

## SHALLOW THERMAL STRUCTURE AND HYDROLOGY OF ASCENSION ISLAND

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**Abstract--**

## INTRODUCTION

The geothermal exploration on Ascension Island, <sup>located in the</sup> South Atlantic Ocean, provided a unique opportunity to study shallow thermal structure and hydrology of a small island. The principal source of information in this study comes from seven core holes that were drilled for the measurement of subsurface temperatures. The core from these holes has also provided abundant information on the geology of the shallow subsurface that is described in Nielson and Sibbett (1996).

Ascension Island is located about 80 km west of the Mid-Atlantic Ridge and about 50 km south of the Ascension Fracture Zone (Fig. 1; van Andel et al., 1973). Ascension rises to 850 m above sea level from the ocean floor 3000 m below sea level (Brozena, 1986). The island has an area of about 100 km<sup>2</sup>. The surface geology of Ascension is characterized by young volcanic activity of both basaltic and rhyolitic character. The basaltic eruptions are probably only a few hundred years old while rhyolites as young as 0.06 Ma have been dated (Nielson and Sibbett, 1996).

As part of the geothermal exploration of the island, seven coreholes were drilled in the locations shown in Fig. 2. The positioning of these holes was based on geology, aeromagnetic interpretation (Ross et al., 1996b ) and electrical resistivity (Ross et al., 1996a). Each was drilled in a location that represented a potential production well site rather than being located to provide a statistical sampling of the heat flow from Ascension Island.

#### TEMPERATURE GRADIENT HOLES

Seven core holes that range in depth from 63 m to 533 m were drilled on Ascension between August 25 and December 12, 1983. The descriptive information for these holes is presented on Table 1. The drilling was done by Tonto Drilling Services of Salt Lake City, Utah using a skid-mounted Longyear 44 rig. The holes were generally started with a 14.3 cm tricone to provide a large enough hole for 11.4 cm (4.5 inch) surface casing to be set to a depth of 12 to 55 m. This was cemented in place to prevent caving and allow the installation of a blow-out preventer. Most of the coring was done using HQ wireline core bits which cut a 9.78 cm diameter hole and recovered 6.35 cm diameter core. In the two deepest holes, it became necessary to reduce to NQ size which resulted in a 7.72 cm hole and 4.7 cm diameter core. At total depth, 3.8 cm (1.5 inch) black iron pipe, which was open at the bottom, was placed in the holes to preserve them for temperature logging.

Details of the drilling of each hole can be found in Sibbett et al. (1984). In general, all holes were drilled without fluid returns. The average drilling rate over the life of the project was 21 m/day with an average cost of \$246/m (exclusive of mobilization).

## THERMAL STRUCTURE

All subsurface temperature measurements were made with logging units made by Natural Progression Instruments. These were calibrated prior to shipment to the island and the ice-point was again checked prior to running the temperature gradient surveys. Due to lost circulation conditions, the holes were cooled by the drilling process. Therefore, a number of measurements were made to establish equilibrium conditions. These data, for each of the holes, are shown in Figs. 3-10.

GH-1 was the first of the thermal gradient holes drilled. It was located on the basis of detailed electrical resistivity measurements (Ross et al., 1996b) which documented a 10 ohm-m resistivity zone at a depth of about 330 m below sea level in this location. The temperature profiles for this hole are shown in Fig. 3. The highest temperature recorded is 42.06°C, and it was encountered at the bottom of the hole. The gradient at the bottom of the hole is about 67°C/km.

GH-2 was drilled to a depth of 533 m near the southern margin of Cricket Valley. The temperature logs for this hole are

summarized in Fig. 4. The elevation of the hole is about 479 m above sea level. This, in conjunction with the high permeability of the rocks and the constant cloudiness and mist on that side of the island, have resulted in a depressed thermal gradient in the upper portions of the hole. This gradient is characteristic of a zone of recharge with downward percolating meteoric water buffering the temperature of the hole to approximately the average atmospheric temperature. Below 150 m, however, the gradient increases to 58°C/km. The maximum temperature measured in this hole was 45.6°C at the bottom, 530 m.

GH-3 was drilled near Booby Hill in an area that is now covered by the rapid turnoff at the southeast end of the runway. Booby Hill is a relatively young basaltic vent area, and the hole was drilled to test for any latent heat along this zone. Due to drilling problems, the hole only reached 63 m. The thermal log from this hole is illustrated in Fig. 5. This log shows that the hole has a negative thermal gradient. That is, it is hotter at the surface than at depth. The higher temperatures near the surface result from heating by the sun. The cooler temperatures at depth suggest that high temperatures will not be found at sea level where water would be expected to be encountered.

Hole GH-4 was drilled near Bear's Back largely to test the geothermal potential of an aeromagnetic trend detected in this area (Ross et al., 1996a). The temperature logs of this hole are shown in Fig. 6. The maximum temperature recorded is 40.27°C at the bottom of the hole. The thermal gradient recorded above the

water table is  $54.7^{\circ}\text{C}/\text{km}$ . Earlier logs show zones between 120 and 130 m and 160 to 170 m which, through time, equilibrated to form a linear gradient. These areas probably represent permeable zones which accumulated large amounts of cooler drilling fluid during drilling and required some amount of time to recover from the cooling effects. The change in slope of the gradient curves at sea level suggests a change in thermal conductivity resulting from water-saturated conditions.

GH-5 was drilled along the Old Mountain Road to the south of Sisters Peak. The hole was designed to test the thermal conditions associated with the young basalt eruptive episode in this area. The equilibrated temperature profile for this hole is shown on Fig. 7. The temperature shows a slightly positive gradient from 60 m to sea level ( $14.4^{\circ}\text{C}/\text{km}$ ), and then a negative gradient to the total depth of the hole. Although the temperature anomaly at sea level is slight, it was persistent through a number of temperature surveys. These higher temperatures appear to result from an approximate 5 m zone of warm water at the top of the water table, which is located at sea level as close as could be determined. It is probable that this thermal anomaly results from leakage from the geothermal system to the south. The low gradient above sea level suggests that temperature is controlled by downward percolation of meteoric water. The decrease in temperature below sea level suggests lateral flow of water, perhaps penetration of sea water through very permeable rock. The temperature of sea water at the

Georgetown dock on the day of the temperature profile of Fig. 7 was 27.7° C.

Hole GH-6 was drilled on the east flank of Devil's Riding School along the NASA road. Fig. 8 shows the temperature logs of this hole. The maximum temperature of 54.4°C was measured at the bottom of the hole. The gradient above the water table is 65.5°C/km. Zones at 240 m and 290 to 300 m were cooled considerably by drilling fluid and had not quite re-equilibrated at the last logging. The straight profile below sea level suggests conductive rather than convective heat transport. The gradient at the bottom of this hole is 71.9°C/km, and the conductive nature suggests that the rocks have little vertical permeability.

LDTGH was drilled approximately halfway between GH-1 and GH-6 to test for a fresh-water resource. Since it was drilled to be used as a water well, the design was different than the other holes described in this report (Sibbett et al., 1984). LDTGH was drilled 22.23 cm in diameter and cased with 16.83 cm pipe to a depth of 190 m. The bottom 24.4 m of the casing was slotted. An 9.78 cm corehole was then drilled to 340 m and 3.8 cm black iron pipe was tied back to the surface preserve the well for temperature measurements. The temperature logs of this hole are shown in Fig. 9. The highest temperature measured was 48.32°C at bottom hole on 4 December, 1983. The last log (3/9/84) shows that the lower portion of the hole has become isothermal with a temperature which is approximately average that found during the

12/4/83 logging. This is due to water flow within the drill hole itself.

Fig. 10 is a composite log of equilibrium temperature profiles plotted with respect to elevation. Plotting in this manner eliminates the bias of temperature measurements in zones of recharge above the water table. Fig. 10 shows that the wells may be grouped into three distinct categories. Wells GH-3 and GH-5 are clearly cold and their temperatures must be controlled by the influx of cold water at depth. GH-1, 2, 6 and LDTGH are warm and show very similar temperature signatures. GH-4 is intermediate between the other two groups. The signatures of these wells suggest the presence of active geothermal processes both in the area of Middleton ridge (GH-1, 6 and LDTGH) and Cricket Valley (GH-2). These locations correspond with the two principal centers of silicic volcanism on the island (Nielson and Sibbett, 1996).

#### HYDROLOGY

Water beneath the surface of Ascension Island will either be infiltrated from the surrounding Atlantic Ocean or fresh water derived from rain and condensation. Rainfall amounts are highly variable over the island with most precipitation falling on Green Mountain and its windward (SE) side. The earlier settlers established catchment basins on Green Mountain and Weather Post to provide their fresh water. The basaltic ash that covers Green Mountain is moist and earlier settlers have also dug shallow

wells to accumulate this water. No springs are known on the island although minor seeps of surface water can be found on the upper portions of Green Mountain. Daly (1925, p. 30) reports a "drip" immediately north of the present town of Two Boats. We were not able to find this feature. Dampier's Drip (Fig. 2) was a freshwater spring that apparently sustained early shipwrecked sailors and was the source for a pipeline to Georgetown in the early 1830's (Packer, 1983). This spring is no longer active. Periodic heavy rains do soak the island and flash flooding is not unknown.

Most of the moisture received by Ascension Island infiltrates the ground quickly due to the high permeability of the volcanic rocks. There is no standing water except for the catchment basins mentioned above. Once in the subsurface, the course of the infiltrating groundwater is determined by distribution of impermeable rock types (including dikes), present topography, and paleotopography.

During the field studies on Ascension two old water well locations were found. It was our intention to sample any water in these wells and log temperature gradients. One well location to the northeast of Two Boats was easily found because the drilling tower is still in place. However, the hole is blocked with debris and efforts to clean it out were unsuccessful. The second location consisted of two wells located on the alluvial flats southwest of Hospital Hill. The deepest of these is open to about 34 m. There is no standing water in the well, but material



adhering to the temperature probe suggested that the walls of the hole are composed of moist volcanic alluvium. The bottom hole temperature measured in this hole was 1.4°C above the surface temperature.

#### FLUID CHEMISTRY

Following the completion of LDTGH on 30 November, 1983, it was airlifted to remove as much drilling fluid as possible. In March, 1984, fluids were sampled from LDTGH using a downhole sampler. This system displaced fluid samples to the surface using compressed nitrogen. This allowed sampling at various depths in the well. The water level in LDTGH was measured at a depth of 174 m, which is sea level. Water samples were taken from depths of 175, 176, 183 and 190 m, within the slotted portion of the 16.83 cm pipe.

When the well was opened for sampling, there was a pronounced "hiss" from the escape of gas. There was no detectable odor from this gas, and it was assumed to be CO<sub>2</sub>.

#### *Analytical Results and Discussion*

The concentrations of 37 major and minor cations, fluoride, chloride, sulfate and bicarbonate, total dissolved solids (TDS) content and pH were determined on each of the six water samples. The cation concentrations were determined by inductively coupled argon plasma spectrometry. The precision and accuracy of this method and the sample preparation techniques have been described

by Christensen et al. (1980). Fluoride and chloride were determined by specific ion electrode, sulfate by silver nitrite titration and TDS by gravimetry. All of the samples were analyzed within one month of their collection. The chemical analyses are given in **Table 2**.

The data in **Table 2** indicate that the water samples fall into two distinct groups. Waters sampled between 174.6 m and 182.6 m are compositionally similar. These waters are relatively dilute with TDS contents of approximately 15,000 ppm. Samples from 190.5 m are more saline with a TDS content of near 32,000 ppm. Despite these compositional differences, both groups have close affinities to seawater. The data suggest that several of the elements have behaved in a conservative manner as indicated by the overall similarities in the elemental ratios of sodium (Na), potassium (K), magnesium (Mg), strontium (Sr), sulfate (SO<sub>4</sub>), bromide (Br), and chloride (Cl) between the water samples collected at 174.6 m and 190.5 m. Because of the very different chemical behavior of these elements during hydrothermal alteration, these similarities imply that the two water types have been controlled by similar water-rock interactions.

The relationship between the chemistry of the two water types to seawater is illustrated in greater detail on the mixing diagram shown in **Fig. 11**. For simplicity only one analysis of each water type was plotted on this diagram. The data were plotted against chloride because it is probably the least reactive of the elements present in the samples and therefore its

concentration is most likely to reflect the nonreactive history of the waters (Ellis, 1979).

Fig. 11 shows that the concentrations of Mg, SO<sub>4</sub>, Na and K decrease systematically from seawater to the sample from 190.5 m to the sample from 174.6 m suggesting that a simple mixing relationship may exist between the three waters. In contrast, the concentrations of calcium, bicarbonate, silica, boron, and fluoride deviate significantly from a simple mixing model. Calcium, bicarbonate, and silica are enriched relative to seawater, whereas boron is relatively depleted. As discussed more fully below, the behavior of these elements, the major cations and sulfate, in general, typify seawater which has not been heated to temperatures above a range of 150 to 200°C.

The low pH of the samples, between 5.9 and 6.3, provides one possible explanation for the enrichments in calcium and bicarbonate. Under these conditions dissolution of calcite leading to increases in calcium and bicarbonate in the waters can occur. Bischoff and Seyfried (1978) have shown that low pH may be produced by the formation of magnesium hydroxide as seawater is heated. However, the similar ratios of Na to Mg in sea water and in the Ascension samples indicate that little Mg has been precipitated.

Both silica and fluoride are highly mobile in geothermal waters (Ellis, 1978), and it has been shown that fluoride is readily leached by thermal fluids even before appreciable hydrothermal alteration has occurred. The concentration of

aqueous silica, in contrast, is temperature dependent and can thus be used as a geothermometer (Fournier, 1981). Estimates of the reservoir temperatures based on the silica geothermometers are discussed below.

Boron, in contrast, is depleted by up to 45% in the Ascension waters compared to seawater. Although boron is typically conserved in geothermal fluids because of the absence of boron minerals (Browne, 1978), Brockamp (1973) has shown that boron can be adsorbed onto clay minerals, and that adsorption increases as the concentration of magnesium in the fluid increases. Clays are present in the weakly altered volcanics on Ascension Island and thus may be important in controlling the abundance of boron in these Mg-rich waters.

#### *Estimation of Reservoir Temperatures*

Reservoir temperatures of active geothermal systems can frequently be estimated from the cation concentrations of the thermal fluid sampled from wells and springs. Although many different chemical geothermometers have been developed during the last fifteen years (see, for example, Fournier, 1981), only the silica geothermometers have proven reliable when applied to waters containing extremely high concentrations of magnesium. The solubility of silica may, however, be controlled by one of several different silica polymorphs. In Iceland, where geothermal host rocks are similar to those of Ascension Island, Arnorsson (1975) has demonstrated a correspondence between

chalcedony-derived temperatures and measured temperatures of fluid from deep (300-2200 m) drill holes. The measured temperature of these fluids ranged from 50° to 110°C. At temperatures of 110° to 180°C, quartz or chalcedony equilibrium controls the solubility of aqueous silica, and at higher temperatures quartz appears to control the solubility of aqueous silica. Temperature estimates based on the silica geothermometers are given in **Table 3**.

Qualitative estimates of the reservoir temperatures can also be made by comparing the elemental concentrations of the Ascension waters to those found in fluids from similar geologic environments or determined from experimental data. The Reykjanes geothermal system of Iceland is perhaps the best documented of the thermal systems where the geothermal fluids are derived from seawater. Here, heating of seawater results in an increase in potassium, calcium and silica and a dramatic decrease in magnesium and sulfate (Arnorsson, 1978). Sodium and chloride are conserved during heating. These changes were experimentally verified by Bischoff and Seyfried (1978), by heating seawater with basalt at 50°C temperature increments up to 350°C. Their analyses indicate that calcium and sulfate concentrations do not change until temperatures reach the range of 150 to 200°C. These relationships suggest that the Ascension waters have not been heated to temperatures above this range.

The relationship between a deep high-temperature geothermal reservoir and the fluids sampled LDTGH may, however, be more

complex. We believe that the fluids sampled represent the mixing of thermal fluids with other subsurface fluids prior to the time they were sampled. However, since we do not know the composition of the mixing fluids, there are several possible scenarios. Fig. 12 illustrates several different mixing models which could explain the characteristics of the high-salinity samples. We have not considered mixing models for the low-salinity waters here because the predicted chalcedony temperatures fall slightly below the measured temperatures and thus give no indication of mixing after heating.

In Fig. 12a we have assumed that the postulated reservoir fluid has mixed with cold seawater with a typical oceanic silica concentration of 6.4 ppm. This model predicts a temperature of 280°C for the reservoir fluid and that the fluid sampled in LDTGH was a mixed fluid consisting of 87% seawater. Chemical concentrations of the hypothetical 280°C fluid calculated using the predicted seawater fraction indicate that the postulated reservoir water would be strongly deficient in potassium and enriched in magnesium, sulfate and fluorine compared to waters from ReykJanes. Thus this model is not likely. However, the reservoir fluid could have mixed with cool seawater that has an elevated silica content. Although cool water has not been sampled at Ascension Island, this is a reasonable assumption because the aqueous concentration of silica in the ocean is biologically controlled (Hem, 1970). This control would be removed once seawater migrated into an island aquifer. At that point, silica

concentration would be controlled by the dissolution rate of amorphous silica, and could have reached saturation with respect to amorphous silica. A model based on mixing chalcedony- or quartz-saturated fluid with amorphous silica saturated fluid is shown in **Fig. 12b**, and predicts a temperature of 111° to 180°C for the reservoir fluid.

The worst case estimate of reservoir temperature would be the mixing of seawater with a dilute fluid, prior to heating. In this case, the silica geothermometers in **Table 3** provide the best estimate of the reservoir temperature of 111°C.

#### CONCLUSIONS

Seven coreholes on Ascension Island have provided data on the shallow thermal structure and the chemical and physical hydrology of the island. Measurements in the wells demonstrate that the water table is encountered at sea level rather than forming a fresh water lens as is predicted by the Ghyben-Herzberg relation (Freeze and Cherry, 1979).

Temperature logging of the wells has defined higher temperature areas that appear to coincide with the distribution of the felsic volcanic rocks in the central and eastern portion of the island.

Chemical analyses of water samples from well LDTGH indicate that the water at, and immediately below sea level is strongly stratified. Fluids from the upper portions of the water column,

to depths of at least 182.6 m, are relatively dilute and characterized by total dissolved solid contents of about 15,000 ppm. Waters at a depth of 190.5 m are more saline, up to 32,000 ppm, and may have been derived from a geothermal reservoir whose temperatures were up to 111°C and may have been as high as 150° to 200°C. Both fluid types display chemical characteristics which suggest that they have been derived from seawater.

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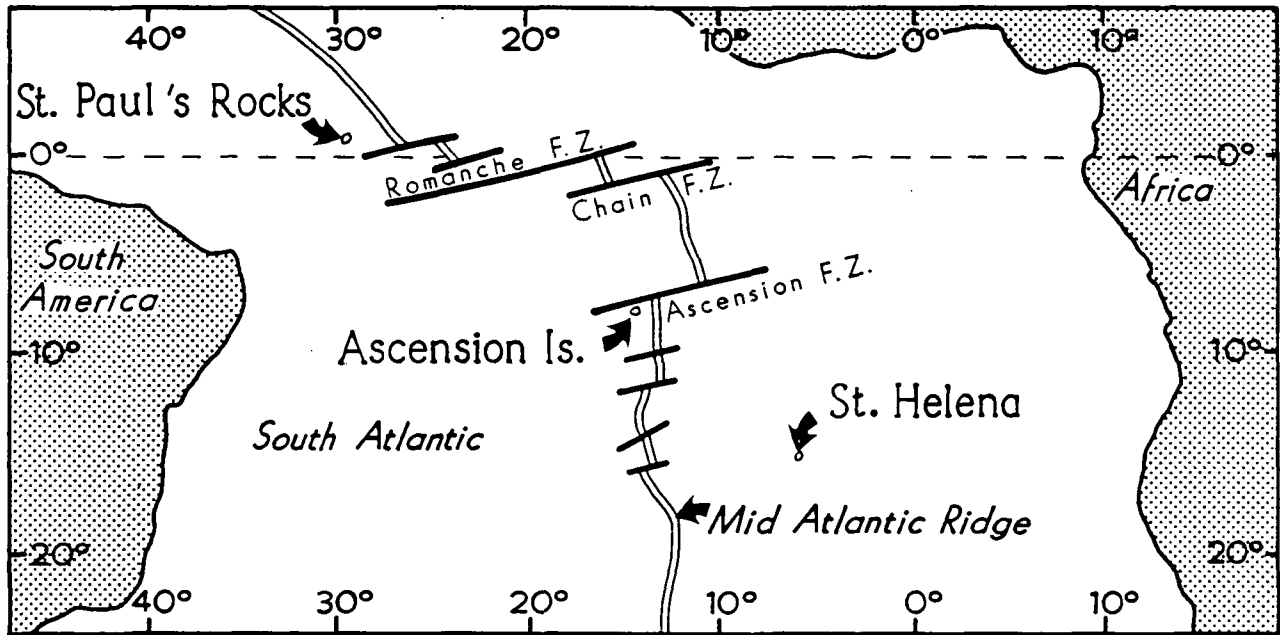
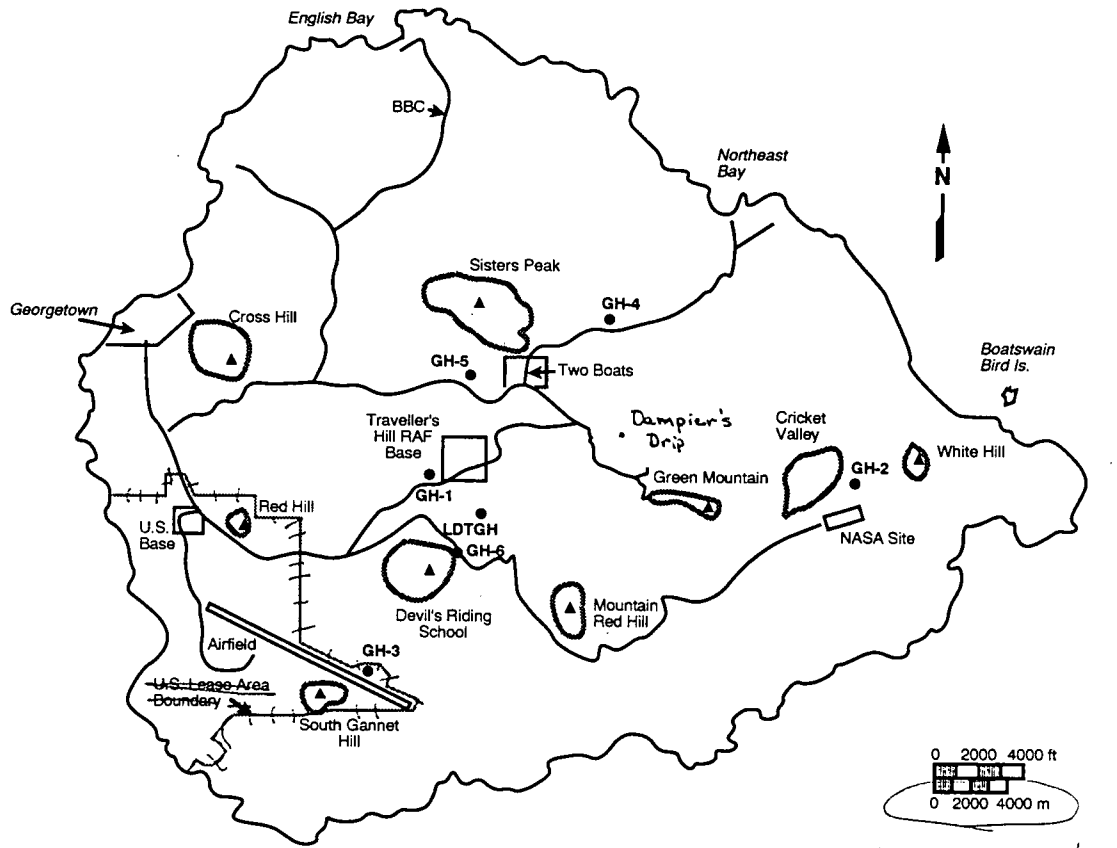


Fig. 1



meters scale not correct  
 1 meter = 3.281 ft

Figure 2

GH1  
Elev. 171.5 m

X—X 1 Sept. '83  
□—□ 9 Sept. '83  
△—△ 14 Sept. '83  
●—● 1 Nov. '83

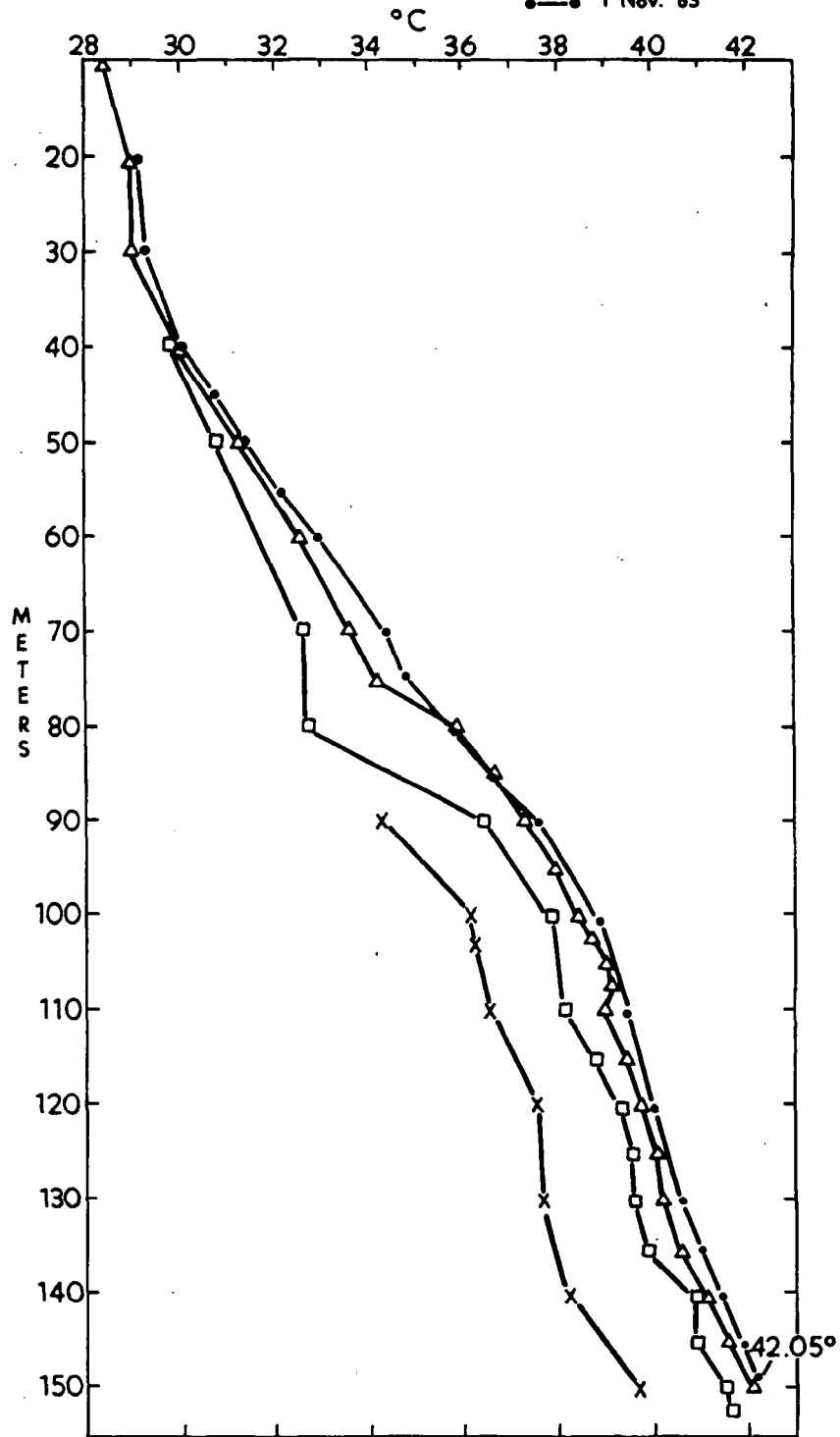


Fig. 3

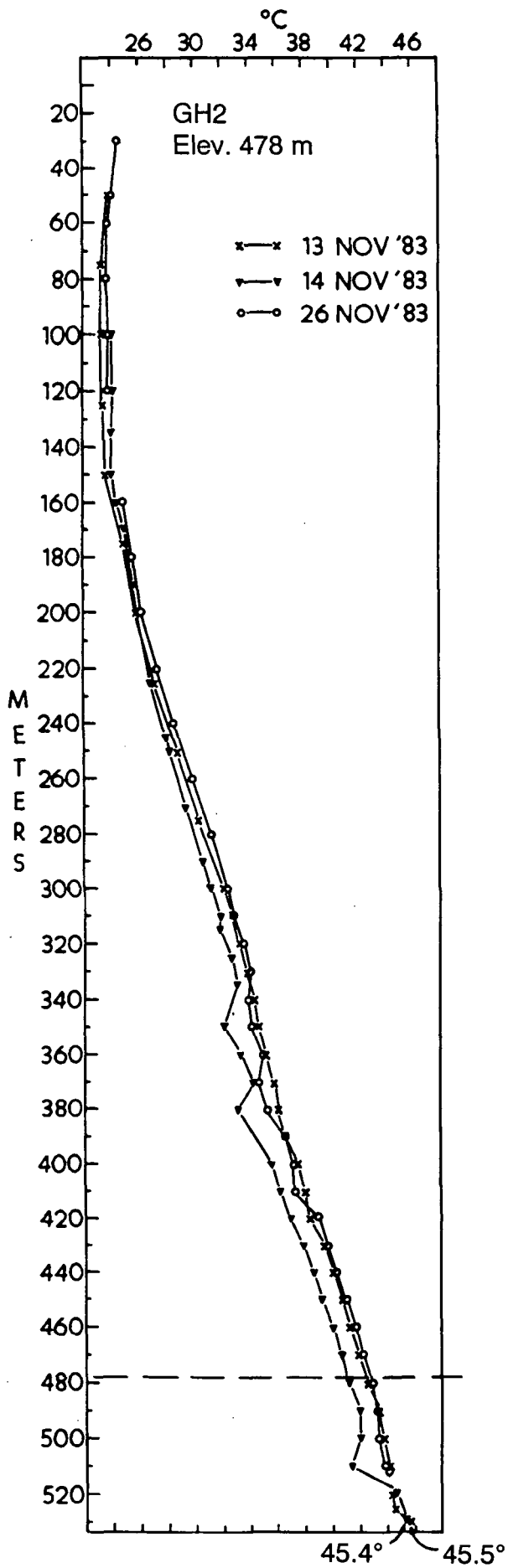


Fig. 4

GH3  
ASCENSION ISLAND  
ELEV. 64.6m

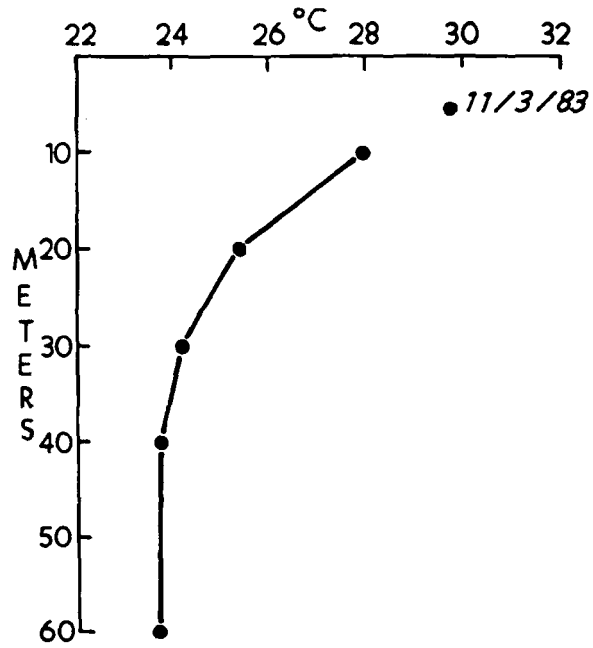


Fig. 5

GH4  
Elev. 178 m

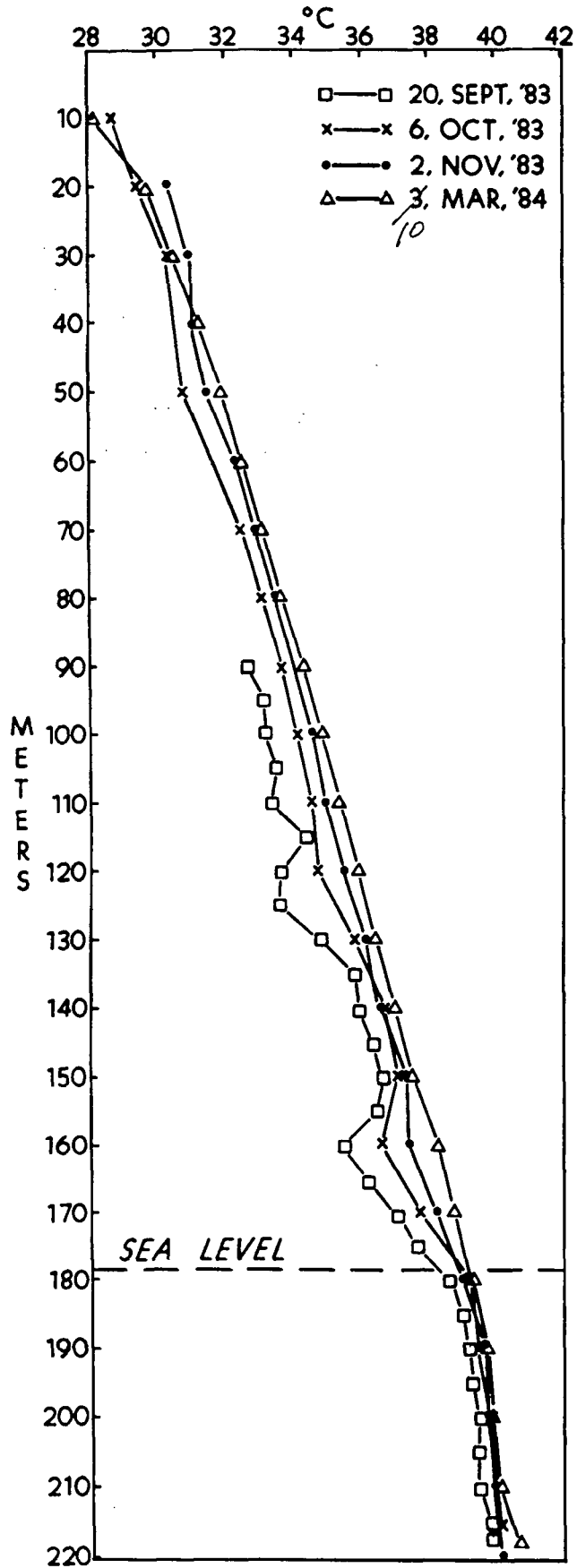


Fig. 6

*Please tick marks  
every 10 m  
and label 50, 100,  
150, 200, 250*

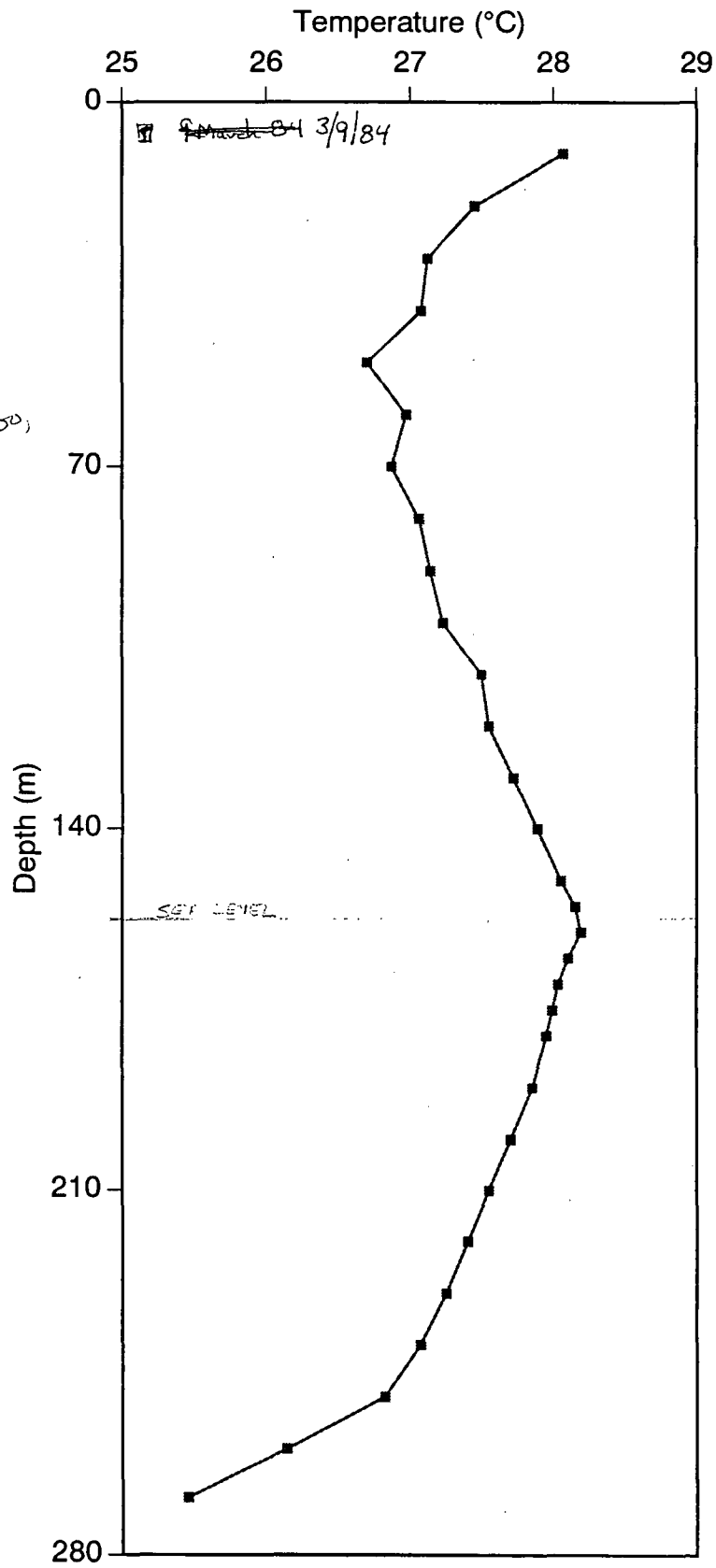


Fig. 7



GH6  
Elev. 189 m

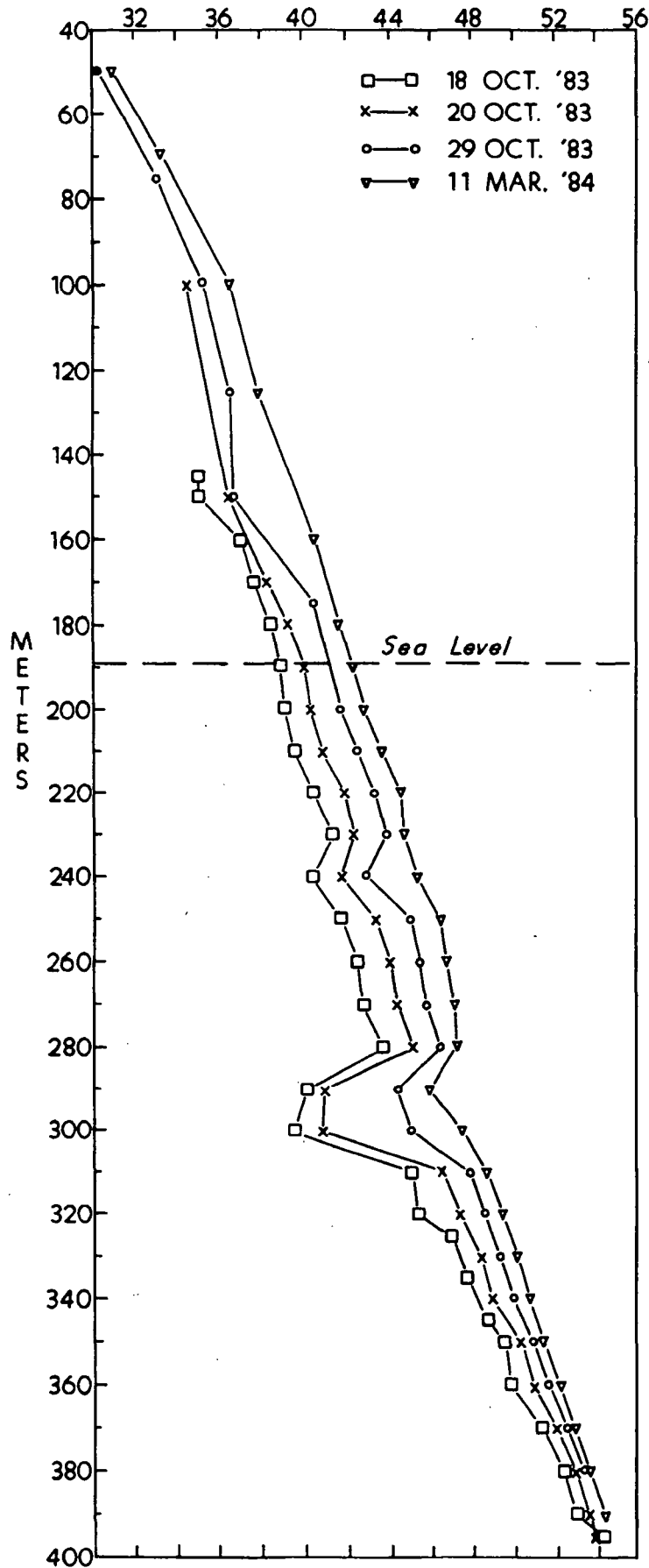


Fig. 8

LDTGH  
Elev. 174 m

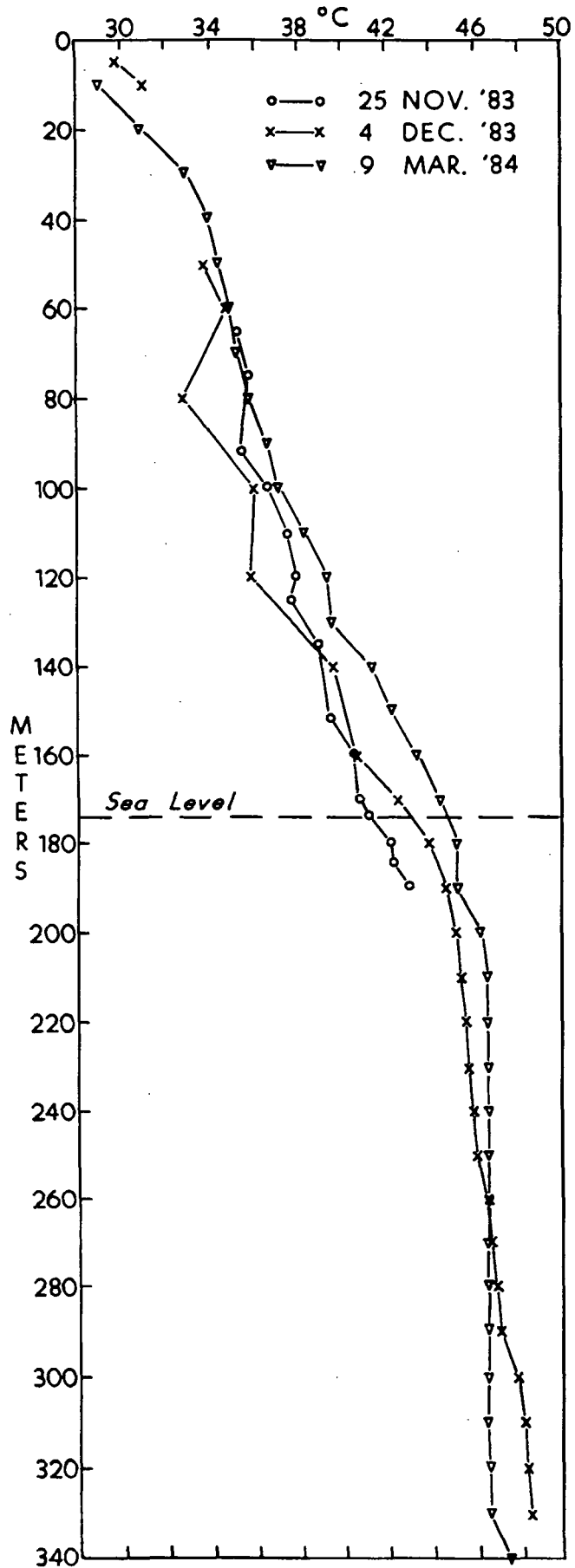


Fig. 9

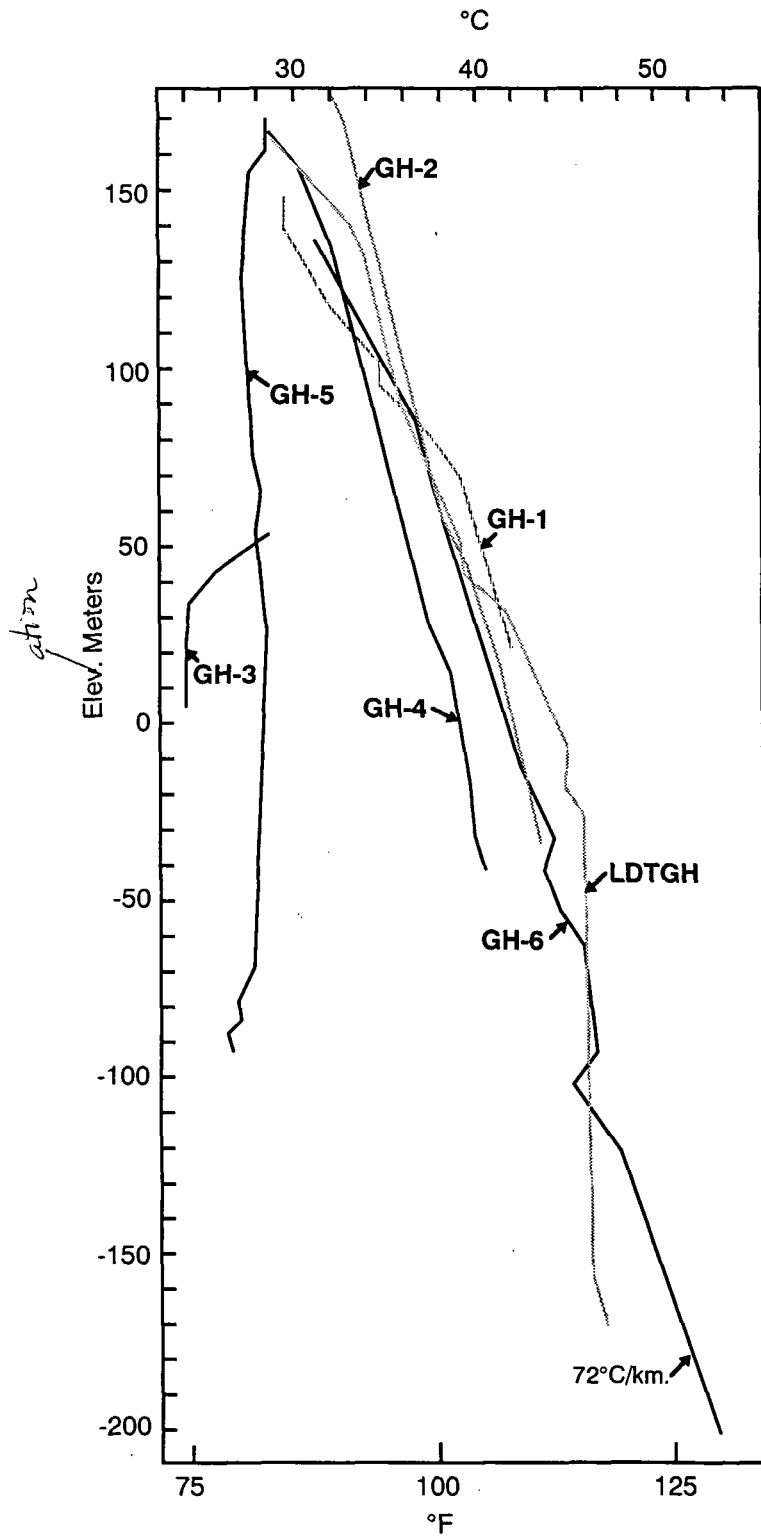


Fig 10

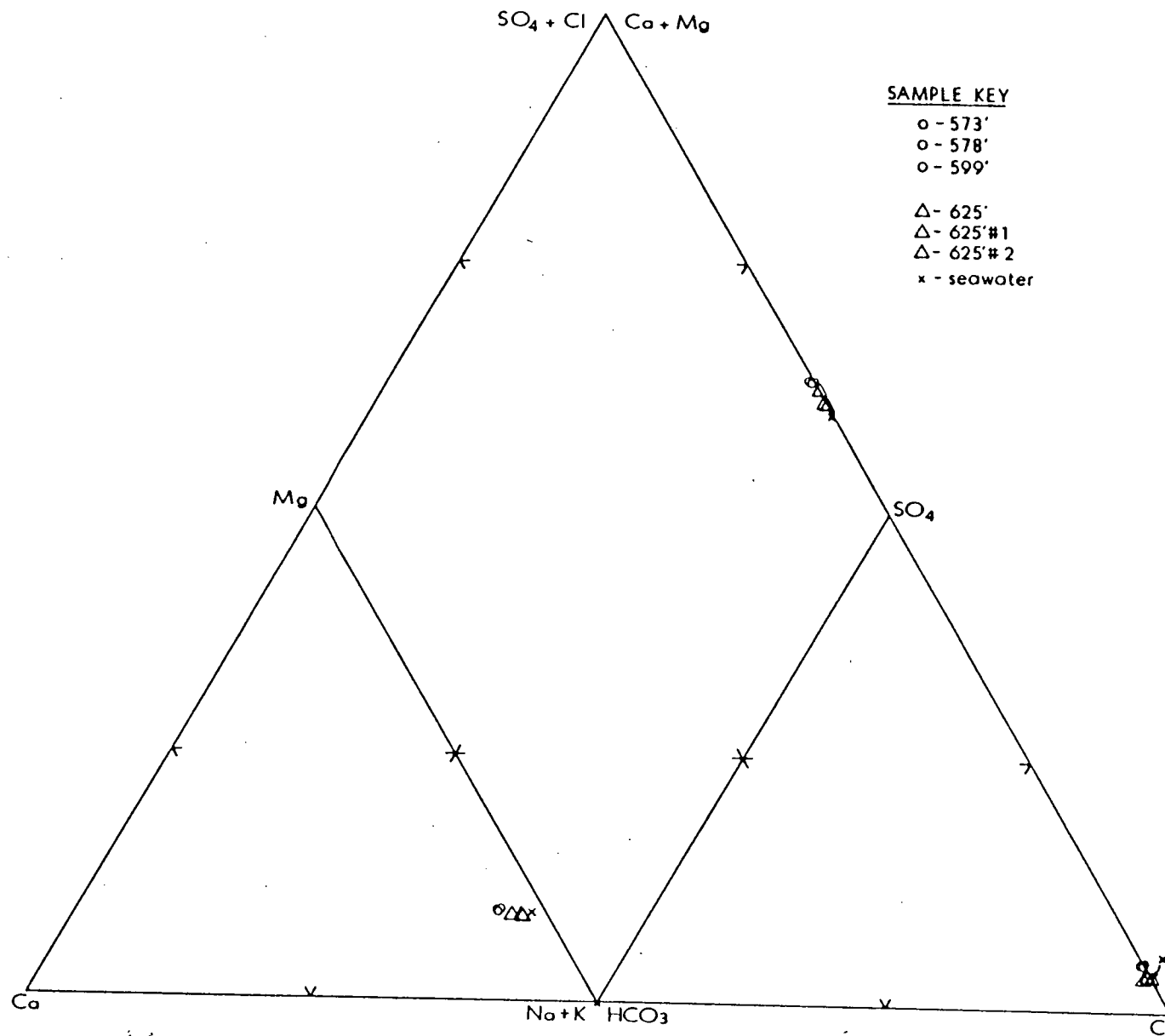


Figure ~~X~~. Trilinear diagram showing chemical character of Ascension Island water samples and sea waters.

11

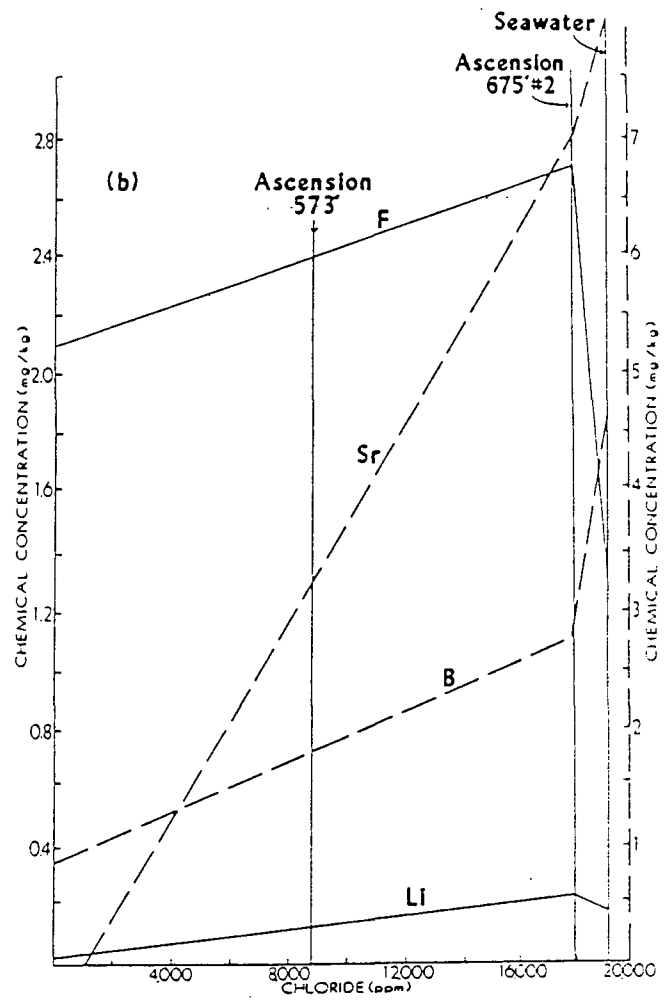
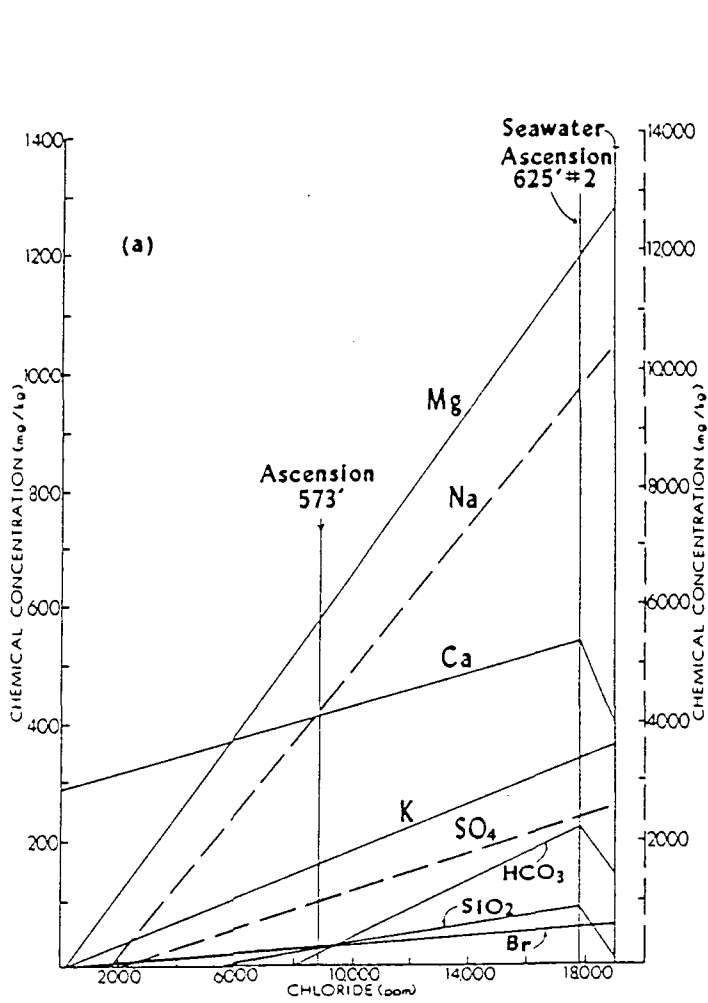


Figure <sup>12</sup>/<sub>32</sub>. Major and minor element concentrations vs. chloride in Ascension Island water samples and sea water.

Table 1 - Summary of temperature gradient holes drilled on Ascension Island.

Hole #	Depth	Surface Elevation	Depth of Casing	Depth of Liner	Date Completed
GH-1	178 m	171.5 m	24.4 m	150 m	Aug 31, 1983
GH-2	533 m	478 m	54.9 m	531 m	Nov. 12, 1983
GH-3	62.8 m	64.6 m	12.2 m	60 m	Sept 4, 1983
GH-4	220.4 m	178.6 m	36.6 m	217 m	Sept 16, 1983
GH-5	271.9 m	157 m	18.3 m	270 m	Sept 26, 1983
GH-6	394.4 m	189 m	18.3 m	391 m	October 16, 1983
LDTGH	340 m	174 m	188.7 m	340 m	Nov. 30, 1983

2  
 Table 5. Chemical Composition of Ascension Island Samples, Seawater and Seawater-Derived Geothermal Brine from Reykjanes, Iceland.

Sample	174.6 m # 573 <sup>1</sup>	174.2 m 578 <sup>1</sup>	182.4 m 599 <sup>1</sup>	190.8 m 625 <sup>1</sup>	190.8 m -625 <sup>1</sup> #1	190.8 m 625 <sup>1</sup> #2	Reykjanes2	Seawater3
Date of Collection	3/12/84	3/12/84	3/12/84	3/12/84	3/13/84	3/13/84	nr	nr
Temperature (°C)	45	45	45	45	45	45	269°C	nr
Na	4,273	4,283	4,272	9,282	9,587	9,710	10,135	10,500
K	167	166	165	318	327	331	1,480	380
Ca	419	433	435	608	538	544	1,628	400
Mg	584	586	578	1,169	1,202	1,222	1.0	1,350
Sr	3.24	3.24	3.24	6.76	6.94	7.03	nr	8
Fe	324	311	334	92	74	78	nr	.01
SiO <sub>2</sub>	25	25	24	94	99.0	101	600	6.4
Li	.13	.14	.13	.22	.22	.22	nr	.17
B	1.84	1.84	1.79	2.71	2.72	2.76	nr	4.6
HC0 <sub>3</sub>	15	<10	13	86	119	225	nr	142
S0 <sub>4</sub>	1,006	1,018	1,003	2,320	2,402	2,446	22.2	2,700
Cl	8,760	8,690	8,640	17,100	17,800	17,800	19,727	19,000
F	2.40	2.00	2.10	2.40	2.70	2.70	.1	1.3
Br	29	na	na	na	na	63	nr	65
TDS	15,430	15,420	15,340	30,770	32,460	32,500	nr	nr
pH	6.1	6.1	6.1	6.1	6.2	6.3	nr	nr

1 na = not analyzed for, nr = not reported

2 analysis from Arnorsson (1978)

3 analysis from Hem (1970)

4 concentrations in mg/kg

3  
 Table 6. Chemical Geothermometer Temperatures and Element Ratios for Ascension Island Water Types.

	<u>Ascension Samples</u>		Seawater	ReykJanes
	625'#2	573'		
Measured Temp (°C)	45	45	<20	269

Geothermometers

Na-K-Ca2	322°F (161°C)	331°F (166°C)	343°F (173°C)	469°F (243°C)
SiO23	232°F 1 (111°C)5	04°F (40°C)5	17.6°F (-8°C)5	516°F (269°C)4

Ratios of Ascension Island Water Types (573'/625#2) For Major and Minor Elements

Na	.44
K	.50
Ca	.77
Mg	.48
Sr	.46
Ln	.59
B	.67
SiO2	.25
S04	.41
Cl	.49
F	.89
Br	.46
TDS	.47

1 Analyses from Arnorsson (1978)

2 Method of Fournier and Truesdell (1973)

3 Method of Fournier (1973)

4 Quartz polymorph

5 Chalcedony polymorph