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UNITED STATES DEPARTMENT
OF THE INTERIOR
GEOLOGICAL SURVEY

Geothermal Resources of São Miguel Island, Azores, Portugal

A summary report for USAID, prepared by W.A. Duffield[1] and L.J.P. Muffler[2], based on research by D.B. Hoover[3], R.B. Moore[4], and A.H. Truesdell[2]

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This report has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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INTRODUCTION

At the request of the Regional Government of the Azores (RGA) and with the financial support of the United States Agency for International Development (AID), scientists of the United States Geological Survey (USGS) carried out geothermal studies on the island of São Miguel, Azores, from 1981 to 1983. The Laboratory of Geosciences and Technology (LGT) within the Secretariate of Commerce and Industry was the RGA agency with which the USGS maintained direct technical contact.

The program consisted of (1) geologic mapping supported by petrographic and chemical analyses of rock samples and by carbon-14 and potassium-argon age determinations of key volcanic map units, (2) hydrogeochemical (including tritium, deuterium, and oxygen-18) analyses of both thermal and non-thermal fluids, and (3) geoelectrical surveys, using primarily the audiomagnetotelluric technique, and secondarily the telluric and self-potential techniques. The principal goals of this program were to characterize the nature of the resource, to estimate its magnitude, and to identify target areas toward which exploration and developmental drilling might be directed. The program was also designed to train LGT technical personnel whenever feasible and to help develop an inhouse capability for geothermal studies by this group.

The main geothermal-resource areas on São Miguel are Furnas, Agua de Pau, and Sete Cidades (Fig. 1), three Quaternary silicic volcanic centers characterized by summit calderas beneath which magmatic (and/or hot plutonic) heat sources provide thermal energy to overlying hydrothermal-convection systems. An idealized system of this sort is illustrated in Figure 2. That some variation of this idealized model exists at each of the three volcanic centers is indicated by the facts that (1) Holocene eruptions of silicic lava imply an active magma reservoir in the upper crust, and (2) the many thermal springs and fumaroles, especially on Furnas and Agua de Pau, are surface leaks from and thus direct evidence of hydrothermal-convection systems within the volcanoes. For each of the known hydrothermal systems, the current studies have defined, with varying degrees of success, the size of the system, the subsurface temperature that may be encountered by drilling into the system, the thermodynamic state of fluid in the system (liquid or vapor), the chemical composition of the fluid, and parts of the system that may be permeable. These are characteristics of a hydrothermal-convection system that should be determined as accurately as possible in the pre-drilling stage of a development program.

Initial USGS studies were restricted to Furnas and Sete Cidades volcanic centers, because concurrently, other organizations were studying Agua de Pau under direct contract to RGA. However, as the results of this contracted work became available, it was apparent that additional work was desirable on Agua de Pau. Thus, the AID, RGA, and USGS combined financial resources

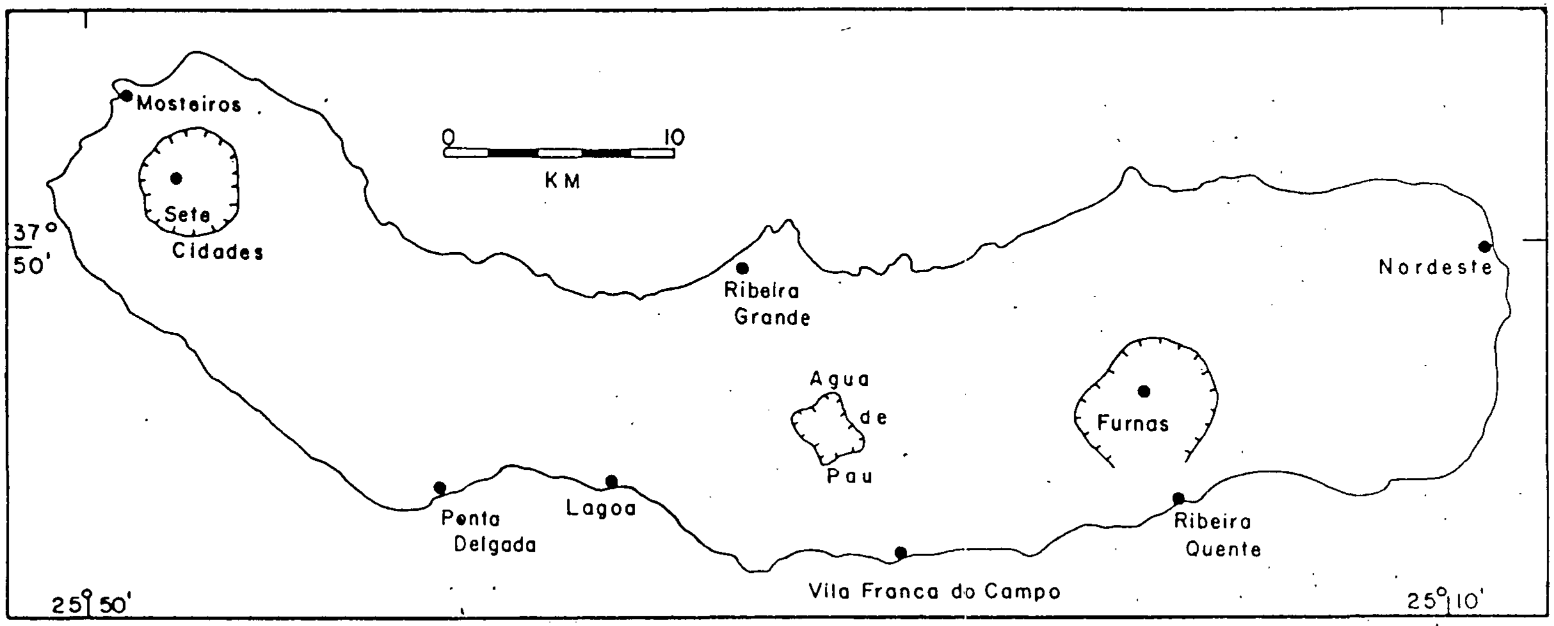

Figure 1. Index map of São Miguel. The topographic rims of the three calderas (Sete Cidades, Agua de Pau, and Furnas from west to east) discussed in this report are indicated by hachured lines. Black dots locate some of the towns of the island.

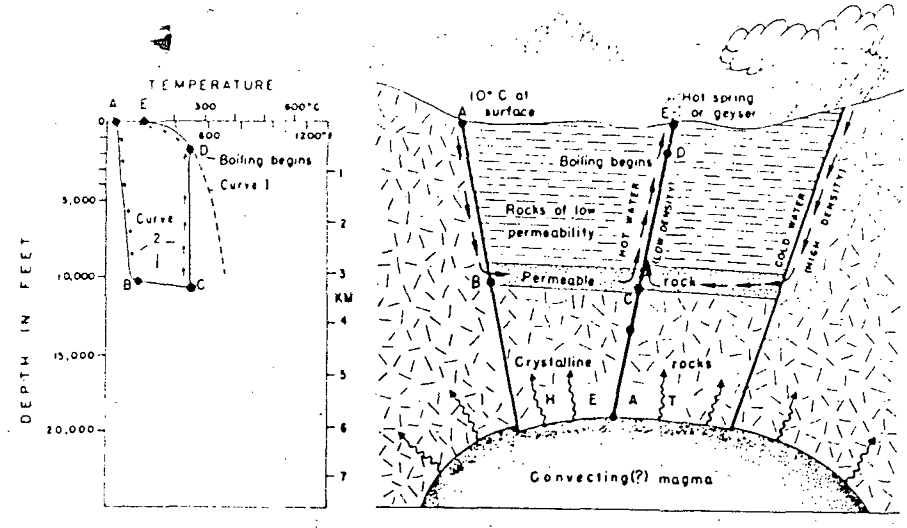

Figure 2. Schematic cross-sectional view of a hydrothermal-convection system heated by magma. The path of convecting water is indicated by arrows, and the corresponding temperature-versus-depth relations are summarized in curve 2 of the accompanying graph. Curve 1 on the graph is the boiling-point curve for pure water. Sete Cidades, Agua de Pau, and Furnas Volcanoes represent variations of this scheme. The calderas of these volcanoes are analogous to the down-faulted block of the diagram. At Agua de Pau some of the circulating thermal water leaks away from the caldera along permeable rock layers that dip down the flanks of the volcano, and/or along permeable fault zones that extend from the caldera down the flanks.

to support USGS studies on Agua de Pau, as well as on Furnas and Sete Cidades, during the final field campaign in the summer and fall of 1983.

Field work was completed in November of 1983. Because of routine delays in laboratory processing, some rock and fluid chemical analyses and radiometric age determinations are still forthcoming as the present report is being written (February, 1984). These results will be forwarded to AID and LGT when they are available. Progress reports based on data now available to the principal investigators have been sent to AID. The present report is a synthesis of these results and as such is the final report to AID under the USGS-AID agreement. We anticipate that the data still forthcoming will corroborate the conclusions and thus support the recommendations contained herein. However, we are prepared to modify our present findings if the new data suggest a need for further evaluation of results.

PREVIOUS WORK

The framework within which and the starting point from which the present geothermal program was carried out were provided mainly by USGS volcanologist David A. Johnston. Johnston visited Sao Miguel in 1979, researched pertinent published literature from all available sources, and subsequently assessed geothermal resources associated with each of the three silicic volcanic centers in a report dated March, 1980. Conclusions and recommendations in his report served as the main basis for RGA's request to AID to support the present USGS program.

Johnston concluded that the combined geothermal electrical potential of hydrothermal-convection systems associated with Furnas, Agua de Pau, and Sete Cidades volcanic centers is nearly 700 megawatts for 30 years. This potential is more than 30 times the presently installed electrical generating capacity (about 20 megawatts) that serves the entire island of Sao Miguel, and thus could provide all electrical energy requirements (including major expansion of energy consumption) for the island from an indigenous source, even if only a few percent of the assessed resource were developed.

For a variety of reasons, resource (in contrast to reserve) assessment tends to produce "optimistic" results. For example, resource as used here and by Johnston refers to the part of a resource base that could be extracted at costs competitive with other forms of energy at a foreseeable time, under reasonable assumptions of technological improvement and economic favorability. In other words, resource assessment assumes a rosier future for whatever commodity is under study. In contrast, reserve refers to that part of the resource that is competitive in the current market place, with no assumption of future conditions. The interrelations of these terms are shown diagramatically in Figure 3.

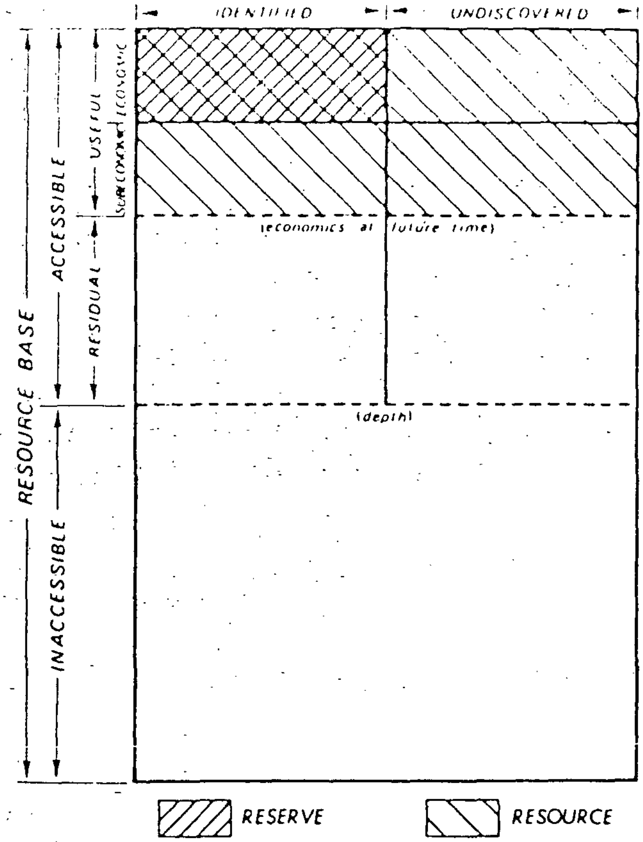

Figure 3. A schematic diagram showing the interrelations of the terms resource base, resource, and reserve for geothermal energy. The vertical axis is degree of economic feasibility, and the horizontal axis is degree of geologic assurance. The scales are arbitrary and thus the relative sizes of the rectangles have no necessary relation to the relative magnitides of the categories.

For an accurate estimation of geothermal reserves, data are needed that can only be obtained by drilling bore holes into a hydrothermal system and test-flowing these wells. Data of this sort are available only for the Ribeira Grande area of Sao Miguel. In view of this situation, Johnston appropriately cautioned that his analysis necessarily included many assumptions, for lack of appropriate data, and was thus subject to undefined but perhaps considerable uncertainty. For example, such key parameters as volume of a hydrothermal-convection system, temperature of the system at depth, and permeability within the system were poorly or unconstrained. Johnston, accordingly, used values based on his best judgment of the significance of general surface geologic features and on analogy to better-documented systems in similar geologic settings, particularly with regard to volume and temperature. Results generated during the present study better constrain temperature and volume for some hydrothermal systems of São Miguel, and though different in many details, the conclusions drawn from the present study are broadly similar to Johnston's in terms of overall resource potential for the island.

Initial attempts to develop part of this resource began in the late 1970's when the RGA initiated a program that led to the installation of a geothermally-powered, 3 megawatt turbine generator in 1980 at Ribeira Grande, on the lower north flank of Agua de Pau Volcano. This RGA program was prompted by the accidental discovery of a hydrothermal-convection system during volcanologic research drilling at Ribeira Grande in 1973 by scientists of Dalhousie University, Canada. By the time of Johnston's resource-assessment study, subsurface temperatures had been measured in bore holes that penetrated this hydrothermal system, and geoelectrical surveys partly delineated the lateral extent of the system. Scientists of Geonomics, under contract to RGA, carried out a variety of studies that predated Johnston's work and concluded that the Ribeira Grande geothermal field has a 200 to 400 megawatt electrical capacity (without specifying a time constraint at this power rating). Based on the same data, Johnston concluded that the capacity was about 14 megawatts for 30 years, and noted that the large discrepancy between his assessment and that of the Geonomics staff apparently reflects a similar discrepancy in the proposed volume of the hydrothermal system. The results of our subsequent studies are consistent with Johnston's interpretation, and, moreover, suggest that the hydrothermal fluids of the Ribeira Grande area represent a relatively thin, tongue-like lateral outflow from a zone of primary hydrothermal-convective upwelling located 2 to 3 kilometers south, higher on the flank of Agua de Pau Volcano. This finding is perhaps the most important result of the USGS study, at least in terms of possibilities for near-term exploitation of geothermal energy on São Miguel. Further documentation and explanation follow in the section on Agua de Pau Volcano.

AGUA DE PAU VOLCANO

Agua de Pau Volcano is built on a subaerial complex of trachytic welded tuffs and basaltic and trachytic lava flows that have yielded potassium-argon ages ranging from about 300,000 to 100,000 years before present (b.p.). The main cone of the volcano is late Pleistocene and Holocene in age and consists principally of trachyte domes, flows, and associated pyroclastic deposits. Three of the domes have yielded potassium-argon ages of about 80,000 years b.p. Charcoal recovered from several levels within the pyroclastic sequence has yielded carbon-14 ages that range from greater than 40,000 years to about 3,000 years b.p. The most recent trachytic eruption occurred in A.D. 1563 and produced pumice that blankets the entire summit region and much of the flanks of the volcano. This history of eruption of trachyte over a period of tens to hundreds of thousands of years extending into the sixteenth century virtually requires the continued existence to the present time of a reservoir of trachytic magma within the upper crust beneath the summit of the volcano.

The summit of the volcano is indented by a 3-km-wide, 100- to 300-m-deep caldera occupied by Fogo Lake (Lagoa do Fogo, Fig. 4). The uneroded, youthful morphology of the caldera indicates relatively recent formation, and the near equivalence in volume of the caldera and that of trachyte pumice erupted about 4,600 years ago suggests that collapse to form the present caldera may have occurred in response to this eruption. In addition, the existence of 15,000-year-old, larger-volume pyroclastic deposits erupted from Agua de Pau suggests an earlier episode of caldera collapse, and thus it is likely that a multi-collapse, composite, caldera structure characterizes the summit region. Much of the evidence for such structure is buried by post-caldera rocks. However, morphologic expression of what is interpreted to be erosional remnants of the 15,000-year-old caldera wall is evident on the northeast, southeast, and west flanks of the volcano. This caldera structure may provide a permeable channelway and thus help localize the primary upwelling of hydrothermal fluids that appear nearby as fumaroles and thermal springs on the north flank of Agua de Pau. We return to this theme in later paragraphs.

Mafic lavas were erupted from vents on the flanks of Agua de Pau throughout the history of the volcano. The two most recent eruptions occurred in A.D. 1563 and 1652. Mantle-derived mafic magma is probably the primary type from which the less mafic magmas are derived, and accordingly, is also the primary source of thermal energy to maintain a long-lived magmatic system in the crust. The relatively higher density of mafic magma prohibits its rise through derivative magmas, and thus the absence of mafic vents in the summit region provides independent evidence of the presence of a reservoir of derivative silicic magma beneath the caldera. Mantle-derived mafic magma is in effect partitioned when it ascends to shallow crustal levels, some being trapped

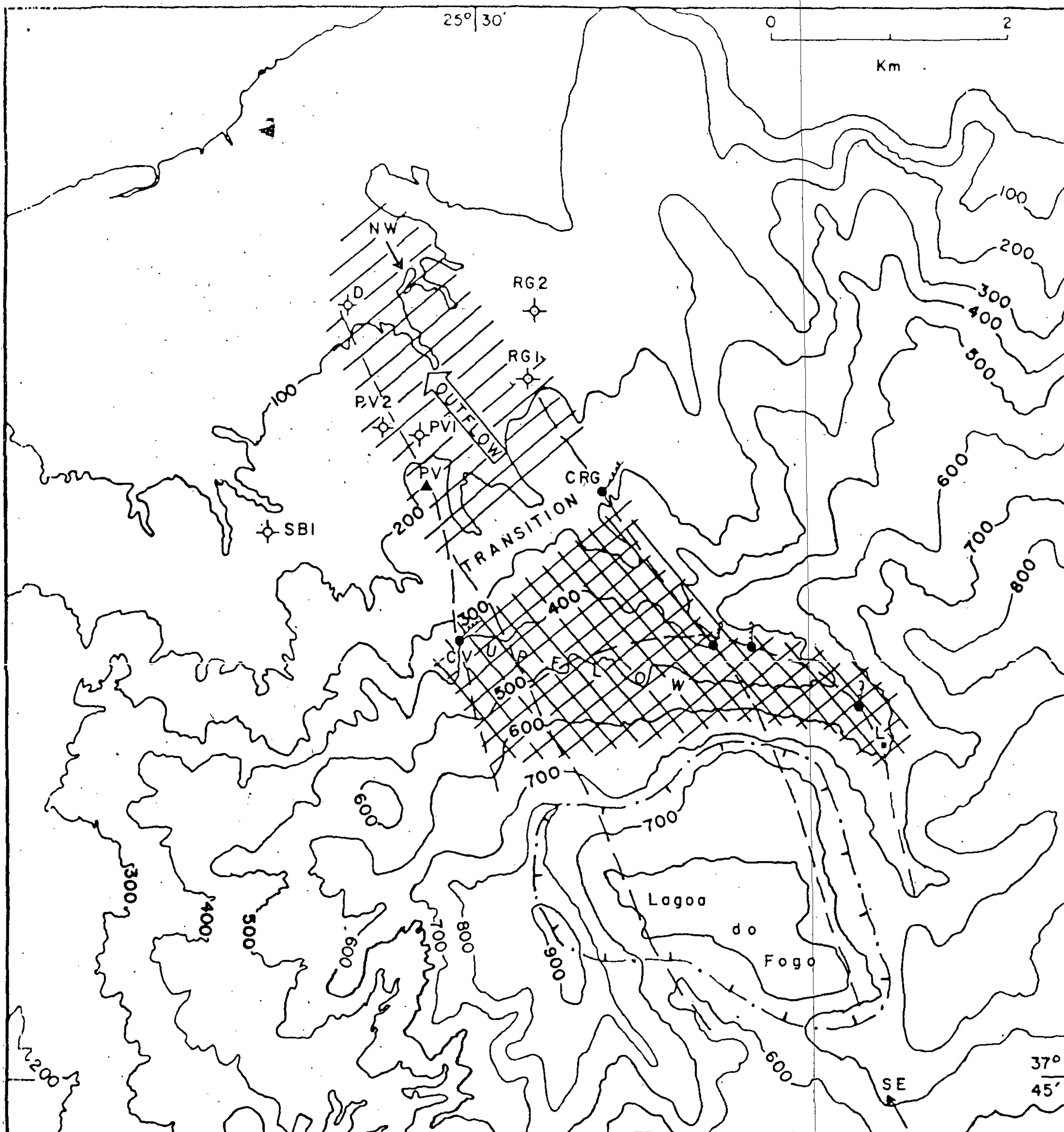

Figure 4. Topographic map of summit area and north flank of Agua de Pau Volcano. Contour interval is 100 meters. The dash-dot-dash hachured line marks the topographic rim of the present caldera. Dashed lines are inferred fault zones; the curved fault is related to caldera collapse of about 15,000 years ago. CRG=Caldeiras da Ribeira Grande thermal area. CV=Caldeira Velha thermal area. L=Lombadas. PV=Pico Vermelho. PV1, PV2, RG1, RG2, and SB1 locate wells of Ribeira Grande geothermal area. D=location of Dalhousie University drill hole. Thermal manifestations are marked by black dot-with-pigtail symbol. NW and SE mark ends of cross section shown in Figure 5. Zones of hydrothermal upflow and lateral outflow are labelled and patterned, and merge across a zone of transition.

beneath the less dense derivatives and some making its way to the surface beyond the perimeter of the low-density barrier.

Johnston assumed the existence of a hydrothermal-convection system directly beneath the caldera, although there are no direct manifestations (for example, as hot springs or fumaroles) of such a system within the caldera; he then calculated a resource equivalent to about 50 megawatts electric for 30 years. The existence of such a postulated hydrothermal system is consistent with the geological evidence and is a reasonable condition for a youthful silicic caldera. For lack of new data from the caldera we cannot carry his analysis further. However, thermal springs and fumaroles on the upper north flank of Agua de Pau Volcano (Fig. 4) may reflect surface leakage from a hydrothermal system associated with summit caldera structure. The probable relations of these manifestations to hydrothermal fluids at Ribeira Grande define a unified model of hydrothermal-convective flow for Agua de Pau.

Temperature-versus-depth profiles that were obtained during research drilling sponsored by Dalhousie University and during subsequent developmental drilling by companies under contract to RGA documented a temperature reversal at several hundred meters depth in the Ribeira Grande area. The most reasonable interpretation of these profiles is that a relatively thin permeable zone, above the depth at which temperature begins to decrease, carries lateral flow fed from a region of hydrothermal upflow located higher on the flank of the volcano. Chemical characteristics of thermal waters from the wells at Ribeira Grande and from thermal springs at Caldeira Velha, Caldeiras da Ribeira Grande, and near Lombadas upslope to the south (Fig. 4) are consistent with this interpretation.

Deuterium and oxygen-18 content of thermal waters from geothermal wells at Ribeira Grande indicate that these waters originated as high-altitude rainfall, most reasonably rainfall on the higher slopes of Agua de Pau. Other chemical characteristics of these waters indicate that they are similar to thermal waters in reservoirs of volcanic rocks at many other localities worldwide. In marked contrast, the chemical compositions of waters from the thermal springs at Caldeiras da Ribeira Grande, Caldeira Velha, and near Lombadas indicate that these springs are fed by the condensation of steam rising from depth and by shallow meteoric ground water heated by this steam. The steam presumably separates from an upwelling plume of thermal water that boils in response to decreasing confining pressure experienced during upflow. A reasonable interpretation of these relations is that primary hydrothermal upflow is localized in the area between Caldeiras da Ribeira Grande, Caldeira Velha, and Lombadas (see Fig.4), and that lateral outflow from this zone of upflow is channeled along structural and/or lithologic aquifers to the Ribeira Grande area on the lower slopes of the volcano. This situation is illustrated schematically in Figures 4 and 5.

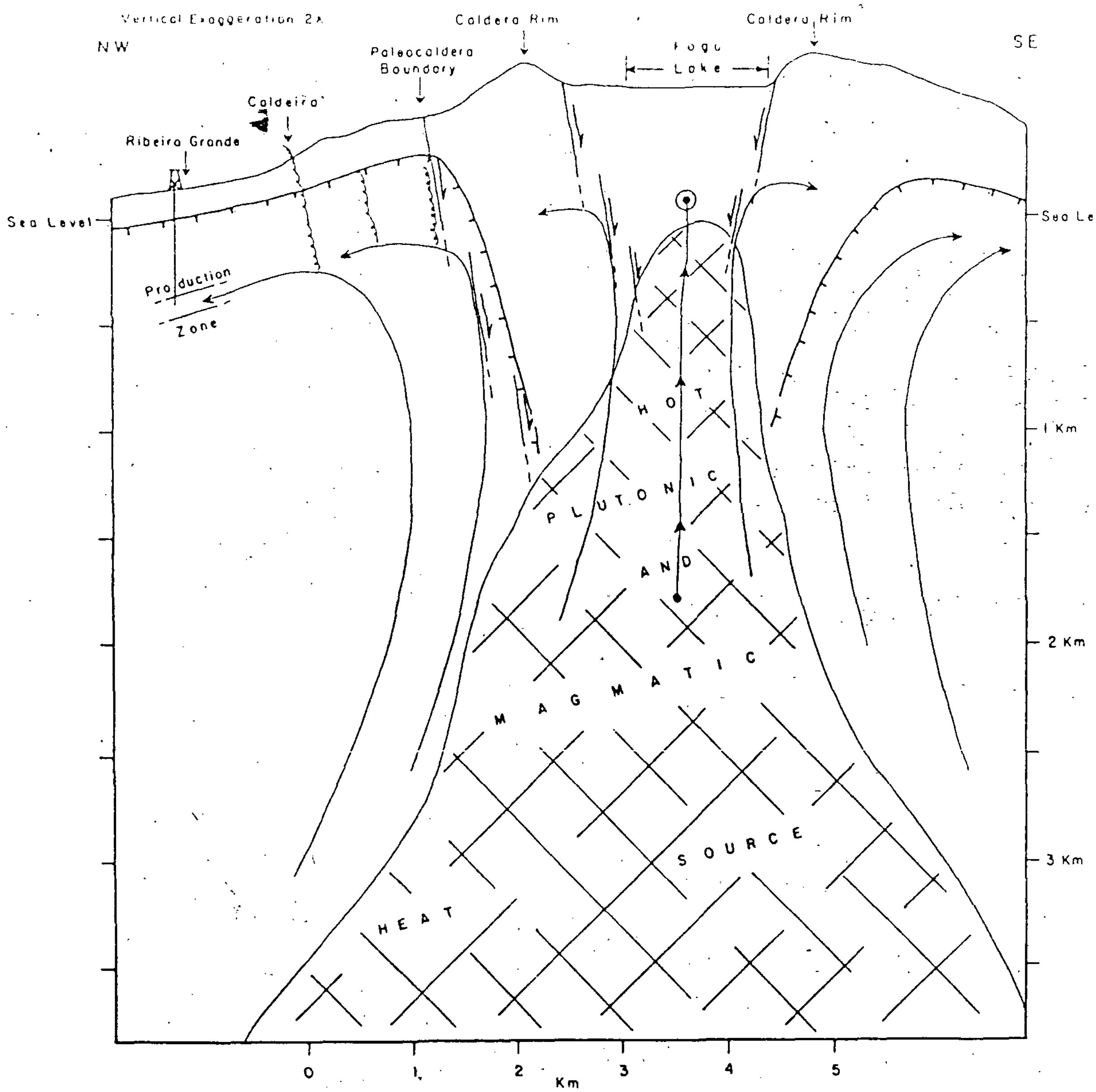

Figure 5. North-30-degrees-west, south-30-degrees-east cross section through Agua de Pau Volcano. The hachured lines mark the top of an electrical conductive zone (10 ohm-meters) identified from audiomagnetotelluric soundings. Inward-dipping solid lines are caldera faults. The curving arrows diagramatically depict flow lines of a hydrothermal convection system. The solid dot at the bottom of the flow line at the center of the system represents flow into the plane of the cross section and the circled dot represents flow out of the plane of the cross section, a reminder that the hydrothermal system has radial rather than bilateral symmetry. The heat source is interpreted to be a composite body of magma and solid, hot plutons.

According to this proposed scheme, thermal fluids within the zone of upwelling should be hotter than those that have flowed laterally away from the heat source. The thermal waters in the upflow zone are not suitable for chemical geothermometry, because they consist of shallow groundwater and condensed geothermal steam, rather than water directly from an underlying hydrothermal system. Moreover, application of geothermometric analysis to geothermal gases of the upflow zone is subject to an undefined but possibly large error due to alteration of gas composition during its ascent to the surface.

The waters from geothermal wells at Ribeira Grande are much more suitable fluids for chemical geothermometry. The silica geothermometer indicates temperatures near or perhaps somewhat greater than 220 degrees Celsius, about the same as temperatures measured directly in bore holes. This is expected because silica and water equilibrate rapidly. The Na/K geothermometer yields similar results, whereas the Na-K-Ca geothermometer yields temperatures of about 285 degrees Celsius. This higher temperature may reflect a higher temperature in the upflow zone, preserved by incomplete re-equilibration during lateral flow and cooling, or it may reflect preferential loss of Ca by precipitation of calcite. Scaling of the geothermal production wells at Ribeira Grande by precipitation of calcite has in fact been a constant serious problem. The most reliable indication that the Ribeira Grande production fluids are from a system at higher temperature than that measured in the wells is provided by the sulfate-water, oxygen-isotope geothermometer. This technique suggests temperatures perhaps as high as 300 degrees Celsius, consistent with the idea that geothermal water is this hot at an unspecified depth within the zone of upflow.

Geoelectrical surveys help delineate this proposed zone of upflow and indicate continuity with the outflow zone downslope in the Ribeira Grande area. Audiomagnetotelluric soundings show northwest-trending conductive zones that pass through Caldeiras da Ribeira Grande and Caldeira Velha. These trends project toward the locations of wells RG 1 and 2, and PV 1 and 2, respectively, and coincide with fault zones (Fig. 4) mapped by several investigators. The conductive zone at Caldeira Velha is better defined than that at Caldeiras da Ribeira Grande. Both are interpreted to mark zones of considerable hydrothermal upflow, although Caldeiras da Ribeira Grande may be near the zone of transition to lateral outflow. The corridor between the two fault zones is also conductive but somewhat less so, perhaps a reflection of lower permeability. A telluric-survey profile about a kilometer east-southeast of Caldeira Velha shows an anomaly that is interpreted to reflect the position of an arcuate fault associated with caldera collapse about 15,000 years ago. The intersection of this fault with a northwest trending fault lies within the strong conductive anomaly associated with the Caldeira Velha area and is an attractive drilling target. The mirror image intersection of faults about two kilometers to the east is also an attractive drilling target but may be less accessible to a drill rig.

Audiomagnetotelluric soundings have also newly identified a conductive zone on the south flank of Agua de Pau Volcano. Gross similarity in electrical expression and geologic setting on the flank of Agua de Pau suggests the potential for a hydrothermal system that may broadly be the mirror image of that on the north flank of the volcano. However, this "discovery" is based on only a few soundings, and additional studies are necessary to evaluate the extent and significance of the conductive zone.

FURNAS VOLCANO

Furnas Volcano is built on a 1- to 4-million-year-old volcanic complex that forms approximately the east fifth of Sao Miguel. The contact between Furnas and these older lavas is exposed along the coast near Ribeira Quente and along the base of the walls of Furnas caldera. Xenoliths of the older lavas are locally common in pyroclastic deposits erupted from Furnas.

Furnas Volcano is late Pleistocene and Holocene in age and some of its oldest lavas, exposed in caldera walls and in sea cliffs near Ribeira Quente, have yielded potassium-argon ages of about 48,000 and 93,000 years b.p., respectively. Charcoal collected at various levels in trachyte pyroclastic rocks stratigraphically above these lavas has yielded carbon-14 ages that range from greater than 33,000 to about 22,000 years b.p.

Eruption of at least 7 cubic kilometers of trachyte pumice resulted in caldera formation about 12,000 years ago. This eruption generated pyroclastic flows, parts of which are preserved locally as welded tuffs on the south, east, and north flanks of the volcano. The caldera is about 6 km in diameter (Fig. 6), and its rim ranges from about 300 m to 400 m high on the west, north, and east; the rim is buried by post-caldera trachyte on the south and also is breached on the south by the canyon of Ribeira Quente. Trachyte domes and pyroclastic cones that immediately postdate caldera formation are, at least in part, about 11,200 radiocarbon years old. At least eleven intracaldera trachytic pyroclastic eruptions, in 4 instances associated with dome growth, have occurred during the past 10,000 years. Carbon-14 age determinations indicate that one of these eruptions was about 2,900 years ago, another about 1,100 years ago, and four others during the past 1,000 years. The most recent of these was in A.D. 1630.

Mafic lavas have been erupted on the flanks of the cone throughout the history of Furnas, but none have been erupted within the caldera. This fact, and the history of frequent eruptions of trachyte during the past many thousands of years indicate the persistence of a reservoir of trachytic magma beneath the caldera area. The situation, in terms of an extant crustal magma reservoir and the relations between mafic and silicic magmas, is entirely analogous to that described for Agua

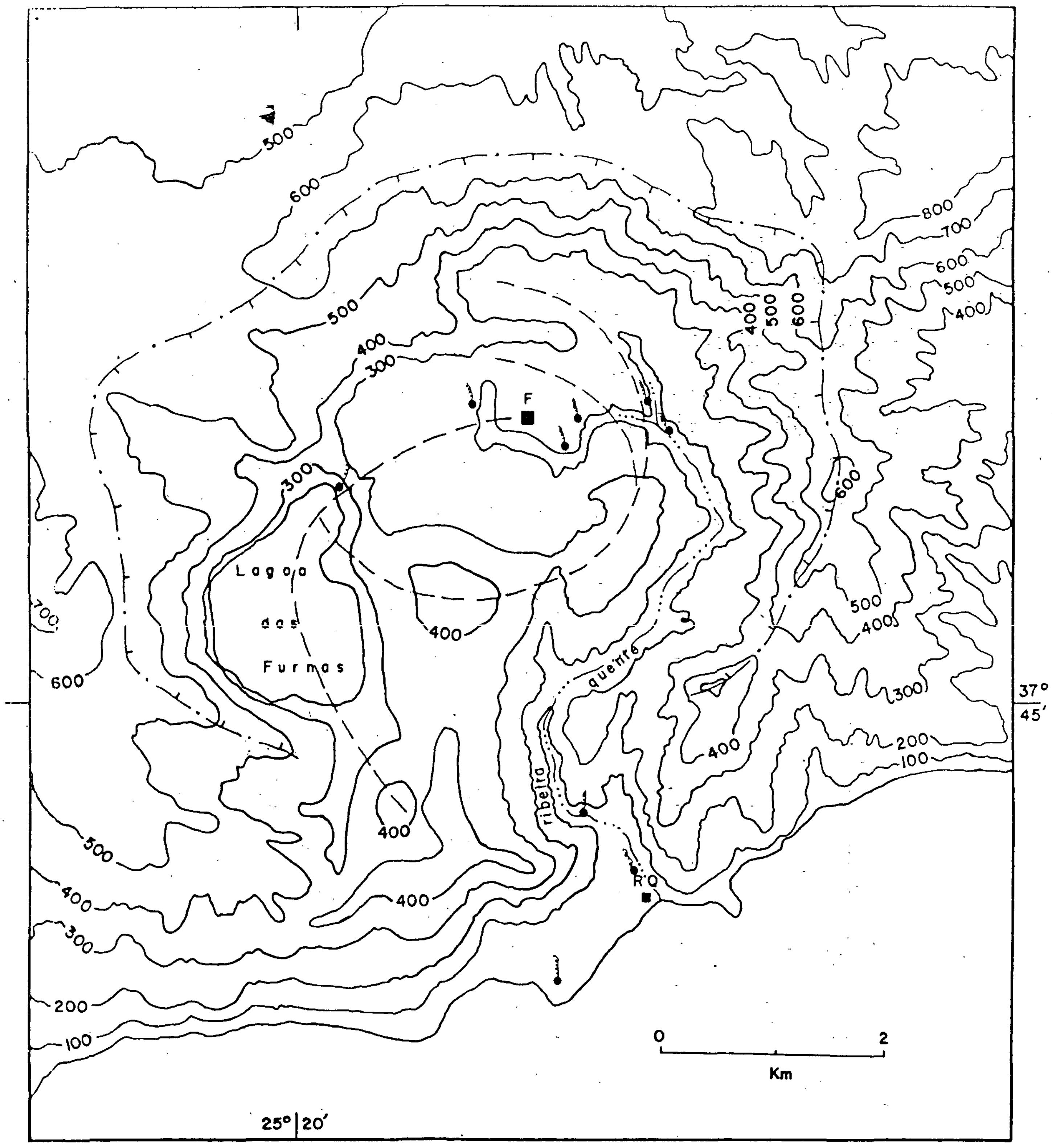

Figure 6. Topographic map of Furnas Volcano. Contour interval is 100 meters. The dash-dot-dash hachured line marks the topographic rim of the caldera. The dashed lines mark fault zones inferred from the distribution of vents for post-caldera eruptions and from the physiography of the caldera. Thermal manifestations are marked by black dot-with-pigtail symbol. F=town of Furnas. RQ=town of Ribeira Quente.

de Pau Volcano in the preceding section.

Thermal springs and fumaroles are abundant within the caldera and are concentrated at the north end of Lagoa das Furnas, within the town of Furnas, and along the course of Ribeira Quente (Fig. 6). The chemical characteristics of these thermal manifestations are quite varied and indicate that thermal water from an underlying hydrothermal-convection system wells upward, boils, and mixes with shallow groundwater. Thus, at the surface, depending principally upon local hydrologic conditions, one may find fumaroles that emit steam and associated gases from the underlying convection system, thermal springs that represent local shallow groundwater heated by such steam, or thermal springs that represent a mixture of geothermal water, condensed geothermal steam, and local shallow groundwater. Application of chemical geothermometers appropriate to these different types of thermal fluids indicates a minimum subsurface temperature of about 210 to 230 degrees Celsius and an actual reservoir temperature that may be as high as 300 degrees Celsius.

Audiomagnetotelluric soundings outline several subsurface conductive zones within the caldera. In general, these conductive zones encompass areas of thermal manifestations. Highly conductive material beneath the thermal area at the north end of Lagoa das Furnas may simply reflect a local anomaly associated with the manifestations, although a broader underlying conductive zone may also be present. A conductive zone beneath the south shore of Lagoa das Furnas is not associated with surface thermal features and may indicate an anomaly of more than local significance. In general, the east and southeast sectors of the caldera are more conductive than other parts. Interestingly, a magnetic low, which may reflect the effects of hydrothermal alteration, is broadly coincident with this area of the caldera, and we suggest that further geoelectrical studies occur here, if any are undertaken. Though many more soundings are needed to provide complete coverage of the caldera floor, the existing data are consistent with the hypothesis that a single, large hydrothermal-convection system underlies most of the caldera. The presence of several thermal springs along the south coast near the town of Ribeira Quente suggests that outflow from this system is largely directed southward across the breached wall of the caldera.

Geothermal development in Furnas caldera may be undesirable for environmental reasons. A tourist industry thrives around the many spectacular thermal manifestations within the caldera, where the ambiance is one of tranquility and scenic beauty undisturbed by industrial development. Experience elsewhere in the world (for example, in New Zealand, Italy, and the United States) has shown that exploitation of a hydrothermal-convection system can cause such associated natural manifestations as hot springs and fumaroles to change character; flow at hot springs may decrease and eventually cease in response to exploitation of a hydrothermal-convection system that feeds them, and fumaroles may become more vigorous as drawdown of a system exposes deeper and therefore hotter rock to the boiling interface between hot-water and vapor-dominated parts of the system. Thus, if development proceeds anywhere within the caldera the possibility that long-term production through well bores might affect the character of the natural manifestations should be considered.

SETE CIDADES VOLCANO

The oldest subaerial rocks of Sete Cidades Volcano are trachyte domes and flows exposed in the caldera wall and in sea cliffs along the west and south coasts. A flow at the base of the northwest sector of the caldera wall has yielded a potassium-argon age of 210,000 years b.p. and a flow along the west coast has yielded a potassium-argon age of 74,000 years b.p. Intercalated flows of mafic lavas and trachytic pyroclastic deposits overlie these oldest exposed rocks, and charcoal from several levels within this sequence yields carbon-14 ages that are all greater than about 30,000 years b.p. - too old for definitive results by the carbon-14 method. About 20,000 years b.p. a 4.5-km-wide caldera (Fig. 7) formed in response to eruption of at least 6 cubic kilometers of trachyte pumice. Locally welded pyroclastic flows of this caldera-forming event crop out in the 180-degree west sector of the caldera wall and on the south and west flanks of the volcano; most of this deposit, however, is covered by post-caldera pumice and lavas.

Post-caldera trachyte domes, flows, and pumice rings are abundant on the west flank of the volcano and within the caldera. At least 22 post-caldera trachytic eruptions occurred from vents within the caldera. One eruption produced a dome, and all others produced pumice rings and associated air-fall pumice deposits. Carbon-14 age determinations indicate that the youngest 14 of these eruptions range in age from about 5,000 years b.p. to 660 years b.p. Five prominent vents for these eruptions lie along a semi-circular arc in the west part of the caldera floor and may be localized along a ring fault that formed during caldera collapse. Lagoa Azul and Lagoa Verde may occupy craters that mark other vents, thus defining a 360 degree ring fracture.

Similar to Agua de Pau and Furnas Volcanoes, mafic lavas were erupted intermittently throughout the history of Sete Cidades and comprise a considerable part of the volcanic edifice. At least 35 such eruptions have occurred in post-caldera time, but no basaltic vents are known within the caldera. The implication of this distribution of mafic vents in terms of an extant crustal reservoir of trachytic magma beneath the caldera is the same as that described for both Agua de Pau and Furnas. A potent derivative magmatic heat source apparently lies within the crust beneath each of the three calderas.

Such thermal manifestations as hot springs and fumaroles are not known within Sete Cidades caldera. Only two thermal springs

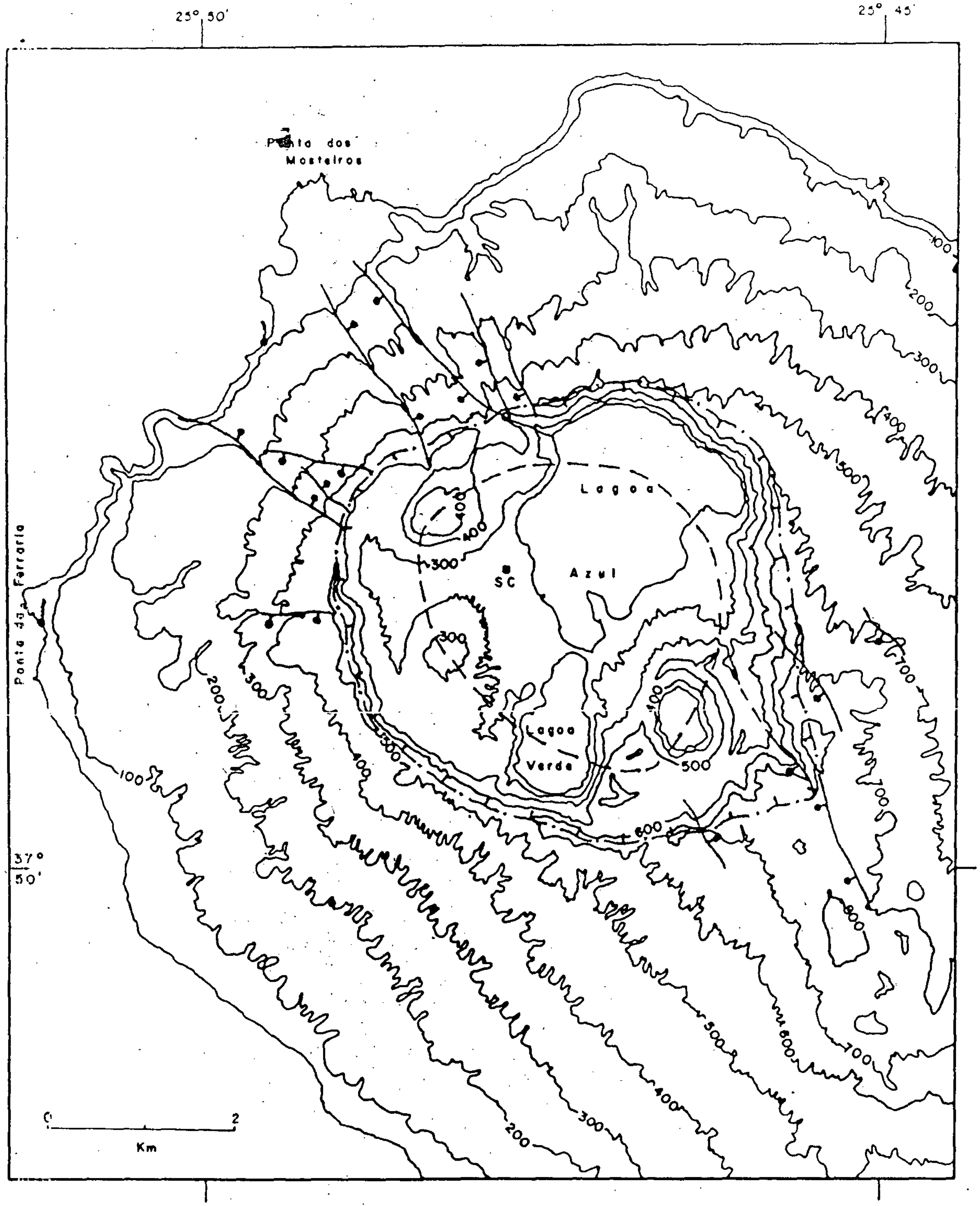

Figure 7. Topographic map of Sete Cidades Volcano. Contour interval is 100 meters. The dash-dot-dash hachured line marks the topographic rim of the caldera. The dashed line mark a ring fault inferred from the distribution of vents on the floor of the caldera. The solid lines mark normal faults; the ball and bar are on the downdropped side of these faults. Thermal manifestations are marked by black dot-with-pigtail symbol. SC=town of Sete Cidades.

are known on the flanks of the volcano, one on the northwest coast near Ponta dos Mosteiros and one on the west coast at Ponta da Ferraria (Fig. 7); each of these is low-temperature and highly diluted with sea water, precluding any attempts to define the temperature and composition of a geothermal-reservoir fluid through geochemical means.

The thermal spring near Ponta dos Mosteiros lies within a southeast-trending zone of normal faults that form a complex graben (hereafter called the Mosteiros graben), extending up the flank to the caldera rim. The mirror image of this fault zone has been mapped on the southeast rim of the caldera, and on projection farther to the southeast a tapering ridge marks the locus of dozens of late Pleistocene and Holocene mafic vents. Thus, Sete Cidades caldera is situated directly astride a major northwest-southeast fault zone that essentially bisects the western third of São Miguel. Though faults of this zone are not expressed directly in rocks on the floor of the caldera, the zone of projection across the caldera may be considered a potential target where one might find permeability, perhaps especially where this zone intersects the ring-fracture zone.

Geoelectrical soundings indicate that the Mosteiros graben coincides with a zone where conductive material occurs at relatively shallow depth. A similar, but less-well-defined conductive zone extends east-southeast from the thermal spring at Ponta da Ferraria to just within the caldera. Mapped faults of similar trend radiate from the caldera. Broadly speaking the entire faulted northwest flank of the volcano is relatively conductive. Our interpretation of these relations is that hydrothermal upflow occurs beneath the caldera, perhaps near the caldera wall, and at least part of this upflow leaks laterally along fault zones that radiate from the caldera. Most soundings within the caldera yield intermediate resistivities. Two soundings, however, showed low resistivities which may reflect a hydrothermal system several hundred meters below sea level.

CONCLUSIONS AND RESOURCE CALCULATIONS

The potential for the existence of commercially exploitable geothermal resources on Sao Miguel is high. The three late Quaternary silicic calderas (Agua de Pau, Furnas, and Sete Cidades), each of which has been the site of voluminous post-caldera silicic eruptions, provide assurance that a crustal magmatic (and/or hot plutonic) heat source exists beneath each volcanic center. Abundant vigorous thermal manifestations within Furnas caldera provide direct evidence of an underlying hydrothermal-convection system; geochemical evidence suggests that this system consists of hot water overlain by local vapor caps and that subsurface temperatures may be as high as 300 degrees Celsius.

Thermal manifestations and drill holes on the north flank of Agua de Pau Volcano provide direct evidence that a vigorous hydrothermal-convection system is associated with this volcanic center. Geochemical evidence suggests that the system is dominated by hot water that convects upward beneath the upper north flank of the volcanic edifice, and feeds (in the subsurface) a zone of lateral outflow that has been penetrated by drilling on lower parts of the flank, at Ribeira Grande; temperatures within the upflow zone may be as high as 300 degrees Celsius.

Direct evidence for a similarly vigorous hydrothermal-convection system at Sete Cidades is lacking, but the general geologic and geophysical relations, and the existence of two thermal springs at sea level on the flanks of the volcano suggest the presence of a hydrothermal system at some depth beneath the caldera. Upflow from such a system may be concentrated where caldera ring faults intersect faults of the northwest-trending system.

We have carried out resource calculations by the same methodology used by Johnston in his 1980 report. We have no well constrained basis to modify the reservoir volume used by Johnston for Furnas, but representative reservoir temperature indicated by our geothermometric studies (about 250 degrees Celsius) is higher than that assumed by Johnston (200 degrees Celsius), and accordingly our assessed resource is about 550 megawatts for 30 years whereas his is 450. Additional studies (for example, more thorough geoelectric conductivity mapping of Furnas caldera) are needed to further refine this resource calculation. Our new data provide no sound basis to modify Johnston's calculation of the resource associated with Sete Cidades Volcano, although the distribution of faults and electrically conductive zones defined by our studies suggests that any future geothermal exploration should be aimed toward the northwest and southeast sectors of the volcano, where fault systems intersect. We also have no sound basis to attempt to modify Johnston's resource calculation for Ribeira Grande. However, we emphasize the importance of Johnston's recognition that the reservoir there is of far more limited vertical extent than proposed by the staff of Geonomics. For the hydrothermal upflow zone between Caldeiras da Ribeira Grande, Caldeira Velha, and Lombadas on the north flank of Agua de Pau Volcano, we calculate an electrical capacity of 140 $\pm$ 70 megawatts for 30 years. Pertinent results of our calculations are summarized in Table 1. The probability distribution for electrical energy at the upflow zone on the north side of Agua de Pau Volcano is shown in Figure 8.

Table 1. Geothermal resources associated with Agua de Pau Volcano

Calculations follow the methodology of U. S. Geological Survey Circular 790 (Assessment of Geothermal Resources of the United States--1978: L.J.P. Muffler, editor; published in 1979); a detailed explanation of the methodology can be found on pages 20-28 of this Circular. Energy values for the upflow zone on the north flank of Agua de Pau Volcano are means and associated standard deviations, assuming the minimum, most likely, and maximum values of the recovery factor are 0.0, 0.25, and 0.5 respectively. Energy values for the outflow zone in the Ribeira Grande area are most likely values.

	Reservoir area (km^2)	Reservoir thickness (km)	Reservoir temperature (°C)	Reservoir thermal energy (10^{18} Joules)	Wellhead thermal energy (10^{18} Joules)	Electrical Energy MWe for 30 yrs
Upflow zone on the north flank of Agua de Pau Volcano (see Figure 4)						
	3.5[a]	1.8[b]	275[c]	4.5 ± 1.2	1.1 ± 0.3	140 ± 70
Outflow zone in the Ribeira Grande area (see Figure 4)						
Johnston	8.0	0.15[d]	200	0.6	0.15	14.3
Geonomics	8.0	2.65	200-250	?	?	200-400[e]

a. Estimated values for reservoir area: minimum 2.0 km^2, most likely 3.5 km^2, maximum 5.0 km^2
b. Estimated values for reservoir thickness: minimum 1.0 km, most likely 2.0 km, maximum 2.5km
c. Estimated values for reservoir temperature: minimum 240°C, most likely 285°C, maximum 300°C
d. Reservoir thickness constrained by temperature reversals in drill holes
e. No time interval for power production specified

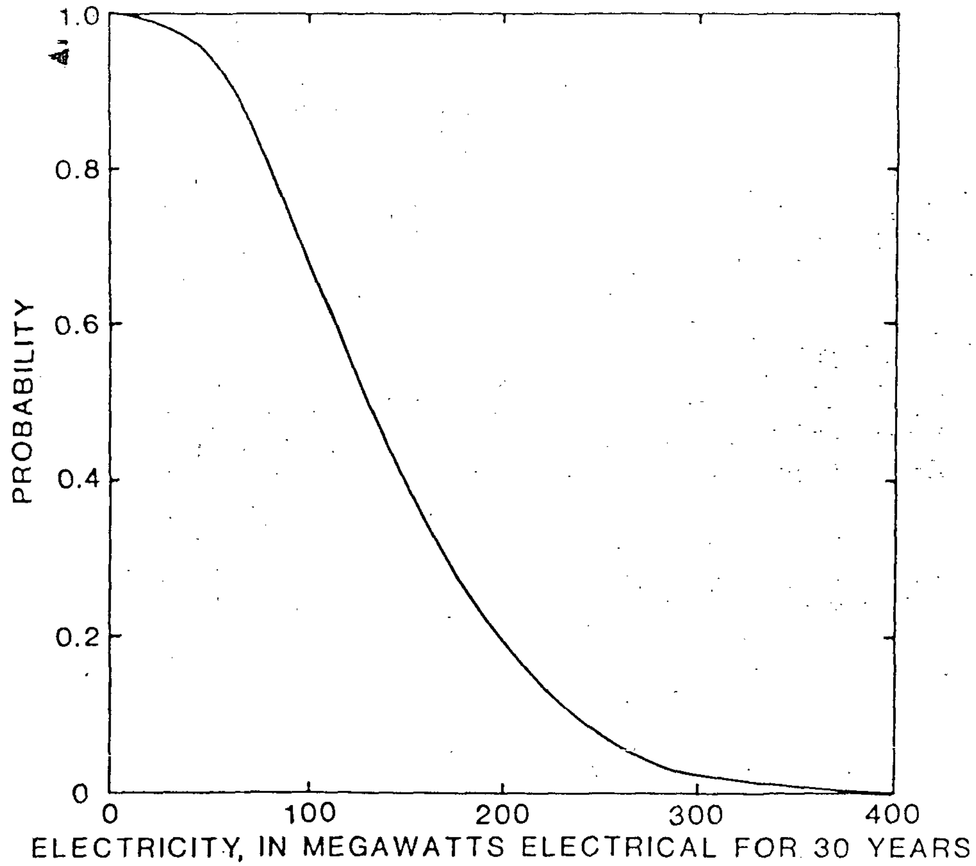

Figure 8. Probability distribution for electrical energy of the upflow zone on the north side of Agua de Pau Volcano. Vertical axis gives the probability that electrical energy is greater than or equal to a value indicated on the horizontal axis.

RECOMMENDATIONS

(1) We recommend that primary emphasis be given to the Caldeiras da Ribeira Grande, Caldeira Velha, Lombadas area, that is, the area we show as an upflow zone in Figure 4. Abundant evidence supports the hypothesis that this is a zone of hydrothermal upflow, whereas the Ribeira Grande area is fed by lateral outflow and is in this sense a secondary feature. As such the resource in the upflow zone can be expected to be hotter, far more extensive vertically, and likely at a higher pressure that can suppress the release of carbon dioxide and the concomitant deposition of calcite. The coincidence of a conductive zone and the intersection of fault zones indicates an attractive drilling target at one to two kilometers depth, about 1 kilometer east-southeast of Caldeira Velha, near an existing paved road. A similar fault intersection about two kilometers to the east is also an attractive drilling target but access by a drill rig may be more difficult.

(2) We recommend that any further development on the Ribeira Grande project be delayed until the area of Caldeiras da Ribeira Grande, Caldeira Velha, Lombadas is evaluated.

(3) Additional geoelectrical surveys on the south flank of Agua de Pau Volcano, at Sete Cidades Volcano, and at Furnas would help to better define conductive zones and structures that may provide permeable channelways for hydrothermal fluids. However, we recommend that this work be done only on a time-and-money-available basis, at a lower priority than work in the area noted in recommendation (1).

In closing we note that, given the present electrical generating capacity for São Miguel (about 20 megawatts), it is not unreasonable to expect to double this capacity with a few successful geothermal wells. Many geothermal fields in similar geologic environments at various locations worldwide produce 5 megawatts electric per well. Thus even moderate success for a project in the Caldeiras da Ribeira Grande, Caldeira Velha, Lombadas area might satisfy increased electrical energy needs for many years to come, and in doing so provide sufficient time for an orderly assessment of geothermal resources elsewhere on São Miguel and of the desirability or need to consider development at other locations on the island at some future date.