LITHOLOGY, MINERALOGY, AND PALEONTOLOGY OF QUATERNARY LAKE DEPOSITS IN LONG VALLEY CALDERA, CALIFORNIA

By R.B. Fournier

U.S. GEOLOGICAL SURVEY

Open-File Report 89-413

Menlo Park, California

1989

DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Conversion factors terms used in this report are listed below:

multiply	by	to obtain
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
feet per second (ft/s)	0.3048	meters per second (m/s)
feet per second (ft/s)	0.0003048	kilometers per second (km/s)
ohm meters (Ωm)	100	ohm centimeters

For conversion of degrees Celsius (^oC) to degrees Fahrenheit (^oF), use the formula $^oF = 9/5^oC + 32$.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) -- a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929.

LITHOLOGY, MINERALOGY, AND PALEONTOLOGY OF QUATERNARY LAKE DEPOSITS IN THE LONG VALLEY CALDERA, CALIFORNIA

By

Reba B. Fournier

ABSTRACT

Drill cores and cuttings from two drill holes, about 3 kilometers apart, in Long Valley caldera, Mono County, California, were studied using x-ray diffraction and optical methods. The mineralogy and lithology of the interbedded tuffs and sediments deposited in or near the Pleistocene saline-alkaline lake are described in detail. Fossil ostracodes and diatoms provide information about the chemistry and depth of the lake as it changed over time. Zeolites, primarily clinoptilolite, formed either on the floor of the caldera lake or within the zone saturated with ground water. The conclusion reached is that much of the zeolite mineralization formed authigenically.

INTRODUCTION

In order to explore the relation of the alteration mineralogy to the distribution of past and present hydrothermal systems in Long Valley caldera, Mono County, California, core and cuttings from two drill holes were studied using X-ray diffraction and optical methods. The wells are located in the eastern half of the caldera, approximately half-way between the resurgent dome and the caldera wall. Nearly complete core was retrieved from the 1,000-foot deep LVCH-1 hole. Cuttings only were collected from the 6,920-foot deep Republic 66-29 hole, about three kilometers to the southeast.

This work was undertaken to study presumed hydrothermal alteration in core from a 1,000-foot drillhole, LVCH-1, in the Long Valley caldera fill. The second drillhole, Republic Well 66-29, drilled in May-June, 1976, penetrated 6,920 feet of caldera fill including 4,170 feet of welded Bishop Tuff. This paper describes the mineralogic, lithologic, and paleontologic data.

ACKNOWLEDGMENTS

Thanks are especially due to Richard M. Forester, who studied the ostracodes, and to J. Platt Bradbury, who studied the fossil diatoms. Both are from the U.S. Geological Survey, Denver, Colorado. Their paleontological work provided the basis for the environmental assumptions outlined in this paper. The present work rests on a foundation laid by Roy A. Bailey, U.S. Geological Survey, Menlo Park, California, who mapped the Long Valley area.

GEOLOGIC SETTING AND HISTORY

The geologic setting of the Long Valley caldera has been described in detail in a special issue of the Journal of Geophysical Research, "Geothermal Investigations of the U.S. Geological Survey in Long Valley, California, 1972-73 (1976, v. 81, p. 721-860 and 1527-1532), especially in the article by Bailey and others (p. 725-744) in that issue. The caldera, which measures about 20 miles along an east-west axis and 10 miles along a north-south axis (Bailey and others, 1976, p. 728), lies just east of the Sierra Nevada (see Fig. 1, inset). It formed about 0.7 m.y. B.P. (million years before present), at the time of the eruption of the welded Bishop Tuff, which blanketed an area of 400 to 450 square miles, predominantly to the north and east of the caldera (Gilbert, 1938, p. 1883), as well as the floor of the caldera. Since the formation of the Long Valley caldera and the emplacement of the Bishop Tuff, there have been four distinct major episodes of rhyolite eruption associated with resurgent doming and peripheral to the dome, plus several rhyodacite eruptions from outer ring fractures (Bailey and others, 1976, p. 732-733). Ages of these eruptions were determined by K-Ar age dating by Brent G. Dalrymple and Marvin A. Lanphere, and are discussed by Bailey and others, 1976, p. 729-733.

During most of the time since caldera formation, probably beginning early in the period of early rhyolite eruption between 0.68 and 0.63 m.y. B.P. (Bailey and others, 1976, p. 732), much of the caldera was occupied by a lake, in which the resurgent dome was an island. The major episode of resurgent doming began in the period of early rhyolite eruption and ended between 0.63 and 0.51 m.y. B.P. (Bailey and others, 1976, p. 732-733). The caldera lake probably overflowed from time to time during pluvial periods, but began to drain about 0.1 m.y. B.P. The present Lake Crowley is not a remnant of the caldera lake, but a modern lake formed by a manmade dam.

DEPTHS TO AND VARIATIONS IN THICKNESS OF THE BISHOP TUFF

Seismic refraction data along an east-west cross section within the Long Valley caldera indicate that there is a rapid change in depth to the top of the welded Bishop Tuff, assuming that the 4.0-4.4 km/s layer is the welded Bishop Tuff. Going from west to east across the Hilton Creek fault zone from the Antelope shot point to the Alkali shot point, Hill (1976, Fig. 7, p. 750) shows a vertical offset of about 1.5 km in the basement just west of the Republic drillhole, which "...is consistent with displacement on the Hilton Creek fault"... but ..."is somewhat east of the inferred location of the Hilton Creek fault zone." Solutions for post-Bishop, pre-early rhyolite, near-surface structures indicative of post-tectonic displacement on the Hilton Creek fault between the two shot points were ambiguous (Hill, 1976, p. 751).

The three drillholes which yielded data about the Bishop Tuff are the Republic drillhole, 66-29, studied by the author, and the Clay Pit and Mammoth drillholes, completed by Unocal[1]. The Clay Pit drillhole (C in Figure 2) is located on the east flank of the resurgent dome. The Mammoth drillhole (M in Figure 2) is located in the southwest moat area of the caldera. Data from these three drillholes are summarized in Table 1. Drilling information about the Clay Pit and Mammoth drillholes was provided to the U.S. Geological Survey by Unocal. Further data about specific gravity, porosity, and conductivity of selected samples from LVCH-1 taken from Lewis (1975) and Sass and others (1974) are shown in Table 2.

In the Mammoth drillhole, the thickness of the welded Bishop Tuff is well delineated. In the Clay Pit drillhole, the depth to the base of the

[1] Use of the firm name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

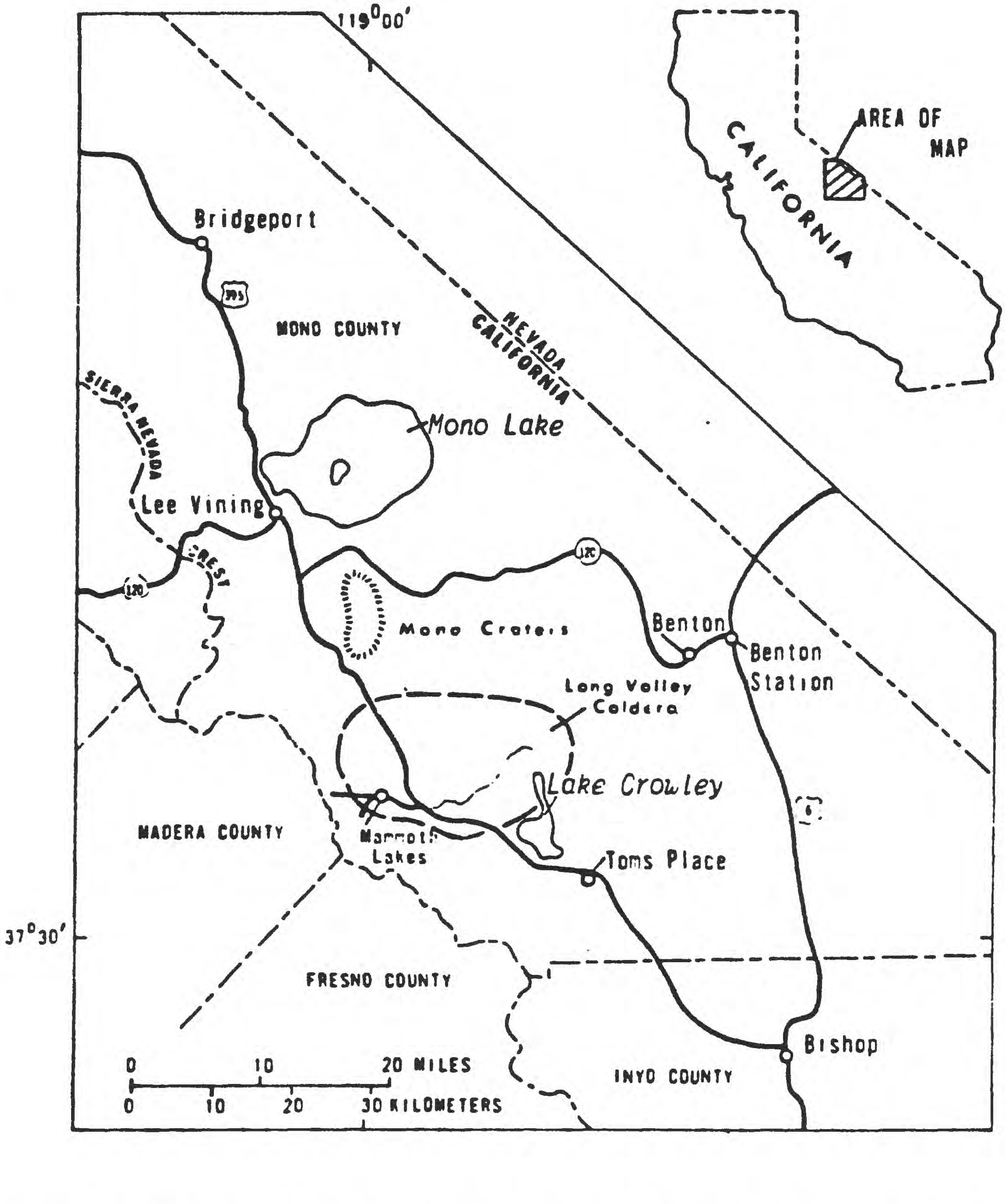
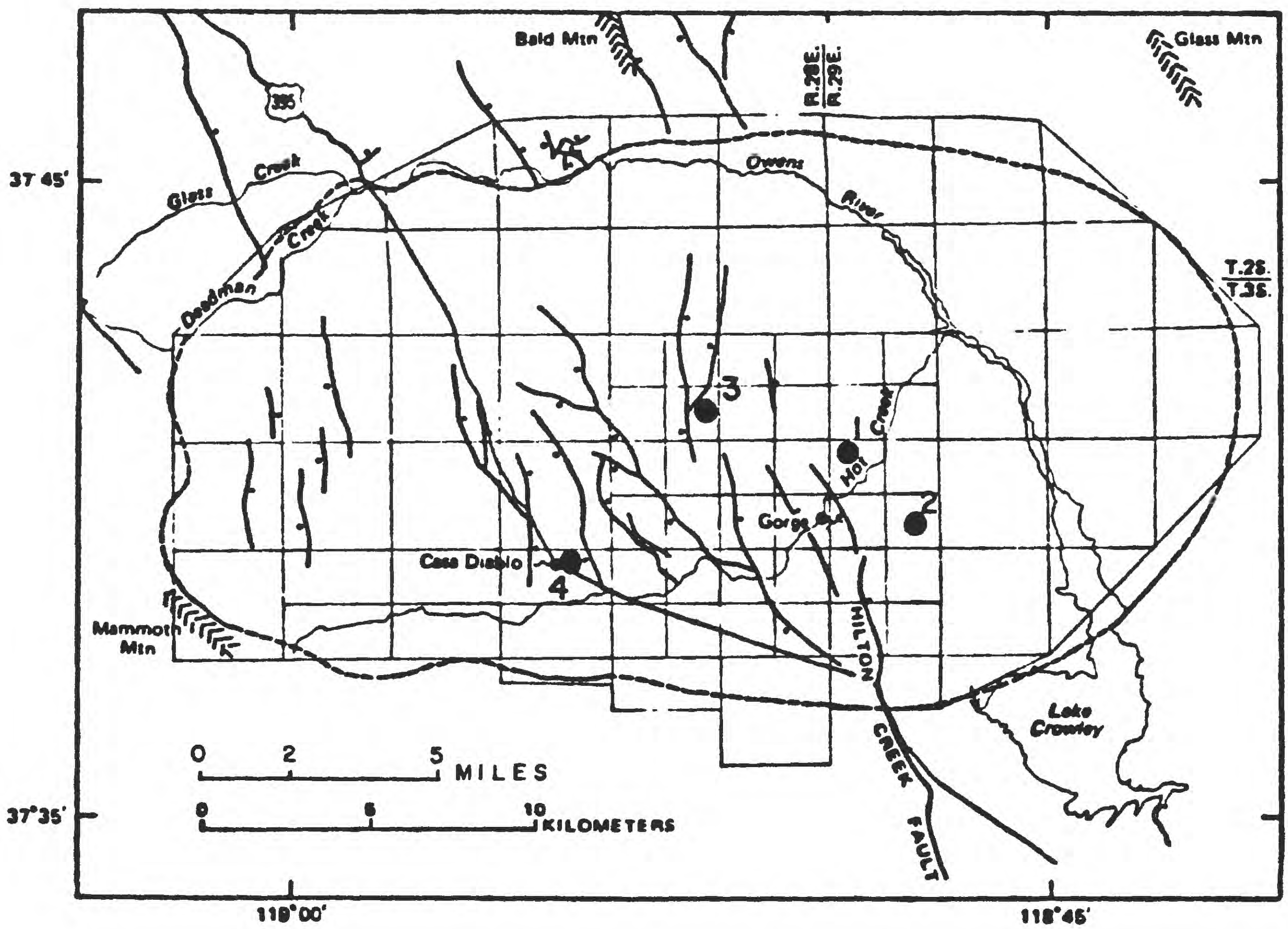


Figure 1 - Location of Long Valley caldera in relation to the Sierra Nevada crest. (adapted from Sorey and others, 1978, Fig. 2, p A7)



EXPLANATION

Normal faults - ball on downthrown side.

Proposed northward extention of the Hilton Creek Fault (see text).

Locations of drillholes: 1 - LVCH - 1; 2 - Republic drillhole 66-29; 3 - Clay Pit drillhole; and 4 - Mammoth drillhole.

Figure 2 - Sketch map of Long Valley caldera showing principal faults and drillholes (from Sorey and others, 1978, Fig. 19, p. A40)

Bishop Tuff is uncertain, and in the Republic drillhole, the base of the Bishop Tuff was not intersected. However, a comparison of color changes at the bottom of the Republic drillhole -- from dark gray to very light gray (see Appendix A) -- with those described in the Mammoth drillhole (data provided by Unocal) leads me to estimate that the Republic drillhole bottomed within thirty feet of the base of the welded Bishop Tuff. This would give a thickness of about 4,200 feet, which agrees well with the estimate of Bailey and others (1976, p. 730).

STRUCTURAL ENVIRONMENT

Although quantitative statements about structural movements in the Long Valley caldera cannot be made, some qualitative comments are possible. At such time as age dating of the lake terraces is feasible, it may be possible to correlate these terraces with certain intervals within the core of LVCH-1 and the cuttings of the Republic drill hole.

It would have been desirable to use potassium-argon age dating and magnetic reversals to date portions of the core. However, the amount of material available in the two-inch diameter core was insufficient for potassium-argon dating with techniques then available. It would have been necessary to perform the measurements of remanent magnetism at the time of core retrieval.

What can be said is that because the caldera lake maintained itself as shallow (or dried up) throughout the deposition of most of the post-Bishop tuffs and sediments, and because the present depth to the top of the Bishop Tuff is more than 1,000 feet in LVCH-1 and at least 2,000 feet in the Republic drillhole, it is necessary to postulate downward movement (presumably along ring fractures) of the caldera floor duing the period of deposition (0.65 - 0.10 m.y. B.P.). Such movement may have been continuous or intermittent; surges of movement could have accompanied eruption of the early rhyolite and the moat rhyolites. Even if 100 percent compaction (to one-half the original thickness) is assumed, it requires downfaulting of the caldera floor with reference to the spillway point on the caldera wall.

The seismic refraction data (Hill, 1976), indicate that the thickness of caldera fill is much greater in the eastern third of the caldera, and suggest a fault surface separating the two sections of the caldera. The northern extension of the Hilton Creek Fault as presently expressed at the surface does not fit the requirements for a vertical fault surface separating the two parts of the caldera (geologic map by Bailey, U.S. Geological Survey, Menlo Park, California, written communication, 1983). It is also not clear whether movement on such a vertical fault occurred principally before or after the eruption of the Bishop Tuff.

LITHOLOGY OF THE LVCH-1 CORE

Tuffs

Tuffs make up the bulk of the LVCH-1 core. Below 100 feet, there are more than 765 feet of tuff and about 110 to 115 feet of sediments. Individual tuff falls vary from 1 to about 20 feet in thickness. In making the distinction between subaerially deposited tuffs and waterlaid tuffs, as illustrated in Plate 1, three factors have been taken into consideration. (1) Tuffs which contain fossils (diatoms or ostracodes) are labeled waterlaid. (2) Tuffs which display structures such as laminations, interbedded sedimentary layers, steeply dipping banding, cross-bedding, flowage bands, slump structures, and brecciated zones overlain or underlain by undisturbed sediments, are also classified as waterlaid. (3) The absence of calcite is tentatively taken as an indication that the tuff was subaerially deposited; however, certain massive tuffs in the upper part of the drillhole which are calcite-free may have been deposited in fresh water, and some tuffs that were subaerially deposited may contain calcite that was precipitated from ground water.

The correlation between the presence of calcite and the occurrence of other indications of waterworking is strong but not perfect. Two-thirds of the tuff samples which were studied by X-ray diffraction and/or in thin-section, and which contain calcite, also display one of the structures enumerated above. Fossils have been recognized in half the calcite-bearing samples. Many samples were not thin-sectioned or otherwise examined for fossils; however, the percentage of samples containing calcite is the same for the 34 thin-sectioned tuff samples as for all the samples. Twenty-two of the thin-sectioned tuffs contain calcite, but only nine of these samples contain visible fossils. Fourteen of the 22 calcite-bearing tuffs show sedimentary structures, but of these 14, only five contain fossils that are visible in thin section. Therefore, the presence of substantial amounts of calcite strongly suggests that the tuff may be waterlaid, but does not positively indicate it. Isotopic measurements were obtained from so few samples (see Appendix C) that they cannot be used to distinguish waterlaid tuffs from subaerial tuffs with calcite deposited from groundwater.

Tuffs below 545 feet

These tuffs are predominantly aphyric; no quartz or feldspars were detected by x-ray diffraction in the airfall tuffs below 545 feet (see Plate 1, in pocket). There are many segments of tuff below 545 feet which show signs of reworking by water, consistent with field observations by Bailey (1976, p. 732), who described early rhyolite tuffs with varying degrees of reworking by water. Some of these waterlaid tuffs contain quartz and K-feldspar, detectable only by x-ray diffraction.

Beginning at the bottom of the available core, between 950 feet and the bottom of the drillhole at 1,000 feet, zones of tuff alternate with zones of sediments. At the base of the core, the tuff is light buff in color and massive, with some small lapilli. It grades upward to a calcite-bearing tuff with gently dipping bands, alternately white and buff-colored, displaying "graded bedding". The bands are offset by small reverse faults (at 964-970 feet) which probably reflect sublacustrine slumping contemporaneous with deposition. A hard gray siliceous zone at 959 feet (to be described in the next section) is underlain by a pod of clay-bearing, buff-colored material displaying probable desiccation cracks. Most tuffs below 950 feet lack calcite, suggesting an airfall origin; exceptions are those at 964 to 970 feet and at 980 feet. In the tuffs between 950 and 1000 feet, as in most tuffs below 545 feet, glass has been completely altered to clinoptilolite and some montmorillonite (see Plate 1). The K-feldspar at 990 feet may have replaced glass lapilli.

Gray, calcite-bearing, fossiliferous tuffs between 942 and 947 feet display steeply dipping bands and slump structures, suggesting near-shore deposition. Lapilli are 2 to 4 mm in diameter.

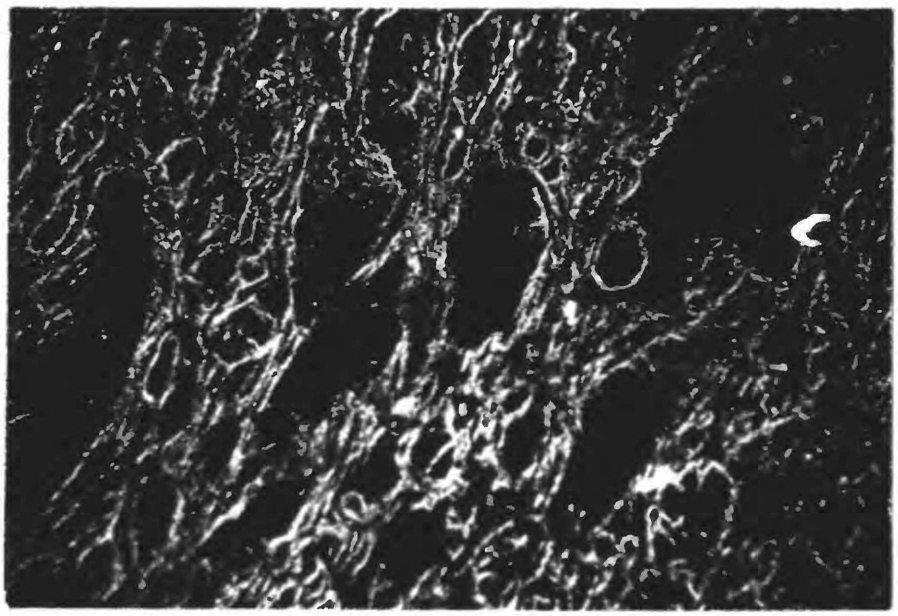
Tuff units between 915 and 942 feet vary from mottled buff and white to solid buff-color. In the core of the zone of lapilli tuff between 925 and 930 feet, a thin section shows that the lapilli are compacted together, and that some fresh glass is preserved despite nearly pervasive alteration to clinoptilolite. X-ray diffraction reveals a trace of a mineral which could be wairakite.

Calcite-bearing, fossiliferous waterlaid tuffs between 906 and 915 feet and between 886 and 894 feet are gray lapilli tuffs with lapilli about 5 mm in diameter, a few as large as 10-50 mm. The lapilli have been entirely altered to clinoptilolite and calcite. Cristobalite is abundant in the upper of the two sets of waterlaid tuffs.

Tuffs in the thick series between 632 and 886 feet vary from white to gray or buff. In some parts of the altered tuffs, broad zones of buff and light green color alternate; buff color predominates below 834 feet. No detectable changes in mineralogy occur with the changes in color. With few exceptions, the tuffs appear to be of airfall origin. Exceptions include the hard, dark gray siliceous zones, which contain ostracodes and/or calcite. Also, the zone between 838 and 886 feet may represent near-shore deposition, in an environment of fluctuating, and generally retreating, lake levels. A puzzling occurrence in this zone (at 863 feet) is a vertical band, 7 to 8 mm thick, of medium- to coarse-grained lapilli tuff. The zone contains both clinoptilolite (analyzed by microprobe, see Petrology and Mineralogy section, p. 44, sample #"862") and traces of K-feldspar. Pervasive alteration to clinoptilolite, with rims of montmorillonite around shards (see Figure 3), is complete except in the zone of lapilli tuffs between 660 and 700 feet. This zone of unaltered tuffs, in which fresh glass persists and no clinoptilolite was detected by X-ray diffraction, contains an exceptionally large proportion of vitric lapilli tuffs.

Between 545 and 632 feet, relatively thin units (less than 10 feet) of tuff alternate with sediments and tuffaceous sediments. (See Plate 1 and Figure 4.) The alternation of permeable (tuff) and impermeable (sediment) zones is clearly shown in Figure 4, just below the top of the clinoptilolite zone. In this figure the permeable zone at 180 - 200 meters (590 - 656 feet) coincides with a zone of lithium-rich montmorillonite that is discussed on page 43 (Clay minerals) and in Appendix B. Tuffs are generally gray or white, but shades of yellow and buff are common in sequences of finely laminated, probably waterlaid ash. Montmorillonite is more abundant in calcite-bearing tuffs than in units that lack calcite. Clinoptilolite occurs in all tuffs and in some sediments in this depth interval. The basal two feet (630-632 feet) are finely laminated ash, buff, white, and gray in color, composed of cristobalite and clinoptilolite, and displaying slump and other soft-sediment structures (see Figures 5 & 6). Two species of ostracodes occur in the overlying banded, calcite-rich, tuffs or tuffaceous sediments at 628 feet. A thin band of massive, calcite-bearing, buff-colored tuff at 583 feet separates two thin zones of laminated sediments. Finely banded yellow, gray, and white ash between 573 and 575 feet is composed of clinoptilolite and calcite. Dips of seventy degrees between 574 and 575 feet flatten upward to ten to twenty degrees at 573 feet.

Very steeply dipping (60^{o}) hard gray siliceous zones, containing cristobalite and calcite, occur at 558 feet and are the shallowest occurrence of such zones in the drillhole. As seen in thin section, poorly banded tuffs which enclose the siliceous zones contain lapilli, up to 0.5 mm

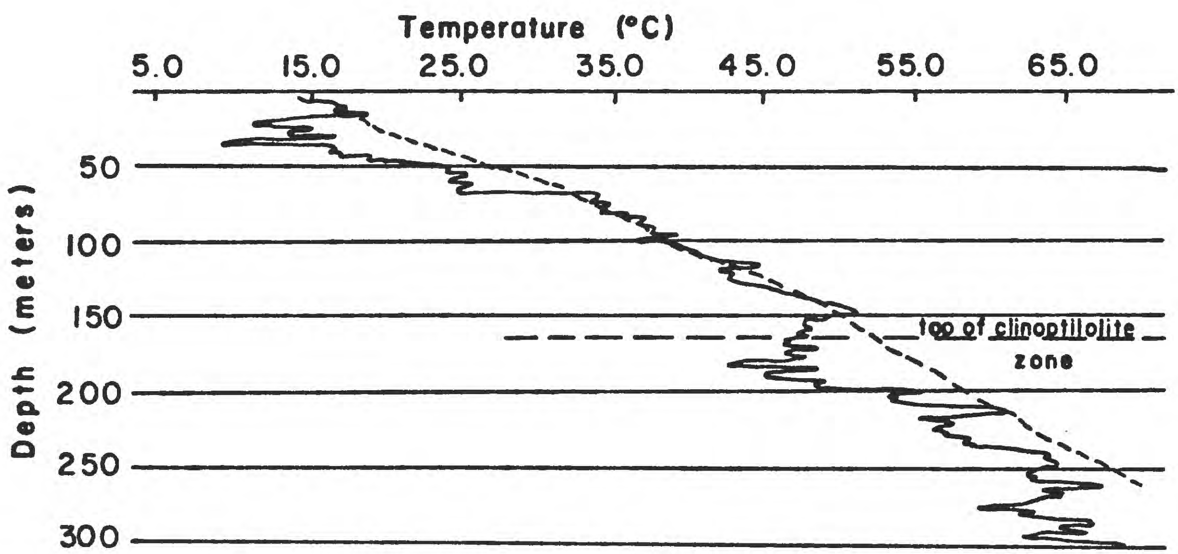


100 μm

EXPLANATION

Fragments of uncollapsed pumice. Ribbons of montmorillonite (bright) between oval areas of unaltered glass (dark), many oval areas enclose voids. Effect is reminiscent of the eyes on a peacock's tail.

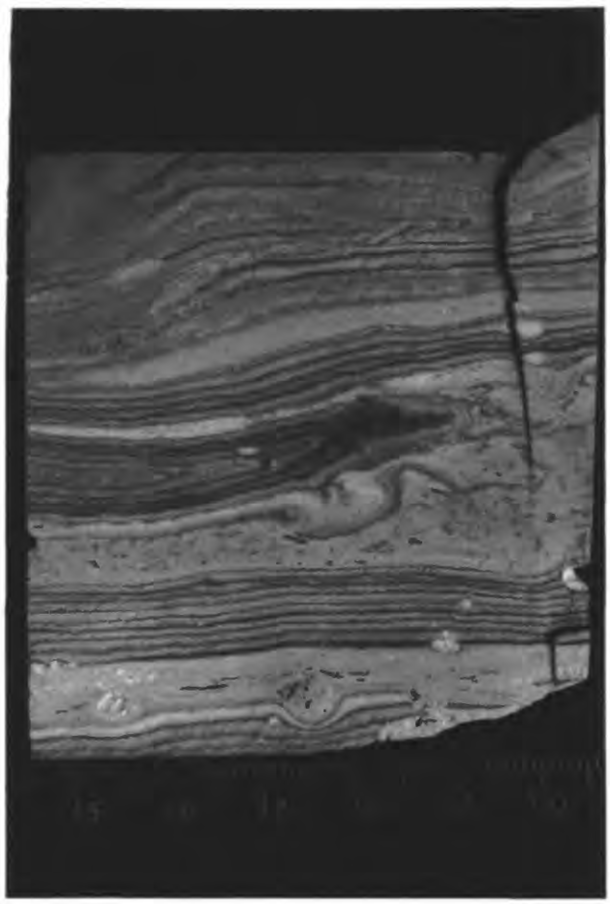
Figure 3. - Photomicrograph with crossed nicols, thin section at 885 feet, LVCH-1.



EXPLANATION

The solid curve is the temperature measured immediately after well completion, showing cemented or impermeable zones (tongues projecting to the right) and permeable zones (tongues projecting to the left).

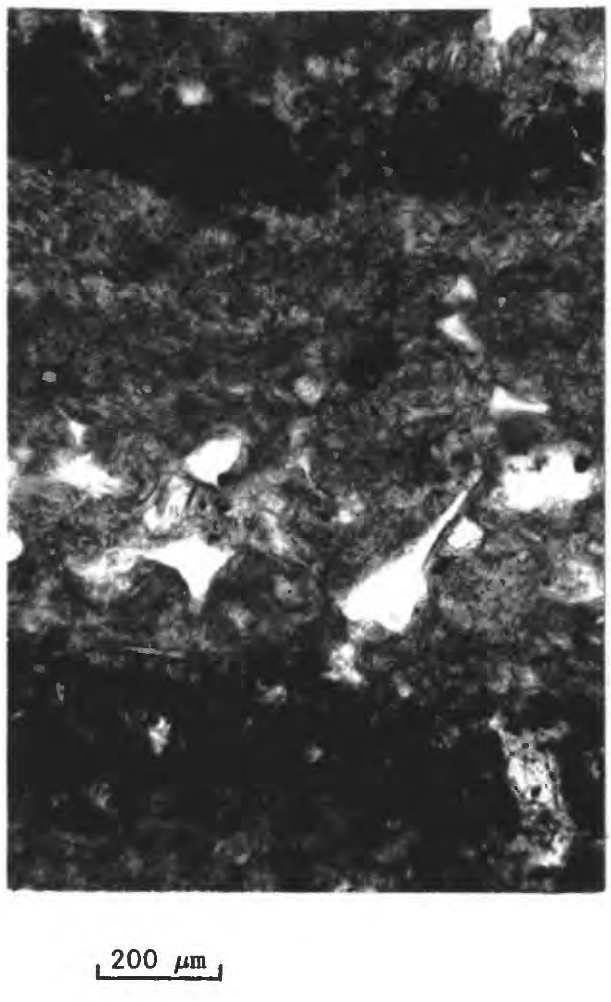
Figure 4. - Temperature-depth curves in LVCH-1 drillhole.



EXPLANATION

Laminae of ash (light) alternating with sediment (dark). Scale in millimeters.

Figure 5. - Hand specimen, segment of LVCH-1 core (at 631 feet).



EXPLANATION

Shards of unaltered glass (light) are visible in ash layers (gray). Material of high relief in the fine-grained sedimentary layers (dark) is calcite.

Figure 6. - Photomicrograph of thin section of same laminae portrayed in Figure 5.

in diameter, of quartz, K-feldspar, unaltered plagioclase, biotite, and some hornblende and basaltic rock, as well as altered vitric lapilli that are up to 10 μm in diameter. Some ostracodes are seen in thin section in waterlaid lapilli tuff at 554 feet and in tuffaceous sediments at 552 feet, where they are too few for paleontological analysis ("barren" according to Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980) and a few ostracode valves are visible in thin section at 545 feet. However, no diatoms were found in any of the core below 545 feet.

Hard gray siliceous zones

These dark gray zones, which are no more than a few millimeters in thickness, stand out conspicuously against the enclosing rock, which is generally light colored airfall tuff (Figure 7). Most zones are subhorizontal, but a few dip steeply. The thickness of the zones changes rapidly, and the zones are apparently discontinuous. Tuff immediately adjacent to a gray siliceous zone is commonly green in color, but no iron-bearing minerals have been detected in these green areas. In this core, hard gray zones are found only below 550 feet, and are most common below 700 feet.

The gray zones are much harder than the enclosing tuff, dense and hard enough to offer considerable resistance to a diamond sawblade. Mineral composition is predominantly quartz and/or cristobalite (see Petrology and Mineralogy section for discussion of the crystallinity of the cristobalite). The silica minerals may be accompanied by K-feldspar, clinoptilolite, and calcite. Fossil ostracodes are visible in thin section in the gray siliceous zones at 857 feet and 943 feet.

The presence of fossils and of calcite, and the occurrence of flowage textures observed in some thin sections (see Figure 8), suggest that the hard gray zones represent localized lenses of surface water. At first I thought that these hard gray zones might have been derived from magadiite; however, no salt molds are visible. As outlined by Surdam and others (1972), magadiite forms from silica-rich solutions with high pH ($\geq$9.5). Although there is no positive evidence for the presence of magadiite in the LVCH-1 core, what evidence is available about the environment (see section on Formation of Deposits) suggests that the hard gray siliceous zones formed in a manner analogous to that of magadiite, in shallow water temporarily ponded on the surface of an ashfall, during a generally dry climatic period. Some of the soft-sediment deformation (for example, flowage folding, see Figure 8) in the hard gray zones is similar to that described by Surdam and others (1972) in magadiite beds.

Tuffs above 545 feet

The unaltered tuffs between 506 and 544 feet are gray or white. White, chalky-looking bands, which do not contain calcite, dip steeply to moderately (75^0 to 40^0), and are enclosed in loosely compacted gray ash between 525 and 530 feet. In contrast, light gray bands beween 537 and 539 feet, which dip as much as 45^0 and are of similar glassy appearance, are composed almost entirely of calcite (with traces of plagioclase, quartz, and clay). This part of the series consists of tuffs in which the glass has been replaced by calcite. No diatoms were found in the sample examined at 538 to 540 feet.

EXPLANATION

Sample contains two hard gray siliceous zones (dark) in airfall tuff that has been altered to clinoptilolite (light). Scale in millimeters.

Figure 7. - Hand specimen, segment of LVCH-1 core (at 857 feet).

500 μm

EXPLANATION

Hard gray siliceous material (dark) with flow banding and inclusions of pumice (light)

Figure 8. - Photomicrograph of thin section of a hard gray siliceous zone (at 943 feet in LVCH-1).

Unaltered tuffs between 506 and 525 feet are gray, massive, loosely to moderately compacted glassy ashes; no feldspars or quartz are detectable by standard x-ray diffraction methods. Montmorillonite replaces borders of glass shards at 506 feet.

Tuffs between 310 and 495 feet show evidence of deposition in a deep freshwater lake. Near the base, between 488 and 490 feet, a diatomite zone has dark, ash-bearing bands, possibly varves, which contain pine pollen. Mineral phases present include well-crystallized cristobalite, K-feldspar, and biotite. The undisturbed nature of the bands suggests a rather deep, (50-100 m) open water environment (J. Platt Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1982). The remainder of the part of the core between 440 and 495 feet consists of gray or white, loosely consolidated, glassy pumiceous tuffs and lapilli tuffs which contain some plagioclase, but no other minerals that are detectable by x-ray diffraction. No calcite is found in tuffs in this part of the core.

The section of core between 410 and 440 feet (see Plate 1) is composed in part of massive but loosely compacted, gray to white, fine-grained pumiceous tuffs and lapilli tuffs, and in part of poorly banded, presumably waterlaid tuffs which lack calcite. They contain some diatoms at 426 feet. A layer of ashy diatomite at 410 feet contains gypsum and is underlain by gypsum-bearing tuffs or tuffaceous sediments. The two species of diatoms which dominate the diatomite, plus the "rather pure nature of the diatomite", "indicate an open water environment in a rather deep fresh water lake of moderate alkalinity" (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1980), similar to the environment inferred from the diatomite at 490 feet. Therefore I deduce that massive tuffs such as those at 439 to 448 feet and 416 to 422 feet were also deposited in a deep lake. Quartz, plagioclase, and K-feldspar are constituents of these tuffs. They contain no clinoptilolite, but montmorillonite can be seen in thin section replacing borders of glass shards.

Eight feet of massive, light gray tuff between 388 and 396 feet lack calcite, but contain pyrite, biotite, and chlorite as well as quartz and two feldspars. These tuffs are both underlain and overlain by calcareous sediments which contain diatoms (at 387 feet and at 398 feet). The massive texture is probably a result of deposition below the zone of wave action.

The overlying set of massive tuffs or tuffaceous sediments, between 310 and 333 feet, are light gray to white, massive tuffs and lapilli tuffs, containing sporadic traces of calcite, very little glass, major amounts of quartz and plagioclase, and some biotite. These tuffs show no textures that suggest deposition in lake waters. Some coarse banding occurs, but only near the base of the series. Like the massive tuffs between 388 and 396 feet, they are underlain and overlain by calcareous sediments containing diatoms, and therefore were probably deposited in a deep lake.

Tuffs between about 250 feet and 305 feet are predominantly lapilli tuffs, containing minor amounts of calcite. Aragonite was tentatively identified at 275 feet. No fossils were found in the four samples examined. These white tuffs are pumiceous, somewhat consolidated, and of variable grain size. In places, they contain abundant lapilli of obsidian and pumice. Mineral phases present include major amounts of quartz, moderate amounts of plagioclase and K-feldspar, and minor amounts of biotite. At some places, (at 249-250 feet and at 260-261 feet), tuff layers dip 40° to 50°.

Above about 250 feet, the white to gray, friable pumiceous tuffs lack calcite, but contain minor to moderate amounts of quartz, plagioclase, and K-feldspar, and some biotite. These tuffs appear to have been deposited subaerially. They contain many large lapilli of obsidian and pumice, and blocks of the same materials up to 4 cm, or rarely up to 10 cm, in diameter. The tuffs above 250 feet are the only ones in the core that enclose blocks of volcanic rocks. The only mordenite found in this drillhole coexists with K-feldspar and cristobalite in a fragment of red rhyolitic rock at 241 feet.

Between 100 and 150 feet, zones of gravels, probably stream-laid, are cemented by chalcedony and/or opal (Terry E.C. Keith, U.S. Geological Survey, Menlo Park, California, written communication,1983) and alternate with poorly consolidated pumiceous ash. In places (for example, 138 to 139 feet), these zones have moderate dips of about 40°. No core was recovered above 100 feet.

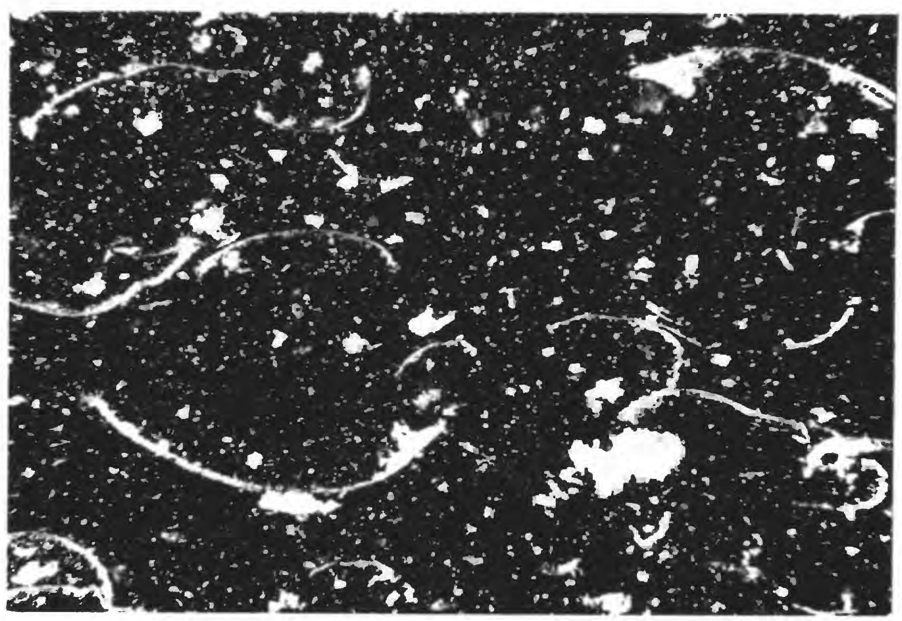
Sediments

Deepest Part of Core

In the deepest part of the drillhole (886 to 995 feet), sediments are gray or white calcareous muds, shales, and siltstones. At 992 to 995 feet, there are hard gray wavy bands (3 to 5 mm thick) of tuffaceous sediments which contain ostracode valves, too few for paleontological analysis.

A varied sequence of sediments at 970 to 976 feet suggests that the saline-alkaline lake went through repeated fluctuations of depth and salinity. A basal, soft white massive calcareous sediment, containing quartz and traces of K-feldspar, is barren of ostracodes. It encloses one of the hard gray siliceous zones described above. This basal sediment is overlain by harder, white and gray, quartz-calcite layers, followed by several thin, soft white layers (at 973 feet) which contain quartz, calcite, and K-feldspar. Many ostracode valves are visible in thin section at 973 feet (Figure 9); some have been infilled with coarse-grained calcite. At 971 feet, a one-foot-thick zone of gray siltstones, barren of fossils, is composed of major amounts of a K-feldspar (near Or_{100}) that is apparently authigenic, and major amounts of quartz and biotite, plus traces of pyrite, calcite, and clay. However, just above this zone (at 970.5 feet), three species of ostracodes are present in white calcareous sediments that contain quartz, K-feldspar, and traces of gypsum and pyrite. (See Appendix D.) At 970 feet, a thin, hard, gray parting, composed of calcite, quartz, and pyrite, overlies soft white cross-bedded sediments. Oxygen and carbon isotopic values from the calcite in the parting are consistent with deposition from very slightly saline lake waters (see Appendix C). In addition, the presence of three species of ostracodes at 970.5 feet indicates a lower salinity, in the range 2-10 ppt (moderately saline by Hem's scale), than that of any earlier periods in the depositional history of the Long Valley lake that are preserved in this core (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980).

A zone of gray shale at 948 to 950 feet, composed of quartz, cristobalite, K-feldspar, and montmorillonite, shows desiccation cracks. The same three species of ostracodes that were seen at 970.5 feet occur in



200 μm

EXPLANATION

Ostracode valves in fine-grained sediments. Bright, curved structures are ostracode tests.

Figure 9. - Photomicrograph of thin section at 973 feet in LVCH-1 core, with crossed nicols.

the mud at the base of this shale interval, but are less abundant. A similar, thinner band of shale at 940 feet overlies an intervening, steeply dipping layer of waterlaid lapilli tuff.

A thin band of gray siltstone at 910 to 911 feet, composed of calcite, quartz, cristobalite, K-feldspar, and traces of clinoptilolite and clay, is intercalated with six feet of waterlaid tuff. The siltstone contains only one species of ostracode, Limnocythere sappaensis, suggesting that the salinity was greater than 3 ppt and up to 30 ppt or even 50 ppt at times in this interval (higher than in the sediments at 950 and 971 feet, but lower than in sediments at 975 to 1000 feet) and that carbonate was greater than sulfate in these waters (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982). Both the waterlaid tuffs and the thin siltstone layer show soft-sediment structures and seem to have been smeared together soon after deposition. A series of 12 feet of light to dark gray, massive silty clay and mud, with mud cracks, at 894 to 906 feet, contains from three to four species of ostracodes, including the same three species that occurred at 950 and at 971 feet, and suggesting salinities in the range 2 to 10 ppt and fairly shallow depths, little greater than 15 feet (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982). Only two species of ostracodes are present in a thin band of siltstone overlying waterlaid tuff at 886 feet, suggesting a subsequent increase in salinity prior to the eruption of the thick series of tuffs (see Plate 1).

Lower Middle Part of Core

Sedimentary zones in the lower middle part of the drillhole, between 552 and 628 feet, are thin (less than six feet and generally less than three feet), and are interbedded with tuffs. Tuffaceous sediments that are interleaved with steeply dipping bands of lapilli tuff at 628 feet contain common Limnocythere sappaensis with rare Candona juveniles, suggesting saline conditions (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982). The three zones of sediments at 620 to 623 feet, 610 to 617 feet, and 605 to 607 feet are thin, parallel, buff-colored laminae, containing large amounts of calcite, montmorillonite, and clinoptilolite, and some cristobalite. Calcite veinlets within these sediments appear to have been generated from within the sedimentary zone. However, isotopic values of a veinlet from 612 feet present some complications (see Appendix C, p. 61). A semi-quantitative spectrographic analysis of a sample at 613 feet (sample #617 in Table 6, Appendix B) yielded 660 ppm of lithium, which substitutes for silicon in the montmorillonite clay (Ruth G. Deike, U.S. Geological Survey, Reston, Virginia, written communication, 1982; see Appendix B, p. 60). Ostracode species at 610 feet indicate that the lake at that time was very shallow, less than 15 feet deep, and still moderately to very saline (3 ppt to greater than 20 ppt) (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982). The species are the same two found at 628 feet, but some Candona may be reworked (Forester, 1982). The presence of abundant Limnocythere sappaensis is consistent with lake waters containing much more sodium than calcium, (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982) and is probably not inconsistent with high lithium concentrations.

Massive, gray-brown sediments at 586-590 feet contain large amounts of calcite, quartz, and K-feldspar, plus some clinoptilolite, but no clay. They are underlain and overlain by waterlaid tuff. Two thin zones of laminated sediments, rich in calcite and cristobalite, the lower one buff-colored, the upper one gray, occur at 582 and 584 feet. These sediments also contain no clay minerals. Fossil ostracode species at 584 feet are the same in type and similar in proportions to those at 628 feet.

The layer of sediment at 576 feet is a light gray, medium-grained sandstone, one foot thick, containing angular to sub-rounded clasts of quartz and unaltered plagioclase, a myrmekite clast, and traces of white mica. It is cemented by calcite.

At about 552 feet a thin zone of pumiceous sediments consists of alternating light gray and dark gray bands, dipping 45°. These bands contain abundant calcite, plus cristobalite and K-feldspar. Ostracodes are visible in thin section, but are too few for paleontological study.

Upper Middle Part of Core

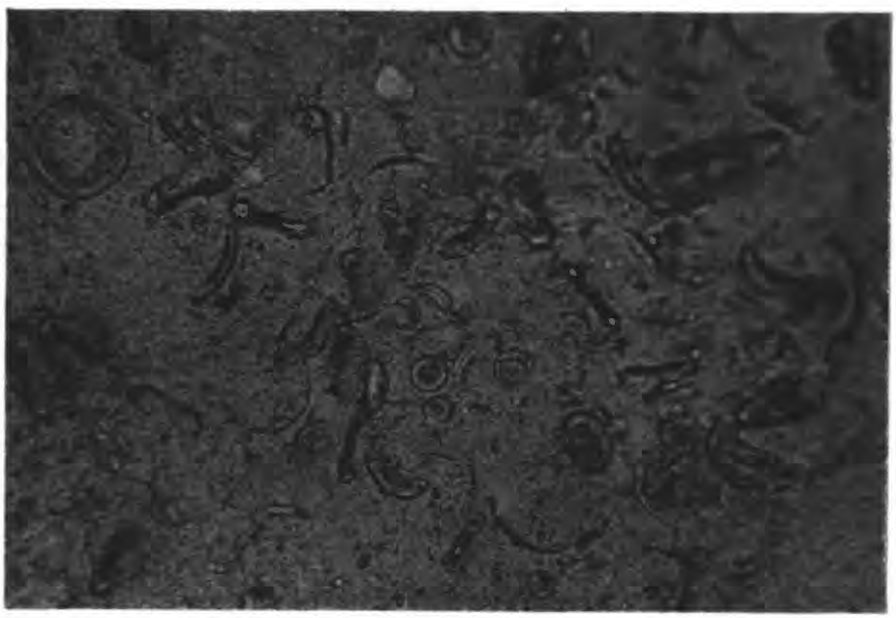
In the part of the core between 410 and 500 feet, the only sediments present are the two feet of horizontally banded, white diatomite at 488 to 490 feet which were discussed in the section on tuffs. The paleontologic evidence indicates that this diatomite was deposited in a rather deep freshwater lake. The diatom assemblage at 410 feet, also in an ashy diatomite, indicates an ecology very similar to that of the lake represented by diatomite at 490 feet (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1982).

Upper Part of Core

The sediments between 333 and 410 feet differ markedly from those below 545 feet. In contrast to most of the sediments in the bottom half of the core, this sequence lacks montmorillonite. Cristobalite is rare; however, samples at 375 feet and at 386 feet contain the most highly ordered cristobalite found in this drillhole; possibly it consists of recrystallized glass shards (see Petrology and Mineralogy section). The K-feldspar in sediments in this interval is probably authigenic (see Petrology and Mineralogy section). Diatoms are abundant (Figure 10); ostracodes are found only in the more calcareous sediments above 355 feet. Evidence suggests that these sediments were deposited in a deep freshwater lake.

Sediments between 360 and 410 feet are massive to poorly bedded, gray, fine-grained, and glass-rich. Biotite is comparatively abundant, and is accompanied by chlorite. Pyrite occurs in most samples. Calcite is absent or minor. Gypsum is sporadic, and associated with minor amounts of calcite; anhydrite may be present in one sample (at 378 feet). Dolomite was tentatively identified at 400 feet. Partings of pumiceous tuff recur throughout this section.

A thin zone of white, colloform, tuffaceous sediment at 387.5 feet is composed of glass, quartz, plagioclase, and K-feldspar. It looks as though it had been deeply eroded on a small scale (2 to 3 cm). The colloform sediment contains diatoms which are visible in thin section but were not submitted for paleontological analysis. It is overlain and infilled by 5 to 10 cm of a gray, glassy-looking sediment which contains quartz, plagioclase, K-feldspar, biotite, and hornblende. Textures suggest erosion and deposition, either near-shore or by bottom currents.



100 μm

EXPLANATION

A variety of shapes of high relief are diatom frustules in sediments.

Figure 10. - Photomicrograph of thin section at 387 feet in LVCH-1 core.

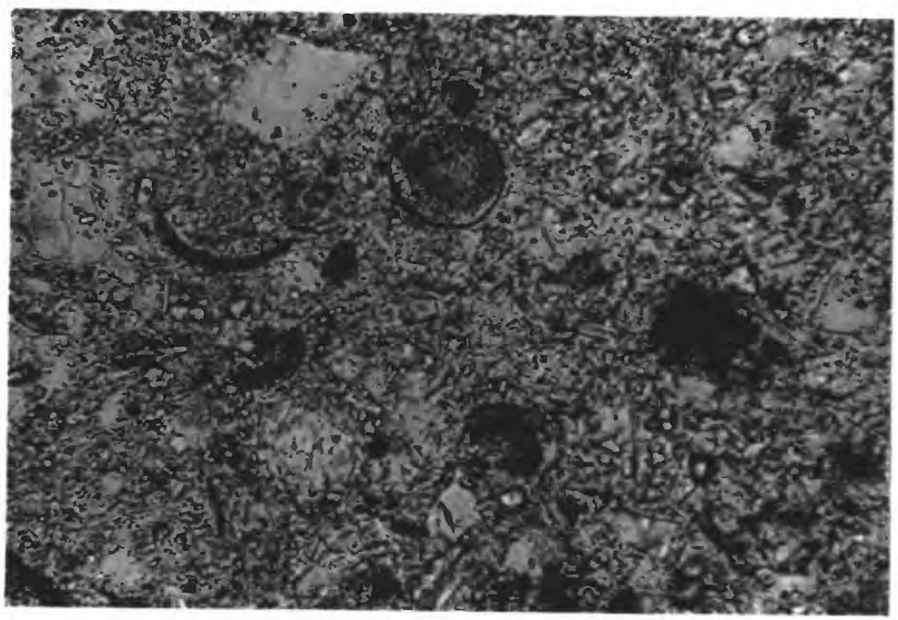
Sediments in the interval 333 to 360 feet are light gray, dark gray, or white, and are composed of detrital quartz, plagioclase, K-feldspar, biotite, and hornblende. Calcite is locally abundant between 340 and 360 feet, and moderate amounts of aragonite occur at 335 to 337 feet. Steep dips of 40° to 70° occur between 343 and 354 feet, and slump structures (flowage folding) are found in gray silts mixed with ashy diatomites at 342 to 343 feet. Also at 343 feet, there is a rich fossil assemblage of six species of ostracodes (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980) and thirteen species of diatoms (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1980), the greatest number of species found in any of the samples submitted for analysis (see Appendix D). Near the top of this sequence of sediments (at 334 feet), ashy silts and sands, containing calcite and some aragonite, yield the same ostracode assemblage as that at 343 feet (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980), but only three of the species of diatoms are represented (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1980). Both ostracodes and diatoms are visible in thin section (Figure 11).

The greatest concentrations of gypsum occur in this part of the core, at about 347 feet and about 360 feet. With one exception, the samples most enriched in gypsum lack calcite. A sample of gypsum from a vein at 358 feet was analyzed for oxygen isotopes (see Appendix C). White calcareous sediments in the vicinity of this gypsum (357-358 feet) are barren of ostracodes (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980). Oxygen and carbon isotopes were analyzed from a thin layer of botryoidal calcite and quartz just above the dipping sediments at 342 feet (see Appendix C).

Approximately five feet of sediments between 305 and 310 feet are quite different from the sequence below them, and contain some different fossils. They are gray-green sands and clays, composed of quartz, plagioclase, K-feldspar, biotite, and hornblende, but lacking chlorite, pyrite, and gypsum. These gray-green sediments grade upward to glassy- looking sands, with a little calcite at the top, and are overlain by lapilli tuffs. A sample of pumiceous sediment at 306 feet yielded two species of diatoms that are different from any found at 334 feet. One of these species was also found at 343 feet, but the other (<u>Hantzschia</u> <u>amphioxys</u> var. <u>major</u>) was not identified elsewhere in the drill core. Both species indicate a fresh water environment (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1980). No diatoms were found in the core above 306 feet.

Sands and Gravels

Pumiceous sands and cemented pebble or gravel zones, some dipping as much as 45°, comprise the upper 50 feet of the core, between 100 and 150 feet below wellhead. These sediments are apparently fluvial. At the top of the available core, the rock is fine angular gravel composed of pumice and obsidian fragments, well cemented (see Figure 4, impermeable zone at top) with chalcedony and/or opal (Terry E.C. Keith, U.S. Geological Survey, Menlo Park, California, oral communication, 1983), and dipping about 15°.



50 μm

EXPLANATION

Round and crescent shapes are diatom frustules in sediments.

Figure 11. - Photomicrograph of thin section at 334-335 feet in LVCH-1 core.

LITHOLOGY OF REPUBLIC DRILLHOLE

The Republic drillhole 66-29 intersected welded Bishop Tuff at 2,750 feet, and bottomed in welded Bishop Tuff at 6,920 feet. The lithology above 2,750 feet can be described in terms of 32 zones, summarized in Table 3. Note that most samples are comprised of more than one rock type. No cuttings were recovered from the interval between 650 and 980 feet.

Tuffs

Between 980 feet and the top of the welded Bishop Tuff at 2,750 feet, there are at least five types of nonwelded tuff. Two or more types occur together in many cuttings samples, but no more than two are major constituents in any one sample.

Very fine-grained tuff with phenocrysts

A very fine-grained white to very light gray (N8) tuff, containing varying amounts of clear and white phenocrysts of quartz and feldspar, extends from 1,730 feet down to 2,750 feet. The phenocrysts are small (less than 0.5 mm) and sparse down to 2,030 feet. An exception is a single large (3 mm) resorbed chatoyant sanidine crystal in the very fine-grained white tuff between 1,730 and 1,760 feet. Below 2,030 feet, the maximum size increases to about 1 mm, but most phenocrysts are less than 0.3 mm in diameter. Crystals are clear and euhedral. Between 2,030 and 2,150 feet, the tuff contains 15 to 20 percent of phenocrysts, and also encloses fragments of a gray aphanitic volcanic rock which contains mafic minerals. There is no biotite in the tuff. Above 2,240 feet, the very fine-grained porphyritic tuff comprises only a minor part of the cuttings except between 1,910 and 2,030 feet, where it is more abundant than the medium-grained tuff.

The abundance of phenocrysts decreases below 2,150 feet, and then increases again to reach 20 to 30 percent in the interval 2,300 to 2,360 feet. The tuff is light gray in color between 2,240 and 2,360 feet, possibly reflecting the presence of comminuted rock particles above a discontinuity at 2,360 feet. Below 2,360 feet, the maximum size of the crystals increases to 1.5 mm and then to 2 mm, and the abundance increases from about 10 percent to between 10 and 20 percent, except at the base of the nonwelded tuff, where it drops to less than 5 percent. This very fine-grained white tuff makes up nearly all of each sample below 2,300 feet except in the interval 2,510 to 2,570 feet, where an aphanitic, light gray volcanic rock, which contains white feldspar phenocrysts, aligned cavities (lithophysae), and pyrite, but no biotite, comprises as much as 50 percent of the cuttings. Some fragments of gray, glassy, flow-banded rhyolite also are present in this interval. It appears that the drillhole penetrated a lava flow or a shallow intrusion.

According to Roy A. Bailey (U.S. Geological Survey, Menlo Park, California, oral communication, 1983), the very fine-grained white tuff may represent the upper, nonwelded part of the Bishop Tuff. The drilling reports of Smith and Rex (1977) place a change in porosity at 2,250 feet, which they equate with the top of the nonwelded Bishop Tuff. By this interpretation, there would be two very fine-grained white tuffs. The lower one, below about 2,240 feet, with 10 to 20 percent of phenocrysts, would correspond to the nonwelded Bishop Tuff. The upper one, crystal-poor except for one zone at 2,030-2,150 feet, would be a post-Bishop tuff. The change in porosity is marked in the cuttings by abundant chips of varied basement rock types (at 2,240-2,300 feet), and by a zone containing many rounded uncemented quartz grains (at 2,030-2,200 feet), which may represent reworking of the surface of the nonwelded Bishop Tuff (Bailey, U.S. Geological Survey, Menlo Park, California, oral communication, 1983).

Fine- to medium-grained tuff with phenocrysts

A fine-grained (0.125-0.25 mm) to medium-grained (up to 0.5 mm) or coarse-grained, white or very light gray tuff with a nubbly texture is the major constituent of most cuttings intervals between 1,640 and 2,240 feet. It contains sparse rounded crystal fragments of quartz ("phenocrysts"), less than 0.5 mm in diameter. These crystal fragments increase in abundance with depth to a maximum of about 40 percent of the volume of the rock at 2,120 to 2,150 feet, but are absent between 2,150 and 2,300 feet. There is no visible biotite in this tuff. There is little calcite in this tuff; exceptions are minor amounts at 1,760 to 1,790 feet, and major amounts at 1,850 to 1,880 feet and in lapilli tuff at 2,030 to 2,090 feet.

Very fine-grained tuff without phenocrysts

A very fine-grained white (N9) or very light gray (N8) tuff is found between 1,160 (or possibly 1,070) feet and 1,640 feet. It contains no phenocrysts of quartz or feldspar. However, between 1,160 and 1,310 feet it does contain many tiny dark fragments of an opaque mineral (as seen in thin section at 1,280 feet). X-ray diffractometer patterns show that this tuff contains no plagioclase above 1,550 feet. At 1,280 to 1,310 feet, small crystals of biotite (less than 35 μm) and green hornblende are visible in thin section in addition to the opaque mineral. Between 1,460 and 1,550 feet, radial clusters of chlorite, apparently secondary, are visible in thin section. Moderate amounts of calcite are found in the tuffs between 1,070 and 1,160 feet, major amounts occur between 1,310 and 1,340 feet, and minor amounts are detected between 1,400 and 1,430 feet. Elsewhere in this tuff, calcite is absent.

In most intervals between 1,160 and 1,640 feet, this very fine-grained white tuff is the predominant component of the cuttings. Between 1,070 and 1,250 feet it is altered to clinoptilolite, and at 1,100 to 1,130 feet and 1,160 to 1,220 feet, it also contains mordenite. Mordenite is more abundant than clinoptilolite in the interval 1,160 to 1,190 feet. At 1,190 to 1,220 feet, mordenite is more abundant than clinoptilolite in yellowish-gray tuff, but clinoptilolite is more abundant than mordenite in this white tuff.

Cristobalite occurs in this white tuff at 1,190 to 1,220 feet. Between 1,250 and 1,520 feet, the zeolite is analcime (with some clinoptilolite at 1,250 to 1,280 feet). Below 1,520 feet, no zeolites are found in this tuff except at 1,940 to 1,970 feet, where analcime-bearing tuff was probably sloughed from shallower depths in the drillhole. Calcite is absent from this tuff except at 1,310 to 1,340 feet, where it is a major constituent, and at 1,400 to 1,430 feet, where it is minor.

The analcime in this very fine-grained white tuff can be seen in thin section, around the edges of the section, as equant, isotropic grains, less than 20 to 55 μm in diameter. The analcime-bearing white tuff has a mosaic texture that is visible with a low-power (30X) microscope. Below 1,250 feet, both K-feldspar and plagioclase become more abundant, and traces of diagenetic chlorite appear. The mottled appearance in thin sections at 1,280 feet and 1,460 feet is attributable to analcime; the thin section at 1,550 feet retains the mottled aspect, but the blotches have low birefringence and low relief, and appear to be feldspar rather than analcime. Thus the K-feldspar appears to have formed by replacement of analcime.

Chips of a medium-grained white tuff found between 1,460 and 1,550 feet may belong to this unit. It contains major amounts of analcime and quartz, minor amounts of K-feldspar, and varying amounts of plagioclase and calcite. The textural relations in a thin section at 1,460-1,490 feet indicate that this rock is either a lapilli tuff or a rock formed when glass lapilli fell into water near shore where sand grains were also accumulating. Lapilli of flow-banded glass have been replaced by calcite. The matrix of quartz and feldspar has apparently been replaced by analcime.

Tuff with dark ash particles

A medium-grained (0.25 to 0.50 mm) white tuff containing ash particles of a dark rock (unidentified) occurs between 1,160 and 1,220 feet. This tuff is present in amounts about equal to the very fine-grained white tuff without phenocrysts. It may simply represent a basal lithic lapilli tuff phase of the very fine-grained white tuff without phenocrysts. The tuff with ash particles is partly altered to mordenite and clinoptilolite, and some cristobalite may be present at 1,160 to 1,190 feet. No calcite is present. No thin sections are available.

Yellowish-gray tuff

A very fine-grained yellowish-gray tuff (5Y7/2) occurs between 980 and 1,400 feet, and as traces, probably sloughed from above, in some intervals between 1,880 and 2,270 feet. It predominates in cuttings between 1,030 and 1,160 feet and between 1,220 and 1,250 feet, but is absent between 1,160 and 1,190 feet and between 1,310 and 1,340 feet. Throughout its range, yellowish-gray tuff is altered to clinoptilolite; at 1,100 to 1,130 feet and especially at 1,190 to 1,220 feet, mordenite is also present. (See Table 3 and Plate 2.) This tuff contains no calcite. A few small green hornblende crystals are visible in thin section at 1,040 to 1,070 feet.

There are only two occurrences of tuffs in the cuttings above 650 feet:
(a) Between 560 and 590 feet, a green vitric lapilli tuff, pervasively altered to clinoptilolite, is predominant; traces of a gray "porphyry" which is similar in appearance occur at 590-620 feet. This is the shallowest occurrence of clinoptilolite in the Republic drillhole.
(b) Between 470 and 560 feet, a white unaltered tuff, containing minor amounts of calcite and biotite and major amounts of cristobalite and quartz, is the major constituent of the cuttings. Minor amounts of the same tuff occur at 440-470 feet and 560-590 feet. In contrast with the LVCH-1 drillhole, there are no tuffs in the upper 440 feet of the Republic drillhole.

Other Volcanic Rocks

The only major occurrence of volcanic rock below 980 feet is found between 2,510 and 2,570 feet, where the cuttings are dominated by a light gray (N7) aphanitic volcanic rock which contains feldspar phenocrysts, biotite, and pyrite, and has aligned cavities (lithophysae) which define a flow texture. X-ray diffraction patterns reveal the presence of quartz, a moderate amount of plagioclase, minor amounts of K-feldspar, and possible chlorite. Roy Bailey (U.S. Geological Survey, Menlo Park, California, oral communication, 1983) would correlate this rock with early rhyolite. There are also many chips of a gray, glassy, flow-banded rhyolite between 2,540 and 2,570 feet.

Elsewhere below 980 feet, a few chips of a very light gray (N8 to N9) aphanitic, non-porphyritic rock occur in many intervals above the welded Bishop Tuff. Some contain two feldspars, some only plagioclase. Most display mafic minerals which are visible without a microscope, and all those that were studied by x-ray diffraction contain some biotite. Similar fragments occur in cuttings below the top of the welded Bishop Tuff but are rare, and may have been sloughed from above.

A pistachio-green porphyry at 440 to 500 feet contains quartz, cristobalite, moderate amounts of calcite, minor feldspar, and a trace of pyrite. At both 260 to 320 feet and 440 to 500 feet, varying amounts of flow-banded, laminar glass occur in the cuttings, and at 500 to 560 feet, there are fragments of clear perlitic glass and of pumice altering to montmorillonite. Pumice predominates at 500 to 530 feet. Between 530 and 560 feet, some rounded grains of glass are frosted, and apparently wind-blown.

Between 500 and 530 feet, there are some cuttings chips of a green breccia containing fragments of unaltered K-feldspar, shredded biotite (80-200 μm), green hornblende, calcite, and glass altering to montmorillonite. The rock contains large amounts of mordenite and cristobalite, which are not visible in thin section. Presumably this mordenite formed elsewhere in some of the breccia fragments, as no other mordenite is found above 1,160 feet in this drillhole. A few fragments of a red porphyry occur at 140-230 feet, and a few chips of red and black scoria are found at 140 to 170 feet and 230 to 290 feet.

Sediments

Sediments in the Republic drillhole below 980 feet are sandstones, which in general lack calcite between 980 and 1,310 feet. Sediment chips are abundant only above 1,550 feet, and no coherent sedimentary rocks are found below 2,060 feet, but rounded, uncemented grains of quartz and some of plagioclase (less than 2 mm in diameter) are abundant in the cuttings between 2,030 and 2,450 feet. In some intervals (2,120-2,180 and 2,420-2,450 feet), they are the most abundant type of material. Biotite grains, less than 1.5 mm in diameter, occur in the cuttings between 2,300 and 2,360 feet. There are at least three major sandstone units and several less common units.

(1) A medium to medium coarse-grained, very light gray (N8) sandstone, which coarsens downward, is one of three major rock types in the cuttings between 1,310 and 1,430 feet. It contains major analcime, in addition to quartz, K-feldspar, variable amounts of plagioclase, and minor to moderate amounts of calcite. This rock type is of much more limited vertical extent than the very fine-grained light gray sandstone (see below).

(2) A very fine to fine-grained light gray (N7) sandstone occurs in some intervals between 980 and 2,030 feet. At 980 to 1,010 feet it is fine-grained, and is the dominant lithologic unit. It contains quartz, cristobalite, minor amounts of feldspars, and minor clinoptilolite. Between 980 and 1,250 feet, trace to minor amounts of clinoptilolite are only intermittently present in this sandstone, although it is abundant in the tuffs in this interval. There is little or no calcite in the sandstone. Between 1,310 and 1,370 feet, this sandstone again makes up a major portion of the cuttings; here, and down to 1,550 feet, it is composed of major amounts of calcite, plus quartz, minor amounts of K-feldspar, and varying amounts of plagioclase and biotite. It does not contain analcime, in contrast to the presence of abundant analcime in the tuffs and in the other sediments in this zone. Between 1,490 and 1,550 feet, the biotite grains are large enough to be visible with a 30X microscope.

(3) The principal sedimentary unit above 650 feet is a fine to medium-grained yellowish-gray (5Y 8/1) sandstone, containing quartz, amounts of K-feldspar varying from trace to major, and minor amounts of plagioclase and biotite. Between 260 and 440 feet, this sandstone makes up about 70 to 95 percent of the cuttings. It contains some dark pebbles, 0.3 to 0.4 mm in diameter. Smaller amounts of sandstone occur between 80 and 140 feet (up to 70 percent of the cuttings at 110 to 140 feet) and between 200 and 230 feet. The sandstone contains trace to minor amounts of calcite between 260 and 440 feet; no calcite is present above 260 feet. In thin section (at 350-380 feet), a number of diatoms are visible. According to J. Platt Bradbury (U.S. Geological Survey, Denver, Colorado, written communication, 1980), diatoms from this sample are a single Stephanodiscus species. Although this sample does not clearly correlate with any of the samples submitted from the LVCH-1 core, this Stephanodiscus species is most closely related to Stephanodiscus kanitzii fo inermis, which is present at 343 feet in the LVCH-1 core (see Appendix D). The yellowish- gray sandstone does not reappear below 980 feet.

Rock and mineral fragments in the sandstone which are visible in thin section are 0.1 to 0.4 mm in diameter and include quartz, unaltered glass, K-feldspar (fresh or with some clay alteration or partial replacement by white mica), biotite, chalcedony with a radial texture, presumably replacing glass, and some shreds of basaltic hornblende. The matrix is not optically resolvable except for some tiny grains of calcite, but based on x-ray data, it presumably is composed of quartz and feldspar.

A few other sediments are of very limited occurrence. Between 980 and 1,010 feet, a few chips of a very fine-grained medium-gray (N5) sandstone occur; they may have sloughed from above the interval in which cuttings are absent at 650 to 980 feet. There are no extensive sedimentary rocks between 470 feet and the gap at 650 feet. Between 590 and 620 feet, a gray mud, possibly drilling mud, is mixed with a wide variety of igneous and metamorphic rock chips; at 620 to 650 feet, the mud contains only a few such chips. Sediments above 650 feet are unaltered except for a trace of clinoptilolite in chips of sandstone between 590 and 620 feet.

A fine-grained, glassy, olive-gray (5Y 4/1) sandstone occurs in minor amounts at 80 to 110 feet and 140 to 230 feet, and is most abundant between 230 and 260 feet. Its x-ray diffraction pattern shows chiefly plagioclase and glass, with traces of quartz, calcite and biotite. No thin sections are available. Between 440 and 500 feet, a very fine-grained, olive-gray

(5Y 6/1) sandstone, which is very similar in appearance to the glassy olive-gray sandstone, is composed of quartz, cristobalite, minor amounts of calcite and K-feldspar, and traces of biotite and pyrite, as determined by x-ray diffraction.

A large proportion of the cuttings between 50 and 230 feet is made up of uncemented sand grains 1 to 3 mm in diameter, predominantly clear or milky quartz. Some grains of plagioclase and K-feldspar are also present, and biotite occasionally occurs. The proportion of uncemented sand grains decreases with increasing depth.

Other Rock Types

(1) Fragments of black hornfels, generally composed of quartz, K- feldspar, and biotite, are abundant at various levels in the Republic drillhole. Above 650 feet, they form about 20 percent of the cuttings between 50 and 80 feet and between 200 and 230 feet. They comprise more than 10 percent of the cuttings at 290 to 320 feet, where they are associated with fragments of flow-banded glass and of a very fine-grained, medium-gray (N6) sandstone, similar to the chips at 980 to 1,010 feet, in cuttings that are predominantly composed of the sandstone. Black hornfels also occurs in smaller amounts between 560 and 620 feet. Between 140 and 200 feet, a dark-colored rock, similar in appearance to the other black hornfels but with an X-ray composition dominated by quartz with traces of plagioclase and mica, makes up about 60 to 80 percent of the cuttings. Possibly this rock is volcanic. Volcanic amygdaloidal black basaltic grains also occur in this depth interval.

Below 980 feet, black hornfels is found in four thirty-foot intervals between 1,850 and 2,300 feet, where, as also at 560 to 620 feet, it is associated with other basement rock types: quartzite, granitic rock, and angular grains of quartz and feldspar. At 2,330 to 2,360 feet, black grains of a different composition, which make up 25 percent of the cuttings, are composed of quartz, plagioclase, and biotite, with traces of K-feldspar, pyrite, and chlorite. Black hornfels also occurs below 2,750 feet throughout the welded Bishop Tuff; it is most abundant above 3,000 feet and below 6,710 feet, at the base of the drillhole. In some intervals, (for example 5,120-5,150 and 6,710-6,770 feet), its presence cannot be explained by sloughing, because a rock which appears to be the same as the most abundant hornfels occurs as inclusions within chips of welded tuff. The black hornfels within the welded tuff zone is not nearly as abundant as it is in the upper part of the drillhole.

(2) Quartzite fragments, generally brownish, greenish, or gray, occur sporadically above 620 feet. At 230 to 260 feet, they form a predominant portion of the cuttings. They also occur sparsely between 1,160 and 2,450 feet, especially at 2,240 to 2,300 feet (see Table 3), and are found even more rarely within the welded Bishop Tuff zone.

(3) Some chips of a biotite-rich metamorphic rock are fairly abundant between 230 and 260 feet, but elsewhere in the drillhole were found only at four intervals, three of them within the welded Bishop Tuff zone.

(4) Chips of a granitic rock with coarse biotite were found above 290 feet; at 230 to 260 feet, they are a predominant portion of the cuttings,

and occur in association with quartzite. A second occurrence of granitic chips is between 2,240 and 2,360 feet; these chips contain pink or red quartz grains, and grains of chlorite and of white mica, as well as grains of coarse biotite. The granitic chips are abundant between 2,240 and 2,270 feet. No granitic rock chips were observed within the welded Bishop Tuff.

PETROLOGY AND MINERALOGY OF CORE AND CUTTINGS

Primary and detrital minerals in the two drillholes include glass, quartz, plagioclase, K-feldspar, biotite, hornblende, and opaque oxides (probably iron-titanium oxides). Authigenic minerals include, in paragenetic sequence, montmorillonite, clinoptilolite, analcime (possibly with some quartz), and some K-feldspar (possibly accompanied by authigenic albite). Mordenite occurs in only a few intervals and cannot be placed in the paragenetic sequence.

Calcite occurs both as a primary sedimentary precipitate and as a replacement of glass and other minerals. It is also present as ostracode valves, which it locally infills.

Feldspars

In the LVCH-1 core, most plagioclase is apparently detrital; it is generally unzoned and is not altered. It is more abundant in sediments than in tuffs. Detrital plagioclase is locally abundant in sediments and waterlaid tuffs down to about 620 feet. Below that depth it is sporadic, occurring only in sediments and in waterlaid tuffs, and it may be authigenic. It is detectable only by x-ray diffraction and in trace amounts, (see Plate 1).

In the Republic drillhole, there is no more than a trace of plagioclase in the nonwelded tuffs above 1,520 feet, except in the calcite-rich tuff at 1,310-1,340 feet (see Table 5). Below 1,520 feet (and above the top of the welded Bishop Tuff), plagioclase is generally absent from yellowish-gray tuff, but is present in varying amounts in white tuffs, where it may be authigenic. At 2,270 to 2,330 feet, plagioclase is more abundant than quartz in very fine-grained white lapilli tuff.

Both plagioclase and analcime are common in the Republic drillhole (see Plate 2), but they rarely occur in the same rock. Plagioclase is present in minor amounts in most sediments above 650 feet and below 1,550 feet. However, the small amounts of sediment present below 1,550 feet were probably sloughed. Between 1,340 and 1,550 feet, plagioclase is absent, or present only in trace amounts, in fine to medium-grained gray sandstones. This depth interval coincides with the basal part of the zone of plagioclase-free tuffs and with most of the analcime zone at 1,250 to 1,550 feet.

K-feldspar in the LVCH-1 core appears to be of both detrital and authigenic origin. Detrital K-feldspar is unaltered (as seen in thin section) except for some argillaceous dusting. Authigenic K-feldspar is extremely fine-grained, and is optically identifiable in only a few thin sections.

An attempt was made to study the crystal structure of authigenic

K-feldspar from two samples, using the methods of Wright (1968) and Wright and Stewart (1968) to analyze the x-ray diffraction patterns. According to Richard Erd (U.S. Geological Survey, Menlo Park, California, oral communication, 1981), both patterns are characteristic of authigenic K-feldspars. However, because of the extremely fine grain size and intergrowths of the crystalline material, I was unable to achieve clean mineral separations. Therefore quartz or cristobalite peaks interfered with some critical K-feldspar peaks. My preliminary results are described in Appendix E. There are apparent anomalies in measurements of some 2θ values; substitution of boron in the feldspar structure might account for some of the discrepancies (Sheppard and Gude, 1973a). More work on these feldspars is needed.

At a number of intervals, I have inferred the presence of authigenic K-feldspar. At these sites, the amount of K-feldspar detected by x-ray diffraction is an order of magnitude greater than the amount of detrital K-feldspar distinguishable in thin section (see Table 4). The inference that such K-feldspar is authigenic is strengthened by two other trends in the data: (1) In general, intervals in which the K-feldspar is inferred to be authigenic coincide with parts of the core where ostracode data indicate moderate to high salinity, for example, at 585 feet, 608 to 610 feet, 911 to 912 feet, and 971 to 990 feet. A comparison of Table 4 with Table 8 shows that the correlation is strong. (2) Most samples in which the K-feldspar is inferred to be authigenic contain K-feldspar in amounts equal to or exceeding the amount of quartz in that sample. This pattern is striking because in most parts of the core, quartz is much more abundant than K-feldspar (see Plate 1).

In the Republic drillhole, K-feldspar is probably detrital in tuffs above 1,550 feet, and authigenic below this depth. It is a minor constituent in the few samples of tuff that occur above 650 feet. However, below 980 feet it is ubiquitous in at least minor amounts in yellowish-gray tuff, in very fine-grained white tuff (1,070-1,370 feet) and in fine- to medium- grained white tuff (1,640-2,270 feet) (see Plate 2). In very fine-grained crystal lapilli tuff, K-feldspar occurs in greater than trace amounts in most samples. K-feldspar is more abundant in white tuffs between 1,550 and 1,790 feet, just below the analcime-rich zone, than it is in tuffs within the analcime zone. (Samples which appear to have been sloughed are omitted.) This distribution suggests an authigenic origin for the K-feldspar in tuffs below 1,550 feet.

At equivalent depths in the Republic drillhole, there is commonly less K-feldspar in sediments than in tuffs. In sediments, K-feldspar is absent or minor above 650 feet except at 350-380 feet, where it is abundant. Between 980 and 1,190 feet it is present in trace to minor amounts. No K-feldspar was detected in sediments between 1,190 and 1,310 feet, and between 1,310 and 1,550 feet its abundance ranges from minor to moderate. K-feldspar is generally minor to moderate in abundance in chips of sediments, probably sloughed, found below 1,550 feet.

Silica Phases

Silica phases that have been identified in rocks from the two drillholes are quartz, chalcedony, cristobalite and opal. Quartz and chalcedony cannot be differentiated in x-ray diffractograms, therefore except where optical data are available, the term "quartz" must be understood to include both. Small amounts of chalcedony with a radial texture can be seen in thin sections of samples between 552 feet and 635 feet in the LVCH-1 core, where it apparently formed by recrystallization of shards of banded rhyolite glass. Chalcedony was also seen (in oils) as colloform cement around some grains in cemented gravels at 103 feet and 118 feet, and as fragments in tuff at 210 feet. Opal was found as cement in two samples of angular gravel, at 103 feet and 136 feet, and in tuff at 453 feet, in the LVCH-1 core (T.E.C. Keith, U.S. Geological Survey, Menlo Park, California, oral communication, 1983). Cristobalite varies in crystallinity. It was studied in detail and will be discussed in a separate subsection. No study was made of glass compositions; refractive indices are less than balsam, consistent with glass of rhyolite composition.

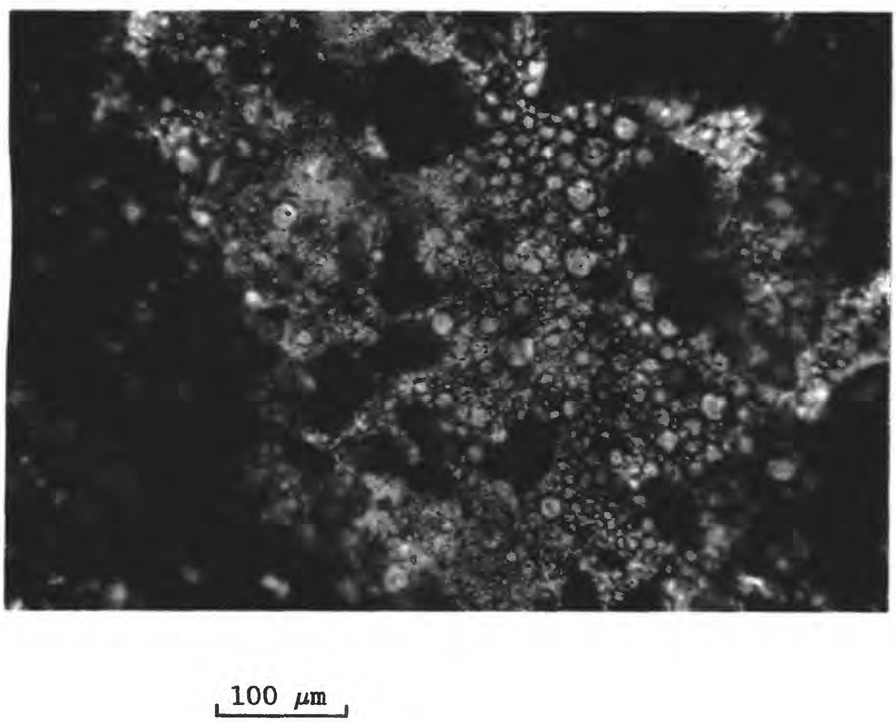
Quartz is present in all rocks in the LVCH-1 core down to 440 feet, but occurs in only minor amounts in tuffs and lapilli tuffs between 200 and 280 feet and between 410 and 440 feet. Quartz which is probably of authigenic origin is abundant in sediments and waterlaid tuffs between 440 and 640 feet and below 886 feet, but is absent or present only in trace or minor amounts in tuffs in these parts of the core.

Quartz occurs in some of the hard gray siliceous bands that occur between 714 and 945 feet. Quartz also coexists with cristobalite in these bands; either phase may be the more abundant. There is no correlation between the quartz : cristobalite ratio and the depth at which the zone occurs.

Cristobalite does not occur above 372 feet in the LVCH-1 core except in xenolithic blocks of rhyolite and welded tuff. Between 540 and 640 feet, cristobalite generally occurs as part of the rock matrix in the same intervals which contain quartz, i.e., in sediments or waterlaid tuffs. Its pattern of occurrence suggests a diagenetic orgin. In the interval 886 to 1000 feet, cristobalite commonly occurs only in waterlaid tuffs and in hard gray siliceous zones, but not in sediments. Cristobalite is also found in hard gray siliceous zones which are enclosed in tuffs below 550 feet.

Within a series of alternating sediments and tuffs between 545 and 620 feet, textures in a tuffaceous sediment seen in thin section (at 552 feet) indicate that the crystallization of cristobalite in the matrix of the rock plus the subsequent formation of chalcedony veinlets occurred later than the deposition of calcite in the same matrix. In this thin section, a honeycomb texture of cristobalite grains, with hexagon diameters in the range 70 to 100 μm, is superimposed on a texture of calcite grains that are 10 to 20 μm in diameter. In the same thin section, discontinuous cross-cutting veinlets are filled with chalcedony (illustrated in Figure 12).

In the Republic drillhole (see Plate 2), quartz is present, generally as a major constituent, in nearly every cuttings interval. In thin section, it is visible as quartz fragments in sandstones and tuffs, and presumably it also occurs as submicroscopic grains in the matrices of both rock types. In the yellowish-gray tuff, 330 feet out of a total of 510 feet of cuttings are quartz-free, and where quartz is present in this rock type, it is a very minor constituent. At 1,100-1,130 and 1,160-1,250 feet, fine-grained white tuff, which occurs in cuttings samples with yellowish-gray tuff, also lacks quartz.



EXPLANATION

Spherules of cristobalite in a veinlet project from a layer of calcite-poor sediment into a zone of calcite-rich sediments that contain ostracode valves and glass shards. Some glass shards show incipient alteration to clinoptilolite.

Figure 12. - Photomicrograph of thin section at 552 feet in LVCH-1 core.

Quartz is the only crystalline silica phase found between 1,250 feet and the top of the welded tuff in this drillhole. Some quartz is primary, but much of the matrix quartz may be diagenetic. Its growth, with or without a cristobalite precursor, would have been facilitated by the relatively high pH of the early caldera lake waters, as well as the absence of clay and the presence of some carbonate (Kastner and others, 1977).

In the Republic drillhole, cristobalite is found in both tuffs and sediments. It is restricted to the interval between 440 and 1,250 feet (see Plate 2). Above the zone from which no cuttings were returned, that is between 440 and 650 feet, cristobalite occurs with quartz in a variety of rock types: sandstone, volcanic breccia, and tuff. In a sandstone at 590 to 620 feet, cristobalite is more abundant than quartz.

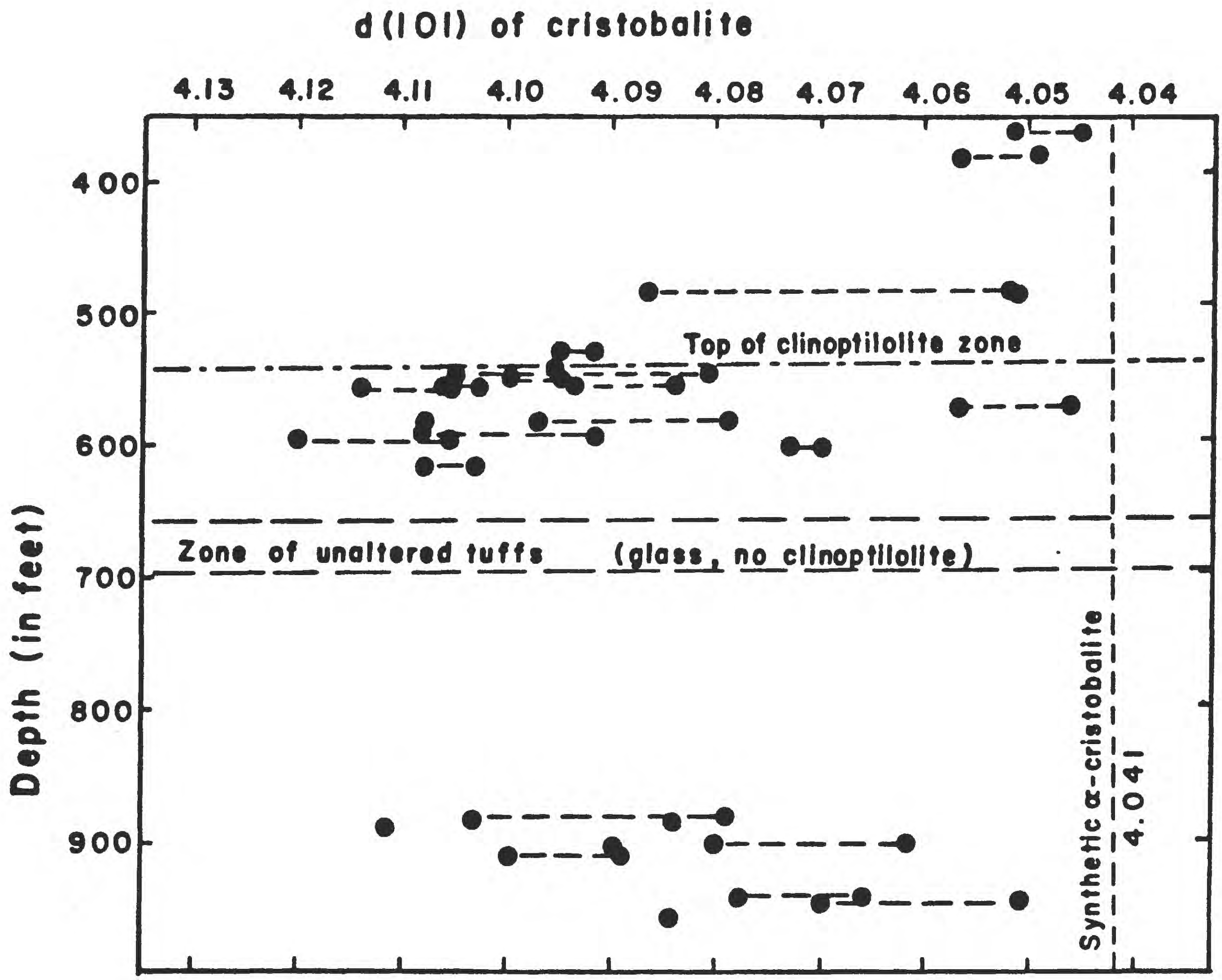
Cristobalite distribution is closely correlated with the presence of clinoptilolite in the Republic drillhole (see Plate 2). Below 980 feet, cristobalite is found in moderate amounts in various rock types, both tuffs and sediments, with or without quartz. It is especially abundant in tuffs, both white and yellowish-gray, at 1,190 to 1,250 feet. The bottom of the cristobalite-bearing zone coincides with the base of the clinoptilolite-mordenite zone. (Depending on which samples are interpreted as sloughed, the base of the cristobalite zone may be as much as 150 feet shallower.) The upper limits of the two mineralogically defined zones similarly correspond within 60 feet.

Crystallinity measurements of cristobalites

It was hoped that investigation of the index of crystallinity of cristobalites in both drillholes would provide some information about the maximum temperatures achieved at some past time at various depths. In general, the results are inconclusive in terms of indicating past surges of hydrothermal activity, and instead, support the hypothesis that the mineralogy is the result of crystallization at low temperature in a saline-alkaline lake. Three sets of cristobalites were studied: (1) cristobalites in whole-rock samples of tuffs and sediments from the LVCH-1 core (Figure 13); (2) cristobalites occurring within the hard gray siliceous zones in the LVCH-1 core (Figure 14); (3) cristobalites from hand-separated samples of specific rock types from the cuttings of the Republic drillhole (Figure 15). The crystallinity of α-cristobalite, 4.041Å, is shown on each figure as the maximum crystallinity possible.

In the cristobalites in tuffs and sediments of the LVCH-1 core below 550 feet, there is no correlation between the degree of crystallinity and increasing depth (see Figure 13). Crystallinities show a large amount of scatter, with d(101) ranging from 4.115Å to 4.045Å. The amount of scatter is the same both above and below the zone of tuffs altered to clinoptilolite (at 700 to 840 feet), which lack cristobalite (see Figure 13). The measured d(101) values in the tuffaceous sediments with honeycomb texture at 552 feet (Figure 12) are about 4.104Å and 4.084Å. These particular silica phases clearly formed <u>in situ</u>.

By comparison with the crystallinities and temperature gradients found by Murata and Larson (1975) in Miocene cherts and diatomaceous shales at depths to 2,788 feet, crystallinities in LVCH-1 are compatible with temperatures of 47° to 75°C. If later calibrations of Murata, Friedman, and Gleason (1977) for the same Miocene strata are used, the LVCH-1 data are



EXPLANATION

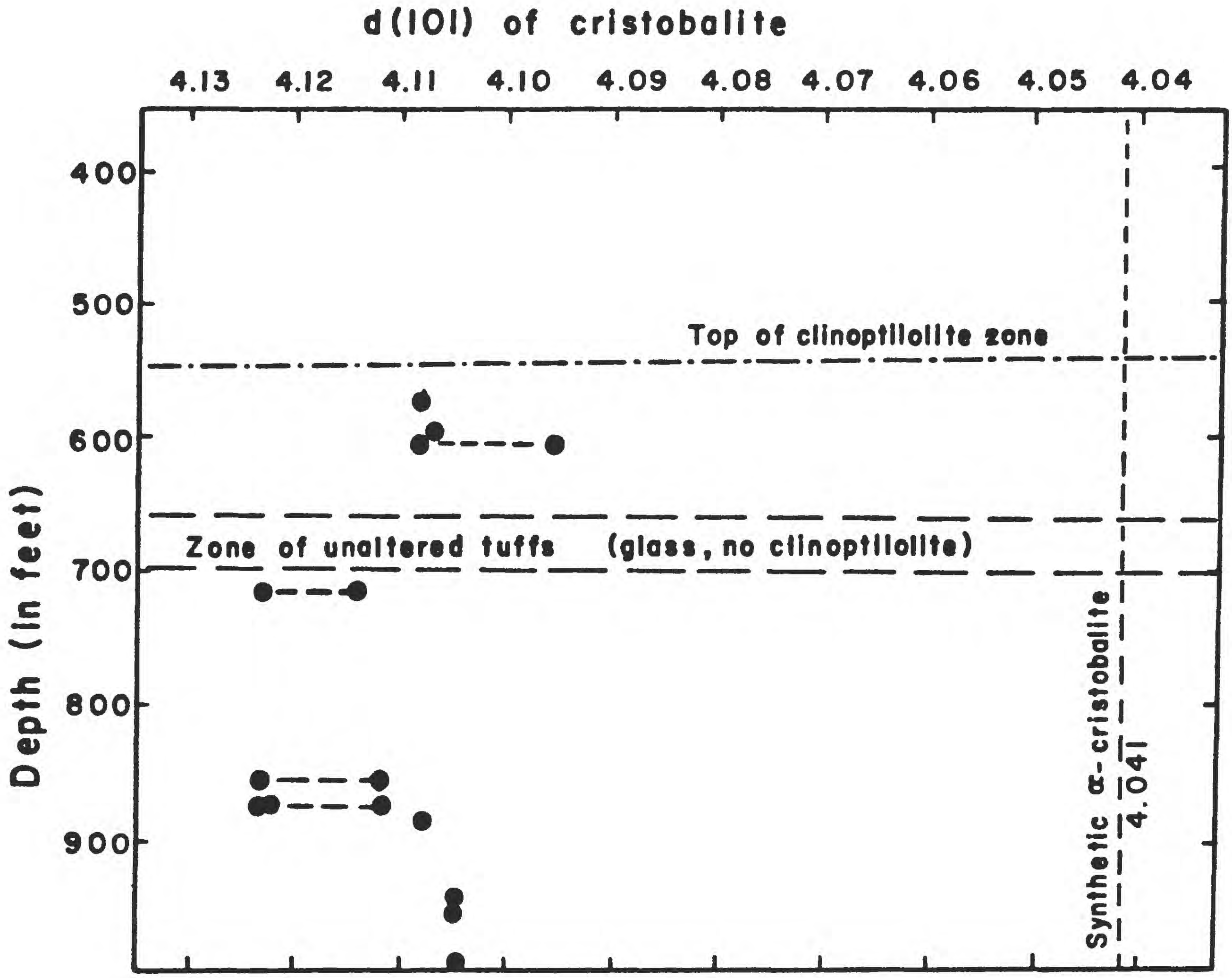
● d(101) of cristobalite for a given sample

Dashed lines show range of values for a specific sample

Ordinate - depth in feet

Abscissa - d(101) of cristobalite. Low d-values are indications of a high degree of crystallinity, approaching d - 0.40410Å (synthetic cristobalite) as a limit.

Figure 13. - Graph of crystallinities of cristobalites in whole-rock samples from LVCH-1 core.



EXPLANATION

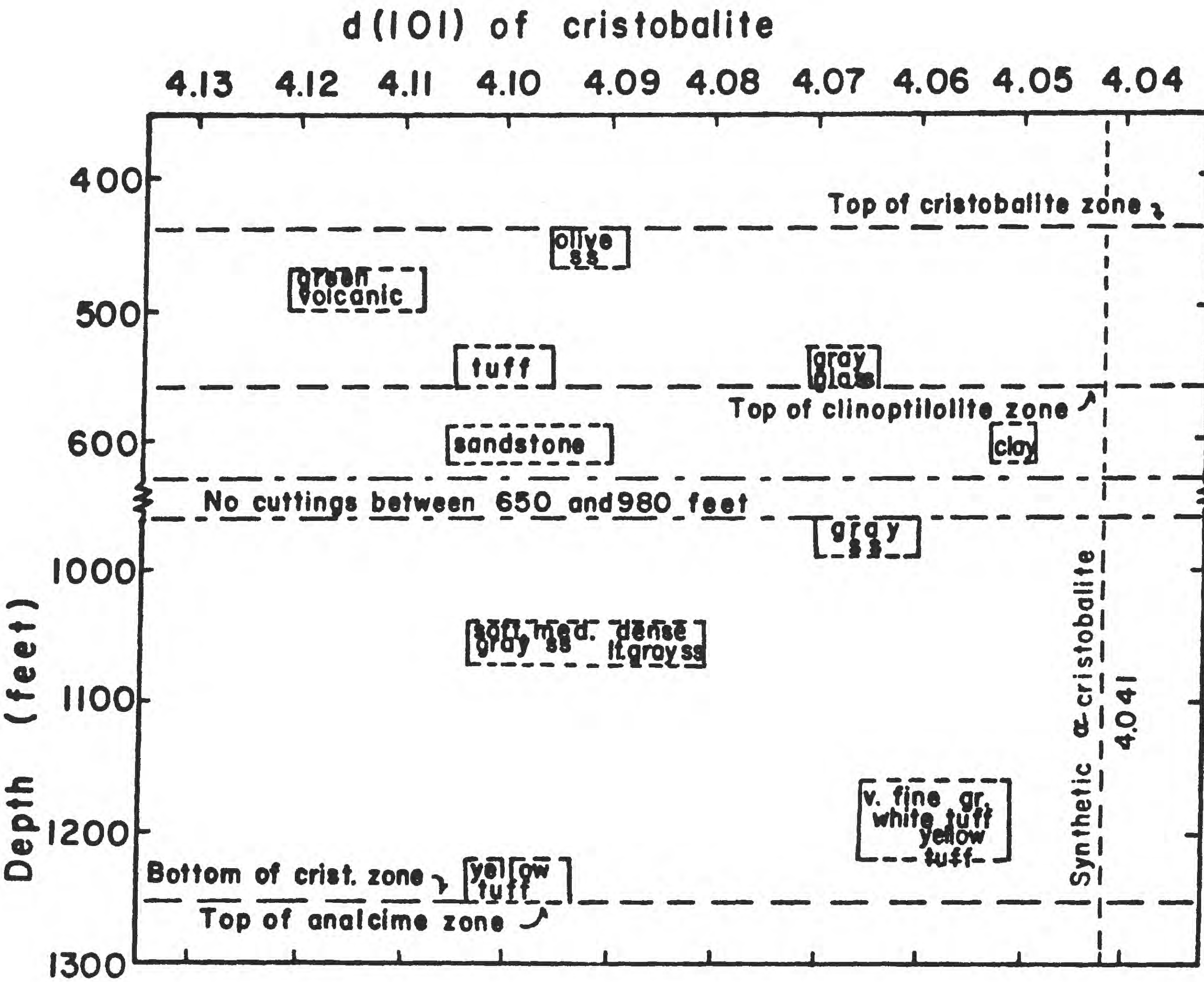
● d(101) of cristobalite for a given sample

Dashed lines show range of values for a specific sample

Ordinate = depth in feet

Abscissa = d(101) of cristobalite

Figure 14. - Graph of crystallinities of cristobalites in hard gray siliceous zones in the LVCH-1 core.



EXPLANATION

Boxes show range of values for a specific rock type in a thirty-foot depth interval.

Different rock types were hand selected and x-rayed separately. Cuttings sampling interval is 30 feet. Ordinate is compressed, with a gap between 650 and 980 feet, the interval from which no cuttings were retrieved.

Figure 15. - Graph of crystallinities of cristobalites in whole-rock samples of cuttings from Republic Well 66-29.

compatible with temperatures of 50° to 100°C; in the lower part of the drillhole, the temperature range would be 50°to 79°C. At the time of drilling (autumn, 1973), measured temperatures ranged from 56° at about 535 feet to 77°C at the bottom of the drillhole (1,000 feet) (Lachenbruch and others, 1976, p. 766). Thus there is no compelling evidence that in the lower half of the LVCH-1 drillhole, temperatures have exceeded present temperatures for any significant period of time.

The only trend in the measurements is a tendancy for cristobalites in the younger layers to have a higher degree of crystallinity (with d(101) less than 4.055Å) than cristobalites in the deeper layers (Figure 13). However, many of these younger layers are composed of volcaniclastic sediments, and therefore the cristobalite (an α-cristobalite or close to it) may have formed elsewhere, as replacement of shards of volcanic glass.

The cristallinities of cristobalites in the hard dark gray siliceous zones (Figure 14) were compared with those of whole-rock samples of tuffs and sediments at equivalent depths (compare Figure 14 with Figure 13). Cristobalites from hard gray siliceous zones are poorly crystalline, with d(101) ranging from 4.126Å to 4.100Å. Crystallinities are lower than those in the cherts described by Murata and Larson (1975). There is no correlation between degree of crystallinity and the thickness of an individual gray siliceous zone, nor is there a good correlation between depth to the siliceous zone and degree of crystallinity. However, there is a tendency for the most poorly crystalline material to occur in or near the zone of tuffs altered to clinoptilolite (at 700 to 840 feet); thus crystallinities of cristobalites in hard gray siliceous zones increase away from the zone of clinoptilolite tuffs, both downwards and upwards (see Figure 14). If the material in the hard gray siliceous zones originated as a silicate gel, in a manner analogous to magadiite (Rooney, Jones, and Neal, 1969), and hardened to its present density early, perhaps this might account for its lower degree of crystallinity.

Cristobalites from a number of different rock types in the Republic cuttings were chosen for measurement of the d(101) spacing in x-ray diffraction pattern (see Figure 15). Eliminating the glass fragments at 530-560 feet, which could have developed cristobalite by recrystallization before emplacement, and the "clay" at 620-650 feet, which might be a drilling mud, then the most ordered cristobalite above 650 feet has a d(101) value of 4.095Å. There is considerable variation in d(101) values; for example, yellowish-gray tuff ranges from 4.054-4.060Å to 4.094Å in two consecutive depth intervals.

The total range of crystallinities of whole-rock cristobalites in cuttings from the Republic drillhole, from d(101) about 4.121Å to 4.053Å, is comparable to the range of whole-rock cristobalites in the LVCH-1 core. The depth ranges are also comparable (see Figure 15 and Plate 2). Despite considerable scatter in the measurements of different rock types at the same depth, especially at 590 to 620 feet, there is a very rough trend, with crystallinity increasing with increased depth, down to the 1,160 to 1,190 foot interval. This depth is near the zone of maximum temperature a few days after drilling (June, 1976): 70°C at 1,000 feet, or greater than 67.5°C between 700 and 1,330 feet (Smith and Rex, 1977). Thus, the cristobalite crystallinities could be explained by the present temperature distribution in the drillhole (see Figures 16 and 17).

Carbonates

Calcite is the only abundant carbonate in the LVCH-1 drill core. Moderate amounts of aragonite occur with calcite between 335 and 337 feet. Traces of dolomite were detected at 400 feet; however, the identification is tentative; only one dolomite peak is present in the diffraction pattern.

Thin sections show that most calcite is typically present as tiny (15-50 μm) round grains scattered throughout the matrix of sediments and waterlaid tuffs. There is no evidence that calcite replaces plagioclase. Plagioclase is unaltered wherever it is visible.

There is, however, ample evidence that calcite replaces glass lapilli (Figures 18 and 19), most commonly along perlitic fractures, but also along lamellae in flow-banded glass fragments. This phenomenon is common below 550 feet, where it was observed in eight thin sections; it was seen in only one thin section (at 334 feet) above 550 feet. Coarse-grained calcite also appears to replace comminuted matrix material, in some places as isolated patches of coarse calcite (at 631 feet), in others more pervasively. For example, in the cross-bedded, very fine to medium-grained sands at 334 feet, mineral and rock fragments appear in thin section to be suspended in calcite cement so that no grains touch each other. Calcite rhombs are embedded in the matrix of the lapilli tuff at 889 feet. In ash layers at 608 feet, coarse calcite in the matrix encloses tiny round calcite grains. Nodules of extremely coarse-grained calcite, possibly broken-up evaporative crusts (Blair F. Jones, U.S. Geological Survey, Reston, Virginia, oral communication, 1982), are enclosed in fine-grained calcareous sediments at 973 feet. Large irregular fragments of similar coarse-grained calcite are found at intervals between 552 feet and 636 feet; at 605 feet, they reach a maximum diameter of 1 mm. Ostracode valves are composed of calcite (Figure 9), and in some samples (for example, at 992 feet), some carapaces are infilled with more coarsely crystalline calcite. Calcite also fills vesicles in pumice lapilli at 585 feet. In addition to calcite, minor amounts of aragonite are probably primary precipitates.

Calcite is the only carbonate detected in the Republic cuttings. There is very little calcite above 650 feet, where it is found in trace to minor amounts in various sandstones. Sediments between 980 and 1,160 feet, all sandstones, lack calcite. Below 1,160 feet, all sediments contain some calcite, generally in minor amounts. The distribution of calcite suggests that above 1,160 feet, sandstones may have been deposited in fresher water.

Tuffs above 650 feet, like the sediments, contain very little calcite; it is present only in the interval 560 to 590 feet. Below 980 feet, all yellowish-gray tuffs lack calcite. There is no calcite in the white tuffs between 980 and 1,310 feet, and it is sparse below 1,310 feet except at some intervals in the very fine-grained white tuff without phenocrysts. In a coarse-grained lapilli tuff at 1,460 to 1,490 feet calcite can be seen in thin section replacing lapilli of flow-banded glass.

In summary, calcite is absent in the Republic drillhole from both tuffs and sediments between 980 and 1,310 feet, is fairly abundant in sediments and in one tuff between 1,310 and 1,430 feet, is somewhat less abundant in

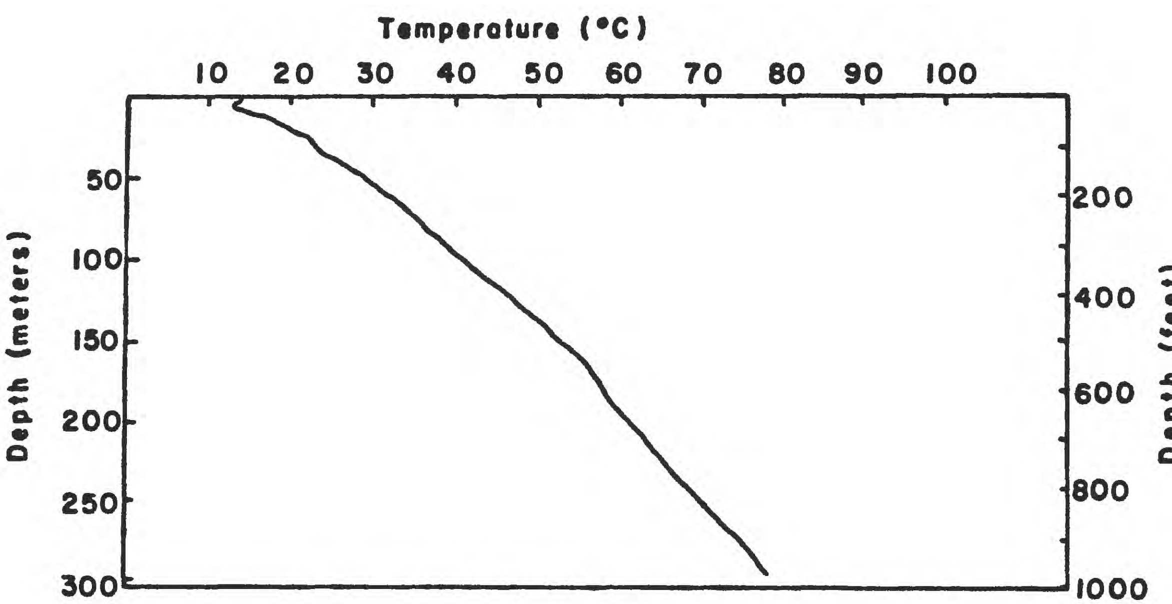
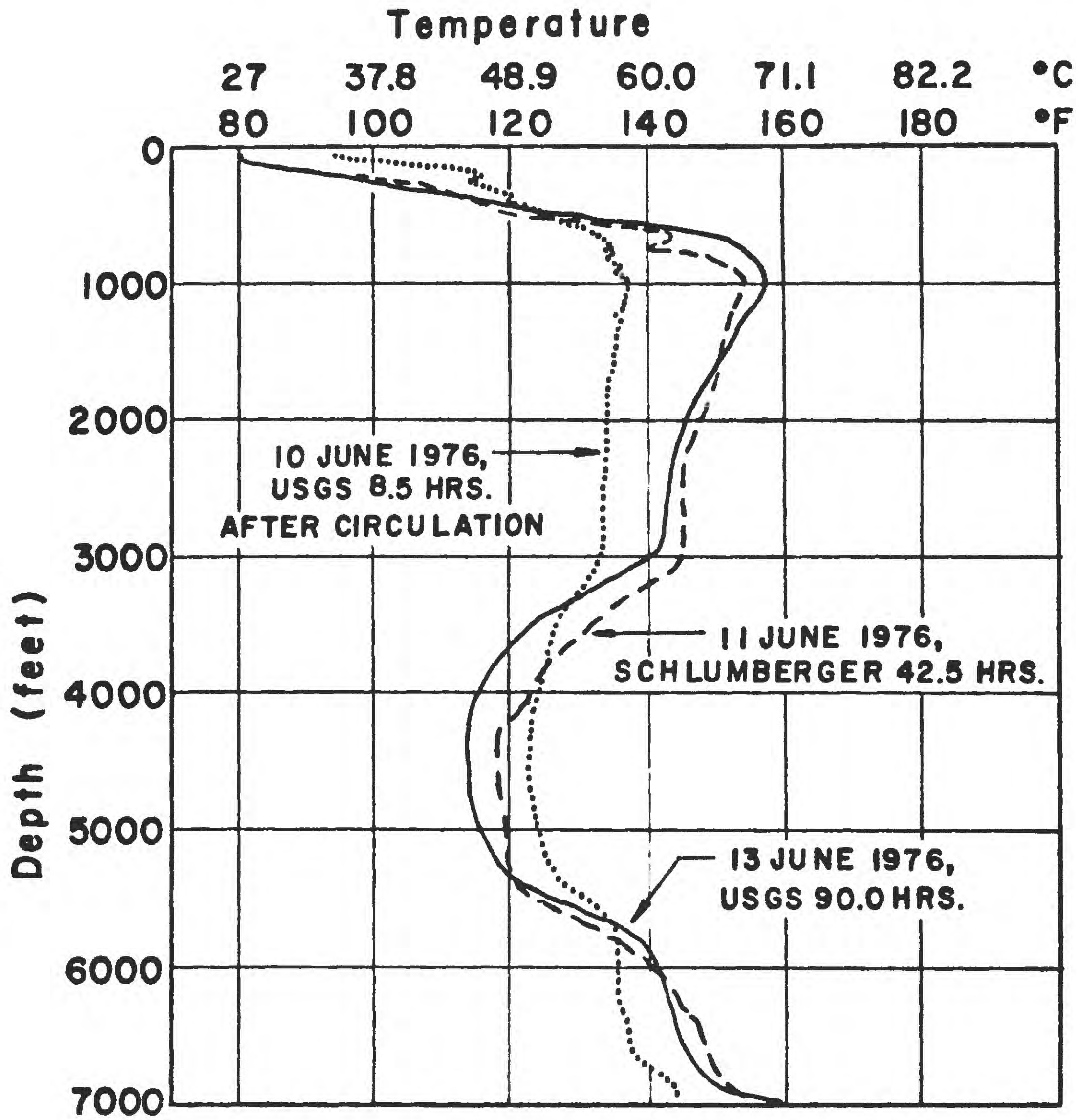


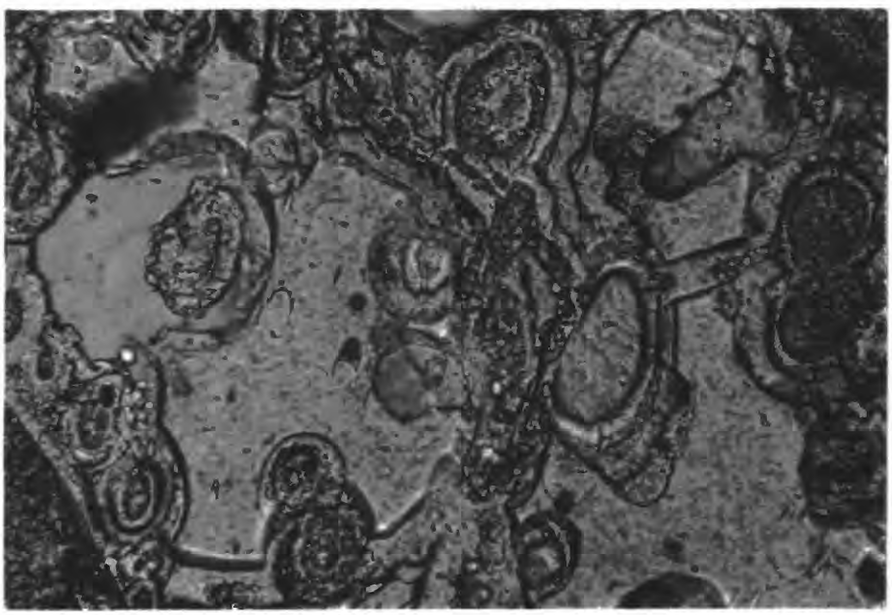
Figure 16. - Temperature-depth curve for LVCH-1 drillhole after equilibrium was attained (from Lachenbruch and others, 1976, Figure 5, p. 766).



EXPLANATION

Temperatures in °C have been added to temperature in °F on the abscissa. Note that the temperature in LVCH-1 at 1,000 feet exceeded the maximum temperature in the Republic drillhole (cf. Figure 16).

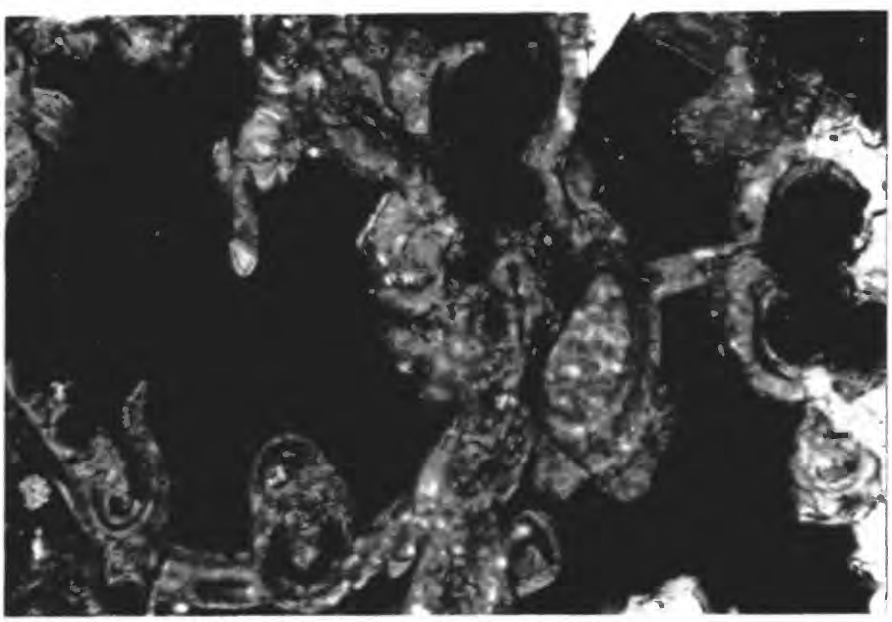
Figure 17. - Temperature-depth curves for Republic 66-29 drillhole (from Smith and Rex, 1977).



EXPLANATION

Pumiceous glass. Some ovoid vesicles are lined with clinoptilolite, with linings of montmorillonite in turn within the clinoptilolite. Other linings alternate from clinoptilolite to montmorillonite to clinoptilolite. Yet other cavities are filled with calcite, which is also replacing the volcanic glass.

Figure 18. - Photomicrograph of thin section at 608 feet, LVCH-1.



100 μm

EXPLANATION

Calcite is apparent as bright material; glass is dark.

Figure 19. - Photomicrograph, same field of view as Figure 18, with crossed nicols.

sediments and tuff between 1,430 and 1,550 feet, and is generally absent from the tuffs below 1,550 feet. There are moderate amounts present in the rare cuttings chips of sediments between 1,850 and 2,450 feet, but no calcite is present between 1,550 and 1,820 feet.

Sheet Silicates

Biotite in both drillholes is a pyroclastic constituent of tuffs, or is detrital in the sediments. In the LVCH-1 core, it is most abundant in tuffs between 530 and 630 feet, and is also especially abundant in sediments between 333 and 410 feet. Biotite is a major constituent of the K-feldspar-rich siltstone at 971 feet. Generally, biotite appears unaltered, but in one thin section (at 608 feet), small amounts of chlorite are visible within biotite grains. In sediments between 333 and 410 feet, the biotite in some samples is wispy and contorted. Chlorite occurs as traces (by x-ray diffraction) in these sediments, where it is associated with both biotite and pyrite and appears to be an alteration product of biotite. It is also found in the gray silt at 972 feet, just below the K-feldspar-rich and biotite-rich siltstone. All samples that contain chlorite also contain biotite, and many contain pyrite (see Plate 1).

In the Republic cuttings biotite and chlorite are common. Biotite occurs in trace to minor amounts throughout the Republic cuttings above 2,750 feet. (It also is found within the welded Bishop Tuff; see Table 5 in Appendix A.) It is especially abundant at 500 to 560 feet, where it can be seen in thin section with chlorite and montmorillonite in pumiceous tuff. At 1,520 to 1,550 feet, biotite and some chlorite occur in very fine-grained white tuff, and at 1,550-1,580 feet, radial sheaves of chlorite are visible in thin section. Traces of chlorite persist down to 2,420 feet in the tuffs. Chlorite is a major constituent of a green breccia at 2,540-2,570 feet. In nonwelded white tuffs, individual grains of biotite up to 1.5 mm in diameter appear in the cuttings between 2,300 and 2,360 feet, but no large (1-2 mm) grains of biotite were observed within chips of tuff in any interval. White mica was recognized only in inclusions of igneous or metamorphic rocks, in thin section.

Clay Minerals

The only clay mineral identified in the LVCH-1 core is montmorillonite; it is common below 536 feet (see Plate 1). It is the first alteration mineral to form along the margins of glass shards and along perlitic fractures, and is especially abundant in some of the waterlaid tuffs. However, it is more commonly a major constituent of sediments than of tuffs. It is particularly prevalent near the top of the gray siltstone at 894 to 906 feet, and in the gray shale with cracks, possibly formed by desiccation, at 948-950 feet. Lithium-rich montmorillonite is a major constituent of the laminated sediments that occur between 610 and 632 feet (see Lithology of LVCH-1 section). No montmorillonite was detected in the Republic cuttings by x-ray diffraction; however, borders of a birefringent clay, apparently montmorillonite, are visible around voids in a pumice inclusion in the welded Bishop Tuff at 4,730-4,760 feet. In the pumice-rich zone at 4,970-5,000 feet, in chips of white pumice mixed with welded tuff, traces of a non-expandable 17Å clay were found.

Zeolites and Analcime

In the LVCH-1 core, mordenite was identified in only one sample, a block of red rhyolite enclosed in friable tuff at 240 feet. In the Republic drillhole, mordenite is a part of the matrix of tuffs in a zone of limited vertical extent (Plate 2). Above 650 feet, it was found only in fragments of a green breccia at 500 to 530 feet. It appears likely that this mordenite had formed at some other site, before emplacement of the breccia at its present location. Below 980 feet, mordenite occurs in yellowish-gray tuff, in very fine-grained white tuff, and in medium-grained white tuff, but only between 1,100 and 1,220 feet. It is accompanied everywhere by clinoptilolite, and in some places by cristobalite. Either mordenite or clinoptilolite may predominate.

Clinoptilolite is the only zeolite that was positively identified in the matrix of rocks in the LVCH-1 core. Heat treatments of sixteen samples from various depths show that it is clinoptilolite and not heulandite (Alietti, 1972; see Appendix E, Methods of mineral identification). No heulandite was detected, although it had been reported by Bailey and others (1976, p. 737) from "cavities" in the tuffs. These "cavities" are actually altered vitric lapilli. Five microprobe analyses of clinoptilolite in lapilli in tuff at 862 feet (analyzed by Melvin H. Beeson, U.S. Geological Survey, Menlo Park) show that Si:Al ratios range from 4.21 to 4.47, which is near the high-silica end of the clinoptilolite-heulandite series. The full range is 2.7 to 5.0 (Hay, 1966, p. 11). In the five analyses, CaO ranges from 1.078 to 1.557 weight percent, Na_2O from 2.40 to 3.26 weight percent, and K_2O from 3.07 to 4.07 weight percent. This clinoptilolite contains slightly more sodium than potassium, and 10 to 15 percent of the cations are calcium. Thus by any of the usual chemical criteria, it is clinoptilolite, not heulandite. Compared with the clinoptilolites of Sheppard and Gude (1969 and 1973b) from the Barstow and Big Sandy formations, this clinoptilolite has comparable Si:Al ratios, but is poorer in CaO and richer in K_2O than their clinoptilolites. Clinoptilolite from the LVCH-1 core has Na_2O contents that are lower than the average in the Barstow formation (ranges overlap), and higher than that of the Big Sandy formation.

Clinoptilolite occurs only below 545 feet in the LVCH-1 core, where it is ubiquitous in tuffs (both airfall and waterlaid) except in the interval between 660 and 700 feet. It occurs as very fine-grained, felted masses replacing both matrix and lapilli, and also as subhedral to euhedral crystals, 40 to 50 μm in diameter, in the partially dissolved interiors of glass bubble-wall shards (see Figure 20). Clinoptilolite also occurs in some sediments which are interbedded with tuffs or with finely banded (waterlaid) ash, but the amounts are generally small.

The absence of clinoptilolite above 545 feet cannot be explained simply by temperature distribution. Fossil evidence indicates that, at least above 490 feet and possibly down to 545 feet, the water in the lake was more nearly fresh (less saline and alkaline) than the water in the lake which received the tuffs and sediments of the lower part of the core. Glass dissolves more rapidly in alkaline solution than in fresh water (Mariner and Surdam, 1970), and this process may be the rate-determining step. Fresh water in the pores of the tuffs and sediments may have inhibited, or at least not facilitated, the formation of clinoptilolite.

100 μm

EXPLANATION

Typical occurrence of clinoptilolite within glass lapilli. At bottom, shard with core replaced by coarse-grained calcite (CC) is surrounded by concentric zones of (from center outwards): small calcite crystals, clinoptilolite, and montmorillonite (MT). At top is a similar shard which has a hollow center (H) and no calcite.

Figure 20. - Photomicrograph of thin section at 608 feet in LVCH-1 core.

In this connection, it is noteworthy that whereas zeolites are common in vitric tuffs in most saline-alkaline lakes including Recent ones (Hay, 1966, p. 15), zeolites are generally not found in silicic ash beds of Pleistocene or younger age that were deposited in fresh water or oceanic environments (Hay, 1966, p. 53). At Teel's Marsh, Nevada, zeolites formed only in the most saline solutions and did not form (within 1,000 years) where salinity was lower (Cook and Hay, 1964, p. 32). In the LVCH-1 drillhole, it appears that the spatial distribution of clinoptilolite is a function not only of temperature, but also of the degree of salinity and/or alkalinity of the pore water.

In the Republic drillhole, clinoptilolite is abundant between 560 and 1,400 feet and in scarce fragments of yellowish-gray tuff in some intervals between 1,880 and 2,120 feet (probably sloughed from above). At 560 to 590 feet, clinoptilolite is a principal phase (with quartz) in a green vitric lapilli tuff. At 590 to 650 feet, it occurs only as small traces in sands and clays. Traces may also be present at 440 to 470 feet in fragments of a very fine-grained white tuff which comprises only a minor fraction of the cuttings sample.

In yellowish-gray tuff, clinoptilolite is a moderately abundant component in most samples throughout the 980 to 1,400 foot zone. It is also found with mordenite in medium-grained white tuff at 1,190 to 1,220 feet. It occurs in minor amounts in very fine-grained light gray sandstone between 980 and 1,310 feet.

Analcime was not positively identified in the LVCH-1 core. It was poorly defined, from single x-ray diffractometer peaks observed in some samples between 850 and 1,000 feet.

In the Republic drillhole, analcime distribution appears to be related to both depth and rock type. It is a major constituent of the very fine-grained tuff without phenocrysts between 1,250 and 1,550 feet, but between 1,310 and 1,430 feet analcime is completely absent from yellowish-gray tuff. In very light gray sandstone from this same depth interval, however, analcime is a major component of the medium- to coarse-grained facies, but is absent from the very fine-grained facies that is the chief component of cuttings between 1,340 and 1,370 feet. Analcime present in the cuttings at 1,940-1,970 feet was probably sloughed.

The distribution of analcime and calcite in the Republic drillhole, as well as the Si:Al ratios of the analcime, suggest that the analcime was formed by authigenic processes in an alkaline-saline lake. Analcime samples from medium-grained, very light gray sandstone in the 1,370 to 1,400 foot interval were studied by the method of Saha (1959)(see Appendix E), measuring d(639) spacings using silicon [d(331) = 1.2459Å] as an internal standard. The average value for six samples was d = 2.09 ± 0.06Å. Using the data of Coombs and Whetten (1967, p. 271), a_0 of this analcime is 13.67Å, and there are between 35 and 36 silicon atoms (out of a possible 36) in each unit cell. It is a very silica-rich analcime, which is comparable to the sedimentary analcime from a playa lake at Yavapai, Arizona, analyzed by Ross (1928) (quoted in Coombs and Whetten 1967, Table 2, p. 274, and Figure 1, p. 271), and is more silica-rich than the analcimes of the Barstow formation (Si:Al = 2.2 to 2.8, Sheppard and Gude, 1969) and the Big Sandy formation (Si:Al = 2.3 to 2.8, Sheppard and Gude, 1973b). The Si:Al ratios of these analcime samples are in the range 2.85 to 2.90, as compared with ratios (based on microprobe data) of 2.13 to 2.76 for five hydrothermal analcimes from Yellowstone National Park (Terry E. C. Keith, U.S. Geological Survey, Menlo Park, California, written communication, 1983).

Other Minerals

Green hornblende is found in trace amounts sporadically throughout the LVCH-1 core. Generally it is detectable only in thin section. It occurs primarily in sediments and waterlaid tuffs, and was seen in only 6 of 21 thin sections of airfall tuffs. The only alteration of hornblende that I observed in this core is replacement by calcite, at 554 feet; such alteration is rare, and hornblende in other samples was not corroded. In the Republic cuttings, hornblende was not detected in x-ray diffraction patterns. A few grains were visible in thin section at intervals between 320 and 1,280 feet, in a variety of rock types. None was detected in thin sections of nonwelded tuff below 1,310 feet (i.e., below the top of the analcime zone). Rare fragments of basaltic hornblende were observed at 320 to 380 feet, in sandstones, and at 2,690 feet, in nonwelded medium-grained tuff. No hornblende was positively identified in the welded Bishop Tuff.

Pyroxene was not observed in the LVCH-1 core, and is rare in the Republic cuttings, where a few grains were seen in volcanic rock and in breccia between 2,510 and 2,570 feet. It was specifically searched for (in chips and in thin sections) in the welded Bishop Tuff, but except for a few grains at 3,470 and 4,190 feet which appear to be unaltered, pyroxene grains seem to have been replaced by an unidentified, fine-grained dark material. Relict grains are most abundant below 5,900 feet. Distribution of relict pyroxene in the welded Bishop Tuff is summarized in Appendix A.

Gypsum was detected only by x-ray diffraction, and only in the LVCH-1 core. In places, for example between 347 and 358 feet, it is concentrated along seams and in dipping open fractures with matching walls. It also occurs disseminated in banded, moderately steeply dipping sediments, both calcareous and non-calcareous, and is present between 342 and 370 feet in horizontally banded sediments. There are traces at 409 to 420 feet, and also deeper in the drillhole at 898 feet and at 963 to 970 feet (see Plate 1). Texturally, the absence of large euhedral crystals suggests that the disseminated gypsum may be primary rather than secondary (Kenneth R. Lajoie, U.S. Geological Survey, Menlo Park, California, oral communication, 1983). Isotopic data were obtained from a seam at 388 feet (see Appendix C). Most gypsum in this part of the core is disseminated, and no isotopic data are available for it. There is no way to determine whether the gypsum was derived from pyrite by oxidation or the pyrite was derived from gypsum by bacterial reduction in a deep lake. The gypsum in seams may have been remobilized from the disseminated material. No gypsum was detected above 342 feet. At 379 feet, anhydrite was tentatively identified by x-ray diffraction, in a horizontal seam.

In the LVCH-1 core, the distribution of pyrite is similar to that of gypsum. Pyrite occurs in sediments, where it is sometimes concentrated in or adjacent to fractures or seams, between 333 and 400 feet. Near the bottom of the core (between 970 and 974 feet), it is concentrated in a gray parting with calcite and quartz, immediately above siltstones that are rich in authigenic K-feldspar. Pyrite also occurs in trace amounts in airfall lapilli tuff, and is moderately abundant at 590-593 feet. Pyrite occurs adjacent to a steeply dipping, hard gray cristobalite zone in waterlaid tuffs at 886 to 890 feet. In the Republic drillhole, pyrite was identified by x-ray diffraction only in sporadic cuttings samples, generally in trace amounts. The greatest concentration of pyrite in the cuttings occurs as minor amounts in fine-grained white tuff at 440 to 470 feet. Pyrite is visible in cuttings chips of welded Bishop Tuff in association with siliceous veinlets above 3,100 feet, and both pyrite and quartz are also present in poorly welded Bishop Tuff at 6,800 to 6,860 feet, near the bottom of the drillhole and approaching the base of the welded tuff.

A phosphate mineral, probably carbonate-apatite (ASTM card 19-272; "collophane", by x-ray diffraction), occurs with clinoptilolite at 827 feet in the LVCH-1 core, in a punky, fibrous, brownish-yellow zone in airfall tuff. It could have formed with vertebrate remains as nuclei. Ames (1959, in Deer, Howie and Zussman, 1962, v. 5, p. 334) "was able to show that alkaline phosphate solutions replace calcite with a carbonate-apatite of variable composition". No sulfates or phosphates were identified in the Republic cuttings. No molds of saline minerals were seen, and no saline minerals were detected by x-ray diffraction, in rocks from either drillhole.

FORMATION OF DEPOSITS IN LONG VALLEY CALDERA

In the two drillholes in Long Valley that were studied, the paleontologic data, the patterns of mineral distribution, and the details of texture and mineralogy all support the hypothesis that most secondary minerals in the tuffs and sediments formed authigenically in or beneath a shallow caldera lake (less than 15 feet deep) of varying salinity and alkalinity. Data from stable isotopes (summarized in Table 7, Appendix C) are consistent with this hypothesis. In addition to yielding data on the alkalinity and chemistry of the caldera-lake waters, fossils give information about the depth of the lake.

Calcite is in part a primary sedimentary precipitate and in part a diagenetic replacement of glass and other minerals. It also is present as ostracode valves; locally, ostracode carapaces are infilled by coarsely crystalline calcite. In one portion of the LVCH-1 core, textural evidence indicates that calcite was deposited before chalcedony (see Figure 12). In addition to calcite, minor amounts of aragonite and gypsum probably are primary precipitates.

At a depth of 335 to 337 feet (see Plate 1), aragonite occurs with calcite in banded, locally cross-bedded sediments. The fossils found in these rocks indicate the presence of comparatively fresh water. These sediments are composed of bands up to 1 cm thick. They may have formed within a "chemical delta", near an inlet where calcium-bearing fresh water entered and mixed with more saline water, as discussed by Smith (1979, p. 80) and earlier by Jones (1965, p. A45). Forester (U.S. Geological Survey, Denver, Colorado, written communication, 1980) suggests that the presence of both calcite and aragonite in these sediments may be indicative of an increased Mg:Ca ratio in the lake waters, compared with waters from which sediments in the lower half of the drillhole were deposited. Because these younger sediments contain no montmorillonite that might remove magnesium by the mechanism postulated by Jones and VanDenburgh (1966, p. 443), magnesium concentrations could have built up. Calcite in these younger sediments is sporadic compared with its occurrence in most sediments deeper in the drillhole.

The occurrence of aragonite in these sediments raises an interesting problem. At Searles Valley, Smith and others (1983, p. 20) found that the oldest aragonite preserved was in strata at a depth of about 213 feet, and suggested that at greater ages, the aragonite converted to calcite. The temperature at the time of drilling was about 40°C at 336 feet in LVCH-1, Long Valley (Lachenbruch and others, 1976, Fig. 5, p. 766). The temperature at 200 feet in Searles Valley was about 26°C (Smith, 1979, Fig. 40). The geothermal gradient there is about three times normal, 95°C/km or 29°C/1000 feet (Smith, 1979, p. 100). Thus, the temperature at about 336 feet in Searles Valley was lower than the temperature at an equivalent depth in the LVCH-1 drillhole, and the temperature at 200 feet was even lower. It seems probable that the higher salinity and alkalinity of the pore fluids at Searles Valley, high enough to precipitate salts, increased the rate of conversion of metastable aragonite to calcite. According to Smith (1979, p. 78), the lake waters in Searles Valley may have exceeded salt percentages of 1.5 and pH values of 9 even at their most dilute stages.

Physical conditions in the caldera lake cannot be unambiguously deduced from stable isotopes of oxygen and carbon in the calcite of sediments and tuffs. (Details of the isotopic data and of how the conclusions discussed in this paragraph were arrived at are discussed in Appendix C.) The data from oxygen isotopes are consistent with the postulate that lake waters varied in salinity from 1 ppt to 35 ppt (slightly saline to very saline, according to Hem, 1979, p. 219). Carbon isotopes are in agreement with oxygen isotopes in six of the seven samples. At some intervals, the calcite is in equilibrium with a water which can best be explained by postulating a local contribution of hot spring water to the lake water. Oxygen isotopic values from sulfate in a gypsum seam at 358 feet indicate that the sulfate did not precipitate in equilibrium with lake water under any reasonable conditions, but are compatible with deposition from hydrothermal waters.

The presence of clinoptilolite in the tuffs, and of authigenic K-feldspar in some of the sediments, indicates that the lake waters were saline and alkaline during the period of time corresponding to the deposition of the earliest sediments. This conclusion is also supported by the nature of the fossils that are present in the sedimentary layers. However, above 550 feet in both drillholes, zeolites and authigenic K-feldspar are lacking. This change in mineralogy is not attributable to a change from hydrothermally altered to unaltered strata, but as the fossil evidence attests, results from a change in the physical-chemical conditions in the caldera lake.

The paleontologic evidence for depositional environment is based on the distribution of certain species of ostracodes and diatoms, visible in thin section. Ostracodes occur in the LVCH-1 core at many levels at and below 334 feet, however, none were seen in the three thin sections of sediments from Republic cuttings. In the LVCH-1 core, diatoms are present at 306 feet, between 342 and 426 feet, and at 490 feet. In cuttings from the Republic drillhole, only one species was identified, at 350-380 feet. Fossil evidence is summarized here; for details see Appendix D and Table 8.

Paleontological analyses by Richard M. Forester (U.S. Geological Survey, Denver; ostracodes) and by J. Platt Bradbury (U.S. Geological Survey, Denver, diatoms) indicate that during the deposition of most sediments below the 545-foot level in LVCH-1, salinities of lake waters varied from 3-5 ppt to 15-20 ppt (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980, p. 6), that is, from moderately saline to very saline, using the salinity scale of Hem (1970). Apparently the pH was in the range 8 to 11, temperature fluctuated over a wide range, Na + K concentrations were high relative to Ca + Mg, and SO_4 was depleted with reference to Cl and HCO_3 (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980). At the time of deposition of sediments at and below 975 feet, the lake waters may even have been briny.

Above 410 feet, the greater diversity of ostracode species suggests waters at the more dilute end of the range (2 to 5 ppt, Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980, p. 6). Diatom species also indicate the presence of more dilute waters.

The earliest known occurrence of diatoms in the LVCH-1 core is at 490 feet, in a layer of diatomite interbedded with tuffs. According to Forester (U.S. Geological Survey, Denver, Colorado, oral communication, 1982) this is supportive evidence that the caldera lake water in which tuffs and sediments below this level were deposited were highly alkaline (pH 9 or greater). Diatom tests, made of silica, would have dissolved in such alkaline waters as soon as the organisms died (Blair F. Jones, U.S. Geological Survey, Reston, Virginia, oral communication, 1982).

Diatom species and the presence of undisturbed (possibly varved) bands at 488 to 490 feet indicate lake depths of greater than 50 feet at the time of deposition of sediments between 410 and 490 feet in the LVCH-1 core (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1982). Later, corresponding to sediments between 334 and 360 feet, the lake may have been somewhat shallower, but exceeding 15 feet in depth. At the time represented by sediments at 306 feet, lake temperatures may have been cooler than at earlier times, and diatom species are consistent with the presence of silica-rich waters, although the evidence is only permissive (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1980).

Diatoms occur in the yellowish-gray (5Y 8/1) sandstone which dominates the Republic cuttings between 260 and 440 feet. The variety of diatom which was identified in yellowish-gray sandstone at 350-380 feet is not identical with any of those identified in the LVCH-1 core. However, it is of the same genus as, and is most closely related to, _Stephanodiscus_ _kanitizii_ fo _inermis_ (Bradbury, U.S. Geological Survey, Denver, Colorado, written communication, 1980), which is one of the species identified in the rich fossil assemblage, including both diatoms and ostracodes, found in the ashy diatomite (at 343 feet) near the top of the sequence of calcareous siltstones in LVCH-1 (Plate 1).

Calcite is virtually absent from the deepest tuffs in the Republic drillhole (below 1,550 feet), which contain K-feldspar and plagioclase. No calcite-bearing sediments occur below 2,060 feet. Perhaps this is because the newly formed caldera lake was surrounded by rhyolites, and at the time when the oldest early rhyolite tuffs (at 2,060-2,250 feet) were deposited, it had not yet received enough calcium from meteoric runoff and continuing evaporation to reach a point of saturation with calcite. The deepest sediments exposed in the LVCH-1 drillhole, at the much shallower depth of

990 to 995 feet, also contain very little calcite.

In the Republic drillhole, the sequence of mineral phases in the post-Bishop tuffs, from top to bottom, is: clinoptilolite, mordenite, analcime, K-feldspar (and albite). This sequence is consistent with the formation of authigenic minerals in a saline-alkaline lake, if the lake were slowly shrinking during the period of formation of these minerals. According to studies by Sheppard and Gude at Barstow (1969) and at Lake Tecopa (1968), K-feldspar (and albite) formed farther from the shoreline, in the most saline waters, and clinoptilolite (plus mordenite) crytallized nearest the shoreline of the saline-alkaline lake, where fresher water was entering (Sheppard and Gude, 1969, p. 27-28).

It seems unlikely that the zeolites in the Republic hole are the result of hydrothermal alteration subsequent to the eruption of the Bishop Tuff. Recent evidence indicates that magma in the easternmost part of the caldera was exhausted by the eruption of the Bishop Tuff, so that subsequently there was no heat source under that area (Sorey, 1985, p. 11,226).

However, one alternative explanation might be that the heat conducted upwards from the underlying, cooling mass of welded and nonwelded Bishop Tuff produced a temperature gradient in the accumulating tuffs on the floor of the caldera lake which was sufficient to produce the mineral zonation in the early rhyolite tuffs (Blair F. Jones, U.S. Geological Survey, Reston, Virginia, oral communication, 1982). To the west of the Hilton Creek fault, the blanket of nonwelded Bishop Tuff was stripped by erosion during formation of the resurgent dome. Cuttings from the Clay Pit drillhole, plus geophysical evidence (presented in Table 1 and in the section Depths to and Variations in Thickness of the Bishop Tuff) show that the welded Bishop Tuff is about 50 percent thicker in the Republic drillhole than in the Clay Pit drillhole, which is located west of the northward projection of the Hilton Creek fault and north of the LVCH-1 drillhole. The presence of a much thinner blanket of insulating tuff in the western part of the caldera may account for the puzzling lack of mineralogic alteration zones deep in the LVCH-1 core, despite the longer persistence of magma to the west of the Hilton Creek fault zone, perhaps even to the present day, as recent seismic events suggest (Savage and Clark, 1982). It is also possible that the mineral zones are present, but are foreshortened and buried in the hundreds of feet of rhyolite tuffs which may lie beneath the bottom of the LVCH-1.

The proposed explanation of Hay and Moiola (1964), that increased compaction at greater depths forced fluid out of the pore spaces, increased the salinity and the K/Na ratio, and produced a progression of authigenic minerals, in this case, clinoptilolite - analcime - K-feldspar - albite, is probably not applicable in the range of low salinities present in the Long Valley lake. In order to increase the K/Na ratio, precipitation of sodium salts is required. Moreover, simply increasing the K/Na ratio in the pore solutions is not a sufficient condition to produce albite.

Structural Movements

Although quantitative statements about structural movements in the Long Valley caldera cannot be made, some qualitative comments are possible. At such time as age-dating of the lake terraces is feasible, it may be possible to correlate these terraces with certain intervals within the core of LVCH-1 and the cuttings of the Republic drillhole.

It would have been desirable to use potassium-argon age-dating and magnetic reversals to date portions of the core. However, the amount of material available in the two-inch diameter core was insufficient for potassium-argon dating with the techniques available at the time. Measurements of remanent magnetism would have had to have been performed at the time of core retrieval.

What can be said is that because the caldera lake maintained itself as shallow (or dried up) throughout the deposition of the lower half of the post-Bishop tuffs and sediments, and because the present depth to the top of the Bishop Tuff is more than 1,000 feet in LVCH-1 and at least 2,200 feet in the Republic drillhole, it is necessary to postulate downward movement (presumably along ring fractures) of the caldera floor during the period of deposition (~0.65 - 0.10 m.y. B.P.). Such movement may have been continuous or intermittent; probably surges of movement would have accompanied eruption of the early rhyolite and the moat rhyolites. Even allowing for 100 percent compaction (to one-half the original thickness) requires donwfaulting of the caldera floor with reference to the spillway point on the caldera wall.

The difference in depth to the top of the Bishop Tuff in the two drillholes, plus the seismic refraction data (Hill, 1976), indicate that the thickness of caldera fill is much greater in the eastern third of the caldera, and suggest a fault surface separating the two sections of the caldera. The northern extension of the Hilton Creek fault as presently expressed at the surface does not fit the requirements for a vertical fault surface separating the two parts of the caldera (map by Bailey, U.S. Geological Survey, Menlo Park, California, written communication, 1983). It is also not clear whether movement on such a vertical fault occurred principally before or after the eruption of the Bishop Tuff.

EVIDENCE OF HYDROTHERMAL ACTIVITY

Information about the presence and distribution of past hydrothermal activity in the Long Valley caldera comes from a number of sources. Evidence for hydrothermal activity in the earliest period of post-Bishop Tuff is meager and permissive only. High concentrations of lithium (660 ppm, see Table 6, Appendix B) are present in the clay-rich sediments between 605 and 632 feet in the LVCH-1 core. Smaller (250 ppm), but still significant concentrations of lithium also occur in the K-feldspar-rich siltstone at 971 feet. A hydrothermal contribution to the lake waters could account for the lithium.

Evidence for an episode of hydrothermal activity culminating about 0.3 m.y. B.P. is derived from field evidence, summarized by Bailey and others (1976, p. 737-738). It indicates that hydrothermal activity was more widespread and more intense at some time in the past than at present. Notably (p. 737), "most of the hot springs and fumaroles are on active extensions of the Hilton Creek fault"; conceivably these may be the same active extensions responsible for differential downfaulting of the eastern part of the caldera. More specifically, Bailey and others (1976, p. 738) refer to extensive hydrothermal alteration of lacustrine sediments that are interbedded with the Hot Creek rhyolite flow, which was age-dated by the potassium-argon method. These sediments are judged to be about 0.3 m.y. old.

New evidence for an episode of hydrothermal activity at about 0.3 m.y. B.P., derived from present work related to this paper, includes the following occurrences between 340 and 380 feet. The occurrence of gypsum in sediments of the LVCH-1 core between 340 and 380 feet (Plate 1) implies that there was a sulfate contribution to the caldera lake waters during the immediately preceding time period. Such a contribution could be of volcanic or hydrothermal origin, or both. As described in Lithology of the LVCH-1 Core, gypsum occurs both disseminated in banded sediments and in seams with parallel, matching walls. Oxygen isotope values from gypsum in a seam at 358 feet, in the LVCH-1 core, are consistent with a gypsum which equilibrated at temperatures of 135^0 to 160^{0}C (hydrothermal conditions).

SUMMARY

A thick sequence of tuffs and lake sediments was encountered in LVCH-1 (1,000 feet deep) and Republic well 66-29 (6,920 feet deep), drilled in the southeast part of the Long Valley caldera. Ostracodes, diatoms, and isotopic data indicate that the sediments and tuffs were deposited in a shallow caldera lake which changed in salinity over time. Conditions ranged from very saline in the older lake to fresh in the youngest. The sequence of secondary minerals from top to bottom is: clinoptilolite, mordenite, analcime, K-feldspar (and albite). In some geothermal systems, this sequence of secondary minerals is a function of temperature; however, the paleontological and isotopic data indicate that the change in secondary minerals with increasing depth is due to the older strata being deposited in a more saline environment. No mineralogical evidence of hydrothermal alteration is present, although the high lithium content of some clays and feldspars and the isotopic composition of some sulfate (gypsum) seems to require a hydrothermal source.

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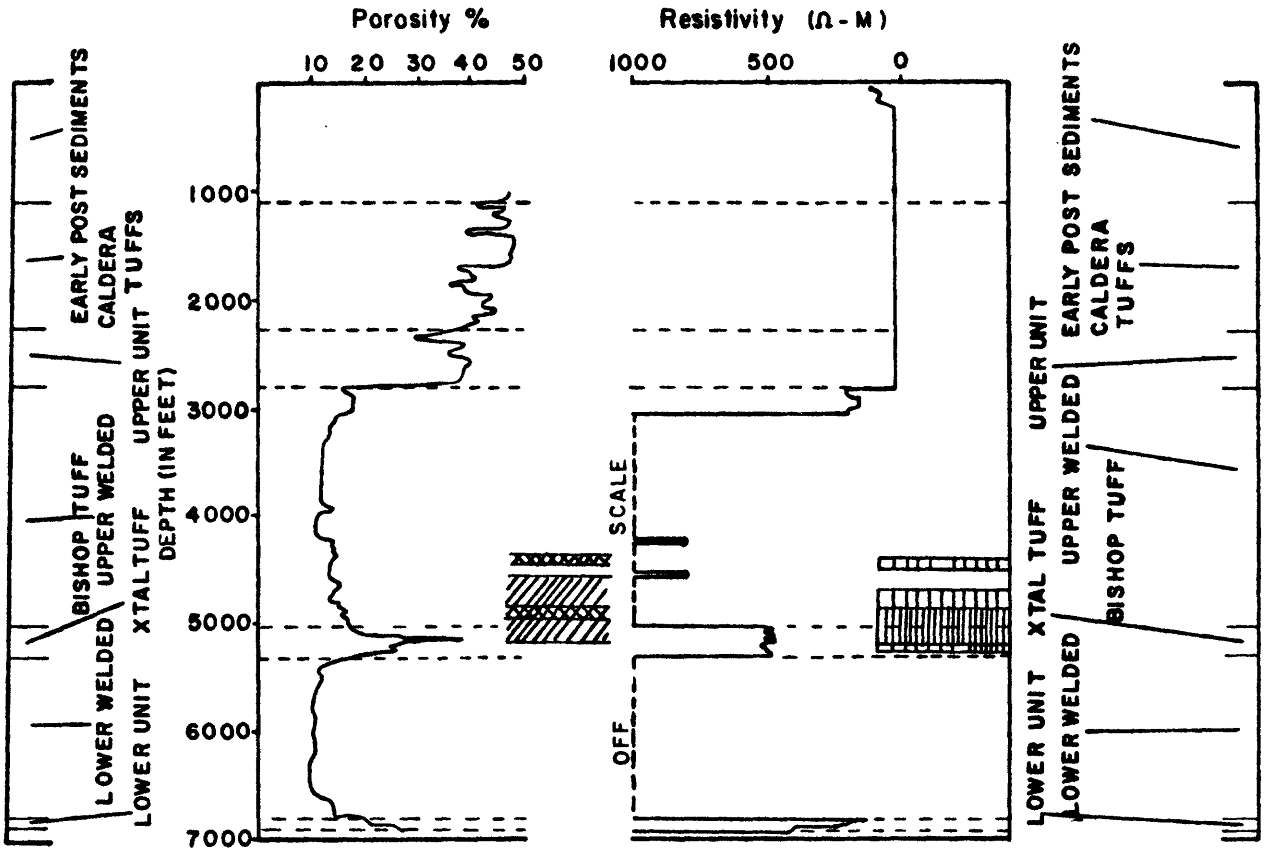
APPENDIX A: LITHOLOGY OF THE REPUBLIC DRILLHOLE COMPARED WITH GEOPHYSICAL LOGS

Cuttings chips of the welded Bishop Tuff below 2,750 feet in the Republic drillhole were examined using a 30X binocular microscope. The details of this work are not discussed in this paper, but are summarized in Table 5, Appendix A. Only those data which pertain to correlation of lithology in the Republic drillhole with the porosity and resistivity data obtained from electric logs (Figure 21) are referred to here.

In general outline, the porosity and resistivity data from electric logs compare well with the lithology as deduced from the cuttings samples. There is a sudden decrease in porosity (from about 38 percent to 10 or 15 percent) progressing downward across the contact between nonwelded and welded tuff (Figure 21). In the same interval, resistivity increases from near zero to more than 1,000 ΩM (off scale) (Kestin, 1980). Within the welded tuff, a porosity maximum and a resistivity minimum at about 5,000 to 5,300 feet roughly correspond to two intervals (cross-hatched in Figure 21, at 4,850-5,000 feet and 5,090-5,150 feet) where the welded tuff contains abundant inclusions of pumice. Between 4,850 and 5,150 feet, the welded tuff is also crystal-rich (more than 25 percent). However, in detail the correspondence is not perfect. The changes in lithology occur at a depth about 100 to 200 feet shallower than the depth of the corresponding changes in physical properties. It is possible than these discrepancies reflect inaccuracies in determining the true depth from which the cuttings came. There were intervals during drilling when the shaker was not operating properly, and sample quality was very poor, namely 650-980 feet, 1,010-1,950 feet, 2,815-3,105 feet, and 5,360-5,410 feet (data from Republic Geothermal, Inc.[2]). Although these are not the same intervals in which the discrepancies occur, they cast doubt on the exact depths from which cuttings samples came. The platform from which the geophysical logs were measured is only 14 feet above ground level (Smith and Rex, 1977), which is too little to account for the discrepancies.

The 300-foot-thick zone of low resistivity (about 500 ΩM) is thought to correspond to the discontinuity between the two Bishop Tuff units observed outside the caldera (Roy A. Bailey, U.S. Geological Survey, Menlo Park, California, oral communication, 1983). Two other, thinner intervals of moderately low resistivity (200 ΩM), each less than 100 feet thick, occur above the major discontinuity, at about 4,250 feet and at about 4,500 feet. These intervals are not closely correlated with lithology. An especially pumice-rich zone at 4,370 to 4,430 feet falls between the two intervals . However, some pumice fragments are present throughout a thicker zone that extends from 4,230 feet down to 5,210 feet, i.e., from the upper zone of high resistivity down to within 100 feet of the base of the major zone of high resistivity and high porosity (Figure 21). It is possible that some of the porosity and resistivity changes may be related to zones of water saturation, as suggested by Ruth B. Deike (U.S. Geological Survey, Reston, Virginia, written communicaltion, 1982), but I do not have sufficient data to attempt these correlations.

[2] Use of the firm name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.



EXPLANATION

Petrographic data from the present study of cuttings chips are superimposed on this diagram:

Zones containing some pumice fragments

Pumice-rich zones with abundant fragments

Crystal-rich zones

Zones with a high percentage of crystals (> 25 percent)

Figure 21. - Porosity and resistivity in the Republic 66-29 well plotted against depth (taken from Smith and Rex, 1977).

Near the bottom of the drillhole, a zone of low resistivity (850 to 875 ΩM) and high porosity (20 to 30 percent) at about 6,850 to 6,920 feet occurs at the same depth as a zone of partly welded tuff and the underlying, very densely welded tuff. In general, the degree of welding decreases from about 6,620 feet down to this densely welded tuff (see Table 5). This zone of low resistivity is symmetrical with a zone at the top of the welded Bishop Tuff, between 2,750 and 3,170 feet, but the zone at the top has low porosity. Pyrite and silica veinlets are present near the top of the welded tuff (silica veinlets at 2,750-2,810 feet, 2,870-2,900 feet, and 3,110-3,140 feet; pyrite at 2,810-2,870 feet and 2,990-3,080 feet), corresponding to the zone of low (about 850 ΩM) resistivity. Similarly, the presence of disseminated pyrite near the bottom of the drillhole (at 6,800-6,890) coincides with the zone of lowest resistivity.

A zone of light-colored, less welded tuff at 3,860 to 4,010 feet, which may contain some vapor phase crystallization, correlates with a slight increase in porosity. There is no detectable decrease in resistivity, which remains off scale. Because of the symmetry of the resistivity minima and the pyrite distribution, as well as because of data discussed in the section Depths to and Variations in Thickness of the Bishop Tuff, I believe that the drillhole bottomed within about 50 feet of the base of the welded Bishop Tuff.

APPENDIX B: LITHIUM AND BORON

From Table 6, it appears that in the process of alteration of glassy airfall tuff (#663) to clinoptilolite (#638, #928) or to K-feldspar (#907), some lithium and boron are lost. Perhaps alteration of glass is the source of the enormous amount of lithium in the clay-rich sediments at 610 to 617 feet. According to Ruth G. Deike (U.S. Geological Survey, Reston, Virginia, written communicaltion, 1982), lithium substitutes for silicon in tetrahedral layers in the montmorillonite. This conclusion is based on use of the Green-Kelly test for silicon vacancies.

The amount of boron in the K-feldspar-rich siltstone at 971 feet is high by comparison with the altered clinoptilolite tuffs, but is the same as that in the glassy unaltered tuffs. It is possible that the authigenic K-feldspar, which has an anomalous structure, contains some boron. It has not been possible to separate the feldspar for analysis because of the very fine grain size of the material.

APPENDIX C: STABLE ISOTOPIC DATA

Stable isotopic values of $\delta^{18}O$ and $\delta^{13}C$ in calcites from five samples taken from core between 342 feet and 970 feet in the LVCH-1 drillhole (Table 7) are consistent with the presence of lake waters that varied from slightly to very saline. The four sedimentary samples (342, 585B, 612, and 970) were chosen from calcite-rich, non-fossiliferous sediments, in order to obtain enough calcite for analysis, while avoiding the calcite that forms ostracode valves. All calculations in the following discussions are based on curves from Friedman and O'Neil (1977). Data are summarized in Table 7.

Salinities in the Long Valley caldera lake at a time corresponding to depths of 970 to 972 feet seem to have fluctuated. At 971 feet in the LVCH-1 core there is a siltstone layer which is extremely rich in biotite and authigenic K-feldspar, and is barren of fossils, suggesting the presence of more saline conditions than the average in this core. Immediately overlying this siltstone are cross-bedded white calcareous sediments, at 970 feet, which contain three species of ostracodes, indicating a relatively low level of salinity (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980, and Table 8). Sample #970, also from a depth of 970 feet in the LVCH-1 core, is a gray parting, composed of calcite, quartz, and minor amounts of pyrite, that lies immediately above these cross-bedded white calcareous sediments. The calcite in this parting (refer to Table 7) would be in equilibrium with a water which is in the range of present-day cold spring waters in Long Valley. These waters have $\delta^{18}O$ values between -14.5 and -17, temperatures of 10°to 16°C (Fournier and others, 1979), and are essentially fresh water. A slight amount of evaporation of such water, producing slightly saline lake water, would drive the $\delta^{18}O$ values of precipitated calcite toward more positive values, while a slight increase in temperature at a constant $\delta^{18}O$ of the lake water would drive the $\delta^{18}O$ of precipitated calcite toward more negative values. Thus, the $\delta^{18}O$ values of the lake water could be in close agreement with those of present-day cold meteoric spring water. The average $\delta^{13}C$ for freshwater limestone is about -5 (Faure, 1977, p. 385), and for Pyramid Lake sediments is +7 (Wedepohl, 1969, II-1, p. 6-B-12, Fig. 6-B-7). Pyramid Lake is a moderately saline lake, at the low end of the range (4820 ppm TDS, Jones, 1966, p. 185), therefore a value of $\delta^{13}C = +2$ for the calcite in the sediments at 970 feet in the LVCH-1 core is compatible with deposition from a slightly saline lake. Possibly the gray parting precipitated either from an influx of fresh meteoric water or from an influx of nearly fresh hot spring waters, with TDS less than 2 ppt.

The sample from 612 feet in the LVCH-1 core is a calcite veinlet, apparently derived from the enclosing buff-colored, laminated, and lithium-rich montmorillonite sediments. A hot spring contribution to the water in equilibrium with this calcite is a reasonable assumption because these veinlets are enclosed in lithium-rich clays. If the presence of uncontaminated lake water is assumed, that lake water would have been nearly fresh. If it were saline, a temperature greater than 75°C would be required to achieve equilibrium with this calcite. The $\delta^{13}C$ value of this calcite is the most depleted of the four sedimentary samples from this drillhole.

The sample from 585 feet is from a massive tuffaceous sediment. The isotopic composition of this calcite is in equilibrium with a saline water which would have a calculated $\delta^{18}O$ value of -8.4 at 25°C, the most saline water in equilibrium with any of the isotope samples from this drillhole.

By comparison, Mono Lake, a briny lake containing about 56 ppt TDS, has $\delta^{18}O = 0$, and Owens Lake, an extremely briny lake with about 300 ppt TDS, has $\delta^{18}O = +4$ (Jones, 1966, p. 185; and Wedepohl, 1969, Fig. 8-B-19, p. 8-B-19). Yet the value of $\delta^{13}C$ for this rock is +1.2, indicating less saline water than the other sedimentary samples from LVCH-1. Clayton and Steiner (1975, p. 1184) found at Wairakei that at some sites, carbon isotopes show no correlation with depth, temperature, or amount of carbonate in the rock, and may be out of isotopic equilibrium. Because the oxygen isotope values are more compatible with the fossil data, I place more confidence in the oxygen isotope data. Moderately saline (3 to 10 ppt) to very saline (10 to 35 ppt) water in equilibrium with this calcite would be in harmony with the ostracode assemblage (see Appendix D).

Sample #342, from 342 feet in the LVCH-1 core, in a white, colloform band of sediment, less than a foot thick. It immediately overlies richly fossiliferous silts and ashy diatomites. Sample #342 is closest to sample #970 (the gray, pyrite-bearing parting) in its isotopic values. The oxygen value is in equilibrium with water that is slightly more evaporated or saline (isotopically heavier) than that for #970. Cold spring waters (10^{0} to 25^{0}C) in Long Valley have $\delta^{18}O$ values in the range -14.5 to -17, (Fournier and others, 1979), and this calcite would be in equilibrium with such waters. A small amount of evaporation plus warming could also produce a water in equilibrium with this calcite.

The $\delta^{13}C$ value for calcite in #342 (+3.5) would also be in equilibrium with water with $\delta^{13}C$ ranging from -16 to -14 at 10^{0} to 25^{0}C. It can be compared with the "average" for fresh-water limestones of -4.93 (Faure, 1977, p. 385) and with Pyramid Lake sediments of +7 (Wedepohl, 1969, 6-B-12). Pyramid Lake has about 4.8 ppt TDS and pH = 8.9 (Jones, 1966, Table I, p. 185), making it a moderately saline lake (Hem, 1970, p. 219). This calcite was probably in equilibrium with a slightly saline to moderately saline lake, about 2 to 4 ppt, in agreement with the interpretation of the ostracode assemblage (see Appendix D). The diatoms suggest moderately saline conditions, and some species are compatible with the local presence of hot springs.

The oxygen isotope value ($\delta^{18}O = -3.40$; analyst, Nancy L. Nehring, U.S. Geological Survey, Menlo Park, California) from sulfate (gypsum) in a seam at 358 feet in the LVCH-1 core is not compatible with evaporation from lake water under equilibrium conditions, assuming that gypsum behaves like anhydrite isotopically. Available values of $\delta^{18}O$ in sulfate formed by evaporation range from +5 to +18 (Wedepohl, 1969, p. 8-B-19), and values in lake waters range from -11 (Deep Springs Lake) to +4 (Owens Lake).

The sulfate at 358 feet is compatible with a hydrothermal origin if one assumes that the gypsum last equilibrated with water at a temperature between 135^{0} and 160^{0}C. Sulfate dissolved in hot springs in Long Valley has $\delta^{18}O$ values ranging from -7.8 to -7.2 (Nehring and Mariner, 1979) and the $\delta^{18}O$ values of the waters range from -14.5 to -17.1. Because maximum reservoir temperatures are estimated at 269^{0} to 273^{0}C (Fournier and others, 1979), this is a reasonable temperature range. The rate of re-equilibration of oxygen isotopes in dissolved sulfate is very slow at low temperatures (McKenzie and Truesdell, 1977), therefore the oxygen isotopes in this sulfate could have equilibrated at some depth in a geothermal system and mixed with lower temperature sulfates (derived from oxidation of H_2S) as the sulfate moved toward the surface. The pattern of distribution of gypsum in the drillhole suggests a sedimentary origin rather than hydrothermal; however, a hydrothermal origin for this seam is conceivable and reasonable if the hydrothermal waters had dissolved gypsum from deeper sedimentary layers and redeposited it at this level. This hypothesis would require an active hydrothermal system after the time of deposition of these sediments. A third alternative, which cannot be evaluated on the basis of available isotopic data, is that some or all of the gypsum originated above the water table, by precipitation from pore waters during transpiration, or capillary evaporation, as appears to have occurred at Teels Marsh (Smith and Drever, 1976, p. 1092). It seems unlikely that such a process occurred at the time of sediment formation, in veiw of the fact that diatoms in this part of the LVCH-1 drillhole suggest the presence of deep water. However, disseminated gypsum may have been precipitated at some later time, even after the removal of the core from the drillhole.

Stable isotopes of oxygen and carbon were measured in calcite from two tuffs in the Republic drillhole cuttings (see Table 7). The same isotopes were measured in much more calcite-rich, clinoptilolite-bearing vitric lapilli tuff from 554 feet in the LVCH-1 core. Calcite in this rock is interstitial and also replaces glass lapilli. The $\delta^{13}C$ values for the three tuffs are all in the same range, -3.17 to -5.54; this range differs markedly from that in the sediments, which have positive values. The shift toward more depleted oxygen values with increasing depth in the Republic drillhole is compatible with higher temperatures at greater depth, but the shift in $\delta^{13}C$ values indicates the opposite, as increasing depletion in $\delta^{13}C$ would point to decreasing temperature if the $\delta^{13}C$ values were in equilibrium.

The calcite in the altered vitric lapilli tuff in the LVCH-1 core (#554) is more similar isotopically to the calcite in the two tuffs from the Republic drillhole than it is to the calcites in the sediments in the LVCH-1 drillhole. Note (Table 7) that both carbon and oxygen isotopes indicate that the calcite in the tuff was in equilibrium with fresher water than any water in equilibrium with the measured sediments, yet fossil ostracodes in a band interstratified with this tuff indicate the presence of high salinity (20 ppt). Possibly the pH of the water in which the tuff was deposited was increased by hydrolysis of glass fragments, thus accounting for the depletion in $\delta^{13}C$ (and $\delta^{18}O$) relative to the sediments (Faure, 1977, pp. 393-394). Hay (1963, pp. 239-244, cited in Sheppard and Gude, 1965) "proposed solution and hydrolysis of vitric material by subsurface water to account for the zeolitic diagenesis of tuff and claystone", and pointed out that "the early alteration of rhyolitic glass to montmorillonite also would increase the pH and salinity of the water".

Cold springs in Long Valley have $\delta^{18}O$ values in the range -14.5 to -17, and warm springs in the temperature range 40^{0} to $90^{0}C$ have $\delta^{18}O$ values in the range -14.8 to -16 (Fournier and others, 1979, pp. 18-19). The $\delta^{18}O$ values in the calcite from sample #554 would be in equilibrium with warm hydrothermal water in the temperature range 65^{0} to $85^{0}C$, or could be in equilbrium with some mixture of cold dilute lake water and hotter spring water which mixed to yield those temperatures.

The $\delta^{13}C$ value (-3.2) in the calcite of LVCH-1 #554 is consistent with sediments deposited from slightly saline lake water (see discussion of sample #970). It is in equilibrium with water having $\delta^{13}C$ values varying from -5.2 to -5.6 in the temperature range 10^{0} to $50^{0}C$. Robert H. Mariner

(Farrar and others, 1985, Table 2, pp. 123-124) found that $\delta^{13}C$ averages about -4.4 for carbon in hot springs at Hot Creek, Long Valley.

At the time of completion of drilling, the temperature at 1,310-1,340 feet in the Republic drillhole was about 65°C, and the bottomhole temperature (at 6,920 feet) was 72°C. The analcime-quartz-plagioclase tuff from 1,310-1,340 feet has cementing calcite which would be in equilibrium with water having $\delta^{18}O$ equal to -21 at 25°C, -13 at 65°C, or -11.7 at 75°C. A $\delta^{18}O$ value of -15 to -16 at about 65°C would be in general agreement with the range of values cited by Fournier and others (1979) for hot springs of the Long Valley area: -14 to -17 (Fournier and others, 1979, Table 1, p. 18-19, and Fig. 12, p. 30). Some contamination with slightly saline lake water having $\delta^{18}O$ = -8 to -10 could account for the less negative value of $\delta^{18}O$ in the water in equilibrium with this calcite.

In the quartz- and K-feldspar-bearing tuff from 2,390-2,420 feet in the Republic drillhole, $\delta^{18}O$ in calcite is much more depleted in ^{18}O than the sample from 1,310-1,340 feet, and is much too depleted to be explained at the temperatures presently occurring in the drillhole. Contamination with lake water or with meteoric water would drive the numbers in the wrong direction. However, if one assumes that the same water that equilibrated with calcite of $\delta^{18}O$ = +8 at 1,310-1,340 feet at 65° to 75°C also equlibrated with calcite of $\delta^{18}O$ = -2.5 at 2,390-2,420 feet at 120° to 140°C, such water would have $\delta^{18}O$ of about -16, within the range -14 to -17. Hot springs in Long Valley which have estimated temperatures (using the silica geothermometer) of 109° to 114°C have $\delta^{18}O$ values of -15.9 to -17.1 (Fournier and others, 1979). A hot spring in Little Hot Creek with an estimated silica temperature of 129°C (Fournier and others, 1979, Table 1) has a $\delta^{18}O$ of -15.34, in good agreement with these calculated values.

APPENDIX D: FOSSILS

Ostracodes between 584 and 992 feet indicate conditions of variable salinity, ranging from slightly to moderately saline (2 to 10 ppt) to very saline water with salinities usually less than 20 ppt, but possibly 50 ppt or more, and with pH in excess of 8. The water chemistry was "characterized by $[Na^+] >> [Ca^{2+}]$, varying Cl^-, and $[HCO_3^- + CO_3^-] \geq$ sulfate" (R.M. Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982).

The samples used for paleontological analysis were deliberately chosen from calcite-bearing sediments. Only a few feet of the sediments that occur above 310 feet and below 560 feet lack abundant calcite, therefore the samples chosen from those segments of the core are representative of those sedimentary volumes. However, only about one third of the sedimentary samples from the interval 333 to 410 feet that were x-rayed contain significant amounts of calcite, so the sampling for ostracodes was restricted to those atypical samples in this interval.

Ostracodes were first recognized by me in thin sections of LVCH-1 core. Table 8 enumerates the depths and rock types in which ostracodes were recognized in thin section or in samples submitted to Forester. In two of the five samples that were "barren" when processed by Forester, a few ostracodes were visible in thin section (#552, #992).

Ostracode species identified in the LVCH-1 core are as follows:

LVCH-1-334: A gray, ashy, diatomaceous silt containing calcite and aragonite.

<u>Candona</u> n. sp.
<u>Candona</u> n. sp.
<u>Candona</u> n. sp.
<u>Linmocythere</u> <u>sappaensis</u> Staplin, 1963
<u>Linmocythere ceriotuberosa</u> Delorme, 1967
<u>Limnocythere</u> n. sp.

LVCH-1-343: Steeply dipping bands of gray, ashy diatomites and silts, mixed, containing calcite, gypsum and a trace of pyrite.

<u>Candona</u> n. sp.
<u>Candona</u> n. sp.
<u>Candona</u> n. sp.
<u>Limnocythere</u> <u>sappaensis</u> Staplin, 1963
<u>Limnocythere ceriotuberosa</u> Delorme, 1967
<u>Limnocythere</u> n. sp.

LVCH-1-357-358: Light gray, ashy silts containing calcite, gypsum, and pyrite.

Barren.

LVCH-1-400: Massive gray siltstone containing calcite and a trace of pyrite.

Barren.

LVCH-1-552: Pumiceous sediments with alternate light and dark gray bands, dipping 45^{o}; abundant calcite, 30-60 μm in matrix; cristobalite and K-feldspar. Ostracodes visible in thin section.

Barren.

LVCH-1-584: Buff-colored tuffaceous sediments with clinoptilolite, cristobalite, and calcite.

Limnocythere sappaensis Staplin, 1963, common
Candona n. sp.

LVCH-1-610: Lithium-rich, clay-bearing laminated sediments with major amounts of calcite and montmorillonite.

Limnocythere sappaensis Staplin, 1963, v. abundant
Candona sp. indet. Juveniles may be reworked.

LVCH-1-628: Waterlaid calcite-rich lapilli tuff, with steeply dipping bands; and tuffaceous sediment

Limnocythere sappaensis Staplin, 1963, common.
Candona n. sp. Rare juveniles.

LVCH-1-886: Massive gray siltstone overlying waterlaid tuff; contains calcite, cristobalite, montmorillonite, and K-feldspar.

Limnocythere sappaensis Staplin, 1963, abundant
Candona, n. sp.
Candona sp. indet.

LVCH-1-898: Gray, silty clay with calcite, K-feldspar, and trace of gypsum. Ostracodes visible in thin section.

Limnocythere sappaensis Staplin, 1963, abundant
Candona n. sp.
Candona n. sp.

LVCH-1-904: Gray shale with mud cracks, containing calcite, K-feldspar, and cristobalite.

Limnocythere sappaensis Staplin, 1963, common
Candona n. sp.
Candona n. sp.

LVCH-1-911: (actually at 912 feet): Tuffs and sediments, intermixed on the scale of a thin section, possibly by slumping. Ostracodes are visible in thin section in the sedimentary patches. Contains clinoptilolite, K-feldspar, and a possible trace of analcime.

Limnocythere sappaensis Staplin, 1963

LVCH-1-950: Gray shale with whitish lenses and desiccation cracks, underlain by airfall tuff. Contains montmorillonite, cristobalite, and K-feldspar.

Limnocythere sappaensis Staplin, 1963, present
Candona n. sp.
Candona n. sp.

LVCH-1-971: Cross-bedded soft white sediments, containing calcite, K-feldspar, and a trace of gypsum. Immediately overlies the K-feldspar-rich gray siltstone, which has no ostracodes visible in thin section.

Limnocythere sappaensis Staplin, 1963, common
Candona n. sp.
Candona n. sp.

LVCH-1-975: Soft white massive sediments, predominantly calcite, with traces of K-feldspar and quartz.

Barren.

LVCH-1-922A: Fine-grained buff-colored sediments or tuffaceous sediments containing much clinoptilolite and patches of calcite. Ostracodes are visible in thin section.

Barren.

According to Richard M. Forester (U.S. Geological Survey, Denver, Colorado, written communication, 1982), ostracode assemblages from the part of the core from 584 feet downward, based on the overall abundance of Limnocythere sappaensis and the abundance and diversity of other ostracode species, indicate waters with salinities ranging from 2 to more than 50 ppt (slightly saline to briny, by Hem's 1970 scale). The fewer the number of species present, the higher the salinity. Where Limnocythere sappaensis is abundant, it occurs in lakes "whose solute composition is dominated by Na^+-HCO_3^- CO_3^{2-}, with $Na^+/[HCO_3^- + CO_3^{2-}]$ ratios between 0.5 and 3.0 in modern lakes". As a natural result of the evolution of closed-basin lakes along fractionation pathways I and IIIA (Eugster and Jones, 1979), amounts of K^+, Mg^{2+}, SO_4^{2-}, and Cl^- can vary from low to dominant, and "Ca is always depleted and in low abundance" (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982). [Na + K]/[Mg + Ca] ratios are high (60:1 to 1800:1). These lakes are usually shallow (less than 5 m), have pH in the range 8 to 11, experience broad temperature variations, and may be temporary. When Limnocythere sappaensis occurs alone, or other species are rare or in low abundance, waters are relatively saline, probably above 3 ppt most of the time and up to more than 50 ppt, but rarely exceeding 20 ppt. When L. sappaensis occurs with other species in moderate abundance, the salinity is usually in the range 2 to 10 ppt (moderately saline by Hem's scale). Candona adunca probably "does not tolerate as high a salinity as L. sappaensis" (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980), but otherwise probably has similar requirements. "The lake was permanent but not too deep", probably closer to 15 feet than to the deeper freshwater lakes described below. By these criteria, ostracode assemblages in the parts of the core between 584 feet and 628 feet and at 911 feet indicate the most saline conditions.

On the other hand, assemblages from the upper part of the core (samples #334 and #343) represent relatively fresh water, about 2 to 5 ppt (slightly to moderately saline on Hem's scale), with possible higher salinities due to seasonal variations. "The presence of L. ceriotuberosa probably indicates that chlorides are present, as well as moderate amounts of Na^{+}" (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1980). The Candona species "suggest the lake was large, permanent and environmentally stable", that temperatures were mild to warm, and that "the lake chemistry [was] probably similar to Goose Lake, Oregon" (1980; see Phillips and Van Denburgh, 1971), i.e., $Na^{+} \geq Ca^{2+}$, $[HCO_3^- + CO_3^{2=}] \geq [SO_4^{2=}] \geq Cl^{=}$, and Mg^{2+} is generally greater than Ca^{2+}, especially where aragonite is present. This phase of the lake could have been either deeper or shallower than the phase represented by the laminated (varved?) diatomite at 490 feet (Forester, U.S. Geological Survey, Denver, Colorado, written communication, 1982).

Diatoms were first recognized in thin section, and also can be recognized in disaggregated samples using a 30X microscope. The deepest sample in which I have found diatoms is at 490 feet in the LVCH-1 core, in a banded (possibly varved) white diatomite interbedded with massive lapilli tuffs.

Diatoms identified in samples submitted to J. Platt Bradbury are:

In the LVCH-1 core:

LVCH-1-306: Coarse-grained gray pumiceous sediment contains rare fragments of:

Melosira teres
Hantzschia amphioxys var. major

LVCH-1-334: Gray, ashy diatomaceous silts, containing calcite and aragonite.

Stephanodiscus subtransylvanicus
Stephanodiscus sp. cf. S. astraea
Stephanodiscus carconensis var. pusilla

LVCH-1-343: Steeply dipping bands of gray, ashy diatomites and silts, mixed, containing calcite, gypsum, and a trace of pyrite.
DIATOM LOCALITY #8 VIII 80-1 (343'). The gray silts contain a flora similar to sample #334. The ashy diatomites contain the following:

Stephanodiscus excentricus
Stephanodiscus carconensis var. minor
Stephanodiscus subtransylvanicus
Stephanodiscus sp. cf. S. astraea
Stephanodiscus kanitzii f. inermis
Melosira teres
Cyclotella comta
Epithemia hyndmannii var. capitata
Cocconeis placentula
Cocconeia pediculus
Rhopalodia gibberula
Cymbella sp.

LVCH-1-410: Ashy diatomite with a trace of gypsum, near the base of an 80-foot section of sediments. Diatom Locality #8 VIII 80-1 (410'):

Stephanodiscus sp. cf. S. astraea
Stephanodiscus carconensis var. minor

LVCH-1-490: Diatomite with ash-bearing bands, possibly varved, containing traces of plagioclase, K-feldspar, and cristobalite with a high degree of crystallinity. A two-foot thick layer of diatomite, interbedded with airfall tuffs.

Stephanodiscus astraea? (aff. niagarae)
Stephanodiscus astraea v. minutula
Stephanodiscus carconensis v. pusilla
Stephanodiscus asteroides (rare, much variation)

LVCH-1-674: Volcanic ash and pumice.

Barren.

In the Republic drillhole:

At 350-380 feet: Yellowish-gray sandstones, with major amounts of K-feldspar in the cuttings of this interval. DIATOM LOCALITY #8 VIII 80-2 (350-380').

A large excentric Stephanodiscus species, closely related to Stephanodiscus kanitzii fo. inermis.

Dark ash-bearing bands at 490 feet in the LVCH-1 core contain some pine (Pinus) pollen (J. Platt Bradbury, U.S. Geological Survey, written communication, 1982). Since pine now pollinates in the early summer and modern Stephanodiscus blooms in fall or very early spring, the pairs of dark and light bands may represent varves. The fact that these layers are preserved is indicative of a comparatively deep lake with a quiet, anoxic bottom, i.e., a dimictic lake. R.M. Forester (U.S. Geological Survey, written communication, 1982) believes that if this was a dimictic lake, average summer temperature exceeded 4°C and average winter temperature could have been below 0°C but may have exceeded that.

At 410 feet in LVCH-1, benthonic diatoms are absent. "The relatively pure nature of the diatomite indicates an open water environment of a rather deep (50-100 m) freshwater lake of moderate alkalinity." (Bradbury, U.S. Geological Survey, written communication, 1980, p. 3).

At 343 feet, there is a mixture of lithologies. The silts have a diatom flora similar to #334. The diatomites have the rich flora listed above. The Stephanodiscus species dominate the assemblage "and suggest open fresh water of moderate depth" (greater than 50 feet) (p. 2). There is suggestive evidence of the local presence of hot springs, inasmuch as some of the benthic species suggest moderate salinity, but the lake as a whole was probably not saline. This assemblage may show that the lake was chemically stratified (Blair F. Jones, U.S. Geological Survey, oral communication, 1982). Two species (Stephanodiscus sp. cf. S. astraea and Rhopalodia gibberula) occur in dilute water in modern Lake Abert, Oregon

(Blair F. Jones, U.S. Geological Survey, oral communication, 1982). Melosira teres is consistent with the presence of cool, silica-rich water.

At 334 feet, the varieties of Stephanodiscus related to S. astraea may develop "in silica-rich lakes with comparatively large nutrient loads" (J. Platt Bradbury, U.S. Geological Survey, written communication, 1980, p. 2). The assemblage probably reflects comparatively fresh water. Some of the Stephanodiscus species are planktonic, suggesting open water of depth greater than 15 feet (moderate depth). The same applies to the silts at 343 feet.

At 306 feet, diatom fragments are rare. One of these species (Hantzchia amphioxys var. major) was not found in other identified samples; one (Melosira teres) was found at 343 feet, but not in the other two samples. M. teres may indicate cool, silica-rich lakes of moderate depth. Hantzschia amphioxys is a benthonic form found in freshwater lakes and ponds.

The species of Stephanodiscus found at 350-380 feet in the sandstones of the Republic drillhole "does not clearly correlate with any of the other samples...although the most closely related forms appear in LVCH-1-343." Since the lithologic facies are so different in the two drillholes, perhaps this is the closest correlation that can be expected.

APPENDIX E: METHODS OF MINERAL IDENTIFICATION

Standard petrographic methods were used, including observation of cuttings chips with a 30X microscope and study of thin sections of both core and handpicked cuttings with a standard petrographic microscope. Most material was friable, so that impregnation with epoxy resin in a vacuum was necessary before attempting to make thin sections.

Most mineral identifications were made by standard whole-rock x-ray diffractometry. Standard methods of glycolation of samples to test for montmorillonite were used. Absence of kaolinite simplified analysis of clays. Often small portions of core or cuttings were handpicked and a slurry slide prepared, using a mixture of acetone and collodian (about 95:5). Working back and forth between x-ray and optical techniques on a small scale facilitated the identification of some of the very fine-grained material; but in some cases, matrix material could only be identified by inference, as in Table 4.

More specialized x-ray diffractometer techniques were used to study K-feldspar, cristobalite, clinoptilolite, and analcime.

Methods of Wright (1968) were used in a preliminary study of two samples of K-feldspar from the LVCH-1 core, at 608 feet and 971 feet. Calcium fluoride, with a strong peak at 28.88Å, was used as an internal standard. Indexing of the feldspar x-ray reflections was carried out by comparison with reflections from low-temperature authigenic K-feldspar from Boron, California, which had been measured and indexed by Richard C. Erd of the U.S. Geological Survey, Menlo Park.

The rock at 971 feet is a sediment, composed of large amounts of K-feldspar, quartz, and biotite. All data available indicate that the K-feldspar in this rock is authigenic. A few of the K-feldspar crystals are visible in thin section as tiny, water-clear rhombs, 20 to 40 μm in diameter. This rock is very fine-grained, and although a fair mineral separation was achieved, some quartz remains in the K-feldspar fraction. There was enough material to prepare a good powder pack.

Measurements of $2\theta(060)$, $2\theta(204)$, and $2\theta(201)$, compared with data of Wright (1968, Figures 3 and 4, p. 92 - 93) and Orville (1967, Table 3C, p. 67) suggest that this feldspar is closest to the high sanidine - high albite series and has a composition in the range Or_{90} to Or_{100}.

Because the whole rock from 971 feet contains 22 ppm boron (see Appendix B) but contains no boron minerals, one must consider the possibility that boron may substitute for aluminum in the K-feldspar structure (Martin, 1971). The amount of boron in the rock is, however, orders of magnitude less than in tuffs of Pliocene lake deposits in which Sheppard and Gude described boron-rich potassium feldspar; those tuffs contained 660 to 2300 ppm boron (Sheppard and Gude, 1973b, p. 19).

The rock at 608 feet is a tuff with alternating finer and coarser grained bands, containing large amounts of clinoptilolite and calcite as well as the K-feldspar, plus small amounts of cristobalite and montmorillonite. In thin section (Figures 18 and 19), calcite can be seen replacing glass along perlitic cracks. In other parts of the thin section, glass shards appear suspended in coarse-grained calcite cement, not touching each other. Small rounded grains of calcite are also contained in the coarse-grained interstitial calcite. Because of very fine grain size and intergrowths of the crystalline material, I was not able to remove all the clinoptilolite and cristobalite from the K-feldspar sample. Also, there was not enough material to make a good powder pack, but only a slurry slide. Therefore, the accuracy of the 2θ measurements is not as good as might be desired.

In this rock, comparison of measurements of the same three peaks with data of Wright (1968, Figures 3 and 4) produce some discrepancies which suggest that the K-feldspar might be anomalous. Comparison with data of both Wright (1968) and Orville (1967) indicate that the feldspar falls in the high sanidine - high albite series and has a composition in the range Or_{65} to Or_{75}.

If this composition is real, one must consider the possibility that the K-feldspar from the tuffs at 608 feet may be primary. Such a composition, far from the potassium-rich end of the K-Na solid-solution series, is more compatible with a volcanic than with a low-temperature authigenic origin. However, the textural data as seen in thin section strongly indicate the influence of lacustrine waters, in which authigenic K-feldspar could form. Unfortunately the data are not precise enough to provide the definitive conclusions about composition and structural state which might resolve this dilemma. Further study of both feldspars is desirable, but was beyond the scope of this paper.

The degree of crystallinity of a number of cristobalites was measured using the value d(101), compared with that of synthetic α-cristobalite as a measure of crystallinity. Quartz was added as an internal standard if it was not present. The methods used were those described by Murata and Larson (1975).

Sixteen samples of clinoptilolite from the LVCH-1 core and seven from the Republic cuttings were studied by heating tests combined with x-ray diffractometry, in order to use thermal stability to distinguish between clinoptilolite and heulandite, using the method of Alietti (1972). No heulandite was found.

In no clinoptilolite sample was there a shift of the (020) peak, 8.92Å, from 9.9° 2θ to higher 2θ values after heating at 550°C for periods of 15 to 20 hours. Such a shift would indicate a collapse of the structure characteristic of heulandite.

In six samples from the LVCH-1 core that were heated at 500°C for 20 hours, there was a decrease in the intensity of the (020) peak, ranging from very little up to about 50 percent. In three of these samples, heated first at 500°C for 20 hours and then at 550°C for 15 hours, there was a subsequent increase of intensity of the (020) peak at the time of the second heat treatment, though not back to the original intensity. The four samples that were heated at 550°C for 15 hours without previous heat treatment showed a marked increase in the intensity of the (020) peak of from ten to 40 percent. It is evident that the structure persists at 550°C, and that by the criteria of Mumpton (1960) and Boles (1972), these samples are clinoptilolite.

Republic samples, heated 15 hours at 530°C, showed no change or very slight increases in the intensity of (020).

Six samples of analcime from the Republic cuttings, from sandstone in the 1,370-1,400 feet interval, were studied to determine the ratio of Si to Al in the structure. The d(639) spacings of the analcime were measured using silicon [d(331) = 1.2459Å] as an internal standard, according to the method of Saha (1959). Using the data of Coombs and Whetten (1967, p. 271), a_0 of this analcime is 13.67Å, and there are between 35 and 36 silicon atoms (out of a possible 36) in each unit cell.

Table 1. Data from Drillholes in Long Valley; estimates of depth to the Bishop Tuff

Drillhole	Wellhead elevation (feet)	Elevation above sea level of top of NONWELDED Bishop	Elevation above sea level of top of WELDED Bishop	Elevation above sea level of base of WELDED Bishop	Thickness of WELDED BISHOP TUFF (estimated)
Clay Pit*	7,304	---	6,204	2,644 to 2,004 (see text)	3,560 to 4,200 feet
Mammoth*	7,304	---	5,624	2,784 ft.	2,840 feet
Republic	6,963	estimated: 2,200 to 2,350 feet	2,750 ft.	estimated 13 feet (see text)	estimated 4,200 feet (see text)

* Data transmitted from Unocal

Table 2. --Specific gravity, porosity, permeability, and thermal conductivity data correlated with lithology and mineralogy

Depth (feet)	Lithology	Mineralogy	Specific gravity of solids (1)	Bulk porosity (%) (1)	Conductivity Hydraulic (m/d) (1)	Conductivity Thermal ($mcal\text{-}cm^{-1}\text{-}s^{-1}\text{-}{}^{0}C^{-1}$) (2)
209 a	Tuff, airfall	Glass, quartz, trace plagioclase	2.40	-	-	-
275	Lapilli tuff, airfall, possibly some waterlaid	Quartz, plagioclase, trace glass, K-feldspar	2.34	59.8	6.88	-
392	Tuff, airfall	Glass, quartz, trace plagioclase, K-feldspar	2.40	35.0	5.3×10^{-1}	-
436	Tuff, probably airfall	Glass, quartz, minor plagioclase, K-feldspar	2.33	50.2	5.9×10^{-2}	-
466 a	Tuff, airfall	Glass only	2.18	-	-	-
475.7	Tuff, airfall	Glass, possibly trace plagioclase	-	-	-	1.79
480	Tuff, airfall	Glass, trace plagioclase	2.33	63.1	3.8×10^{-1}	-
492	Lapilli tuff, airfall	Glass only	-	-	-	2.13
515	Tuff, airfall	Glass only	2.37	56.9	2.9×10^{-2}	-
522	Tuff, airfall	Glass only	-	-	-	1.91
545.5	Tuff, waterlaid	Quartz, cristobalite, K-feldspar, calcite trace clinoptilolite	-	-	-	2.04
553.5	Lapilli tuff, waterlaid	Calcite, clinoptilolite, trace cristobalite minor montmorillonite	-	-	-	1.62
563	Tuff, airfall	Clinoptilolite, trace quartz, K-feldspar, glass, montmorillonite	2.60	39.6	4.6×10^{-7}	-
572	Lapilli tuff, airfall	Clinoptilolite only	-	-	-	1.10

Table 2. --Specific gravity, porosity, permeability, and thermal conductivity data correlated with lithology and mineralogy

Depth (feet)	Lithology	Mineralogy	Specific gravity of solids (1)	Bulk porosity (%) (1)	Conductivity Hydraulic (m/d) (1)	Conductivity Thermal ($mcal\text{-}cm^{-1}\text{-}s^{-1}\text{-}{}^{0}C^{-1}$) (2)
209 a	Tuff, airfall	Glass, quartz, trace plagioclase	2.40	-	-	-
275	Lapilli tuff, airfall, possibly some waterlaid	Quartz, plagioclase, trace glass, K-feldspar	2.34	59.8	6.88	-
392	Tuff, airfall	Glass, quartz, trace plagioclase, K-feldspar	2.40	35.0	5.3×10^{-1}	-
436	Tuff, probably airfall	Glass, quartz, minor plagioclase, K-feldspar	2.33	50.2	5.9×10^{-2}	-
466 a	Tuff, airfall	Glass only	2.18	-	-	-
475.7	Tuff, airfall	Glass, possibly trace plagioclase	-	-	-	1.79
480	Tuff, airfall	Glass, trace plagioclase	2.33	63.1	3.8×10^{-1}	-
492	Lapilli tuff, airfall	Glass only	-	-	-	2.13
515	Tuff, airfall	Glass only	2.37	56.9	2.9×10^{-2}	-
522	Tuff, airfall	Glass only	-	-	-	1.91
545.5	Tuff, waterlaid	Quartz, cristobalite, K-feldspar, calcite trace clinoptilolite	-	-	-	2.04
553.5	Lapilli tuff, waterlaid	Calcite, clinoptilolite, trace cristobalite minor montmorillonite	-	-	-	1.62
563	Tuff, airfall	Clinoptilolite, trace quartz, K-feldspar, glass, montmorillonite	2.60	39.6	4.6×10^{-7}	-
572	Lapilli tuff, airfall	Clinoptilolite only	-	-	-	1.10

Table 2. --Specific gravity, porosity, permeability, and thermal conductivity data correlated with lithology and mineralogy -- continued

Depth (feet)	Lithology	Mineralogy	Specific gravity of solids (1)	Bulk porosity (%) (1)	Conductivity Hydraulic (m/d) (1)	Conductivity Thermal ($mcal{-}cm^{-1}{-}s^{-1}{-}^{0}C^{-1}$) (2)
576	Sandstone, calcite cemented	Quartz, cristobalite, K-feldspar, plagioclase, calcite, trace clinoptilolite	-	-	-	1.78
587	Sediments, soft, massive	Quartz, K-feldspar, calcite, trace cristobalite and clinoptilolite	-	-	-	2.46
606	Laminated (varved) sediments, buff-colored	Calcite, cristobalite, quartz, K-feldspar, montmorillonite, trace clinoptilolite	2.72	45.2	1.1×10^{-6}	-
612	Laminated (varved) sediments, buff-colored	Calcite, montmorillonite, trace plagioclase, clinoptilolite(?)	-	-	-	1.87
625	Tuff, waterlaid	Glass, montmorillonite, calcite, trace clinoptilolite	-	-	-	1.85
685	Lapilli tuff, airfall	Glass only	2.37	62.4	1.9×10^{-6}	-
750	Top of lapilli tuff or base of airfall tuff	Clinoptilolite, some montmorillonite	2.69	62.3	4.1×10^{-6}	-
817.5	Tuff, airfall	Clinoptilolite only	-	-	-	1.69
822.5	Tuff, airfall	Clinoptilolite only	-	-	-	2.37
823	Tuff, airfall	Clinoptilolite only	2.67	52.1	8.7×10^{-7}	-
984.8	Tuff, possibly some waterlaid	Clinoptilolite, K-feldspar	-	-	-	1.69
1,000	Tuff, airfall	Clinoptilolite, minor K-feldspar and quartz	2.69	56.5	5.9×10^{-7}	-

a - sample disturbed

(1) - Data from R.E. Lewis (1975)

(2) - Data from Sass, Lachenbruch, and Monroe (1974)

Table 3. Lithology and mineralogy of the Republic drillhole above 2,750 feet

Depth (feet)	Lithology of major components	Characteristic minerals
90 - 110	Many individual quartz grains, 1-3 mm, black hornfels fragments, some fine-grained yellowish-gray (5Y8/1) sandstone at 80-110 feet	
110 - 140	Yellowish-gray sandstone, some individual quartz grains	
140 - 200	Black hornfels, individual quartz grains	
200 - 230	Yellowish-gray sandstone, fragments of black hornfels, quartzite, and granitic rock, some olive-green (5Y4/1) sandstone	
230 - 260	Fragments of granitic rock, quartzite, amphibolite, some olive-green sandstone	
260 - 440	Fine to medium-grained yellowish-gray sandstone, 5Y8/1, diatoms present	
440 - 560	White pumiceous tuff, lamellar glass abundant at 440 to 470 feet	cristobalite
560 - 650	Green vitric lapilli tuff, plus fragments of many rock types	cristobalite, clinoptilolite
980 -1,010	Fine-grained, light gray sandstone, N7	cristobalite, clinoptilolite
1,010-1,070	Very fine-grained yellowish-gray tuff, 5Y7/2, some fine light gray sandstone	clinoptilolite, K-feldspar
1,070-1,160	Very fine-grained yellowish-gray tuff	clinoptilolite, K-feldspar, quartz
1,160-1,220	Very fine-grained white tuff and medium-grained white tuff	mordenite, clinoptilolite
1,220-1,250	Very fine-grained yellowish-gray tuff	clinoptilolite, K-feldspar, quartz, cristobalite
1,250-1,310	Fine-grained, very light gray (N8) tuff, with mosaic texture	analcime, quartz
1,310-1,370	Medium-grained very light gray sandstone, very fine-grained light gray (N7) sandstone, very fine-grained white (N9) tuff	analcime, K-feldspar, calcite, quartz

Table 3. Lithology and mineralogy of the Republic drillhole above 2750 feet -- continued

Depth (feet)	Lithology of major components	Characteristic minerals
1,370-1,400	Medium to coarse-grained very light gray sandstone, and white siltstone	analcime, K-feldspar, calcite, quartz
1,400-1,430	Medium to coarse-grained very light gray sandstone, very fine-grained white tuff, and very fine-grained light gray sandstone	analcime, K-feldspar, calcite, quartz
1,430-1,490	Very fine-grained white tuff	analcime, K-feldspar, quartz
1,490-1,550	Very fine-grained light gray sandstone, and medium-grained white sandstone	calcite, K-feldspar, quartz
1,550-1,640	Very fine-grained white tuff	K-feldspar, quartz, plagioclase
1,640-1,730	Fine to medium-grained white tuff, some scattered phenocrysts, 0.5 mm	K-feldspar, quartz, plagioclase
1,730-1,820	Fine-grained white tuff with sparse phenocrysts less than 0.5 mm	K-feldspar, quartz, plagioclase
1,820-1,910	Medium-grained white tuff without phenocrysts, and some silt-size tuff	K-feldspar, quartz, plagioclase
1,910-2,030	Very fine-grained white tuff with sparse phenocrysts less than 0.5 mm	quartz, with K-feldspar, plagioclase at some horizons
2,030-2,150	Medium to coarse-grained white tuff with a few rounded phenocrysts, 0.3 to 0.5 mm, increasing downward to 40% phenocrysts at 2120-2150 feet	quartz, minor K-feldspar, plagioclase
2,150-2,240	Medium-grained white tuff without phenocrysts, and very fine-grained white tuff with some euhedral phenocrysts(0.3-1mm)	quartz, minor K-feldspar, plagioclase
2,240-2,300	Very fine-grained, very light gray or white tuff with a few phenocrysts (<0.5 mm). Fragments of granite, quartzite, and hornfels	quartz, plagioclase
2,300-2,360	Very fine to fine-grained very light gray tuff with 20-30% phenocrysts(<1 mm), plus biotite grains (<1.5 mm)	quartz, plagioclase

Table 3. Lithology and mineralogy of the Republic drillhole above 2750 feet -- continued

Depth (feet)	Lithology of major components	Characteristic minerals
2,360-2,390	Very fine-grained white tuff with less than 10% phenocrysts (<1.5 mm)	quartz, K-feldspar, plagioclase
2,390-2,510	Very fine-grained white tuff with about 20% phenocrysts (<0.5 mm), also fragments of black hornfels	quartz, K-feldspar, plagioclase
2,510-2,570	Light gray aphanitic volcanic rock with white feldspar phenocrysts, aligned cavities, and pyrite	
2,570-2,750	Very fine-grained white tuff with 10-20% clear phenocrysts(<1 mm), (less than 5% at base, 2,690-2,750 feet)	quartz, K-feldspar abundant at 2630-2690 feet, plagioclase

Table 4. Distribution of potassium feldspar in the LVCH-1 drillhole

Depth in feet	Liothology	Other minerals (major components underlined)	Amounts of K-feldspar X-ray	thin-section
334	Ashy, diatomaceous silts	Quartz, calcite, plagioclase, biotite, trace pyrite, hornblende, glass	Minor	Small amounts of microcline as clasts
387	Interbedded fine-grain-ed sediments and tuff	Glass, quartz, plagioclase, biotite, calcite, hornblende	Minor to moderate	Probably some lapilli
426	Fine-grained pumiceous tuff	Glass, possible trace quartz	Trace	None
505	Pumiceous tuff	Glass, possible trace quartz	Trace(?)	None
537	Banded°pumiceous tuff, dip 45	Calcite, glass, quartz, traces of plagioclase, montmorillonite	None	None
545	Massive pumiceous sediment	Quartz, cristobalite, calcite, biotite, clinoptilolite, traces plagioclase, hornblende	Minor to moderate	One clast(?)
552	Banded tuffaceous° sediments, dip 45	Quartz, calcite, cristobalite, trace plagioclase, clinoptilolite biotite	Minor	A few clasts
554	Vitric lapilli tuff	Calcite, clinoptilolite	Minor	Unaltered lapilli
563	Faintly banded airfall tuff	Clinoptilolite, glass, traces of quartz	Possible trace	None
584	Tuff, fine-grained	Clinoptilolite, plagioclase, quartz, montmorillonite	None	Some lapilli of K-feldspar
585A	Lapilli tuff	Quartz, clinoptilolite, calcite, cristobalite, montmorillonite, traces of plagioclase, glass	Moderate	None
585B	Soft, massive tuff, waterlaid	Quartz, clinoptilolite, calcite, cristobalite, montmorillonite, traces of plagioclase, glass	No X-ray see 585A	None
598	Laminated ash, alter-nating dark and light layers	Clinoptilolite, quartz	None	Fragments of Carlsbad twins and microcline
602	Vitric lapilli tuff	Clinoptilolite, quartz, glass, calcite	None	None

Table 4. Distribution of potassium feldspar in the LVCH-1 drillhole -- continued

Depth in feet	Liothology	Other minerals (major components underlined)	Amounts of K-feldspar X-ray	thin-section
604	Tuff with irregular banding	Glass, clinoptilolite, quartz	Trace	None
605	Laminated siltstone, buff-colored	Calcite, quartz, cristobalite, clinoptilolite, trace montmorillonite	Moderate	Some clasts
608	Ash, alternate fine and coarse-grained bands	Clinoptilolite, interstitial calcite, trace cristobalite, montmorillonite	Moderate to major	Some lapilli
631	Laminated ash, waterlaid	Clinoptilolite, cristobalite	None	None
635A	Cross-bedded tuff	Clinoptilolite	None	None
635B	Lapilli tuff	Clinoptilolite	None	None
636	Laminated ash	Clinoptilolite, cristobalite	Trace	One fragment(?)
660	Tuff, airfall	Glass, clinoptilolite	Trace	A few lapilli
674	Tuff, with flowage bands	Glass, a few patches of calcite	None	None
739	Hard gray siliceous zone in tuff	Clinoptilolite, quartz, cristobalite	None	None
771	Tuff, airfall	Clinoptilolite, glass, possible trace analcime	None	None
825	Tuff, airfall	Clinoptilolite, glass	None	None
857	Hard gray siliceous zone in tuff	Clinoptilolite, cristobalite	Moderate	Possibly a few crystals in altered glass
862	Vertical band of lapilli tuff	Clinoptilolite	Trace	None
885	Vitric lapilli tuff, airfall	Clinoptilolite, quartz and montmorillonite in lapilli	Minor, in lapilli	Microcline lapilli
889	Lapilli tuff, waterlaid	Clinoptilolite, calcite	Trace	Carlsbad twinned feldspar lapilli

Table 4. Distribution of potassium feldspar in the LVCH-1 drillhole -- continued

Depth in feet	Liothology	Other minerals (major components underlined)	Amounts of K-feldspar X-ray	thin-section
898	Silty clay	Quartz, calcite, plagioclase traces biotite, gypsum	Major	Possible in clasts
911	Tuff and sediments, slump structures	Clinoptilolite, quartz, calcite	Moderate to major	Clasts, microcline
927	Lapilli tuff, tightly compacted	Clinoptilolite	Trace	None
943	Hard gray siliceous zone in tuff	Cristobalite, clinoptilolite, trace calcite	Moderate to major	None
959	Hard gray siliceous zone in tuff	Cristobalite, clinoptilolite	None	None
967	Ash, banded, gently dipping, faulted	Clinoptilolite, trace calcite	Trace to minor	None
971	Siltstone	Quartz, biotite, trace pyrite, montmorillonite	Major	Some small euhedral crystals (<70 μm)
973	Soft white calcareous sediment	Quartz, calcite	Major	None
990	Lapilli tuff with brecciated zone	Clinoptilolite, possible trace analcime	Moderate to major	None
992	Soft buff-colored tuff	Clinoptilolite, trace	Trace	None

Table 5 -- Lithology of the welded Bishop tuff in the Republic drillhole

Depth (feet)	Color	Degree of welding	Comments	Quartz, K-feldspar	Biotite	% phenocrysts
2,750 - 2,780	N8, very light gray, (N6, N7)	Partly	Recrystallized pumice inclusions, silica veinlets, green vugs and veins, green chalcedony fragment	Some chatoyant <1 mm	Small	<5
2,780 - 2,810	N6, medium-light gray (N7, N8)	Partly	Glass shards, obsidian fragments, green crystals in vugs, silica veinlets	Chatoyant <1 mm	Sparse	15-20
2,810 - 2,840	N7, light gray (many N8)	Densely	Shards, pyrite	Chatoyant <0.3 mm	Small minor	10
2,840 - 2,870	N7-N8, light to very light gray	Partly	Glass shards, no pumice inclusions, pyrite	<0.5 mm		<5
2,870 - 2,900	N7 and N8, light and very light gray	Partly	Pumice inclusions, some glass shards, silica seams	Some chatoyant	Some	<10
2,900 - 2,930	N6, medium-light gray (N7, N8)	Densely	Some shards, pumice inclusions	Some chatoyant, most <0.5mm	Some	<5
2,930 - 2,960	N6, medium-light gray and N7, N8, light to very light gray	Densely	Pumice inclusions, silica seams	<1mm	Small minor	<5
2,960 - 2,990	N8, very light gray and N6, medium-light gray		Very large glass shards	Some chatoyant <1-1.5 mm	Much 0.5-1 mm	<5
2,990 - 3,050	N5, medium gray and some N6, medium light gray (some N7 at 2990)	Densely	Elongate shards, silica veinlets, pyrite		<0.3 mm	<10
3,050 - 3,080	N5, medium gray (N4-N7, N8)	Some partly welded	Angular shards, silica veinlets, pyrite	<1 mm	<0.3 mm	<5
3,080 - 3,170	N6, medium-light gray (few N5, N8)	Partly	Obsidian fragments at top. Many blebs, silica stringers 3110-40 ft.	<1.5 mm	top <1 mm <0.5 mm	<5-10
3,170 - 3,200	N6, medium-light gray, some N7, light gray	Partly	Blebs	Some chatoyant <1 mm	<0.5 mm	<10
3,200 - 3,230	N6, medium-light gray (N7-N8)		Rounded chips. No tuff inclusions	<1 mm	Some	<10

Table 5 -- Lithology of the welded Bishop tuff in the Republic drillhole -- continued

Depth (feet)	Color	Degree of welding	Comments	Quartz, K-feldspar	Biotite	% phenocrysts
3,230 - 3,350	N5, medium gray (N4,N6)		Some tuff inclusions (nonwelded)	<1 mm some 2 mm	Sparse <1 mm	5-10
3,350 - 3,380	N5, medium gray and N4, medium dark gray		Some inclusions of pumice with voids	most <1 mm some <2 mm	<0.25 mm	10
3,380 - 3,440	N5, medium gray (N4-N7)			Some chatoyant	<0.25 mm	5-10
3,440 - 3,470	N6, medium light gray (N4, N5, N7)		A few pumice or nonwelded tuff inclusions	<1 mm	<0.25 mm	5
3,470 - 3,530	N5, medium gray (some N6)	Moderate	Many blebs	<1 mm most <0.5 mm	<0.5 mm	5
3,530 - 3,590	N5, medium gray, some N6, N7, N8	Less dense> than underlying 30 feet		<1 mm	Sparse <1 mm	5
3,590 - 3,680	N5, medium gray, >N6 (Some N7, N8)		Parallel structures near top	<0.5 mm	<0.25 mm	5
3,680 - 3,770	N5, medium gray (some N6, N7)	Partly	Obsidian inclusions	Most <0.5 mm	Sparse <0.5 mm	5
3,770 - 3,800	N5, medium gray and N6, medium light gray	Partly		<0.5 mm	Sparse <0.25 mm	<<5
3,800 - 3,860	N6, medium light gray (some N8, N5)	Partly		<0.5 mm	Sparse <0.25 mm	<<5
3,860 - 3,920	N7-N8, light gray to very light gray (some N4, N5, N6)	Partly (vapor phase ?)	Silica veinlets, hornfels inclusions	<0.5 mm	Sparse <0.25 mm)	<<5
3,920 - 3,950	N6, medium light gray (Some N7)	Partly (vapor phase ?)	Possible pyroxene, parallel structure	<1 mm	Sparse <0.25 mm	<<5
3,950 - 3,980	N5, medium gray (minor N6)	Partly (vapor phase ?)	Glass shards, flow structure	<1 mm	<0.5 - 0.75 mm	<5
3,980 - 4,010	N5, medium gray and N6, medium light gray (some N7)	Partly	Hornfels inclusions	<1 mm Chatoyant <2 mm	<0.5 mm	<5

Table 5 -- Lithology of the welded Bishop tuff in the Republic drillhole -- continued

Depth (feet)	Color	Degree of welding	Comments	Quartz, K-feldspar	Biotite	% phenocrysts
4,010 - 4,040	N4, medium dark gray (N6)		A few nonwelded white tuff fragments	<1 mm	<0.5 mm	5-10
4,040 - 4,070	N4, medium dark gray and N5, medium gray	Moderate		<1 mm	<0.5 mm	<5
4,070 - 4,160	N5, medium gray (some N4 base)	Partly		<1 mm	<0.5 mm	<10
4,160 - 4,190	N5, medium gray	Not densely	A few black hornfels grains	<0.5 mm	<0.25-0.5	<5
4,190 - 4,220	N5, medium gray and N6, medium light gray	Moderate to less	Some are recrystalized pumice	<1 mm	<0.25	<5-10
4,220 - 4,250	N5, medium gray	Moderate	Obsidian chips, no pumice	<0.5	0.5-1.0	<10
4,250 - 4,280	N6, medium light gray	Partly	No pumice inclusions. Few aphanitic inclusions. Deepest occurrence of black hornfels inclusions except trace at 4280-4310	<2 mm few chatoyant	Sparse <1 mm	<10
4,280 - 4,370	N5, medium gray (some N6, minor N4)	Partly	Some pumice inclusions. Obsidian blebs and stringers. A few aphanitic inclusions.	<1 mm; Chatoyant <2 mm	Minor <0.5	10
4,370 - 4,400	N4, medium dark gray and N5, medium gray	Partly	Many rounded pumice inclusions, light gray aphanitic inclusions, obsidian streaks	1 mm	Minor <0.25 mm	20
4,400 - 4,430	N4 and N5	More than above	Many pumice inclusions, aphanitic inclusions, obsidian stringers	1 mm	<0.25-0.5 mm	20
4,430 - 4,460	N5, medium gray (some N4)		Many dense vitreous blue-gray inclusions, some pumice inclusions	<1 mm some chatoyant	<0.5 mm euhedral	15-25
4,460 - 4,490	N4, medium dark gray (some N5)		Fewer vitreous inclusions, pumice inclusions	<1 mm some chatoyant	<0.5 mm euhedral	15-25
4,490 - 4,520	N5, medium gray (some N6)		Some pumice (collapsed) some grains of nonwelded white tuff.	<1 mm	Sparse <0.5	<15

Table 5 -- Lithology of the welded Bishop tuff in the Republic drillhole -- continued

Depth (feet)	Color	Degree of welding	Comments	Quartz, K-feldspar	Biotite	% phenocrysts
5,150 - 5,180	N5, medium gray		Some pumice fragments and inclusions	0.5-0.1 mm	Coarse <0.5	25-30
5,180 - 5,210	N5 to N6, medium to medium-light gray		Pumice fragments, a few inclusions	0.5-1.0 mm		10-20
5,210 - 5,240	N5, medium gray, some N4 medium dark gray	Varies	Some white nonwelded pumiceous tuff grains	Some chatoyant 0.5-1 mm	Small	<10
5,240 - 5,270	N5, medium gray (some N4)	Densely	No pumice	Some chatoyant <0.5-1 mm	Some	10-15
5,270 - 5,300	N6, medium light gray and N5 medium gray		Few non-welded grains. Recrystallized pumice(?) Vapor phase recrystallization(?)	<0.5-1 mm Chatoyant up to 2 mm		15
5,300 - 5,330	N5, medium gray (N6, N8)		Some myrmekite(?) No pumice	Chatoyant 0.5-1.5 mm	Some	15
5,330 - 5,390	N6, medium light gray (few N4, N3)			Some chatoyant <0.5-1.5		15
5,390 - 5,450	N5, medium gray and N6, medium light gray		Some shards, or stretched pumice (parallel structure)	Some chatoyant		10 av. 0-15
5,450 - 5,480	N5, medium gray (N6, N7)			<0.5 mm	<0.25 mm	10-15
5,480 - 5,570	N5, medium gray (Some N4 at base)			Some chatoyant <0.5 mm	0.25- -0.5 mm	10
5,570 - 5,600	N5, medium gray			Most <0.5 mm	Small	<10

Table 5 -- Lithology of the welded Bishop tuff in the Republic drillhole -- continued

Depth (feet)	Color	Degree of welding	Comments	Quartz, K-feldspar	Biotite	% phenocrysts
4,520 - 4,550	N5, medium gray and N4, medium dark gray		Some collapsed pumice inclusions	<1 mm	Minor	<15
4,550 - 4,640	N5, medium gray (N6, N4)		Pumice inclusions with frayed ends, fragments of obsidian (?)	Some chatoyant up to 1.5	Some coarse-grained	<20
4,640 - 4,670	N4, medium dark gray and N5, medium gray, some N3 dark gray		Pumice inclusions, myrmekitic? Some light gray vitreous inclusions	Some chatoyant <1-2 mm	<0.5 <0.5	<20 <20
4,670 - 4,700	N5, medium gray		Collapsed pumice inclusions, many light gray vitreous inclusions	 Chatoyant <1 mm	<0.5 <1 mm	<20 25-30
4,700 - 4,760	N4, medium dark gray and N5, some N6		At 4730 hornfels. Some collapsed pumice with frayed ends, many inclusions of dull white rock	Chatoyant	Minor <1 mm	20-30
4,760 - 4,790	N5, medium gray, some N4 medium dark gray		Inclusions of collapsed pumice	Some up to 2 mm	<1 mm	<25-30
4,790 - 4,850	N4, medium dark gray, some N5 and N6		Few black hornfels, pumiceous(?) inclusions, light gray aphanitic inclusions	<1 mm		20-30
4,850 - 4,970	N4, medium dark gray (N5)	Densely	Many pumice chips, some with biotite to 1 mm. Cavities in pumice at 4850.	Chatoyant 0.5-1 mm	Minor	25-40
4,970 - 5,000	N4, medium dark gray, N5, medium gray		20% pumice inclusions, some with black obsidian layers	<0.5-1.0 Chatoyant	Few	30
5,000 - 5,030	N5, medium gray, N4, medium dark gray		Few pumice fragments	Chatoyant <1-2 mm	Minor	20-30
5,030 - 5,060	N4, medium dark gray (N6, no N5)		Fragments light gray pumice, black hornfels (?)	Chatoyant		20-30
5,060 - 5,090	N4, medium dark gray	Densely	Collapsed pumice, partly flattened	Many chatoyant 1.5 mm	up to 0.3 mm	35-50
5,090 - 5,150	N4, medium dark gray, many N5		High porosity, 38%. Pumice inclusions and fragments	Some chatoyant <0.5-2 mm	Coarse <0.5 mm	10-20

Table 6. -- Semiquantitative spectrographic analysis for lithium and boron in LVCH-1 core

Depth (feet)	Rock type	Minerals present ( ) indicate trace amounts	Li (ppm)	B (ppm)
613 (labeled 617)	Buff-colored, laminated sediments	Calcite, montmorillonite, (plagioclase, quartz)	660	15
638	Light gray, finegrained airfall tuff	Clinoptilolite	48	13
663	White, massive, unaltered airfall tuff	Glass (with trace of clinoptilolite)	72	24
907	Gray lapilli tuff (waterlaid)	Matrix: quartz, calcite, and K-feldspar. Clinoptilolite in lapilli	49	11
928	Dense, well compacted white and buff air-fall tuff (sample from below compacted zone)	Clinoptilolite	37	10
971	Gray siltstones	K-feldspar, quartz, biotite (traces of pyrite, plagioclase, and montmorillonite)	250	22

Analyses by Janet D. Fletcher, 1976, for Spectrographic Services and Research, Reston, Virginia.

Table 7.-- Isotopic data and inferences made from estimated lake water salinities and temperatures

Sample No. Depth (ft.)	Lithology and Mineralogy	$\delta^{18}O$ (SMOW)	$\delta^{13}C$ (PDB)	Inferred conditions of lake water $\delta^{18}O$	Temp. (°C)	Salinity	Criteria for salinity
LVCH1-342	Colloform white white sedim., overlying richly fossil. diatomites	+16.00	+3.54	-17 to -14.5	10 - 25	Slightly more saline than #970	Oxygen isotopes Carbon isotopes Diatoms
LVCH-1-358	Gypsum in seam with matching walls	-3.40	-	-40 to -21.5	25 -100	-	-
LVCH-1-554	Altered vitric lapilli tuff, prob. waterlaid calcite-rich clinoptilolite	+ 3.96	-3.17	-	65 - 85	Less saline than any sed. interstrat w/tuff, mod. to high salin. (20 ppt)	Oxygen isotopes Carbon isotopes Fossil ostracodes
LVCH1-585B	Altered tuff-aceous sedim. Calcite, qtz, K-feld, trace cpt, biot. cristobalite	+20.0	+1.19	- 8.4	25	Moderate to very saline 3-35 ppt. Most saline in LVCH-1	Ostracodes
LVCH-1-612	Calcite vein in montmorill. rich sedims.	+10.08	-0.57	-8 to -10 mixed w/hot spr. wtr. -14 to -17	50	Slightly saline	Oxygen isotopes
LVCH-1-970	Gray parting calcite, qtz, minor pyrite	+14.83	+2.15	-17 to -13	10 or 25	Slightly saline	3 spec. ostracodes Oxygen isotopes
LVCH-1-970'	X-bedded white calc. sedim.	-	-	-	-	Less saline than #970	3 spec. ostracodes
LVCH-1-971	Siltstone, v. rich in K-feldspar	-	-	-	-	Less saline than #970	No ostracodes
Republic 1310-1340	White tuff Analcime, qtz, plagioclase	+8.03	-3.33	-21 or -12	25 or 75	-	-
Republic 2390-2420	White tuff qtz, K-feldspar	-2.51	-5.54	-30.5 or -22.5	25 or 75	-	-

Table 8. -- Distribution of diatoms and ostracodes in the LVCH-1 drill core

Sample No. (depth-ft)	Thin section	Disaggregated samples	Paleontological analysis	Lake chemistry and depth	Lithology	Mineralogy (underlined abundant)
251	-	no diat. or ostr.	-	-	-	-
265-268	-	"	-	-	-	-
274(+)	-	"	-	-	-	-
282.5	-	"	-	-	-	-
306	-	-	Rare fragments of 2 spp diatoms	Cool, silica-rich, fresh, moderately deep	Silt and sand, gray, calcareous	-
328	-	no diatoms	-	-	-	-
334	Diatoms and a few ostracodes	-	3 spp diatoms (rare), 6 spp ostracodes	Silica-rich, fresh to slightly saline-alkaline, open water (>50 feet)	Ashy, diatomaceous silt, gray	Calcite and aragonite
342	-	3 types diatoms	-	-	-	-
343	-	-	Diatoms: same as #334 in silts, plus 12 spp in ashy diatomites. Ostracodes: 6 spp, same as #334	Fresh water (>50 feet). Moderate salinity, local hot springs(?)	Steeply dipping bands of light and dark gray	Calcite, gypsum, tr. pyrite
357-358	-	-	No ostracodes	Possibly more saline and alkaline than above and below	Soft, massive, light gray sediments	Calcite, gypsum, pyrite
379.5	-	Diatoms (1-2 types)	-	Relatively fresh water, 2-5 ppt	Soft, massive light gray sediments	Quartz, plag., tr. calcite
387	Diatoms	-	-	Relatively fresh water, 2-5 ppt	Tuffs interbedded with fine-grained sedim.	Quartz, plag., K-feldspar, calcite, glass
398	-	Diatoms (4-5 types)	-	Relatively fresh water, 2-5 ppt	Soft, massive, light gray sediments	Quartz, plag., calcite

Table 8. -- Distribution of diatoms and ostracodes in the LVCH-1 drill core -- continued

Sample No. (depth-ft)	Thin section	Disaggregated samples	Paleontological analysis	Lake chemistry and depth	Lithology	Mineralogy (underlined abundant)
400	-	-	No ostracodes	More saline and alkaline than above	Soft, massive, light gray sediments	Quartz, plag., K-feldspar, calcite
410	-	-	Diatoms (2 spp) Not examined for ostracodes	Open water, 50 - 100 feet deep, fresh water, moderate alkalinity	Diatomite, ashy, overlies tuff	Glass, quartz, tr. gypsum
426	No diatoms	A few diatoms (1-2 types)	-	-	Pumiceous tuff, fine-grained, gray	Glass, trace of pyrite, calcite
490	-	Diatoms (3 types)	Diatoms (4 spp)	Probably dimictic (>30 feet)	Thinly banded, waterlaid, white diatomite	Quartz, cristobalite plag.
540	-	None	-	-	Tuffaceous sed.	Glass
545	Ostracodes	-	-	<15 feet deep	Tuffaceous sed.	Quartz, cristobalite K-feldspar calcite, tr. cpt.
546-548	-	None	-	-	Massive tuff. sediment	Quartz, cristobalite K-feldspar calcite, tr. cpt.
552	Ostracodes (a few)	-	No ostracodes	Very saline and alkaline (>10ppt) pH 9-10, 10-15 feet deep	Banded tuff. sediment dips 45°	Quartz, calcite, K-feldspar plag. cristobalite tr. cpt.
554	Ostracodes (a few)	-	-	-	Tuff. sediment and vitric lapilli tuff	Quartz, cristobalite, calcite in sediment Calcite and cpt. in tuff

Table 8. -- Distribution of diatoms and ostracodes in the LVCH-1 drill core -- continued

Sample No. (depth-ft)	Thin section	Disaggregated samples	Paleontological analysis	Lake chemistry and depth	Lithology	Mineralogy (underlined abundant)
555	-	None	-	-	Tuff or tuff-sediments, poorly defined bands, dip 45°	Glass, quartz, feldspar, no calcite
563	None	-	-	-	Massive pumic. tuff, bands reflect amount of pumice	Cpt.
576	None	-	-	-	Sandstone, calcite cemented	Cristobalite quartz, calcite, K-feldspar
584	None	-	Osrtacodes 2 spp (in sediments)	Moderately saline 10 feet deep	Tuff zone above massive tuff-sediments	In tuff: cpt. quartz, mont. In sediment: calcite, cristobalite
598	Ostracodes (a few)	-	-	-	Laminated ash	Cpt., quartz
605	Ostracodes (large)	-	-	-	Thin laminae of siltstone, buff-colored	Calcite, quartz, cpt. K-feldspar, cristobalite
608	None	-	-	-	Ash, altern. coarse and fine-grained, waterlaid	K-feldspar, cpt., calcite
610	-	-	Ostracodes 2 spp (one rare)	Moderately saline (3-10 ppt), 5-10 feet deep	Thin laminae (varves) of buff sediment	Calcite, mont. (high lithium content)
628	-	-	Ostracodes 2 spp	Moderately saline (3-10 ppt)	Tuff- sediment steeply dip-ping banding, lapilli tuff	Cristobalite, cpt.; calcite in lapilli tuff

Table 8. -- Distribution of diatoms and ostracodes in the LVCH-1 drill core -- continued

Sample No. (depth-ft)	Thin section	Disaggregated samples	Paleontological analysis	Lake chemistry and depth	Lithology	Mineralogy (underlined abundant)
635	None	-	-	-	Waterlaid ash interbedded w/lapilli tuff, slump structures	Cpt., cristobalite
674	None	No diatoms	-	-	Banded tuff airfall(?)	Glass only, patches of calcite
739	None	-	-	-	Hard gray zone in tuff	Cpt., cristobalite
857	Ostracodes (a few)	-	-	-	Hard gray zone in tuff	Cpt., K-feldspar, cristobalite (calcite in tuff)
885	None	-	-	-	Vitric lapilli tuff	Cpt. in matrix. Lapilli: Mont., quartz K-feldspar
886	-	-	Ostracodes 3 spp	Slightly saline (1-3 ppt), pH 9-10	Massive siltstone	Cristobalite, Mont., K-feldspar, calcite
889	Ostracodes (large, 0.5mm)	-	-	-	Lapilli tuff, interbedded mud	Cpt., calcite, K-feld. in mud; cristobalite
898	Ostracodes 0.5 mm, many infilled with calcite	None	Ostracodes 3 spp	Slightly saline (1-3 ppt), pH 9-10	Banded silty clay	Quartz, calcite, K-feldspar, tr. cpt.
911	Ostracodes up to 1 mm	-	Ostracodes 1 sp (at 912 ft.)	Very saline (>10 ppt)	Tuffs and sediments, mixed, slump structures	Cpt., quartz K-feldspar, calcite, (tr. analcime ?)

Table 8. -- Distribution of diatoms and ostracodes in the LVCH-1 drill core -- continued

Sample No. (depth-ft)	Thin section	Disaggregated samples	Paleontological analysis	Lake chemistry and depth	Lithology	Mineralogy (underlined abundant)
943	Ostracodes (in gray zone)	-	-	-	Hard gray zone in buff-colored tuff	Cristobalite, K-feldspar, Cpt. in gray zone
950	-	-	Ostracodes 3 spp	Slightly saline (1-3 ppt), pH 9-10	Mud, overlying tuff	Mont., cristobalite K-feldspar
971a	-	-	Ostracodes 3 spp	Slightly saline (1-3 ppt), pH 9-10	Cross-bedded white sediment	Calcite K-feldspar, tr. gypsum
971b	None	-	-	>20 ppt saline (low end of very saline)	Siltstone	K-feldspar, biotite, (moderately high lithium)
973	Ostracodes, many infilled w/coarsely crystal. calcite	-	-	Very saline (>10 ppt)	Soft, white layered calc. sediments, w/ calcite nodules	Quartz, calcite, K-feldspar,
975	-	-	No ostracodes	High salinity, even briny (>35 ppt)	Soft white massive calcareous sediment	Calcite, K-feldspar
990	None	-	-	High salinity, even briny	Lapilli tuff, slump struct. and breccia	Cpt., K-feldspar, calcite, tr. analcime(?)
992(A)	Ostracodes, in sediment, some infilled	-	No ostracodes	Very saline or briny (>35 ppt)	Soft, buff tuff, underlain by hard gray laminated sediments, reverse fault on small scale?	Cpt. in tuff Cristobalite, calcite, cpt., tr. K-spar in sedim.

PLATE 1 - LITHOLOGY AND MINERAOLOGY OF THE LVCH-1 CORE.

The left-hand column portrays the lithologic units.

"Airfall" tuff; i.e., massive tuff, lacking calcite, fossils, and any structures indicative of water-working. Note, however (see text) that some of these tuffs may have been deposited in a deep, fresh-water lake, below the level of wave action.

Lapilli tuff (either with or without calcite). Where a dashed line separates orange from yellow or green, the lapilli tuff grades to more even-grained tuff.

K-feldspar-rich sedimentary layer.

"Waterlaid" tuffs, those containing calcite and/or fossils, and/or recognizable sedimentary structures.

Sediments, including stream gravels.

Sediments, nearly 100 percent calcite; possibly tufa.

Hard dark gray siliceous zones, found only below 500 feet.

Zones from which no core was retrieved.

Bars in the column at the extreme right indicate the locations of samples which were studied by X-ray and/or optical methods.

The widths of the remaining thirteen columns indicate estimates of the abundance of the mineral at that depth, based on microscopic observation and x-ray diffraction analysis.

Bars with full width - major constituent;
Bars with 3/5 width - moderate amount;
Bars with 1/5 width - minor amount;
Line segment - trace amount.

Vertical continuity of the presence of the mineral is assumed except where the abundance of the mineral becomes zero, in which case the zero point is arbitrarily placed one foot from the last occurrence of the mineral.

PLATE 2 - MINERALOGY OF CUTTINGS FROM REPUBLIC WELL 66-29.

Mineralogy is plotted for each of three principal lithologic types: sediments (chiefly sandstones), white tuffs, and yellowish tuff. Because cuttings were sampled at 30-foot intervals, each box is 30 feet from top to bottom.

The width of the box indicates an estimate of relative abundance of the mineral in that depth interval, based chiefly on x-ray diffraction analyses:

Bars with full width - major constituent;
Bars with 3/5 width - moderate amount;
Bars with 1/5 width - minor amount;
Line segment - trace amount.

Solid boxes indicate that this rock type constituted an important fraction (greater than 30 percent) of the cuttings, as estimated from visual examination of cuttings with a 30X microscope.

Open boxes indicate that this rock type was present in minor amounts at that depth interval.

Dashed lines indicate a very small trace of the mineral, presence questionable.

Isolated boxes with dashed outlines indicate that the amount of that rock type was very small (even a few grains).

Dashed boxes connected on both sides to open or solid boxes indicate that amounts of minerals are extrapolated.

A box divided diagonally into solid and open segments indicates that two different types of sediment were present in this depth interval; one contained major amounts of analcime, the other none.