THE HYDROTHERMAL SYSTEM OF THE CALABOZOS CALDERA, CENTRAL CHILEAN ANDES

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Abstract

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Active thermal springs associated with the late Pleistocene Calabozos caldera complex occur in two groups: the Colorado group which issues along structures related to caldera collapse and resurgence, and the Puesto Calabozos group, a nearby cluster that is chemically distinct and probably unrelated to the Colorado springs. Most of the Colorado group can be related to a hypothetical parent water containing $\sim$400 ppm Cl at $\sim$250°C by dilution with $\geq$50% of cold meteoric water. The thermal springs in the most deeply eroded part of the caldera were derived from the same parent water by boiling.

The hydrothermal system has probably been active for at least as long as 300,000 years, based on geologic evidence and calculations of paleo-heat flow. There is no evidence for economic mineralization at shallow depth. The Calabozos hydrothermal system would be an attractive geothermal prospect were its location not so remote.

Introduction

Hot springs and steam vents occur along faults associated with collapse and resurgence of the Calabozos caldera, a late Pleistocene structure on the crest of the central Chilean Andes. This active hydrothermal system is of interest for four reasons:

(1) It is the present surface manifestation of a major hydrothermal system that has probably persisted for 300,000 years or more.

(2) Similar hot-spring systems are important targets for geothermal exploration.

(3) Sinter deposits associated with hydrothermal systems can bear economic Au and Hg mineralization.

(4) It may be the surficial analog of hydrothermal systems that produce Cu-porphyry mineralization.

Chemical analyses of hot waters and associated hydrothermal deposits from the Calabozos region are used to calculate subsurface water temperatures and to compare the Calabozos system to other active hydrothermal systems. Although there is no surficial evidence that economic mineralization is present at shallow levels in the Calabozos system, the dilute waters and high calculated subsurface temperatures of the reservoir make it an attractive geothermal exploration target.
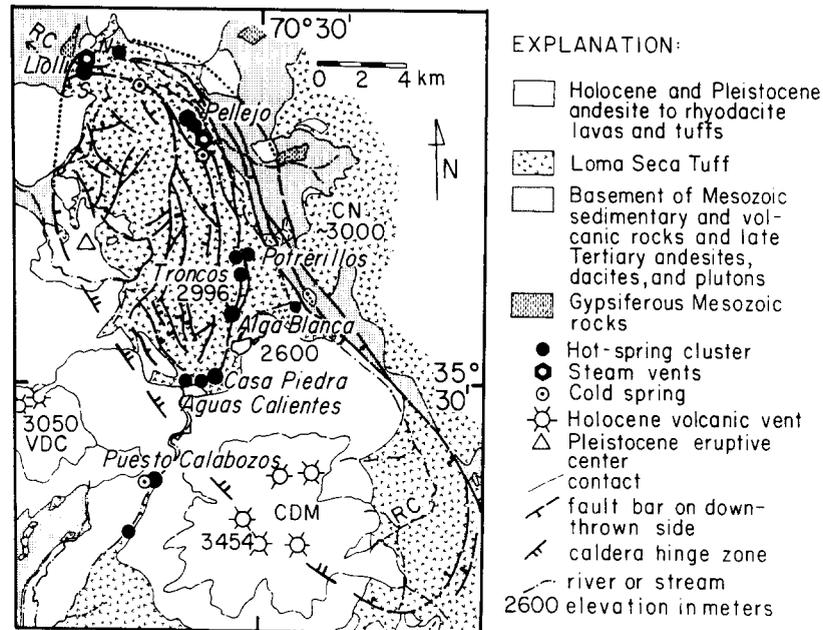
Fig. 1. Simplified geologic map of the Calabozos caldera. RC = Rio Colorado; VDC = Volcán Descabezado Chico; CDM = Cerro del Medio; CN = Cerro Negro. Llolli N and Llolli S refer to thermal vents on the north and south banks, respectively, of the Rio Colorado.

Geologic setting

The Calabozos caldera is located at 35°30'S at an elevation of ~2600 m (Fig. 1). It has been the locus of voluminous intermediate to silicic volcanism during the late Pleistocene. The geology, presented by Hildreth et al. (1984), is summarized below.

Regional basement rocks, exposed on the northern and eastern side of the caldera, are composed of late Mesozoic volcaniclastic sedimentary rocks interbedded with limestones, gypsum, and thin lavas and tuffs; a gypsum diapir several 100 meters in diameter, is exposed at Llolli (Fig. 1). The Mesozoic rocks are unconformably overlain by flat-lying to gently west-dipping, Pleistocene andesite lavas. Basement rocks exposed to the south and west of the caldera are chiefly late Tertiary lavas and tuffs of the Campanario formation (Drake, 1976), also capped by subhorizontal andesite lavas. Late Tertiary granitoid intrusions are exposed locally throughout the region.

At least two major ash-flow sheets erupted

from the Calabozos caldera 0.30 and 0.15 Ma ago, composing Unit V and Unit S, respectively, of the Loma Seca Tuff. A 0.8-Ma-old ash-flow, Unit L, underlies Unit V near the southern and eastern caldera margin and is compositionally and mineralogically similar to Units V and S, but it has not been conclusively linked to the Calabozos caldera. Each unit of the Loma Seca Tuff represents 200–350 km^3 of compositionally zoned magma ranging from rhyodacite to dacite.

The present 8-by-26-km Calabozos caldera is a composite trap-door collapse feature caused by eruption of Units V and S. On the northern and eastern sides of the caldera (Fig. 1), collapse is defined by a well-exposed series of near-vertical faults with combined displacement of at least 500 m, which lessens southward. The western margin of the caldera appears to be a flexural hinge zone and is largely covered by Holocene lavas and cones. Broad step-faulted regions characterize the eastern and southern margins of the caldera.

After caldera collapse, magmatic resurgence domed the northern half of the caldera. Like

collapse, caldera resurgence was asymmetric, with maximum uplift on the eastern side of the dome and an asymmetric graben on the western, hinged side. A complex web of normal faults, many with offsets antithetic to uplift, characterize the resurgent structure (Fig. 1).

The outflow facies of the Loma Seca Tuff occurs as densely welded, plateau-covering sheets and as thick remnants of flows that once filled deep glacial gorges. Within the northern portion of the caldera, Unit V is as much as 500 m thick and its base is nowhere exposed. It is chiefly poorly welded and is overlain by no more than ~100 m of densely welded Unit S on top of the resurgent dome. At depth, within the caldera, Unit V is almost certainly densely welded, based on comparison to deeply eroded ash-flow systems of similar composition and dimension (e.g., Fridrich and Mahood, 1984; Lipman, 1984; Boden, 1986).

The hot springs are geographically divisable into two groups: (1) the Colorado hot springs that lie along a north-trending arc, concave to the west, skirting the base of the resurgent dome; and (2) the Puesto Calabozos group that lies at the head of Cajon los Calabozos near the hinged margin of the caldera (Fig. 1). Solfataric activity occurs only in the northern, most deeply eroded portion of the area, at Llolli and at Pellejo (Fig. 1).

Age of the hydrothermal system

No direct evidence, such as K-Ar ages of minerals within alteration assemblages, is available to constrain the age of the Calabozos hydrothermal system. Several indirect lines of evidence suggest that it may be at least as old as Unit V, namely 300,000 years. For instance, most of the intracaldera section of Unit V is chalky owing to pervasive argillic alteration by acid leaching. The hydrothermal activity that caused the alteration must have existed immediately after eruption of Unit V, because an overlying intracaldera lava, which has an indistinguishable K-Ar age is locally unaltered.

Extensively altered rocks, including Unit S, and fossil sinter deposits associated with the caldera structure attest to the presence of hydrothermal activity since eruption of Unit S.

Whether or not hydrothermal activity was continuous between 0.3 and 0.15 Ma is uncertain, but the existence of a long-lived, deep, meteoric hydrothermal system at the Calabozos caldera is indicated by unusually low $\delta^{18}O$ values of plagioclase from fresh samples of Unit S (5.2–5.8). These values are lower than those typical of silicic volcanic rocks (Taylor, 1968) and indicate that the Unit S magma interacted with low-$\delta^{18}O$ rocks that had been previously altered by meteoric water (Grunder, 1987). These altered rocks were probably formed during vigorous hydrothermal activity within the shattered, permeable caldera-floor rocks, after eruption of Unit V.

Sampling and analytical methods

A total of 29 hot and cold water samples were collected from spring clusters in the Calabozos region during austral summer 1981, 1982, and 1984 (Table 1). The hottest spring in any given cluster was sampled in order to represent most closely the thermal waters at depth. All but the 1981 samples were collected using the backpacking method described by Thompson (1975). Temperature and pH were measured in the field, and spring discharge rates were estimated. Temperatures were measured with a maximum reading mercury-in-glass thermometer. Spring water was filtered through a 0.45-μm membrane; a 125-mL aliquot was acidified with hydrochloric acid for cation analysis, and another 250-mL portion was left unacidified for anion analysis. Bubbles were observed at most of the thermal springs and presumably represent CO_2 saturation. One cold spring in the Calabozos group is quite strongly carbonated and is reputed by local tradition to be a therapeutic beverage. Concentrations of NH_3 and H_2S in samples collected during 1982 were measured

TABLE 1

Representative analyses of springs of the Calabozos caldera complex

Location:	Llolli		Pellejo	Potrerillos	Troncos	Casa Piedra
Spring No.:	South LSW2	North LSW20	LSW10	LSW1	LSW17	LSW7
Discharge, L/min	15	10	2000	20	3000	300
T, °C	98.5	95.5	50.5	64	50	68
Field, pH	8.5	4.5	6.5	6.8	6.2	7.1
Lab, pH	9.30	2.97	7.15	7.79	8.03	8.32
Al (ppb)	0.2*	black*	olive*	–	1.2	–
SiO_2	582*	239	133	84	56	40
Fe	<0.05	2.8	3.8	0.8	0.1	1.3
Mn	0.03	0.80	0.88	0.22	0.02	<0.05
Ca	9	26	110	99	43	17
Mg	<0.02	18.1	25.6	10.5	2.5	0.8
Sr	0.2	–	1.0	2.2	0.4	0.2
Ba	0.6	–	6.4	6.9	–	1.4
Na	381	34	235	207	131	191
K	56	9.3	16.2	6.6	4.5	1.9
Li	3.5	<0.02	1.0	0.5	0.2	0.4
Rb	0.3	0.1	0.8	<0.02	<0.02	0.8
Cs	0.5	0.1	0.6	<0.02	0.2	0.5
H_2S	0.2	–	0.04	0.1	–	0.05
NH_3	1.7	–	3.3	1.8	–	0.5
HCO_3	98	5.3[H]	561	211	288	256
SO_4	144	630	111	390	60	66
Cl	549	4	196	109	49	107
F	3.8	0.1	2.3	2.9	3.1	1.0
B	14	0.9	1.5	0.6	0.3	0.8
δD	−89	–	−96	−96	–	−96
$\delta^{18}O_{H_2O}$	−9.8	–	−13.5	−13.3	–	−13.2
$\delta^{18}O_{SO_4}$	−4.5	–	−0.2	–	–	−2.8
Na/K	6.1	3.7	14.5	31.4	29.5	89.1
K/Li	16.0	–	16.2	13.2	18.9	4.8
Na/Ca	40.6	1.3	2.1	2.1	3.1	10.1
Cl/HCO_3	5.6	–	0.3	0.5	0.2	0.4
Cl/SO_4	3.8	0.0	1.8	0.3	0.8	1.6
Cl/B	39	4	131	182	163	134
Cl/F	145	35	85	38	16	107

Analytical data in ppm except Al (in ppb). Isotopic data are in standard delta notation relative to SMOW.
Cold springs identified by name of nearest thermal spring (Fig. 1). Rio C. = Rio Colorado sampled near Potrerillos.
See Thompson (1985) for analytical methods: Ca, Mg, Mn, and Fe by atomic absorption spectroscopy; Na, K, Li, Cs, Rb, Sr, and Ba by flame emission spectroscopy; SiO_2, Al, and B by spectrophotometric methods. F by F-specific electrode; SO_4 by ion chromatography; Cl and HCO_3 by titrametric methods and field Cl concentrations (not shown here) by use of 'Quantab' indicators. Laboratory and field Cl determinations are in close agreement.
[H]indicates that the value cited is for acidity.

Alga Blanca LSW8	Aguas Calientes LSW12	Calabozos		Cold springs			Estimated error ±
		LSW23	LSW18	Pellejo LSW11	Llolli LSW6	Rio C.	
5000	4000	30	75	60	300	60,000	20%
39	40	78	80	22	4	10	0.5
6.3	6.2	5.9	5.9	5.9	6.0	5.7	0.1
7.63	8.22	8.47	7.97	8.29	7.67	7.54	0.05
<0.1	–	–	olive*	–	–	–	20%
55	43	148	134	71	11	20	2%
0.6	0.7	2.8	6.5	10.9	–	–	10%
0.02*	<0.05	0.98	0.89	1.36	–	–	10%
21	25	127	165	217	8	3	4%
3.3	3.7	5.9	5.3	61.8	1.6	1.0	4%
0.3	0.4	1.6	1.4	1.4	–	–	5%
2.0	2.0	5.3	–	–	–	–	10%
116	157	488	488	193	6	18	2%
2.3	2.5	15	22	7	<0.1	1	2%
0.3	0.4	1.8	1.3	0.5	<0.1	<0.1	2%
0.3	0.3	0.7	0.2	<0.1	–	–	10%
0.1	0.3	0.7	0.3	0.1	–	–	10%
0.05	–	0.04	–	–	0.04	–	5%
0.4	–	2.2	–	–	0.6	–	5%
123	326	424	144	576	26	28	2%
40	58	390	468	239	10	4	10%
80	73	531	522	23	10	32	1%
1.6	1.6	2.6	3.3	1.5	0.2	0.2	5%
0.9	1.0	2.0	2.8	0.23	1.1	0.2	10%
–95	–93	–98	–	–	–95	–95	1
–13.1	–13.2	–13.5	–	–	–13.2	–13.6	0.1
–	–0.9	–1.5	–	–	–	–	0.1
51	58	30	22	26	56	15	
7.6	7.0	8.1	16.9	15	–	>12	
6	6	4	3	1	1	6	
0.7	0.2	1.3	3.6	0.0	0.4	1.1	
2.0	1.3	1.4	1.1	0.1	1.0	8.0	
89	73	266	187	98	9	160	
50	46	204	158	15	56	178	

*indicates that value is taken from analysis of the same spring in a different year, either because of analytical problems, or because data is for an element not analyzed in 1982.

#Olive and black refer to the color of the oxime chelate in the MIBK extract and indicate that high Fe^{3+} content in the water interfered with the extraction (see Afifi, 1983).

$\delta^{18}O$ and δD determinations were done by C. Janik and J. Borthwick, respectively, at the U.S. Geological Survey, Menlo Park. Tritium value of LSW2 = 0.08 ± 0.09 Tritium Units (TU) and of LSW4 = 1.29 ± 0.07 TU. Data from University of Miami RSMAS Tritium laboratory.

in the field by spectrophotometry as described by Thompson (1985). To obtain water samples suitable for Al analysis, selected spring waters were filtered through a 0.1-μm membrane and Al was extracted following the MIBK complexing method outlined by Barnes (1975) as modified by Afifi (1983). A sample for SiO_2 analysis was prepared in the field by diluting 10 mL of spring water with 50 mL of distilled water; volume was adjusted to 100 mL in the laboratory. From springs LSW2 and LSW4 (Table 1) one liter samples of unfiltered water for Tritium analysis were collected in glass bottles. The two pilot samples collected in 1981 were plain, untreated water samples. Representative analyses are in Table 1.

Results

Most of the Calabozos thermal waters are very dilute (Cl < 550 ppm) and plot along the meteoric water line of Craig (1961) (Fig. 2). No major nor systematic differences in the composition of thermal waters collected from the same springs in different years are evident. Thermal waters from the Colorado group, excluding Llolli, commonly define composition trends radiating from local cold waters, suggesting that they are related to each other by varying degrees of dilution of a parent hydrothermal water with meteoric water (Fig. 3).
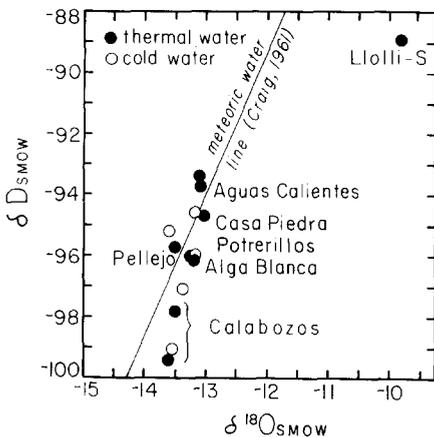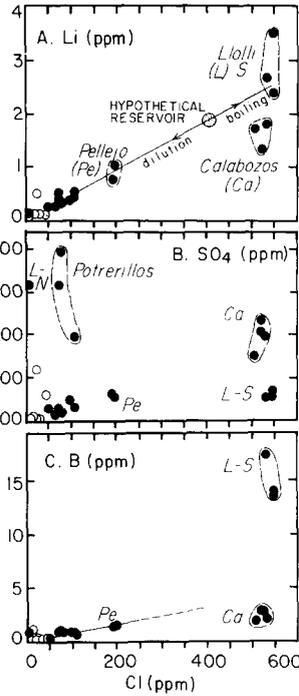

Fig. 3. Chemical variation diagrams for the Calabozos hydrothermal system. Filled circles represent thermal waters, open circles represent cold waters. Data are from Table 1, Hildreth et al. (1984), Thompson et al. (1983), and this study. L-S = Llolli, south bank of Rio Colorado; L-N = north bank.
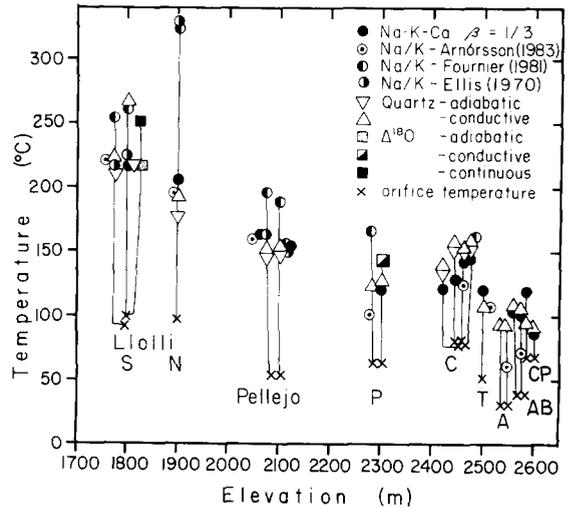

Fig. 2. Isotopic composition of Calabozos thermal waters and cold waters of the region. Locations in Fig. 1.

Fig. 4. Orifice temperature and calculated subsurface temperatures versus spring elevation. P = Potrerillos; C = Puesto Calabozos; T = Troncos; A = Aguas Calientes; CP = Casa Piedra; AB = Alga Blanca. Locations in Fig. 1. Data are from Table 2 and references cited in Fig. 3.

TABLE 2

Chemical geothermometry of Calabozos waters

Location:	Llolli		Pellejo	Potrerillos	Troncos	Casa Piedra	Alga Blanca	Aguas Calientes	Calabozos	
Sample:	LSW2	LSW20	LSW10	LSW1	LSW17	LSW7	LSW8	LSW12	LSW4	LSW23
Orifice temp. °C	98	95	50	64	50	68	39	40	78	80
SiO₂										
(1) cond.-qtz	240	192	154	128	107	92	107	95	160	155
(2) max. stm-qtz	221	178	147	125	107	94	107	97	152	147
(3) chalcedony	237	173	129	100	78	61	77	65	137	130
Na/K										
Fournier	252	322*	187	(136)	(139)	(77)	(108)	(102)	(132)	158
Ellis	233	329*	151	(91)	(95)	(27)	(61)	(54)	(86)	(117)
Arnórsson	238	*	160	101	107	–	72	60	98	126
Na-K-Ca										
β=4/3	235	79	87	59	60	57	53	54	88	97
β=1/3	233	205	153	118	120	85	102	98	125	142
δ¹⁸O SO₄-H₂O										
(4) conductive	280		133	144		172			148	
(5) adiabatic	238		122	139		156			140	
(6) continuous	250		124	139		160			141	
√Mg-Li	351	59	67	57	65	58	47	48	83	94

Sample numbers as in Table 1.
The silica geothermometer applied according to Fournier and Rowe (1966); (1) is the value if cooling is conductive (for springs well below boiling) and the water is in equilibrium with quartz, (2) cooling is with maximum steam loss (for springs near boiling), and (3) the water is in equilibrium with chalcedony.
The Na/K geothermometers are after Fournier (1981), Ellis (1970), and Arnórsson et al. (1983). *indicates 'not applicable' because the water is acidic. Values in parentheses are below the cited limits of applicability (150°C). '–' indicates the calculated temperature < measured orifice temperature.
The Na-K-Ca geothermometer is from Fournier and Truesdell (1973).
The oxygen isotope geothermometer is taken from McKenzie and Truesdell (1977); (4) is the value if cooling is conductive (best for springs below boiling, viz., all but Llolli), (5) if there is one episode of steam separation (best for springs near boiling), and (6) if there is continuous steam loss (best for springs associated with fumaroles).
The √Mg-Li geothermometer is taken from Kharaka and Mariner (1987).

Puesto Calabozos and Llolli waters are the most concentrated and form distinct compositional clusters. One Llolli water (Sample LSW20), which was collected amidst a bank of steam vents, has very low concentrations of Cl, B, K, and Na (Table 1), suggesting the water condensed from steam. Its acid pH and relatively elevated SO₄ concentration are consistent with steam condensation accompanied by oxidation of H₂OS to H₂SO₄.

Geothermometry

Both measured orifice temperatures and cal- culated subsurface temperatures of the Colorado suite decrease southward as elevation increases (Fig. 4). It appears that erosion has afforded a cross section of a vertically, thermally zoned hydrothermal system. Estimated subsurface temperatures range from ~250° to <100°C (Table 2). SiO₂, Na/K, Na-K-Ca, and SO₄-H₂O oxygen isotope geothermometers agree well for the Llolli spring, LSW-2 (Table 2) and indicate the water came from a reservoir at ~250°C, which corresponds to the lower reservoir temperature estimated previously by Thompson et al. (1983). This temperature is intermediate to values predicted if cooling of the

water during ascent is adiabatic (maximum steam loss) or conductive (Table 2 and Fig. 4). High temperatures calculated with the Na/K geothermometer for spring LSW-20 may reflect acid leaching of wall rocks, which makes the geothermometer unreliable.

The remaining springs record lower temperatures, suggesting that they have been diluted with cold water (Fig. 4). The Na-K-Ca geothermometer using $\beta = 1/3$ was used, as recommended for mixed waters by Fournier (1981). For the Colorado suite, the thermometers based on SiO_2 content, modelled without steam loss, and Na-K-Ca ($\beta = 1/3$) are in good agreement. Reservoir temperatures for the Puesto Calabozos group cluster between 140 and 150°C and do not follow the temperature versus elevation trend defined by the Colorado group. The $\sqrt{Mg}$-Li geothermometer of Kharaka and Mariner (1987) yields temperatures similar to measured orifice temperatures (except for Llolli water) (Table 2) and suggests that Mg content in the springs is controlled by chemical reactions near the surface.

A model

A simple model can be derived for the Colorado springs using a plot of enthalpy versus chloride (Fig. 5). Fluid from a parent reservoir with enthalpy of ~ 1100 J g^{-1} and Cl content of ~ 400 ppm evolves by boiling (evaporative concentration) to yield the Llolli hot springs and by dilution with meteoric water to produce the thermal springs between Aguas Calientes and Potrerillos. Such a model is supported by the fact that the main Llolli spring (LSW-2 and 22, Table 2) yields a subsurface temperature estimate of approximately 250°C, the temperature indicated by the intersection of the dilution and boiling trends (Fig. 5). Moreover, Llolli water is enriched in ^{18}O relative to meteoric water (Fig. 2), consistent with a history of steam loss.

If the Llolli water is in fact derived by boiling from a reservoir at 250°C, then a minimum depth of 500 m to the reservoir can be estimated
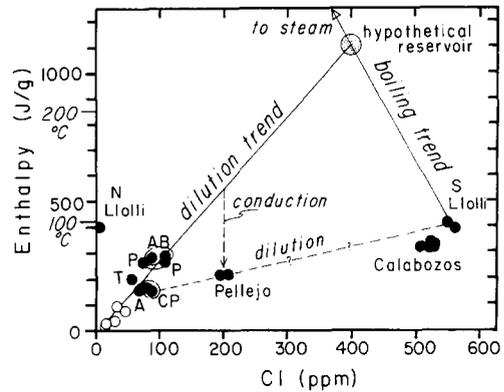

Fig. 5. Enthalpy-chloride plot of the Calabozos hydrothermal system, constructed according to Fournier (1979). Open circles = cold waters, filled circles = thermal waters. Data from Tables 1 and 2 and sources referenced in Fig. 3. Enthalpy-temperature conversions are taken from steam tables (Keenan et al., 1969).

from the boiling curve of White (1968), by assuming that the waters are sufficiently dilute to behave like pure water.

The Pellejo spring does not fall on the same dilution trend as the other Colorado springs (Fig. 5). We infer that its departure from the dilution trend in Fig. 5 is the result of conductive cooling. It is alternatively possible that the Pellejo water evolved by mixing between a boiled water, like the Llolli water, and meteoric water (Fig. 5), but because its chemical signature (Fig. 3) is consistent with the dilution trend defined by the remaining Colorado springs the hypothesis of conductive cooling is preferred. The Calabozos thermal springs, if derived from the same or a similar reservoir, represent waters evolved largely by boiling with only a minor component of dilution or conductive cooling.

The constant ratio of Li to Cl of the Colorado group bears out the dilution and boiling model (Fig. 3a). Li and Cl are highly soluble elements and their proportion should not be affected by removal of steam or addition of cold water low in Cl and Li. Based on the Li/Cl trends the southern Colorado waters represent mixtures of as much as 50% (Pellejo) to 30% (Potrerillos) and to as little as 10% of hot, concentrated reservoir water with cold water of the region. The Li content of the parent reservoir would be 1.9

ppm according to this model. Such a high Li content is consistent with the reservoir water having interacted with, or being hosted in, silicic volcanic rocks (Ellis and Mahon, 1977). Compositional data of the Calabozos thermal waters cluster off of the Li-Cl trend, which in addition to their lower $\delta^{18}O$ and δD values, and deviation from the enthalpy-Cl trends (Fig. 5), suggests that they are from a different geothermal reservoir than the Colorado thermal springs.

The contents of B and SO_4 of the Colorado springs do not follow the simple trend defined by Li versus Cl (Fig. 3). The Llolli springs data are high in B with respect to the Colorado dilution trend, which may reflect that the water passed through sedimentary rocks (Ellis and Mahon, 1977, p.219); of all the springs, Llolli is nearest to exposed Mesozoic sedimentary rocks. The presence of gypsum near the Llolli springs appears to have no major effect on the chemical composition of spring LSW2, on the southern side of the Rio Colorado. In contrast, Spring LSW20 on the north bank of the river has relatively elevated Mg and Ca, in addition to elevated SO_4, which may reflect the leaching of gypsum at shallow levels by acid water. Potrerillos water is similarly elevated in SO_4 from which it might be inferred that the water is interacting with gypsiferous deposits at depth.

Deposits associated with the springs

Most of the active springs in the Calabozos system issue into small pools or rivulets that have banks and bottoms coated with orange Fe-oxide mud. Alternating laminae of mud and carbonaceous material indicate that mud and algae, which are common in the springs, repeatedly cover each other. Calcareous sinter is actively depositing at Troncos (Fig. 1), and siliceous sinter and incrustations, locally with yellow specks of native sulfur, are forming at Llolli. Active sinters of both kinds occur in the Rio Colorado fault zone and terraces are typically 100 m^2 and 0.5–2 m thick. Extensive banks

of Fe-rich calcareous terraces with alternating limonitic and hematitic laminae are found along faults near Pellejo (Fig. 1). The most common deposits related to past and present hydrothermal activity are silicified and Fe-oxide encrusted volcaniclastic breccias.

Representative samples of incrustations, sinters and variously altered rocks were analyzed for precious- and base-metals. The highest Au, Ag, and Hg values (0.07, 0.02, and 8.7 ppm, respectively) occur in siliceous incrustations at Llolli near LSW-20. Calcium-carbonate-coated crusts of Fe-oxide mud from the Calabozos group yielded > 1000 ppm As and 68 ppm Sb, but no other significant anomalies were detected. The concentration of the common metal-complex-forming species Cl^- and S^{2-} (Barnes, 1979) (<0.08% NaCl, and $<10^{-6}$ moles kg^{-1}, respectively) are lower than typical for active metal-rich hydrothermal systems such as Broadlands, New Zealand (salinity: >0.37% NaCl and S^{2-}: 3×10^{-5} to 5×10^{-4}; Weissberg, 1969), and salinities are lower than those inferred for ore fluids in ore deposits probably related to hot-spring systems in the Great Basin (0.2% to 7.3%; White and Heropoulos, 1983). Thus the Calabozos system is likely to be barren at shallow depth. The absence of high metal concentrations at the surface does not preclude the existence of economic mineralization at greater depth because hydrothermal ore deposits are commonly strongly vertically zoned (White, 1981).

Geothermal potential and heat flow

The Calabozos hydrothermal system is an attractive target for geothermal exploration for the following reasons:

(1) The calculated reservoir temperature compares favorably with temperatures of the Coso geothermal project in California (240–250°C; Fournier et al., 1980) and the Roosevelt hot springs geothermal prospect in Utah (270°; Capuano and Cole, 1982).

(2) The dilute nature of the water, the very

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                    ↑ qSURFACE
                         ↑
                      magma chamber
T = 800°C      ↑ q₁              ↓
  rhyodacite        ρ₁ = 2.21 g/cm3
T = 900°C      ↑ q₂  ν₁ = 5 x10⁵poise
  dacite            ρ₂ = 2.27 g/cm3
T = 1000°C     ↑ q₃  ν₂ = 1 x10⁵poise
  andesite
```
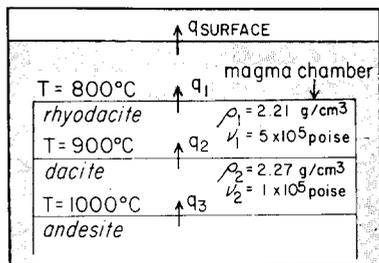
Fig. 6. Layered model of the Calabozos magma chamber prior to eruption of both Unit V (0.30 Ma) and Unit S (0.15 Ma) simplified from the data of Grunder (1986). Vertical scale is arbitrary.

reason why it is a poor prospect for mineral exploration, would facilitate geothermal exploitation because conduits and turbines would not be encumbered by excessive mineral deposition.

(3) The Calabozos caldera has collapsed at least twice and the subsided block is likely to be severely fractured, and is probably capped by relatively impermeable densely welded tuff, thereby providing a good reservoir for the hydrothermal fluid, as at Los Humeros, Mexico (Ferriz, 1982).

(4) Silicic magmatism and hydrothermal activity at the Calabozos center are long-lived.

Paleo-heat flow of $\sim 10^{-5}$ cal cm^{-2} s^{-1} at the Calabozos caldera complex can be estimated for the time immediately preceding eruption of Units V and S based on a layered model of the compositionally zoned magma chamber (Fig. 6). Composition, viscosity, density, and temperature are simplified from the data of Grunder (1986). Assuming that heat transfer is only vertical, and no heat is generated within a layer, then, at steady state, heat flow at the surface must equal heat flow across each horizontal boundary. Heat transfer within the magma is dominated by convection because the Rayleigh number of the magma is far greater than critical if the thickness of a layer is greater than 10 m. In fact, the thickness of the magma layers is probably on the order of 1 km, based on estimated eruptive volumes of several hundred km^3. When heat transfer within the layer is by convection, heat flow can be expressed as:

$$q = \left(\frac{\kappa \Delta T}{z}\right)\left(\frac{R^{\frac{1}{3}}}{R_c}\right)$$

where κ = thermal conductivity (5×10^{-3} cal cm^{-1} s^{-1} °K^{-1}), ΔT = the temperature gradient across the layer, z = layer thickness, R = Rayleigh number, and R_c = the critical Rayleigh number = 2000 (Sleep and Langen, 1981; Christensen, 1985). Substitution of the Rayleigh number:

$$R = \frac{z^3 \Delta T \alpha \rho g}{\kappa \nu}$$

(from Bartlett, 1969; $\alpha = 5 \times 10^{-5}$ °K^{-1}, ρ = density, ν = viscosity, g = gravitational acceleration) results in removal of thickness as a variable. Calculated heat flows are: $q_1 = 4 \times 10^{-5}$ and $q_2 = 7 \times 10^{-5}$ cal cm^{-2} s^{-1} for densities and viscosities summarized in Fig. 6. Comparable heat flows, i.e. between 10^{-4} and 10^{-5} cal cm^{-2} s^{-1}, have been measured in the hydrothermally active Lassen and Medicine Lake volcanic regions (Mase and Sass, 1980), in the Long Valley caldera region (Sorey et al., 1978), and have been estimated by Fournier and Pitt (1985) for the Yellowstone caldera system.

In spite of the many factors that make the Calabozos caldera system an interesting geothermal target, geothermal exploitation of the Calabozos system is unlikely in the near future owing to the inaccessibility of the Calabozos caldera (40 km to the nearest road) and the existing hydroelectric potential of the central Chilean Andes.

Summary and conclusion

The Calabozos hydrothermal system is associated with voluminous, late Pleistocene, caldera-related magmatism. It has been active, perhaps intermittently, for at least as long as 300,000 years and is presently expressed as a suite of thermal springs and steam vents issuing along caldera-related structures in the Rio Colorado fault zone. A nearby cluster of hot springs, the Puesto Calabozos group, are chemically distinct and are not directly related to the

Colorado thermal waters. They may be related to Volcán Descabezado Chico (Fig. 1), the most recently active cone in the immediate vicinity of the Calabozos caldera.

The Rio Colorado springs can all be related to one reservoir water containing ~400 ppm Cl near 250°C and at a minimum depth of 500 m. Hot springs water in the northern, most deeply eroded part of the caldera system, were evolved from the parental reservoir by boiling; reservoir water diluted with ≥50% regional meteoric water issues as springs along the eastern margin of the resurgent dome.

None of the thermal waters nor related sinters and incrustations in the Calabozos region have significantly elevated metal concentrations, so the area is not a promising mineral prospect at shallow depths. The dilute water compositions and the high calculated reservoir temperature, coupled with the longevity of the system, earmark the Calabozos hydrothermal system as an interesting geothermal target that is, however, unlikely to be exploited given its remote location.

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