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Microthermometry of Fluid Inclusions from
the VC-1 Core Hole in Valles Caldera, New Mexico.

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Abstract

Fluid inclusions in vein quartz and calcite from core samples of the VC-1 hole were studied with microscope heating/freezing and crushing stages. All samples orignate from hydrothermally altered Pl~~a~~eozoic rocks pre-dating formation of the Jemez Mountains volcanic field and Valles caldera. Most homogenization temperatures (Th) of the liquid-rich inclusions are above the present well temperature, but some Th of primary inclusions from 515 m and those of secondary inclusions from 723 m fit the present well temperature curve measured 10 months after completion of the well. The maximum temperature recorded by the primary inclusions is 275°C from hydrothermal quartz in the Sandia Formation at 811 m depth. The total range of Th for samples from several depths (90°C) indicates cooling from the maximum temperature. The salinity of fluid inclusions in hydrothermal quartz and calcite is generally low, < 1 wt % NaCl equiv. High salinity fluid, up to 5 wt % NaCl equiv., has been found in several calcite veins from the lower part of the Madera Limestone. The salinity decreases with decrease of Th of the secondary inclusions, and that with the lowest Th at the lower part of the Madera Limestone is similar to those from the other depths. These data show that the early hot water circulation system involved several types of fluid, whereas the later one was a homogeneous fluid. The salinity of fluid inclusions in detrital quartz (presumably inherited inclusions) is higher than that in hydrothermal minerals. Some of these inclusions show extraordinary low temperature of final melting point of ice, ∿-40°C,

suggesting that a $CaCl_2$ component is present. CO_2 contents in fluid inclusions were estimated by the bubble behavior on crushing. Crushing results indicate that the CO_2 content of the early fluid is $\geqq$ 0.35 wt %, and that of the later fluid is $\sim$ 0.2-0.3 wt %. The Th of primary inclusions at 511 m and those of the secondary inclusions at 723 m fit the present core hole temperature curve. The geothermal fluid trapped in the fluid inclusions representing the present temperature regime are comparable in composition to those from the Baca geotermal field inside the caldera and to those from hot springs in San Diego Canyon.

Introduction

Fluid inclusions are very useful in studies of hydrothermal processes in geothermal areas, because they record various stages of the thermal and compositional evolution of hydrothermal fluids (e.g. Roedder, 1984). Fluid inclusions from the VC-1 core hole in Valles Caldera (1.1 Ma) (Fig.1) have been studied to elucidate hydrothermal evolutionary processes in a postulated lateral flow system outside the ring-fracture zone of the caldera (Goff et al., 1986). Seven vein samples were collected from the Paleozoic sedimentary rocks underlying post-caldera volcanics of the southwest moat: they are calcite veins in the Abo Formation and the Madera Limestone, and quartz veins in the Sandia Formation.

All fluid inclusions observed in the veins are liquid-rich which indicates that the entrapped fluids have not boiled. These liquid-rich inclusions are classified into three types: primary and secondary inclusions in hydrothermal minerals and inherited inclusions in the detrital quartz.

Homogenization temperatures (Th) and final melting point temperatures of ice (Tm) were determined using a USGS-type heating/freezing stage (Woods et al., 1981). The calibration method follows Sasada et al. (1986). Bubble behavior on crushing was observed under the microscope crushing stage (Roedder, 1970) to estimate the CO_2 content semiquantitatively (Sasada, 1985; Sasada et al., 1986).

Description of Veins

Paleozoic rocks in VC-1 show increasing hydrothermal alteration with depth with high-angle fractures and mineralized breccia zones. The vein from the Abo Formation consists of two linings of calcite. Isolated primary inclusions are present in both linings. Secondary inclusions occur on a healed fracture plane. Many secondary inclusions also occur in detrital quartz of the host sandstone. Most of them are presumably inherited inclusions.

Many calcite veins of varying size and orientation are present in the Madera Limestone and four of these veins were studied. Two veins sampled from the upper part of the unit consist of transparent calcite crystals several milimeters to centimeters wide, and two from the lower part consist of aggregations of small crystals. Primary inclusions exist on the growth zone of the large calcite crystals from 515 m (Fig. 2-1). Isolated primary inclusions are also present in all veins (Fig. 2-2). Secondary inclusions are aligned on the healed fracture planes in all the veins except that at 515 m.

In the Sandia Formation and the breccia zone of Sandia and Precambrian rocks most hydrothermal quartz is overgrown on detrital quartz. Some primary inclusions start at the boundary between the hydrothermal and detrital quartz (Fig. 2-3). Three phase inclusions are occasionally found in the detrital quartz grains. One is an inherited inclusion with a halite crystal (Fig. 2-4), and another contains liquid CO_2. They reflect the provenance of the original quartz which is Precambrian igneous and metamorphic rocks.

Th and Tm

Th and Tm of 167 inclusions have been measured using the USGS type stage. The results of these measurements are shown on Fig. 3 and described by geologic formation below.

Abo Formation (361 m): Th of the primary inclusions in the outer linings of the calcite vein (200°C) is 30°C higher than that in the inner calcite. These Th correspond to two episodes of calcite precipitation. Tm of both primary and secondary inclusions in hydrothermal calcite are close to 0°C, indicating very low salinity. On the other hand, the fluid inclusions in the detrital quartz show a wide range of Th and Tm. Detrital quartz and microcline in the Abo Formation are primarily devised from Precambrian basement rocks of the region. Most of these inclusions are presumably inherited inclusions that formed before deposition of the quartz grains but the low-salinity secondary inclusions in quartz might have formed during later hydrothermal events associated with the Jemez volcanic field.

Madera Limstone (450, 515, 727, 745 m): Th of the primary inclusions in the calcite vein at 450 m are about 210°C, and those of the secondary ones are 5-25°C lower than those of the primary ones. Tm of several inclusions are close to 0°C and those of some secondary ones are a little lower. The calcite vein at 515 m is made up of coarse transparent crystals. Th ranges from 105 to 115°C; this is the lowest Th found from the core hole. No secondary inclusions were observed. Tm is also the closest to 0°C. In the lower part of the Madera Limestone (727 and 745 m), Th of the primary inclusions are a little higher than those from 450 m. Tm of the primary inclusions are lower, that is, the salinity is higher, than any other inclusions from the hole. Tm of the secondary inclusions approach 0°C as the Th decreases. This means that the salinity of the hydrothermal fluid decreased as geothermal activity proceeded.

Sandia Formation and Sandia-Precambrian Breccia Zone (811, 839 m): There are two populations of Th-Tm data of the fluid inclusions. One population is in fluid inclusions in hydrothermal quartz and the other is in detrital quartz. Th of the primary inclusions in prismatic hydrothermal quartz at 811 m is about 270°C, the highest Th found in the hole. Th of the secondary inclusions in the hydrothermal quartz ranges from 185 to 250°C. Th of the fluid inclusions in the hydrothermal quartz at 839 m (about 205°C) are lower than those at 811 m. The Tm of the fluid inclusions in hydrothermal quartz from both depths are close to 0°C, and the resulting salinity is as low as that in the hydrothermal minerals from the Abo Formation and the upper part of the Madera Limestone.

Th and Tm of the fluid inclusions in the detrital quartz range widely. Some of the inclusions show an extraordinary low temperature of final melting point of ice, Tm, down to -40°C. This suggests that a $CaCl_2$ component is present. Most inclusions of this type are presumably inherited ones from the original Precambrian source rocks. However, some inclusions have Th and Tm similar to the primary and secondary inclusions in hydrothermal quartz, suggesting they might stem from Tertiary to Quaternary geothermal fluids.

CO_2 Content Estimated from Crushing

Bubble behavior on crushing depends on the internal pressure of the non-condensable gas (Roedder, 1970). When the internal pressure is higher than 1 atm, the bubble expands. By contrast, if the pressure is lower than 1 atm, it shrinks on crushing. Because CO_2 is the major non-condensable gas in most geothermal fields (Henley et al., 1984), the CO_2 content can be determined semiquantitatively, based on a simplified model in which all the non-condensable gas is assumed to be CO_2 (Sasada et al., 1986).

The CO_2 contents in some primary and secondary inclusions are estimated to be 0.35 wt % or more, and those in some other inclusions whose Th is lower than 170°C range from 0.2 to 0.3 wt % (Table 1). Furthermore there is no evidence of clathrate and liquid CO_2 on freezing. This also indicates that the CO_2 content in the fluid inclusions is lower than 4 wt % (Sasada, 1985).

Salinity of the Hydrothermal Fluid

The NaCl equivalent solid solute salinity is determined from the Tm data after correction for CO_2 contents, because the CO_2 effects the freezing point depression (Larsen, 1955; Hedenquist and Henley, 1985). According to the method of Sasada et al. (1986), the CO_2 correction for most fluid inclusions measured is a minimum of 0.1°C. The resulting NaCl equivalent solid solute salinity is shown on Fig. 4.

The salinity of most fluid inclusions in hydrothermal minerals other than in the lower part of Madera Limestone is less than 1 wt %. On the other hand the primary inclusions from the lower part of the Madera Limestone show high salinity, more than 3 wt % NaCl equivalent solid solute. The salinity of the secondary inclusions from this part is also higher than those from any other depths. These saline fluids many have originated from high-temperature connate water in the limestone or from saline, high-temperature fluids representing a seperate but early hydrothermal event during Jemez Mountains volcanism.

The salinity decreased as the geothermal activity proceeded in the lower part of the Madera Limestone. The salinity of the secondary inclusions with the lowest Th at 723 m is as low as any inclusions from the other formations. This means that during later stages of geothermal activity the salinity of the hydrothermal fluids in the Madera Limestone was like that of the fluids in the other formations.

Discussion

The fluid inclusions have recorded the hydrothermal history of geothermal fluids over 90°C in the VC-1 hole (Fig. 5). The maximum paleo-temperature is estimated to be 275°C at 811 m after the pressure correction of the Th. This temperature is also 50°C higher than the highest paleo-temperature above and below this depth. This may suggest that the fractured sandstone at 811 m was a permeable flow channel for low-salinity hydrothermal fluid. Molybdenum mineralization is associated with quartz-sericite-phengite alteration in brecciated Precambrian gneiss near the bottom of VC-1 (Hulen and Nielson, 1986). It appears to be correlative to the high temperature hydrothermal activity recorded in the fluid inclusions from this part of the hole.

The Th of the primary inclusions at 511 m and secondary inclusions at 723 m fit the present core hole temperature curve (Fig. 5). This indicates that they may represent fluids of the present geothermal system. The salinity and CO_2 content estimated above are 0.1-0.7 wt % NaCl equivalent solid solute and 0.2-0.3 wt % respectively. The lateral flow of the hot water from Valles Caldera down the Jemez fault zone to San Diego Canyon has been postulated from geologic and geochemical arguments (Trainer, 1974; Goff et al., 1981; Goff et al., this volume). The salinity of the present geothermal fluid at Baca is less than 0.9 wt % (Goldstein et al., 1982), and that from the hot springs in San Diego Canyon is less than 0.3 wt % (Goff et al., 1981). The content of the non-condensable gas, principally CO_2, is 0.4-0.5 wt % at Baca (Goldstein et al., 1982). The salinity and CO_2 content of the fluid inclusions representing the present geothermal fluid are consistent with the fluid chemistry of Baca and the hot springs in San Diego Canyon. This investigation supports the concept of present lateral flow along the Jemez fault zone although it is clear that multiple hydrothermal events may have occured during the history of the Jemez volcanic field (≤ 13 Ma). Some of these events may pre-date formation of Valles Caldera and the present hydrothermal system (< 1.1 Ma).

Conclusions

Study of the fluid inclusions has recorded the cooling history of the VC-1 hole above temperatures of 90°C. The maximum paleo-temperature was about 275°C, or 115°C higher than the present temperature. In the early stage of geothermal activity, the fluids were chemically heterogeneous and saline fluid was present in the Madera Limestone. As geothermal activity proceeded, the fluid system became more homogeneous and less saline. This model is summarized on Fig. 6. The geothermal fluid trapped in fluid inclusions representing the present temperature regine is comparable to present thermal water from the Baca geothermal field inside Valles caldera and in hot springs discharging in San Diego Canyon.

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Captions

Fig. 1. Sketch map of Valles caldera showing the location of VC-1 (Goff et al., 1986). Stars denote locations of post-caldera rhyolite vents. Heavy dashed line shows the position of the ring-fracture zone. Stipple pattern shows area of intense intracaldera alteration.

Fig. 2.
1. Primary inclusion on the growth zone in calcite from 515 m.
2. Primary inclusion in calcite from 515 m.
3. Primary inclusion on the hydrothermal quartz side in the sandstone from 839 m. It starts at the boundary between the hydrothermal (H) and detrital (D) quartz.
4. Inherited inclusions with daughter crystal of halite (X) in detrital quartz at 839 m.

Fig. 3. Th-Tm diagram for fluid inclusions.
Th: Homogenization temperature, Tm: Final melting point of ice.
Open circles: primary inclusion in hydrothermal minerals; solid circle: secondary inclusion in hydrothermal minerals; solid triangle: inherited inclusion in detrital minerals.

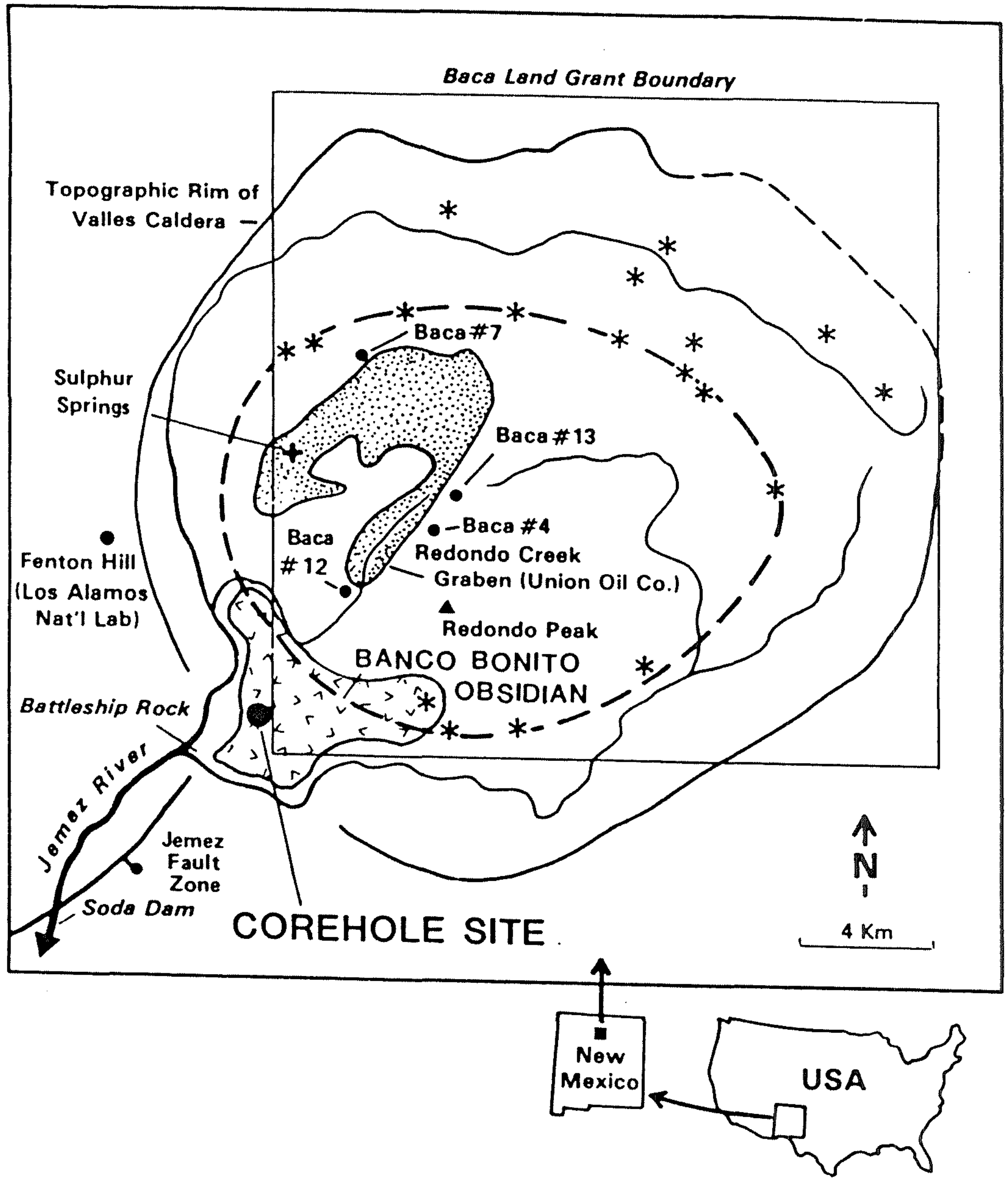
Fig. 4. NaCl equivalent solid solute salinity of fluid inclusions in hydrothermal minerals.
Open squares: primary inclusion; solid squares: secondary inclusion.

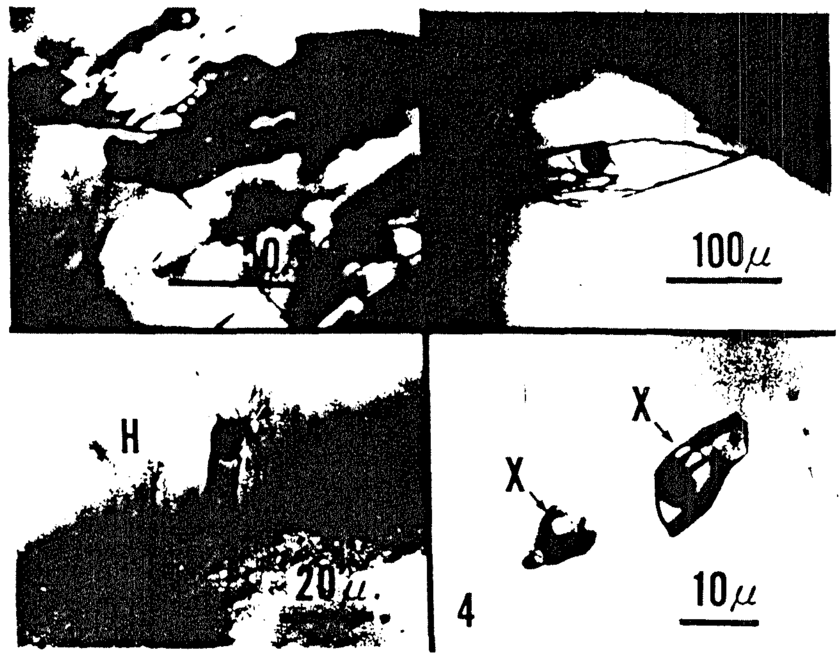
Fig. 5. Th-depth diagram with temperature profiles and geologic column. The temperature profiles and geologic column are based on Goff et al. (1986). W.T. means water table at the time the thermal gradient was measured.

Fig. 6. A possible hydrothermal evolutionary model for rocks in the VC-1 core hole.

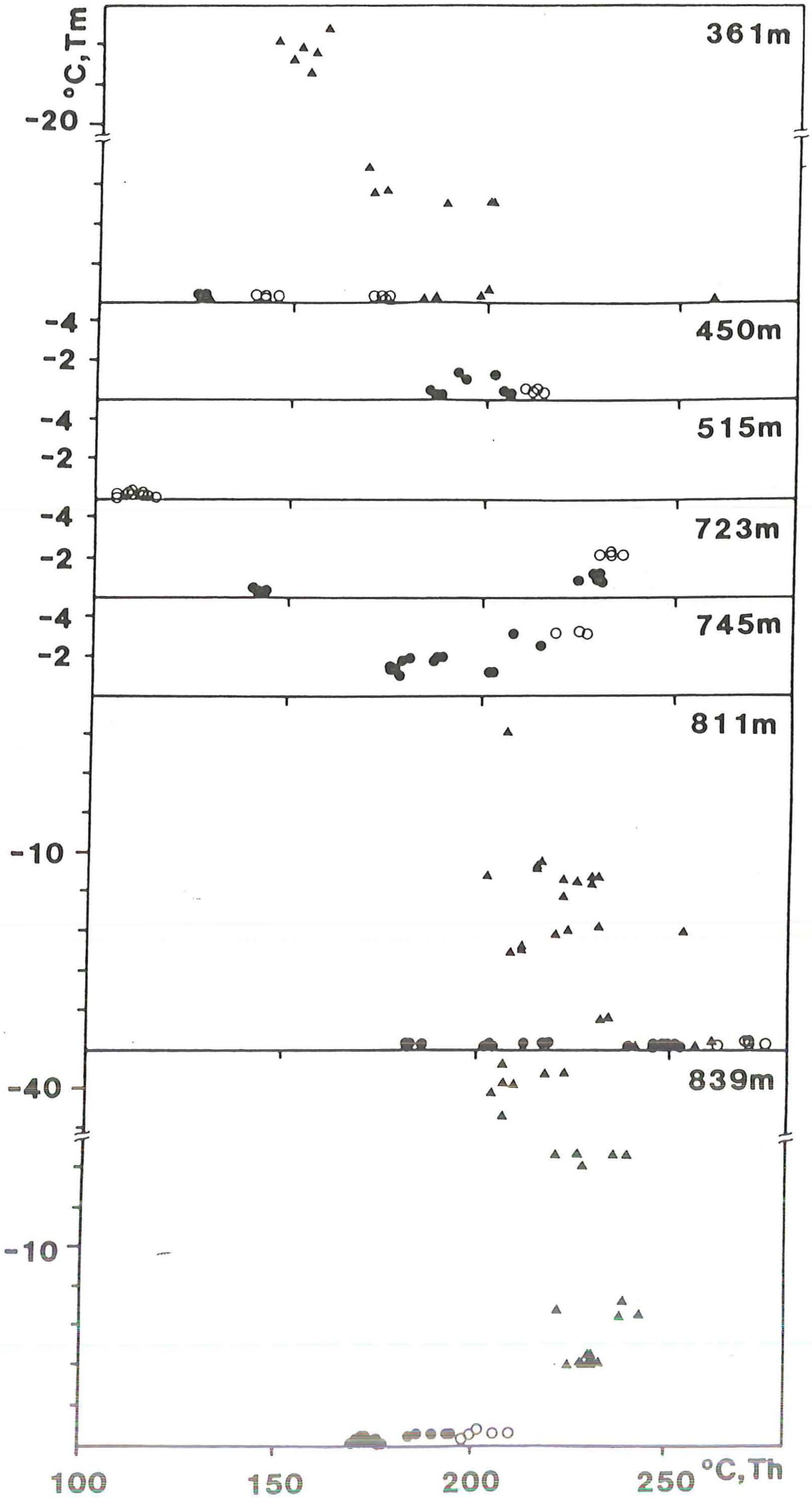
Table 1 Bubble behavior on crushing and estimated CO_2 contents of selected fluid inclusions, VC-1 core hole.

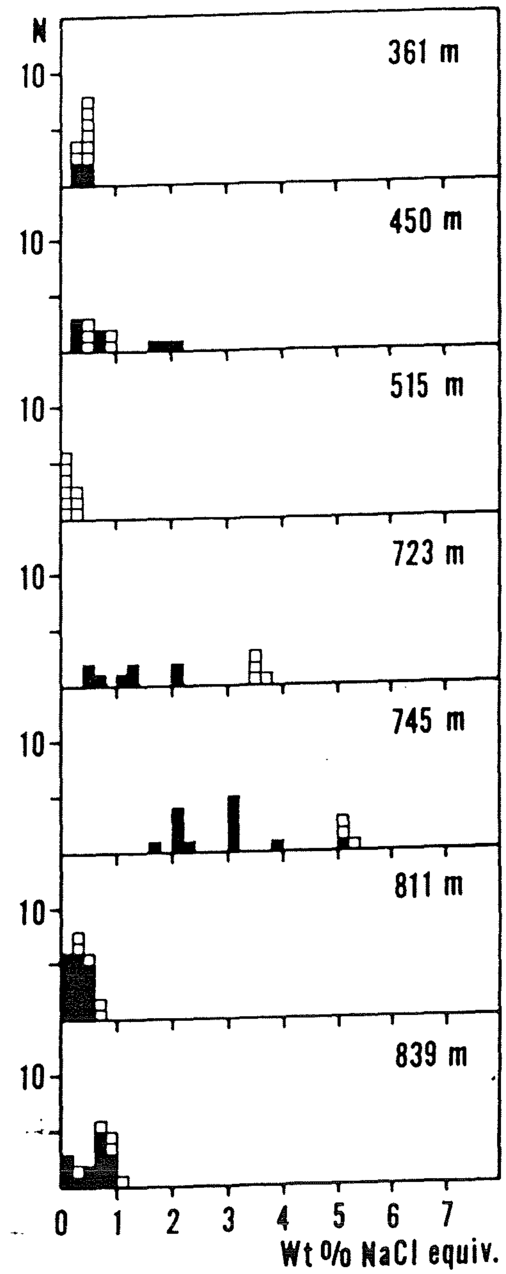
Depth(m)	Type	Bubble behavior	CO_2 content (wt%)
361	Primary	becomes merely large	0.2-0.3
	Secondary	ditto	0.2-0.3
450	Primary	fills the inclusion	≥0.35
515	Primary	becomes merely large	0.2-0.3
723	Primary	fills the inclusion	≥0.37
745	Primary	ditto	≥0.37
	Secondary	ditto	≥0.35
811	Primary	ditto	≥0.39


Baca Land Grant Boundary
Topographic Rim of Valles Caldera
Baca #7
Sulphur Springs
Baca #13
Baca #4
Baca #12
Redondo Creek Graben (Union Oil Co.)
Fenton Hill (Los Alamos Nat'l Lab)
Redondo Peak
BANCO BONITO OBSIDIAN
Battleship Rock
Jemez River
Jemez Fault Zone
Soda Dam
COREHOLE SITE
N
4 Km
New Mexico
USA

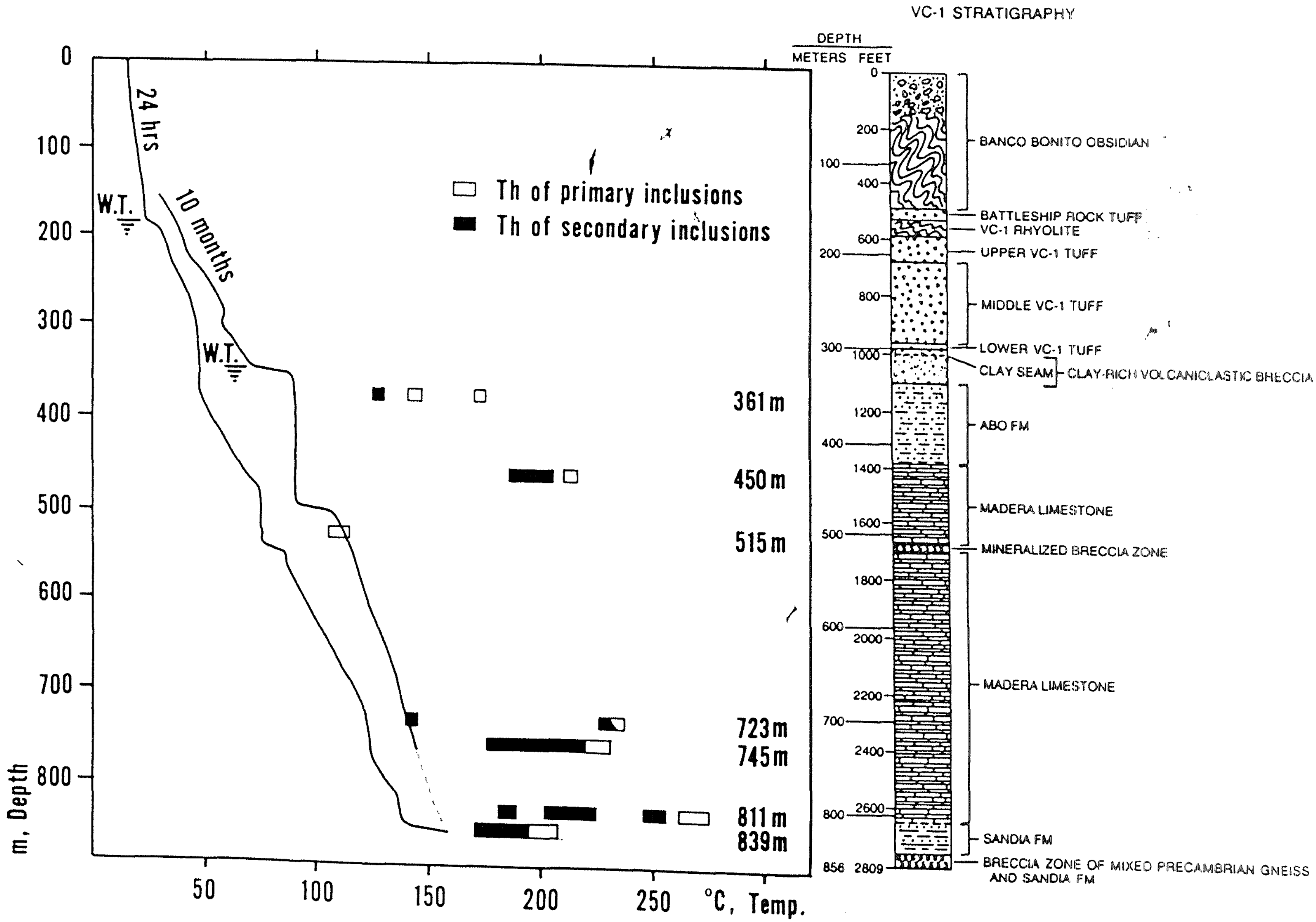


100μ
H
20μ.
4
X
X
10μ

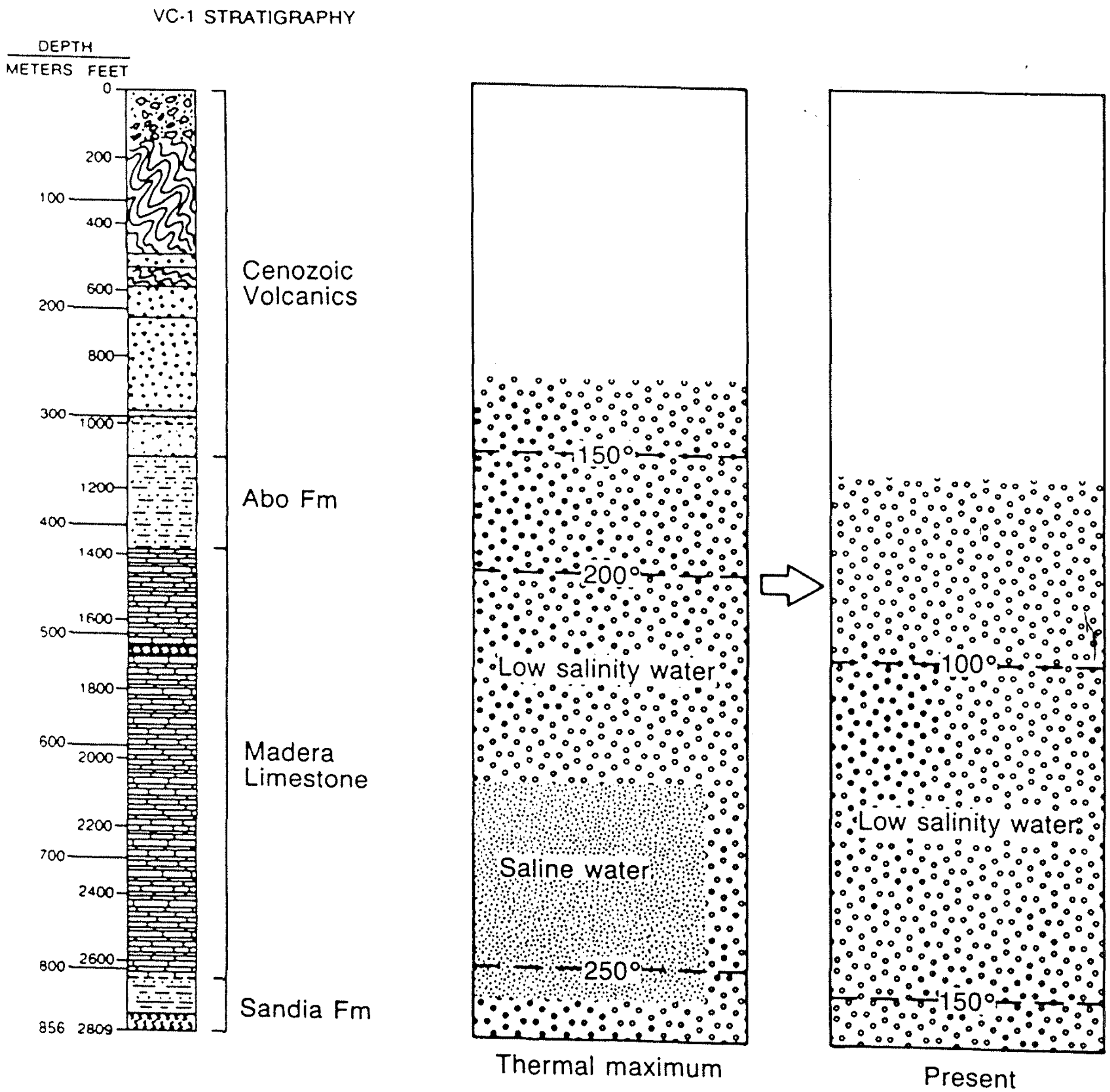

361m
°C,Tm
-20
-4
-2
450m
-4
-2
515m
-4
-2
723m
-4
-2
745m
811m
-10
-40
839m
-10
100
150
200
250
°C,Th



N
10
361 m
450 m
515 m
723 m
745 m
811 m
839 m
0 1 2 3 4 5 6 7
Wt % NaCl equiv.



VC-1 STRATIGRAPHY
DEPTH
METERS FEET
24 hrs
10 months
W.T.
Th of primary inclusions
Th of secondary inclusions
361m
450m
515m
723m
745m
811m
839m
m, Depth
°C, Temp.
BANCO BONITO OBSIDIAN
BATTLESHIP ROCK TUFF
VC-1 RHYOLITE
UPPER VC-1 TUFF
MIDDLE VC-1 TUFF
LOWER VC-1 TUFF
CLAY SEAM
CLAY-RICH VOLCANICLASTIC BRECCIA
ABO FM
MADERA LIMESTONE
MINERALIZED BRECCIA ZONE
MADERA LIMESTONE
SANDIA FM
BRECCIA ZONE OF MIXED PRECAMBRIAN GNEISS AND SANDIA FM
856 2809


VC-1 STRATIGRAPHY
DEPTH
METERS FEET
0
200
100
400
600
200
800
300
1000
1200
400
1400
1600
500
1800
600
2000
2200
700
2400
800
2600
856
2809
Cenozoic Volcanics
Abo Fm
Madera Limestone
Sandia Fm
150°
200°
Low salinity water
Saline water
250°
Thermal maximum
100°
Low salinity water
150°
Present