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Memorandum

To: Carolyn Coleman
USAID/NE/TECH/HRST

From: Paul Teleki, U.S. Geological Survey
Office of International Geology

Subject: Azores geothermal project, TA Grant 150-0001 (B.IV.D)

We are pleased to forward the final report on the geochemical study of thermal fluids from Sao Miguel Island, Azores, by Alfred Truesdell, Nancy L. Nehring and Cathy J. Janik. Seven copies are enclosed for your use, as well as transmittal to Lisbon and Ponta Delgada.

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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Final Report: Geochemical study of thermal fluids from São Miguel Island, Azores

by

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under USGS-USAID Azores Geothermal Project

TA Grant 150-001 (BIVD), PASA no. POR-0001-P-IC-2123-00

Introduction

The Laboratorio de Geociencias e Tecnologia (LGT), an agency of the Azorean Regional Government (RGA), has an ongoing program for the exploration and development of geothermal resources on the various islands in the Azores Group. At the request of the RGA and to assist in that program, the United States Agency for International Development (AID) has provided funding for an agreement with the U.S. Geological Survey (USGS) to carry out limited geological, geochemical, and geophysical surveys on the Island of São Miguel as the Azores geothermal project TA Grant 150-001 (BIVD). This report presents the results of a geochemical survey of hot and cold fluids of São Miguel. The funding for this work was from PASA no. POR-0001-P-1C-2123-00.

Several trips were made to São Miguel Island, Azores, to investigate the use of fluid chemistry in assessing the geothermal potential of the island, and to consult on the utilization of hot waters in the Ribeira Grande development. The sampling of natural springs and existing drill holes resulted in uneven data coverage because, although thermal springs are fairly numerous in the Furnas area, they are rare near Ribeira Grande and essentially nonexistent at Sete Cidades. A range of hot and warm springs were sampled at Furnas, and the two hot springs and the geothermal wells were sampled at Ribeira Grande. In addition, some cold springs and CO_2-charged cold springs were sampled. Earlier geochemical data from Geonomics (1977), Sheppard (1981), and Aquater (1982) have been compiled and included in the interpretations. The preliminary report was found to contain discrepancies in data based upon analytical error. All data for this report has been reviewed and found to be correct.

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Hydrochemistry of cold waters

Cold (and thermal) springs are not numerous on São Miguel due to the highly porous nature of the volcanic rock of which the island is composed. However, the compositions of shallow cold groundwaters are important to geothermal exploration because they form the deep and shallow recharge (or shallow dilution) to the thermal waters. Although springs are few and isotopic data are very scant, enough data (mostly from Geonomics, 1977) are available to indicate the probable range of chemical compositions. The mean annual temperature is about 17°C at lower elevations (Geonomics, 1977) and may be 5-8°C cooler on the upper slopes of the volcanoes. Thus, cold waters in Table 1 are taken to be any water below 22°C. Analyses in Table 1 include our collections in 1982 and those of Geonomics (1977), Sheppard (1981), and Aquater (1982).

The chemistry of São Miguel cold springs reflects: 1) seaspray which produces Cl concentrations in rain of 10-25 mg/kg, significantly higher than those of typical inland continental cold waters; 2) reaction of CO_2 (either atmospheric, from organic decay or less commonly, volcanic) with fresh volcanic rock to form bicarbonate and metal ions (mostly Na^+) in solution; and 3) local thermal additions such as F and H_2S, which oxidizes to SO_4. The chemistry of typical cold water is Na>>K>Ca>Mg and HCO_3>>Cl>SO_4 using the notation of Truesdell (1976).

The isotopes of oxygen and hydrogen have been analyzed on a few cold groundwaters of São Miguel (Table 1d). The limited isotopic data also include Fogo rain (Table 2) and IAEA precipitation data (from Ponta Delgada) compiled by Aquater (1982) which define a precipitation line of $\delta D = 5.2\delta^{18}O + 1.9$. This differs from the meteoric water line of $\delta D = 8\delta^{18}O + 10$

proposed by Craig (1961) for continental areas. Our new analyses of cold waters also fall close to the São Miguel precipitation line (Fig. 1).

The upflow of volcanic CO2 on São Miguel occurs mainly in the areas of most recent volcanism and present geothermal activity. The analyses of fumarole gases (Table 3) show that CO_2 is the dominant gas component in steam. When steam rises in a large conduit with a strong flow, the steam appears at the surface as a fumarole, and CO_2 remains in the gas phase. Fumaroles are found at Caldeiras do Ribeira Grande, Caldeira Velha and at Furnas. When the conduit is smaller and the flow less intense, the steam may condense resulting in flows composed only of CO_2. Examples of CO_2 gas emissions are found at Lombadas, at Aguas Vermelhas, in the bed of the upper Ribeira Grande, and notably in a closed depression near Santa Barbara where CO_2 accumulates, endangering man and wildlife.

For the smallest deep-vapor flows, water is condensed and all CO_2 is absorbed in groundwater as carbonic acid (H_2CO_3) and as HCO_3 resulting from reaction with volcanic glass and other aluminosilicate minerals to form alkali bicarbonate solutions by

$$CO_2 + H_2O + \text{Na-silicate} = Na^+ + HCO_3^- + \text{H-silicate}.$$

This reaction is not limited by solubility or charge balance (as are direct solution of CO_2 as H_2CO_3 and HCO_3^-) but only by the supply of the reactants. Thus the smallest flows of steam and CO_2 will be evidenced by neither gas in a vapor phase but by the presence of dissolved HCO_3^- ions.

Using this concept we have plotted in Figure 2 the HCO_3/Cl weight ratios of cold springs, cold wells, and surface waters (rivers and lakes) on the map of sample locations from Geonomics (1977). The normal value of the HCO_3/Cl ratio in cold groundwaters of São Miguel is near 3, but on the western side of

Fogo and in the Furnas area HCO_3/Cl ratios are greater than 4 and attain 21 at Lombadas. A similar pattern would be shown by HCO_3 contents because Cl in cold water is nearly constant at 15-20 mg/kg and is probably entirely of seaspray origin. The increase of HCO_3 with temperature is shown in Figure 3 for cold and warm springs.

Unfortunately, our coverage of cold springs on São Miguel is very poor and is essentially limited to the Fogo and Furnas calderas. A program has been started with the cooperation of Dr. Antonio Da Silva of the LGT to collect cold-spring waters which will be analyzed at the U.S. Geological Survey for Cl, HCO_3, SiO_2, and water isotopes. The results of this program will not be available for the geothermal energy assessment of São Miguel.

Thermal waters of Ribeira Grande

Thermal springs are rare on Agua de Pau, probably because upward migration of hot waters is generally inhibited by large shallow, downslope flows of cold groundwater resulting from high rainfall. The geothermal development at Ribeira Grande was prompted by the discovery of high-chloride hot water in a research well drilled by Dalhousie University for geologic studies. Later resistivity and thermal-gradient studies by Geothermics showed that a thermal anomaly was located relatively close to the surface in this area which was interpreted as an upflow zone. Production wells drilled on the basis of the geophysical indications exhibit temperature reversals (as did the Dalhousie well), demonstrating that this is a zone of lateral outflow with thermal waters probably discharging offshore.

The center of the system is most probably located under the upper parts of the Agua de Pau (Fogo) Volcano, possibly near large hot springs at Caldeiras

do Ribeira Grande (97°C) and Caldeira Velha (98°C). The chemical compositions of these springs indicate that they are condensed steam and steam-heated, shallow groundwater with essentially no contribution of deep thermal water (Table 1c). The chloride contents are as low as or lower than those of normal, shallow groundwaters, but sulfate contents produced by surface oxidation of H_2S carried in steam are very high (>700 mg/kg). These waters are greatly enriched in deuterium and oxygen-18 (Table 2) resulting from nonequilibrium evaporation. Analyses of a few warm springs from the Ribeira Grande area (Agua Azeda, Aguas Vermelhas, and Ladeira Velha) are included in Table 1c, but their isotopic compositions are not available.

The production wells RG-1 and PV-1 have been extensively sampled by Aquater (1982) during full-flow tests. We collected samples of both wells using a downhole sampler (Tables 1de, 2). Ideally a downhole sampler should collect a sample of aquifer water without flashing and steam loss during passage to the surface. During our sampling, however, a spring-closed valve may have malfunctioned and some steam may have been lost after collection; the resulting analyses (Table 1d) are compared in Table 1e to those of flashed samples collected by Aquater(1982) and Sheppard (1981).

The chemistry of the Ribeira Grande production fluid is dominated by sodium chloride with lesser amounts of HCO_3, SiO_2, K, and SO_4, minor F, B, Ba and Sr, and very little Ca, Mg, and rare alkalis. This water is similar chemically to geothermal waters in volcanic rocks (White, 1957). The source of the chloride in volcanic geothermal waters is considered to be rock leaching (Ellis and Mahon, 1964) or magmatic (White, 1957). On São Miguel, seawater is another possible source of chloride. The major geochemical problem with the Ribeira Grande fluid is calcite scaling caused by flashing

and CO_2 loss in the well or in the aquifer. Probably neither the Aquater analyses (which were flashed) nor ours (which may have flashed in the sampler) give true values for calcium or bicarbonate in the subsurface reservoir fluid. Using the Na-K-Ca geothermometer with the Na and K analyses and the known aquifer temperature of 230°C, Ca in the aquifer fluid can be calculated to be 50-100 mg/kg. Using a different method, Aquater (1982) calculated 60 to 800 mg/kg Ca.

There is considerable spread in the isotopic analyses of fluids from the wells PV-1 and RG-1 (Fig. 4 and Table 2). The analyses (Sheppard, 1981) of weirbox waters taken from PV-1 in 1981 are reasonably consistent with the downhole samples from RG-1 and PV-1 taken in 1982. The 1981 samples indicate the aquifer fluid is -16 permil in deuterium and -3.5 in oxygen-18. The 1982 downhole samples have the same deuterium content, but are heavier by +0.5 permil in oxygen-18. The other collections of separated samples from PV-1 (Aquater, 1982) are significantly lower in deuterium. A new collection of downhole or separated samples may be necessary to resolve these differences.

The data suggest a high-altitude recharge for the Ribeira Grande fluid with deuterium values similar to those of Lombadas waters. The well samples show an "oxygen isotope shift" to more positive $\delta^{18}O$ values from exchange with rock oxygen at high temperatures. The indicated high-altitude recharge and oxygen isotope shift of the borehole waters are consistent with the interpretation that the main upflow zone is closer to the center of the volcano, but do not rule out other possible paths of fluid flow.

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Geothermometry of the Ribeira Grande waters

The hot springs of Caldeiras do Ribeira Grande and Caldeira Velha are not suitable for water geothermometry because they do not contain any direct contribution of aquifer water, and are only related to the geothermal aquifer through the rising steam that heats them. Application of the D'Amore-Panichi (1980) empirical gas geothermometer to the gas analyses indicates temperatures of 209-240°C (with one outlier at 128°C; Table 3). These temperatures are not unreasonable, but are subject to error due to alteration of gas compositions during ascent to the surface and in surface pools.

The waters from the geothermal wells are much more reliable fluids for geothermometry (Tables 1de,2,4). The silica contents indicate temperatures of quartz saturation of 220-250°C depending on the assumed amount of steam loss (Table 4b). The lower figure (assuming flashing to atmospheric pressure without conductive cooling) is similar to the measured downhole temperatures, and suggests that dissolved silica equilibrates with quartz in the aquifer. This is in accord with observations in other fields (e.g., Mahon, 1966), and is expected from the rapid experimental equilibration of quartz and water.

The temperature of 286°C indicated by the Na-K-Ca geothermometer is significantly higher. This may indicate higher temperatures in the upflow zone with incomplete re-equilibration of cations to the lower temperatures near the wells. This is in accord with the slow equilibration observed experimentally and at Cerro Prieto (Truesdell et al., 1981). However, the tendency of the Ribeira Grande fluids to calcite scaling suggests that flashed fluids have lost Ca by precipitation of calcite when CO_2 pressures were reduced by flashing. Loss of Ca will cause the Na-K-Ca geothermometer to indicate higher temperatures, and without knowledge of the amount of Ca loss,

no adjustment can be applied. The Na/K geothermometer of White and Ellis (in Truesdell, 1976) can give a valid indication of subsurface temperature if the original Ca concentration is not too high. This geothermometer indicates 232°C in agreement with quartz saturation with maximum steam loss.

The most reliable indication of higher-than-observed temperatures in the Ribeira Grande production fluids is from the sulfate-water isotope geothermometer. This depends on the exchange of oxygen isotopes between water and dissolved sulfate, and is known to be very slow to equilibrate at neutral pH (McKenzie and Truesdell, 1977). Using our (USGS) analyses, and assuming no flashing, temperatures of 326° and 329°C are indicated (Table 4d). Data from Aquater (1982) for samples presumably flashed to 120°C and conductively cooled afterwards indicate temperatures from 207-263°C. Because we do not have a complete description of the Aquater collection or their method for analyzing ^{18}O in SO_4, we have more confidence in our own analyses. If we use the average aquifer water $\delta^{18}O$ value of -3.3 permil (based on USGS, Sheppard (1981), and Aquater analyses) with the reported $\delta^{18}O$ (SO_4) values, we obtain a spread from 198-329°C. The average of all production-fluid sulfate-water isotope temperatures in Table 4d is 265°C. These higher indicated temperatures suggest that higher temperatures will be found in the upflow zone of the Agua de Pau geothermal system.

Summary of Ribeira Grande geochemistry

Geothermal waters sampled in the geothermal drill holes are chemically unlike any cold or thermal spring waters on Agua de Pau. These waters must flow laterally downslope and discharge from submarine vents offshore of Ribeira Grande town. The large acid hot springs of Caldeiras do Ribeira

Grande and Caldeira Velha, as well as a few other warm springs, contain steam-heated waters formed where rising plumes of steam from boiling aquifer waters mix with cold groundwater flowing down the flanks of the volcano. The location of these springs probably indicates zones of upflow of the geothermal reservoir water (originally about 300°C) where decreasing pressure causes boiling and release of steam. The steam composition is probably altered by reaction with rocks and mixture with cold water, and can yield only approximate indications of subsurface temperatures. Fluids from the geothermal wells have re-equilibrated with quartz at 230°C after cooling by steam loss and possibly mixture with cold water to produce silica temperatures equal to those measured downhole, and have lost calcium to give ambiguous Na-K-Ca temperatures. Only sulfate-water isotope temperatures give clear indications of the original reservoir temperatures.

Boiling springs and fumaroles at Furnas

Hot springs and fumaroles are located within the Furnas caldera in three areas. Fumaroles occur along the shore of the Lagoa das Furnas; boiling springs, warm springs, and fumaroles occur in a park within the town of Furnas; and warm springs and fumaroles occur between the towns of Furnas and Ribeira Quente. These manifestations are probably outflows from a single geothermal system which is separate from the geothermal system of Agua de Pau-Ribeira Grande.

The chemical characteristics of the Furnas thermal manifestations are quite varied. The Lagoa das Furnas fumarole pool, which occurs in a cold stream, carries no deep Cl-containing water, so the Cl content of its drainage is lower than that of the inflow stream (Table 1d). The steam does carry

H_2S which oxidizes to produce high concentrations of SO_4 (~200 mg/kg) compared to the cold inflow. The oxidation of H_2S produces acid (pH3) water which dissolves surface rock to produce high silica, alkalis and other cations. The composition of the water is locally produced from surface leaching, so water geothermometers cannot give meaningful subsurface temperature indications. The D'Amore-Panichi gas geothermometer can be used and indicates 228°C (Table 3).

The fumaroles at Ribeira Quente and near Furnas on the road to Ribeira Quente, which are also unsuitable for water geothermometry, give gas thermometer indications of 194° and 213°C. These are in reasonable agreement with other Furnas temperatures.

The boiling springs in the town of Furnas are apparently fed by both steam and deep, high-Cl water. These spring waters contain 200-300 mg/kg Cl, as well as high HCO_3, SiO_2, Na, and K, and resemble bicarbonate-chloride geothermal waters from other volcanic areas (e.g., Yellowstone or New Zealand). Geothermometer calculations from these analyses are consistent (Tables 3 and 4) with temperatures of 207-227°C indicated for quartz saturation, 170-185°C for Na-K-Ca, 197-228°C for gas thermometry, but with higher indicated temperatures of 230-340°C for sulfate-water. Silica temperatures must be minimum values because the waters are saturated with and deposit amorphous silica. A reservoir at 200-250°C is suggested with the sulfate-water isotope temperatures possibly indicating higher temperatures at a deeper level.

The isotopic data suggests that these Furnas waters are highly evaporated at the surface. Both deuterium and oxygen-18 are greatly enriched relative to expected compositions (Fig. 1) with an isotopic pattern similar to acid-

sulfate waters (including Caldeiras do Ribeira Grande and Caldeira Velha at Agua de Pau). The pH and chemistry of the springs do not, however, resemble those of acid-sulfate springs. Their occurrence on a sinter terrace and their relatively high flow rates (to 1 $Lsec^{-1}$) are characteristic of neutral, high-chloride springs, rather than of acid-sulfate springs. Tritium in these waters is very low (Table 1d), showing little surface water addition. Tentatively we will assume that the interpretation of the isotopic data is incorrect and that these waters are what they otherwise appear to be; i.e., neutral bicarbonate-chloride waters which are somewhat re-equilibrated samples of the Furnas deep water.

Warm springs of Furnas

Near the town of Furnas are a number of high-CO_2 warm springs (Table 1cd). These springs could have two origins: either from mixture of cold and hot waters or from mixture of cold water with steam. If mixing with cold dilute waters has occurred, cation geothermometer temperatures, which depend on ratios, are little affected, but silica temperatures, which depend on concentrations, are lowered (Fournier and Truesdell, 1974). The warm-spring data for Furnas shows much higher cation temperatures than silica temperatures, showing that mixing is likely. In addition, Cl/HCO_3 ratios are constant despite a wide range in chlorinity (Table 4ab). This suggests mixing of a high-HCO_3, Cl water with a dilute water. The silica mixing model I (TWSMMI, Table 4ab) usually does not converge, showing that the spring waters have more silica than can satisfy the simultaneous heat and silica balance equations involving the mixed water, cold water at 18°C with 70-130 mg/kg SiO_2, and quartz saturated hot water. The silica mixing model II

(TWS2, Table 4ab) converges in all cases and indicates temperatures (average 216°C, see below) close to those indicated by the Na-K-Ca geothermometer (average 220°C, Table 4c) and much higher than those indicated by quartz saturation (average 158°C). The silica (or warm spring) mixing model II is based on the assumption that the thermal water cools by boiling and steam separation (adiabatically) to an intermediate temperature (taken as 100°C in Table 4c) and that afterwards it mixes with cold water to reach its final temperature. It is assumed that there is no precipitation of silica during cooling either by boiling or dilution (mixing). In the calculation the temperature and silica content of the cold water and the mixed water are used along with the relation of silica contents and temperature for quartz saturation. The methods and assumptions are described in Truesdell and Fournier (1977). The temperatures calculated in this manner (TWS2 in Table 4, 12 samples) average 216°C with a standard deviation of 23°C. (Without sample nos. 68 and AZ-9, the average and standard deviation are 224°C and 15°C.) This subsurface temperature is close to the maximum temperatures indicated by quartz saturation and gas thermometry for the boiling springs at Furnas.

Since the silica mixing models are independent of chloride, the chloride concentration of the hot end member may be calculated as a check on the validity of the model. These numbers are given in Table 4c for assumed cold water chloride of 18 mg/kg (average for 45 groundwaters in Table 1b excluding the five highest-Cl samples) and 10 mg/kg (perhaps typical of the highest-altitude recharge). The averages of hot-end-member chloride contents (excluding three outliers) are 218 (±76) mg/kg assuming 18 mg/kg Cl in cold water and 244 mg/kg assuming 10 mg/kg. These are quite comparable to the chloride contents of boiling springs at Furnas. This chloride content is for

water after boiling to 100°C; the aquifer concentrations (at 220°C) would be 167 to 187 mg/kg chloride.

These calculations support the validity of the mixing model which suggests that thermal water of about 220°C and 180 mg/kg Cl boils and loses steam to cool to 100°C. Some of this emerges as boiling springs and some mixes with cold groundwaters to form warm springs. A few warm springs (e.g., Agua Padre Jose) are formed by mixture of cold water and steam as shown by low-chloride contents. Some steam separated from boiling water emerges as fumaroles and some mixes into groundwaters.

The subsurface temperatures of the warm and boiling spring waters as indicated by silica contents must be considered minimum values since the waters are just saturated with amorphous silica at 100°C. Since, unlike quartz, amorphous silica precipitates rapidly and does not supersaturate readily, it limits the range of the quartz saturation geothermometer to about 210-230°C (Truesdell and Fournier, 1976) which is similar to temperatures indicated at Furnas. The cation temperatures of warm and boiling springs also suggest re-equilibration and only the sulfate isotope geothermometer may indicate the original reservoir temperatures near 300°C.

Summary of Furnas waters

The intensity and large area of thermal manifestations and the chemistry of boiling and warm springs at Furnas suggest the presence of a large geothermal system with temperatures in excess of 210-230°C. All geothermometer indications, with the possible exception of SO_4-H_2O isotope fractionation, must be considered minimum values because of re-equilibration during passage to the surface.

Recommendations

Although many deductions can be made from the presently available geochemical data, there is a need for better coverage of the isotope analyses in order to determine the origin of warm and hot springs in areas other than Furnas. The clear indications of a large geothermal system at Furnas may not be useful if a decision is made to reserve this area for tourism. Further geochemical work should concentrate on areas which can be developed. The coverage of isotopic samples from Agua de Pau and Sete Cidades calderas is not adequate, and, although the small number of thermal springs in these areas may make interpretations difficult and inconclusive, more sampling and analysis should be done.

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Table 1a. Chemical analyses of surface waters from Geonomics(1977).

No	Sample	Date	Description	Temp	Flow	pH	Cond	SIO2	Ca	Mg	Na	K	Fe	HCO3	Cl	SO4	NO3	NH3	B	F
1	69	77FEB	Rainwater	15	-	7.2	87	2.1	0.4	1.6	10	0.72	0.05	9.9	37	5	0.03	1.8	<0.2	0.1
2	15-L	77FEB	Lagoa do Fogo	17	-	-	-	9	0.56	0.8	18	17	<0.05	-	9.7	2.5	0.01	<0.4	0.01	0.15
3	16-L	77FEB	Lagoa das Furnas	22.5	-	6.4	147	29	2.2	2.1	8	6.6	0.05	146	14	7	-	-	<0.2	0.46
4	23-L	77FEB	Lagoa Verde	18.5	-	6.2	109	25	0.2	0.76	6	2.5	0.03	29	15	5	<0.1	<0.06	<0.2	1.2
5	24-R	77FEB	Rib dos Tambores	22.5	300	6.3	365	100	10	5	30	16	0.42	195	31	9	0.88	<0.08	0.46	0.98
6	25-R	77FEB	Rib dos Tambores	23	300	6.8	390	100	10	4.8	35	17	0.74	354	31	10	81	<0.08	<0.2	1
7	38-R	77FEB	Rib do Teixeira	15	20	6.8	113	65	1.8	1.6	14	5.5	0.02	52	12	3	0.94	<0.08	<0.2	0.78
8	39-R	77FEB	Rib Grande	15.5	600	7.7	325	70	13	7.6	50	15	0.47	232	13	6	0.16	<0.08	<0.2	1.9
9	41-R	77FEB	Rib das Grannas	17.5	25	5.3	194	68	5.2	3.2	21	8.3	0.02	76	25	57	0.33	<0.08	<0.02	0.53
10	49-R	77FEB	Rib das Lombadas	14	10	6.3	80	59	0.2	0.82	9	4.7	0.01	37	11	2	<0.02	<0.08	0.44	0.3
11	62-R	77FEB	Rib do Lameiro	12	8	6.7	158	91	1.4	1.9	10	9	0.31	62	16	25	<0.3	<0.08	<0.2	0.44
12	63-R	77FEB	Rib do Lameiro	14.5	8	7.2	210	86	3.9	3.3	40	11	0.03	54	30	9	0.7	<0.08	0.26	0.58
13	64-R	77FEB	Rib Grande	15.5	10	7.7	280	90	8.8	5	40	11	0.21	57	16	6	<0.3	<0.08	<0.2	0.86
14	65-R	77FEB	Rib das Grannas	15.5	6	6.9	192	77	5.5	2.9	30	9.6	0.09	63	25	8	<0.3	<0.08	0.26	0.47

Table 1b. Chemical analyses of cold groundwaters from Geonomics(1977).

No	Sample	Date	Description	Temp	Flow	pH	Cond	SIO2	Ca	Mg	Na	K
1	1	77FEB	Lombadas (nasc)	15	0.2	5.5	240	120	4.6	2.2	62	16
2	2	77FEB	Cald do Ribeira Grande	17	8	6.9	130	54	2.8	2	30	5.4
3	4A	77FEB	Lad Velha-nasc Meneses	20.5	0.6	6	174	78	5.3	3.2	41	6.6
4	6	77FEB	Agua da Magarca	20.5	0.5	5.2	200	68	4	2.6	41	8.5
5	7	77FEB	Nasc	14.5	0.3	5.5	210	68	3	3.8	38	8.4
6	9	77FEB	Macico do Fogo nasc	15.5	1	5.3	210	94	3.1	2.6	41	8.3
7	10	77FEB	Lombinhos	14.5	1	5.5	194	54	3	3	42	7.4
8	10A	77FEB	Lombinhos	-	-	-	-	-	2.8	2.8	20	7.7
9	11	77FEB	Nasc Mariana Crater	19.5	0.005	6	195	58	4.1	3.4	30	7.2
10	12	77FEB	Nasc Salto do Cabrito	17	-	5.9	225	68	2.7	1.6	26	6
11	13	77FEB	Nasc das Lagrimas	21	2	5.9	195	61	3.6	2.8	35	9.5
12	14	77FEB	Nasc do Cha-Canto	16.5	5	5.2	117	44	1.8	1.4	21	3.5
13	18	77FEB	Nasc Quenturas	20	0.25	6	180	96	5	0.72	8	9.2
14	19	77FEB	Azeda do Rebentao	14.5	0.5	5.8	280	120	8.6	3.4	20	20
15	21	77FEB	Nasc Lagoa do Canario	17	0.5	5.4	185	68	5.5	3.8	8	6.2
16	22	77FEB	Nasc do Moinhos	13	0.5	5.8	167	-	-	-	-	-
17	26	77FEB	Nasc Lag do Congro	13	0.5	5.3	117	84	2.4	2.1	16	6.5
18	27	77FEB	Nasc Lag Nenufares	13	3	5.3	175	88	4.8	4.7	19	11
19	28	77FEB	Nasc da Agua Ferrea	20	0.5	4.7	210	85	4.8	2.8	10	8.6
20	29	77FEB	Nasc da Cidreira	13.5	3	5.2	142	64	4.8	3	18	5.2
21	30	77FEB	Fonte do Louro	14.5	2	5.3	138	56	2.6	2.1	18	5.8
22	31	77FEB	Nasc do Pedreira	14	2	6.7	115	66	0.72	2.1	21	7.6
23	32	77FEB	Nasc Monte Gordo	15.5	20	5.2	126	51	2.4	1.7	15	6
24	33	77FEB	Nasc Bandeirinhas	12.5	30	5.3	96	73	0.2	1.2	33	4.2
25	35	77FEB	Nasc no Verde Tinto	14	2	5.2	144	54	2.5	3.2	16	4.8
26	37	77FEB	Cald Velha Nasc	13.5	0.005	5.2	118	61	3.6	2.9	3.6	0.095
27	42	77FEB	Nasc Passirinhos	13	2	5.3	140	80	1.2	1.5	17	8.5
28	43	77FEB	Nasc Mato da Correia	11.5	40	6.3	90	65	0.96	1.3	10	33
29	44	77FEB	Nasc dos Casteunhos	16.5	-	5.2	300	130	9.5	3.8	29	14
30	45	77FEB	Agua Serra do Trigo	15.5	0.1	4.9	200	110	8	3.6	21	12
31	45B	77FEB	Agua Serra do Trigo	15.6	440	4.85	201	87	6.57	2	26.4	10.1
32	46A	77FEB	Agua "Dr. Bruno"	17	0.1	5.3	420	110	17	64	45	22
33	46B	77FEB	Agua "Dr. Bruno"	20.4	0.07	-	-	96	23.6	14	141.2	22.7
34	46C	77FEB	Agua "Dr. Bruno"	19.4	0.13	5.85	469	94.5	16.3	6.8	62	23.6
35	50	77FEB	Nasc nas Lombadas	11	2	6.3	102	76	0.2	0.3	14	4.1
36	51	77FEB	Nasc nas Lombadas	12.5	2	5.2	200	110	5.7	2.5	23	16
37	52	77FEB	Nasc nas Lombadas	15.5	0.005	5.3	310	120	11	4.6	20	19
38	53	77FEB	Nasc nas Lombadas	18.5	0.005	5.3	460	120	16	9.8	40	23
39	58	77FEB	Agua Azeda	15	0.4	5.1	300	120	12	4.2	20	19
40	59	77FEB	Agua Chalet Frio	17.5	0.03	4.8	310	120	13	3.6	40	18
41	66	77FEB	Nasc Miguel Henrique	17.5	0.5	5.3	350	120	11	3.1	44	26
42	67	77FEB	Nasc Dr. Dinis	15	0.01	4.6	290	130	11	5	32	20
43	70	77FEB	Nasc do Camaiga	13.5	0.5	6.7	153	81	4	3.9	18	7.8
44	71	77FEB	Nasc da Mae d'Agua	15.5	25	6.5	150	79	2.7	2.7	19	5.3
45	72	77FEB	Nasc do Rosario	14	4	6.5	172	69	2.7	3	21	5.9
46	73	77FEB	Nasc Espanhola	14.5	1	6.5	140	71	2.7	2.2	16	4.9
47	74	77FEB	Nasc do Galego	14.5	40	55	130	82	4.2	2.8	10	6.4
48	75	77FEB	Nasc no Lagoa S.Br'as	13	0.2	6	121	58	0.98	1.4	15	4.6
49	36	77FEB	Nasc no Verde Tinto	13	2	5.2	98	46	1.8	1.9	13	3.3
50	8	77FEB	Well JK3	21.5	-	6.2	1940	58	16	72	160	21
51	20-W	77FEB	Well JK2	17	-	5.5	230	87	9.5	10	18	11
52	54-W	77FEB	Canadian drillhole	21	-	5.5	4300	210	9.2	0.34	900	59

Table 1b continued.

Sample#	Fe	HCO3	Cl	SO4	NO3	NH3	B	F
1	<0.05	-	12	5.3	0.1	2.3	0.03	1
2	<0.05	-	14	4.9	0.13	0.6	0.03	0.64
4A	<0.05	-	19	4.1	0.25	0.7	0.03	0.27
6	<0.05	-	24	5.9	0.5	<0.4	0.01	0.1
7	<0.05	-	28	14	0.92	1.3	0.03	0.54
9	<0.05	-	23	53	3.4	0.5	<0.01	0.56
10	<0.05	-	-	6.3	1.1	-	0.02	-
10A	-	40	33	9	1.4	<0.08	<0.2	1.9
11	<0.05	-	27	6	0.26	0.9	<0.01	0.35
12	<0.05	-	14	3.4	0.17	0.4	<0.01	0.53
13	<0.05	-	23	6	0.94	<0.4	<0.01	0.42
14	<0.05	-	14	3.5	0.29	1.2	0.01	0.31
18	0.09	59	16	5	0.16	-	<0.2	0.88
19	11	117	18	25	<0.1	0.72	<0.2	0.47
21	0.02	63	16	7	0.33	<0.08	<0.2	0.29
22	-	-	-	-	-	-	-	-
26	0.02	40	18	0.5	0.53	<0.08	<0.02	0.25
27	0.01	71	16	21	0.52	<0.08	<0.2	0.29
28	0.02	54	26	44	1	<0.08	<0.2	1
29	0.01	54	17	4	1.6	<0.08	<0.2	0.28
30	0.04	43	20	5	2.3	<0.08	<0.2	0.25
31	0.02	50	16	6	2.8	<0.08	<0.2	0.37
32	0.01	45	17	2	0.15	<0.08	<0.2	0.52
33	<0.005	38	14	2	0.61	<0.08	<0.2	0.36
35	0.02	38	16	23	0.74	0.16	<0.2	0.17
37	11	41	15	2	0.5	<0.08	<0.2	0.13
42	0.04	55	18	2	0.03	<0.08	<0.2	0.52
43	<0.005	35	35	2	<0.02	<0.08	<0.2	0.38
44	0.12	79	16	3	1.5	<0.08	<0.2	0.73
45	0.02	94	19	2	<0.02	<0.08	<0.2	0.35
45B	0.03	70.8	20.2	8.1	0.5	-	-	0.27
46A	0.01	171	34	9	2	<0.08	<0.2	0.95
46B	1.4	289.8	52.5	26.2	-	<0.08	-	-
46C	0.07	197.6	37.3	12.2	2	<0.08	-	2.1
50	0.04	40	12	4	0.03	<0.08	<0.2	0.93
51	0.01	109	12	3	0.04	<0.08	0.26	1.1
52	0.02	171	13	2	<0.3	<0.08	<0.2	1
53	6.4	256	12	8	<0.3	<0.08	0.26	1.1
58	6	134	16	18	<0.3	<0.08	0.26	0.9
59	4.6	118	18	41	<0.3	<0.08	<0.2	1.4
66	4.9	158	17	32	0.06	0.8	<0.2	1.2
67	4.9	118	17	28	0.07	0.4	<0.2	1.6
70	<0.01	72	13	5	0.07	0.36	<0.2	0.81
71	0.04	46	24	5	0.06	0.24	<0.2	0.67
72	<0.01	45	31	5	0.05	0.	<0.2	0.36
73	<0.01	40	22	5	0.05	0.2	<0.2	0.26
74	0.03	59	14	5	<0.1	<0.08	<0.2	0.26
75	<0.01	41	18	5	0.44	0.2	<0.2	0.24
36	0.01	38	14	3	0.3	<0.08	<0.2	0.27
8	<0.05	-	470	59	1.2	0.5	0.05	1.6
20-W	0.04	102	25	10	2	0.88	<0.2	0.57
54-W	34	634	690	160	<0.3	<0.8	0.34	0.34

Table 1c. Chemical analyses of thermal waters from Geonomics(1977).

No	Sample	Date	Description	Temp	Flow	pH	Cond	SIO2	Ca	Mg	Na	K	Fe	HCO3	Cl	SO4	NO3	NH3	B	F
1	2A	77FEB	Cald do Ribeira Grande	96.5	1	3.5	2400	320	26	9.6	98	40	25	-	2.5	750	0.16	3	0.06	0.1
2	3	77FEB	Cald Velha	98	0.3	6	2200	200	13	6.6	54	21	40	-	9	730	0.13	<0.4	0.09	0.1
3	3A	77FEB	Cald Velha	38	100	6.3	150	96	4.5	2.6	29	4.6	0.3	-	14	24	0.03	<0.4	0.01	0.4
4	4	77FEB	Ladeira Velha	30	1	6	290	120	9.4	3.8	54	9.5	<0.05	-	16	5.9	0.02	<0.4	0.03	0.63
5	5	77FEB	Asuas Vermelhas	43	0.02	8	2400	130	51	25	350	80	<0.05	-	39	20	<0.01	1.3	0.13	3.2
6	17	77FEB	Cald Lasoa das Furnas	70.6	1	5.8	215	180	46	24	30	20	19	-	15	-	-	-	-	-
7	18A	77FEB	Nasc Quenturas	56.7	0.3	5.9	1425	260	38	15	200	56	1	756	70	10	0.07	<0.08	0.6	7.9
8	19A	77FEB	Asua Santa	95.6	0.05	8.1	1050	130	1.4	6	180	30	0.05	366	100	190	0.1	<0.08	3.2	28
9	34-W	77FEB	Nasc Ferraria	54	-	6.8	-	250	400	500	5100	380	<0.01	744	9300	1200	0.67	<0.08	2	0.95
10	40	77FEB	Asua "Azeda"	25	0.035	4.3	220	110	4.4	2.4	20	14	0.02	37	20	45	0.01	<0.08	0.32	0.17
11	47A	77FEB	Asua da Moranguera	37.5	0.06	5.3	1690	210	50	24	260	42	0.11	951	84	6	0.1	<0.08	0.32	3.2
12	47B	77FEB	Asua da Moransuera	43.5	0.04	6.4	1580	199	-	-	-	-	4.03	-	-	-	-	-	-	15.12
13	48A	77FEB	Asua do Torno	39.5	4	5.3	1410	170	32	13	210	30	0.72	744	89	12	0.05	<0.08	0.38	5.7
14	48B	77FEB	Asua do Torno	39.2	1.07	-	-	-	-	-	-	-	-	-	68.2	-	-	-	-	-
15	48C	77FEB	Asua do Torno	39.8	0.26	6.12	1300	164	-	-	-	-	4.03	-	-	-	-	-	-	4.4
16	55	77FEB	Asua do San Guinhal	28.5	2	5.2	460	150	11	4.2	130	26	0.18	232	29	4	<0.3	<0.8	0.34	0.34
17	56	77FEB	Asua do Posso	43.5	2	6.2	1400	190	46	20	420	48	0.1	744	77	10	<0.3	<0.8	0.38	0.28
18	57	77FEB	Asuas GrutinhasI	44.5	0.3	6.2	1430	210	43	18	440	47	0.06	780	77	12	<0.3	<0.8	0.62	3.9
19	60	77FEB	Asua Prata	31.5	0.1	5.2	380	135	13	3.2	40	22	7	159	16	30	<0.3	<0.08	<0.2	1.3
20	61	77FEB	Nasc Padre Jose	60	0.3	5.9	820	270	19	5.6	130	36	19	329	33	56	<0.3	<0.08	0.6	2.3
21	68	77FEB	Nasc Parque Terra Nostra	42.5	10	5.6	550	130	15	9.6	64	17	10	183	58	4	0.16	0.8	<0.2	1.3

Table 1d. Chemical and isotopic analyses of cold and thermal waters analysed by the U. S. Geological Survey (nos 1-15) and by Sheppard (1981, nos 16-19).

No	Samp#	Date	Description	Temp	fpH	lpH	SiO2	Fe	Mn	Ca	Mg	Sr	Ba
1	AZ-01	82JUL20	Nasc Lagoa das Furnas	19	4.9	7.39	64	0.4	0.1	10.1	2.96	0.01	6.6
2	AZ-02	82JUL20	Cald Lagoa das Furnas	75	3	2.33	134	3	0.5	10.9	4.28	0.03	7.2
3	AZ-03	82JUL21	Cald Asmodeu	97	7.5	8.41	365	0.1	0.2	0.64	0.05	0.02	3.86
4	AZ-04	82JUL22	Cald Grande	100	-	8.38	362	0.1	0.1	1.59	0.02	0.04	2.3
5	AZ-05	82JUL23	Cald Esguicho	100	-	8.28	298	0.5	0.1	1.22	0.1	0.01	1.77
6	AZ-08	82JUL23	Nasc Azeda	17	-	7.58	109	5.5	0.5	7.27	3.96	0.04	6.3
7	AZ-09	82JUL23	Agua Caldeirao	70	-	7.9	152	3.1	1.1	7.62	3.53	0.05	5.53
8	AZ-11	82JUL23	Agua Padre Jose	59.5	-	7.9	234	2.7	1.4	13	4.48	0.04	9.37
9	AZ-12	82JUL23	Aguas Grutinhas I	47.5	-	8.18	189	3.3	0.6	29.7	13.8	0.07	22.1
10	AZ-13	82JUL25	Lombadas CO2	-	4.7	7.42	96	0.8	1	4.38	2.64	0.01	3.3
11	AZ-14	82JUL25	Lombadas	-	5.3	7.21	61	1.2	0.2	1.69	0.3	0.01	1.01
12	AZ-15	82JUL25	Lombadas black	-	-	7.79	103	-	-	9.38	4.55	0.04	6.8
13	AZ-16	82JUL26	PV-1 downhole	-	-	9.41	450	-	-	0.78	0.007	1.5	4.36
14	AZ-17	82JUL27	Rib Quente Fe pool	28	6	7.95	133	26	5.4	81.4	42.7	0.4	62.7
15	AZ-18	82JUL27	Furnas fumarole pool	93	6	7.56	207	8.6	1.1	6.84	2.61	0.02	5.45
16	DS-20	81FEB26	PV-1 Weirbox	92	-	9.6	-	-	-	1.1	0.01	-	-
17	DS-21	81MAR20	PV-1 Weirbox	96	-	9.6	-	-	-	1.22	0.03	-	-
18	DS-22	81MAR20	Cald Grande	98	-	8.3	-	-	-	1.4	0.03	-	-
19	DS-23	81MAR20	Cald Lagoa das Furnas	93	-	3.8	-	-	-	7.52	4.33	-	-

No	Na	K	Li	Rb	Cs	HCO3	SO4	Cl	F	B	Trit	D/H	O18	C13(w)	C13(g)	O18-SO4
1	26	7.3	0.01	0.01	0.01	62	4	20	0.5	0.1	15.4	-17	-3.35	-13.62	-	-
2	30.6	10.6	0.003	0.01	0.01	0	120	18	0.61	1	-	0.3	0.77	-	-	5.16
3	551	22.7	0.28	0.12	0.05	714	120	295	16.9	12.1	-	6.1	2.58	-3.67	-4.17	8.84
4	486	18.4	0.25	0.13	0.05	668	34	299	18.3	12.6	0.62	-2.7	0.78	-4	-	3.97
5	392	16.4	0.19	0.13	0.03	605	70	210	12.4	9	0.38	4.6	1.38	-3.76	-3.85	3.66
6	36.3	15.4	0.005	0.011	0.01	116	7	21	1.13	0.1	4.43	-17.4	-3.65	-8.3	-	6.62
7	78.9	14.4	0.033	0.01	0.01	196	3	42	1.96	1	3.24	-15.9	-3.29	-5.22	-	5.97
8	119	30.4	0.052	0.03	0.01	323	25	40	1.89	0.5	8.92	-17.3	-3.53	-5.09	-	2.88
9	261	30.5	0.15	0.05	0.01	743	5	94	3.52	0.5	3.75	-14.8	-3.12	-6.73	-	-
10	38	13.4	0.008	0.01	0.01	126	1	16	0.75	0.1	17.6	-16.9	-3.81	-	-	-
11	16.9	3.6	0.002	0.01	0.01	34	1	17	0.61	0.1	17	-18.6	-3.78	-6.81	-	-
12	81.3	34.5	0.027	0.066	0.01	309	1	20	0.77	0.1	11.3	-17.7	-3.85	-5.87	-	-
13	1240	181	2.76	0.01	0.18	529	170	1690	24.1	5.9	0.36	-16.2	-2.74	-	-4.83	1.19
14	337	31.8	0.13	0.01	0.02	1190	2	55	2.93	0.1	1.85	-12.5	-3.05	-5.67	-	-
15	308	30.6	0.103	0.22	0.04	84	550	41	5.53	0.3	2.15	6.2	1.99	-12.91	-4.04	-
16	1851	-	-	-	0.24	1090	182	2370	25	-	-	-8.7	-2.2	-	-	-
17	1829	-	-	-	0.24	1290	164	2320	25	-	-	-10.6	-2.2	-	-	-
18	509	-	-	-	0.012	1039	72	292	18	-	-	-4.2	0.2	-	-	-
19	29	-	-	-	0.0019	-	144	14	1.2	-	-	-7.8	-2.3	-	-	-

Table 1e. Chemical composition of samples from geothermal wells (in mg/kg, °C and pH units).

Source	PV-1 downhole	PV-1* flashed calculated	PV-1 flashed	RG-1 flashed	PV-1 flashed	PV-1 downhole calculated	RG-1 flashed
ref	1	1	2	2		3	3
temp	--	100	92	96		--	
pH	9.41		9.6	9.6		--	
SiO_2	450	602	--	--	558	408	324
Ca	0.78	1.0	1.1	1.2		60-800	
Mg	0.007	0.01	0.01	0.03			
Sr	1.5	2.0	--				
Ba	4.4	5.9	--				
Na	1240	1660	1851	1829	1870	1403	1748
K	181	242	--		282	211	168
Li	2.8	3.7	--		1.1	0.09	0.15
Rb	0.01	0.01	--				
Cs	0.18	0.24	0.24	0.24			
HCO_3	529	708	1090	1290			
SO_4	170	228	182	164			
Cl	1690	2263	2370	2320	2489	1879	2517
F	24	32	25	25	29	21	1.1
B	5.9	7.9	--	--	--	--	--

Data from 1) Aquater (1982), 2) Sheppard (1981), 3) U.S. Geological Survey.

Table 2. Isotope data on drillhole waters and other isotope data without chemical analyses.

No.	Date	Description	δD (H_2O)	$\delta^{18}O$ (H_2O)	$\delta^{34}S$ (SO_4)	$\delta^{18}O$ (SO_4)	$\delta^{13}C$ (w)	$\delta^{13}C$ (g)	Cl	Ref.
1	82 MAR	Lagoa do Fogo rain	-25.0	-5.02	--	--	--	--	--	1
2	82 MAR	PV-1 weir	-12.3	-2.72	--	--	--	--	2490	1
3	82 MAR	RG-1 separator	- 7.0	-1.60	--	--	--	--	2219	1
4	1980	PV-1 water	-15.0	-1.90	+15.1	+4.3	--	--	--	1
5	1980	PV-1 water	-21.0	-2.74	+14.8	+4.9	--	--	--	1
6	1980	PV-1 water	-18.0	-1.52	+15.2	+3.1	--	--	--	1
7	1980	PV-1 steam	-37	-6.93	--	--	--	--	--	1
8	81 MAR	PV-1 weir	- 8.7	-2.2	--	--	--	--	2370	2
9	81 MAR	PV-1 weir	-10.6	-2.2	--	--	--	--	2320	2
10	82 JUL	PV-1 downhole	-16.2	-2.74	--	+1.19	--	-4.83*	1690	3
11	82 JUL	RG-1 2nd downhole	-16.4	-3.33	--	+0.52	--	-4.01*	--	3
12	82 JUL	RG-1 1st downhole	-13.7	-2.7	--	--	--	--	--	3
13	82 JUL	Cald dos Vimes	--	--	--	--	--	-3.78	--	3
14	82 JUL	97°Fumarole nr river	+ 0.9	+0.22	--	+3.08	--	--	--	3
15	82 JUL	Furnas (unnamed) 42°C	-12.8	-2.90	--	+5.99	--	-3.17	--	3
16	82 JUL	Furnas San Guinhal	-13.5	-3.09	--	+7.90	--	--	--	3
17	81, 82	Cald Rib Grande	+ 3.9	+0.66	--	--	--	-4.55	--	3
18	81, 82	Cald Velha	+17.2	+0.15	--	--	--	-3.79	--	3

*Gas from lubricator.
Data from 1) Aquater (1982), 2) Sheppard (1981), 3) U.S. Geological Survey.

Table 3. Gas analyses and gas geothermometer temperatures.

No.	Sample	Location	Steam/ gas	CO_2	H_2S	H_2	CH_4	NH_3	N_2	O_2	Ar	He	Tgas, °C
1	AZ81-4	Cald Rib Grande	4.32	99.5	0.25	0.19	0.004	0	0.10	0	0.003	0.0016	209
2	AZ81-5	Cald Velha	0.200	99.6	0.097	0.009	0.018	0	0.18	0	0.005	0.0016	128
3	AZ82-16	PV-1	0	99.7	0.16	0.08	0.0018	0	0.030	0	0.001	0.0002	190
4	--	RG-1	0.027	99.5	0.24	0.11	0.005	0	0.074	0	0.0028	0	194
5	AZ81-1	Lag das Furnas	0.080	99.6	0.19	0.088	0.00003	0.005	0.17	0	0	0.0008	228
6	AZ82-3	Cald Asmodeu	15.6	99.1	0.50	0.23	0.005	0.014	0.18	0	0.006	0.0008	221
7	AZ82-5	Cald Esguicho	3.94	99.1	0.39	0.20	0.007	0	0.31	0	0.010	0.0005	212
8	AZ82-6	Cald dos Vimes	1.86	99.2	0.36	0.20	0.007	0	0.23	0	0.009	0.0005	211
9	AZ82-7	97° Furnas unnamed	0.550	99.4	0.20	0.21	0.019	0.006	0.18	0	0.006	0.0003	197
10	AZ82-18	Furnas road to R. Quente	0.103	98.9	0.38	0.26	0.013	0.009	0.38	0	0.013	0.00015	213
11	AZ81-2	Furnas unnamed	16.3	99.2	0.54	0.21	0.005	0.009	0.10	0	0.003	0.0007	219
12	AZ81-3	R. Quente	0.986	98.9	0.30	0.15	0.016	0	0.59	0	0.013	0.0002	194
13	81G10	PV-1	--	98.5	1.3	0.01	0.017	0.024	0.16	0.006	0.003	0.0015	212
14	81G11	Cald Grande	--	98.9	0.62	0.31	0.009	0.007	0.15	0.002	0.0018	0.0016	226
15	GN1	Lag das Furnas	--	93.8	3.3	0.13	0.0009	--	2.9	0.63	--	--	248
16	GN7	Cald Velha	--	95.0	3.2	0.12	0.013	--	1.4	0.29	--	--	221
17	GN11	Cald Rib Grande	--	94.2	3.7	0.13	0.0024	--	1.1	0.29	--	--	240
18	GN14	Dalhousie drill hole	--	83.3	6.4	0.015	0.0005	--	3.4	1.5	--	--	209

Analyses 1-12 by N. Nehring, in mole percent; analyses 13, 14 from Sheppard (1981), in mole percent; analyses 15-18 from Geonomics (1977), in volume percent. Tgas calculated from equations in D'Amore and Panichi (1980).

Table 4a. Chemical geothermometer temperatures and mixing calculations for thermal waters analysed by Geonomics (1977).

NAME	T OR P	SIO2	CL	NA	K	CA	HCO3	CO3	SO4	B	MG
Cald do Ribeira Grande	96.5	320	2.5	98	40	26	0	0	750	0.06	9.6
Cald Velha	98	200	9	54	21	13	0	0	730	0.09	6.6
Cald Velha	38	96	14	29	4.6	4.5	0	0	24	0.01	2.6
Ladeira Velha	30	120	16	54	9.5	9.4	0	0	5.9	0.03	3.8
Aguas Vermelhas	43	130	39	350	80	51	0	0	20	0.13	25
Cald Lagoa das Furnas	70.6	180	15	30	20	46	0	0	0	0	24
Nasc Guenturas	56.7	260	70	200	56	38	756	0	10	0.6	15
Agua Santa	95.6	130	100	180	30	1.4	366	0	190	3.2	6
Nasc Ferraria	54	250	9300	5100	380	400	744	0	1200	2	500
Agua "Azeda"	25	110	20	20	14	4.4	37	0	45	0.32	2.4
Agua da Moranguera	37.5	210	84	260	42	50	951	0	6	0.32	24
Agua da Moranguera	43.5	199	0	0	0	0	0	0	0	0	0
Agua do Torno	39.5	170	89	210	30	32	744	0	12	0.38	13
Agua do Torno	39.2	0	68.2	0	0	0	0	0	0	0	0
Agua do Torno	39.8	164	0	0	0	0	0	0	0	0	0
Agua do San Guinhal	28.5	150	29	130	26	11	232	0	4	0.34	4.2
Agua do Poso	43.5	190	77	420	48	46	744	0	10	0.38	20
Aguas GrutinhasI	44.5	210	77	440	47	43	780	0	12	0.62	18
Agua Prata	31.5	135	16	40	22	13	159	0	30	0	3.2
Nasc Padre Jose	60	270	33	130	36	19	329	0	56	0.6	5.6
Nasc Parque Terra Nostra	42.5	130	58	64	17	15	183	0	4	0	9.6

NONMIXED-CL=299 T=100 COLD-CL=18 T=20 SIO2=70 TEMP STEAM SEP=100
BSMM USING SIO2 TEMP

NAME	T	CL	SIO2	TQA	TQC	TCH	TAM	TNK	T13	MC	T43	MC	TBS	XH	CLAQ	EAQ	TWSMM1	XH	TWS2	XH	CLHCO3	CLSO4	CLB
Cald do Ribeira Grande	97	3	320	198	216	199	90	413	255*	-24	150	-24	0	.26	2	846	0(130)	0	201	.95	0	0.003	41.66
Cald Velha	93	9	200	170	180	158	56	402	245*	-40	132	-40	0	.22	8	720	243(70)	.33	171	.97	0	0.012	100
Cald Velha	38	14	96	126	135	107	15	243	187	MC>0	93*	MC>0	0	.16	12	531	225(70)	.08	160	.22	0	0.583	1400
Ladeira Velha	30	16	120	136	148	121	26	258	190*	MC>0	109	MC>0	0	.18	13	573	288(100)	.03	215	.12	0	2.711	533.3
Aguas Vermelhas	43	39	130	141	153	126	31	298	236*	MC>0	184	MC>0	0	.25	32	595	307(80)	.07	183	.28	0	1.95	300
Cald Lagoa das Furnas	71	15	180	161	173	150	50	555	255	-20	90*	-20	0	.22	13	681	300(70)	.16	179	.63	0	0	0
Nasc Guenturas	57	70	260	181	199	180	74	334	240*	MC>0	165	MC>0	0	.39	54	766	0(130)	0	221	.45	0.092	7	116.6
Agua Santa	96	100	130	147	153	126	31	250	240*	-48	261	-48	291	.44	90	618	175(70)	.48	148	.94	0.273	0.526	31.25
Nasc Ferraria	54	9300	250	178	196	177	71	158	200*	RD50	252	RD50	27	.57	7228	755	0(130)	0	222	.42	12.5	7.75	4650
Agua "Azeda"	25	20	110	132	143	115	22	572	278*	MC>0	132	MC>0	0	.19	16	554	288(100)	.01	244	.06	0.540	0.444	62.5
Agua da Moranguera	38	84	210	166	183	162	59	246	207*	MC>0	147	MC>0	340	.41	65	703	0(130)	0	246	.21	0.088	14	262.5
Agua da Moranguera	44	0	199	164	180	158	56	0	0*	MC>0	0	MC>0	0	0	0	693	0(130)	0	222	.29	0	0	0
Agua do Torno	40	89	170	155	169	146	46	229	200*	MC>0	142	MC>0	322	.40	71	654	0(130)	0	218	.24	0.119	7.416	234.2
Agua do Torno	39	68	0	0	0	0	0	0	0*	MC>0	0	MC>0	0	0	0	0	0(0)	0	0	0	0	0	0
Agua do Torno	40	0	164	153	167	143	44	0	0*	MC>0	0	MC>0	0	0	0	646	0(130)	0	213	.24	0	0	0
Agua do San Guinhal	29	29	150	147	161	136	39	277	222*	MC>0	161	MC>0	0	.23	23	621	0(130)	0	256	.10	0.125	7.25	85.29
Agua do Poso	44	77	190	161	177	154	53	202	197*	MC>0	164	MC>0	345	.38	61	682	0(130)	0	218	.29	0.103	7.7	202.6
Aguas GrutinhasI	45	77	210	167	183	162	59	195	195*	MC>0	166	MC>0	349	.39	60	706	0(130)	0	225	.30	0.098	6.416	124.1
Agua Prata	32	16	135	142	155	129	33	493	264*	MC>0	130	MC>0	0	.19	13	599	232(120)	.05	222	.14	0.100	0.533	0
Nasc Padre Jose	60	33	270	183	202	183	77	332	238*	MC>0	159	MC>0	0	.30	26	778	0(130)	0	219	.49	0.100	0.589	55
Nasc Parque Terra Nos	43	58	130	141	153	126	31	324	222*	MC>0	122	MC>0	357	.30	48	595	261(90)	.08	184	.28	0.316	14.5	0

Table 4b. Chemical geothermometer temperatures and mixing calculations for thermal waters analysed by the U. S. Geological Survey.

NAME	T OR P	SIO2	CL	NA	K	CA	HCO3	CO3	SO4	B	MG
Cald Lagoa das Furnas	75	134	18	30.6	10.6	10.9	0	0	120	1	4.28
Cald Asmodeu	97	365	295	551	22.7	0.64	714	0	120	12.1	0.05
Cald Grande	100	362	299	486	18.4	1.59	668	0	34	12.6	0.02
Cald Esguicho	100	298	210	392	16.4	1.22	605	0	70	9	0.1
Agua Caldeirao	70	152	42	78.9	14.4	7.62	196	0	3	1	3.53
Agua Padre Jose	59.5	234	40	119	30.4	13	323	0	25	0.5	4.48
Aguas Grutinhas I	47.5	189	94	261	30.5	29.7	743	0	5	0.5	13.8
PV-1 downhole	0	450	1690	1240	181	0.78	529	0	170	5.9	0.007
Furnas fumarole pool	93	207	41	308	30.6	6.84	84	0	550	0.3	2.61

NONMIXED-CL=299 T=100 COLD-CL=18 T=20 SIO2=70 TEMP STEAM SEP=100
BSMM USING SIO2 TEMP

NAME	T	CL	SIO2	TQA	TQC	TCH	TAM	TNK	T13	MC	T43	MC	TBS	XH	CLAQ	EAQ	TWSMM1	XH	TWS2	XH	CLHCO3	CLSO4	CLB
Cald Lagoa das Furnas	75	18	134	146	154	128	32	376	227*	-6	102	-6	0	.21	16	616	203(70)	.29	157	.68	0	0.15	18
Cald Asmodeu	97	295	365	207	227	212	100	108	185*	-11	311	-11	209	.98	233	885	0(130)	0	209	.96	0.413	2.458	24.38
Cald Grande	100	299	362	207	226	211	100	102	170*	RC.5	243	RC.5	207	1	237	884	0(130)	0	207	1	0.447	8.794	23.73
Cald Esguicho	100	210	298	194	210	192	84	110	174*	MC>0	242	MC>0	241	.77	172	827	0(130)	0	194	1	0.347	3	23.33
Agua Caldeirao	70	42	152	152	162	137	39	263	210*	MC>0	137	MC>0	0	.28	36	642	241(70)	.21	168	.62	0.214	14	42
Agua Padre Jose	60	40	234	175	191	171	67	317	235*	MC>0	162	MC>0	0	.31	32	741	0(130)	0	209	.49	0.123	1.6	90
Aguas Grutinhas I	48	94	189	162	176	154	53	205	193*	MC>0	148	MC>0	321	.43	75	682	0(130)	0	209	.34	0.126	18.8	188
PV-1 downhole	0	1690	450	222	247	234	118	232	286*	RC.5	614	RC.5	0	0	0	952	0(0)	0	0	0	3.194	9.941	296.4
Furnas fumarole pool	93	41	207	172	182	161	59	187	202*	MC>0	203	MC>0	0	.31	35	726	262(70)	.28	175	.91	0.488	0.074	136.6

Table 4c. Calculated aquifer temperatures and chloride contents of the hot end member for Furnas warm springs compared with indicated temperatures and chloride contents of Furnas boiling springs (last three analyses).

No.	Name	Temp. meas. °C	Cl meas. mg/kg	Fraction hot	Aquifer temp. °C	Na-K-Ca temp. °C	Model	Cl hot, mg/kg Cl cold=18	Cl hot, mg/kg Cl cold=10
18A	Nasc Quenturas	56.7	70	0.45	221	240	II	135	143
19A	Agua Santa	95.6	100	.48	(175)	240	I	(188)	(198)
47A	Agua Moranguera	37.5	84	.21	246	207	II	332	362
48A	Agua do Torno	39.5	89	.24	218	200	II	313	339
55	Agua do San Guinhal	28.5	29	.10	256	222	II	128	200
56	Agua do Pogo	43.5	77	.29	218	197	II	221	241
57	Aguas Grutinhas I	44.5	77	.30	225	195	II	215	233
60	Agua Prata	31.5	16	.05	(232)	264	I	—	(130)
				.14	222		II	--	(53)
61	Nasc Padre Jose	60	33	.49	219	238	II	(48)	(57)
68	Piscina Parque	42.5	58	.08	(261)	222	I	(518)	--
				.28	184		II	161	181
AZ09	Agua Caldeirao	70	42	.21	(241)	210	I	(132)	(162)
				.62	(168)		II	(57)	(62)
AZ11	Nasc Padre Jose	60	40	.49	(209)	235	II	(63)	(71)
AZ12	Aguas Grutinhas I	48	94	.34	209	193	II	241	257
AZ03	Cald Asmodeu	97	295	.97	209	185	II	303	304
AZ04	Cald Grande	100	299	1.0	207	170	II	299	299
AZ05	Cald Esguicho	100	210	1.0	194	174	II	210	210

Notes: I = warm spring (silica) mixing model without boiling.
II = warm spring (silica) mixing model with boiling and steam loss at 100°C before mixing.
Parentheses: apparently steam-heated waters, and calculations from WSMM1 not included in averages.

Table 4d. Sulfate-water isotope geothermometer temperatures.

No.	Sample	Location	Collection temp, °C	$\delta^{18}O$ (SO_4)	$\delta^{18}O$ (H_2O)	T1	T2	T3
1	20-80	PV-1	120?	+3.1	-1.5	302	263	274
2	21-80	PV-1	120?	+4.3	-1.9	256	232	237
3	22-80	PV-1	120?	+4.9	-2.7	223	207	210
4	23-80	PV-1	120?	+3.8	-2.5	253	230	235
5	AZ82-16	PV-1 downhole	230?	+1.2	-2.7	326	310	313
6	--	RG-1 downhole	230?	+0.5	-3.3	329	313	316
7	AZ82-2	Lagoa das Furnas	75	+5.2	+0.8	310	249	268
8	AZ82-3	Cald Asmodeu	97	+8.8	+2.6	255	224	232
9	AZ82-4	Cald Grande	100	+4.0	+0.8	356	285	308
10	AZ82-5	Cald Esguicho	100	+3.7	+1.4	399	306	337
11	AZ82-8	Agua Azeda	17	+6.6	-3.7	175	145	153
12	AZ82-9	Agua Caldeirao	70	+6.0	-3.3	191	172	176
13	AZ82-10	Furnas unnamed	97	+3.1	+0.2	379	291	317
14	AZ82-11	Nasc Padre Jose	70	+2.9	-3.5	250	212	273
15	--	Furnas unnamed	42	+6.0	-2.9	198	168	176
16	--	Agua San Guinhal	34	+7.9	-3.1	164	142	147

Notes: T1 calculated with conductive cooling. Used for warm springs and wells collected using a downhole sampler.
T2 calculated with cooling by steam loss at collection temperature. Used for separated well samples.
T3 calculated with cooling by continuous steam separation. Used for boiling hot springs.
Analyses 1-4 from Aquater (1982), remainder from U.S. Geological Survey.

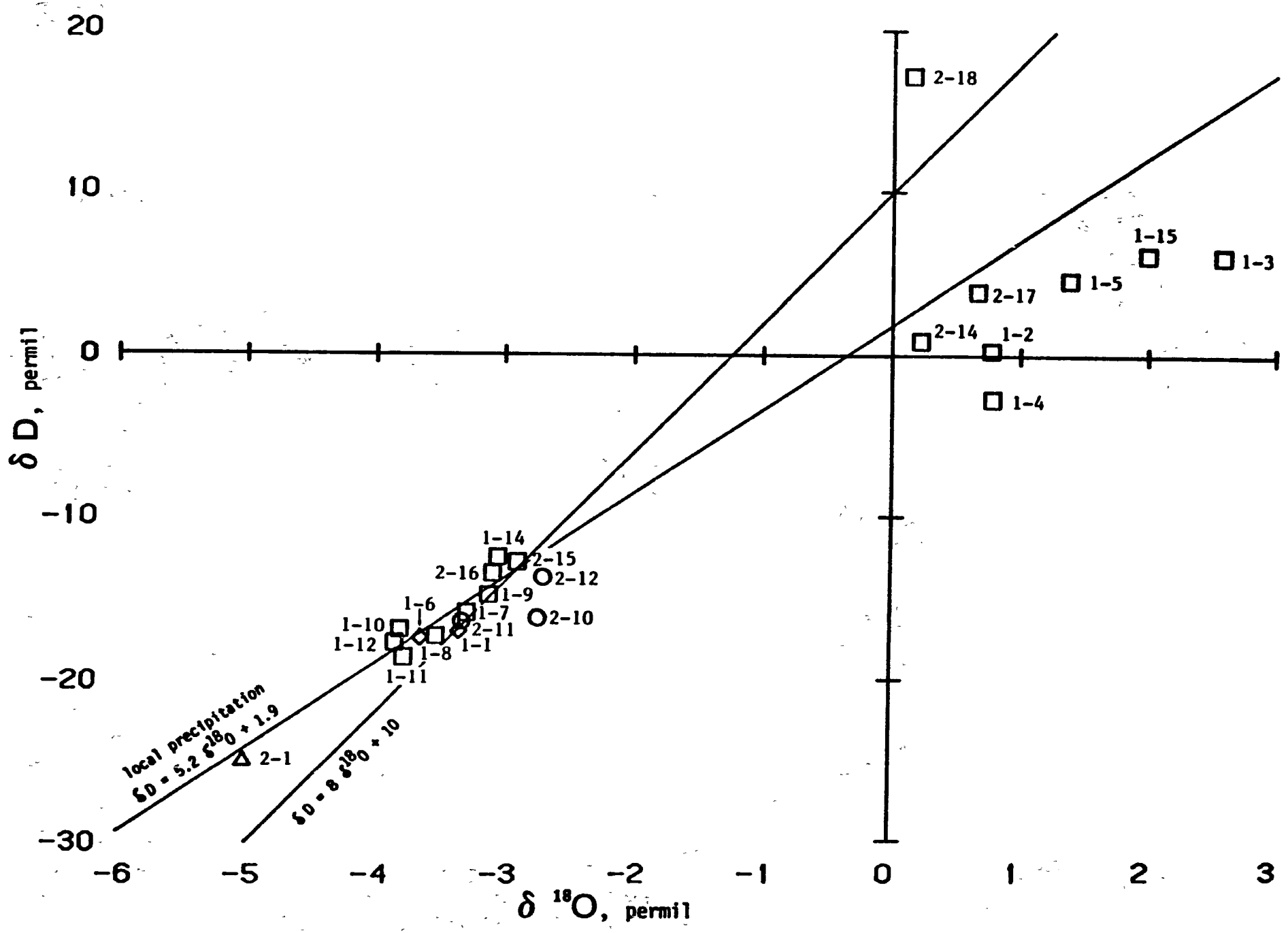

Figure 1. Isotopic compositions of cold and thermal waters. Numbers refer to sample numbers in tables 1d and 2.

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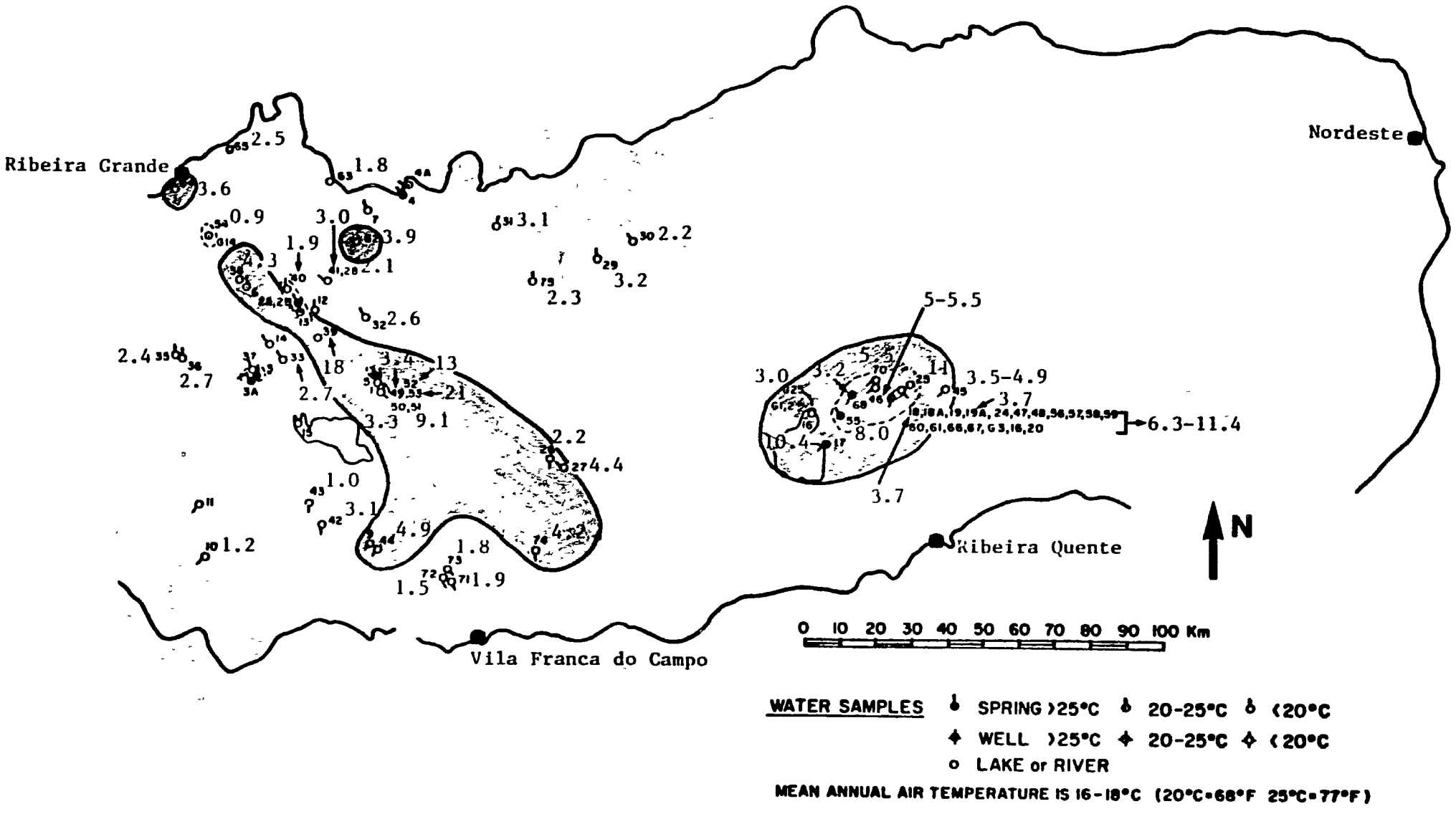

Figure 2. Areas of anomalous HCO_3 concentrations in São Miguel groundwaters shown by HCO_3/Cl weight ratios of cold springs, cold wells, and surface waters on a map of sample locations from Geonomics (1977).

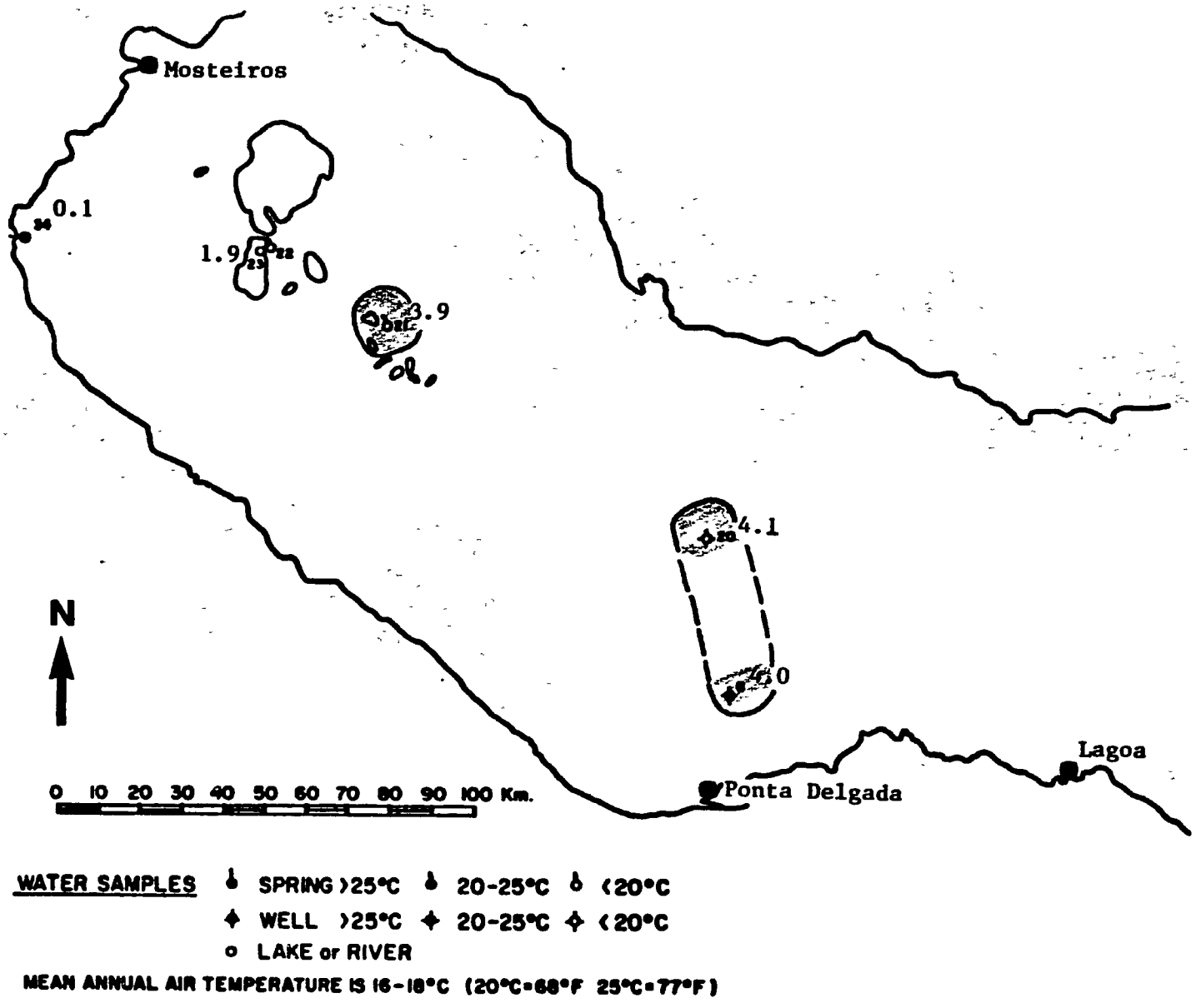

Figure 2. Continued.

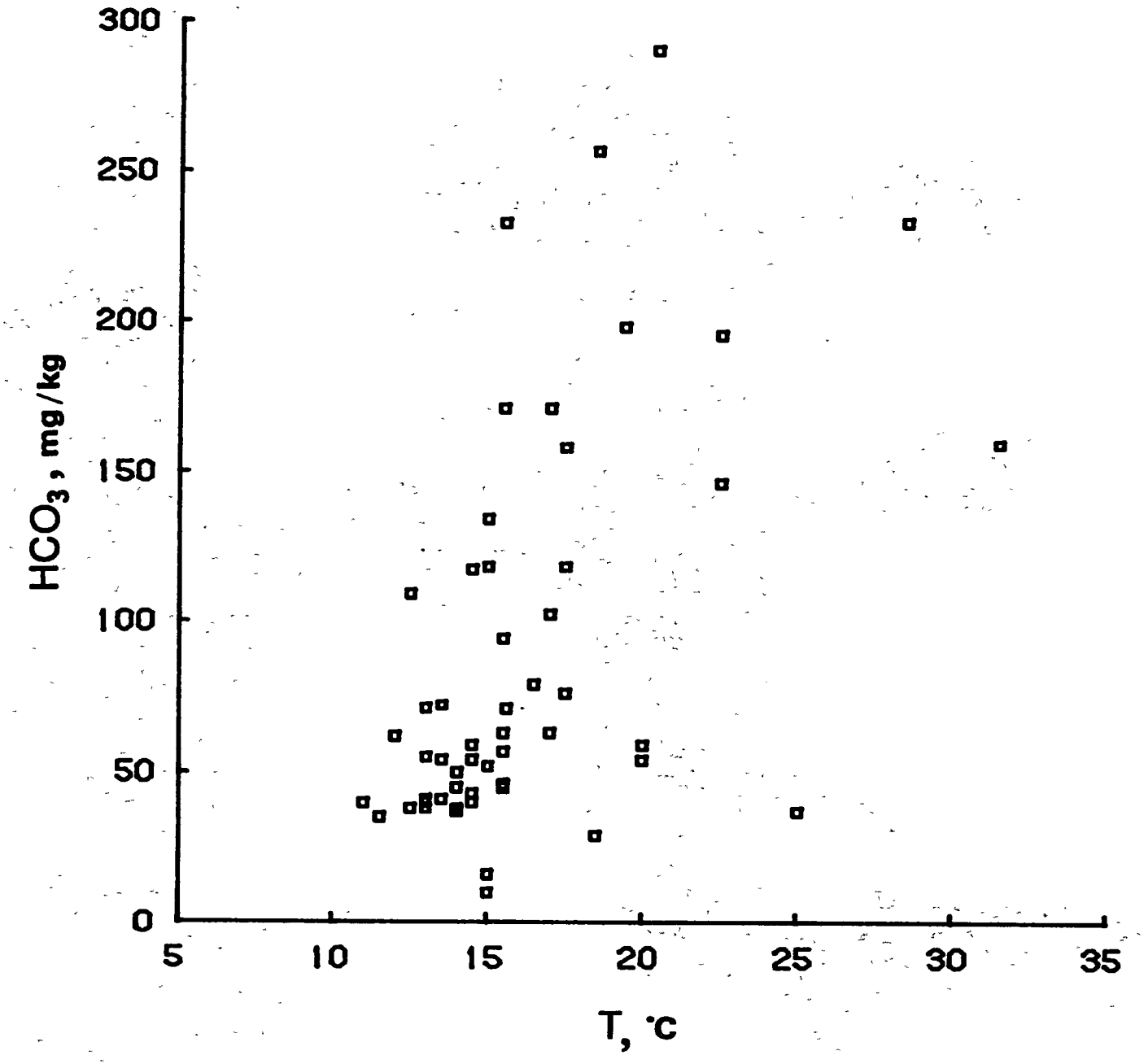

Figure 3. Plot showing a positive correlation between HCO_3 concentration and temperature of cold and warm springs. (Data from Table 1.)

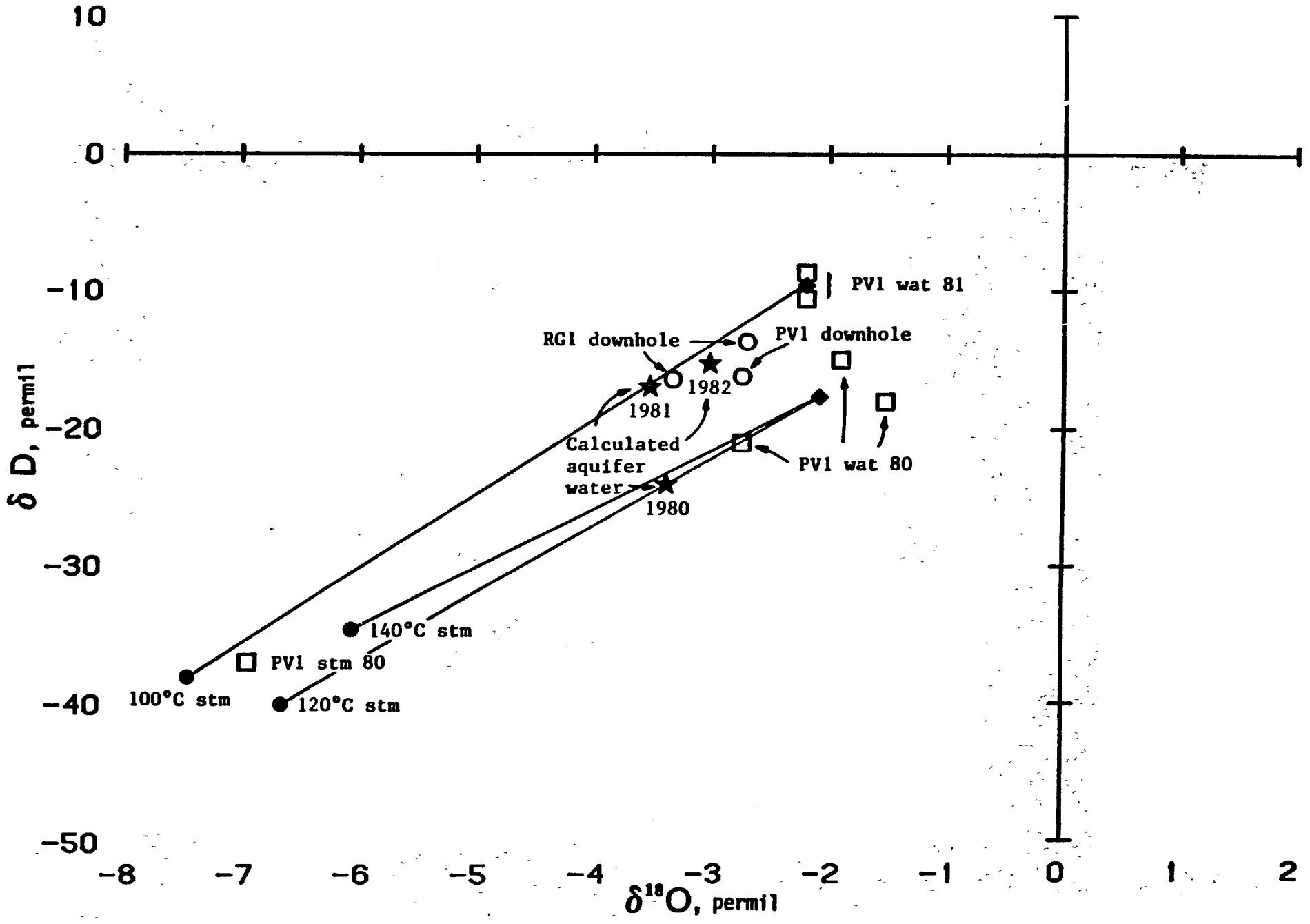

Figure 4. Isotopic compositions of geothermal well samples