powder-density measurements varies from about 24 to 48 percent in the sinter, glacial and volcaniclastic sediments, and pumiceous tuffs, it generally ranges between 5 and 19 percent in the Elephant Back flow and 6 to 16 percent in the Mallard Lake flow. One exception occurs at 66.1 m where a sample of Elephant Back flow has a porosity of 40 percent, probably due to the abundance of pumiceous fragments in the flow breccia. The porosity and resultant permeability of the sediment and tuff beds are uniformly higher than in the rhyolitic rocks, although the degree of hydrothermal alteration, while quite variable, appears to be only slightly greater. The permeability and consequent extent of hydrothermal alteration of the rhyolitic rocks is undoubtedly increased by the abundance of fractures in the rock.

Unaltered obsidian grains occur sporadically throughout the glacial sediments to a depth of about 28.2 m, where the temperature measured during drilling was about 115°C (see Fig. 2). Dark-gray, fairly fresh banded perlite occurs at 79.9 m at a temperature only slightly below the reference boiling-point curve. Rhyolitic glass is metastable and is readily altered to more stable minerals. The persistence of glass at temperatures to about 162°C suggests that temperature is not the most important factor controlling glass alteration, a conclusion consistent with work of Keith et al. (1978b) for Y-7 and Y-8.

Several minerals appear to be independent of temperature because they occur over a range of temperature. Minerals that occur in more than one zone or are distributed throughout a wide temperature range include clinoptilolite, β-cristobalite, α-cristobalite, quartz, chalcedony, intermediate heulandite, mordenite, calcite, chlorite, adularia, hematite and pyrite (Fig. 2). Other minerals are sparsely distributed over a narrow temperature range in the core and may or may not be temperature dependent; these include erionite, analcime, wairakite, dachiardite, laumontite, yugawaralite, truscottite, fluorite, siderite, aegirine, manganite, cryptomelane, pyrolusite, groutite, goethite, pyrrhotite, and portlandite(?).

Erionite was found only at a depth of 11.3 m, where the temperature was probably around 90°C. This mineral also occurs in Y-1, Y-5, and Y-8 at temperatures below 100°C (Honda and Muffler, 1970; Keith and Muffler, 1978; Keith et al., 1978b).

The clay minerals appear to be partially independent of temperature as shown in Figure 9 by the distribution of various calcium, sodium, and potassium phases. Some temperature dependence appears likely, as a sharp break between montmorillonite and mixed-layer illite-montmorillonite occurs at about 60.7 m, corresponding to a temperature of about 155°C. The break between illite-montmorillonite and illite is not as abrupt and occurs at about 110–120 m at a temperature of about 180–190°C. In the Salton Sea and Ohaki-Broadlands geothermal areas, these two breaks occur at temperatures of about 100°C and 210°C, respectively (Muffler and White, 1969; Browne and Ellis, 1970).

Most of the opal in Y-2 was deposited as hot-spring sinter that has been altered to β-cristobalite and zeolite minerals with preservation of original textures. Some opal occurs as fragile white blocky or clear beaded cavity fillings and white horizontally bedded deposits in the bottoms of a few cavities. Several similar open-space fillings a little deeper in the core composed of β-cristobalite, α-cristobalite, or chalcedony lead us to believe that these silica minerals may have been precipitated as opal and later converted to more stable silica phases depending on temperature and silica solubilities. Some chalcedony appears to have formed with replacement of calcite in the shallow travertine deposits. Probably the more extensively distributed open-space prismatic quartz crystals were deposted directly from solution. These interpretations of silica mineral distribution are consistent with conclusions based on studies of other Yellowstone drill cores. The criteria for the formation of the various silica phases are discussed in more detail by Honda and Muffler (1970), Keith and Muffler (1978), and Keith et al. (1978b).

Factors such as rock composition, pressure, temperature, permeability, and time all undoubtedly influence, in varying degrees, the formation of hydrothermal minerals in the Y-2 drill core. The single most important influence appears to be water chemistry. Change in water composition with depth and time is indicated by the alternation of calcium-rich and sodium- and potassium-rich hydrothermal minerals and deposition of interbedded travertine and siliceous sinter.

Acknowledgments

References

Alberti, A. (1975) Sodium-rich dachiardite from Alpe de Siusi, Italy. Contributions to Mineralogy and Petrology, 49, 63–66.

Alietti, A. (1967) Heulanditi e clinoptiloliti. Mineralogica Et Petrographica Acta, 13, 119–138.

Alietti, A. (1972) Polymorphism and crystal-chemistry of heulandites and clinoptilolites. American Mineralogist, 57, 1448–1462.

Allen, E. T., and Day, A. L. (1935) Hot springs of the Yellowstone Park. Carnegie Institute of Washington Publication, 466.

Arnold, R. G. (1966) Mixtures of hexagonal and monoclinic pyrrhotite and the measurement of the metal content of pyrrhotite by X-ray diffraction. American Mineralogist, 51, 1221–1227.

Bargar, K. E., Beeson, M. H., Fournier, R. O., and Muffler, L. J. P. (1973) Present-day deposition of lepidolite from thermal waters in Yellowstone National Park. American Mineralogist, 58, 901–904.

Bargar, K. E., Beeson, M. H., and Keith, T. E. C., (1981) Zeolites in Yellowstone National Park. Mineralogical Record, 12, 29–38.

Berman, H. (1925) Notes on dachiardite. American Mineralogist, 10, 421–428.

Boles, J. R. (1972) Composition, optical properties, cell dimensions, and thermal stability of some heulandite-group zeolites. American Mineralogist, 57, 1463–1493.

Browne, P. R. L., and Ellis, A. J. (1970) The Ohaki-Broadlands hydrothermal area, New Zealand: mineralogy and related geochemistry. American Journal of Science, 269, 97–131.

Boyd, F. R. (1961) Welded tuffs and flows in the rhyolite plateau of Yellowstone Park, Wyoming. Geological Society of America Bulletin, 72, 387–426.

Christiansen, R. L., and Blank, H. R., Jr. (1974) Geologic map of the Madison Junction quadrangle, Yellowstone National Park, Wyoming. U.S. Geological Survey Geologic Quadrangle Map GQ-1190

Coombs, D. S. (1955) X-ray observations on wairakite and noncubic analcime. Mineralogical Magazine, 30, 699–708.

Eaton, G. P., Christiansen, R. L., Iyer, H.M., Pitt, A. M., Mabey, D. R., Blank, H. R., Jr., Zietz, I., and Gettings, M. E. (1975) Magma beneath Yellowstone National Park. Science, 188, 787–796.

Eberlein, G. D., Erd, R. C., Weber, F., and Beatty, L. B. (1971) New occurrence of yugawaralite from the Chena Hot Springs area, Alaska. American Mineralogist, 56, 1699–1717.

Fenner, C. N. (1936) Bore-hole investigations in Yellowstone Park. Journal of Geology, 44, 225–315.

Fournier, R. O., and Rowe, J. J. (1966) Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells. American Journal of Science, 264, 685–697.

Fournier, R. O., and Truesdell, A. H. (1970) Chemical indicators of subsurface temperatures applied to hot spring waters in Yellowstone National Park, Wyoming, U.S.A. Geothermics, Special Issue 2, 2, 529–535.

Fournier, R. O., White, D. E., and Truesdell, A. H. (1976) Convective heat flow in Yellowstone National Park. Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, USA, 20–29 May, 1975, 1, 731–739. U.S. Government Printing Office, Washington D.C.

Gottardi, G. (1960) Sul dimorfismo mordenite-dachiardite. Peridico Di Mineralogica (Rome), 29, 183–191.

Grim, R. E. (1968) Clay mineralogy. McGraw-Hill, San Francisco.

Hamilton, W. (1963) Petrology of rhyolite and basalt, northwestern Yellowstone Plateau. U.S. Geological Survey Professional Paper 475-C, C78–C81.

Hawkins, D. B. (1974) Statistical analyses of the zeolites clinoptilolite and heulandite. Contributions to Mineralogy and Petrology, 45, 27–36.

Honda, S., and Muffler, L. J. P. (1970) Hydrothermal alteration in core from research drill hole Y-1, Upper Geyser Basin, Yellowstone National Park, Wyoming. American Mineralogist, 55, 1714–1737.

Honda, S., and Sasaki, K. (1977) Scanning electron micrographs of zeolites produced by hydrothermal alteration—an example in core from research drill hole Y-1, Yellowstone National Park, U.S.A. Ahido University Mineralogy Publication, 44, 16.

Hower, J., and Mowatt, T. C. (1966) The mineralogy of illite/montmorillonite. American Mineralogist, 51, 825–854.

Keith, T. E. C., and Muffler, L. J. P. (1978) Minerals produced during cooling and hydrothermal alteration of ash flow tuff from Yellowstone drill hole Y-5. Journal of Volcanology and Geothermal Research, 3, 373–402.

Keith, T. E. C., Beeson, M. H., and White, D. E. (1978a) Hydrothermal minerals in U.S. Geological Survey research drill hole Y-13, Yellowstone National Park, Wyoming. (abstr.) Geological Society of America Abstracts with Programs, 10, 432–433.

Keith, T. E. C., White, D. E., and Beeson, M. H. (1978b) Hydrothermal alteration and self-sealing in Y-7 and Y-8 drill holes in northern part of Upper Geyser Basin, Yellowstone National Park, Wyoming. U.S. Geological Survey Professional Paper 1054-A.

Muffler, L. J. P., and Bargar, K. E. (1974) Hydrothermal alteration of rhyolitic ash-flow tuff in the vapor-dominated geothermal system at Mud Volcano, Yellowstone National Park, U.S.A. (abstr.) International Symposium on Water-Rock Interaction, Prague, Czechoslavakia, Abstract Volume, 52.

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. Geological Society of America Bulletin, 80, 157–182.

Mumpton, F. A. (1960) Clinoptilolite redefined. American Mineralogist, 45, 351–369.

Murata, K. J., and Larson, R. R. (1975) Diagenesis of Miocene siliceous shales, Temblor Range, California. Journal of Research of the U.S. Geological Survey, 3, 553–566.

Pierce, K. L., Obradovich, J. D., and Friedman, I. (1976) Obsidian hydration dating and correlation of Bull Lake and Pinedale Glaciations near West Yellowstone, Montana. Geological Society of America Bulletin, 87, 703–710.

Pongiluppi, D. (1977) A new occurrence of yugawaralite at Osilo, Sardinia. Canadian Mineralogist, 15, 113–114.

Rowe, J. J., Fournier, R. O., and Morey, G. W. (1973) Chemical

analysis of thermal waters in Yellowstone National Park, Wyoming, 1960–65. U.S. Geological Survey Bulletin 1303.

Seki, Y. (1973) Ionic substitution and stability of mordenite. Journal of the Geological Society of Japan, 79, 669–676.

Steiner, A. (1977) The Wairakei geothermal area, North Island, New Zealand: Its subsurface geology and hydrothermal rock alteration. New Zealand Geological Survey Bulletin 90.

Thompson, J. M., Presser, T. S., Barnes, R. B., and Bird, D. B. (1975) Chemical analysis of the waters of Yellowstone National Park, Wyoming from 1965-1973. U.S. Geological Survey Open-file Report 75-25.

Thompson, J. M., and Yadav, S. (1979) Chemical analyses of waters from geysers, hot springs and pools in Yellowstone National Park, Wyoming from 1974 to 1978. U.S. Geological Survey Open-file Report 79-704.

Waldrop, H. A., and Pierce, K. L. (1975) Surficial geologic map of the Madison Junction quadrangle, Yellowstone National Park, Wyoming. U.S. Geological Survey Miscellaneous Geologic Investigations Map I-651.

Walker, G. F. (1957) On the differentiation of vermiculite and smectites in clays. Clay Minerals Bulletin, 3, 154–163.

Warshaw, C. M., and Roy, R. (1961) Classification and a scheme for the identification of layer silicates. Geological Society of America Bulletin, 72, 1455–1492.

Weaver, C. E. (1956) The distribution and identification of mixed-layer clays in sedimentary rocks. American Mineralogist, 41, 202–221.

White, D. E. (1955) Thermal springs and epithermal ore deposits. In A. M. Bateman, Ed., Economic Geology pt. 1, p. 99–154, Economic Geology Publishing Company, Urbana, Illinois.

White, D. E., Fournier, R. O., Muffler, L. J. P., and Truesdell, A. H. (1975) Physical results of research drilling in thermal areas of Yellowstone National Park, Wyoming. U.S. Geological Survey Professional Paper 892.

Wise, W. S. (1978) Yugawaralite from Bombay, India. Mineralogical Record, 9, 296.

Wise, W. S., and Tschernich, R. W. (1976) Chemical composition of ferrierite. American Mineralogist, 61, 60–66.

Wise, W. S., and Tschernich, R. W. (1978) Dachiardite-bearing assemblages in the Pacific Northwest. In L. B. Sand, and F. A. Mumpton, Eds., Natural Zeolites: Occurrence, Properties, Use. p. 105–111, Pergamon, New York.