Saint Lucia is part of the Lesser Antilles volcanic island arc in the eastern Caribbean (Figure 1). Volcanic activity has been concentrated in the southern half of the island for the last several million years (Wohletz et al., 1986). The Sulphur Springs geothermal area lies within what has been identified as the Qualibou Caldera. Geologic studies have shown that recent volcanic activity in the area has been of a type that is likely to emplace a magma heat source for high-temperature geothermal systems to naturally develop. Any evidence for a supposed intrusion beneath Sulphur Springs comes from temperature measurements of the superheated steam and wells, and from microseismic data (GENZL, 1992). Aspinall et al. (1976) suggest two fluid bodies, one near Sulphur Springs at a depth between 0.5 and 2 km and a second on the northern caldera rim at depths greater than 1 km.

Surface geothermal activity is evidenced by acidic mud pools and fumaroles. Shallow groundwater is heated by steam from depth and may be locally acidified by the presence of gases in the steam. A hot (200°C) brine aquifer, heated by steam from a deeper source, is present about 200-500 m below the area of surface manifestations. A deeper reservoir encountered by well SL-2 at 800-1300 m appears to be high temperature (285°C), steam-dominated, and with a liquid component possibly being low concentration brine. The reservoir lies in a zone of dacite lavas, which may be providing permeability. The lateral extent of this steam-dominated reservoir is unknown but the small size of the overlying brine and alteration layers, together with the low temperatures in well SL-1 at similar elevations, indicate that it may be confined to a small area. This reinforces the assumption that vertical permeability is an important feature of the Sulphur Springs activity.

One proposed geothermal model, supported by numerous investigations (Aquater, 1982; LANL, 1984; GENZL, 1992) of the caldera, is a vapor-dominated system of three components: (1) an upper steam condensate zone; (2) an intermediate two-phase (vapor) zone; and (3) a lower brine zone. Measured temperatures at depth are over 200°C and estimated to be 250°C and greater in the brine layer (Williamson, 1979). Results from testing several wells indicate that the geothermal reservoir is steam dominated and probably confined to a relatively small area beneath the main fumarole activity. The steam discharge has a high gas and acid content, which make utilization for electricity production at Sulphur Springs extremely expensive.

Review of exploratory wells. Merz and McLellan performed exploratory drilling of Sulphur Springs in 1975 and 1976 with the hope of drilling 4-5 wells to produce approximately 10 MW of energy. The program drilled seven shallow wells all unsuccessful for development. Under the auspices of the U.N. Revolving Fund for Natural Resource Exploration (UNRFNRE) and the U.S. Agency for International Development (USAID) two much deeper wells were drilled in 1987-1988.

The shallow wells were drilled to a maximum depth of 600 m. The wells nearest Sulphur Springs (wells 3, 4, 5, and 6) all showed high maximum temperatures (170-220°C). Over a central zone (wells 3, 4, and 7), 200°C was measured at a depth of about 200 m. These wells indicate the presence of a permeable, shallow, high temperature aquifer. These central wells had moderate permeability and were able to discharge, with the best output from wells 4 and 7. The fluids discharged from well 4 showed variable chemistry and were very briny, possibly modified seawater. Wells 5 and 6 showed steadily increasing temperatures with depth, reaching 200°C at 600 m. Well 5 was able to discharge, but well 6 had low permeability and was not discharged. Well 1 showed a max-
imum temperature of 65° C at 520 m depth and appears outside the active zone. Well 2 was drilled in cold andesite and stopped at only 114 m depth. Well 3 had large losses of circulation and repeated caving in during drilling; hence it could only be safely drilled to a depth of 136.5 m.

Based on the first seven wells, and analysis by Aquater (1982) and Los Alamos (1984), it was proposed that a second set of wells be drilled to explore the supposed high temperature deep aquifer. SL-1 was drilled to 2208 m and SL-2 to 1408 m.

SL-1 showed high permeability, but low temperatures in the shallow formations and high temperature and low permeability at depth. The well was never discharged even when stimulated. It appears to have passed beyond the region of activity for the main hot body beneath Sulphur Springs. SL-2 encountered a region of high permeability at depths greater than 1 km and achieved a maximum temperature of 285° C.

Institute of Geological Sciences. In the early 1970s, the Government of Saint Lucia requested assistance from the Overseas Development Ministry of England in developing an exploration program for its geothermal resources in Sulphur Springs. A component of the program was a geophysical study conducted by Greenwood and Lee of the Institute of Geological Sciences (IGS). They performed 50 line-km of resistivity surveys (Figure 2) in the region from September to December 1974, including a line running northwest to southeast through Sulphur Springs (line 9). Line 9 is the subject of this study and the only line chosen for detailed interpretation.

The main objective of the line 9 interpretation was to produce a general resistivity image of the subsurface. Four important questions were to be answered: (1) To what extent is the apparent resistivity cross-section simply a reflection of the changes in true resistivity of the near-surface material? (2) Does a body of high resistivity exist at depth beneath Sulphur Springs? (3) What is the extent of the area of low resistivity near the surface at the Sulphur Springs? (4) What is the resolution of the survey technique in this situation?

Figure 3 shows resistivity data from Greenwood and Lee (1976). The apparent resistivity value range is 4-650 ohm-m, with the exception of the surface on the southern edge where values are low (5-50 ohm-m). The data have several features: a resistive block at the surface near Belfond, a diagonal zone of less than 10 ohm-m running to the southeast, another conductive zone at depth to the south, and a small 50 ohm-m area at depth under Sulphur Springs.

In mid-1975, the standard interpretation method for dipole-dipole data was to simply plot them as pseudo sections with no numerical processing. Inversion codes for true resistivities had not yet been developed. Two computer programs were used to make interpretations. The first, RES1 developed by Lee, calculated theoretical apparent resistivity curves for horizontally layered structures of up to 10 layers. The second, RESCAL (Geotronics Corporation), calculated apparent resistivity sections due to a two-dimensional model made up of blocks of various resistivities. The resulting model data are compared with the field data as the model is revised/updated, and so on until a satisfactory fit is achieved. Resistivity line 9 was interpreted in detail with these programs. Figure 4 shows the best-fit model of true resistivities for line 9. This result was the best possible with the available technology in computer codes of that day. The model shows a high conductivity zone (2-5 ohm-m) at Sulphur Springs to a depth of 225 m and a resistive block (100-500 ohm-m) near Belfond to a depth of 200 m. Below 200 m under Sulphur Springs is a large area of 30 ohm-m, to the north 15 ohm-m, and a conductive 5 ohm-m zone to the south.

Lee and Greenwood (1976) stated the following, based on these results: “The resistivity interpretation shows no evidence for a high-resistivity body at depth beneath Sulphur Springs” ... “The shape and extent of the low resistivity directly under the emanations is uncertain” ... “It is impor-
tant to note that lack of resistivity evidence for the existence of these structures (an impermeable confining layer, a resistive body) should not be taken as a positive indication that they do not exist. They may be too thin, or have too small a resistivity contrast, to be resolved. Any structure situated at a depth greater than about 400 m would have to be very large and highly contrasting to be detected in this environment."

**MIT reinterpretation.** The Earth Resources Laboratory (ERL) at the Massachusetts Institute of Technology has been studying the geothermal resources of Sulphur Springs for several years. This effort includes several expeditions to Saint Lucia. Upon finding the work of Greenwood and Lee (1976), it was decided to reinterpret the resistivity data with a 2D inversion. The apparent resistivity data for line 9 were obtained and inverted for a resistivity tomogram. The ERL has developed modeling and inversion codes which are fast, accurate, and stable (Zhang et al, 1995; Zhang et al., 1996; Shi, 1998). They use finite difference and the biconjugate gradient method for both the forward and inverse algorithms. The fundamental equation is Ohm’s law, for our interest given by

\[ \nabla (\sigma(x) \nabla V(x)) = -I(x) \]

where \( x \) is the position vector, \( \sigma \) is conductivity, \( V \) is voltage, and \( I \) is current. Stability and improved accuracy are achieved in the inversion algorithm by the use of Tikhonov regularization. The objective function \( \psi(m) \), which is minimized is:

\[ \psi(m) = ||d - G(m)||^2 + \tau ||\mathbf{l}(m)||^2 \]

where \( d = \) data, \( G = \) model, \( L = \) Laplacian, \( \tau = \) regularization parameter, and \( m = \) model parameter.

The main feature of the tomogram (Figure 5) is a very resistive (30 000 ohm-m) body at depth beneath Sulphur Springs overlain by material of low resistivity (40 ohm-m and less). The low-resistivity material has a layer within it of 5-15 ohm-m with several very conductive (1 ohm-m) pockets. The tomogram also shows the Belfond resistive block at the surface and a conductive area at depth to the north. In fact, the entire northern edge from the surface to depth is low resistivity (15-30 ohm). The result answers the questions from the Lee and Greenwood report; the tomogram is not inhibited by the near surface resistivity, confirms the existence of a resistive body, delineates the shape and extent of the low resistivity zone, and shows good resolution.

**Detailed interpretation.** The locations of the British wells, their loss of circulation depths, and temperature isotherms were added to the tomogram to aid interpretation analysis (Figure 6). Clearly, a high-temperature vapor-dominated geothermal system with convective circulation of fluids exists. The conductive layer displays the shape expected for cooling, descending waters on the margins of such a system. The circulation fluids come to the surface directly at Sulphur Springs and slightly to the south over a total extent of 250 m.

Wells 1 and 2 were relatively cold and unproductive and appeared outside the zone of activity. The tomogram confirms this conclusion for these wells; well 2 is in a distinct block of 100-120 ohm-m resistivity and well 1 is just on the edge of the resistive body.

Wells 4, 5, and 7 all lost circulation at a depth on the bottom boundary of the conductive zone beneath Sulphur Springs in material of 40-50 ohm-m resistivity. According to
the tomogram, well 6 should have had similar characteristics to these wells encountering briny fluids (1 ohm-m) at a depth of 200 m. SL-1 appears to have just missed two fluid pockets to the north and south of its location at depths of 200-600 m. SL-1 had low temperatures in the top and high temperatures below 1 km, indicating circulating cooling fluids in the system. SL-2 encountered a shallow reservoir from 200 to 500 m depth and at depths greater than 1100 m penetrated a hot, highly permeable formation.

Volcanic rocks such as andesite and dacite are low in pore volume; therefore they have high resistivities. Rocks in which the pore liquids have boiled away (i.e., vapor-dominated such as Sulphur Springs) are resistive because there are minimal fluids left. For example the typically resistivity of wet andesite is 170 ohm-m and dry andesite is 45 000 ohm-m (Telford et al., 1990) which places the resistive body near this range.

Greenwood and Lee acquired dipole-dipole data on a line extending line 9 from Belle Plaine southeast to Motet. The extension line did not have a detailed interpretation performed; only a contour plot of apparent resistivity was generated from which the data for inversion was obtained. Line 9 and the extension tomograms join together very well at 3800 m in distance (Figure 7). The extension segment has a very distinct feature of two vertical briny bodies separated by 200-600 m. There is also a wide area of approximately 1.4 km where conductive fluids are at or near the surface. The zone from 5 to 6 km distance is a new location, not previously investigated for possible geothermal production. The existence of hot fluids cannot be determined from the tomogram; only the presence of a large briny fluid area is confirmed. Probably it is cold modified seawater considering its distance from the heat source at Sulphur Springs.

The best fit model from Lee and Greenwood (1976) was colorized for comparison with the present MIT tomogram (Figure 8). The two results are similar for the top 200 m—showing the Belfond resistive block, a conductive zone from the surface to 200 m at Sulphur Springs, and the slightly higher resistivity to the north. At depth, the results diverge significantly. The 1976 model does not show the most important feature, a highly resistive body beneath Sulphur Springs, seen in the MIT tomogram. The two models agree on a conductive zone to the south beneath Belfond.

The MIT image generally shows much more resolution of conductive/resistive features.

Conclusions. The reinterpretation of line 9 from Greenwood and Lee by inversion has confirmed the existence of a highly resistive body beneath Sulphur Springs and a briny shallow aquifer. Circulation data from the British wells show permeability at the bottom margin of this aquifer. The tomogram shows connectivity of fluids from south to north through Sulphur Springs. The numerous investigations of the caldera have concluded that the Sulphur Springs is a vapor-dominated system with three layers. The tomogram has imaged the first layer of steam condensate and the top margin of the two-phase (vapor) second layer. The third brine layer is at much greater depth than the dipole-dipole survey. The tomogram also highlights the importance of determining exploratory well locations. SL-1 appears to have just missed conductive zones 200 m north and south of its location.


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