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DACHIARDITE FROM YELLOWSTONE NATIONAL PARK, WYOMING

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ABSTRACT

Dachiardite [$(Ca,Na_2,K_2)_5Al_{10}Si_{38}O_{96} \cdot 25H_2O$] crystals have been identified in a few isolated fractures and cavities within hydrothermally altered Late Pleistocene rhyolite flows, tuffs, and glacial sediments in drill-core samples from Yellowstone National Park, Wyoming. The colorless, radiating, bladed to acicular, euhedral crystals are elongate (as much as 1.5 mm) on [010] and flattened on {001}. Dachiardite is monoclinic, space group *C2/m*. Optical data from the best specimen, Y3-73.2, show slightly variable indices of refraction: α 1.488–1.490, β 1.490–1.492, γ 1.494–1.496, $2V_z$ 71–72°, and moderate dispersion $r > v$. Corresponding unit-cell parameters are: *a* 18.636(3), *b* 7.505(2), *c* 10.239(1) Å, β 107.95°, *V* 1362.4(3) Å^3. Results of more than 40 microprobe analyses of dachiardite from 3 drill cores in Lower Geyser Basin indicate that the crystals are chemically inhomogeneous and contain higher concentrations of calcium than previously reported from other areas. A nearly continuous solid-solution series between dachiardite and sodium dachiardite may exist, although our data suggest a gap for intermediate compositions due to greater potassium concentrations. The Yellowstone dachiardite precipitated from thermal waters, at approximately 100–200°C, along with several other Ca-rich zeolites (including yugawaralite, mordenite, and epistilbite) and other calcium-bearing minerals.

Keywords: dachiardite, yugawaralite, mordenite, epistilbite, hydrothermal alteration, zeolites, optical properties, electron-microprobe chemical data, Yellowstone National Park, Wyoming.

SOMMAIRE

On a identifié des cristaux de dachiardite $(Ca,Na_2,K_2)_5Al_{10}Si_{38}O_{96} \cdot 25H_2O$ dans quelques fissures et cavités isolées dans des carottes traversant coulées et tufs rhyolitiques altérés d'âge pleistocène tardif et sédiments glaciaires, dans le parc national de Yellowstone (Wyoming). Les cristaux sont incolores, fibroradiés, en lames ou en aiguilles selon [010] atteignant 1.5 mm, idiomorphes et applatis sur {001}. La dachiardite est monoclinique, groupe spatial *C2/m*. Le meilleur échantillon, Y3-73.2, montre des indices de réfraction légèrement variables: α 1.488–1.490, β 1.490–1.492, γ 1.494-1.496, $2V_z$ 71–72°, dispersion moyenne $r > v$. Les paramètres du réseau sont: *a* 18.636(3), *b* 7.505(2), *c* 10.239(1) Å, β 107.95°, *V* 1362.4(3) Å^3. Plus de 40 analyses à la microsonde des cristaux prélevés sur carottes du bassin Lower Geyser révèlent une hétérogénéité, et en plus une teneur plus élevée en calcium que la dachiardite décrite d'autres endroits. Une solution solide quasi-continue existerait entre dachiardite et dachiardite-Na, quoique nos données font penser qu'il y a lacune de miscibilité pour les compositions intermédiaires due à la présence du potassium. À Yellowstone, la dachiardite aurait précipité d'eaux thermales à environ 100–200°C, avec plusieurs autres zéolites calciques (dont yugawaralite, mordenite, épistilbite) et minéraux qui contiennent du calcium.

(Traduit par la Rédaction)

Mots-clés: dachiardite, yugawaralite, mordenite, épistilbite, altération hydrothermale, zéolites, propriétés optiques, analyses à la microsonde électronique, parc national de Yellowstone, Wyoming.

INTRODUCTION

Dachiardite apparently is a rare member of the mordenite group of zeolites. It was known only from a single occurrence at the type locality (San Piero di Campo, Elba, Italy) from the time of its discovery and description (D'Achiardi 1905, 1906) until a second occurrence was found in Japan in 1964 (Nishido & Otsuka 1981). The sodium analogue, from the Alpe di Siusi, Italy, was described by Alberti in 1975. Thus there were only two published accounts for dachiardite in a seventy-year period. Undoubtedly the rarity of dachiardite is more apparent than real, for in the eleven subsequent years there have been about a dozen occurrences of "calcium-rich" or "sodium-rich" dachiardites reported (Nishido & Otsuka 1981, Postl & Walter 1982, Gottardi & Galli 1985). The paucity of published pre-1976 accounts of dachiardite appears to be due primarily to lack of recognition of the mineral. In all subsequent occurrences, dachiardite has been found to more closely resemble mordenite (with which it is commonly associated) in appearance than it does the type material, which appears to be unique in its morphology, size and perfection of crystals. In fact, Gottardi & Galli (1985, p. 235) stated that ". . . there are two kinds of dachiardite: non-fibrous (Elba) with nearly 1% of Cs_2O, fibrous (all others) without Cs_2O."

In a careful comparative study of the seven occurrences then known, Nishido & Otsuka (1981) outlined the features that distinguish dachiardite from its sodium analogue, described the new occurrence of a possible intermediate phase, and suggested that a continuous series may exist between the two minerals. Sufficient additional data have been accumulated since Nishido's and Otsuka's study, including those of the present investigation, to largely confirm their conclusions and to enlarge upon them.

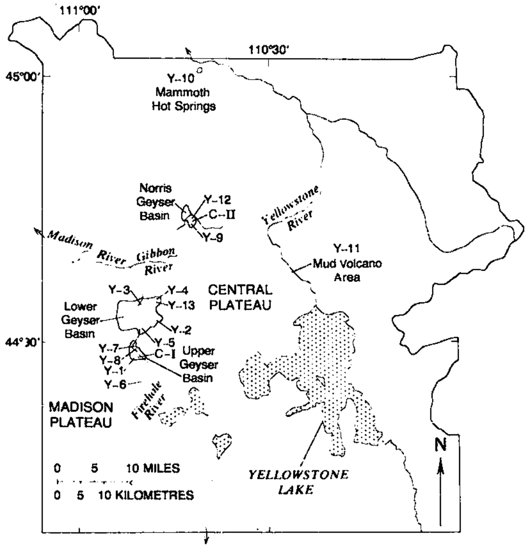

FIG. 1. Index map of Yellowstone National Park showing the location of the 13 (Y-1 through Y-13) U.S. Geological Survey drill holes. Drill holes C-I and C-II were drilled by the Carnegie Institution of Washington in 1929 (Fenner 1936). Dachiardite was identified in Y-2, Y-3, Y-6 and Y-13.

We concur with the conclusions of Nishido & Otsuka but, in addition, follow the nomenclature and formulation of Fleischer (1983, p. 40, 151) in distinguishing "Dachiardite, $(Ca,Na_2,K_2)_5Al_{10}Si_{38}O_{96}\cdot 25H_2O$" from "Sodium dachiardite, $(Na_2,Ca,K_2)_{4-5}Al_8Si_{40}O_{96}\cdot 26H_2O$". The reasons for making this distinction are significant. Described occurrences of material that may be classified as sodium dachiardite are double those of recognized dachiardite.

Thirteen research diamond-drill holes (Fig. 1) were completed in hot spring and geyser areas of Yellowstone National Park, Wyoming by the U.S. Geological Survey in 1967 and 1968 in order to collect detailed physical and chemical data on the upper part of an active deeply circulating high-temperature geothermal system (White *et al.* 1975). Extremely minute quantities (<100 mg total sample) of dachiardite were discovered in fractures and cavities of hydrothermally altered Late Pleistocene rhyolite, tuff, and glacial sediments in four of the thirteen drill holes. Three drill holes containing dachiardite (Y-2, Y-3 and Y-13) are clustered in Lower Geyser Basin; a fourth (Y-6) occurs in the upper reaches of the Firehole River. This hydrothermal dachiardite is of interest in that some specimens (Table 3) are near the Ca end-member in composition; it is nonfibrous but of different morphology than the Elba material, and occurs in fine crystals that give sharp X-ray-diffraction maxima (so far only reported for Elba dachiardite). In addition to dachiardite, optical and crystallographic data are given for accompanying mordenite, epistilbite, and yugawaralite. Information on the optical properties of these zeolite minerals has been only sparsely reported (Gottardi & Galli 1985).

GEOLOGICAL OCCURRENCE

The four Yellowstone drill holes in which dachiardite has been found penetrate hydrothermally altered Late Pleistocene rhyolite flows and tuffaceous deposits that are mantled by Late Pleistocene to Holocene glacial sediments, and, in some drill cores, hot-spring travertine or siliceous sinter deposits (Keith *et al.* 1978, Bargar & Beeson 1981, 1984, 1985). Hydrothermal alteration in the Yellowstone Park area appears to have been active during the past 266,000 years and may possibly date back to about 600,000 years B.P. (Silberman *et al.* 1979). Maximum temperatures and near- bottom fluid pressures measured for the four dachiardite-bearing drill holes (141.7–157.3 m deep) vary from 180.8 to 203.4°C and from 1,497 to 1,607 kPa, respectively (White *et al.* 1975). Fluid-inclusion studies of hydrothermal quartz crystals from these drill holes indicate that temperatures and pressures, at a given depth in the drill holes, were probably somewhat higher between about 14,000 and 45,000 years ago owing to the additional weight of up to about 490 m of glacial ice (Bargar *et al.* 1985).

In drill hole Y-2, aggregates of intergrown tabular dachiardite crystals occur in altered tuffaceous sediment at 20.7–25.1 m along with kaolinite, later mordenite and Na-smectite, and earlier heulandite (Fig. 2). At this depth the temperature measured during drilling was about 100–110°C. Colorless blocky dachiardite crystals also line a fracture in a rhyolite flow at 152.0 m (temperature measured during drilling was about 200°C) in association with earlier euhedral quartz, bladed calcite, tabular yugawaralite crystals, and later fibrous mordenite.

In drill core Y-2, several Ca-bearing hydrothermal alteration minerals (dachiardite, calcite, laumontite, Ca-mordenite, yugawaralite, fluorite, wairakite, truscottite, Ca-smectite, and heulandite) were deposited in zones that alternate with zones containing Na- or K-bearing minerals (analcime, clinoptilolite, Na-mordenite, Na-smectite, illite–smectite, illite, and adularia) (Bargar & Beeson 1981). These alternating calcium and sodium plus potassium mineral zones probably formed by deposition from two or more aquifers that contained thermal waters of significantly different chemical compositions. Dachiardite from drill core Y-2 is intermediate in composition (with respect to Ca, Na and K) and was deposited at an apparent boundary between Ca-rich and (Na + K)-rich zones.

Dachiardite in drill core Y-3 lines cavities and veins at scattered locations between 60.2 and 80.9 m. The colorless, radiating, blocky-bladed dachiardite crystals were deposited later than chalcedony and quartz, and they formed earlier than mordenite and smectite in Figure 3B; however, in other Y-3 occurrences, mordenite appears to be deposited earlier or is codepositional with dachiardite. Clear, tabular yugawaralite crystals occur at 71.1 m and are codepositional or slightly later than dachiardite. At these depths the temperatures measured during drilling varied from about 150 to 170°C.

In drill hole Y-3, hydrothermal minerals that contain Na as the dominant cation (analcime, clinoptilolite, Na-mordenite, Na-smectite, and aegirine) are predominant in the sedimentary section of drill core above 42 m. The deeper volcanic section of this drill core contains several hydrothermal minerals rich in Ca (laumontite, mordenite, yugawaralite, calcite, fluorite, Ca-smectite and truscottite) in addition to dachiardite. A comparison of chemical compositions of water from nearby Ojo Caliente Hot Spring with water from 88 m and from the bottom of the Y-3 drill hole show about 35% loss of calcium between the bottom of the drill hole and the surface (Bargar & Beeson 1985). Part of this Ca is probably taken up by dachiardite and associated Ca minerals in Y-3.

In Y-6, the dachiardite crystals fill cavities in three widely separated samples from depths of 21.2, 72.2, and 98.1 m, where the temperatures measured during drilling varied from about 50 to 150°C. The dachiardite appears to have formed later than clinoptilolite, calcite and quartz, and earlier than mordenite and smectite. A cavity filling at 72.2 m contains short, stubby bundles of bladed dachiardite crystals that are closely associated with mordenite (Fig. 4). At 98.1 m, the dachiardite consists of acicular aggregates of bladed crystals (Fig. 5) that were deposited before associated smectite and mordenite. The aggregates are formed by bladed crystals repeatedly twinned on {001} (Fig. 6).

In Y-13 drill core, clear blocky crystals of dachiardite occur at 50.9 m depth in two small cavities of a hydrothermally altered rhyolite flow. Tiny clear quartz euhedra with sporadically associated chlorite and pyrite line cavities in the rhyolite. Small amounts of dachiardite, epistilbite, laumontite, mordenite and truscottite were deposited upon the quartz. Temperature measured during drilling was approximately 162°C at this depth.

Dachiardite in Y-13 occurs over a vertical distance of 0.3 m within a 2-m interval containing other dominantly calcic minerals (truscottite, laumontite, wairakite, mordenite, calcite and scarce fluorite), all of which were deposited later than chlorite, pyrite, and abundant quartz. Hydrothermal minerals with Na as the dominant cation (analcime, albite and aegirine) as well as adularia immediately overlie and underlie the Ca-rich interval. Some Ca- and Na-rich minerals overlap, but in Y-13 no Na-rich minerals coexist with dachiardite.

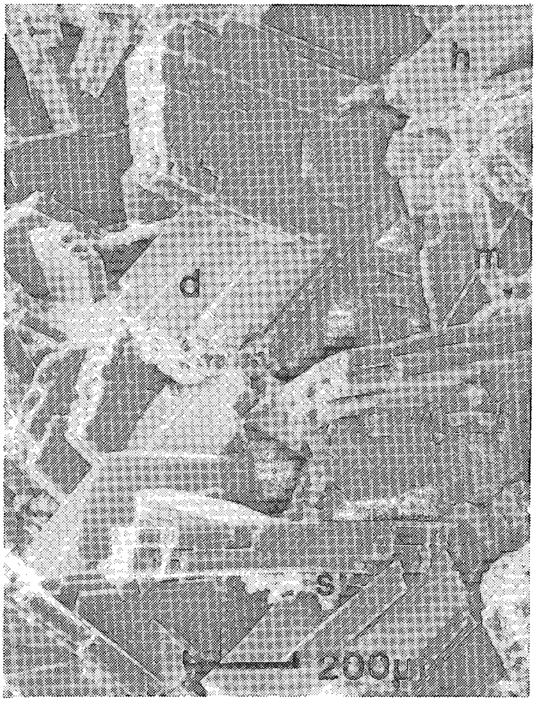

FIG. 2. Scanning-electron micrograph showing tabular aggregates of dachiardite (d) crystals intergrown with intermediate heulandite (h) from 23.0 m in drill core Y-2. Smectite (s) and tiny mordenite (m) fiber were deposited later than dachiardite.

CRYSTALLOGRAPHY

Morphology

The Yellowstone dachiardite occurs principally as radiated, bladed to acicular, euhedral crystals elongated (as much as 1.5 mm) on [010] and flattened on {001} or, less commonly, on {100}. The length/width ratio is 7-10 for most crystals but may be as great as 20 for some acicular crystals. None of the dachiardite that we have examined might properly be termed "fibrous", which is a point of distinction from most of the other reported occurrences of dachiardite or sodium dachiardite. Forms identified with a two-circle optical goniometer are {001}, {100}, {110}, {101}, {201} and {$\bar{2}$01}. The most common habit is illustrated by the crystal near the centre of Figure 3A (arrow), which is elongate on [010], flattened on {001}, and shows the bounding forms {100} and {110}. This habit is also commonly shown in SEM micrographs of dachiardite

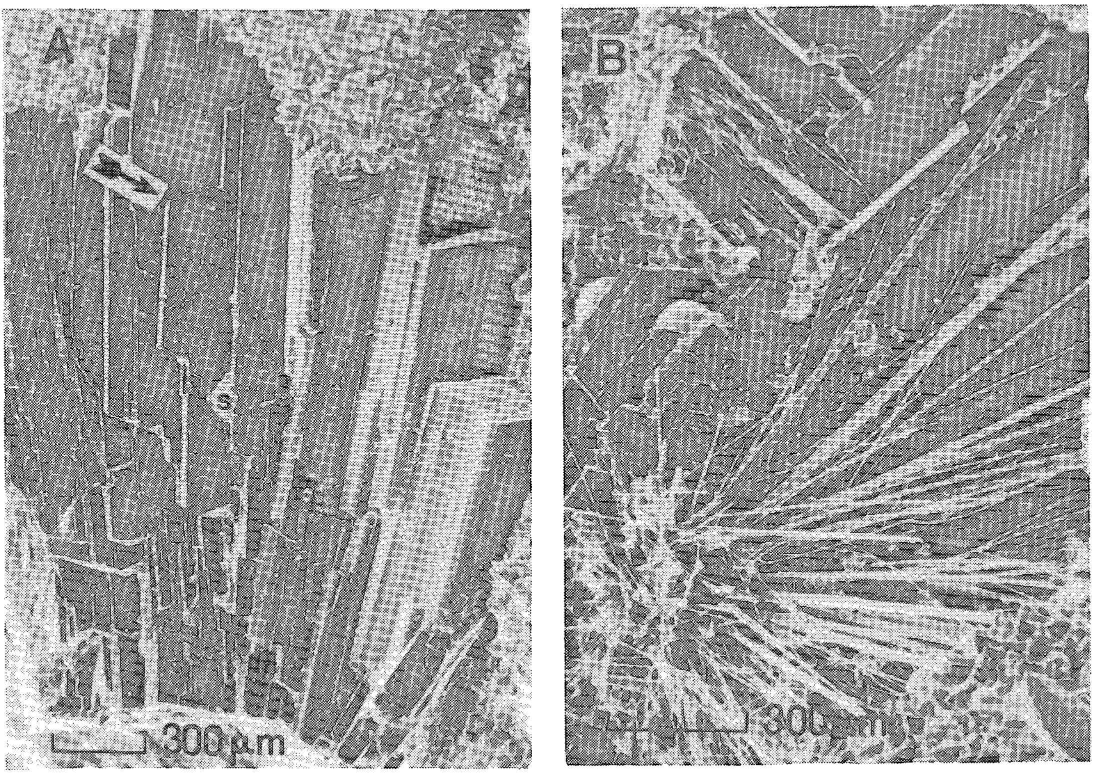

FIG. 3. Scanning-electron micrographs of dachiardite from cavities at 60.2 m in drill core Y-3. A, a radiating cluster of dachiardite crystals deposited later than quartz crystals and earlier than smectite (s). Arrow shows terminated crystal with {100}, {110}, and {001} present. B, paragenetic sequence of quartz (upper left and lower right), blocky dachiardite crystals (extending from upper right to left centre), radiating fibrous mordenite crystals, and numerous clusters of tiny smectite crystals (after Bargar *et al.* 1981).

and sodium dachiardite from other occurrences (*e.g.*, Postl & Walter 1982, Figs. 10, 11). Comparative morphological data are given in Table 1. Most of the dachiardite in the Yellowstone drill core is twinned by repeated parallel twinning on {001}, with {100} as the twin axis. This twinning produces striations parallel to {010} (Fig. 6). However, we have found several crystals in Y-3 (72.3 m) that show no sign of twinning, either optically or in single-crystal X-ray-precession photographs.

X-ray data

Single-crystal X-ray-precession photographs of the $h0l$, $hk0$, and $0kl$ nets of dachiardite crystals from Y-2 (20.7 m), Y-3 (73.2 m), and Y-13 (50.9 m) were taken using Zr-filtered Mo radiation. All crystals gave sharp diffraction-spots, in contrast with the diffuse and streaked diffraction-maxima typically reported for k-odd reflections for dachiardite and especially for sodium dachiardite from other localities (Nishido & Otsuka 1981). This is thus the second known occurrence of dachiardite after the type material (Gottardi & Galli 1985) that exhibits sharp X-ray-diffraction maxima.

Powder-diffraction data for dachiardite from Y-3 (73.2 m) were obtained with a diffractometer (Chart No. X4833; graphite monochromator; Cu/Ni radiation; $\lambda \mathrm{Cu}K\alpha_1 = 1.540598$ Å; CaF_2 used as internal standard; scanned at ⅛ °2θ per minute from 8 to 92° 2θ) and agree closely with those of Galli (1965) for dachiardite from Elba, Italy. Intensities, however, show effects of strong preferred orientation for $hk0$ reflections due to the perfect {001} and {100} cleavages. Our intensity data are in very good agreement with those of Alberti (1975) for sodium dachiardite from Alpe di Siusi, Italy, which also were obtained with a diffractometer. The unit-cell data obtained from refinement of the X-ray powder data, using the least-squares program of Appleman & Evans (1973), are shown in Table 2.

OPTICAL DATA

Optical data for dachiardite from the Yellowstone drill core are presented in Table 1. A comparison of these data with the chemical data given in Table 3 shows that indices of refraction and optic axial angle appear to correlate positively with the compositional ratio $R^{2+}/(R^{+}+R^{2+})$ and negatively with the ratio $Si/(Al+Fe^{3+})$. If data for dachiardite from other localities (Table 2) are considered, however, the correlations are not as evident. Clearly, more chemical and optical data are needed to confirm the trend seen in our study.

Dachiardite from the Yellowstone drill core is colorless and transparent to cloudy. Dachiardite from Y-2 shows no zoning and very few inclusions, in contrast with the moderately to strongly zoned material in Y-13 and Y-3, respectively. The zoning is best seen along [010] and leads to an increase in indices of refraction from core to rim, apparently reflecting increasing Ca + Al and decreasing Na + Si contents with crystal growth. Much of the dachiardite from Y-13 and Y-3 is transected by randomly oriented needles and fibers of mordenite and may also have inclusions of small quartz euhedra.

Optical and crystallographic data for mordenite, epistilbite and yugawaralite associated with dachiardite in the Yellowstone drill core are also shown in Table 1. Chemical compositions for Y-3 mordenite and yugawaralite are reported in Bargar & Beeson (1985).

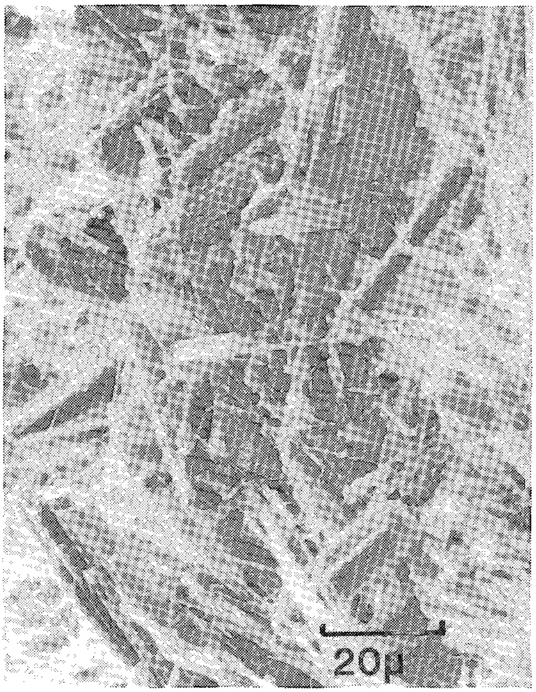

FIG. 4. Scanning-electron micrograph showing closely associated fibrous mordenite and stubby bundles of bladed dachiardite crystals from 72.2 m in drill core Y-6 (after Bargar *et al.* 1981).

CHEMICAL COMPOSITION

The chemical composition of dachiardite from three of the Yellowstone drill cores was determined on an ARL-EMX electron microprobe using natural and synthetic mineral standards. A defocused beam was used at an accelerating voltage of 15 kV, a sample current of 15 nA, and a counting time of 10 seconds.

Electron-microprobe analyses of dachiardite from drill core Y-2 in Bargar & Beeson (1981) and an additional analysis (Table 3, column 1) show that the mineral from this drill core is intermediate in composition (in terms of Ca, Na and K) compared to other published compositions, including those referring to Yellowstone Park material (Table 3, columns 2–6; Fig. 7).

Dachiardite from drill hole Y-6 was not analyzed by electron microprobe. Qualitative analyses by energy-dispersion X-ray analysis (EDX) used with the SEM show only Si, Al and Ca; however, owing to differences in the detection limits, minor sodium may not be precluded (Bargar & Beeson 1984).

Wise & Tschernich (1978) reported a considerable variation of Ca and Na within a single bladed crystal of dachiardite from Altoona, Washington. Compositions of Y-3 dachiardite show a similar lack of homogeneity within an individual crystal as well as between crystals, with Ca content varying from 1.5 to 2.09 atoms per unit cell in sample Y3-60.4 (Table 3, columns 2 and 3) and from 1.89 to 2.66 atoms per unit cell in sample Y3-73.2 (Table 3, columns 4 and 5). Dachiardite from drill core Y-13 (Table 3, column 6) contains 2.37 Ca atoms per unit cell. All of the compositions from drill cores Y-3 and Y-13 contain considerably greater amounts of calcium than the Y-2 or most other published dachiardite compositions, where the Ca atoms per unit cell are about 1.0 or less (except for the Elba dachiardite, which has 1.76 Ca atoms per unit cell) (Bonardi *et al.* 1981). The Y-3 and Y-13 dachiardite is much richer in calcium than the Elba dachiardite, which has previously been described as Ca-rich (Bonardi 1979).

Si/Al values for published dachiardite compositions vary from about 3.75 to 6.09 (Bonardi *et al.* 1981). Dachiardite from Yellowstone has Si/Al values between 3.4 and 4.7; the lower values correspond to the most Ca-rich compositions.

Trace amounts of Cs (0.05–0.07 wt.% Cs_2O), Ba (0.02–0.05 wt.% BaO) and Sr (0.06–0.08 wt.% SrO) have been found in the Y-13 dachiardite, as well as in other zeolite minerals from Yellowstone National Park (Keith *et al.* 1983). These elements have been reported in previously published compositions of dachiardite (Bonardi *et al.* 1981); the Elba

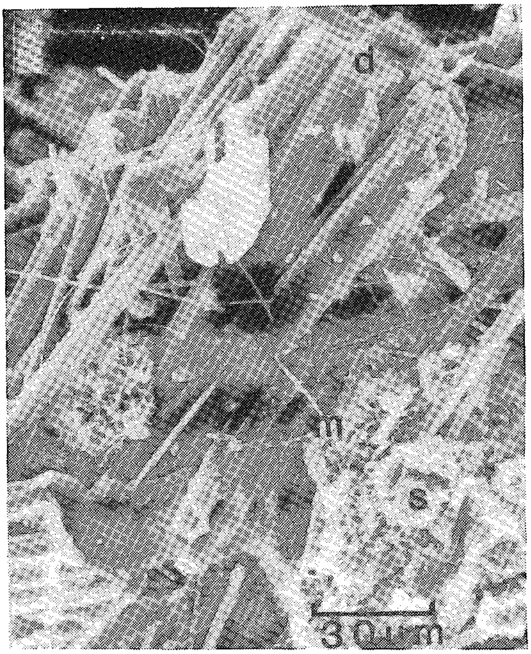

FIG. 5. Scanning-electron micrograph of acicular aggregates of bladed dachiardite (d) from 98.1 m in drill core Y–6. Clusters of platy smectite (s) and fibrous mordenite (m) are deposited later than the dachiardite (after Bargar & Beeson 1984).

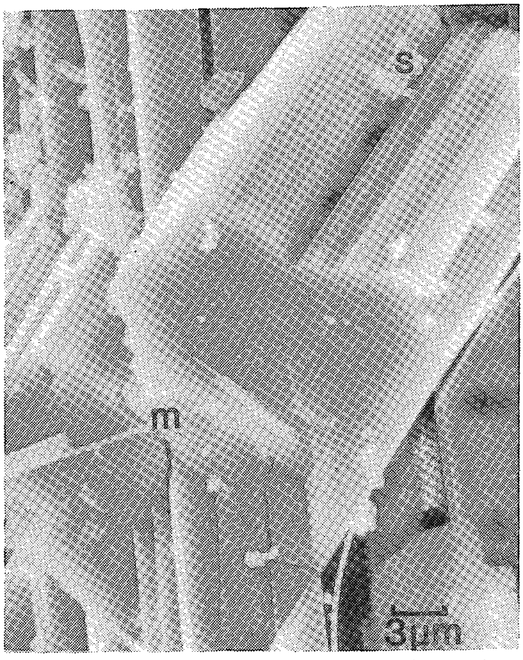

FIG. 6. Scanning-electron micrograph showing a closer view of an acicular aggregate of parallel twinned bladed crystals of dachiardite from 98.1 m in drill core Y–6. Fibrous mordenite (m) and smectite (s) are later deposits (after Bargar & Beeson 1984).

dachiardite contains 0.96 wt.% Cs_2O (Bonardi 1979); in fact, Gottardi & Galli (1985) suggested that the well-crystallized state of the Elba dachiardite may be attributed to its cesium content.

DISCUSSION

For the Yellowstone occurrences of dachiardite, it appears that dachiardite is not stable in conditions where Na-minerals are deposited, although other Ca- and Na-rich species may coexist. The precipitation of dachiardite must result from high concentrations of Ca in the thermal waters.

Chemical data for the Yellowstone material fill in some of the blank spaces in the known compositional range for dachiardite (Fig. 7), and suggest that the possible solid-solution series between sodium dachiardite and dachiardite advocated by Nishido & Otsuka (1981) is influenced by the presence of potassium. Thus dachiardite may have a wide chemical range somewhat analogous to the heulandite–clinoptilolite solid-solution series (Gottardi & Galli 1985).

The temperature at the depths where dachiardite was found in the four Yellowstone drill cores varies from about 50 to 200°C. Fluid-inclusion studies of quartz from these drill cores suggest that the minimum temperature of crystallization was significantly higher, probably over the range of about 100–200°C. Dachiardite has been produced in the laboratory at 250°C (Knauss & Beiriger 1984).

We have carefully selected and completely described material near the end members for dachiardite and sodium dachiardite from various localities and have given comparative optical, crystallographic, and selected chemical data for them (Table 2). Clear distinctions exist between the two, which may be summarized as follows:

	Dachiardite	*Sodium dachiardite*
All indices of refraction	≥ 1.488	≤ 1.482
Optic sign	Positive	Negative
Dispersion	$r>v$	$r<v$
Extinction $c{:}z$	-32→-43°	-8→-18°
β	$\leq 108.2°$	$\geq 108.3°$
Axial ratio c/b	≤ 1.367	≥ 1.371
$Si/(Al+Fe^{3+})$	≤ 3.81	≥ 4.46
$R^{2+}/(R^{+}+R^{2+})$	≥ 0.53	≤ 0.05

We do not attempt to establish a boundary between dachiardite and sodium dachiardite, nor do we suggest limiting values. Using these observed values as rough guiding criteria, however, all of the reported occurrences can be clearly differentiated as either dachiardite or sodium dachiardite. The occurrences of sodium dachiardite are more abundant and include those at Susaki, Ogasawara, Japan (Nishido

TABLE 1. OPTICAL AND SELECTED CRYSTALLOGRAPHICAL DATA FOR YELLOWSTONE DACHIARDITE AND ASSOCIATED ZEOLITES

	DACHIARDITE			MORDENITE	EPISTILBITE	YUGAWARALITE
Source	Y2 (20.7m)	Y3 (73.2m)	Y13 (50.9m)	Y3 (73.2m)	Y13 (50.9m)	Y3 (73.2m)
α	1.481*	1.488-1.490*	1.489*	1.476*	1.499*	1.494*
β	1.483	1.490-1.492	1.492	1.479	1.506	1.498
γ	1.487	1.494-1.496	1.497	1.481	1.507	1.501
2V	(+)70°**	(+)71-72°**	(+)75°**	(-)80°**	(-)45°**	(-)82°**
Dispersion	r>v, moderate	r>v, mod.	r>v, mod.	r<v, weak	r<v, strong	r<v, mod.
Orientation	a:Y =-15° b = X c:Z = -33°	a:Y =-16→-25° b = X c:Z =-34→-43°	a:Y = -21° b = X c:Z = -39°	a = Y b = Z c = X	a:X = -24° b = Y c:Z = -10°	a:X = +7° b = Z c:Y = -14°
Maximum size (mm)	0.25 x 0.1 x 0.04	1.1 x 0.15 x 0.03	1.5 x 0.2 x 0.04	2.2 x 0.1 x 0.04	0.6 x 0.45 x 0.15	0.45 x 0.3 x 0.05
Habit	Tab. {001}	Prism.; elong. [010]; flat. {001} or {100}	Prism.; elong. [010] flat. {001}	Fib.→Acic.; elong. [001]	Tab {100}	Tab. {010}
Forms	{001},{100}, {110}	{001},{100}, {110},{101}, {201},{$\bar{2}$01}	{001},{100}, {110}	{100},{010}, {110}	{001},{010}, {110},{013} {$\bar{1}$01}	{100},{010} {120},{011}, {$\bar{1}$11}
β	108.17°	107.95°	107.93°	90.00°	124.45°	111.00°

* All values ±0.001. Determined using X-ray oriented crystals on the Supper Spindle Stage; Na light; 25° C.

** Values ±1°.

et al. 1979), Kapfenberg, Steiermark, Austria (Postl & Walter 1982), Altoona, Washington, and Cape Lookout, Oregon, U.S.A. (Wise & Tschernich 1978). Occurrences of dachiardite, in addition to the ones listed in Table 1, are those from the Fassa Valley, Italy (Demartin & Stolcis 1979) and Hatsuneura, Ogasawara Islands, Japan (Nishido & Otsuka 1981). Data for the Hatsuneura material show that it is a nearly intermediate member of the series, as stated by Nishido & Otsuka (1981), as is our material from drill hole Y-2. Nonetheless, both of these are still recognizable as dachiardite rather than sodium dachiardite. Two other occurrences are attributed properties that appear to be contradictory. The first is the complexly twinned mineral described (from west of Zvezdel, eastern Rhodopes, Bulgaria) as "svetlozarite" by Maleyev (1977) and shown to be dachiardite by Gellens *et al.* (1982). The second, in Washington and Oregon, was described by Wise & Tschernich (1978). Using our criteria, "svetlozarite" would be classed as sodium dachiardite, but the optic sign is described as positive, and the dispersion is given as $r > v$, distinct, which would agree with dachiardite. The content of potassium in this material is relatively high (Gellens *et al.* 1982), but no more so than dachiardite from our Y-2 material (Table 3, Fig. 7), and thus seems unlikely to account for the optical anomaly. Chemically, both dachiardite and sodium dachiardite appear to be present in the Oregon and Washington occurrences, but the optical data (except for the optic orientation,

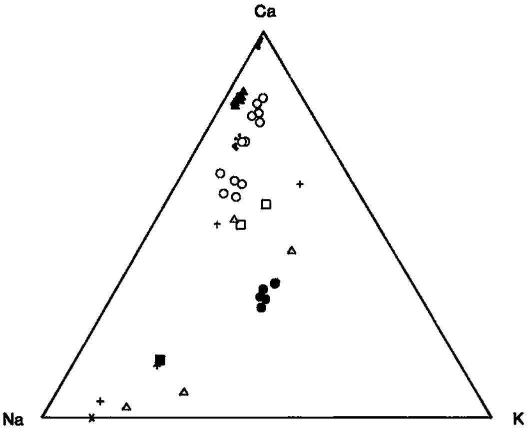

FIG. 7. Ca–Na–K triangular diagram showing data for dachiardite from Yellowstone National Park compared with other published compositions. Data from Table 2: Y2-20.7 (closed circles), Y3-60.4 (open circles), Y3-73.2 (dots), and Y13-50.9 (closed triangles). Other data from Wise & Tschernich (1978) (open triangles), Bonardi (1979) (open squares), Alberti (1975) (closed square), Bonardi *et al.* (1981) (cross), and original data from Nishido & Otsuka (1981) (plus signs).

TABLE 2. OPTICAL, CRYSTALLOGRAPHICAL, AND SELECTED CHEMICAL DATA FOR DACHIARDITE AND SODIUM DACHIARDITE*

	DACHIARDITE			SODIUM DACHIARDITE		
	1	2	3	4	5	6
α	1.489	1.494	1.490(1)	1.471	1.480	1.471(1)
β	---	1.496	1.492(1)	---	---	1.475(1)
γ	1.494	1.499	1.496(1)	1.477	1.482	1.476(1)
2V	(+)58-62°	(+)73°	(+)71(1)°	(-)76-80°	---	(-)52°
Dispersion	---	$r > v$, rather strong	$r > v$, moderate	---	---	$r < v$, moderate
Orientation	b = X c:Z = -32°(?)	b = X c:Z = -38°	b = X c:Z = -43°	b = X c:Z = -8°	b = X ---	b = X c:Z = -18°
a(Å)	18.652(5)	18.676	18.636(3)	18.641	18.647(7)	18.67(1)
b	7.517(3)	7.518	7.505(2)	7.512	7.506(4)	7.488(4)
c	10.274(5)	10.246	10.239(1)	10.299	10.296(4)	10.282(6)
β	108.00(5)°	107.87°	107.95(1)°	108.48°	108.37(3)°	108.74(8)°
V(Å^3)	1370(1)	1369.2	1362.4(3)	1368	1368(1)	1361.2
c/b	1.367	1.363	1.364	1.371	1.372	1.373
Si/(Al+Fe^{3+})	3.66	3.75	3.81(avg.)	4.46	4.48	5.70
$R^{2+}/(R^{+}+R^{2+})$	0.61	0.53	0.84(avg.)	0.05	0.15	0.00

* Arranged in order of increasing Si/(Al+Fe^{3+}).
1 Onoyama mine, Kagoshima Pref., Japan. Nishido & Otsuka (1981). Extinction angle given is c:z = 58°.
2 San Piero di Campo, Elba, Italy. D'Achiardi (1929); Bonatti (1942); Bonardi (1979); Vezzalini (1984).
3 Research drill hole Y3 (73.2m), Lower Geyser Basin, Yellowstone National Park, Wyoming, U.S.A. Bargar & Beeson (1985); this study.
4 Tsugawa district, Niigata Pref., Japan. Yoshimura & Wakabayashi (1977).
5 Alpe di Siusi, Bolzano, Italy. Alberti (1975).
6 Francon quarry, St-Michel, Montreal Island, Quebec, Canada. Bonardi et al. (1981).

TABLE 3. CHEMICAL COMPOSITION OF DACHIARDITE FROM DRILL CORE IN YELLOWSTONE NATIONAL PARK

No.*	Y2-20.7	Y3-60.4**		Y3-73.2**		Y13-50.9
SiO_2	66.93	63.96	70.35	60.84	68.44	62.65
Al_2O_3	13.65	14.29	12.65	14.00	13.81	14.84
Fe_2O_3	0.09	0.00	0.02	0.00	0.00	0.00
MgO	0.06	0.09	0.00	0.00	0.00	0.00
MnO	0.07	0.02	0.00	0.00	0.00	0.00
CaO	3.08	6.50	4.98	8.12	6.24	7.38
Na_2O	2.21	0.36	1.34	0.09	1.04	0.59
K_2O	3.18	0.57	1.10	0.03	0.59	0.24
Total	89.27	85.79	90.44	83.08	90.12	85.70
	Numbers of atoms on the basis of 48 oxygens					
Si	19.39	19.04	19.82	18.58	19.40	18.78
Al	4.66	5.05	4.20	5.44	4.61	5.24
Fe	0.02	0.00	0.00	0.00	0.00	0.00
Mg	0.03	0.04	0.00	0.00	0.00	0.00
Mn	0.02	0.01	0.00	0.00	0.00	0.00
Ca	0.96	2.09	1.50	2.66	1.89	2.37
Na	1.24	0.21	0.73	0.05	0.57	0.34
K	1.18	0.22	0.40	0.01	0.21	0.09
Si + Al	24.05	24.09	24.02	24.02	24.01	24.02
Si/Al+Fe^{3+}	4.2	3.8	4.7	3.4	4.2	3.6
$R^{2+}/(R^{+}+R^{2+})$	0.3	0.8	0.6	1.0	0.7	0.8
Bal. error†	6.0	7.4	1.7	1.1	0.9	1.3

*Sample numbers consist of drill hole number and depth in metres.
**Reported individual analyses are for different crystals in the same sample and were selected to show extremes of calcium content as plotted in Fig. 7. Compositions obtained by electron microprobe.
†Cation-balance errors calculated after method of Passaglia (1970).

which is unique to this material) are apparently uniform and agree with our optical criteria for sodium dachiardite. Further careful study of the optical properties of members of the dachiardite - sodium dachiardite series is clearly in order. As data accumulate from new occurrences, the demarcation of the members of this series undoubtedly will be improved.

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