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THE QUALIBOU CALDERA, ST. LUCIA, WEST INDIES

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ABSTRACT

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Recent geological, geophysical, and hydrogeochemical studies conducted in the Qualibou area of St. Lucia, West Indies, provide new data for reevaluation of the geothermal resource and recommendation of sites for renewed drilling activities. This work supports the original hypothesis of Tomblin that the Qualibou depression is a caldera.

Precaldera volcanic activity was concentrated along faults associated with regional NE- and NW-trending structures. Basaltic lavas, dated at 5.5 Ma, crop out along the western coast and are overlain by andesitic composite cones, dated at 1.2 and 0.9 Ma, which form the highest ridges of the island. Superimposed upon the andesitic cones are dacitic domes (0.25 Ma), the eroded plugs of two of these form the spectacular Pitons. The major event in this volcanic field was the intermittent eruption of the Choiseul Pumice concurrent with the formation of the Qualibou caldera (32,000 to 39,000 yrs ago). About 6 km^3 (dense rock equivalent) of lithic-crystal andesitic tephra was erupted mainly as nonwelded to welded pyroclastic flows and surges. Some of these tuffs have been identified in geothermal drill holes within the 12-km^2 caldera. Postcaldera eruption of dacitic tephra and dome lava (20,000 to 32,000 yrs ago) occurred from vents within the caldera and appear to be a result of magmatic resurgence.

A 5.2-km-long dipole-dipole DC resistivity survey, measured along a north—south-trending line through the caldera gave apparent resistivity results similar to those obtained in previous studies. These results are compatible with a caldera substructure where low apparent resistivities (< 10 ohm-m) correspond in location to thermal upwellings along major caldera faults at depths of 1 km or more.

Analysis and interpretation of hydrogeochemical data from the Qualibou caldera 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; and (3) a lower brine zone. Measured temperatures at depth of 212°C are complemented by estimated temperatures of 250°C in the brine layer. The water chemistry of various thermal springs indicates upwelling primarily near the caldera center at Sulphur Springs, which feeds steam to steamcondensate hot springs along the northern caldera wall.

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INTRODUCTION

St. Lucia is a volcanic island of the Lesser Antilles island arc located between Martinique and St. Vincent (Fig. 1). The last large eruptions occurred 20,000 to 40,000 yrs ago, and previous geological and geophysical studies indicate that a significant geothermal resource exists in the area of the Qualibou caldera (Williamson and Wright, 1978). Steam was found in four of seven exploratory boreholes drilled by the U.K. Ministry of Overseas Development. Results of that project indicated a favorable economic feasibility for geothermal development but further studies were recommended.

Tomblin (1964) prepared the first detailed description of geology of southern St. Lucia. That work was centered in the area of Soufrière, where the Qualibou caldera was first identified. Petrologic analysis revealed the andesitic to dacitic compositions of lavas and tuffs and subsequent K/Ar and ^{14}C dating, summarized by Westercamp and Tomblin (1980), suggested that the caldera age is between 0.04 and 0.30 Ma. More recently, Roobol et al. (1983) and Wright et al. (1984) have proposed that the most recent eruptions originated from the highlands located east of Qualibou and that the caldera is really a depression formed by a gravity slide. Our work does

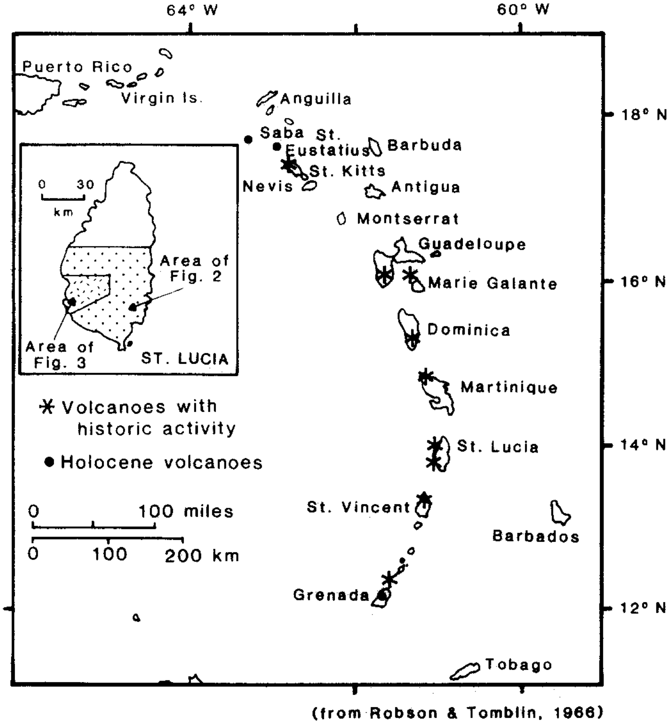

Fig. 1. Location map, Lesser Antilles, including St. Lucia.

not support this idea and we discuss the evidence for this in a concluding section.

The purpose of this study is to build upon previous work by Tomblin (1964), Merz and McLellan (1976), and Aquater (1982) in an attempt to model more precisely the caldera substructure. This report summarizes results of a geological reconnaissance, hydrogeochemical survey, and electrical resistivity survey of the Qualibou caldera in preparation for further drilling. The methods used during geological reconnaissance included stratigraphic analysis of over 100 sections near or in the caldera. Caldera faults were located and the caldera structure was analyzed using recent models of caldera formation, volcanic rock facies variations, analyses of pumice, lava, and lithic clasts, and bedding structures in tuffs and breccias.

STRATIGRAPHY

The known volcanic history of southern St. Lucia (Table 1; Fig. 2) spans over 8 Ma (Le Guen de Kerneizon et al., 1983) and consists of several overlapping periods of eruptive activity. In the area of the Qualibou caldera there are: (1) 5 to 6-Ma-old basaltic lava flows, overlain by andesitic to dacitic composite cones 0.75—1.0 Ma old; (2) caldera-related rocks that consist of andesitic to dacitic tephra falls and pyroclastic flows ($\simeq$0.04 Ma); and (3) intracaldera dacitic tephra and lava domes ($\simeq$0.020—0.032 Ma). The most recent activity consists of steam explosions at the Sulphur Springs area.

Older volcanoes within and adjacent to the Qualibou caldera

Basalt flows. Basalt flows are exposed along the western coast of Jalousie and the base of Coubaril ridge (north and south of the Petit Piton) (Fig. 3). Tomblin (1964) has proposed that the 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 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 and authigenic quartz (?).

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

TABLE 1

Stratigraphic sequence, Qualibou caldera

Stratigraphic unit		Ages
Post-Qualibou caldera		
Historic phreatic blast, Sulphur Springs (Reported by Lefort de Latour, 1782).		1766 A.D.
Belfond Formation	- Pyroclastic fall, flows, surges, and domes; craters in domes, with associated tephra	20,900 to 34,000 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	91,000 yrs (Kerneizon et al., 1983)
Qualibou caldera		
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)
Pre-Qualibou caldera		
Andesites and dacites	- Fond Doux composite(?) cone — andesite	No date
	- Domes(s) of Rabot, Plaisance and Malgrétoute 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 (Westercamp and Tomblin, 1980), 0.9 ± 0.08 Ma (Aquater, 1982)
	- Older andesitic lava	3.13 ± 0.16 Ma Kerneizon et al., 1983)
Basalt flows of Jalousie and Malgrétoute		5.61 ± 0.25 Ma, 5.21 ± 0.15 Ma 6.1 ± 0.6 Ma 6.5 ± 0.6 Ma (Briden et al., 1979; Aquater, 1982)

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.

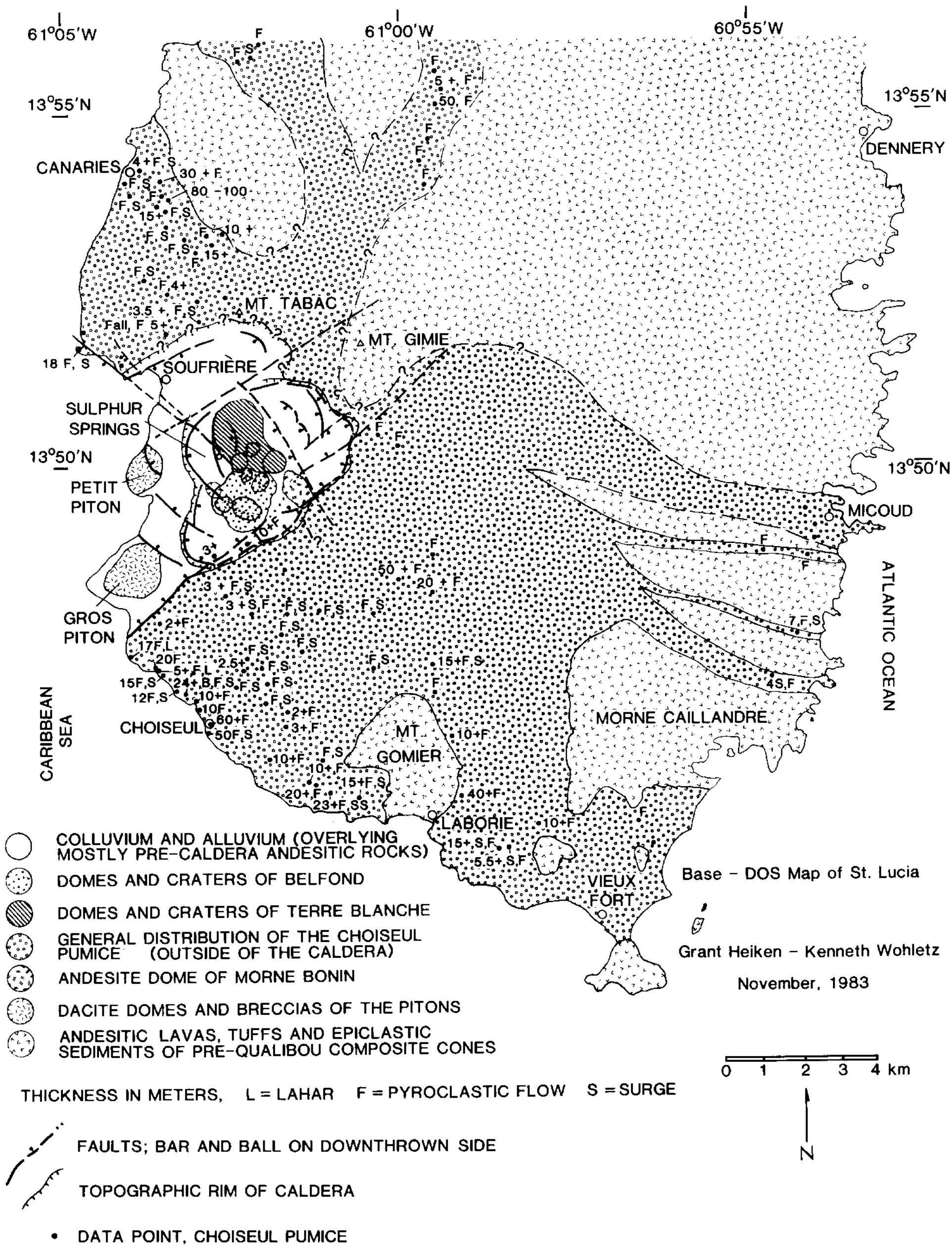

Fig. 2. Reconnaissance geologic map, Qualibou Caldera and tuff, St. Lucia.

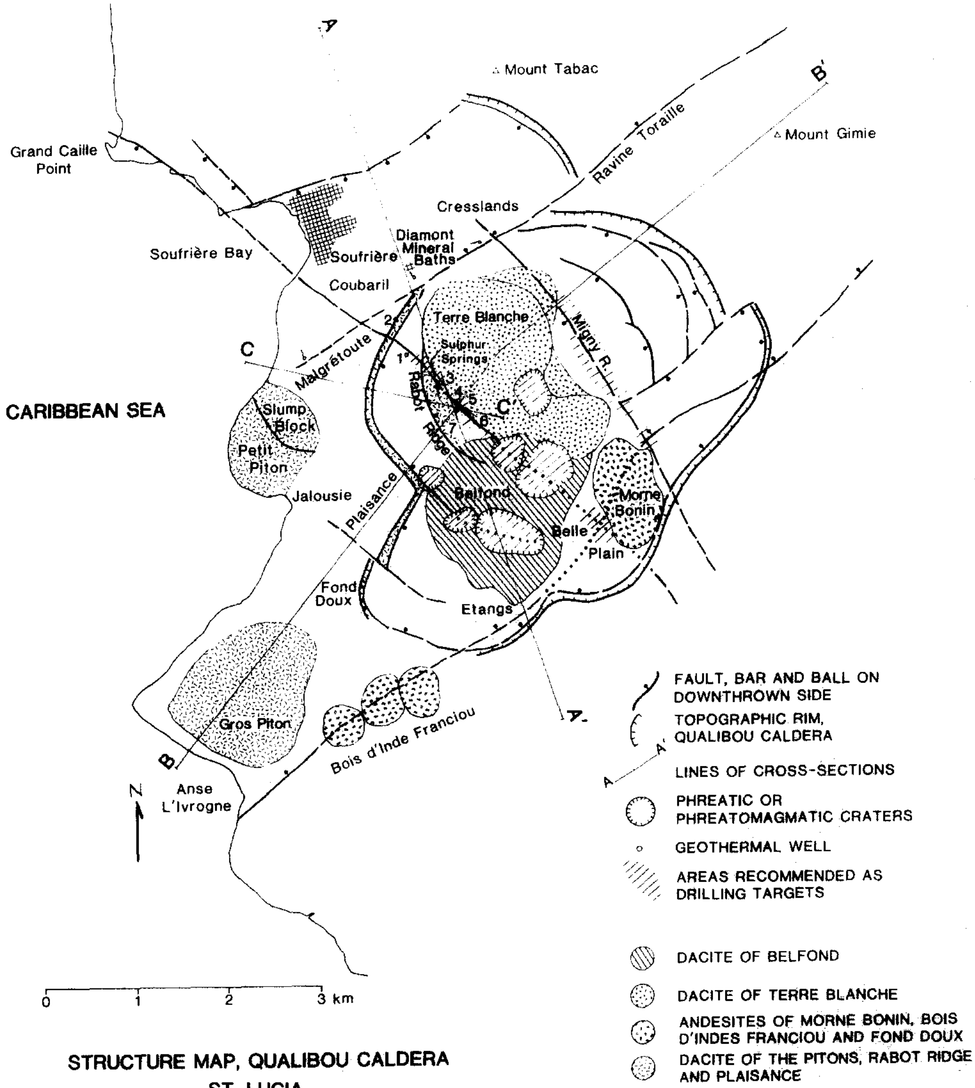

Fig. 3. Structural geologic map, Qualibou Caldera.

Andesitic composite cones (Stratovolcanoes). Andesitic lavas, laharic breccias, fanglomerates, and epiclastic sediments are exposed along the cliffs north of Soufrière and along parts of the easternmost caldera wall. Similar rocks crop out along the southeastern coast of St. Lucia 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 dip 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 and normally and reversely graded bedding. They dip southwest away from source at an angle of 5—10°. Interbedded with the laharic breccias are light grey andesitic lavas of unknown maximum thickness. The lavas and laharic breccias within the highlands, above 500 m elevation, are deeply weathered to clays, but there are excellent relict textures that indicate rock type. These deposits are well preserved at lower elevations and were 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 (Westercamp and Tomblin, 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. An andesite lava south of Mt. Gimie near Migny is structurally lower than these two dated samples and has a K-Ar age of 3.13 ± 0.16 Ma (Le Guen de Kerneizon et al., 1983).

The ridge between the town of Soufrière and Plaisance (the Coubaril ridge) has been described as an andesitic cone, contemporaneous with the cones of Mt. Gimie and Mt. Tabac (Tomblin, 1964). This correlation is difficult to confirm. There are primarily dacitic lavas and breccias exposed along the road around Coubaril. Although deeply altered to clays, chlorite and carbonates, the Coubaril lavas can be described as quartz-rich porphyritic andesites.

Andesitic and dacitic lavas of Malgrétoute, 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, N—S to N—NE-trending ridges, each about 1 km long and 0.5 km wide. A similar ridge (Plaisance) extends south from Rabot. Tomblin (1964) has 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 dome-like 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) indicating previous hydrothermal activity. The lavas have been described as an orthopyroxene-hornblende andesite (Tomblin, 1964).

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 km in diameter at the base and has a summit 743 m above sea level. A large fragment of the dome on the north side has slumped 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 what appears to be a tuff ring that consists of well-consolidated tuff-breccia (visible from the sea). Tomblin (1964) described a "Piton-type" dacite agglomerate that consists of 70% sub-angular blocks, up to 2 m long, within 12.5 km of the base of the Pitons. These consist of grey or pink dacite clasts.

The Pitons formed between 200,000 and 300,000 yrs ago. A K-Ar date for the Petit Piton is 0.26 ± 0.04 Ma (Briden 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, amphibole, and plagioclase phenocrysts in a holocrystalline groundmass.

Domes of Bois d'Inde Franciou. Near the Gros Pitons 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 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).

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) had 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—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. Characteristic glass and plagioclase chemical compositions and modes are shown in Tables 2 and 3, and Wright et al. (1984) give bulk chemical compositions. In outcrop it is light brownish-grey to light brown, dependant 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.

TABLE 2

Choiseul Pumice and feldspars — Chemical analyses (all in wt.%) of glass and plagioclase pyroclasts

Glass[a]:	#3	#4	#7	#8
SiO_2	75.26	75.07	74.76	74.18
TiO_2	0.08	0.15	0.12	0.12
Al_2O_3	12.68	12.39	12.47	12.49
FeO	1.15	1.16	1.20	0.97
MnO	0.04	0.03	0.02	0.06
MgO	0.19	0.18	0.17	0.20
CaO	1.65	1.62	1.63	1.66
Na_2O	2.47	3.01	2.44	3.13
K_2O	2.38	3.43	3.48	3.57
Total	96.99	97.04	96.30	96.38

[a]All analyses of pumiceous glass pyroclasts.

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	0.0	0.0	0.0	0.02
Al_2O_3	35.23	32.49	29.69	30.58	33.38	30.79
FeO	0.17	0.14	0.14	0.16	0.19	0.17
MnO	0.03	0.0	0.03	0.02	0.01	0.02
MgO	0.0	0.0	0.0	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	0.04	0.11	0.21	0.17	0.11	0.17
Total	99.15	100.11	99.54	99.98	101.31	100.37

[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.

Results of scanning electron microscopic (SEM) and energy dispersive spectral (EDS) analyses of tephra morphology and surface features are shown in Tables 4 and 5. EDS data show a variation of glass compositions (altered surfaces) between flow and surge deposit tephra. The flow tephra show surface compositions nearly the same as "fresh" analyses obtained by the electron microprobe (Table 3); however, those of the surge tephra

TABLE 3

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 4

Energy-dispersive spectral analyses of pyroclast surfaces

	Choiseul		Belfond
	Flow (5)	Surge (4)	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 5

Scanning electron microscope description of pyroclast textures

Texture	Choiseul			Belfond	
	Surges (3)	Flows (2)	Fall (1)	Surge (1)	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.

surfaces are somewhat 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 shape data (Table 5) indicate a greater influence 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.

Plateaux located south, southeast, and northwest of the caldera are composed of pyroclastic flows and surges of the Choiseul Pumice. These plateaux 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 400 m the tuff is well-preserved; above this elevation it is deeply weathered.

Thicknessess 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 caps on ridge tops. At Choiseul (Fig. 2) 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 thicknessess are up to 100 m. Within the caldera, boreholes have penetrated up to 180 m of tuff that are petrographically equivalent to units described by Tomblin (1964) and now called the Choiseul Pumice.

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 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 roadcut 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 southeast coast of St. Lucia. Some of these channel fillings are visible along the main highway between Vieux Fort and Castries (Figs. 2 and 6). Well-bedded surge deposits are plastered onto the sides and base of the paleovalleys and, in places, ash is injected

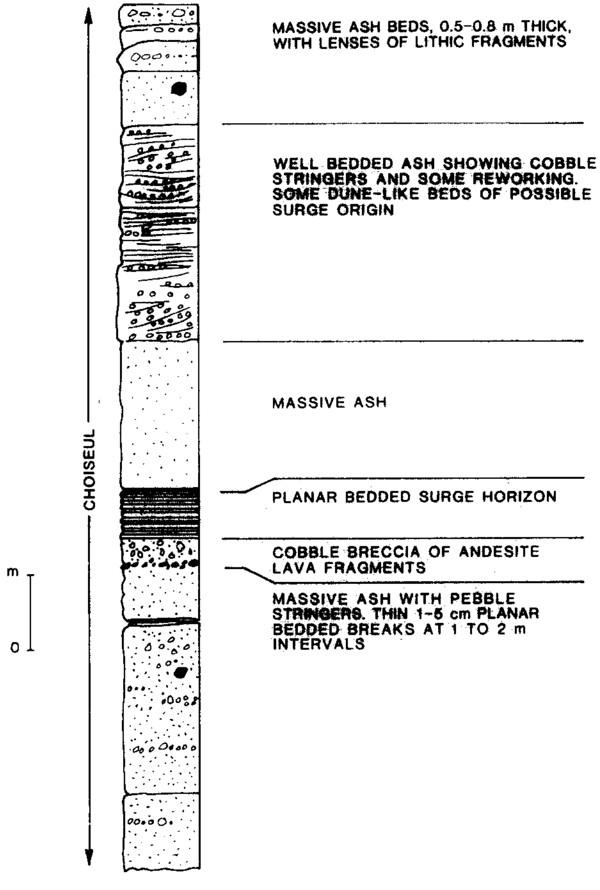

Fig. 4. Choiseul Pumice. Near Laborie on the south coast.

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 Soufrière 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 Soufrière 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 east-southeast of Canaries, there is over 80 m of massive welded tuff that partly fills the valley. It consists of 20—30% subangular dacite blocks in a grey ash matrix with columnar jointing. Three and one-half km east of Ravine Duval, the deposit is nonwelded. In

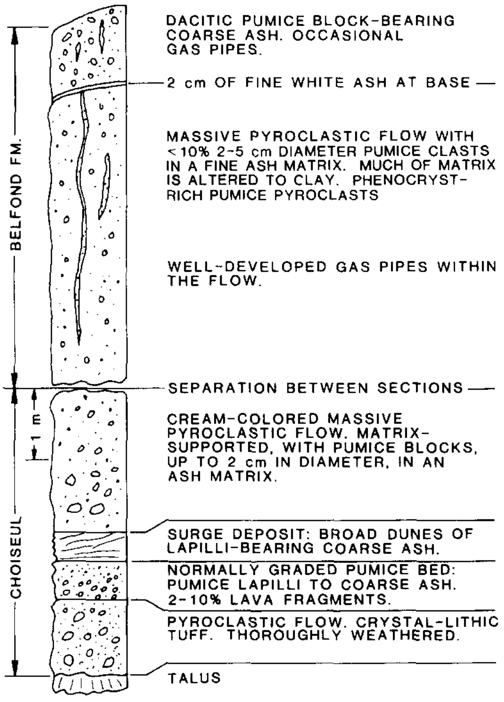

Fig. 5. Choiseul Pumice and Belfond Formation. Composite stratigraphic section in road cuts near Choiseul.

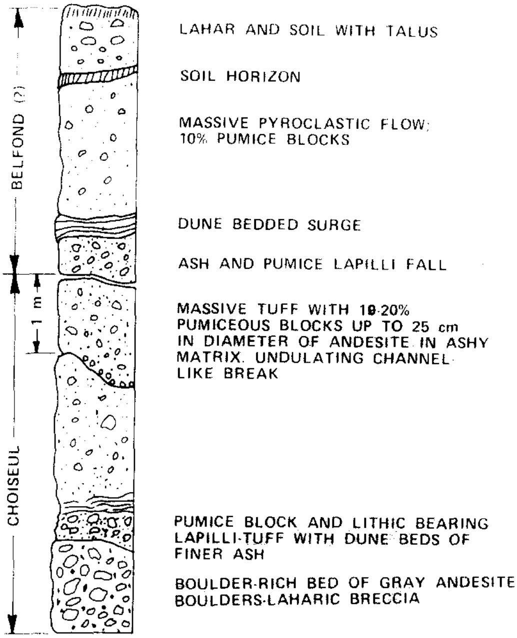

Fig. 6. Choiseul Pumice and Belfond Formation. East coast, 3 km south of Micoud.

the Millet River valley, due north of the caldera, the deposit is also non-welded and 50 m thick.

South caldera rim. At elevations of over 400 m it is difficult to identify the Choiseul Pumice because of 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.

Discussion

The Choiseul Pumice represents a major caldera-forming event. 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 phase was followed by deposition of pyroclastic surges, block-rich pyroclastic flows (that filled many paleovalleys), and finally 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) described the facies variations.

The vent (or vents) for this eruption were apparently located within the ~12 km^2 of the Qualibou caldera with pyroclastic flows and surges moving down the southeast, south, west, and northwest flanks of the volcanic field. This conclusion differs from that of Wright et al. (1984), who suggested central vent locations near Mt. Gimie. Our conclusions are based on the location of the caldera structure, flow thickness variations, and well-log data within the caldera.

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 D.R.E.). This compares favorably with an estimated volume for caldera collapse of between 5 km^3 and 10 km^3.*

Wright et al. (1984) have dated one piece of carbonized wood in the Choiseul Pumice, collected south of Saltibus at >32,480 yrs. They suspect that the carbon sample collected by Tomblin (1964) was from one of the Choiseul Pumice deposits; it has an age of 39,050 ± 1500 yrs; at the limit of the technique. Le Guen de Kernizon et al. (1983) give a K-Ar age of 0.87 ± 0.07 Ma for a sample of pumice from near Micoud, which is probably Choiseul Pumice. Thus ^{14}C and K-Ar techniques have provided very different results for the Choiseul Pumice and the deposit remains poorly dated.

Intracaldera volcanic rocks

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 Plain. It is believed from its location to be a postcaldera dome, erupted along 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. A K-Ar age from a Morne Bonin sample (Le Guen de Kerneizon et al., 1983) of 0.91 Ma indicates that it is of precaldera age. However, in view of the obviously erroneous K-Ar ages from the neighboring Belfond dome (see below) this age should be viewed with suspicion.

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-grain-sized ash surge deposits exposed on the northeast flank. Drilling at Sulphur Springs indicates a total thickness of the dome of 600 m at this location with an approximate volume of 0.6 km^3. The dome consists of pink to grey dacite

*Volume was estimated on the assumption that tuffs on the plateaux 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 dense rock equivalent (D.R.E.) was determined by multiplying the volume by 0.6.

with well-developed flow banding. The west side of the dome has 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 large cone, with a fault scarp crossing near the summit. The dome lava consists of hornblende-orthopyroxene dacite, but on the west flank most mineral phases have been replaced by hematite, authigenic quartz, and clays.

Belfond dome and tephra. The latest eruptive activity within the caldera (not including a historic phreatic blast) produced a complex of coalescing domes and craters, located in the Belfond area, which is 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 width of 1.5 km and summit elevation of 472 m the dome-crater complex rises 170 m above the surrounding moat (Belle Plaine) and contains 4 craters:

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

Massive dacite of the dome crops out at the summit and at a few places on the flanks. It is a porphyritic dacite, consisting of 42% phenocrysts in a glassy groundmass. The dome lava contains 2% granodiorite xenoliths. The dome is buried by tephra from the tuff rings or tuff cone (La Dauphine) (Figs. 7—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 partly filled with Belfond tephra of unknown thickness.

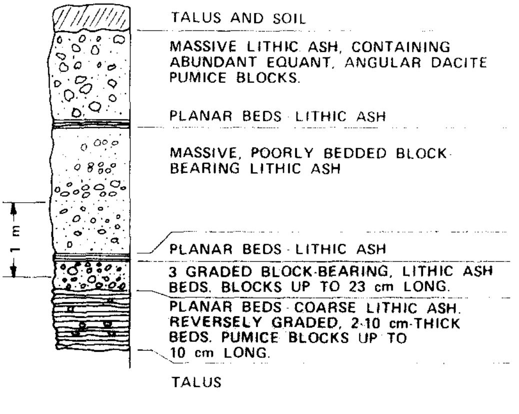

Fig. 7. Belfond Formation. Partial stratigraphic section, western slope of the Belfond tuff ring. Attitude 340°, 24°W (dip slope).

The tuff cones and rings have dip slopes of 10—20° and typically consist of more than 5 m of graded tephra-fall and surge deposits in cross section. Fall deposits are normally graded block-bearing medium lithic ash. Surge deposits are planar, reversely graded plane beds with block lenses and some show plastic deformation around blocks. Belfond tephra consist of mostly subequant, subangular to subrounded, porphyritic dacite pyroclasts that

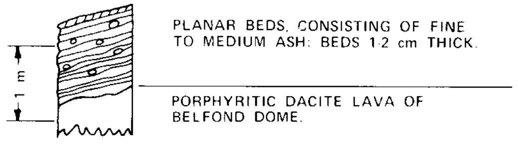

Fig. 8. Belfond Formation. North rim of Belfond crater.

TABLE 6

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	0.05	0.15	0.19
Al_2O_3	13.99	11.66	13.41
FeO	1.03	1.46	1.68
MnO	0.04	0.00	0.03
MgO	0.09	0.19	0.36
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

[a]Analyses of glass crusts around phenocrysts.

Plagioclase[b]:	#1	#2	#4	#5	#7	#8
SiO_2	55.97	54.63	45.69	53.67	56.76	53.20
TiO_2	0.01	0.04	0.04	0.07	0.03	0.02
Al_2O_3	28.40	28.55	34.61	30.28	27.55	29.79
FeO	0.08	0.12	0.18	0.16	0.05	0.15
MnO	0.00	0.02	0.01	0.02	0.00	0.00
MgO	0.00	0.00	0.03	0.03	0.00	0.00
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	0.32	0.29	0.05	0.24	0.36	0.20
Total	100.52	99.35	99.27	101.02	100.21	99.53

[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.

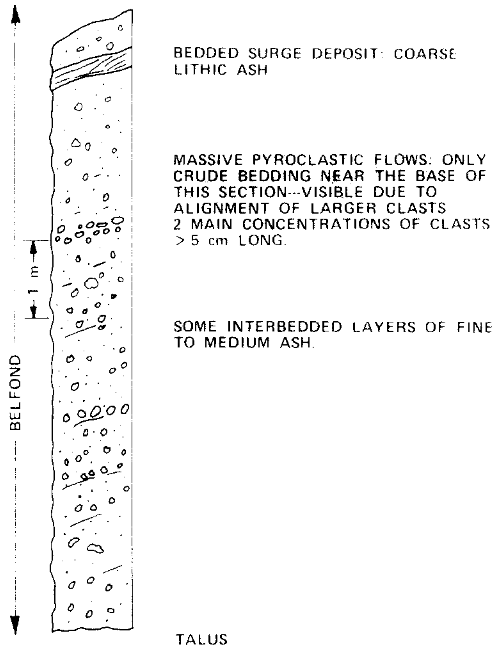

Fig. 9. Belfond Formation. Southern slope of Belfond tuff ring, at Etangs.

TABLE 7

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.

contain only rare vesicles (Table 5; more pumiceous clasts have less than 10% vesicles). As can be seen in Tables 6 and 7, the tephra were probably derived from the dome lavas, possibly by explosive interaction of volatile-poor magma and meteoric water within the dome, resulting in some grain-surface chemical alteration (Table 4).

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. Charcoal from Belfond pyroclastic deposits shows a range of ages from 20,900 yrs to 34,000 yrs (Wright et al., 1984). 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 addition to the large biotite and hornblende phases, there are phenocrysts of plagioclase, quartz, Fe-Ti oxides, clinopyroxene, and orthopyroxene. In some pyroclastic flow deposits south of the caldera, there are pumice clasts with the same phenocryst assemblage. Diorite, basalt and granodiorite xenoliths are present in the Belfond Tuff. Two K-Ar ages of samples from the southern part of the Belfond dome are much too old: 5.30 ± 0.39 Ma and 3.30 ± 0.24 Ma (Le Guen de Kerneizon et al., 1983). These authors suggest a syn- or postcrystallization enhancement in magmatic ^{40}Ar to explain their results.

Deposits from the phreatic eruption of 1766 A.D. (?). The Sulphur Springs area, which includes over 20 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, 1782, 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.

STRUCTURE OF THE QUALIBOU CALDERA

The present-day structure of the Qualibou caldera is dependent upon three factors: (1) the regional stress field of the Lesser Antilles island arc, 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. Combination of these three structural elements has produced a complex pattern resulting from the intersection of deep, linear, regional, 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).

Regional faults

Volcanic rocks of almost all ages from the middle Miocene ($\simeq$ 15 Ma) to the present are exposed on St. Lucia (Briden et al., 1979; Le Guen de Kerneizon et al., 1983). The general locus of magmatism appears to have migrated to the southwest over this period. Seismically, St. Lucia overlies a NNE-trending Benioff zone, which changes in orientation to a NNW trend beneath the arc north of St. Lucia (Wadge and Shepherd, 1984). Estimates of the rates of relative plate convergence vary from about 0.5 cm yr^{-1} (Westbrook, 1975) to about 4 cm yr^{-1} (Sykes et al., 1982). Westercamp (1979) argued that plate convergence had fractured the arc lithosphere into a series of NE-trending blocks. There is good evidence for this assertion in the geology of Martinique, but the evidence for large, NE-trending faults is not as strong elsewhere.

Two major ENE-trending faults occur adjacent to the Qualibou caldera. These faults effectively bound the caldera; the northernmost one parallels Ravine Toraille and cuts the north slopes of Mt. Gimie and the southernmost is parallel to the drainage of L'Ivrogne River, aligned with three small domes near Bois d'Inde Franciou and Morne Bonin near Migny. They are also 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.

These faults can be traced on aerial photographs across the island; trending about N60°E (Fig. 2). This transverse tectonic zone coincides with a gravity anomaly that interupts the main N—S trend of the gravity structure of St. Lucia (Andrew et al., 1970). Perhaps the best evidence for 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 two NE—SW alignments of major edifices: (1) Mt. Gimie, Terre Blanche, and Petit Piton; (2) Gros Piton, Fond Doux, and Belfond.

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

Less developed SE—NW faults occur along the Migny River and near Anse Chastanet. This faulting produced offsets in Choiseul Pumice evident near Bouton, and at Anse Chastanet near Grand Caille Point and Rachette Point where, in places, the Choiseul Pumice is in contact with old pre-caldera andesite agglomerates. This latter fault extends across Soufrière Bay, cutting older andesites at Coubaril, as well as extending into the Sulphur Springs area, and may project across the caldera and be coincident with the Ravine Citron.

Caldera faults

Caldera-related faulting began sometime between 20,000 and 40,000 yrs ago in response to collapse of the volcanic edifice 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 cut by and also drape the fault scarps, which supports the conclusion that 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; 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—Malgrétoute. The major western caldera fault along the ridge of Malgrétoute 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 #1 and #2 drilled by Merz and Mclellan (1976). The southern caldera faults also 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 appears to have occurred within earlier caldera margins but with a smaller radius. Such faults are largely covered by lavas and tuffs but are apparent west of Terre Blanche in the Sulphur Springs area and along the St. Phillip—Migny River drainage. Movement along these faults is estimated from well data to be around 100—200 m.

The caldera fault scarps display marked topographic effects. Their dips range between 45° and vertical, and because of their limited areal extent, they probably have only shallow projections of no more than several kilometers. 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.

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 (Merz and Mclellan, 1976) in 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.

Precaldera rocks consist of basaltic lavas and andesitic to dacitic lavas, domes, and tephra. Stratovolcanoes in the Lesser Antilles consist of domes and lavas and lower slopes of breccias (agglomerates), tuffs, and mudflows (Robson and Tomblin, 1966). The distribution of these rock types, however, is fairly uniform 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 be below the present-day moat level.

The extent of caldera collapse can be estimated. At least 300 m is evident on caldera walls to the northeast and 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 ($\sim$6 km^3 D.R.E.) 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—1500 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).

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

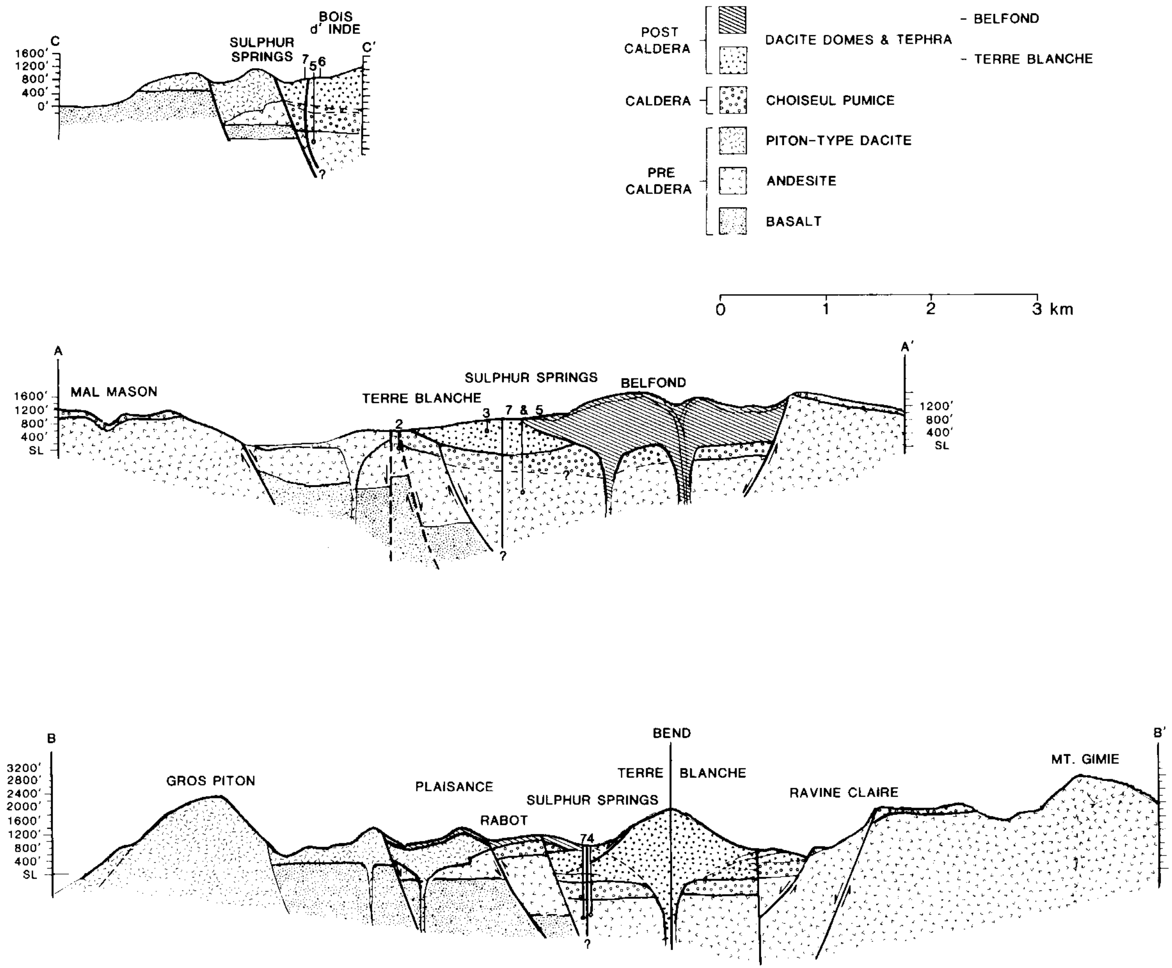

Fig. 10. Cross-sections through the Qualibou Caldera. A—A′: Mal Mason to Belle Vue (342°); B—B′: Anse L'Ivrogne to Mount Gimie (40° and 50°). C—C′: Malgrétoute through Sulphur Springs (282°).

not only to show important mapped structures but also to intersect the geothermal wells drilled near Sulphur Springs.

The N—S section (A—A′) 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 wells #7 and #5. Above the breccia within the caldera is ~200 m of Choiseul Pumice overlain by ~300 m of Terre Blanche dacite and Belford dacite. 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.

The 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 late Miocene basaltic lavas underlie precaldera andesites and Piton-type dacites on the western caldera rim and andesite breccias within the caldera. Their position in the caldera has been extrapolated from Well #1, where basalt was intersected at a depth of between 400 and 500 m below the surface. The inner caldera fault between Rabot and Terre Blanche appears to have displaced the basalt even deeper, as revealed by intersection of only younger rocks in wells #7 and #4.

Terre Blanche lavas fill in the caldera directly above the Choiseul Pumice and precaldera andesites, as revealed in wells #7 and #4. A tuff ring collar, which is exposed near the Migny River, surrounds the Terre Blanche dome and appears to coincide with steam-producing strata in well #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.

The ESE—WNW cross-section (C—C′) highlights displacement along caldera faults. The aphyric basalt occurs at sea level near Jalousie but is found at several hundred meters below sea level in Well #1. Piton-type dacite of the western caldera margin appears to be stratigraphically equivalent to the later 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.

Deep resistivity measurements

Direct current (DC) electrical resistivity methods have proven to be a valuable tool for geothermal exploration. Liquid-dominated (>200°C) geothermal reservoirs are characterized by a resistivity of less than 10 ohm-m, regardless of the resistivity of the host rock*.

Previous shallow resistivity studies in the Qualibou caldera consisted of 13 dipole-dipole D.C. profiles to a depth of 700 m (Greenwood and Lee, 1976). Low apparent resistivity values associated with the geothermal system were found around Soufrière, La Pearle, Cresslands and in other areas north of Sulphur Springs. Additional lows were centered in the areas of Belle Plaine, Etangs, and Fond Doux.

A deep dipole-dipole D.C. resistivity survey was conducted by Ander (1984), centered on Sulphur Springs. The survey line was 5.2-km-long and trended NNW—SSE. A nominal dipole length of 200 m was used in order to obtain high resolution. To obtain resistivity data to a depth of 2 km, we used a 35-kW DC resistivity transmitter capable of producing a square wave of up to 70 A peak-to-peak at 1,000 V.

Apparent resistivity data from the dipole-dipole soundings are plotted as a function of depth (pseudosection) in Fig. 11. Also shown for comparison in Fig. 11 is the geologic cross-section A—A′, which is nearly coincident with the resistivity cross-section.

The upper 700 m of the pseudosection shows characteristics similar to those of the dipole-dipole data of Greenwood and Lee (1976). In general, there is conductive material with an apparent resistivity of less than 40 ohm-m immediately north of Sulphur Springs. Below the Belfond domes there is an apparent resistivity high (>1000 ohm-m); beneath this high is material that has an apparent resistivity of <10 ohm-m. Below the Etangs area there is a zone of very low apparent resistivity (<1 ohm-m).

The regions containing material with resistivities of <10 ohm-m are probably due to the presence of thermal waters. Water rising along the southern caldera wall is indicated by low resistivity values and its surface manifestation is a swampy area located on a hillside possessing good drainage. Highly resistive rocks above a depth of 0.5 km along the southern third of the survey line correspond to the dacite domes of Belfond. Zones of low resistivity along the northern half of the line may indicate hot water along tectonic and caldera-bounding faults. The deepest part of the profile (2.2 km depth) indicates yet more hot water.

In general, the resistivity variations define zones of hot water that typify active, structurally controlled hydrothermal systems. Existing within the caldera above permeable zones saturated with hot water are highly resistive blocks that correspond to intracaldera dacite domes. The deep zone of high resistivity located beneath Sulphur Springs can be interpreted in two ways: (1) the presence of dry steam, or (2) the presence of impermeable caprock. Dry steam encountered in four of the drillholes suggests that the first interpretation is probably correct.

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*For a discussion of the dipole-dipole technique, see Bhattacharya and Patra (1968) or Keller and Frischknecht (1966).

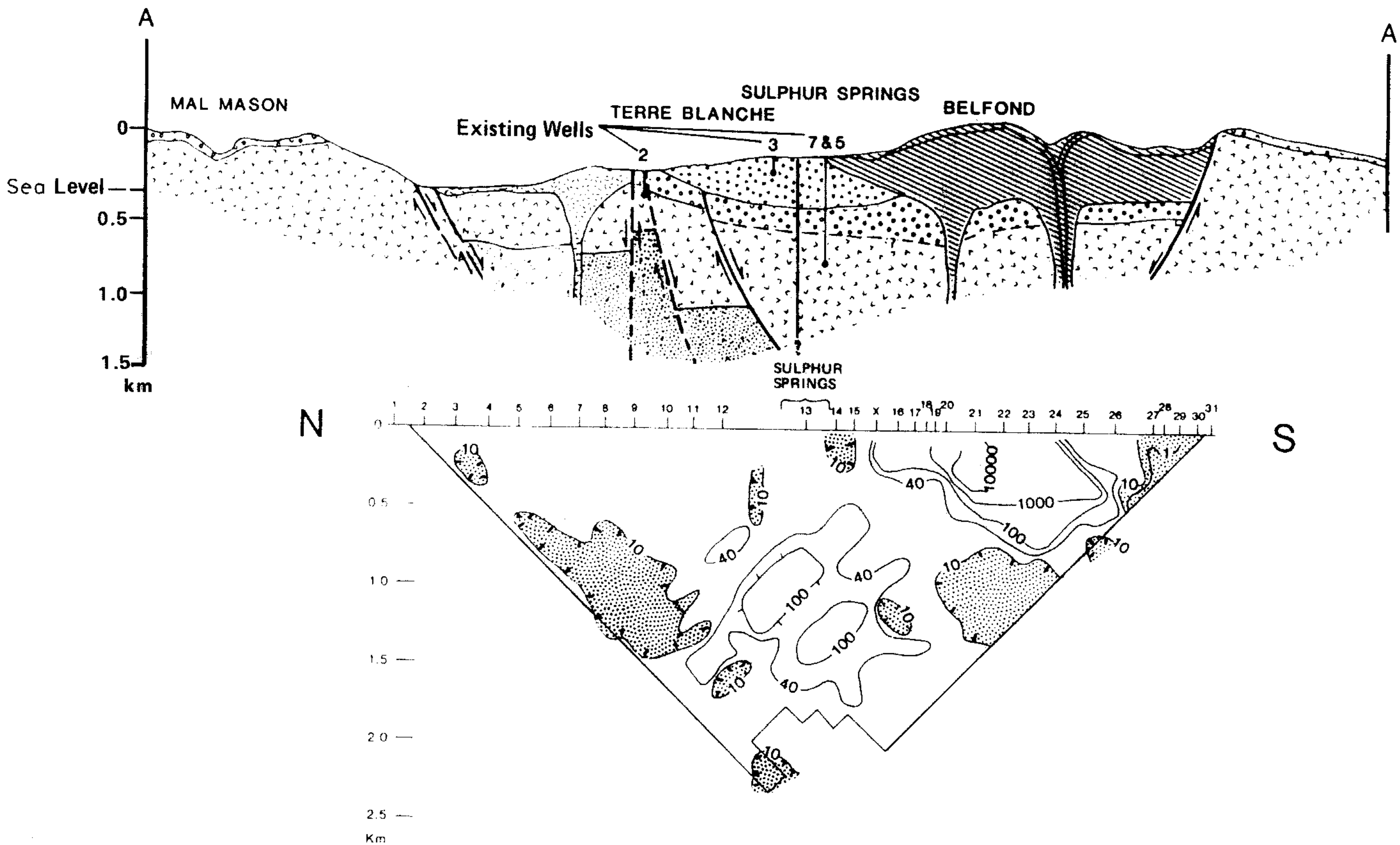

Fig. 11. Resistivity psuedosection through the Qualibou Caldera.

Structural control of thermal springs

Faulting and hydrology has controlled the pathways to the surface for thermal waters originating at depth. Porous stratigraphic units such as the vent breccia/tuff collar of Terre Blanche appear to be near surface steam collectors and therefore provide an intermediate reservoir for rising vapor (Figs. 3 and 10).

An example of spring location is Cresslands, at the intersection of a major NE—SW regional fault and the western caldera fault, which is located between wells #1 and #2. It is interesting to note that all along the major western caldera fault, running from Dasheene northward along the east side of Malgrétoute Ridge, are hydrothermally altered rocks, evidence of previous geothermal activity in that area. Sulphur Springs occurs along an arcuate fault concentric to Terre Blanche and much hydrothermal alteration is apparent on the western flanks of Terre Blanche and on Rabot Ridge along a NW—SE-trending regional fracture. Spring locations appear to be controlled by the level of water table, which on the northern caldera moat is at an elevation of 61 m. Since numerous fault intersections occur throughout the caldera it is likely that thermal waters are present at depth throughout the caldera.

Deep structure of the Qualibou caldera

Results of exploration drilling near Sulphur Springs and geophysical surveys made during 1974, 1975, and 1984 have given 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. The lithologies, intersected by boreholes (Merz and McLellan, 1976), may be correlated with post-Miocene stratigraphy of the area; however, no information was obtained on rock units deeper than an aphyric basalt.

The resistivity survey (Greenwood and Lee, 1976) provided data to depths approaching 1 km and revealed 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 those of this report and 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 nature of the deep basement below the Qualibou can only be surmised. By analogy with the northern half of the island, basaltic and andesitic lava flows overlying andesitic tuffs and breccias of middle to late Miocene age may underlie Qualibou (Martin-Kaye, 1969; Westercamp and Tomblin, 1980). These breccias contain intercalated lenses of fossiliferous, nodular limestone up to 10 m thick. Below these rocks, volcanic rocks of Oligocene and perhaps Eocene age can be expected with a substantial sedimentary

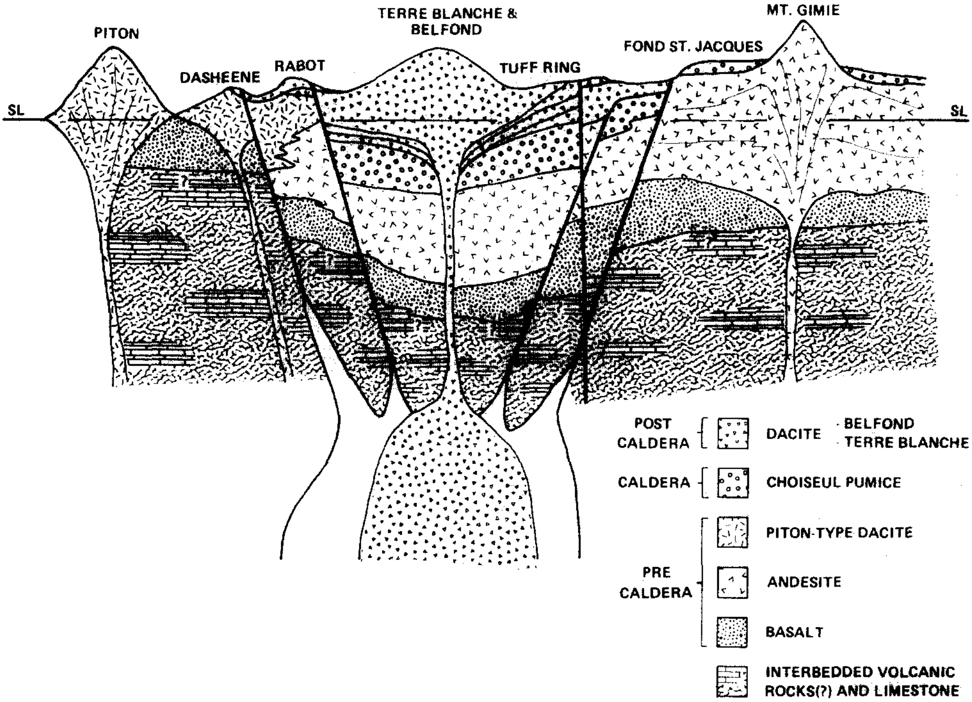

Fig. 12. Schematic cross-section, Qualibou Caldera.

component, perhaps including thick ($\simeq$ 100 m) carbonates, as in the Grenadines. Martin-Kaye (1969) suggested that metasedimentary xenoliths in southern St. Lucia volcanic rocks originated from these lower Tertiary beds. The seismic refraction profile of Boynton et al. (1979) shows the top of the upper crustal layer with an average velocity of 6.2 km s^{-1}, at a depth of only 2 km below the surface for most of St. Lucia. This layer is probably predominantly intrusive rocks of intermediate composition. For modeling purposes (Fig. 12), the caldera may overlie a magma body or bodies located at depths of 3 to 4 km. The magma has intruded inferred interbedded Oligocene limestones and volcanic rocks below Miocene basaltic and andesitic lavas and tuffs that are nearly 2 km thick. These are overlain by caldera-related rocks about 0.5 km thick.

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.

THERMAL REGIME AND FLUID GEOCHEMISTRY

The state of the present heat source occurring at depth below the Qualibou Caldera can only be inferred. The following thermal 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). We assume that young magmatic activity drives the overlying hydrothermal system discussed below.

Evolution of magmas at Qualibou have 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 desposition of the Choiseul Pumice;

(2) moat eruption of Morne Bonin andesite lava;

(3) eruption of the dacite lava dome of Terre Blanche;

(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: large-scale collapse associated with eruption of the Choiseul Pumice, producing a 4—5-km-diameter caldera; and possibly ring faults, associated with the Terre Blanche dome, producing additional collapse with a diameter near 2 km.

The conclusion tentatively drawn from petrologic and structural considerations is that a complex, multiple 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 1 order of magnitude larger. The Choiseul Pumice represents about 10 km^3 of magma and its chamber was likely in the range of 100 km^3. The magma chamber of the post-caldera 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 yrs to cool to 300°C. Considering the maximum age of the Choiseul Pumice as 40,000 yrs, its magma chamber is likely still in a postmagmatic stage with temperatures of between 300° and 800°C (an approximate maximum temperature for subsolidus dacitic magma). Since Belfond eruptions are dated at 21,000 to 34,000 yrs, magmatic temperatures were present at that time and near-magmatic temperatures can still exist in the chamber underlying the Qualibou caldera.

Qualibou caldera contains a high-temperature geothermal system that

TABLE 8

Chemistry of some geothermal fluids, Qualibou caldera, St. Lucia; analysis in mg/l[a]

	Temp. (°C)	pH	SiO_2	Na	K	Li	NH_4	Ca (mg/l)	Mg	HCO_3	SO_4	Cl	F	B	Br
Sulphur Springs															
Steam condensate zone															
Flowing spring	93	6.2	197	49	6.8	0.04	16.6	61.5	10.3	309	35.6	39.7	0.11	10.9	<0.1
Vapor zone															
Drowned fumarole	100	1.6	360	6	6.7	0.05	2.4	220	72	0	6750	5.0	0.02	22.9	<1.0
Superheated fumarole	103	8.2	<1	—	—	—	—	—	—	—	121	1.3	0.03	95	<0.2
Brine zone															
Well #4[b]	200	5.1	212	5900	293	—	—	11600	100	—	1195	37000	—	3500	0.5
Outlying thermal springs															
Diamond warm spring	43	6.45	171	129	11.0	0.22	0.24	69.2	42.3	686	21.8	40.0	0.15	11.1	<0.1
Cresslands hot springs	56	6.55	110	257	16.5	0.67	0.01	163	56.5	1215	0.77	153	2.60	15.0	0.5
Malgrétoute hot springs[c]	57	6.4	101	267	15.4	0.41	<0.01	23.1	20.3	648	105	74	0.16	8.9	0.1

[a] Analyses by P. Trujillo and D. Crounce, Los Alamos National Laboratory.
[b] Analysis from Bath (1976); Br analysis from another sample and is, therefore, only approximate.
[c] Temperature and pH from Aquater (1982).

has been explored superficially and is geochemically unique (Bath, 1976, 1977; Williamson, 1979; Aquater, 1982; Goff and Vuataz, 1984a, 1984b). An area of boiling acid-sulfate springs, steam condensate springs and superheated fumaroles occurs at Sulphur Springs (Fig. 2); this suggests that vapor-dominated conditions exist at shallow depths. Isolated hot springs (as hot as 57°C) issue at several points along the northwestern caldera boundary and are chemically similar to steam condensate springs at Sulphur Springs (Table 8).

During the 1970's, 7 wells were drilled to depths of up to 726 m at Sulphur Springs (Merz and McLellan, 1976); temperatures in these wells exceeded 200°C. As documented by Williamson (1979), the vapor zone beneath Sulphur Springs is two-phase, extremely CO_2-rich (21% by weight of steam) and fracture-dominated. From his model, based on an estimated thermal gradient of 220°C/km and the boiling point vs. depth curve of water, Williamson indicates that the thickness of the vapor zone might be 1—1.2 km. This thickness roughly coincides with a zone of higher resistivity shown in Fig. 11. However, the near-surface thermal anomaly at Sulphur Springs is limited; well #1, located 0.5 km NW of Sulphur Springs (and outside of an inner caldera fault) is only 66°C at 457 m. The DOS drilling project was terminated because of a lack of fracture permeability in some wells, high CO_2 content in the steam, and lack of funds.

Well #4 is noteworthy because it discharged geothermal brine during wet/dry cycling and contained as much as 70,000 mg/l Cl (Bath, 1976). This brine is unusual because the Ca concentration is twice Na by weight (Table 8). The brine also contains abundant boron. Discovery of brine in the vapor zone is perplexing because a complicated mechanism is required to explain the subsurface plumbing (Williamson, 1979). Presence of the brine substantiates interpretation of deep electrical resistivity data presented earlier in this paper; those data indicate that brines are present at depths >1 km below the Sulphur Springs—Belfond area and beneath the northern part of the caldera.

A stable isotope plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters of Qualibou caldera is shown in Fig. 13. Surface waters, cold springs and outlying thermal springs all fall along the world meteoric water line, whereas compositions of geothermal brine from well #4 and condensed steam from other wells (Bath, 1976) plot considerably to the right of the line. Thermal springs at Sulphur Springs show effects of evaporation and mixture of condensed steam with surface ground water. An extreme example of the processes is the drowned fumarole at Sulphur Springs. Note that the isotopic compositions of fumarole steam overlie the compositions of steam flashed from wells. The isotopic composition of brine from well #4 is essentially identical in D but much heavier in ^{18}O than local meteoric water, a feature characteristic of many high-temperature geothermal fluids (Craig et al., 1956). The shift in ^{18}O of the Sulphur Springs brine away from the meteoric water line is as much as +13‰, an extreme shift indicating extensive isotopic exchange between fluid and rock in a high-temperature environment.

From a combination of geochemical, electrical resistivity surveys, and drillhole data, our model for the geothermal system at Sulphur Springs consists of three layers: (1) an upper steam condensate zone; (2) an intermediate vapor zone; and (3) a lower brine zone. The vapor zone may be localized at Sulphur Springs, implying that elsewhere in the caldera a zone of steam condensates overlie the deeper brine zone. Goff and Vuataz (1984a, b) suggest that deep convective upflow is occurring beneath the Belfond—Sulphur Springs area and that geothermal fluids are flowing laterally in the subsurface toward the northern caldera wall. From examination of the fluid and gas geochemistry, the brine zone is believed to be over 230°C and possibly as hot as 280°C.

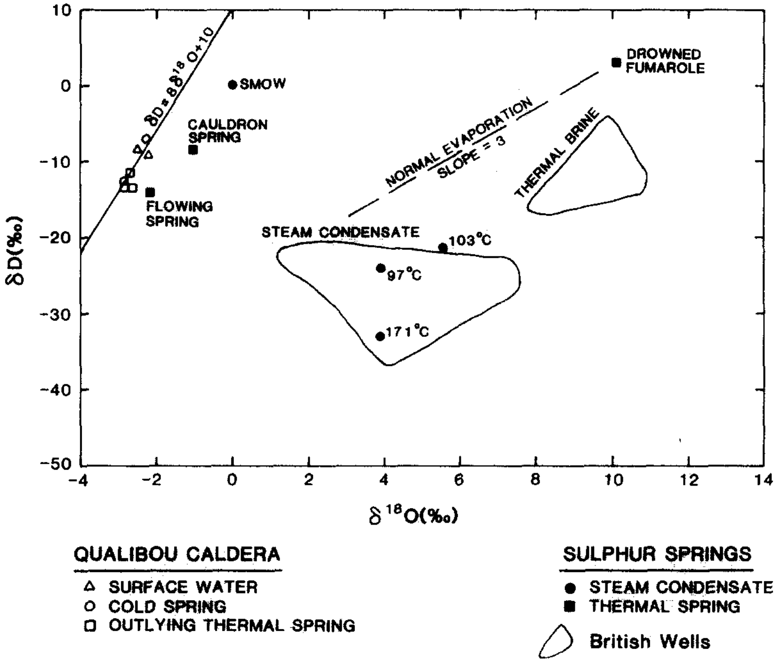

Fig. 13. Plot of deuterium versus ^{18}O for Qualibou geothermal waters.

Origin of geothermal brine and CO_2

As mentioned above, geothermal brine discharged from DOS well No. 4 is chemically unusual, because Ca is twice Na by weight. Calcium-rich brines are commonly described at geothermal areas near the ocean, such as the Salton Sea, California and the Reykjanes field, Iceland and along oceanic spreading centers like the Atlantic II Deep (Hardie, 1983). However, even these hot brines contain more Na than Ca. Hardie (1983) presents convincing evidence, based on a geochemical balance model, that $CaCl_2$-rich geothermal brines are generated by reaction of seawater with basaltic rocks at temperatures >250°C. The basalts are transformed into albite-epidote-chlorite rocks, accompanied by deposition of quartz, calcite and anhydrite. Circumstantial evidence suggests that the Sulphur Springs brine may have formed originally at depth in this manner because the area is within 4 km of the ocean and overlies a precaldera sequence of basaltic lavas.

On the other hand, Bath (1977) has pointed out that the D content of the brine does not indicate a seawater origin because it resembles St. Lucia meteoric waters (Fig. 13). He also notes that the Br/Cl ratio of the brine is much lower than seawater, although it is not clear how Br would behave in such an unusual geothermal fluid. Because unexposed Tertiary marine carbonate rocks are postulated to underlie the Qualibou caldera (Martin-Kaye, 1969), Bath suggests a possible mechanism for brine formation in which HCl-rich volatiles from magmatic sources react with carbonates to release CO_2, Ca^{2+}, and Cl^-.

If this model is correct we would expect the ^{13}C signature of CO_2 at Sulphur Springs to be close to 0—2‰ (PDB), the value in average marine limestones (Hoefs, 1973). Instead, samples of CO_2 from 6 Sulphur Springs fumaroles and springs display a uniform ^{13}C value of -5.95 ± 0.08‰ or a value more consistent with a magmatic origin (-5 to -8‰, Barnes et al., 1979). If Sulphur Springs CO_2 originates by thermal breakdown of carbonates, the marine limestones underlying the caldera must have been isotopically reequilibrated to heavier ^{13}C compositions. Another possibility is that the CO_2 originates from thermal breakdown of secondary (hydrothermal) carbonate that is relatively heavy in ^{13}C (Goff et al., 1985).

We offer another possible mechanism for formation of the Sulphur Springs brine in which seawater initially reacts with basaltic rocks in the geothermal reservoir but is steadily replaced by local meteoric water during continuous cycles of boiling and recharge. Perhaps this seawater infiltrated the subsurface or poured into the caldera depression during and soon after caldera formation. Stabilization of the caldera structure, followed by hydrothermal sealing of fractures and pore space around the margins inhibited further seawater recharge. Because most salts have low solubility in steam, they remain within the subsurface brine reservoir while the original seawater is boiled off and replaced by meteoric water. Such a model in which the salts of a geothermal brine are derived from seawater while the existing water is derived from another source is not unique; Truesdell et al. (1979) and Rex (1972) have explained the geochemistry of the Cerro Prieto and Salton Sea brines in similar fashion. Clearly, a complete analysis of the origin of the brine and CO_2 must wait until the brine reservoir has been adequately drilled and samples of fluids and hydrothermal alterations have been analyzed.

DISCUSSION OF THE GRAVITY-SLIDE MODEL OF QUALIBOU

Roobol et al. (1983) reinterpreted the geology of southern St. Lucia and proposed that the Qualibou caldera of Tomblin (1964) and Robson and Tomblin (1966) is not a caldera but a large gravity slide. After some mapping of the Choiseul Pumice and Belfond Pumice deposits, with particular attention to textural features (reported in Wright et al., 1984), they suggested that the source was not associated with the Qualibou depression, but with vents located in the central highlands. They admitted in the paper that they could not identify these highland vents; however, they interpret their evidence as unsupportive of a caldera source.

As was described earlier in this paper, the central highlands are composed of andesitic composite cones, dated at 1.7 ± 0.2 Ma (Westercamp and Tomblin, 1980) and 0.9 ± 0.08 Ma (Aquater, 1982); these rocks are much older than the Choiseul Pumice (dated at 30,000 to 40,000 yrs by Wright et al., 1984). No rocks younger than the Choiseul Pumice have been dated in the highlands. The explanation by Wright et al. (1984) that highland vents of the Choiseul Pumice are now plugged by lava domes, surrounded by aprons of block and ash flows, is yet to be substantiated. Accordingly, a considerable time break exists between building of the highland cones and the eruption of Choiseul Pumice flows. This time break suggests either renewed explosive activity from these earlier highland vents without any contemporaneous outpourings of lava or explosive activity at other vent locations. Our mapping did not distinguish any stratigraphic or textural evidence (such as lag-fall breccias, coarsening of size and abundance of lithic fragments and pumices, and steepening of original depositional slopes) to indicate that the Choiseul Pumice came from the central highlands. In contrast, the topographically high, older highlands cones appear to have been barriers during eruption of Choiseul Pumice from the Qualibou depression; there are no outcrops of Choiseul pyroclastic flows northeast of Mt. Gimie and Mt. Tabac, in the "shadow" of the highlands (Fig. 2). The Choiseul Pumice appears to onlap the slopes of Mt. Gimie and Mt. Tabac, filling low areas between these cones. Had Choiseul Pumice vents been located in the central highlands, tuff units should have covered the entire southern half of the island.

Wright et al. (1984) report that the Choiseul Pumice is nonwelded. While this fact is true for most exposures of the unit, a thick (>80-m) welded tuff is exposed near Canaries, about 8 km from the central highlands. This observation is difficult to explain if the Choiseul Pumice had been deposited during small-volume eruptions of pumice from central highland vents. A thick welded tuff could, however, have been erupted from nearby caldera source during closely spaced eruptions of ash and pumice.

With respect to the multiflow nature of the Choiseul Pumice, many textural variations are evident including pumice fall, ash and pumice flows, and crystal-enriched, fines-depleted surge units. Tomblin (1964) initially mapped three distinct flow units. We believe that these flow units collectively make up the Choiseul Pumice, and that they represent a caldera-forming eruption sequence. The Choiseul Pumice is composed of a complex sequence deposited during closely spaced explosive eruptions. Glass shard compositional variations, measured by energy dispersive spectral analysis, variations of glass and crystal alteration and SEM textures, and amounts of fine ash demonstrate that these eruptions reflect varying contributions of magmatic and phreatomagmatic volatiles during course of eruption.

The Belfond Pumice is petrographically related to the Belfond dacite dome and represents early explosive phases associated with construction of the Belfond tuff cone complex and late-stage Vulcanian disruption of lava domes that were extruded in the Belfond area. Consequently, the areal extent of the Belfond Pumice is limited with respect to that of the Choiseul Pumice and is only found well-exposed within and on the flanks of the previously formed caldera, in coastal regions southwest of the Qualibou depression, and as small valley fills in unconformable contact with the Choiseul Pumice below.

Information from the British DOS (Merz and Mclellan, 1976) geothermal boreholes substantiate the location and depth of the Qualibou caldera, as described earlier. Excellent stratigraphic markers, such as the oldest basalt flows in the volcanic field, define inwardly dipping, normal faults on the western margin of the caldera. The caldera faults also cut across older, Piton-type dacite domes and have served as conduits for hot water and steam from the caldera's geothermal system (also marked by hydrothermally altered rocks). Well data and recent mapping of the region by us (Wohletz and Heiken, 1984) indicate the presence of a young, 5-km-diameter caldera that was formed during eruptions of the Choiseul Pumice, between 30,000 and 40,000 yrs ago. The location and depth of this structure has been tested by drilling and deep DC electrical resistivity surveys. There is no evidence whatsoever for a large rotational slump as indicated by Roobol et al. (1983) in their cross-section figure 4. Well data show a throw on faults between Terre Blanche and the Petit Piton opposite to that portrayed by Roobol et al. (1983). Their stratigraphy is not substantiated by borehole information; there is a sequence of tuffs, which overlies deposits of the older andesitic deposits and underlies the tuffs of the intracaldera eruptions of Terre Blanche and Belfond that are not shown in the Roobol et al. (1983) cross-section. We have, however, identified several smaller rotational slumps formed by oversteepening of lava dome slopes and caldera walls.

For the last million years or so, magmatism in St. Lucia appears to have been confined to the western part of the ENE transverse belt which crosses the middle of St. Lucia. The emphasis of this discussion has been to counter the argument that no caldera collapse was involved in the eruptions of the last 40,000 years. We do not dismiss the likelihood that there was some vertical volcano-tectonic movement at the margins of the Qualibou volcanic field prior to the eruption of the Choiseul Pumice, which may have had a component of seaward-sliding under gravity. However, positive support of this idea is not yet available.

In summary, we have field, drillhole, and geophysical data that define a caldera associated with eruption of about 6 km^3 (DRE) of andesitic tephra (the Choiseul Pumice). The volume of this 5-km-diameter caldera has been calculated to be about 6 km^3. Fault patterns are those one would expect to find associated with a caldera and do not coincide with a large slump. Our hydrogeochemical data are compatible with those representing upwelling fluids in many young calderas and the Qualibou caldera includes a high-grade geothermal system that does not show characteristics of control by a large slump fault system.

SUMMARY OF ERUPTION HISTORY AND STRUCTURE OF 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 Malgrétoute (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 plug-domes of Petit Piton and Gros Piton, dated at about 0.25 Ma. The Pitons are located at the coastline, peripheral to the volcanic field. It must be stressed here that we believe that all of the cones and domes of this period of activity were erupted before formation of the Qualibou caldera, along ENE- and N-trending faults.

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 (D.R.E.) of lithic-crystal andesitic tephra, mainly as pyroclastic flows and surges, filled paleovalleys surrounding much of the present-day caldera and formed tuff plateaux 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. Carbon-14 dates of this event range from 32,000 to at least 39,000 yrs. The magma body associated with this eruption must be a major source of heat contributing to Sulphur Springs today.

Morne Bonin, an andesite dome, erupted along a fault located on the SE 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 small slumps.

The latest magmatic activity within the caldera was the eruption of the large dacite domes and associated tephra of Belfond. Wright et al. (1984) reports ages of 21,000—34,000 yrs for these eruptions. Le Guen de 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 of about 1 Ma. The dome(s) rise 120 m above the caldera moat and are cut by craters up to 150 m deep. Dacitic tephra from these eruptions have formed a well-developed tuff cone complex and blankets the surrounding area. Some pyroclastic flow and surge deposits reached the south coast.

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

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