LA-10234-MS

EVALUATION OF THE ST. LUCIA GEOTHERMAL RESOURCE

Geologic, Geophysical, and Hydrogeochemical Investigations

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Evaluation of the St. Lucia Geothermal Resource, Macroeconomic Models (LA-10212-MS)

Evaluation of the St. Lucia Geothermal Resource, Geologic, Geophysical, and Hydrogeochemical Investigations (LA-10234-MS)

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Evaluation of the St. Lucia Geothermal Resource

Geologic, Geophysical, and Hydrogeochemical Investigations

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EVALUATION OF THE ST. LUCIA GEOTHERMAL RESOURCE: GEOLOGIC, GEOPHYSICAL, AND HYDROGEOCHEMICAL INVESTIGATIONS

by

Mark Ander, Fraser Goff, Bob Hanold, Grant Heiken,
François Vuataz, and Kenneth Wohletz

ABSTRACT

St. Lucia is a volcanic island of the Lesser Antilles arc. Much of the southern portion of the island is dominated by mountainous landscape that, along with steam fumaroles and boiling pools near the town of Soufriere, attests to its volcanic origin. The major event in this volcanic field was eruption of the Choiseul Pumice and formation of the Qualibou caldera (32,000 to 39,000 years ago). The latest magmatic activity within the caldera was the eruption of large dacitic domes and associated tephra at Belfond (20,000 to 32,000 years ago).

Two major NE-SW-trending faults straddle the caldera; they cross St. Lucia and are parallel to small graben-forming faults. Caldera faults are best developed in northern sections of the caldera; they define an arcuate western caldera margin, whereas those of the southern margin are crescent shaped and form a scalloped caldera margin, affected by regional fault trends. Faulting and hydrology have controlled the location of thermal springs. Regional linear faults and caldera faults are the most important in providing pathways to the surface for thermal waters originating at depth. A complex, multiple magma body probably underlies the caldera; the size of the magma chamber is estimated to be in the range of 100 km^3.

A 5.2-km-long dipole-dipole DC resistivity survey was conducted along a north-south trending line through the Qualibou caldera. The survey was centered over Sulphur Springs and the profile location was selected on the basis of the previous British resistivity investigation and the detailed geologic evaluation performed by Los Alamos. There is an apparent resistivity high, greater than 1000 ohm-m, located below the Belfond area. Beneath this apparent resistivity high, there is deeper low-resistivity material that is measured at less than 10 ohm-m. There is a zone of very low apparent resistivity, less than 1 ohm-m, underlying the Etangs area. The zone beneath Etangs is related to thermal upwelling along a fault, probably the caldera-bounding fault.

Beneath Sulphur Springs and starting at a depth of approximately 600 m, there is higher apparent resistivity material ranging from 40 ohm-m up to 150 ohm-m in the center of a 1-km-diameter high-resistivity closure. Interpretation of the data strongly suggests the presence of a very hot dry steam field beneath Sulphur Springs.

Analysis and interpretation of hydrogeochemical data from the Qualibou caldera indicate that a main geothermal reservoir underlies the Sulphur Springs area and it consists of three two-phase layers: (1) an upper steam condensate zone; (2) an intermediate vapor zone, which may be restricted to the Sulphur Springs area only; and (3) a lower brine zone. Temperatures as high as 212°C were measured at a depth of 600 m during previous shallow drilling at Sulphur Springs. Additional evidence indicates that temperatures of the brine layer may exceed 250°C.

Three other outlying thermal springs discharge in Qualibou caldera, including two along the northern caldera collapse zone, but their geochemistry does not indicate they overlie high-temperature reservoirs. Rather, they appear to be waters derived from a steam condensate layer in the vicinity of Sulphur Springs. If this is the case, it supports the theory that the high-temperature brine upflows in the area of Belfond-Sulphur Springs and flows laterally northwards toward the caldera wall.

Each of the scientific investigations yielded individual yet remarkably similar recommendations for the location of the exploratory geothermal wells. The recommendations made by each field team are covered in greater detail in the appropriate sections of this report. The selected well site locations are a synthesis of the results of the geologic, geophysical, and hydrogeochemical investigations. Based on all available data, the recommended locations for exploratory drilling in the Qualibou caldera are as follows:

(1) Craters of Belfond - Caldera-related faulting and recent phreatomagmatic volcanism indicate fracture permeability, and low resistivity suggests that geothermal brines occur at a depth of less than 1 km.

(2) Valley of Sulphur Springs - The presence of hot springs and fumaroles, the fluid chemical compositions, and the low formation resistivity all indicate a geothermal brine reservoir near a depth of 2 km with the possibility of a hot dry steam field above the brine reservoir.

(3) Etangs - The southern caldera fault and a very low shallow resistivity suggest a reservoir of geothermal brine at a depth as shallow as 1 km.

(4) Diamond Spring, Belle Plaine, and the Valley of the Migny River are also recommended for further exploration to delineate the size of the Qualibou geothermal reservoir. Initial exploratory drilling at these locations, however, is not recommended.

In summary, the Qualibou caldera has excellent geothermal potential and exploratory drilling should result in the discovery of a high-temperature brine reservoir. Geothermal brines (and perhaps dry steam) should be found at a depth of 1-2 km under the central and southern caldera area and in abundance where permeable formations and faults allow greater fluid movements.

GEOLOGIC EVALUATION OF THE QUALIBOU CALDERA GEOTHERMAL RESOURCE, ST. LUCIA, WEST INDIES

(Kenneth Wohletz and Grant Heiken)

St. Lucia is a volcanic island of the Lesser Antilles island arc. Much of the southern portion of the island is dominated by mountainous landscape that, along with steam fumaroles and boiling pools near the town of Soufriere, attests to its volcanic origin.

Basaltic lavas, dated at 5.5 Ma, crop out along the western coast and are overlain by andesitic composite cones of Mt. Gimie and Mt. Tabac, which form the highest ridges on the island and have been dated at 1.2 and 0.9 Ma. Superimposed upon the andesitic cones are dacitic domes. The most spectacular of these domes are the dacitic plug domes of Petit Piton and Gros Piton, dated at 0.25 Ma. It must be stressed here that all of the cones and domes of this period of activity were erupted before formation of the Qualibou caldera, along faults associated with NE- and NW-trending structures.

The major event in this volcanic field was eruption of the Choiseul Pumice and formation of the Qualibou caldera (32,000 to 39,000 years ago). About 6 km^3 DRE (dense rock equivalent) of lithic-crystal andesitic tephra was erupted mainly as pyroclastic flows and surges. Some of the thickest deposits are located within the 12-km^2 caldera and have been identified in geothermal drill holes. Postcaldera eruptions of dacite at Terre Blanche and Belfond were centered slightly off-center within the caldera. The latest magmatic activity within the caldera was the eruption of large dacite domes and associated tephra at Belfond (20,000 to 32,000 years ago).

Two major NE-SW-trending faults straddle the caldera; they cross St. Lucia and are parallel to small graben-forming faults. Caldera collapse faults are best developed in northern sections of the caldera; they define a nearly circular western caldera margin, whereas those of the southern margin are crescent shaped and form a scalloped caldera margin, affected by the regional fault trends. A collapse of 500 m over an area of 12.6 km^2 would be nearly equal to the volume of tephra (DRE) ejected. Resurgent magmatism, represented by Belfond and Terre Blanche lavas and pyroclastic debris, accounted for another 2 km^3 of magma that may have allowed another several hundred meters of collapse in the central portion of the caldera.

Faulting and hydrology have controlled the location of thermal springs. Regional linear faults and caldera faults are the most

important in providing pathways to the surface for thermal waters originating at depth. A complex, multiple magma body probably underlies the caldera; the size of the magma chamber is estimated to be in the range of 100 km^3. The magma chamber is likely still in a post-magmatic stage with temperatures of between 300° and 800°C. Because Belfond eruptions are dated at 2.0 - 3.2 x 10^4 years ago, near-magmatic temperatures can still exist in the chamber underlying the Qualibou caldera.

Recommendations for further geothermal development in the Qualibou caldera are in the following areas: (1) Valley of Sulphur Springs, (2) Craters of Belfond, (3) Belle Plaine, and (4) Valley of the Migny River.

I. INTRODUCTION

St. Lucia, an independent country of the Eastern Caribbean Commonwealth, is a volcanic island of the Lesser Antilles island arc (Fig. 1). The southern portion of the island is dominated by mountainous landscape which, along with steam fumaroles and boiling pools near the town of Soufriere, attests to its volcanic origin. Although the last large eruptions occurred between 20,000 and 40,000 years ago, geologic and geophysical studies indicate a significant geothermal resource exists in the area of the Qualibou caldera. The U.K Ministry of Overseas Development retained engineers, drillers, and geological and geophysical consultants in the mid-1970s to explore the geothermal resource (Williamson and Wright, 1977; 1978). Steam was found in four of seven exploratory boreholes. Results of the overall project indicated a need for further studies but indicated a favorable economic feasibility for geothermal development. This report summarizes results of a three-week geologic reconnaissance of the Qualibou caldera in preparation for further geophysical study and drilling. The purpose of the study is to build upon previous work by Tomblin (1964), Merz and McLellan (1976), and Aquater (1982) in an attempt to more precisely model the caldera substructure with preparation of geologic cross sections. To this end, cross sections drawn from previous maps using inferred structural constraints, stratigraphic descriptions, and well log data were prepared prior to field confirmation. These preliminary sections indicated a need for further work to confidently predict subsurface structure. Building upon previous studies the field work was successful in clarifying the inconsistencies in previous models and collecting important data for a refined structural model.

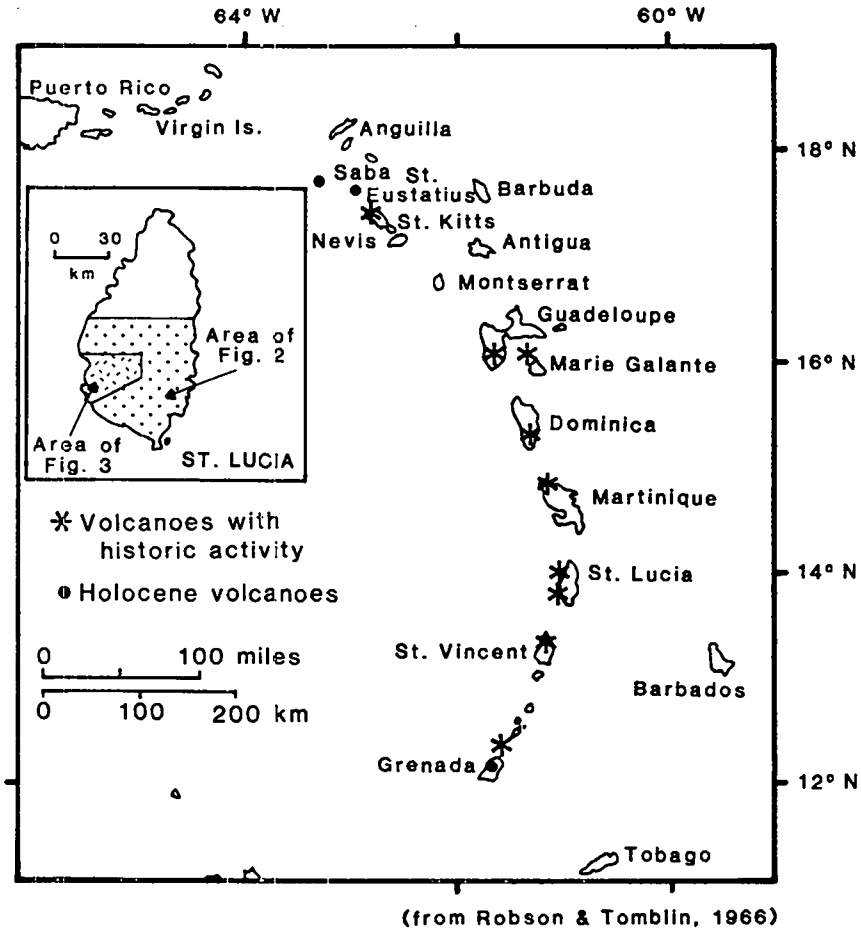


Fig. 1.
Location map, Lesser Antilles, including St. Lucia.

The methods used during reconnaissance included detailed stratigraphic analysis of over 100 sections near or in the caldera. Using recent models of caldera formation, volcanic rock facies variation, description of pumice, lava, and lithic clasts, and bedding structures in tuffs and breccias, caldera faults were located and the caldera structure was analyzed.

Tomblin (1964) prepared the first detailed description of geology of southern St. Lucia. In that work a detailed study was centered in the area near Soufriere where the Qualibou caldera was first identified. Petrologic analysis revealed the andesitic to dacitic compositions of lavas and tuffs, and K/Ar and ^{14}C dating suggested that the caldera age is between 0.04 to 0.30 Ma. This work is summarized by Robson and Tomblin (1966) and Aquater (1982).

Geothermal aspects of St. Lucia have long been recognized (Bodvarsson, 1951; Robson and Willmore, 1955), especially because of accessibility to

Sulphur Springs and nearby hot springs that have been used for mineral baths since early European settlement. More recent studies (Williamson, 1979; Greenwood and Lee, 1976; Merz and McLellan, 1976; Aquater, 1982) outline new geologic and economic studies of the Sulphur Springs area and document a vapor-dominated but noncondensible gas-rich geothermal system with a relatively shallow reservoir. The likelihood of a deeper resource in which meteoric water is heated by magmatic sources is encouraging for further geothermal exploration and development.

The following sections summarize our analysis and conclusions about the stratigraphy of the Qualibou caldera and its structural framework. Again, our emphasis has been to create geologic cross sections of the caldera that are consistent with previous studies and well logs. This type of information is lacking and is very useful for new geophysical interpretation and well siting.

II. STRATIGRAPHY

The volcanic history of southern St. Lucia (Table I; Fig. 2) spans over 5 Ma and consists of several periods of eruptive activity that overlap in time. These are: (1) 5 to 6 Ma basaltic lava flows, overlain by andesitic to dacitic composite cones 0.75 to 1.0 Ma; (2) caldera-related rocks that consist of andesitic to dacitic tephra falls and pyroclastic flows (≈0.04 Ma); and (3) intracaldera dacitic tephra and lava domes (≈0.020 to 0.032 Ma). The most recent activity consists of steam explosions at Sulphur Springs.

A. Oldest Volcanoes Within and Adjacent to the Qualibou Caldera

1. Basalt Flows. Basalt flows are exposed along the western coast at Jalousie and the base of Coubaril Ridge (north and south of the Petit Piton). Tomblin (1964) proposed that vents for these flows are near Coubaril. Basalt crops out from sea level to an elevation of 230 m at Jalousie and to about 45 m on the western slope of Coubaril. Well No. 1, drilled northwest of Sulphur Springs (Fig. 3), encountered basalt at a depth of 182 m below sea level (Merz and McLellan, 1976). Other major outcrops of basalt form part of a ridge (Mt. Gomier) that reaches the southern coast at Laborie.

The lavas are massive, aphyric basalts that are metamorphosed and deeply weathered. Outcrops appear to be massive, although Tomblin (1964) noted the presence of flow banding. Joints and amygdules in the basalts are filled with calcite, authigenic quartz (?), and green clays.

TABLE I

STRATIGRAPHIC SEQUENCE, QUALIBOU CALDERA

Stratigraphic Unit		Ages
Historic phreatic blast, Sulphur Springs (Reported by deLatour, 1782).		1766 A.D.
Belfond Formation	- Pyroclastic fall, flows, surges, and domes. Craters in domes, with associated tephra.	20,900 to 34,200 yrs (Wright et al., 1984)
St. Phillip Dacite--Possibly Belfond tephra.		39,000 yrs (Tomblin, 1964)
Terre Blanche	- Dacite domes, craters. Probable tuff ring around base of dome.	No date
Morne Bonin Dome	- Andesite dome that may or may not be an intracaldera unit.	No date
Choiseul Tuff	- Quartz-rich andesitic pyroclastic flows and surge deposits that flank the Qualibou caldera. Present below intracaldera lavas and tuffs within the caldera.	39,000 yrs (Tomblin, 1964) >32,840 yrs (Wright et al. 1984)
Precaldera Andesites	- Fond Doux composite(?) cone - andesite.	No date
	- Domes(s) of Rabot, Plaisance and Malgretoute Ridges (dacite similar to that of the Pitons).	No date
	- Domes of Bois d'Inde Franciou - andesite.	No date
	- Gros Piton and Petit Piton Domes.	0.23 ± 0.10 Ma 0.29 ± 0.10 Ma 0.26 ± 0.04 Ma (Briden et al., 1979; Aquater, 1982)
	- Composite cones of Mt. Gimie and Mt. Tabac (laharic breccias, epiclastic gravels, and andesitic lavas).	1.7 ± 0.2 Ma (Tomblin & Westercamp, 1980)
	- Andesitic cone of Coubaril (contemporaneous with Mt. Gimie?).	No date
Basalt flows of Jalousie and Malgretoute		5.61 ± 0.25 Ma 5.21 ± 0.15 Ma 6.1 ± 0.6 Ma 6.5 ± 0.6 Ma (Aquater, 1982; Briden et al., 1979)

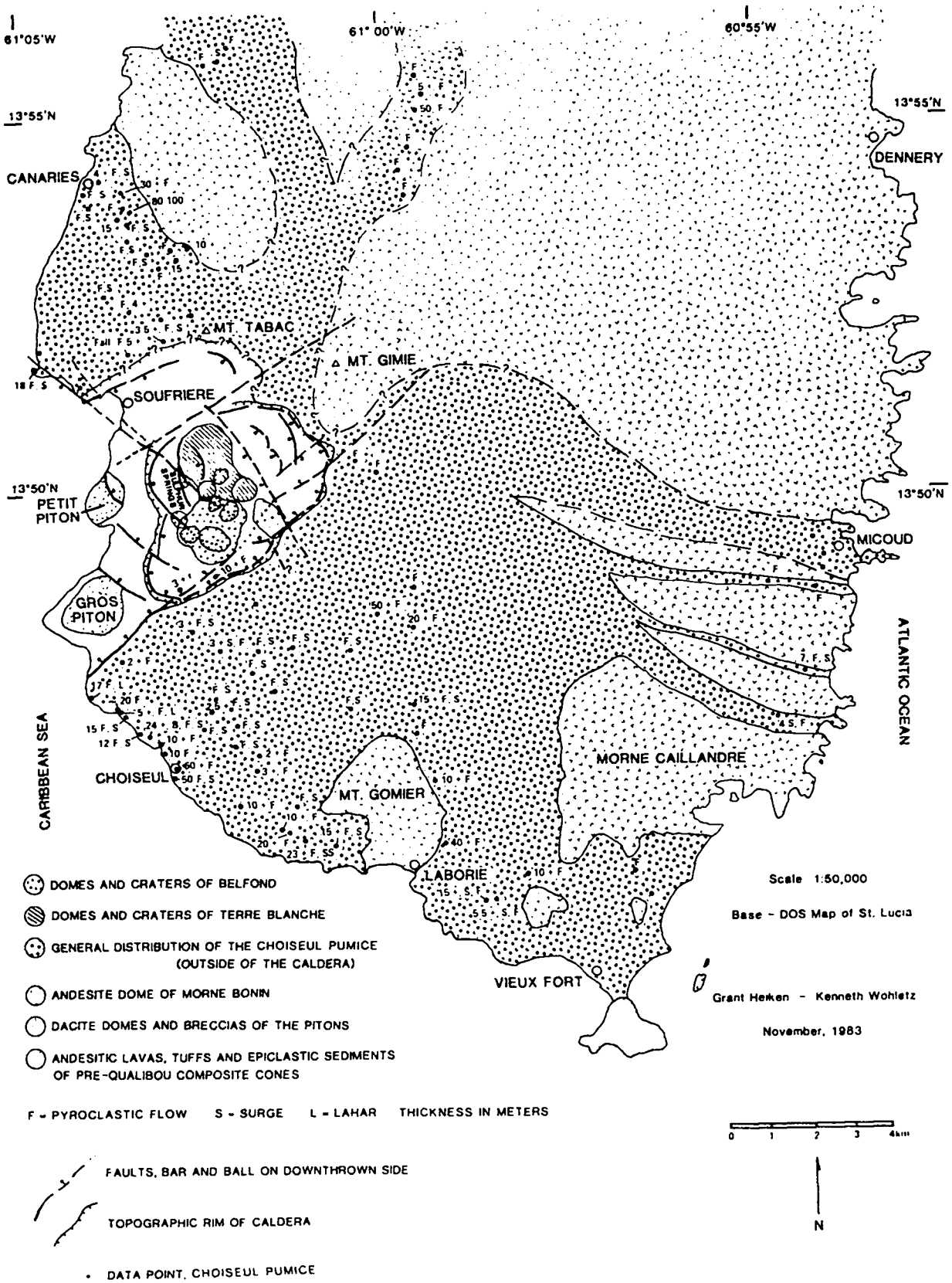
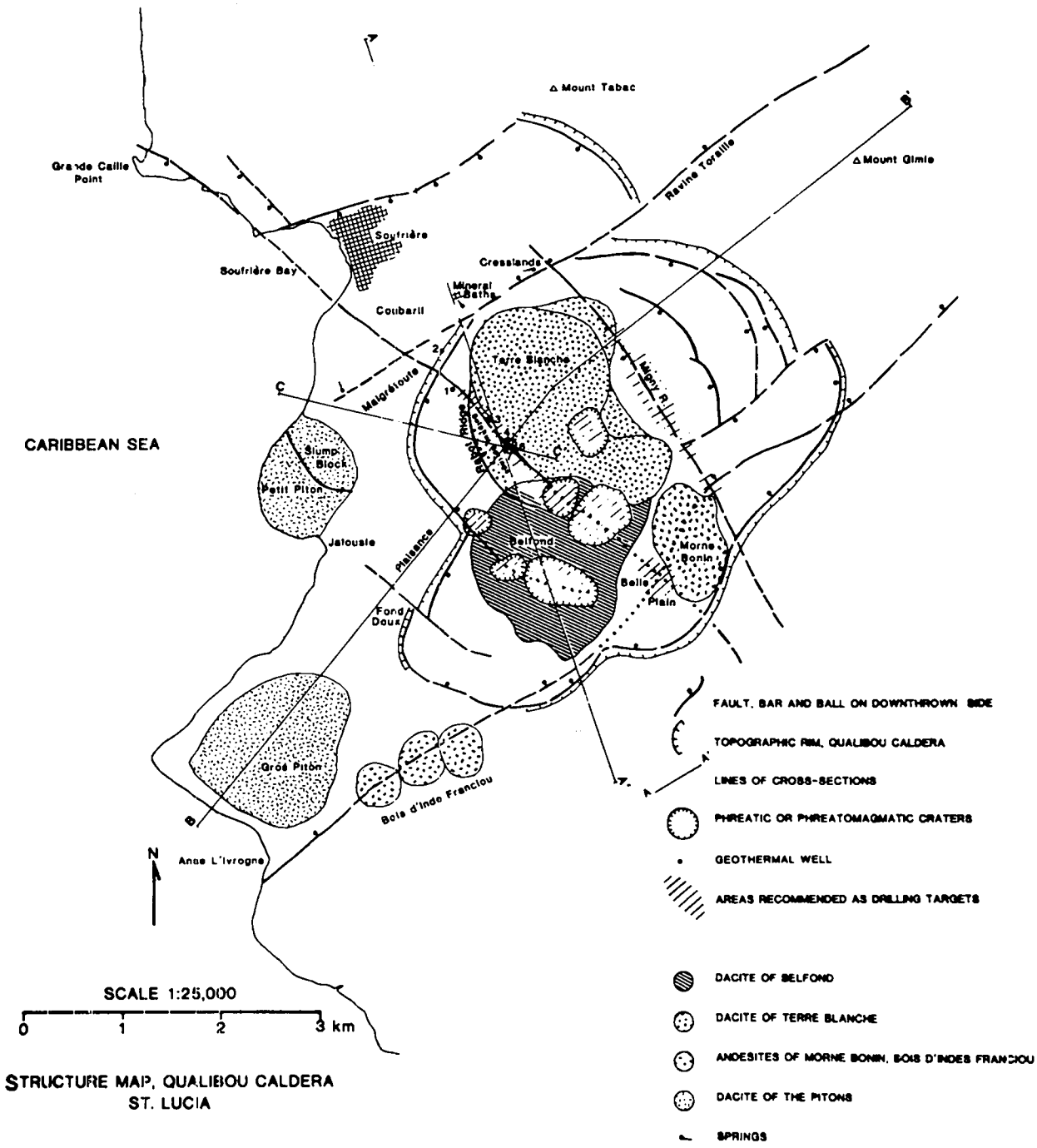


Fig. 2.
Reconnaissance geologic map, Qualibou caldera and tuff, St. Lucia.



STRUCTURE MAP, QUALIBOU CALDERA
ST. LUCIA

Fig. 3.
Structural geologic map, Qualibou caldera.

The basalts have been dated, using the K-Ar method. Briden et al. (1979) published dates of 5.61 ± 0.25 Ma for a sample from Coubaril (Malgretoute) and 5.21 ± 0.15 Ma for a sample from Savannes (location uncertain). K-Ar analyses by Hunziker (Aquater, 1982) of basalt from Jalousie indicate ages of 6.1 ± 0.6 Ma and 6.5 ± 0.6 Ma.

Lavas sampled at Jalousie are generally aphanitic, with rare plagioclase phenocrysts (zoned, An_{55-78}) and clinopyroxene (Aquater, 1982). Most mafic phases have been replaced by hematite and chlorophaeite.

2. Andesitic Composite Cones (Stratovolcanoes). Andesitic lavas, laharic breccias, fanglomerates, and epiclastic sediments are exposed along the cliffs north of Soufriere and along parts of the easternmost caldera wall. Similar rocks crop out along the coastline east of Qualibou and along pre-Qualibou ridges located southeast of the caldera. These deposits are much thicker on the east and north, being closer to source and sloping to the southwest. The source(s) for these deposits are the composite cones (or cone remnants) of Mt. Gimie (950-m elevation), Mt. Tabac (680-m elevation), and ridges located between them.

Laharic breccias within this sequence exhibit massive, normally graded and reversely graded bedding. They slope southwest, away from source at an angle of 5-10°. Interbedded with the laharic breccias are light grey andesitic lavas of unknown thickness. The lavas and laharic breccias within the highlands, above 457-m elevation, are deeply weathered to clays; there are, however, excellent relict textures that indicate rock type. These deposits are well preserved at lower elevations. These deposits are called the "caldera wall andesite agglomerate" by Tomblin (1964). They are encountered in geothermal wells 7, 4, and 5 at a depth of 250 m below sea level and at about 60 m above sea level in well No. 2.

Andesite lavas of Mt. Gimie have been dated by Snelling at 1.7 ± 0.2 Ma (Tomblin and Westercamp, 1980) and 0.9 ± 0.08 Ma by Hunziker (Aquater, 1982). Mt. Gimie lavas are two-pyroxene andesites with phenocrysts of orthopyroxene and plagioclase in an aphanitic groundmass. Plagioclase phenocrysts have reaction rims and traces of resorbed olivine are present.

The ridge between Soufriere town and Plaisance (the Coubaril ridge) has been described as an andesitic cone, contemporaneous with the cones of Mt. Gimie and Mt. Tabac. This correlation is difficult to confirm. There are mostly dacitic lavas and breccias exposed along the road around Coubaril; most

have been altered to clay. Although deeply weathered to clays, chlorite and carbonates, the Coubaril lavas have been described as quartz-rich porphyritic andesite.

3. Andesitic and Dacitic Lavas of Malgretoute, Rabot, Plaisance, and Fond Doux Ridges. These lava domes and cones(?) are located along a N-S line, immediately east of the Pitons. Little is known of the extent or structure of these volcanoes; they appear to be cut by caldera-boundary faults and are partly buried by a blanket of tephra from the Belfond craters.

Malgretoute and Rabot are parallel, NS to NNE-trending ridges, each about 1 km long and 0.5 km wide. A similar ridge (Plaisance) extends south from Rabot. Tomblin (1964) mapped Plaisance ridge as a Piton-type dome lava. These lavas at well No. 1 (located at the northern end of Rabot ridge) have a total thickness of about 600 m. Field relationships indicate that the Malgretoute, Rabot, and Plaisance ridges are domes that were cut by faults during caldera collapse.

Fond Doux, located immediately south of Plaisance, is a 506-m-high andesite ridge. There are agglomerates, believed to be associated with this domelike ridge, that crop out along the L'Ivrogne River near the coast. Seen from the north, Fond Doux appears to have a crater at the summit, open toward the north. Dark green lavas exposed near the summit are highly fractured and chloritized (fractures are filled with carbonate). The lavas have been described as an orthopyroxene-hornblende andesite (Tomblin, 1964) and as an "evolved" andesite (Aquater, 1982).

4. The Piton Dacite Domes. The most visible and best exposed dacite domes in the volcanic field are the Petit and Gros Pitons, which are located along the coast south of Soufrière town. The Petit Piton is 1 x 2 km, elongated NNE and has a summit 743 m above sea level. A large fragment of the dome, on the north side, has slumped about 300 m along a NW-SE-trending fault. Flow banding is nearly vertical and is visible on all sides of the dome.

Gros Piton is about 3 km in diameter at the base and has a summit 777 m above sea level. It is an asymmetric pyramid, with faces oriented NNE, N-S and E-W. At the base, from sea level to an elevation of about 200 m, is an apparent tuff ring consisting of well-consolidated tuff-breccia (visible from the sea). Tomblin (1964) described a "Piton-type" dacite agglomerate composed of 70% subangular blocks, up to 2 m long, within 12.5 km of the base of the Pitons. These blocks consist of grey or pink dacite clasts.

The Pitons were erupted between 200,000 and 300,000 years ago. A K-Ar date for the Petit Piton is 0.26 ± 0.04 Ma (Bryden et al., 1979). K-Ar dates for the eruption of the Gros Piton are 0.23 ± 0.1 Ma and 0.29 ± 0.1 Ma (Hunziker, in the Aquater report, 1982).

Lavas from the Pitons are characterized by large, rounded quartz phenocrysts. They also contain olivine, hornblende, and plagioclase phenocrysts, in a holocrystalline groundmass.

5. Domes of Bois d'Inde Franciou. Near the Gros Piton are three domes that form a line trending N60°E. Stratigraphic relations of these domes are not known, but all three appear to have erupted along a NE-trending fault that may or may not be associated with caldera collapse. It is most likely that the fault is part of a NE-trending graben that crosses the volcanic field. The domes are described by Tomblin (1964) as pale andesite. Samples from the talus around these domes are weathered orthopyroxene-hornblende andesites (Aquater, 1982).

B. The Caldera-Forming Eruption - The Choiseul Pumice

Qualibou caldera is flanked on nearly all sides by pyroclastic flow and surge deposits collectively called the Choiseul Pumice. Tomblin (1964) separated various subunits within the Choiseul Pumice and designated them "older andesitic pumice fall and flow," "vulcanian andesitic agglomerate," and "younger andesite pumice." We believe that these represent different phases of the Choiseul Pumice eruption. The name "Choiseul Pumice" was chosen by Wright et al. (1984) to describe many of the pyroclastic flow, pyroclastic surge and pumice fall deposits covering the southern and southwestern slopes of St. Lucia. Figures 4 to 6 show representative stratigraphic sections of this unit and illustrate the geographical variations as described below.

The Choiseul Pumice is a vitric-crystal or crystal-vitric tuff whose glass composition is rhyolitic (Tables II and III), which is not unusual for volcanic rocks composed of a nonequilibrium combination of glass and crystals. In outcrop it is light brownish-grey to light brown, dependent upon grain size and degree of weathering. There are generally lapilli to block-size clasts of dark and light grey, poorly vesicular dacite and, in some facies, dacitic pumice. Except in the lower part of Ravine Duval, north of the caldera, the tuff is nonwelded.

Results of energy dispersive spectral (EDS) analyses of pyroclast surfaces and scanning electron microscopic (SEM) analyses of pyroclast shapes are shown in Tables IV and V. EDS data show a variation of glass compositions

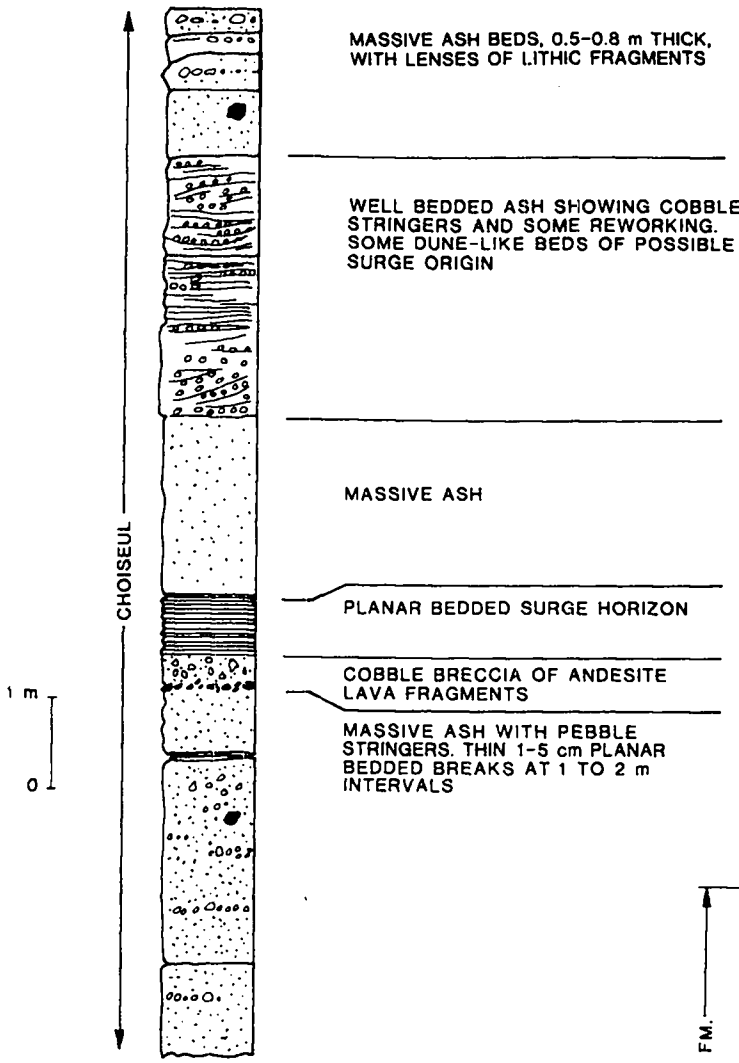


Fig. 4.
Choiseul Pumice. Near Saphire on the south coast.

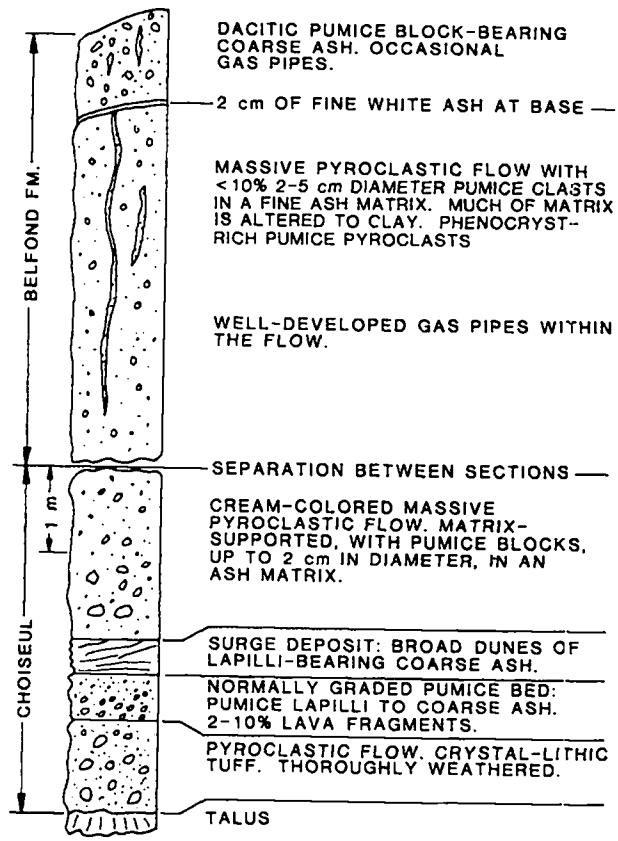


Fig. 5.
Choiseul Pumice and Belfond Formation. Composite stratigraphic section in road cuts at Newfield, near Choiseul.

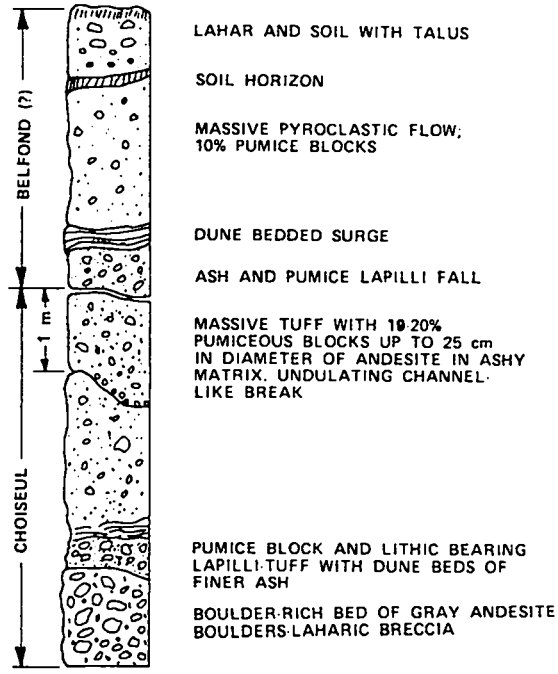


Fig. 6.
Choiseul Pumice and Belfond Formation. East coast, near Anse Ger.

(altered) between flow and surge deposit tephra. The flow tephra shows surface compositions more similar to "fresh" analyses obtained by the electron microprobe (Table III) than those of the surge tephra surfaces, which are highly altered towards dacitic composition. This alteration appears to reflect wetter eruption and emplacement conditions, which cause hydrothermal effects on grain surfaces. Typically this relationship is a product of phreatomagmatic eruption. Grain morphological data (Table V) indicate greater effect of phreatomagmatic pyroclast formation in samples from surges and flows than those from fall deposits, which are mostly vesicular. Correspondingly, alteration and transport abrasion features are greatest for surge tephra. A similar relationship is demonstrated for Belfond tephra and is discussed below.

Plateaus located south, southeast, and northwest of the caldera are composed of pyroclastic flows and surges of the Choiseul Pumice. These plateaus slope toward the sea at angles of 3 to 6° and are cut by subparallel stream valleys. Tuffs of this sequence are exposed along ridge tops, in stream valleys, in road cuts, and in sea cliffs. East and north of the caldera the tuff fills only the bottoms of stream valleys. Below an elevation of 396 m, the tuff is well preserved; above this elevation, it is deeply weathered.

TABLE II

CHOISEUL PUMICE AND FELDSPARS--CHEMICAL ANALYSES (ALL IN WT%)

Glass[a]	#3	#4	#7	#8
SiO_2	75.26	75.07	74.76	74.18
TiO_2	.08	.15	.12	.12
Al_2O_3	12.68	12.39	12.47	12.49
FeO	1.15	1.16	1.20	.97
MnO	.04	.03	.02	.06
MgO	.19	.18	.17	.20
CaO	1.65	1.62	1.63	1.66
Na_2O	2.47	3.01	2.44	3.13
K_2O	3.48	3.43	3.48	3.57
Total	96.99	97.04	96.30	96.38

Feldspars[b]	#1	#2	#5	#6	#9	#10
SiO_2	45.89	49.51	53.86	52.02	49.04	52.24
TiO_2	.0	.0	.0	.0	.0	.02
Al_2O_3	35.23	32.49	29.69	30.58	33.38	30.79
FeO	.17	.14	.14	.16	.19	.17
MnO	.03	.0	.03	.02	.01	.02
MgO	.0	.0	.0	.0	.0	.02
CaO	16.75	15.15	11.42	13.10	16.24	12.94
Na_2O	1.33	2.72	4.53	3.90	2.34	4.00
K_2O	.04	.11	.21	.17	.11	.17
Total	99.15	100.11	99.54	99.98	101.31	100.37

[a] All analyses of pumiceous glass pyroclasts.

[b] Sample used for electron microprobe analyses is from a pyroclastic flow deposit near Canaries.

Analyses 1 and 2--core and rim of a plagioclase phenocryst in a pumice clast. Analyses 5 and 6--core and rim of another large plagioclase phenocryst in the same pumice. Analyses 9 and 10--core and rim of a plagioclase phenocryst.

Thicknesses of this tuff are difficult to determine. Most of our stratigraphic sections are partial. Along the coast it is possible to see substantial lateral variations in thickness from thick valley fills to thin cappings on ridge tops. At Choiseul, located on the south coast, the Choiseul Pumice is 50 m thick in a valley fill. Over paleoridges, the thickness may be only a few meters. Close to the caldera, it is possible that thicknesses are up to 100 m; near the village of Daban, it is over 50 m. Within the caldera,

TABLE III

CHOISEUL PUMICE--MODAL ANALYSES

Mode	1 (%)	2 (%)	3 (%)	4 (%)
Glass	47.3	29.3	44.0	43.6
Vesicles	36.6	20.0	29.6	39.0
Plagioclase	9.0	22.6	17.3	11.0
Hornblende	0.0	0.0	0.0	5.0
Biotite	0.0	1.3	0.0	0.0
Fe-Ti oxides	0.3	1.0	0.6	tr
Quartz	2.3	11.3	2.6	0.0
K-feldspar	1.6	1.0	0.0	0.0
Hypersthene	2.6	13.0	5.6	1.3
Xenoliths	0.0	0.3	0.0	0.0

Modes based on 300 points.

1. Porphyritic pumice clast from pumice fall unit 1 km NW of Choiseul.
2. Vitric-crystal tuff from surge bed, 1 km NW of Choiseul.
3. Porphyritic pumice pyroclast from pyroclastic flow near Canaries.
4. Plinian pumice fall from 1 km north of Soufrière.

TABLE IV

ENERGY DISPERSIVE SPECTRAL ANALYSES OF PYROCLAST SURFACES

	Choiseul Flow(5)	Choiseul Surge(4)	Belfond Flow(12)
SiO_2	74.33	68.82	65.79
TiO_2	0.10	0.11	0.10
Al_2O_3	14.98	22.29	17.04
FeO	1.65	6.08	7.65
MnO	0.10	-.-	0.13
MgO	0.52	1.50	3.69
CaO	1.68	0.69	3.11
Na_2O	0.85	0.06	4.69
K_2O	3.16	0.32	1.27
Total	97.37	99.87	103.47

Average analyses; number of pyroclast surfaces analyzed is shown in parentheses.

TABLE V

SCANNING ELECTRON MICROSCOPE DESCRIPTION OF PYROCLAST TEXTURES

Texture	Choiseul Surges(3)	Choiseul Flows(2)	Choiseul Fall(1)	Belfond Surge(1)	Belfond Flow(1)
Shape:					
Blocky	55	33	38	50	47
Vesicular	29	58	63	25	47
Fused	16	10	0	25	6
Alteration:					
Fresh	5	16	25	0	29
Partly	25	74	75	33	71
Totally	70	11	0	67	0
Abrasion:					
Rounded	70	26	25	67	71

Percentages determined by grain counts for number of samples shown in parentheses.

boreholes have penetrated up to 180 m of tuff; these tuffs are petrographically equivalent to units described by Tomblin that are now called the Choiseul Pumice (Tomblin, 1964). Most river valleys on the southern, southwestern, and northwestern slopes of the volcanic field appear to be resurrected pre-Choiseul paleovalleys, exposing only the thickest sections of tuff.

1. Geographic Variations

South Coast. Massive pyroclastic flow deposits, ranging from 10 to 50 m thick, fill paleovalleys along the south coast (Figs. 4 and 5). One of the thickest of these deposits, at Choiseul, consists of nonvesicular and pumiceous dacite blocks, up to 30 cm long, in a matrix of lapilli-bearing medium ash. Breccia lenses are intermittent throughout the massive pyroclastic flow deposits. These are, in turn, overlain by thin pyroclastic flow and surge deposits. Surge deposits are visible at the top of the section in almost every road cut, along ridges that run from the caldera rim to the coast.

Southeast Coast. The Choiseul Pumice fills paleostream channels but does not crop out on ridge tops along the southeastern coast of St. Lucia. Some of these channel fillings are visible along the main highway between Vieux Fort and Castries (Fig. 6). Well-bedded surge deposits are plastered onto the sides and base of the paleovalleys and, in places, ash is injected into spaces between boulders of the underlying conglomerate. Surge deposits are overlain by about 4 m of pyroclastic flow deposits containing 10-20% blocks in an ash

matrix. In several valleys, pyroclastic flows are overlain by surge deposits a few meters thick. At Ravine Languedoc, the tuff sequence is underlain by 40 cm of very well bedded, very fine brown ash.

Northwest Coast. A large, dissected, fan-shaped plateau located between Soufriere and Canaries is almost entirely underlain by Choiseul Pumice (Fig. 2). Representative of the tuff in this area is a 30-m-thick section at Grand Caille Point that overlies andesitic breccias of Mt. Gimie and is, in turn, overlain by grey laharic breccias and gravels derived from intracaldera volcanoes. At the base of this sequence are well-bedded surge deposits, overlain by 15 reversely graded pyroclastic flow deposits and some interbedded surge deposits; most have a pinkish hue.

Between Soufriere and Canaries, Choiseul Pumice is visible in road cuts and consists of massive pyroclastic flows overlain by well-bedded surge deposits. In the Ravine Duval, 1 km ESE of Canaries, there is over 80 m of massive welded tuff that partly fills the valley. It is massive, consisting of 20-30% subangular dacite blocks in a grey ash matrix. There is well--developed columnar jointing within the unit; 3.5 km east of Canaries the deposit is nonwelded. In the Millet River valley, due north of the caldera, the deposit is 50 m thick.

South Caldera Rim. At elevations over 396 m it is difficult to identify the Choiseul Pumice because of the deep weathering. It is composed of mostly red or brown clay, but relict textures and bedding are visible and may be used to identify the tuff.

2. Discussion. The Choiseul Pumice represents a major caldera-forming event in this volcanic field. It exhibits multiple facies laterally and vertically. The eruption may have begun with a Plinian phase, but outcrops of the pumice fall are rare; only a few meter-thick beds were seen along the south coast. This was followed by deposition of pyroclastic surges, block-rich pyroclastic flows (that filled many paleovalleys), and ended with pyroclastic surges. There are some lenses of gravel and volcanic mudflows interbedded with the tuff that may have been deposited by floods that occurred during the eruption. Wright et al. (1984) describe the facies variations.

The vent (or vents) for this eruption were apparently located within the $\sim$12 km^2 of the Qualibou caldera, with pyroclastic flows and surges moving down the southeastern, southern, western, and northwestern flanks of the volcanic field. This conclusion differs from that of Wright et al. (1984), who suggest

central vent locations near Mt. Gimie. Our conclusions are based on the location of the caldera structure, outflow thickness variations, and well log data within the caldera. For example, Choiseul Pumice was not distributed towards the northeast because of the shielding effect of the high composite cones of Mt. Gimie and Mt. Tabac.

At this time we can only provide a crude estimate of the volume of the Choiseul Pumice. Much of it must have been deposited in the sea. Pyroclastic flow and surge deposits studied on land have a minimum volume of 11 km^3, about 6.5 km^3 DRE. This compares favorably with an estimated volume for caldera collapse of between 5 and 10 km^3.*

Wright et al. (1984) dated one piece of carbonized wood in the Choiseul Pumice, collected south of Saltibus; it has an age of >32,480 years. They suspect that the carbon sample collected by Tomblin (1965) was from one of the Choiseul Pumice deposits; it has an age of 39,050 ± 1500 years.

C. Intracaldera Volcanic Rocks

1. Morne Bonin Dome. Located in the southeast corner of the caldera, Morne Bonin dome has been called a pale andesite by Tomblin (1964). The summit is about 330 m above the caldera floor at Belle Plaine. It is believed to be a postcaldera dome, erupted from a caldera-bounding fault. All samples are from talus; there are no *in situ* exposures. A sample from this talus consists of a quartz-poor dacite; a porphyritic, holocrystalline lava with phenocrysts of orthopyroxene, plagioclase, quartz, and Fe-Ti oxides.

2. Terre Blanche. Terre Blanche is a 1.5-km-diameter, 450-m-high dome, located immediately northeast of Sulphur Springs. Associated with the dome are two craters and one small dome (100 m high) located between it and the Belfond dome-crater complex. Terre Blanche dome appears to have erupted through a tuff ring, with well-bedded medium-ash size surge deposits exposed on the northeast flank. Drilling at Sulphur Springs indicates a total dome thickness of 600 m, with an approximate volume of 0.6 km^3. The dome consists of pink or grey dacite with good flow banding. The west side of the dome has

*Volume was estimated on the assumption that tuffs on the plateaus filled paleovalleys that are now resurrected in part. This observation was confirmed in seacliff exposures. Volume in the caldera was determined by an estimate of caldera area and tuff thickness seen in drill holes. No estimate was made of the ash that went into the sea or was carried off in a plume. The DRE was determined by multiplying the volume by 0.6.

been altered by hydrothermal activity from the base to about 300 m above the base. The side affected by hydrothermal activity is broken by numerous slumps, including a major one, with a fault scarp crossing just below the summit.

The dome lava consists of hornblende-orthopyroxene dacite; on the west side of this dome, most mineral phases have been replaced by hematite, authigenic quartz, and clays.

3. Belfond Dacite Dome(s) and Tephra. The latest eruptive activity within the caldera (not including a historic phreatic blast) is that of the Belfond dome and craters, located near the center of the caldera, south of Sulphur Springs. The lavas and lithic-crystal tephra are easily distinguished by the presence of large (>5-mm) biotite and hornblende phenocrysts. With a summit elevation of 472 m, the dome-crater complex rises 170 m above the surrounding moat (Belle Plaine); 1.5 km wide at the base, the Belfond dome is cut by four craters:

1. La Dauphine Estate - 0.75 x 0.5 km; 150 m deep.
2. East of La Dauphine - 0.37 x 0.25 km; 50 m deep.
3. Near Dasheene (filled with water) - 0.25 km; depth not known.
4. Between Belfond and Bois d'Inde - 0.6 x 0.5 km; 60 m deep.

Massive dacite of the dome crops out at the summit and at a few places on the flanks. The Belfond dome(s) consist of porphyritic dacite, containing 42% phenocrysts in a glassy groundmass. The dome lava contains 2% granodiorite xenoliths. The dome(s) are buried by tephra from the tuff rings or tuff cone (La Dauphine) (Figs. 7 to 9). Belfond tephra also drapes most of the pre- and postcaldera domes with a blanket ranging in thickness from less than 1 m to 40 m at Sulphur Springs. Belle Plaine appears to have been filled, in part, with Belfond tephra; the thickness is unknown.

The tuff cones and rings have dip slopes of 10-20° and consist of 5 m+ of graded tephra-fall and surge deposits. Fall deposits are normally graded, block-bearing medium lithic ash; surge deposits are planar, reversely graded plane beds with block lenses. Some surge deposits show plastic deformation around blocks. Belfond tephra consists of mostly subequant, subangular to subrounded, porphyritic dacite pyroclasts; most contain only rare vesicles (Table V--more pumiceous clasts have less than 10% vesicles). As can be seen in Tables VI and VII, the tephra was most likely derived from the dome lavas, possibly by explosive interaction of volatile-poor magma and meteoric water

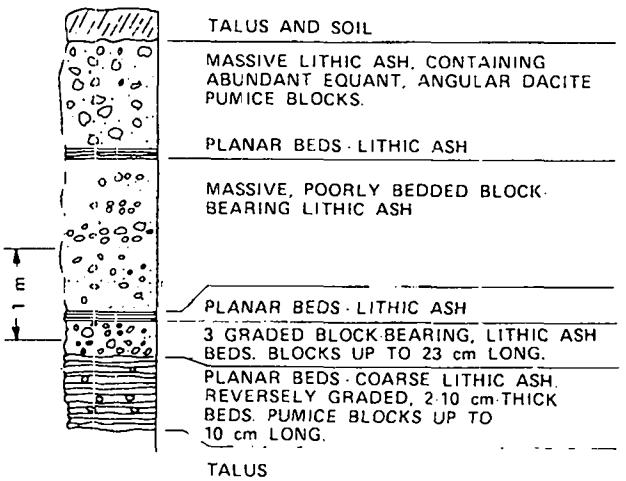


Fig. 7.
Belfond Formation. Partial stratigraphic section, western slope of the Belfond tuff ring. Attitude 340°, 24°W (dip slope).

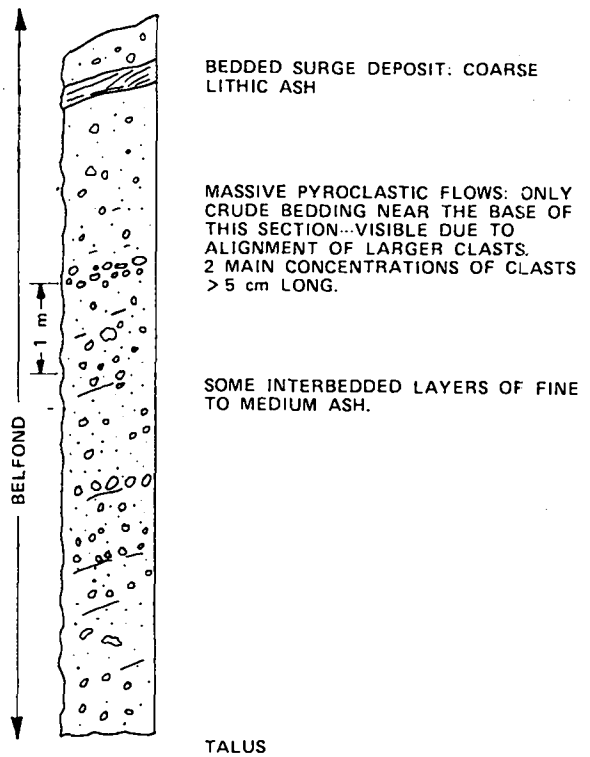


Fig. 9.
Belfond Formation. Southern slope of Belfond tuff ring, at Etangs.

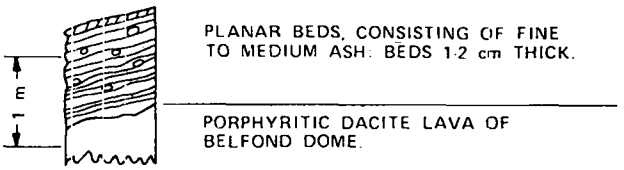


Fig. 8.
Belfond Formation. North rim of Belfond crater.

TABLE VI

BELFOND FORMATION--CHEMICAL COMPOSITIONS OF GLASS AND PLAGIOCLASE CRYSTALS (ALL IN WT%)

	Glass[a]	#3	#6	#11
SiO_2	72.02	74.65	73.65	
TiO_2	.05	.15	.19	
Al_2O_3	13.99	11.66	13.41	
FeO	1.03	1.46	1.68	
MnO	.04	0.00	.03	
MgO	.09	.19	.36	
CaO	2.13	1.08	1.75	
Na_2O	3.35	2.46	3.36	
K_2O	3.64	4.17	3.71	
Total	96.35	95.75	98.06	

Plagioclase[b]	#1	#2	#4	#5	#7	#8
SiO_2	55.97	54.63	45.69	53.67	56.76	53.20
TiO_2	.01	.04	.04	.07	.03	.02
Al_2O_3	28.40	28.55	34.61	30.28	27.55	29.79
FeO	.08	.12	.18	.16	.05	.15
MnO	.00	.02	.01	.02	.00	.00
MgO	.00	.00	.03	.03	.00	.00
CaO	10.18	10.55	17.43	12.06	9.24	11.43
Na_2O	5.56	5.15	1.24	4.49	6.23	4.73
K_2O	.32	.29	.05	.24	.36	.20
Total	100.52	99.35	99.27	101.02	100.21	99.53

[a] Analyses of glass crusts around phenocrysts.

[b] Analyses 1 and 2--core and rim of a 300-mm-long plagioclase from a lithic pyroclast.
Analyses 4 and 5--core and rim of a plagioclase phenocryst from a lithic pyroclast.
Analyses 7 and 8--core and rim of a plagioclase pyroclast.

within the dome, which resulted in some grain-surface chemical alteration (Table IV).

A few valleys south and southwest of Belfond (outside the caldera) contain relatively thin (∿10-m) pyroclastic flows and surge deposits that originated at Belfond. Flow and surge deposits are present on the summit of Fond Doux volcano, west of Belfond.

Most clasts in these deposits consist of vesicle-poor, hornblende-biotite dacite (up to 50% dacite pyroclasts). In some pyroclastic flow deposits,

TABLE VII

BELFOND FORMATION MODES AND GRAIN COUNTS

Mode	1 (%)	2 (%)	Grain Count	3 (%)	4 (%)	5 (%)
Groundmass	51.3	45.6	Porph.Dacite	54.6	54.3	54.6
Vesicles	5.0	9.0	----------	-	-	-
Plagioclase	22.3	32.6	Plagioclase	27.0	26.3	29.6
Hornblende	5.0	3.0	Hornblende	4.0	4.0	0.6
Biotite	1.3	1.3	Biotite	0.3	0.3	1.6
Fe-Ti oxide	1.0	0.6	Fe-Ti oxide	0.3	-	Tr
Quartz	8.6	7.6	Quartz	6.0	8.0	4.3
K-feldspar	3.3	-	K-feldspar	5.0	4.3	6.3
Xenoliths	2.0	-	Xenoliths	1.6	2.3	2.3
			Hypersthene	1.0	0.3	0.3

All modes and grain counts based on 300 points or grains.

1. Porphyritic dacite lava from the northern summit of the Belfond dome.

2. Pumice pyroclast from planar beds, western slope of the Belfond tuff ring.

3. Tephra from sample 2.

4. Tephra from massive lithic ash, western slope of the Belfond tuff ring.

5. Tephra from massive pyroclastic flows, southern slope of the Belfond tuff ring.

south of the caldera, there are pumice clasts with the same phenocryst assemblage. Diorite and granodiorite xenoliths are present in the Belfond Tuff. In addition to the large biotite and hornblende phases, there are phenocrysts of plagioclase, quartz, Fe-Ti oxides, clinopyroxene, and orthopyroxene. Charcoal from the Belfond Formation shows an age range from 20,900 years to 34,000 years (Wright et al., 1984).

4. Deposits from the Phreatic Eruption of 1766 A.D. (?) The Sulphur Springs area, which includes abundant hot springs and fumaroles, was the site of a phreatic explosion in 1766 that "spread a thin layer of cinders far and wide" (Lefort de Latour, 1787, as reported in Robson and Tomblin, 1966). The fumaroles and springs are located in slump blocks derived from a fault scarp along the east face of Rabot Ridge. Deposited on one of these slumps, within the area affected by hydrothermal activity, is a thin (70-cm) deposit of thinly bedded lithic ash. It overlies a breccia that may be part of that deposit or rubble from the slumps. The well-bedded ash is peripheral to one

of the largest hot pools, 10 m in diameter. It is possible, although difficult to confirm, that this pool was the site of the phreatic explosion in 1766.

III. STRUCTURAL FRAMEWORK

The present-day structure of the Qualibou caldera is dependent upon three primary structural mechanisms: 1) the regional stress field of the Lesser Antilles, which has developed in response to island arc subduction, 2) local tectonic adjustments related to caldera formation associated with volcanism, and 3) gravity slumping and sliding of oversteepened topographic surfaces. Combinations of these three structural elements have produced an area of complex structural nature resulting in the intersection of both deep, linear, through-going, vertical faults with curvilinear, moderate- to low-angle local faults associated with caldera collapse. Delineation of these structural features is difficult because of the lateral facies variations typical of silicic volcanic fields. Hence many of our structural observations are geomorphological and volcanological. Aerial photo interpretation has been discussed by Aquater (1982). An important result of our work, as discussed below, is that a structural evaluation consistent with information from geothermal drill holes is developed, which builds upon the interpretations of Tomblin (1964) and Aquater (1982).

A. Regional Faults

The age of the western Lesser Antilles island arc is inferred from geophysical data to be around 9 Ma (Pitman and Talwani, 1972; Briden et al., 1979); however, volcanic rocks span ages from 0 to 40 Ma in the southern part of the island arc. A present-day subduction rate of 2 to 4 cm/year (Sykes et al., 1982) or 0.5 cm/year (Westbrook, 1975) is reflected in ongoing seismicity and volcanism. Westercamp (1979) analyzed the regional fabric of the Lesser Antilles showing NE-SW faults related to the lithospheric block above the subduction zone.

Two major NE-SW-trending faults occur adjacent to the Qualibou caldera. These faults straddle the caldera; the northernmost one parallels Ravine Toraille and cuts the north slopes of Mt. Gimie, and the southernmost one is parallel to the drainage of the L'Ivrogne River, aligned with three small domes near Bois d'Inde Franciou and Morne Bonin near Migny. These faults cross St. Lucia and are parallel to small graben-forming faults such as those near Fond St. Jacques and Fond Cannes.

Overall movement on the faults appears to be dominantly vertical, with little variation in trend. Movement on these faults has occurred over a long time, as is shown by large displacement of 5 Ma aphyric basalts and smaller displacement of younger units such as the Choiseul Pumice. Present-day drainage follows these fault lines, often cutting into considerable thicknesses of tuff, indicating that caldera-related tuffs were deposited in fault-controlled paleovalleys.

Perhaps the best evidence of the deep projection of regional faults is the alignment of vents along them. Examples are the domes of Bois d'Inde Franciou and Morne Bonin and the NE-SW alignment of major edifices such as Mt. Gimie, Terre Blanche, and Petit Piton, Gros Piton, Fond Doux, and Belfond. The occurrence of major volcanic vents along regional faults is typical of volcano-tectonic regions such as the West Indies, as well as the Cascade volcanoes and the Jemez Mountains of New Mexico.

The influence of regional faults on the present-day shape of the Qualibou caldera is reflected in its apparent elongation along the trend and offset of caldera faults in the Migny area and in Ravine Toraille; hence the discontinuous boundaries and noncircular shape of the Qualibou caldera.

Cutting across the regional fault trend are SE-NW faults, one of which is evident along the Migny River. This fault produces offsets in Choiseul Pumice evident near Bouton. Another SE-NW fault is well defined at Anse Chastanet near Grand Caille Point and Rachette Point where, in places, the Choiseul Pumice is in contact with old precaldera andesite agglomerates. This fault also extends across Soufrière Bay and cuts older andesites at Coubaril as well as extending into the Sulfur Springs area. This fault may project across the caldera and be coincident with the Ravine Citron.

B. Caldera Faults

Caldera-related faulting began sometime between 40,000 and 30,000 years ago as a response to collapse of the volcanic edifice into a shallow, partially evacuated magma chamber during eruption of the Choiseul Pumice. Aphyric basalts and andesitic agglomerate/breccias show the greatest displacement by these curvilinear, steeply dipping faults. Younger units such as the Choiseul Pumice and dome lavas are partly cut by and partly drape the faults. As a result, the major collapse occurred nearly simultaneously with eruption of the Choiseul Pumice. The volume of this tuff is nearly equal to that of

the caldera and is strong evidence that it represents most of the material erupted during caldera collapse.

Major caldera faults are best developed in northern sections of the caldera where over 300 m of topographic and stratigraphic displacement are evident near Ravine Claire and the ridge along Plaisance-Malgretoute. The major western caldera fault along the ridge of Malgretoute no doubt projects through the area of Belfond and Fond Lloyd where it has been covered by more recent lavas. Its position is further constrained by the remarkably different lithologies encountered in wells No. 1 and No. 2. These faults define a nearly circular western caldera margin, whereas those of the southern margin are crescent shaped and form a scalloped caldera margin affected by the regional fault trends. The southern caldera faults show at least 300 m of displacement.

With the resurgence of dominantly effusive activity in the caldera during formation of the Terre Blanche and Belfond domes and associated craters, further piecemeal collapse may have occurred within earlier caldera margins but with a smaller radius. Such faults are largely covered by lavas and tuffs. They are, however, apparent west of Terre Blanche along the Sulfur Springs area and the St. Phillip-Migny River drainage. Movement along these faults is estimated from well data to be around 100-200 m.

Although the caldera faults display marked topographic effects, they likely have only shallow projections of no more than several kilometers. Their dip is between 45° and vertical, consistent with their origins. The inner caldera faults, associated with eruption of Terre Blanche and Belfond domes, are of major importance to circulation of thermal waters at and near Sulphur Springs.

C. Slump Faults

Oversteepened caldera margins and dome slopes have produced both large and small slump blocks. Although of minor extent and displacement, these faults have caused movement of large slump blocks near Zenon, on the northern caldera rim, and on Terre Blanche dome. These faults are important because they have caused blocks of "mega-breccia" to come to rest over surface exposures of major faults like those at Cresslands. Faults of a slump nature often form a caprock for surface thermal emanations. Slumps from Terre Blanche and Rabot Ridge appear to have covered portions of the Sulphur Springs thermal area.

D. Discussion of Volcano-Tectonic Relationships

Consideration of the distribution and thicknesses of major stratigraphic units with the discussion of faults summarized above allows a three-dimensional structural model of the caldera to be constructed. A major constraint of the model is stratigraphic data from well logs of the Sulphur Springs area. Previous attempts to fit well log data to structural features were unsuccessful (Aquater, 1982); recognition of the nature of major caldera faults has improved our understanding of these data.

Perhaps the biggest limitation in 3-D modeling is determining the subsurface extent of stratigraphic units and lateral facies changes within these units. Precaldera rocks consist of basalts and andesites. Eruption of these lavas in the Lesser Antilles typically results in the formation of a stratocone with upper slopes of lava and lower slopes of breccias (agglomerates) and mudflows. All these units tend to interfinger with larger volumes of clastic rock than lavas, as seen on other nearby islands such as St. Vincent. The distribution of these rocks, however, is fairly continuous across the area of the Qualibou caldera. Postcaldera rocks, especially lavas, are largely confined to the moat and central areas of the caldera. Much of their volume may have been emplaced below the present-day moat level (an elevation of ~305 m).

The extent of caldera collapse can be estimated. At least 300 m is evident on caldera walls to the northeast and 200 m on the south. Much of the moat and dome area has been filled by Terre Blanche and Belfond lavas and pyroclastic materials so that the previous level of the caldera floor may have been considerably lower.

Smith (1979) has shown that, typically, caldera-forming eruptions empty about 10% of their underlying magma chambers. This estimate is based upon chemical and eruptive mechanism considerations of an evolving silicic, volatile-rich magma chamber, such as the one at Crater Lake, Oregon, which is of similar size and composition as the Qualibou caldera. Furthermore, in Smith's models, caldera margins have a diameter equivalent to that of the underlying chamber. Knowledge of the volume of the caldera-forming eruption then allows an estimate of the volume involved in collapse. A conservative estimate of the volume of the caldera-forming Choiseul Pumice (including distal and submarine ash) is 11 km^3 (~6-km^3 DRE) and the diameter of its caldera is about 4 km. A collapse of 500 m over an area of 12.6 km^2 would be nearly equal to the volume of magma ejected.

Resurgent magmatism, represented by Belfond and Terre Blanche lavas and pyroclastic debris, accounted for another 5 km^3 of magma that may have allowed another several hundred meters of collapse in the central portion of the caldera. Assuming a precaldera volcano height of 1000 to 2000 m (similar to Mt. Gimie and other Lesser Antilles volcanoes), as much as 1000 m of precaldera andesites and postcaldera fill may exist below the general level of today's caldera floor (e.g., Sulphur Springs, Belle Plaine, Fond Doux).

E. Caldera Cross Sections

Three profiles for the Qualibou caldera are shown in Fig. 10, corresponding to NE-SW, NW-SE, and E-W cross sections. The sections were drawn not only to show important mapped structures but also to intersect the geothermal wells drilled near Sulphur Springs.

The A-A' (NW-SE) section shows the multiple caldera faults on the northern margin, with greatest offset occurring just northwest of the Terre Blanche dome; however, the caldera topographic rim appears near the Cresslands hot springs where several hundred meters of precaldera andesite breccia is exposed. This fault also appears to be related to a major regional NE-SW fault or caldera margin fault. Within the caldera, precaldera andesite breccia is displaced downward several hundred meters as shown in well Nos. 7 and 5. Above the breccia within the caldera is ∿200 m of Choiseul Pumice overlain by ∿300 m of Terre Blanche dacite and Belfond dacite (south). Note that vent(s) of the Belfond dacite are shown to occur along arcuate caldera faults and that these lavas and related pyroclastic material partly fill the southern caldera moat.

NE-SW section B-B' highlights the major vents of Gros Piton, Terre Blanche, and Mt. Gimie. Again, multiple caldera faults are evident with major displacement along those near Plaisance on the west and Ravine Claire to the east. The basalt, which represents the oldest dated lava of the volcanic field, underlies precaldera andesites and Piton-type dacites on the western caldera rim and andesite breccias within the caldera. Its position in the caldera has been extrapolated from well No. 1, where the basalt was intersected at a depth between 400 and 500 m. The inner caldera fault between Rabot and Terre Blanche appears to have displaced the basalt even deeper in the section, as revealed by intersection of only younger rocks in well Nos. 7 and 4.

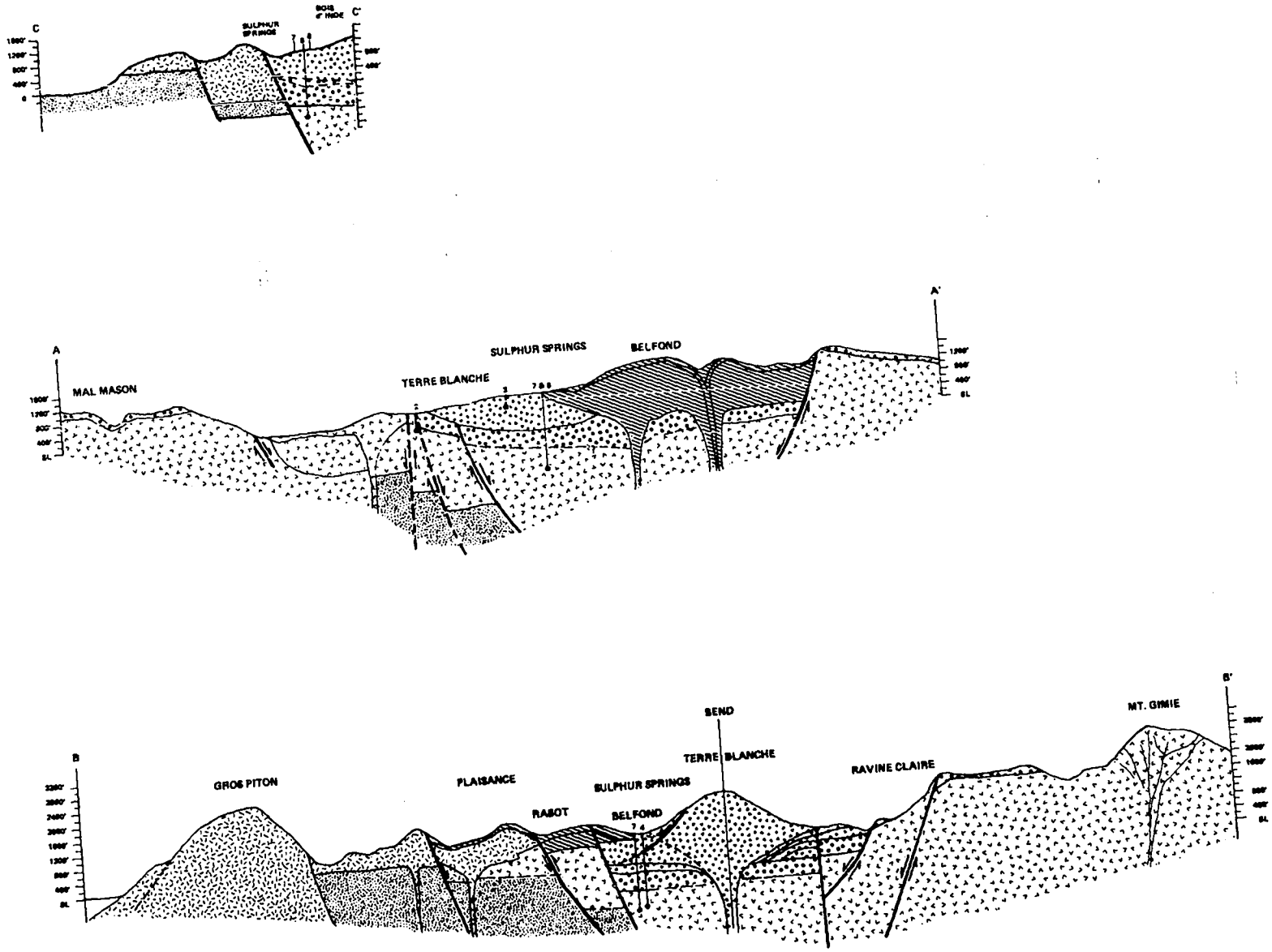


Fig. 10.
Cross sections through the Qualibou caldera: A-A' - Mal Mason to Belle Vue (342°); B-B' - Anse L'Ivrogne to Mt. Gimie (40° and 50°); C-C' - Malgretoute through Sulphur Springs (282°).

Terre Blanche lavas fill in the caldera directly above the Choiseul Pumice and precaldera andesites, as revealed in well Nos. 7 and 4. A tuffaceous collar, which is exposed near the Migny River, surrounds the Terre Blanche dome and appears to coincide with steam-producing strata in well No. 7 above the Choiseul Pumice. On the northeast side of the caldera, the Choiseul Pumice shows successive upward displacements of ∿300 and ∿400 m stepping out of the caldera.

East-west cross section C-C' especially shows displacement along caldera faults. The aphyric basalt occurs at sea level near Jalousie but is not found to several hundred meters below sea level in well No. 1. Piton-type dacite of the western caldera margin appears to be stratigraphically equivalant to the precaldera andesite breccias.

In all of the cross sections, Belfond tephra fall and flow deposits blanket the caldera moat area with up to 30+ m of unconsolidated material. Belfond tephra completely blankets Rabot Ridge, making it difficult to ascertain the nature of the underlying structural block.

F. Deep Structure of the Qualibou Caldera

Results of exploration drilling near Sulphur Springs and geophysical surveys made during 1974 and 1975 give clues to the nature of the subsurface. The drilling program provided lithologic descriptions to depths of over 600 m. Well locations were based upon early geological mapping and an electrical resistivity survey conducted a year earlier. The lithologies intersected by boreholes (Merz and McLellan, 1976) may be correlated with post-Miocene stratigraphy of the area; however, no information was obtained as to rock units deeper than an aphyric basalt.

The resistivity survey (Greenwood and Lee, 1976) provided information on water circulation at shallow depths that has structural significance relating to caldera wall margins and faults. Comparison of resistivity profiles illustrated in that report with the location of mapped faults in this area shows good agreement, especially for faults along the west caldera margin and in the area of Sulphur Springs and Diamond (mineral baths).

The only information missing that is needed to complete this structural model is the total thickness of the island's volcanic section and the nature of interbedded sedimentary rocks. Regional surveys (Aquater, 1982) indicate that basalt and andesite (Miocene?) overlie limestones in the northern part of the island. Martin-Kaye (1969) found limestone blocks within

the Choiseul Pumice. If a similar arc structure occurs on the southern part of St. Lucia, one would expect interbedded volcanic rocks and limestone to be located below the basalts of the Qualibou volcanic field (Fig. 11). For modeling purposes, the caldera may overlie a magma body or bodies with the top of the magma chamber located within 6-7 km of the surface. The magma has intruded volcanics containing interbedded limestones below basaltic and andesitic lavas and tuffs that are nearly 2 km thick. These are overlain by caldera-related rocks about 0.5 km thick. The high CO_2 content of Sulphur Springs gasses may reflect the decarbonization during contact metamorphism of limestones near the magma chamber but the ^{13}C signature of -5.95°/oo in CO_2 at Sulphur Springs (see section by Goff and Vuataz) indicates a magmatic/mantle origin. The subsurface model also includes a picture for the documented magmatic resurgences. Initial caldera collapse indicates a chamber nearly 4 km in diameter, topped with andesitic to dacitic magma. Apparent collapse associated with resurgence of Terre Blanche and Belfond extrusives may have occurred above a second intrusion 2 km in diameter and consisting of crystal-rich dacite. Accordingly, Kerneizon et al. (1981) have dated plutonic xenoliths of metadacite, hornfels, and diorites in Belfond dacites. The K/Ar dates indicate cooling ages of an initial magma body nearly 1 Ma ago. Belfond dacites have an age of 0.02 to 0.03 Ma.

IV. DISCUSSION

A. Summary of Eruption History in the Qualibou Volcanic Field

Basaltic lavas, dated at 5.5 Ma, crop out along the western coast and are believed to have been erupted from nearby vents, although none of these vents have been identified. These basalts are overlain by the andesitic composite cones of Mt. Gimie and Mt. Tabac, which form the highest ridges on the island of St. Lucia. Deposits from these cones include laharic breccias, lava flows and associated epiclastic sediments that form aprons reaching the sea. The andesites have been dated at 1.2 and 0.9 Ma.

Superimposed upon the andesitic cones of Mt. Gimie and Mt. Tabac are domes and cones located along north-south trends near the coast. These include the ridges of Rabot, Plaisance, and Malgretoute (dacitic lavas) and the andesitic Cone of Fond Doux. Small andesitic domes located along a NE-trending fault at Bois d'Inde Franciou may be contemporaneous with Fond Doux. The most spectacular of the dacite domes of this period of activity are the

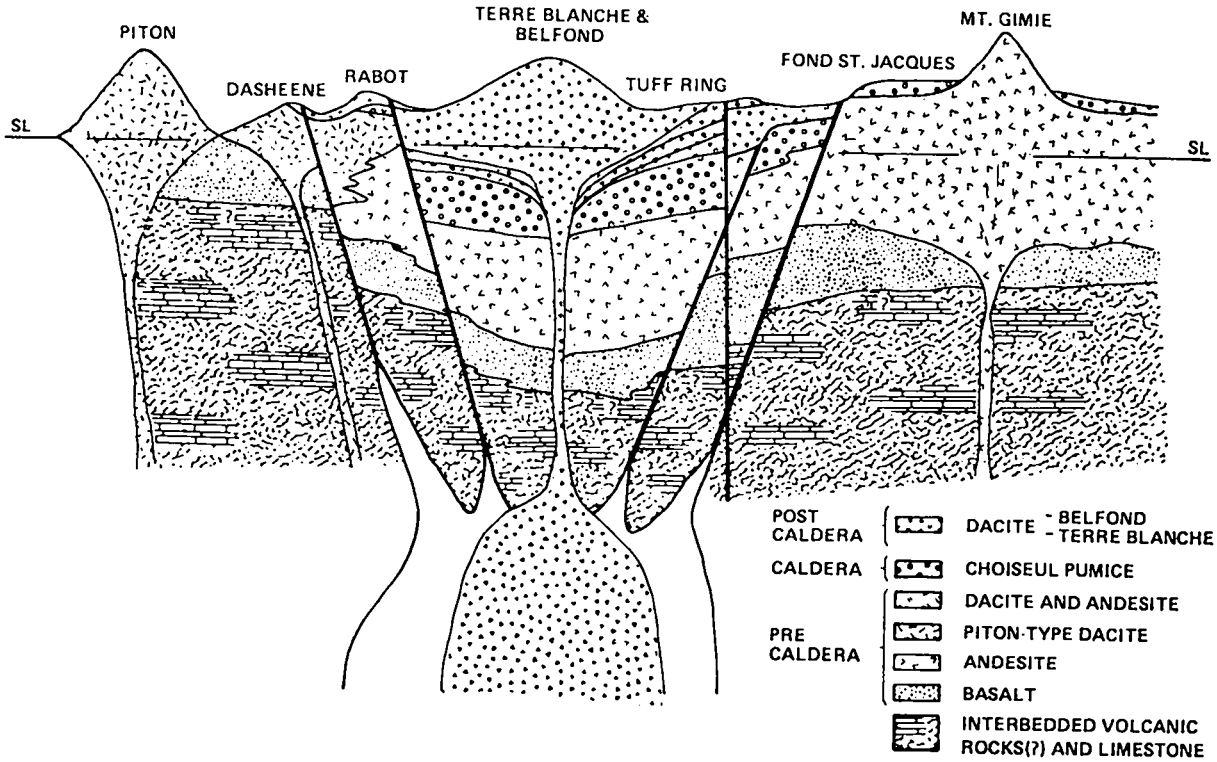


Fig. 11.
Schematic cross section, Qualibou caldera.

plug domes of Petit Piton and Gros Piton, dated at 0.25 Ma. The Pitons are located at the coastline, peripheral to the volcanic field. It must be stressed here that we believe all of the cones and domes of this period of activity were erupted before formation of the Qualibou caldera, along faults associated with NE- and N-trending structures.

The major event in this volcanic field was eruption of the Choiseul Pumice and formation of the Qualibou caldera. Eruption of between 5 and 10 km^3 (DRE) of lithic-crystal andesitic tephra, mainly as pyroclastic flows and surges, filled paleovalleys surrounding much of the present-day caldera and formed tuff plateaus sloping towards the sea. Some of the thickest deposits are located within the 12-km^2 caldera and have been identified in geothermal drill holes. Dates of this event are 32,000 to 39,000 years. The magma body associated with this eruption must be a major source of heat.

Morne Bonin, an andesite dome, erupted along a fault located on the southeastern edge of the caldera. Postcaldera eruptions of dacite were centered slightly off-center within the caldera and adjacent to caldera faults located on the caldera's west side. Terre Blanche is a hornblende-orthopyroxene

dacite dome with a volume of 0.6 km^3. Associated with it are two craters and one small, peripheral dome. The west side of this dome has been deeply altered by the hydrothermal activity of Sulphur Springs and is the site of several major slumps.

The latest magmatic activity within the caldera was the eruption of the large dacite dome (or domes) and associated craters of Belfond. Tomblin (1964) has a ^{14}C date of 39,000 years for the Belfond eruption, and Roobol et al. (1983) report ages of 29,000 to 34,000 years. The dome(s) rise 120 m above the caldera moat and are cut by craters up to 150 m deep. Dacitic tephra from this eruption has formed a well-developed tuff cone complex and blankets the surrounding area. Some pyroclastic flow and surge deposits from this eruption reached the south coast.

The latest explosive activity was a short phreatic blast in the Sulphur Springs area in 1766 A.D. Since 1766 A.D. there has been only hot spring and fumarolic activity.

B. Thermal Regime

The state of the present heat source occurring at depth below the Qualibou caldera can only be inferred. The following model outlines the nature of that heat source, assuming that it is the cooling magma body responsible for the Pleistocene volcanism of Qualibou. The model is primarily based upon observed petrologic and structural constraints (Fig. 11).

Evolution of magmas at Qualibou has occurred in several stages. Those stages directly related to caldera formation appear to have culminated several million years of volcanism and took place over the last several tens of thousand years. Four and possibly five extrusive phases can be associated with these last stages: (1) eruption of large volumes of andesitic to dacitic ash and pumice concurrent with collapse of the Qualibou caldera and deposition of the Choiseul Pumice; (2) moat eruption of Morne Bonin andesite lava; (3) eruption of the dacite lava dome of Terre Blanche; and (4) dacite lava dome eruption at Belfond. The possible fifth stage might include renewed activity at Belfond evidenced by vulcanian eruption of Belfond lava, pumice, and ash, which destroyed part of the Belfond complex. Recent phreatic activity, by definition, is not considered to be a primary magmatic event. [An additional consideration of this evolution is that later lavas appear to be more crystal-rich, which indicates that crystal fractionation may have occurred in the magma system.]

Concurrent with the last stages of magma extrusion are two prominent tectonic phases: (1) large-scale collapse associated with eruption of the Choiseul Pumice, producing a 4- to 5-km-diameter caldera; and (2) possibly ring faults, associated with the Terre Blanche dome, producing additional collapse with a diameter near 2 km.

The conclusion drawn from petrologic and structural considerations is that a complex, episodically replenished magma body underlies the Qualibou caldera. Using the caldera model of Smith (1979), we can estimate the size of the magma chamber by measuring the volume of caldera-forming tuffs and lavas; the volume of the magma chamber is approximately one order of magnitude larger. The Choiseul Pumice represents about 6 km^3 of magma and its chamber was likely in the range of 100 km^3. The magma chamber of the postcaldera Terre Blanche-Belfond eruptions was likely no more than 20 km^3. Using the conductive cooling model of Smith and Shaw (1975), the Qualibou chamber needed over 3×10^5 years to cool to 300°C. Considering the maximum age of the Choiseul Pumice as 40,000 years, its magma chamber is likely still in a post-magmatic stage with temperatures of between 300° and 800°C. Since Belfond eruptions are dated at 21,000 to 32,000 years, magmatic temperatures were present at that time and near-magmatic temperatures can still exist in the chamber underlying the Qualibou caldera.

At present Williamson (1979) has developed the only geothermal model for Sulphur Springs, and the reader is referred to his work for more details. Important points of that model are as follows: The presence of dominantly CO_2 gas in noncondensible geothermal vapors at Sulphur Springs and the likely existence of subvolcanic limestone on the island (Martin-Kaye, 1969) indicate that the magma chamber intrudes limestones. Furthermore, the temperature gradient measured at 220°C/km suggests magmatic temperatures at a shallow depth. The steam-producing interval intersected in the previous drilling program was near 300 m and thought to correspond to permeable lava breccias underlying Terre Blanche lavas. This permeable horizon serves as a steam trap for dry steam separating from hot brines rising to the surface. The pathway for the steam, gases and fluids to the surface is provided by the inner caldera margin fault west of Terre Blanche and a through-going, NW-SE fault cutting the north edge of Rabot Ridge. Thus the extent of the model at Sulphur Springs largely reflects drilling experience there. However, geothermal fluids and vapors should be found at a depth of 1 to 2 km under the

entire caldera area and in abundance where permeable rocks allow greater fluid movement. Particularly well fractured areas at depth should occur in the Belfond tuff cone crater complex (vents) and Belle Plaine, Fond St. Jacques, and Cresslands areas (intersecting caldera margin and regional faults). Deep sources (2 to 4 km) of geothermal fluids may occur, depending on the permeability of precaldera breccias and possibly the underlying carbonate rocks.

V. RECOMMENDATIONS FOR DRILLING IN THE QUALIBOU CALDERA

Recommendations for further development in the Qualibou caldera are based upon relationships between the regional tectonic framework, faults associated with collapse of the Qualibou caldera, interpretations of eruption mechanisms (the degree of involvement of meteoric water in the youngest eruptions), and size and nature of the thermal source or sources (Fig. 3).

A. Valley of Sulphur Springs

In addition to the presence of active surface manifestations of a hydrothermal system, this valley marks the edge of an inner caldera fault and intersects what may be a precaldera fault. The area is 1.5 km long and 0.5 km wide. These faults may continue through the crater of Fond Lloyd and the unnamed crater adjacent to it. Because of fractures associated with such vents at depth, both craters are potential drilling targets (neither, however, has access roads).

As has already been proved by drilling in the Sulphur Springs area, deep permeability is related mostly to fractures along fault systems. Drilling here will involve the usual problems of searching for fracture permeability along faults.

B. Craters of Belfond

Three deep craters on the Belfond dacite dome define the youngest activity in the area. They appear to line up along extension of the outermost western caldera fault. The presence of pyroclastic surge deposits in medium- to fine-ash beds interbedded with pyroclastic fall and flow in the tuff rings surrounding these craters supports the hypothesis that some magma/water interaction was involved in these eruptions. As there is no evidence for the presence of a crater lake, this implies the presence of a permeable groundwater reservoir at some unknown depth below this crater. Not enough lithic fragments are present, however, to identify the reservoir rocks. On this basis, plus the possible fracture permeability associated with vents, we

recommend that these craters be drilled. There is a road into the largest of the Belfond craters. As it is part of a working farm, there may be some land and environmental problems associated with drilling.

C. Belle Plaine

Located in the caldera moat, this area is filled with tephra from the youngest eruption and is the most accessible of all targets. We believe it overlies an intersection between a major NE-trending fault and a caldera fault.

D. Valley of the Migny River

It is possible that a major tectonic (and caldera) fault is present along the Migny River in the northeastern part of the caldera. This proposed fault intersects a NE-trending fault at Cresslands (a hot spring).

E. Reservoir Rocks

The deepest rocks intersected by drilling within the caldera are the andesitic breccias of Mt. Gimie (at 620-m depth). Alteration of tuffaceous sandstone matrix or tuff matrix to clay within these rocks indicates that there would be low permeability.

Stratigraphically, basalt flows lie below the andesitic breccias. The flows are fractured, but most of the fractures (in outcrop) are sealed. We don't know what lies below the basalt but infer the presence of limestone (because of the high CO_2 content and limestone in older rocks exposed in northern St. Lucia).

Explosive breccias below the craters of Terre Blanche and Belfond may be very permeable; as discussed earlier, these breccias, consisting of fractured dacite blocks, may have intersected a permeable ground-water unit during the eruption.

F. Engineering Problems

Most of the sites we recommend are accessible by road (although considerable improvement will be needed for some of those roads before a drill rig can be brought in). In areas of considerable hydrothermal alteration, slope stability is a serious problem. Most of the flanks of the valley of Sulphur Springs (Rabot Ridge, Terre Blanche dome) are broken by numerous landslides; it appears that the Sulphur Springs are within one of these landslides. Location of any well site in this area must be made with slope instability in mind.

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APPENDIX

PROJECTED DRILLING LITHOLOGY: QUALIBOU CALDERA

Areas within the Qualibou caldera that were considered for geothermal exploration include: (1) Sulphur Springs, (2) Belfond, and (3) Belle Plain. These locations are shown on the geologic map (Fig. 3). Previous drilling experience in the Sulphur Springs area was gained by Merz and McLellan (1976 drilling report) and extends to a depth of about 600 m. Geologic cross sections of the Qualibou caldera were prepared that included data from well logs. These cross sections are here extrapolated to 2,000 m to predict drilling lithologies and potential difficulties at the three areas listed above.

Sulphur Springs area is located in a valley between Terre Blanche dome and Rabot Ridge (Figs. 3 and 11). The area is 1.5 km long by 0.5 km wide and is accessible by one maintained road. Two major faults crossing this area are shown on the geologic map: (1) a curvilinear caldera fault along the east side of Rabot Ridge, dipping at a high angle toward the east with a vertical displacement of 300-400 m and (2) a linear NW-SE-trending regional fault with a vertical displacement of 300-400 m to the west. A slump block on the west side of Terre Blanche dome may fracture surface rocks at Sulphur Springs to a depth of 100-200 m. The following general lithology may be expected below the Sulphur Springs area.

	Estimated Thickness	Lithology
1.	0-10 m	Ash; fine-grained, well-bedded, hydrothermally altered, clay-rich, containing dacite boulders from nearby slopes.
2.	1-40 m	Ash; coarse-grained tephra of the Belfond Formation, hydrothermally altered and lithified.
3.	200-250 m	Dacite lava of Terre Blanche dome; altered, mineral phases replaced by hematite, authigenic quartz, and clays.
4.	50-100 m	Bedded tuff; permeable, containing blocks up to 1 m, dacite, steam-producing horizon.
5.	125-175 m	Andesite agglomerate, pumiceous tuff; partly lithified Choiseul Pumice.

6.	500-1500 m	Andesite lava and breccia interbedded with some dacite lava breccia, laharic breccia, fanglomerate, and bedded epiclastic sediments; precaldera andesitic rocks of Mt. Gimie.
7.	100-1000 m	Basalts; massive and aphyric, locally altered to greenstone, containing amygdules and joints.
8.	400-2000 m	Interbedded basaltic lavas, limestone and clastic sedimentary rocks; probably altered to skarn and hornfels.

Wellhole wall stability may be a problem in layers 1, 2, and 4. Lost circulation is expected in layer 4; fractured rock may be encountered locally to TD.

Belfond area is characterized by a series of closely spaced explosion craters, each several hundred meters in diameter and up to 50 m deep. These craters appear to be located along the southern ring fracture of the caldera, which is of unknown displacement (Figs. 3 and 11). Access to the floor of several of these craters is possible by graded but nonmaintained gravel roads. Because these craters represent explosive eruptive activity that occurred late in the development of the caldera, much of the subsurface is expected to be characterized by strongly fractured and brecciated rock. The width of the brecciated conduit beneath each crater is on the order of a crater radius to one diameter. Each conduit appears to have pierced a similar stratigraphy projected for the Sulphur Springs area.

	Estimated Thickness	Lithology
1.	200-2000 m	Brecciated dacite lava and tuff intersected locally by dacite dikes 1-20 m wide; crater conduit material, vertically fractured.
		(The following stratigraphy is expected if the drilling does not follow the crater conduit material.)
2.	0-100 m	Dacite tuff; well-bedded, poorly consolidated, containing some large blocks of lava up to 1 m.
3.	175-200 m	Andesite agglomerate, breccia, and tuff; Choiseul Pumice, locally fractured and brecciated with hydrothermally altered, clay-rich horizons.

4.	500-1500 m	Andesitic lava and breccia; cut locally by dacite dikes.
5.	100-1000 m	Basalt; altered and fractured.
6.	400-2000 m	Limestone; locally altered to hornfels and cut by dacite dikes.

Drilling difficulties are expected to be mainly related to hole stability because of the fractured and brecciated nature of the vent conduit fillings. Increased permeability and possible loss of circulation may occur at depths of 250-500 m, the depth at which eruptive explosions may have initiated beneath the craters.

Belle Plaine area is a flat-lying rural site covering several square kilometers. The surface geology indicates that the area is a graben filled by poorly consolidated tuffs and sediments to a depth of as much as several hundred meters. Because this location is in the southeast moat area of the caldera, faulting is expected. 300-500 m of vertical displacement related to both caldera collapse and through-going regional faults is projected. The intersection of two major regional faults, one NE-SW and the other NW-SE, appears to occur in the Belle Plaine area. The following stratigraphy is probable.

	Estimated Thickness	Lithology
1.	20-200 m	Pumiceous ash and fine-grained sediments; Belfond pumice fall, loosely compacted.
2.	0-100 m	Dacite lava and breccia of Belfond; locally hydrothermally altered.
3.	0-50 m	Dacite tuff; well-bedded, poorly consolidated, permeable, possible alteration.
4.	0-250 m	Andesite lava and breccia of Morne Bonin.
5.	0-200 m	Caldera wall breccia; andesite lava and tuffaceous material forming large blocks tens of meters in size contained within a permeable breccia.
6.	100-200 m	Andesite agglomerate and breccia; Choiseul Pumice.

7. 500-1500 m Andesite lava, breccia, and epiclastic sediments; fractured.

8. 100-1000 m Basalt; massive, aphyric, partly altered, fractured.

9. 400-2000 m Interbedded limestone and basalt; fractured, altered, possibly permeable.

The main difficulty in drilling this area may be due to the proximity of two, large, intersecting faults. Also the nearness of the caldera wall suggests a likelihood of intersecting coarse breccias that commonly form in the area. Caldera wall breccia present highly variable drilling conditions from hard lavas to soft clastic material on 10-m intervals. The problems of lost circulation and hole stability, however, should be less than those at the other two locations.

In summary, previous experience with shallow drilling at Qualibou indicates geothermal fluids will be intersected at a depth of several hundred meters with temperatures as high as 220°C. Lost circulation in zones of steam production and high permeability is expected. A large proportion of poorly consolidated and incompetent rock will be intersected by drill holes.

DEEP RESISTIVITY MEASUREMENTS IN THE QUALIBOU CALDERA, ST. LUCIA, WEST INDIES

(Mark Ander)

A 5.2-km-long dipole-dipole DC resistivity survey was conducted along a north-south-trending line through the Qualibou caldera from just north of Ruby to just north of Victoria Junction. A nominal dipole length of 200 m was selected to obtain high resolution and measurements were made at a total of 32 electrode stations. To get resistivity data to a depth of 2 km, a 35-kW trailer-mounted DC transmitter was used. The survey was centered over Sulphur Springs and the profile location was selected on the basis of the previous British resistivity investigation and the detailed geologic evaluation performed by Wohletz and Heiken of Los Alamos. The apparent resistivity profile shows similar characteristics to the British dipole-dipole data in the upper 700 m. There is an apparent resistivity high of greater than 1000 ohm-m located below the Belfond area. Beneath this resistivity high, there is deeper low apparent resistivity material that is measured at less than 10 ohm-m. The regions containing less than 10 ohm-m material are highly suggestive of zones containing thermal waters. There is a zone of very low apparent resistivity, less than 1 ohm-m, underlying the Etangs area. The zone beneath Etangs is related to thermal upwelling along a fault, probably the caldera-bounding fault. Beneath Sulphur Springs, starting at a depth of approximately 600 m, there is higher apparent resistivity material ranging from 40 ohm-m up to 150 ohm-m in the center of a 1-km-diameter high-resistivity closure. Interpretation of the data strongly suggests the presence of a very hot dry steam field beneath Sulphur Springs. Based on the deep apparent resistivity data, the recommended drilling sites are at (1) Craters of Belfond, (2) Valley of Sulphur Springs, and (3) Etangs.

I. INTRODUCTION

Direct current (DC) electrical resistivity methods have been employed for geothermal exploration in many countries and have proved to be an invaluable adjunct to the drilling of shallow or deep holes. Numerous case studies indicate that high-quality (>200°C) liquid-dominated geothermal reservoirs are characterized by a resistivity of less than 10 ohm-m. This fact prevails regardless of the resistivity of the host rock, which may be many orders of

magnitude higher in resistivity than that of the high-quality reservoir. Field data from drilled geothermal fields such as Wairakei, Broadlands, East Mesa, Heber, Salton Sea, North Brawley, Niland, Yellowstone, Roosevelt, Dieng, and Kawah Kamojang show remarkable correlations between the resistivity anomaly and the occurrence of an economically viable hydrothermal reservoir (Hatherton et al., 1966; Lumb and MacDonald, 1970; Risk et al., 1970; Risk, 1975; Banwell and MacDonald, 1965; Meidav and Rex, 1970; Meidav and Furgerson, 1972; Meidav et al., 1976; Harthill, 1978).

The range of resistivities of rocks in geothermal environments varies over many orders of magnitude. The electrical resistivity of rocks is affected by six factors: 1) temperature, 2) porosity, 3) degree of fluid saturation of the pore space, 4) salinity of the saturating fluid, 5) pore space geometric factors, and 6) rock matrix resistivity (Keller and Frischnecht, 1966). Rocks such as granite, basalt, limestone and sandstone are essentially infinitely resistive at temperatures of less than 450-500°C. The electrical current conduction in rocks other than clays, shales, or massive metalliferous zones is carried through an electrolyte, or ground water, that fills the pore space. The interrelationship between electrical resistivity and the many factors that may influence it in a geothermal environment is very complex. Fortunately, many of these factors combine to enhance the resistivity contrast of the reservoir making DC resistivity a highly successful geothermal exploration tool.

II. DEEP RESISTIVITY MEASUREMENTS AS A GEOTHERMAL EXPLORATION TOOL

Electrical resistivity is a geophysical technique permitting the determination of the distribution of earth resistivities as a function of depth. Depth control is achieved through control of the geometry and spacing between a set of transmitting electrodes and another set of receiving electrodes. The earth's apparent resistivity (ρ_a) is defined as:

$$\rho_a = 2\pi \frac{V}{I} K$$

where I is the current injected in the ground at the transmitting electrodes, V is the voltage measured at the receiving electrodes, and K is a geometry factor given by:

$$K = \left(\frac{1}{R_{11}} + \frac{1}{R_{22}} - \frac{1}{R_{12}} - \frac{1}{R_{21}} \right) .$$

The R_{ij} are the distances between the ith voltage electrode and jth current electrode. The depth of current flow is a function of the inter-electrode distance. As the electrode distance is expanded, the current is forced to penetrate deeper and deeper into the ground.

The apparent resistivity is that which is measured when the earth is not homogeneous. The apparent resistivity may also be defined as the resistivity of a layered or heterogenous medium relative to the resistivity of a homogeneous medium. To obtain the actual resistivities in a layered or heterogeneous medium, the apparent resistivity data must be computer modeled.

There are many different standard arrays in which the current and voltage electrodes may be placed (Bhattacharya and Patra, 1968; Van Nostrand and Cook, 1966). The dipole-dipole array is often selected because of its ability to obtain an almost continuous cross section to total depth. Because of this, the dipole-dipole array has gained considerable popularity in geothermal exploration. The dipole-dipole array combines horizontal and depth profiling but requires long straight cable runs to achieve results. It is quite sensitive to lateral changes in resistivity. In this method, constant dipole lengths are usually employed for the transmitter and receiver dipoles. For geothermal exploration, dipole lengths of 200-1000 m are characteristic, although both shorter and longer spacings have been used.

A. Previous Resistivity Studies on St. Lucia

Shallow resistivity studies have been carried out in the Qualibou caldera of St. Lucia by the Institute of Geological Sciences, London, England (Greenwood and Lee, 1976). They performed 13 dipole-dipole DC resistivity profiles throughout the region, obtaining data to a maximum depth of 700 m. Low apparent resistivity values were found in the north around Soufrière, La Pearle, and Cresslands and other areas generally north of Sulphur Springs. Additional lows were centered in the south around Belle Plaine, Etangs, and Fond Doux. Apparent resistivity highs were associated with the Belfond area and beneath Sulphur Springs, starting at a depth of 600 m. The typically low apparent resistivity values are associated with the geothermal system. It was

suggested that the higher values seen at depths beneath the Sulphur Springs area may be due to a steam field.

B. Field Operations in the Qualibou Caldera

After evaluating all available data, Los Alamos performed a deep resistivity survey (to a depth of 2.0 km) centered on Sulphur Springs. The profile location was determined based on the previous British resistivity study and a geologic study performed by the Los Alamos National Laboratory. The decision was made to run a 5.2-km-long, north-south trending, dipole-dipole DC resistivity profile from just north of Ruby to just north of Victoria Junction (Fig. 1). This profile traverses extreme topography and dense jungle and was conducted during January 1984.

A nominal dipole length of 200 m was selected for the St. Lucia survey to obtain high resolution. Because of the difficult terrain on St. Lucia, it was impossible to keep a constant 200-m spacing. Two short regions along the profile have electrode spacings of less than 100 m, giving even higher resolution in these critical areas. The 5.2-km-long profile line across the Qualibou caldera contained a total of 32 electrode stations as depicted in Fig. 1.

To get resistivity data to a depth of 2 km, a 35-kW trailer-mounted DC transmitter (Fig. 2) was used. This transmitting system was built by the Los Alamos National Laboratory and is designed to handle high current output, up to 70 amps peak-to-peak, over a single dipole or to automatically alternate high current output over two separate dipoles. This capability permits the transmitter to be easily used in a wide variety of DC resistivity methods requiring both single and multiple current electrodes. The transmitter operates with an input of 440 to 480 V AC, three phase, 50 to 60 Hz at 35 amps or less. The transmitter output can be selected from 0 to 1000 V DC and from 0 to 70 amps peak-to-peak (maximum current is not available at maximum voltage). The output current is reversed positive/negative (to produce a square wave) at selectable times of 1 to 99 seconds. The negative current is selected so that it may have either the same duration as the positive current, or twice the positive current, thus allowing for polarity identification.

Figure 3 shows an electrical block diagram of the DC resistivity transmitter and Table I contains the detailed transmitter specifications. The

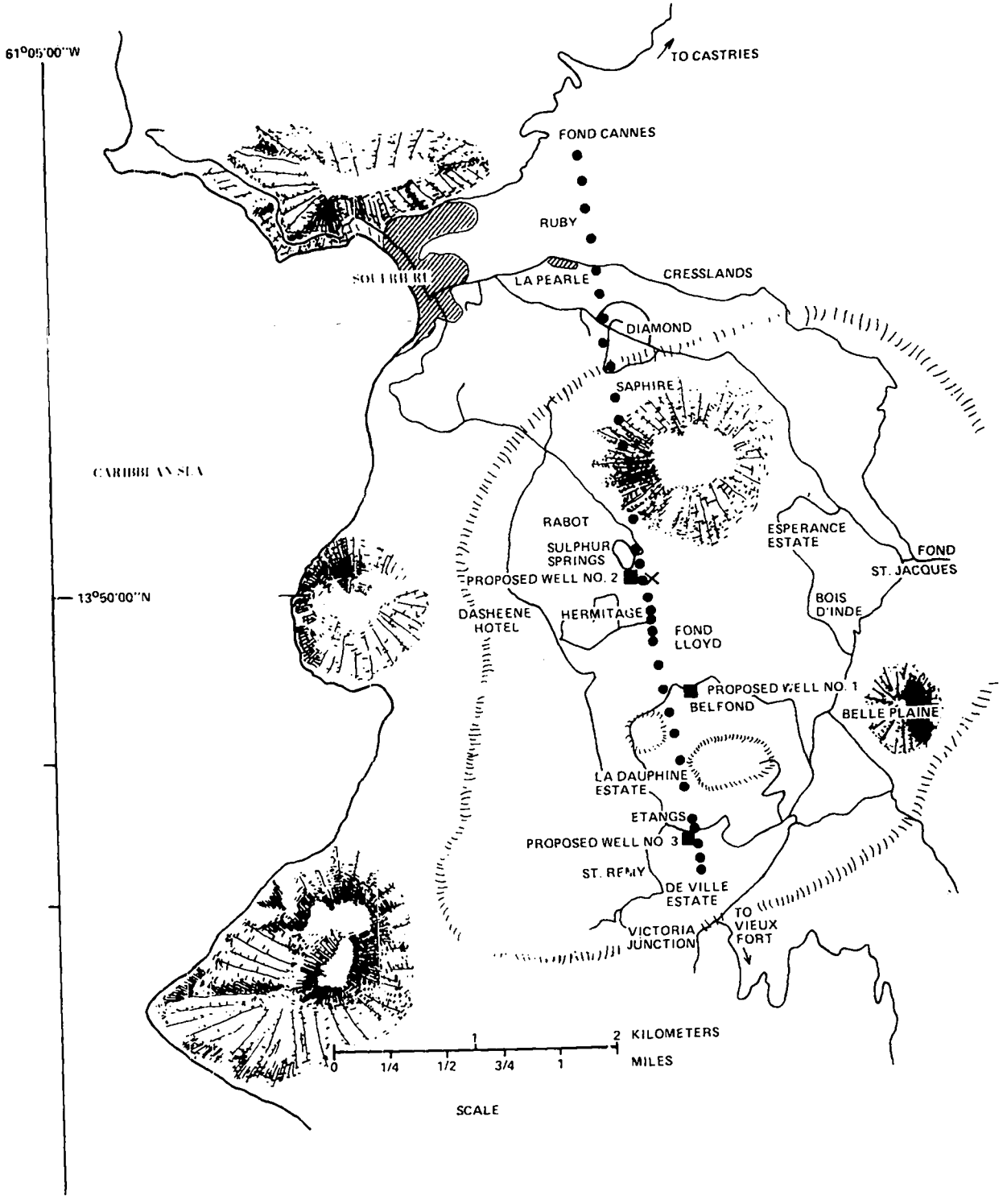

Fig. 1.
Location of the 5.2-km-long resistivity profile line (containing 32 electrode stations) across the Qualibou caldera.

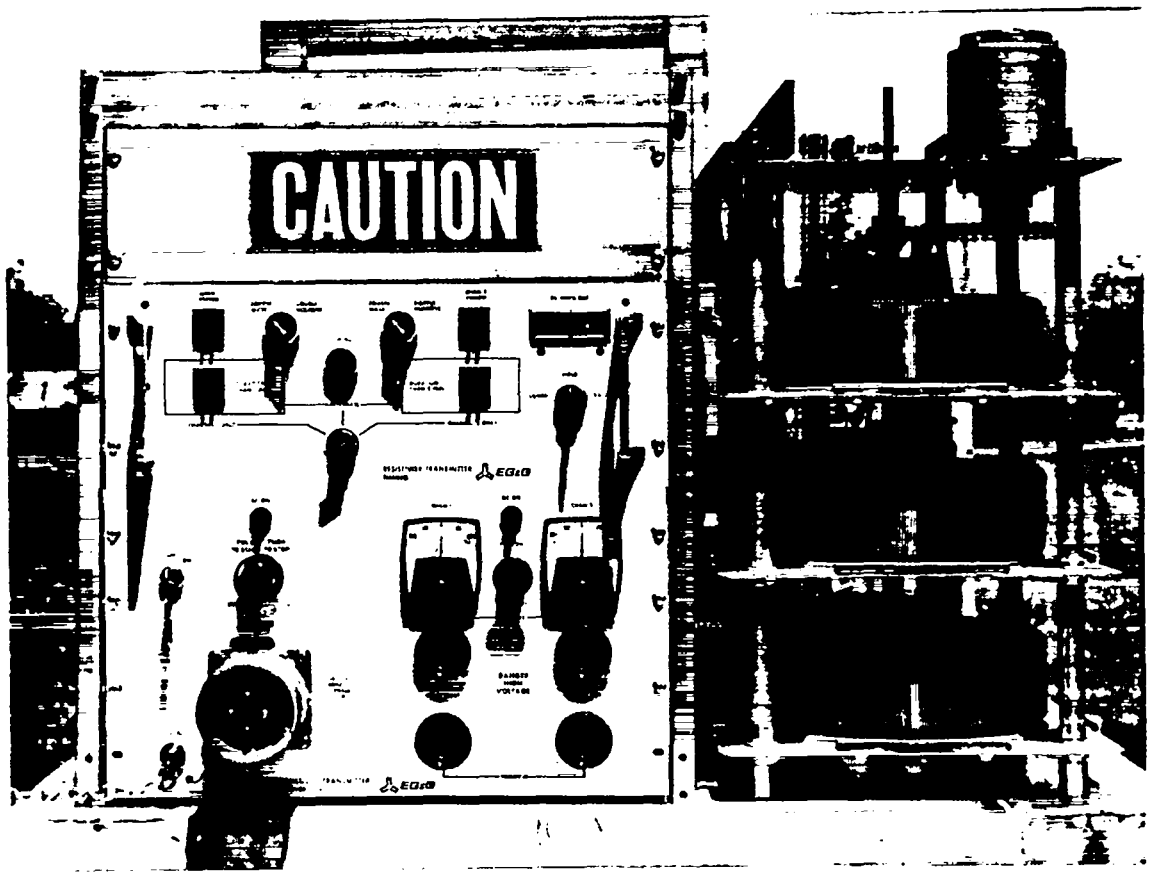

Fig. 2.
Photograph of the DC resistivity transmitter showing operator's console.

DC transmitter is powered by a trailer-mounted 60-kW diesel generator. The generator output is 480 V, 60 Hz, three phase.

Each of the four portable voltage measuring units (Fig. 4) consists of a voltage strip chart recorder and a DC voltage bucking box. The strip chart recorder and bucking box is shock mounted in a small portable aluminum transportainer. They are designed to apply a DC offset voltage to the incoming signal before it is plotted on the strip chart recorder. This is necessary to keep the measurements on scale because the currents produced by the DC transmitter (signal) are superimposed on natural earth currents (noise) known as telluric currents, which rapidly fluctuate in magnitude. Telluric currents have several sources. The two most important are inductions from the motion of charged particles in the ionosphere and the motion of charged

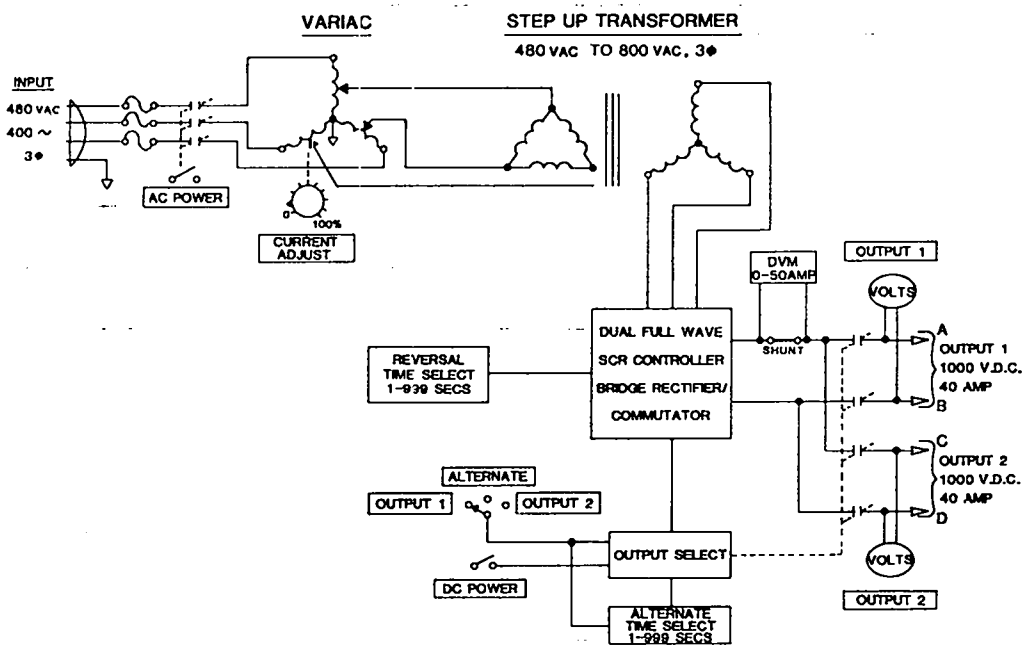

Fig. 3.
Electrical block diagram of the DC resistivity transmitter.

TABLE I

DEEP DC RESISTIVITY TRANSMITTER SPECIFICATIONS

INPUT:
440-480 VAC line-to-line
Three phase WYE pulse neutral
50/60 Hz
35 amps
40 kVA or less

OUTPUT:
Adjustable 0 to 1000 VDC, isolated from input
Ripple voltage less than 1%, at 720 Hz
0 to 70 amps peak-to-peak (max current not available at max voltage
Two independent outputs isolated from chassis, each controllable as follows:
- Output current reversed positive/negative at selectable time of 1-99 seconds.
- Negative current selected for same or double the duration of the positive current.
- Output on time selectable for 1-99 minutes.

Either output may be selected, or the outputs may alternate at independently selected time durations.

SIZE:
Approximately 3 ft x 3 ft x 4 ft enclosed

WEIGHT:
Approximately 1500 lb (without trailer)

CONTROLS:
AC power on/off (panic button OFF)
DC power on/off (panic button OFF)
Digital OUTPUT CURRENT meter, 0-50 amp, 0.1 amp resolution
Bipolar analog voltmeters on each output (2), ± 1000 V
Output Select
- Output 1
- Alternate
- Output 2

Output 1 on time select 1-99 minutes
Output 2 on time select 1-99 minutes
Output 1 current reversal time select 1-99 seconds
Output 2 current reversal time select 1-99 seconds
Negative current time Normal/Doubled
RESET TIME

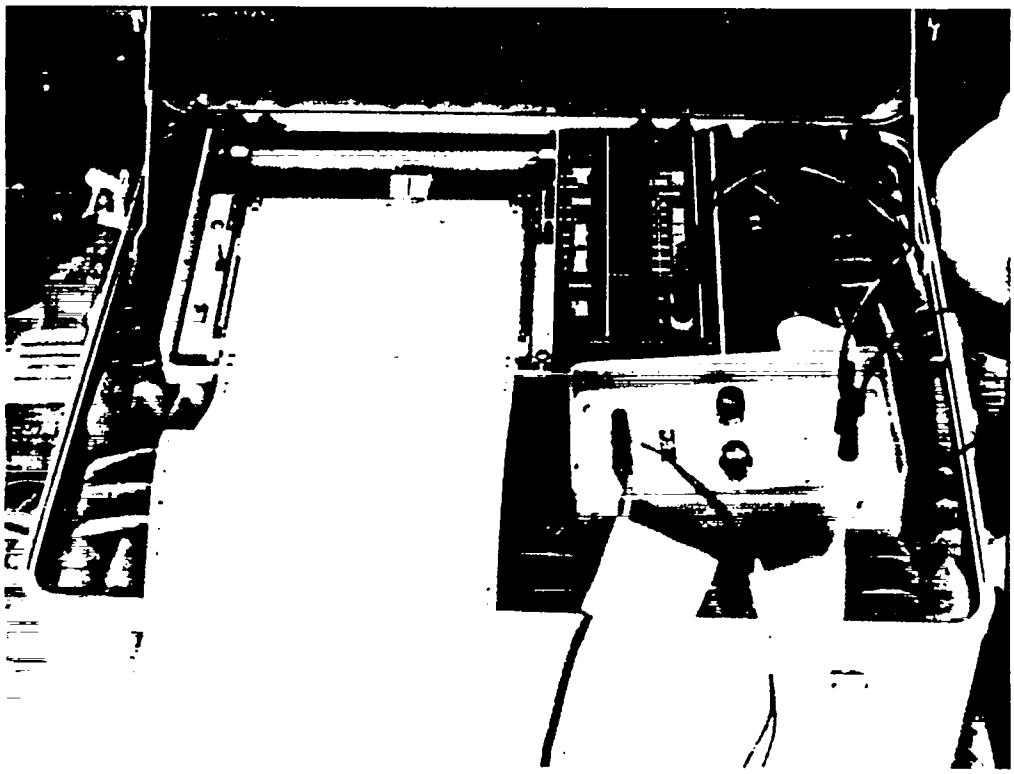

Fig. 4.
Photograph of a portable measuring unit showing voltage strip chart recorder and DC voltage bucking box.

clouds. The smallest signal that can be recorded by this receiving system is 2μV. The receiver system is powered by an internal rechargeable Ni-Cd battery, which gives approximately 10 hours of continuous use on a single charge.

III. RESISTIVITY DATA

The resulting apparent resistivity data from the dipole-dipole soundings are plotted as a function of depth in Fig. 5 (a plot of apparent resistivity versus depth is called a pseudosection). Also shown for comparison in Fig. 5 is the geologic cross section A-A' developed by Los Alamos. The geologic cross section is oriented approximately 10° counterclockwise relative to the dipole-dipole apparent resistivity cross section, with the sections intersecting at Sulphur Springs.

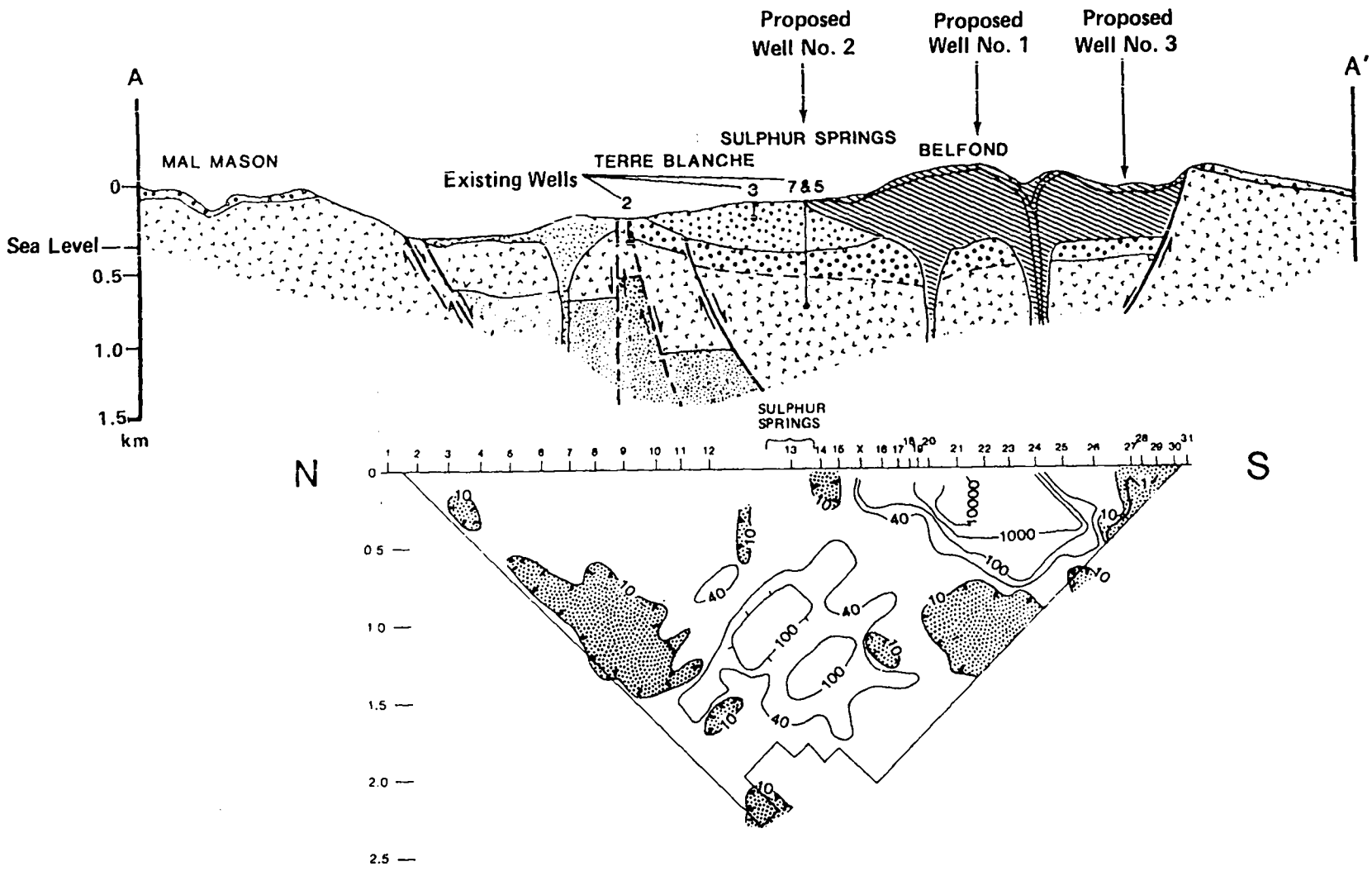

Fig. 5.
Apparent resistivity data from the dipole-dipole survey plotted as a function of depth. Resistivity values are in ohm-m and are shown beneath the appropriate geologic cross section. Shaded areas depict resistivity contours of 10 ohm-m or less.

The upper 700 m of the pseudosection shows similar characteristics to the British dipole-dipole data. In general, there is conductive material with a resisitivity less than 40 ohm-m located to the north of Sulphur Springs. There is an apparent resistivity high, greater than 1000 ohm-m, located below the Belfond area. Beneath this resistivity high, there is deeper low apparent resistivity material that is measured at less than 10 ohm-m. There is a zone of very low resistivity, less than 1 ohm-m, underlying the Etangs area. Beneath Sulphur Springs and starting at a depth of approximately 600 m, there is higher apparent resistivity material ranging from 40 ohm-m up to 150 ohm-m in the center of a 1-km-diameter high apparent resistivity closure.

IV. INTERPRETATION OF RESISTIVITY DATA

There are some interrelated interpretations possible from the apparent resistivity data. The regions containing less than 10 ohm-m material are highy suggestive of zones containing thermal waters. The zone beneath Etangs, containing material of less than 1 ohm-m, is related to thermal upwelling along a fault, probably the caldera-bounding fault, mapped earlier by Los Alamos geologists between Etangs and Belfond. A swampy area (at electrodes 30 and 31) located on a hillside with good drainage could be a surface manifestation of the fluid upwelling. The highly resistive shallow block associated with the Belfond area is a zone devoid of fluid penetration. It is fault bounded to the south and may also be fault bounded to the north. Beneath this highly resistive block, however, is a large zone of low apparent resistivity material (less than 10 ohm-m) that strongly suggests the presence of a large thermal reservoir. This region could not have been identified without the use of the deep DC resistivity survey. The location of Sulphur Springs is believed to be entirely fault controlled.

Based on the resistivity data alone, the deep higher resistivity zone located beneath Sulphur Springs can be interpreted in two ways: (1) the higher resistivity layer is due to a very not dry steam field; wet steam fields typically have resistivities around 30-60 ohm-m, while very hot dry steam fields can reach the higher resistivities measured in this area, (2) the higher resistivity zone beneath Sulphur Springs is due to a more

fluid impermeable caprock. The presence of steam in four of the seven shallow drill holes around Sulphur Springs and results from the hydrogeochemical studies suggest that the first interpretation is correct. The region between the two resistive zones (deep under Sulphur Springs and shallow under Belfond) most probably represents a fault along which thermal fluids are moving up dip from south to north to emerge in Sulphur Springs at the surface. This would suggest that the geothermal reservoir that feeds Sulphur Springs is located to the south beneath Belfond. This model is supported by the presence of upwelling, fault-controlled fluids in the Etangs area.

V. RECOMMENDATIONS FOR DRILLING IN THE QUALIBOU CALDERA

Based on the interpretation of the deep resistivity data, the following drilling recommendations are made:

(1) Craters of Belfond. The first well should be drilled in the Belfond area, preferably close to the location of the Belfond dance hall because of the ease of access for a drilling rig. The well is expected to encounter dry volcanic materials to a depth of 600-900 m where it is expected to pass through an impermeable hydrothermal boundary into a geothermal brine.

(2) Valley of Sulphur Springs. The second well should be drilled in the valley of Sulphur Springs, preferably south of the area of surface manifestations. This well is expected to encounter very hot dry steam between 600-1700 m and a geothermal brine by approximately 1800 m. It is also possible that a more impermeable, less fluid-bearing rock will be encountered instead of a steam zone above the deeper lying brine reservoir.

(3) Etangs. The third well should be drilled in the Etangs area, preferably south of the road near the Nutmeg Bar. This well should pass through the southern caldera-bounding fault and is expected to encounter geothermal fluids at shallow depths associated with the fault. The depth of the reservoir in this location could be as shallow as 1000 m.

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HYDROGEOCHEMICAL EVALUATION OF THE QUALIBOU CALDERA GEOTHERMAL SYSTEM, ST. LUCIA, WEST INDIES

(Fraser Goff and François-David Vuataz)

Analysis and interpretation of hydrogeochemical data from the Qualibou caldera, St. Lucia, indicate that a geothermal reservoir underlies the Sulphur Springs area and consists of three layers: (1) an upper steam condensate zone; (2) an intermediate two-phase (vapor) zone, which may be restricted to the Sulphur Springs area only; and (3) a lower brine zone. Although temperatures of 212°C at depths of 600 m were encountered by previous drilling at Sulphur Springs, four lines of evidence indicate that temperatures of the brine layer may exceed 250°C. Three other outlying thermal springs discharge in the Qualibou caldera, including two along the northern caldera collapse zone but their geochemistry does not indicate they overlie high-temperature reservoirs. Rather, they appear to be waters derived from the steam condensate layer in the vicinity of Sulphur Springs. If this is the case, it supports the theory that the high-temperature brine upflows in the area of Belfond-Sulphur Springs and flows laterally northwards toward the caldera wall. Only the weakest evidence suggests a small component of south lateral flow. On the basis of this evaluation, four sites are suggested for deep exploratory drilling to define the resource and investigate its hydrological dynamics. These sites are at (1) Belfond area near the youngest silicic volcanism, (2) Sulphur Springs proper, (3) Etangs area near the southern caldera collapse fault, and (4) Diamond Spring near the north caldera wall.

I. INTRODUCTION

Several hot springs discharge within Qualibou caldera but by far the most impressive thermal features occur at Sulphur Springs (Robson and Willmore, 1955), which is close to the caldera center and the youngest pyroclastic vents. Curiosity regarding St. Lucia's geothermal potential began many years ago (Bodvarsson, 1951), but nothing was initiated until the 1970s when the U.K. Ministry of Overseas Development financed a drilling project at Sulphur Springs (Williamson, 1979). Although seven shallow wells were drilled

to depths as great as 700 m and steam was encountered at temperatures above 200°C, this project was terminated because of high CO_2 content of the vapor, difficulty in finding permeable fractures, and lack of money. Soon thereafter, the Italian consulting firm Aquater (1982a) conducted a comprehensive geothermal evaluation of Qualibou caldera and recommended areas for deep exploration drilling. To date, however, the only wells drilled on St. Lucia are the shallow wells at Sulphur Springs.

The purpose of this report is to combine previous geochemical data with new data recently acquired by the authors to determine: (1) the type of geothermal system present, (2) the temperature of various geothermal horizons at depth, and (3) the possible configuration and dimensions of the geothermal reservoirs. This latter objective considers available geologic and geophysical data as well. Finally, four sites are recommended for deep exploration drilling. A brief summary of our work has been previously reported (Goff and Vuataz, 1984).

II. GEOLOGIC AND GEOPHYSICAL BACKGROUND

The geology of St. Lucia consists of several distinct volcanic sequences interstratified with minor marine sedimentary rocks (Aquater, 1982a). In general, volcanism was initiated in the north around 10 Ma ago and migrated southwards. Rock compositions evolved from basaltic to andesitic to dacitic types through time but andesites volumetrically dominate. The precaldera rocks surrounding Qualibou caldera are composed almost entirely of andesites in the 2.5-Ma range (i.e. Mt. Gimie). Later dome eruptions built the dacite edifices of Petit and Gros Pitons (0.25 Ma) before caldera formation. These extrusive eruptions produced large quantities of breccias and tuffs as well as typical domes and flows.

The exact age of formation of Qualibou caldera was previously estimated at 0.5 Ma (Aspinall et al., 1976), but new radiocarbon ages by Roobol et al. (1983) indicate an age less than 40,000 years. This is confirmed by recent geologic work by Wohletz and Heiken (1984) who find that caldera formation postdates the Pitons. Following caldera collapse, a large central dacite dome was extruded inside the caldera that constructed the towering peak of Terre Blanche. The most recent volcanism has centered around Belfond in the south-central part of the caldera with creation of up to 10 phreatomagmatic

vents of rhyodacitic composition. These vents are dated at 39,000 to 20,000 years by ^{14}C techniques on organic remains in the ash deposits (Tomblin, 1965; Roobol et al., 1983). The well-preserved cones testify that these vents are very young. Because Sulphur Springs lies a scant 1 km northwest of these vents, it is assumed that the shallow magma chamber producing the silicic pyroclasts is the heat source driving surface hydrothermal activity.

Qualibou caldera is 3 to 4 km across from NW-SE, small in comparison with many known caldera systems (Smith, 1979). The caldera is elongate in a SW-NE direction because of a major regional tectonic pattern (Wohletz and Heiken, 1984). The caldera margins are very distinct on the north, east, and southwest sides because rivers have entrenched along the caldera-bounding faults. The west caldera margin is now recognized by Wohletz and Heiken (1984) from stratigraphic relations to pass between the ridges of Dasheene and Rabot. Although some silicic domes have erupted along intracaldera faults in the Belfond area, the pronounced "ring" of domes observed at many large calderas (such as the Valles Caldera; Smith and Bailey, 1968) is not seen at Qualibou caldera. Hot springs at Diamond and Cresslands issue from the northwest sector of the caldera collapse zone and Aquater (1982b) noted that H_2S and B anomalies are found around the north and south caldera margins.

According to Williamson (1979), the main thermal area, Sulphur Springs valley, is oriented parallel to faults and fractures that strike NW-SE and dip 60 to 70°NE. Faults of this trend are also shown on the maps of Aquater (1982a). Wohletz and Heiken (1984) believe that the Sulphur Springs faults consist of an arcuate collapse fault associated with the inner western wall of Qualibou caldera and a major through-going regional NW-SE fault system.

Aquater (1982a) conducted a gravity survey over Qualibou caldera that yielded a very surprising result; a <u>positive</u> gravity anomaly of roughly 20 Mgals underlies the caldera depression. The depth to the high-density layer is about 500 m in the south but nearly 1000 m in the north. Because calderas form large "holes" in the earth's surface that fill up with low-density tuffs and breccias, they invariably produce negative gravity anomalies (i.e. Segar, 1974). Therefore, the cause of the high-density layer in Qualibou caldera invites speculation. Williamson (1979) notes that the drill holes at Sulphur Springs penetrate "caldera-wall agglomerates" at depth, presumably precaldera basaltic and andesitic rocks. The authors observed several hundred meters of what appears to be precaldera basalt or basaltic andesite along the sea coast

north and south of Petit Piton. These outcrops are shown on the maps of Aquater (1982a). There is no obvious reason, however, why denser precaldera rocks of basaltic or andesitic composition would not occur both within and outside the caldera.

A second possibility is that neutral-chloride geothermal fluids at depth have been hydrothermally altering the host volcanics such that their bulk density has increased. This would occur if the Ca contained in the volcanics was converted to calcite and epidote, both stable minerals at the temperatures known beneath Sulphur Springs and common alteration minerals in basaltic and andesitic rocks.

Aspinall et al. (1976) performed a microearthquake survey at Qualibou caldera and recorded seven events during a 39-day period. The seismic records are characterized by emergent P-waves and missing or attenuated S-waves, characteristics that denote the presence of fluid bodies (magma or water) at depth. Analysis of the data indicates that the attenuating medium occurs at depths less than 2 km extending from Sulphur Springs to the north caldera wall; thus, these researchers conclude that a geothermal system occupies this zone. The distribution of known hot springs inside the caldera is coincident with the attenuating zone.

Electrical resistivity measurements (Williamson and Wright, 1978; Aquater, 1982a) indicate that conductive zones $\leq$30 ohm-m occur to depths of 700 m in the Sulphur Springs area, correlating well with the known presence of 200°C steam and near-surface acid alteration. Each of the above authors implies that the conductive zones extend well beyond Sulphur Springs to the north and south but hastens to add that the steep topography and complicated contacts among intracaldera rocks may cause apparent anomalies that have no geothermal significance. Conductive zones at depth in geothermal areas often denote the presence of hot saline waters and/or clay-bearing hydrothermally altered rocks.

The best evidence for presence of neutral-chloride hot waters at depth comes from drilling (Williamson, 1979). Large quantities of concentrated geothermal fluid were discharged from British well #4 at Sulphur Springs during wet/dry cycling with Cl concentration ranging from 10,000 to 70,000 mg/ℓ. Because of the cyclic discharge, samples of unevaporated deep fluids

were never obtained (Bath, 1977), although Williamson and Wright (1978) state the actual Cl content is probably about 25,000 mg/ℓ.

In summary, geologic data show that Qualibou caldera is very young (∿40,000 years) and contains relatively shallow magmatic heat sources. Geothermal fluids appear to be fault and fracture controlled both inside the caldera and along the northwest caldera margin. Gravity data indicate that "high-density" material of unexplained origin fills or underlies the caldera at shallow depths. If the buried, high-density zone is caused by extensive hydrothermal alteration in precaldera mafic rocks, this would correlate with the depth of shallow fluid bodies inferred from microseismic data and with the distribution of conductive zones delineated by electrical methods. Because drilling has yielded hot, neutral-chloride brines from one well at 600 m beneath Sulphur Springs (Bath, 1977), it is easy to assume that a large deep geothermal system underlies the central and northern portions of Qualibou caldera. It remains to be seen from drilling of more widely spaced wells how large this system really is, whether it consists of several subsystems, and how permeable the reservoir is. Clearly, however, Qualibou caldera has great geothermal potential.

III. GEOCHEMISTRY

Although thermal springs in Qualibou caldera have been known and used in the past, no scientific data were reported from the Sulphur Springs area until Bodvarsson (1951) first investigated its geothermal possibilities. Robson and Willmore (1955) estimated the natural heat flow at 36 MW(t). The first comprehensive geochemical studies were performed by Bath (1976; 1977) during the geothermal drilling project of the 1970s. Chemical and isotopic data from these wells provide fundamental data to our interpretations. Little data on outlying springs were available until the reconnaissance work of Aquater (1982b). The authors visited St. Lucia in July, 1983, and obtained samples from Sulphur Springs and from outlying hot springs and cold waters within the caldera. For the purposes of this report, the geochemistry in later sections is discussed by area because information on the temperature of the resource comes from Sulphur Springs while ideas on the dimensions of the resource come from the outlying springs.

Temperature, pH, Eh, and conductivity of all sample locations were measured using a portable digital meter. All waters were collected, preserved, and chemically analyzed according to methods described in Goff et al. (1982) and Vuataz et al. (1984). Stable isotope samples of water were analyzed by either the Centre d'Etudes Nucléaires de Saclay, France, or C. Janik, U.S.G.S., Menlo Park, California. Tritium samples were analyzed at the Tritium Laboratory of the University of Miami, Florida. Gases were collected in evacuated 125-mℓ tubes according to methods described in Goff et al. (1984) and analyzed by B. Evans and D. White (U.S.G.S., Menlo Park) for bulk composition and stable isotopes of CO_2. Sulfur isotopes were analyzed by Geochron Laboratories, Cambridge, Massachusetts, and alteration phases were determined by x-ray diffraction (D. Bish, Los Alamos National Laboratory).

A. Sulphur Springs

Sulphur Springs is one of the most impressive areas of acid springs and fumaroles ever seen by the authors, rivaling the Mud Volcano of Yellowstone, Bumpass Hell at Lassen, and Ketetahi Springs in New Zealand. The most common thermal features are numerous broad pools or cauldrons filled with bubbling and fountaining black water. A sketch map and temperature survey was made at Sulphur Springs (Fig. 1 and Table I) to positively identify the sources of samples. Table II lists the locations, field data, and types of samples taken.

The main zone of activity occurs in a northwest-trending belt about 100 by 250 m at the base of the northeast flow of hornblende dacite from Rabot and along the southwest side of Diamond Creek, but the entire altered zone extends across the dacite lavas on the flanks of Terre Blanche. The original dacites surrounding Sulphur Springs have been converted to cristobalite-quartz-natroalunite-kaolinite-bearing rocks. Sulfur, gypsum, and pyrite are concentrated near fumaroles and steaming ground. Iron oxides form orange and red stains in dry spots and around the margin of the active area. All these features are characteristic of acid-sulfate hot spring systems (White et al., 1971).

1. Fluid Chemistry of Surface Manifestations. Spring waters at Sulphur Springs display chemical compositions that are very characteristic of acid-sulfate systems (Tables III and IV). They have relatively low pH, high SO_4, and low Cl with one important exception discussed below (steam

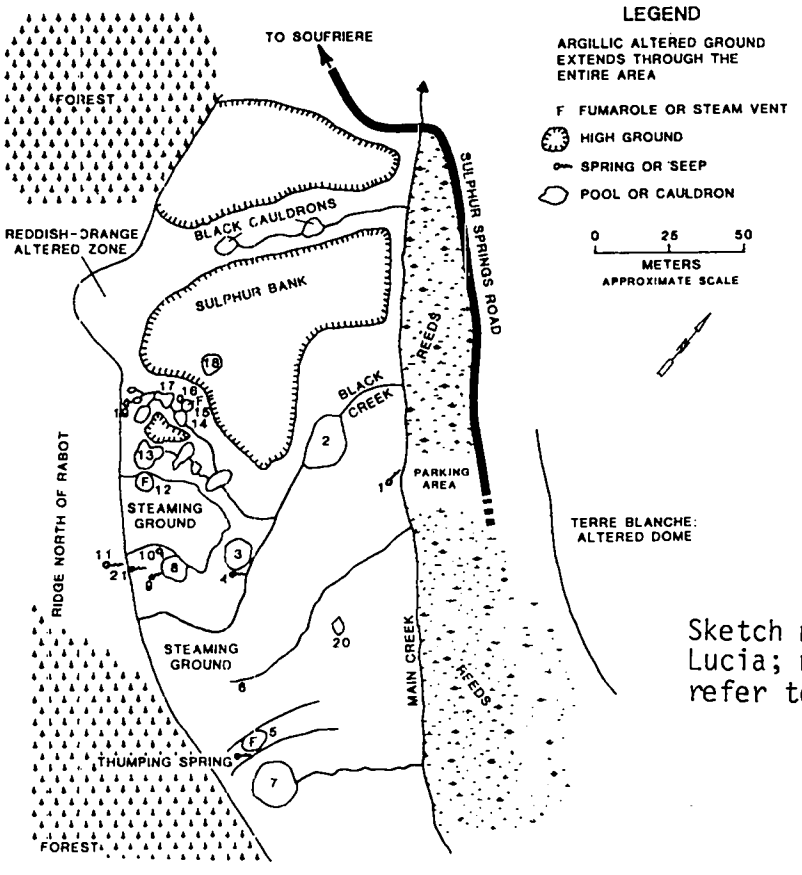


Fig. 1.
Sketch map of Sulphur Springs, St. Lucia; numbers by thermal features refer to Table I.

TABLE I
TEMPERATURE SURVEY OF THERMAL FEATURES AT SULPHUR SPRINGS, ST. LUCIA, LESSER ANTILLES

Map location # (Fig. 1)	Description	Temperature (°C)
1	seep	94
2	black bubbling pool	63
3	grey bubbling pool	96
4	bubbling seep	88
5	steam vent	103
6	steaming ground	
7	boiling cauldron	90
8	clear bubbling pool	72
9	flowing clear spring	69
10	flowing clear spring	93
11	flowing clear spring	58
12	superheated steam vent	171
13	large black cauldron at edge	88
14	black cauldron	73
15	steam vents	96-98
16	light grey boiling pool	95
17	black cauldron	81
18	grey pool	96
19	bubbling pool	80
20	very small bubbling pool	80
21	flowing clear spring	56

TABLE II

FIELD DATA AND PHYSICAL PARAMETERS OF WATERS AND GASES FROM ST. LUCIA (July, 1983)

Map[a] no.	Name	No.	Temperature (°C)	pH	Eh(mV)	Conduct. (μS/cm)	Discharge (ℓ/min)	Sampling
Sulphur Springs								
5	Steam vent	SL-1	103					gas
5	Steam vent	SL-2	103					gas
14	Black cauldron	SL-3	73					gas
14	Black cauldron	SL-4	73					gas
8	Clear bubbling pool	SL-5	72					gas
—	Leak around geoth. well	SL-7	37.8	4.8	—	484	—	water
10	Flowing clear spg.	SL-8	92.7	6.2	-322	800	1.5	water
8	Clear bubbling pool	SL-9	64.8	2.50	-38	3300	—	water
16	Light grey boil. pool	SL-10	96.0	1.55	+110	10900	—	water
5	Steam vent	SL-11[b]	103	7.78	+489	970	—	condensate
8	Clear bubbling pool	SL-19	72					gas
16	Drowned fumarole	SL-20	95					gas
16	Drowned fumarole	SL-21	95					gas
15	Steam vents	SL-22[b]	96-98	8.19	+413	1050	--	condensate
19	Bubbling pool	SL-23	≥80					gas
19	Bubbling pool	SL-24	≥80					gas
12	Superheated steam vent	SL-25	171					gas
12	Superheated steam vent	SL-26	171					gas
12	Superheated steam vent	SL-27	171					condensate
Thermal springs, Qualibou Caldera								
--	Diamond warm spg.	SL-12	43.1	6.45	-106	1300	3	water
—	Cresslands hot spg.	SL-15	55.7	6.55	-0.20	2490	2	water
—	Malgretoute warm spg.	SL-17	35.2	8.57	+16	1530	--	water
Cold waters, Qualibou Caldera								
--	Diamond Creek, Sul. Spgs.	SL-6	26.3	6.60	+200	170	--	water
—	Waterfall at Diamond	SL-13	27.3	4.33	+164	1070	1200	water
—	Cresslands cold spg.	SL-14	26.5	6.24	+186	272	18	water
—	Migny River	SL-16	25.9	8.06	-37	165	2400	water
--	Dasheene spg.	SL-18	26.5	6.80	+10	267	--	water

a Numbered points except SL-7 can be located on Fig. 1; SL-7 was sampled approximately 100 m southeast of Sulphur Springs.

b For the condensates SL-11 and SL-22, pH, Eh, and conductivity were measured in the laboratory

TABLE III

MAJOR AND MINOR ELEMENTS (mg/ℓ) FOR THE WATERS FROM ST. LUCIA
(July, 1983)

Name	No.	Li^+	Na^+	K^+	Mg^{++}	Ca^{++}	Sr^{++}	Mn^{++}	Fe^{++}	HCO_3^-	SO_4^{--}	Cl^-	F^-	SiO_2	B	TDS	$\sum$cations[a]	$\sum$anions[a]
Sulphur Springs																		
Leak ar. geoth. well	SL-7	0.06	27	6.3	10.7	50.2	0.21	0.88	0.32	0	230	16.9	0.17	151	0.36	494	4.78	5.27
Flowing clear spg.	SL-8	0.04	49	6.8	10.3	61.5	0.27	0.54	0.02	309	35.6	39.7	0.11	197	10.9	721	6.25	6.93
Clear bubbling pool	SL-9	0.09	54	13.7	9.3	72.3	0.66	0.81	16.4	0	1085	32.9	0.05	186	15.1	1486	7.72	18.47
Drowned fumarole	SL-10	0.05	6	6.7	72.0	220	0.04	6.53	68.6	0	6750	5	0.02	360	22.9	7518	20.03	110.72
Steam vent	SL-11	-	-	-	-	-	-	-	-	-	121	1.3	0.03	<1	95	-	-	-
Steam vents	SL-22	-	-	-	-	-	-	-	-	-	109	6.7	0.05	1	0.60	-		-
Thermal springs, Qualibou caldera																		
Diamond warm spg.	SL-12	0.22	129	11.0	42.3	69.2	0.47	0.29	0.20	686	21.8	40.0	0.15	171	11.1	1183	12.88	12.83
Cresslands hot spg.	SL-15	0.67	257	16.5	56.5	163	1.41	0.35	1.71	1215	0.77	153	2.60	110	15.0	1994	24.58	24.38
Malgretoute warm spg.	SL-17	0.41	267	15.4	20.3	23.1	0.69	<0.01	0.03	648	105	74	0.16	101	8.91	1264	14.91	14.90
Cold waters, Qualibou caldera																		
Diamond Cr., Sul. Spgs.	SL-6	<0.01	15	4.0	3.28	13.1	0.07	0.02	0.27	57.3	10.6	18.1	0.10	61	0.15	183	1.69	1.68
Waterfall at Diamond	SL-13	0.08	37	6.1	18.3	84.6	0.30	1.18	0.71	0	508	36.0	0.07	96	26.2	815	7.58	9.08
Cresslands cold spg.	SL-14	<0.01	16	2.2	7.2	23.8	0.13	<0.01	<0.01	103	11.7	20.6	0.07	46	0.10	231	2.54	2.52
Migny River	SL-16	<0.01	12	1.7	4.4	13.4	0.07	0.01	0.04	69.6	2.73	13.1	0.08	47	0.11	164	1.60	1.57
Dasheene spg.	SL-18	<0.01	20	3.9	5.9	19.3	0.08	<0.01	0.04	97.6	7.6	22.8	0.11	82	0.16	260	2.42	2.41

[a] Cations and anions are summed in meq/ℓ.

TABLE IV

TRACE ELEMENTS (mg/ℓ) FOR THE WATERS FROM ST. LUCIA[a] (July, 1983)

Name	No.	Al	Ba	Br	Cd	Co	CO_3	Cr	Mo	NH_4	Ni	NO_2	NO_3	PO_4	Rb	Sb	Se	Zn
Sulphur Springs																		
Leak ar. geoth. well	SL-7	<0.05	0.05	<0.1	<0.001	<0.001	0	0.002	<0.05	0.22	<0.001	0.6	0.2	1.1	0.18	<0.1	<0.5	<0.02
Flowing clear spg.	SL-8	0.15	0.12	<0.1	<0.001	0.002	0	<0.001	<0.05	16.6	<0.001	<0.5	<0.1	<0.1	<0.01	<0.1	<0.5	<0.02
Clear bubbling pool	SL-9	22	0.13	<0.1	<0.001	0.004	0	0.026	<0.05	46.7	0.014	1.5	<0.1	<0.1	0.11	<0.1	<0.5	0.09
Drowned fumarole	SL-10	290	0.03	<1	0.001	0.010	0	0.173	0.25	2.42	0.045	<0.5	<1	<1	1.48	0.41	1.2	0.28
Steam vent	SL-11	-	-	<0.2	-	-	0	-	-	-	-	<0.5	<0.1	<0.2	-	-	-	-
Steam vents	SL-22	-	-	<0.1	-	-	0	-	-	-	-	<0.5	<0.1	<0.1	-	-	-	-
Thermal springs, Qualibou caldera																		
Diamond warm spg.	SL-12	<0.05	0.09	<0.1	<0.001	<0.001	0	<0.001	<0.05	0.24	0.001	7.9	2.1	<0.1	<0.01	<0.1	<0.5	<0.02
Cresslands hot spg.	SL-15	<0.05	0.40	0.5	<0.001	<0.001	0	<0.002	<0.05	0.01	<0.001	<0.5	0.3	<0.1	0.10	<0.1	<0.5	<0.02
Malgretoute warm spg.	SL-17	<0.05	0.06	0.1	<0.001	<0.001	13.8	<0.001	<0.05	<0.01	<0.001	1.0	4.9	<0.1	<0.01	<0.1	<0.5	<0.02
Cold waters, Qualibou caldera																		
Diamond Cr., Sul. Spgs.	SL-6	0.84	0.05	<0.1	<0.001	<0.001	0	<0.001	<0.05	<0.01	<0.001	<0.5	<0.1	<0.1	0.05	<0.1	<0.5	<0.02
Waterfall at Diamond	SL-13	8.8	0.04	<0.1	<0.001	0.007	0	0.003	<0.05	29.3	0.002	<0.5	1.1	<0.1	0.09	<0.1	<0.5	0.04
Cresslands cold spg.	SL-14	<0.05	<0.01	<0.1	<0.001	<0.001	0	<0.001	<0.05	0.03	<0.001	<0.5	2.7	<0.1	<0.01	<0.1	<0.5	<0.02
Migny River	SL-16	0.20	<0.01	<0.1	<0.001	<0.001	0	<0.001	<0.05	<0.01	<0.001	<0.5	0.9	<0.1	0.05	<0.1	<0.5	<0.02
Dasheene spg.	SL-18	<0.05	<0.01	<0.1	<0.001	<0.001	0	<0.001	<0.05	<0.01	<0.001	<0.5	2.9	0.5	0.15	<0.1	<0.5	0.07

[a] The following trace elements concentrations are below the detection limit for all the samples: Ag <0.001; As <0.05; Cu <0.001; Hg <0.1; Pb <0.001; U <0.5

condensate springs). Divalent and trivalent cations (Ca, Mg, Al, Fe) dominate over Na+K and most trace elements other than B are relatively low. Acid-sulfate waters are mixtures of rising steam and gases that condense in the near-surface environment. Oxidation of H_2S to H_2SO_4 leads to acidic conditions. The condensed acid waters may or may not mix with near-surface ground water to produce hybrid compositions (White et al., 1971).

No attempt was made to sample every feature at Sulphur Springs because its acid-sulfate nature was known from earlier work. Instead, samples were taken from unique features after our sketch map and temperature survey were completed to obtain ranges in chemical composition that would help us understand the dynamics of the system. From our data and observations, we can identify four types of thermal features.

(1) Steam Condensate Springs (Hot Spring #10): This group of springs issues only from high ground around the southwest margin of Sulphur Springs. A cluster composed of springs 9, 10, 11, and 21 and a number of seeps above spring 19 (Fig. 1) all discharge similar water. These springs are noteworthy because they form small deposits of $CaCO_3$ (travertine), which is unstable in acid environments. Chemically they are near neutral in pH and contain HCO_3^- as the major anion.

Waters of this type issue from higher levels at many vapor-dominated (steam) geothermal systems. Examples include The Geysers (White et al., 1971) and Lassen (Muffler et al., 1982), both in California. According to Mahon et al. (1980), HCO_3^--rich steam condensate waters commonly form a cap or carapice to many deep neutral-chloride systems in excess of 200°C (i.e. Broadlands, New Zealand, and Kamojang, Indonesia). Recognition of this water type around acid-sulfate zones has useful applications in formulating a model of a geothermal system.

(2) Cauldron Springs (Hot Spring #8): As mentioned above, these are the most common type at Sulphur Springs. They are typical acid-sulfate waters containing various amounts of surface ground waters. They discharge as interconnected pools to Diamond Creek.

(3) Drowned Fumaroles (Hot Spring #16): Only one spring obviously belongs to this group. Hot spring #16 lies in a shallow depression and boils violently from steam and noncondensible gas passing rapidly through the water. Because of continuous condensation and evaporation of steam and

only minor dilution from surface ground water, drowned fumaroles are the most acid and concentrated of the springs.

(4) Fumaroles (Steam Vents #5, #12 and #15): These are merely open cavities discharging steam and gas to the surface, ranging from steaming ground to gaping holes. Most features discharge at boiling temperatures but two features, #5 and #12, were superheated. Vent #12 was measured at 171°C and is one of the hottest fumaroles known, surpassing the 159°C recorded for a fumarole at Lassen, California (Muffler et al., 1982). Williamson (1979) recorded a temperature of 185°C at vent #12 in the 1970s. Partial analysis of the steam shows high SO_4 and low Cl. Most interesting, however, is the extremely high B/Cl ratio in the superheated vents, a characteristic noted by Aquater (1982b). High B/Cl ratios in steam generally indicate the steam originates by deep boiling of high-temperature brine (Tonani, 1970; Ellis and Mahon, 1977).

Acid-sulfate waters do not necessarily indicate that a vapor-dominated system lies at depth. The available drilling data reported by Williamson (1979) indicate variable two-phase conditions in the vapor zone beneath Sulphur Springs. Temperatures approach 220°C and pressures are $\leq$32 b.a. "True" vapor-dominated systems ideally display temperatures of 240°C and pressures of 32 b.a. (White et al., 1971), thus conditions at Sulphur Springs are suggestive of a vapor-dominated zone of as yet unknown size.

2. Deep Reservoir Fluid, Well #4. Wells #4 through #7 were drilled about 100 m south of Sulphur Springs in a flat area adjacent to Terre Blanche. Well #4 is unusual in that it produced slugs of geothermal brine during wet/dry cycling. The temperature of this brine at a depth of 600 m was 203°C (Bath, 1977). Partial chemical analyses of the brine (Table V) show tremendous chemical variation but display rather constant molar ratios of Na, K, Ca, and Mg to Cl as documented by Bath (1977, Table 2). Because of this, the variations are thought to be due to steam loss from liquid in a fracture system of limited volume.

It is impossible to say what the exact composition of the reservoir brine is because of the variable discharge of the well. Williamson and Wright (1978) suggest a true Cl level of 25,000 mg/ℓ but do not indicate why they believe this. The brine chemistry is extremely unusual because Ca is roughly

TABLE V

LIQUID FLOW AND CHEMICAL GEOTHERMOMETRY[a] FROM WELL #4, SULPHUR SPRINGS, ST. LUCIA[b]

Date	pH	Na	K	Mg	Ca	SO_4	Cl	SiO_2	B	$\sum$cations[c]	$\sum$anions[c]	Qtz	Na-K-Ca β = 4/3	Na-K-Ca β = 1/3	Na-K
--	—	5650	—	220	21100	180	53500	>300	550	1310	1510	>209	--	--	--
7/20/75	—	4500	255	190	12100	500	31600	--	--	820	900	--	109	153	172
4/2/76	5.69	3500	151	42	5300	--	18000	--	--	420	510	--	107	143	155
4/3/76	5.39	6300	330	130	13700	—	40500	--	--	980	1140	--	120	153	167
4/4/76	5.80	360	20	6.6	710	30	2330	36	--	50	65	89	59	135	171
4/6/76	5.85	500	50	17	1850	174	6120	88	870	120	175	130	71	160	216
4/10/76	5.07	5900	290	100	11600	1195	37000	212	3500	890	1070	172	120	151	163
4/15/76	4.75	8300	390	140	16300	240	49700	120	--	1200	1400	148	126	151	159
4/22/76	4.52	11100	565	190	22200	850	70200	103	—	1610	2000	138	137	158	166

a Fournier (1981).

b Analyses in mg/ℓ are listed by Bath (1976). The first sample was produced from 315 m, all others from 612 m.

c Cations and anions summed in meq/ℓ.

twice Na by weight and the brine is extremely rich in B. It is unfortunate that the data of Bath (1976; 1977) are not more comprehensive. The cation-anion balance of the analyses in Table V is consistently low on the cation side. This may be compensated by the relatively low pH of the brine. It is probable that the brine contains substantial Li, Br, and possibly other trace elements. The extreme variation in SiO_2 suggests that the silica analyses are unreliable.

$CaCl_2$-rich geothermal brines are very unusual compared with most geothermal fluids. They occur only in settings near the ocean such as the Salton Sea, California, the Reykjanes field in Iceland, or along oceanic spreading centers like the Atlantic II Deep (Hardie, 1983). Even these geothermal brines, however, contain more Na than Ca, making the Sulphur Springs brine truly remarkable.

3. Subsurface Temperature of Brine Reservoir. Several lines of evidence point to extremely high temperatures beneath Sulphur Springs and its underlying brine reservoir. Drilling to depths of 700 m encountered temperatures of 220°C (Williamson, 1979), but the following data indicate that higher temperatures exist.

(1) Stable Isotopes of Water: A plot of deuterium (D) versus oxygen-18 (^{18}O) is shown in Fig. 2 in which discrete symbols refer to data collected by the authors, while the two clouds refer to brines and steam condensates collected from well #4 during wet/dry cycling (Bath, 1977). The composition of brine is essentially identical in D but considerably heavier in ^{18}O than surface water, indicating extensive exchange of oxygen between water and rock in the reservoir (Craig et al., 1956). A pronounced "shift" in ^{18}O is a characteristic repeatedly observed in the deep reservoir fluids of geothermal systems $\geq$250°C (White, 1968). The magnitude of the shift at Sulphur Springs is rather extreme (13°/₀₀), rivaling the shift observed in the geothermal brines of the Salton Sea, California (14°/₀₀).

The composition of ^{18}O in Sulphur Springs brine is unusually heavy (+10°/₀₀) but the cause of this is not entirely clear. If the brine is reacting isotopically with silicic intracaldera rocks, which should possess $\delta^{18}O$ of +10°/₀₀ and possibly higher (Taylor, 1968), it suggests the volume of water is small compared to the volume of rock

and/or the system is so young it is isotopically dominated by the signature of the rocks. Because we know the caldera is only 40,000 years old, we would favor the second argument.

(2) Gas Geothermometry: Six samples of gas were collected from various thermal features, including the two superheated fumaroles (Table VI). When air contamination is corrected, all samples are virtually identical. CO_2 is the dominant noncondensible gas as it is in all high-temperature geothermal systems. There are also substantial quantities of H_2S and H_2. Several samples contain minute but detectable quantities of CO, which is produced only in relatively high-temperature geothermal systems (Evans et al., 1981). Using the empirical gas geothermometer of D'Amore and Panichi (1980), Sulphur Springs gases indicate a consistent subsurface reservoir temperature of 280°C.

(3) Enthalpy of Superheated Fumaroles: Muffler et al. (1982) discuss the thermodynamic significance of the superheated fumaroles at Lassen, California, in some detail. According to these authors, superheated fumaroles discharge steam from subsurface reservoirs by means of an adiabatic rather than isothermal process. If we plot the measured temperature of steam vent #12 on Fig. 3 (which shows the relationship between saturated steam and the isothermal decompression paths of superheated steam for pure water), we note that an isoenthalpic (vertical) line lies to the right of the maximum enthalpy of saturated steam, approximately 236°C at 31 bars. If we analyze Fig. 3 qualitatively, the curve surrounding saturated steam is shifted to the right if the fluid system consists of a brine instead of pure water. The temperature of maximum enthalpy of steam is also increased in a brine system. Thus, if the steam discharging from vent #12 originates from isoenthalpic decompression in the reservoir, the deep brine temperature must be >236°C, possibly in the neighborhood of 260°C.

(4) High-temperature Behavior of Boric Acid: Tonani (1970) and Ellis and Mahon (1977) discuss the behavior of volatile boric acid in high-temperature geothermal systems and the use of B in geothermal exploration. Both authors state that high B/Cl ratios in geothermal steam indicate that the steam probably originates from high-temperature B-rich brine. Although the B analyses of the brine from British well #4

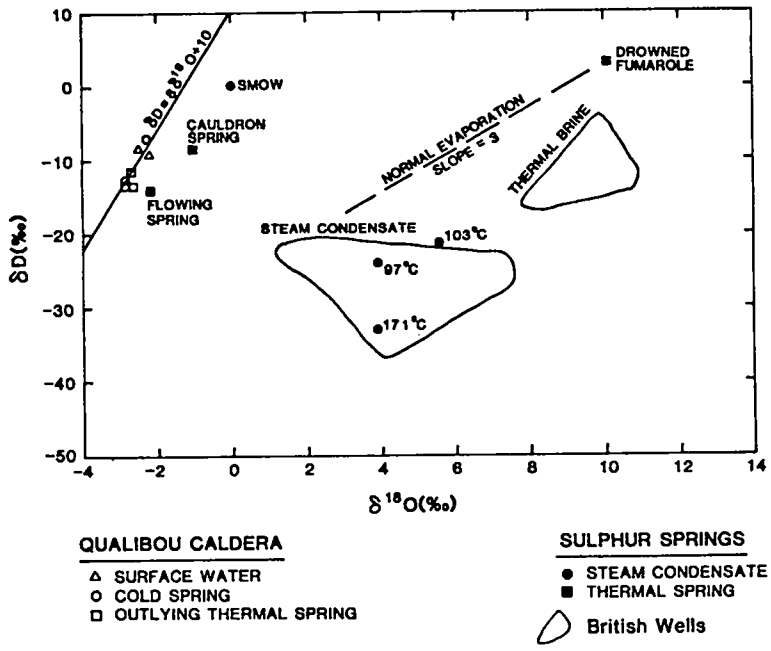


Fig. 2.
Plot of deuterium versus oxygen-18 of surface waters, steam, and brine from Sulphur Springs, St. Lucia.

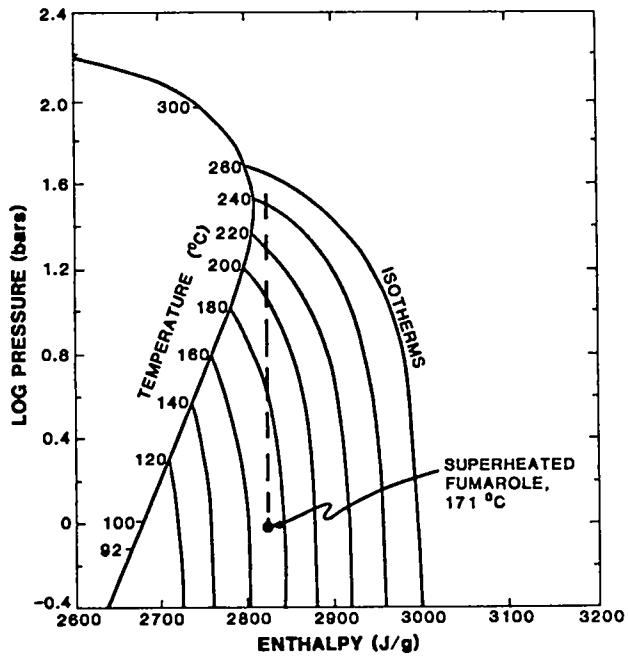


Fig. 3.
Plot of log pressure versus enthalpy showing the relations between saturated steam, the isothermal decompression paths of superheated steam, and the surface enthalpy, temperature and pressure of a superheated fumarole, Sulphur Springs, St. Lucia. The vertical dashed line is an isoenthalpic line (adapted from Muffler et al., 1982).

TABLE VI

CHEMICAL AND ISOTOPIC ANALYSES OF GASES AT SULPHUR SPRINGS, ST. LUCIA
(July, 1983)

Name	Steam Vent	Black Cauldron	Clear Bubbling Pool	Drowned Fumarole	Bubbling Pool	Superheated Steam Vent
Map No.	5	14	8	16	19	12
Sample No.	SL-2	SL-4	SL-19	SL-21	SL-24	SL-26
Temp. (°C)	103	73	72	95	72	171
Gases (vol-%)						
He	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
H_2	4.90	5.40	5.04	4.89	4.95	5.63
Ar	<0.003	0.013	<0.003	<0.003	<0.003	0.03
O_2	0.035	0.105	0.022	0.020	0.012	0.54
N_2	1.08	1.87	1.11	1.06	1.00	2.51
CH_4	0.62	0.70	0.64	0.63	0.62	0.69
CO_2	91.53	90.24	91.93	92.07	91.67	89.59
C_2H_6	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
H_2S	1.78	1.20	1.67	1.84	1.78	1.09
CO	0.003	0.006	<0.003	0.006	<0.003	0.006
Total	99.95	99.53	100.41	100.52	100.03	100.09
Isotopes on CO_2 (‰)						
$\delta^{13}C$	-6.1	-6.0	-6.0	-6.0	-6.0	-5.6
$\delta^{18}O$	+38.4	+44.7	+37.4	+34.3	+35.9	+38.4
Empirical Gas Geothermometer (°C)[a]						
CO_2-H_2S-H_2-CH_4	284	280	283	284	284	280

[a] D'Amore and Panichi (1980).

are not systematic (Table V), we can calculate a rough estimate of the subsurface brine temperature by using the B data of Table V and Fig. 4 modified from Ellis and Mahon. As mentioned, Williamson and Wright (1978) suggested the brine chemistry was approximately 25,000 mg/ℓ Cl or closest to the analysis of sample 4/10/76, Table V, which contains 3500 mg/ℓ B. If we calculate the value of -log K_d (where K_d = concentration of B in vapor/concentration of B in brine) using values for B of 95 mg/ℓ (Table III) and 3500 mg/ℓ respectively, the estimated

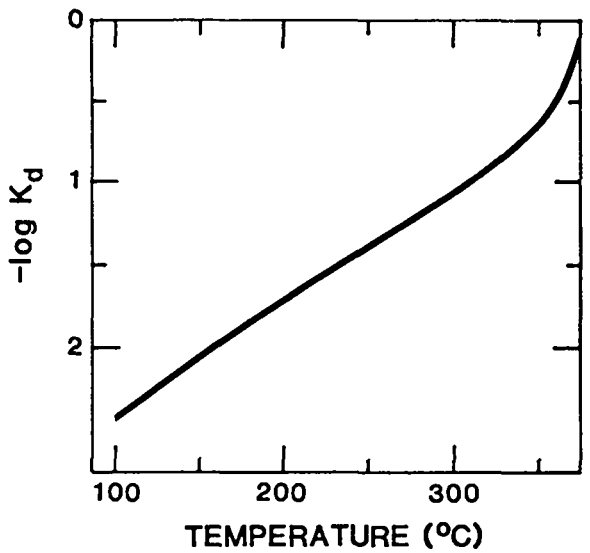


Fig. 4.
Plot of -log K_d versus temperature for boric acid in the steam-liquid water system (adapted from Ellis and Mahon, 1977).

reservoir temperature is 230°C. If we use the other analyses of B in the brine from Table V, the calculated reservoir temperatures are even higher (≥300°C). The B concentration of tne brine at Sulphur Springs is very high, exceeding values reported from such high-B geothermal provinces as Ngawha, New Zealand, and The Geysers in California.

4. Chemical Geothermometry of Brine. Curiously, the estimated temperature of tne brine reservoir using the brine chemistry and standard geothermometers (Fournier, 1981; Table 4.1) is much lower than the temperatures measured in the British drill holes (≥200°C) or the inferred temperatures discussed above (≥230°C). For example, T(Qtz, maximum steam loss) = 172°C, T(Na-K-Ca) = 151°C, and T(Na-K) = 163°C using analysis 4/10/76, Table V. There may be several reasons for these anomalies. The brine chemistry is so unusual that it may not represent an equilibrium fluid of the type used by Fournier and Truesdell (1973) to define their empirical equation for the Na-K-Ca geothermometer. Because the brine is flashing before collection, there may be complex but rapid precipitation reactions that change

the brine chemistry, reflecting, perhaps, the flashing temperature. Also, we must recall that British well #4 is cycling wet/dry and could be located near the interface between an overlying vapor zone and underlying brine zone. Thus, there may be complicated mixing going on between descending steam condensate waters and deep geothermal brine that disturbs the true equilibrium chemistry. Finally, the SiO_2 analyses of Table V are so unsystematic that they may not be reliable.

5. Speculations on the Origin of Sulphur Springs Brine and CO_2. As mentioned above, Hardie (1983) has argued convincingly that $CaCl_2$-rich geothermal brines are generated by reacting sea water with basaltic rocks at temperatures above 250°C. The original basalts are transformed into albite-epidote-chlorite rocks accompanied by deposition of quartz, calcite, and anhydrite. Circumstantial evidence suggests the Sulphur Springs brines may have formed in this manner because the area lies a mere 3 to 4 km east of the ocean where a thick sequence of precaldera basaltic rocks can be seen beneath the later silicic rocks. Wohletz and Heiken (1984) show these basaltic rocks occuring inside the caldera based on lithologic information from the British wells. On the other hand, Bath (1977) has pointed out that the deuterium content of the brines is roughly -10°/₀₀ corresponding to meteoric water on the island, not sea water (Fig. 2). Bath also notes that the Br/Cl ratio of the brine is much lower than sea water, although it is not clear that Br would behave as conservatively as Cl in such an unusual, hot fluid. Possibly, the salt content of the brine was derived originally from sea water and by subsequent reactions with basaltic rocks, but this water has since been boiled away and replaced by recharging meteoric water in a manner suggested by Truesdell et al. (1979) for the Salton Sea geothermal field.

Bath (1976) offers an interesting mechanism for formation of the Ca-rich brine in which HCl-rich volatiles from magmatic sources react with carbonate rocks thought to underlie the volcanic sequence to release CO_2 gas and Ca and Cl into solution. Xenoliths of marine carbonate have been identified in some of the intracaldera pumice eruptions (Martin-Kaye, 1969) and marine carbonates outcrop on the north edge of St. Lucia. However, the ^{13}C signature of Sulphur Springs CO_2 is -5.95 ± 0.08°/₀₀ (Table VI) or within the range of -5 to -8°/₀₀ reported for mantle-derived carbon (Barnes et al., 1978). If we calculate the isotopic composition of ^{13}C in $CaCO_3$ that

would produce CO_2 at reservoir temperatures of 200 to 300°C (using methods described in Goff et al., 1984), the resulting parent ^{13}C would be -6.3 to -8.1°/oo. This is considerably lighter than the 0 to -2°/oo in ^{13}C reported for world average marine carbonate (Hoefs, 1973; p. 26). If we assume that the carbonates beneath the Qualibou caldera have not undergone any isotopic reconstitution, then it would seem that Bath's mechanism of brine formation does not fit the carbon isotope data and that the CO_2 at Sulphur Springs is primarily magmatic/mantle derived, not formed by thermal breakdown of marine carbonates.

B. Outlying Thermal Springs and Cold Waters

Three areas occur west and north of Sulphur Springs where other hot springs emerge: Diamond, Cresslands, and Malgretoute. These areas were previously visited by Aquater (1982b). The authors asked many local people if they knew of other thermal areas but to no avail. As hot springs go, none of the areas are very impressive except for the luxurient rain forest and steep topography in which they issue. The first two sites occur within andesitic to dacitic rocks along the north collapse zone of Qualibou caldera. Diamond Spring and several related seeps issue from E-W-trending fractures above the east bank of Diamond Creek about 100 m north of Diamond Waterfall. Water from the main spring flows down a drain to a series of mineral baths. Cresslands Spring discharges from a mound of iron-stained $CaCO_3$ travertine along the southern edge of the Migny River. Aquater (1982b) did not sample this spring during their investigations but did sample a somewhat cooler spring of different chemistry that we could not relocate. Malgretoute Spring flows from what appears to be a contact zone between precaldera basalts and andesites. The outflow of this spring was sampled at a waterfall spilling over a cliff, and our analysis is very similar to Aquater (1982b) who measured an emergence temperature of 57°C. No attempt was made to assess possible hydrothermal alterations at any of these sites because of the weathered nature of the rocks and poor exposure. However, no obvious alterations were noted.

1. Fluid Chemistry. The striking fact about the chemistry of this group is the general resemblance to steam condensate waters at Sulphur Springs. They contain high HCO_3^-, high B, variable SO_4^{--}, and relatively low Cl (Table III). Although Na is the dominant cation, Ca+Mg may

be relatively high. Trace element concentrations are low (Table IV). Analyzed values of B, Cl, and F in Diamond Spring are identical to those of Hot Spring #10 (Table III), suggesting they have formed by similar processes. Waters of this type form along the cooler margins and tops of deep geothermal systems by condensation of CO_2-rich steam (Mahon et al., 1980). The CO_2 is converted to HCO_3^- and volatile boric acid appears as B. H_2S may be converted to SO_4. The Cl comes from leaching of surface rocks into which these vapors condense. Because the solubility of Ca+Mg decreases with increasing temperature in any fluid that has appreciable HCO_3^-, these waters do not indicate equilibration at temperatures above 100°C.

Cresslands hot spring contains the most Cl and Br of this group, suggesting somewhat deeper circulation and/or longer residence time in the ground than the other two. This spring resembles many HCO_3^- and B-rich waters that discharge east of The Geysers geothermal system in California (Goff et al., 1977). Although they do not directly tap a deep neutral-chloride system, the HCO_3^--rich waters often indicate a zone of condensation above a high-temperature deeper zone of boiling.

2. Chemical Geothermometry, Outlying Springs. Chemical geothermometers are widely used with the chemistry of hot spring waters to explore for geothermal resources. They rely on the temperature-dependent solubility of particular chemical components to infer the temperature of the reservoir at depth from which springs issue (Fournier, 1981). Many assumptions must be made regarding equilibrium conditions at depth, re-equilibrium situations as the waters rise to cooler surface temperatures, and mixing between aquifers. The geothermometers themselves can be problematic in that many are empirical or depend on solubility relations with chemical phases that may or may not be present. In spite of the difficulties, the geothermometers are very useful in approximating the probable temperatures of geothermal systems.

Subsurface temperature estimates using chemical data from the outlying springs are listed in Table VII for four widely used geothermometers: (1) silica, (2) Na-K-Ca, (3) Na-K, and (4) Na-Li. The first two are broken down into several variations depending on high- or low-temperature situations (consult Fournier, 1981 for explanation of variations). It is beyond the scope of this report to analyze the subtleties of each variation. However, two conclusions can be drawn from this data:

TABLE VII

CHEMICAL GEOTHERMOMETRY OF OUTLYING THERMAL SPRINGS, ST. LUCIA, CARIBBEAN

		Measured T	Silica			Na-K-Ca			Na-K	Na-Li
			Qtz	Chal.	Amorph.	β = 4/3	β = 1/3	Mg-corr.		
SL-12	Diamond Spring	43.1	169	147	47	77	(157)	41	171	108
SL-15	Cresslands Spring	55.7	143	117	22	80	(148)	58	144	136
SL-17	Malgretoute Spring	35.2	138	111	18	(126)	159	—	135	101

(1) The most optimistic estimate of temperature at depth is approximately 170°C using T(Qtz) and T(Na-K) if we assume the outlying springs are connected to the deep geothermal system; and

(2) The more conservative estimate of temperature is 100°C or less, suggesting these springs are not connected to the deep system.

Conclusion (2) is favored because the HCO_3^--rich character of the waters indicates they are merely formed in a condensation zone. It is not clear, however, whether the condensation zone is directly above the source of steam or laterally displaced from the source.

3. Gas Chemistry, Outlying Springs. Aquater (1982b) obtained gas analyses on the dissolved gases in the outlying springs discussed herein and their data appear in Table VIII. It must be remembered that the temperature and chemistry of the spring that Aquater sampled at Cresslands do not resemble in any way the spring sampled by the authors. Thus, the gas chemistry reported in Table VIII from Cresslands is of limited value. Nonetheless, several facts suggest these gases are not derived directly from a high-temperature resource at depth and that the main condensation zone is laterally displaced from the springs: (1) the gases contain no measurable H_2S, (2) their concentrations of H_2 are exceptionally low, (3) their concentrations of N_2 (presumably from air) are very high, and (4) their differences from analyses of deep gases at Sulphur Springs (Table VI) are remarkable.

Several authors have used the ratio of H_2S/CO_2 from a series of widely dispersed gas seeps to find the main source of upflow in a geothermal

TABLE VIII

ANALYSES OF DISSOLVED GASES FROM OUTLYING THERMAL SPRINGS, QUALIBOU CALDERA, ST. LUCIA
[values in vol%; data from Aquater (1982b)]

	Diamond Spring (Sample 1130)		Cresslands Spring (Sample 1107)			Malgretoute Spring (Sample 1109)		
CO_2	7.46	6.30	90.80	90.36	a	62.5	63.98	a
H_2S	-	-	-	-	a	-	-	a
H_2	0.0006	tr	0.0005	-	0.003	0.001	-	0.0012
He	tr	tr	tr	tr	0.0009	0.0008	0.0008	0.0024
N_2	78.53	89.91	8.25	9.46	91.34	37.00	35.43	98.52
O_2	13.84	3.77	0.76	0.17	1.81	0.58	0.12	0.32
Ar	-	-	-	-	-	-	-	-
CH_4	0.17	0.53	0.20	0.73	6.80	0.39	0.47	1.16
C_2H_6	-	-	-	-	-	-	-	-
CO	-	-	-	-	-	-	-	-
Total	100.00	100.51	100.01	100.72	99.95	100.47	100.00	100.00

[a] CO_2 and other soluble gases absorbed into NaOH.

system (D. Glover, D.S.I.R., Wairakei, New Zealand, oral commun., 1983). Seeps above the upflow have the highest H_2S/CO_2, whereas seeps displaced away from the upflow have lower H_2S because of oxidation to H_2SO_4 or to pyrite. Because there is so little H_2S at Diamond and Malgretoute Springs (even though the waters resemble steam condensate waters at Sulphur Springs), one suspects that H_2S has been lost during lateral flow from a main zone of condensation near Sulphur Springs. If this is not the case, it suggests that the geothermal fluids beneath Diamond and Malgretoute are much cooler in temperature and/or the zone of condensation is so thick it removes H_2S from the gas.

4. Tritium, Qualibou Caldera. Tritium (^3H) is an isotopic tracer that was produced in copious amounts during atmospheric nuclear testing from 1953 to 1964. Because it has a short half-life of 12.3 years, ^3H is very useful for tracing shallow ground-water flow (Vuataz et al., 1983). The ^3H values of 10 natural waters around Qualibou caldera are listed in Table IX. Surface waters such as Migny River and Diamond Creek, which certainly have

TABLE IX

ISOTOPE ANALYSES OF WATERS AND ROCKS FROM ST. LUCIA (July, 1983)

Name	No.	Water ^3H(TU)[a]	Water δ^2H(‰)[b]	Water $\delta^{18}O$(‰)[b]	Rock $\delta^{34}S$(‰)[c]
Sulphur Springs					
Flowing clear spg.	SL-8	5.01±0.21	-14.1*	-2.15*	-
Clear bubbling pool	SL-9	4.76±0.19	-9.5 -10.2	-1.1 -1.0	-
Drowned fumarole	SL-10	0.72±0.12	+3.0	+10.08 +10.11	-
Steam vent	SL-11	-	-20.7 -21.6	+5.48 +5.57	-
Steam vents	SL-22	-	-24.0	+3.88 +3.97	-
Steam vent	SL-27	-	-33.6 -32.3	+3.89 +3.87	-
Sulphur sublimate	F83-46	-	-	-	-9.4 -8.9
Sulphur sublimate	F83-47	-	-	-	-11.4 -11.1
Outlying thermal springs, Qualibou caldera					
Diamond warm spg.	SL-12	0.97±0.11	-11.5*	-2.65*	-
Cresslands hot spg.	SL-15	0.51±0.20	-12.8 -13.8	-2.91 -2.78	-
Malgretoute warm spg.	SL-17	1.89±0.12	-11.9* -12.4 -15.2	-2.70* -2.70 -2.54	
Cold waters, Qualibou caldera					
Diamond Cr., Sul. Spgs.	SL-6	3.11±0.16	-8.9*	-2.20*	-
Cresslands cold spg.	SL-14	3.72±0.18	-7.0*	-2.25*	-
Migny River	SL-16	4.46±0.18	-7.9* -7.9 -9.0	-2.45* -2.56 -2.48	-
Dasheene spg.	SL-18	9.13±0.29	-12.6	-2.85	-

a Analyzed by the Tritium Laboratory, University of Miami, Florida.

b Analyzed by C. Janik, U.S. Geological Survey, Menlo Park, California; precision is $\delta^2H = \pm 0.5$‰ and $\delta^{18}O = \pm 0.1$‰. Data with * were determined by the Centre d/Etudes Nucleaires de Saclay, France; precision is $\delta^2H = \pm 0.5$‰ and $\delta^{18}O = \pm 0.15$‰.

c Analyzed by Geochron Laboratories Division, Krueger Enterprises, Inc., Cambridge, Massachusetts; precision is $\delta^{34}S = \pm 0.5$‰.

short residence time in the ground, range from 3 to 5 tritium units (T.U.); this is less than half the background value of the southwestern U.S.A. ($\sim$30 T.U.) because of the latitude effect. Cresslands cold spring has short residence time because of its ^3H value of 3.7 T.U., similar to surface waters. Dasheene Spring, on the other hand, contains the highest tritium measured (9 T.U.) and thus represents a slightly older water that was infiltrated when the ^3H background was higher. The underground transit time of Dasheene Spring is probably a few years (2 to 5 ?).

At Sulphur Springs, variable ^3H contents are observed in the thermal features, ranging from <1 to 5 T.U. The pool and flowing spring, which are mixed with surface water, show ^3H values equivalent to cold surface water. A negative correlation exists between ^3H and mineralization while a positive correlation exists between ^3H and pH. The drowned fumarole (SL-10) shows the lowest ^3H because it is composed almost entirely of condensed steam boiling off a deep geothermal reservoir. Presumably, the geothermal reservoir contains water having 0 T.U. (prebomb), thus its age is relatively old, at least >30 years. This is no surprise because most deep geothermal reservoirs contain 0 to 1 T.U.

The three outlying thermal springs of Qualibou caldera have rather low ^3H contents, indicating they are composed mostly of older water with an underground transit time $\geq$20 years. As mentioned above, the chemical similarities between the flowing condensate spring at Sulphur Springs (SL-8) and Diamond/Malgretoute Springs suggest they have all formed by similar processes. The fact that Malgretoute and Diamond Springs have significantly lower ^3H argues that these two springs originate from a main condensation zone above a geothermal system. Their ^3H values of 1 to 2 T.U. suggest that they are composed mostly of steam from the geothermal reservoir with a few percent of young surface water or composed of steam condensate waters near the Sulphur Springs area that flow laterally to the north and west.

5. Leakage Anomalies. The report of Aquater (1982b) contains a rather lengthy discussion of what they term leakage anomalies. These anomalies are comprised of volatile components CO_2, NH_3, and H_3BO_3 (boric acid), which are released with steam during boiling of underlying geothermal fluids. Besides the Sulphur Springs area, three other areas contain measurable quantities of these volatile substances:

(1) the zone northwest and north of Sulphur Springs (i.e. Malgretoute to Diamond Spring),

(2) the north caldera collapse zone from Diamond Spring to about 1.5 km east of Cresslands, and

(3) the southwest caldera collapse zone between Fond Doux and Gros Piton.

The quantity of anomalous volatile components decreases from area (1) to area (3) and, in fact, area (3) is only weakly anomalous. Aquater (1982b) interpret these data only in the broadest sense, stating that they originate from a geothermal resource at depth. Because Sulphur Springs is overwhelmingly anomalous in these substances while other areas are only weakly anomalous by comparison, it suggests major upflow of fluids in the Sulphur Springs area and lateral flow to the north and northwest. Possibly there is a small amount of lateral flow from Sulphur Springs to the southwest.

6. Lateral Flow Volcanic Geothermal Systems. This section is added as comment but it should be seriously considered as a mechanism for the Qualibou caldera. Geothermal systems in volcanic terrains, whether they are andesitic stratovolcanoes or silicic calderas, often display lateral flow or outflows (Healy and Hochstein, 1973). There are many examples of this phenomena, including the geothermal systems at Lassen, California (Muffler et al., 1982), Valles Caldera, New Mexico (Goff et al., 1981), El Tatio, Chile (Healy and Hochstein, 1973), and Mokai, New Zealand (Hulston et al., 1981). The essential ingredients appear to be steep rugged terrain, a potent centralized heat source, permeability through volcanic pyroclastics, breccias and/or faults, and recharge by precipitation on nearby heights. Geothermal fluids rise above the heat source by convection and then flow horizontally away from the heat source down the hydrologic gradient following stratigraphic horizons, tectonic fractures or both. A vapor zone may appear above the lateral outflow as evidenced by surface acid-sulfate springs. These springs, however, do not necessarily occur directly above the upflow zone; they may be displaced off the upflow zone as at Mokai (Hulston et al., 1981). If the outflow zone is relatively deep, it may appear many kilometers away from the main geothermal area down the hydrologic gradient as Cl-rich thermal springs (i.e. Valles Caldera; Goff et al., 1981). Sometimes the outflow zone is so deep that it never intersects ground surface and this may be the case at Qualibou caldera.

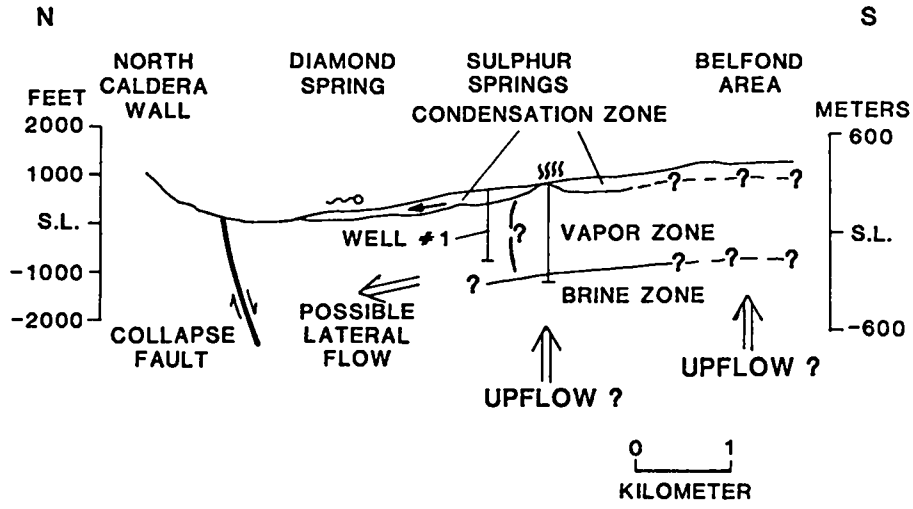
Importantly, the temperature gradient over the upflow zone rises but then goes nearly isothermal to the bottom of the reservoir, where presumably it will rise conductively. In contrast, the temperature gradient rises over the zone of horizontal flow but goes through a temperature reversal beneath the plume of geothermal fluid. This is the most decisive criteria by which outflow zones in geothermal systems are recognized. Temperature reversals such as this are documented in wells drilled through outflowing plumes of geothermal water at Mokai, New Zealand, Et Tatio, Chile, and Valles Caldera, New Mexico.

Both the resistivity data reported by Williamson and Wright (1978) and the deeper resistivity results of Ander (1984) indicate that a zone of low resistivity extends from the Sulphur Springs-Belfond area in the south of Qualibou caldera toward the north caldera wall. Because the acid-sulfate springs of Sulphur Springs suggest a vapor zone centrally located at relatively high elevation overlying a deeper brine zone, we strongly suspect there is lateral flow of deep brine to the north where it pools against collapse faults of the north caldera wall. The outlying thermal springs are not connected directly to this brine but represent either steam condensed from boiling directly underneath them or lateral flow of condensed steam and shallow ground water from the Sulphur Springs area.

IV. CONCLUSION: MODEL OF GEOTHERMAL RESERVOIR, QUALIBOU CALDERA

A model of the geothermal system beneath the Sulphur Springs area, Qualibou caldera is presented in the two schematic cross sections of Fig. 5. No stratigraphy is shown on these sections to avoid any more speculation than necessary, but readers are referred to the cross sections of Wohletz and Heiken (1984) and to the resistivity pseudosection of Ander (1984) for more information. The only definite subsurface control is provided by the cluster of wells drilled at Sulphur Springs. Using these data and our interpretations of the geochemical data presented above, the geothermal system at Sulphur Springs consists of three layers: an upper condensation zone; an intermediate vapor zone or two-phase zone (Williamson, 1979); and a lower brine zone.

The vapor zone reaches ground surface only at Sulphur Springs, no doubt because of localized faulting and fracture permeability. The thickness of the vapor zone is conjectural because of the highly variable discharge



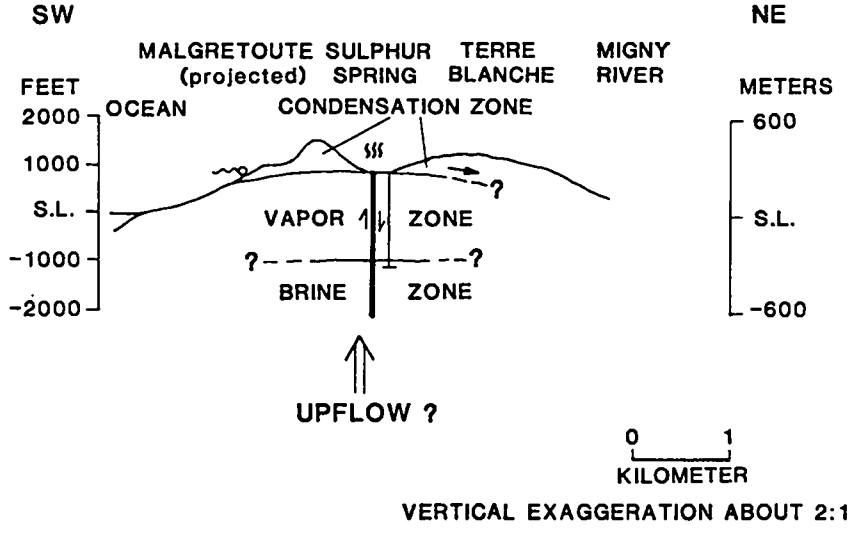


Fig. 5.
Schematic cross sections through the Sulphur Springs area, St. Lucia, showing postulated layered structure of fluid zones in geothermal reservoir.

characteristics of the wells at Sulphur Springs; a rough estimate is 600 m based on the experience of the British wells, but it may be as great as 1 to 1.2 km (Williamson, 1979). The shape of the vapor zone is even more conjectural; it apparently does not extend 700 m north of Sulphur Springs to well #1 where a temperature of only 66°C was recorded at 450 m (Williamson, 1979). The extent of the vapor zone in other directions is completely unknown and it may be that the vapor zone is merely a vapor conduit existing only at Sulphur Springs. In that case, the zone of condensation would surround the vapor zone and directly overlie the brine zone.

We know even less about the brine zone except that it exists beneath Sulphur Springs. Seismic and electrical resistivity data suggest it extends as far north as the caldera wall. From its composition, it appears to be derived from sea water that has reacted with basaltic rocks in the subsurface and is then replaced by recharging meteoric water. Several lines of evidence indicate the deep brine exists at temperatures $\geq$250°C. It is not clear, however, whether it upflows beneath Sulphur Springs or beneath the Belfond area where the youngest volcanism is. It is also not clear if there are several isolated systems, perhaps beneath Sulphur Springs and the north caldera collapse zone. Evidence for existence of a separate high-temperature system in the northern collapse zone is not good because there are no high-temperature springs or gas discharges.

Our best information on the dynamics of the Qualibou caldera geothermal system comes from the condensation zone. Waters formed from condensation of steam and noncondensible gases mixed with surface ground water extend from Sulphur Springs to Malgretoute and Diamond Springs. It appears from gas chemistry and ^{3}H that these fluids are condensing in the vicinity of Sulphur Springs and flowing laterally to the northwest and north down the hydrologic gradient. Leakage anomalies suggest that there may be some additional outflow of condensed steam to the southwest. Recognition of lateral flow in the condensation zone may indicate similar lateral flow in the underlying brine zone as suggested by electrical resistivity data. The setting of Qualibou caldera and the position of Sulphur Springs at relatively high ground in the center of the caldera would encourage such a system to develop.

A. Recommendations on Exploratory Drilling

Four sites for relatively deep drilling are recommended below that will provide information on the size of the geothermal resource and the dynamics of its flow. The sites are discussed in order of importance.

1. Well near Belfond. We recommend the first site to be located not more than 1.5 km southeast of Sulphur Springs in the Belfond area. The object of this well is to see if the main area of geothermal upflow is centered within the area of youngest volcanism. We recommend that this well be drilled to a depth of not less than 1.5 km; deeper if temperatures of 150°C and fluids are encountered. The Belfond area is peppered with young pyroclastic vents that may afford excellent shallow permeability. It may be in this area where much hot fluid is easily extracted.

2. Deep Well at Sulphur Springs. We recommend that the second well be sited in the same flat area as wells #4 and #7 and drilled to a depth of at least 2 km. The importance of this well cannot be stressed enough. It will penetrate far beneath the vapor (two-phase) zone and provide us with reliable samples of fluid from the brine zone. It should be deep enough to see if there is a temperature inversion in the well and, thus, infer where the main upflow in the reservoir is.

3. Well near Etangs. We recommend the third site to be located near Etangs where leakage anomalies noted by Aquater (1982b) and resistivity lows observed by Ander (1984) suggest geothermal brine may be located at depth. It is not clear if the fluid is flowing laterally from the Belfond area and is trapped against the southern caldera collapse faults or if fluid is rising convectively from depth.

4. Well near Diamond Spring. An alternate site is suggested near Diamond Spring, drilled to a depth of at least 1.5 km; deeper if temperatures exceed 150°C at this depth and hot fluid is encountered. The object of this well is to determine whether or not deep geothermal fluids exist in the northern collapse zone of Qualibou caldera. If fluids are encountered, their chemistry will indicate whether it is a unique system or connected to the system beneath Sulphur Springs. Temperature inversions will also be looked for to determine the hydrology at this depth.

B. General Recommendations

We urge that 3-m or longer oriented core samples be obtained from these wells at intervals of 100 m. These cores will provide information on permeability, porosity, density, lithology, fracture orientations, and hydrothermal alterations that cannot be matched with cuttings. The additional information will provide data to constrain geophysical models and establish sound stratigraphic and structural control. Alteration assemblages will yield information on age, evolution, and dynamics of the reservoir.

V. ACKNOWLEDGMENTS

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RECOMMENDED SITES FOR EXPLORATORY DRILLING

(Bob Hanold)

In each of the previous sections of this report, recommendations were made for the location of exploratory wells within the Qualibou caldera. Each of the evaluations (geologic, geophysical, and hydrogeochemical) yielded individual yet remarkably similar recommendations for the location of the wells. In summary, the identified locations were as follows:

Geologic	Geophysical	Hydrogeochemical
Sulphur Springs	Belfond	Belfond
Belfond	Sulphur Springs	Sulphur Springs
Belle Plaine	Etangs	Etangs
Migny River		Diamond Spring

Each of the field teams individually agreed that an exploration well should be drilled in the Craters of Belfond and the Valley of Sulphur Springs. In terms of priority, it was suggested that the initial exploratory well be drilled at Belfond because of:

(1) The anticipated shallower depth of the geothermal reservoir.
(2) The higher probability of intercepting a high-temperature brine reservoir in a horizon that has high fracture permeability.
(3) The uncertainty associated with the existence of a hot dry steam field beneath Sulphur Springs and overlying the anticipated brine reservoir.
(4) The expectation that the drilling experience gained in the Belfond well would be very valuable during the drilling of the deeper Sulphur Springs well.
(5) The more secluded location of the Belfond well would be an advantage during initial setup, drilling, logging, and flow-testing operations.

Based on the above considerations, it is recommended that the first exploration well be drilled in the Craters of Belfond and the second in the Valley of Sulphur Springs. In selecting the third location, it was noted

that part of the significance of a well in the Valley of the Migny River or at Diamond Spring was to delineate the size of the Qualibou geothermal reservoir. Although this could eventually be of importance, a higher priority was assigned to completing the initial production well field and establishing geothermal power for the island of St. Lucia. Drilling a step-out well in the northern or eastern Caldera margins would not be consistent with this priority. This decision narrowed the choice for the third site to Etangs and Belle Plaine.

A synthesis of the available field and laboratory data suggests that the third well be drilled at Etangs because:

(1) A zone of very low apparent resistivity, less than 1 ohm-m, underlies the Etangs area.
(2) The low-resistivity zone beneath Etangs is related to thermal fluids upwelling along a fault, probably the southern caldera-bounding fault.

These recommended well locations are illustrated in Fig. 1. Initial drilling operations may suggest changes in the ranking of the subsequent sites and each new well location should be reevaluated based on available drilling data.

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