DEPARTMENT OF THE INTERIOR
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## GEOLOGIC SUMMARY

Sete Cidades Volcano, a stratovolcano with a maximum elevation of 873 m above sea level, is located on the western end of São Miguel, Azores (Zbyszewski and others, 1958). A nearly-circular caldera about 5 km in diameter, with walls up to 400 m high, truncates its summit. Geologic mapping of about 125 $km^2$ indicates that eruptive units that predate formation of the caldera crop out chiefly in the caldera walls and in sea cliffs eroded into the flanks of the volcano. Post-caldera units are trachyte cones and pumice rings distributed across the caldera floor and ankaramite, basanite, basalt, hawaiite, and minor trachyte cones and flows erupted from fissures, radial to the caldera, that may have formed at about the same time that caldera collapse occurred.

The oldest subaerial rocks of Sete Cidades Volcano are Pleistocene and include trachyte domes and flows exposed at the bases of the caldera walls and in sea cliffs on the west and south coasts. Flows of ankaramite, basanite, basalt, and hawaiite that are interbedded with trachyte pyroclastic deposits overlie the earlier trachyte domes and flows. The trachyte pyroclastic deposits include pyroclastic flows, mudflows, blast deposits, and pumice deposited during Plinian and sub-Plinian eruptions. $^{14}C$ ages of charcoal recovered from these deposits are greater than 30,000 years (M. Rubin, written commun., 1983).

Approximately 22,000 years ago, the caldera of Sete Cidades Volcano formed in response to rapid ejection of at least 6 $km^3$ of trachyte pumice. This eruption produced pyroclastic flows, locally welded, and blast deposits that were directed primarily southeast; the resulting composite deposit is more than 60 m thick 13 km southeast of the caldera, but only 5 m thick on the west flank of the volcano.

Major faulting, partly coincident with caldera collapse, formed grabens with as much as 60 m of vertical offset on the northwest and southeast flanks of the volcano. These faults are parallel to the Azores Fracture Zone (Laughton and Whitmarsh, 1975) and likely are the surface expression of a deeper structure that may have contributed to the localization of Sete Cidades Volcano. Fractures that radiate from the caldera and served as conduits for subsequent eruptions probably formed at the same time, since vents aligned along these fractures are overlain only by post-caldera deposits.

At least 22 eruptions of trachyte have occurred from vents within the caldera. Booth and others (1978) studied the products of 12 of the 14 youngest of these eruptions, from four vents. The oldest of these pumice deposits, which they designated Sete A, is about 5,000 years old; the youngest, Sete L, is 663 ± 105 years old (Shotton and Williams, 1971). The six vents in the caldera occur in a roughly circular pattern that suggests that magmas rose along a fracture, concentric to the caldera, that may have formed at about the same time that caldera collapse occurred.

At least 35 eruptions of ankaramite, basanite, basalt, and hawaiite have occurred from fissures on the flanks of Sete Cidades Volcano since the formation of the caldera. A group of post-caldera trachyte cones and flows occurs on the west flank of the volcano. The most recent mafic eruptions occurred 1,020 ± 60 years ago (Ferrarias basalt cone and flow near Feteiras) and 840 ± 60 years ago (Pico das Camarinhas ankaramite cone and Ponta da Ferraria lava delta)($^{14}C$ ages from M. Rubin, written commun., 1983). The absence of young mafic lavas within the caldera and the recent trachyte eruptions there suggest that trachytic magma may currently underlie the caldera.

## REFERENCES

Booth, B., Croasdale, R., and Walker, G.P.L., 1978, A quantitative study of five thousand years of volcanism on Sao Miguel, Azores: Philt. Trans. Roy. Soc. London, Ser. A, v. 288, p. 271-319.

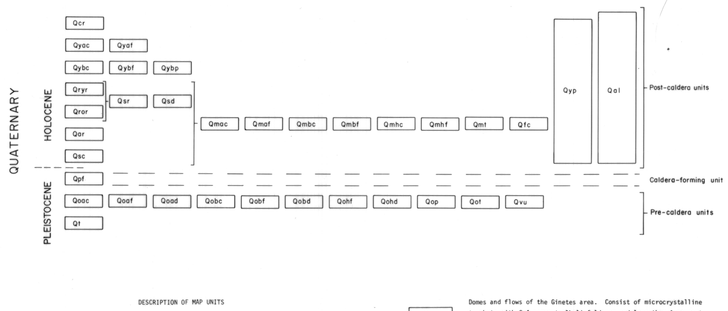
Laughton, A.S., and Whitmarsh, R.B., 1975, The Azores-Gibraltar plate boundary, In L. Kristjansson (Editor), Geodynamics of Iceland and the North Atlantic area. Reidel, Dordrecht, p. 63-81.

Shotton, F.W., and Williams, R.E.G., 1971, Birmingham University radiocarbon dates, V.: Radiocarbon, v. 13, p. 150.

Walker, G.P.L., and Croasdale, R., 1970, Two Plinian-type eruptions in the Azores: J. Geol. Soc. London, v. 127, p. 17-55.

Zbyszewski, G., Almeida, F.M. de, Ferreira, O. da V., and Assuncao, C.T. de, 1958, Carta geologica de Portugal na escala de 1:50,000: Serv. Geol. de Portugal, Lisboa.

## CORRELATION OF MAP UNITS




## DESCRIPTION OF MAP UNITS

**Qal** Alluvial, littoral, and lacustrine deposits, consisting chiefly of silt- to boulder-sized clasts of pumice and mafic and trachytic lava flows. Approximately coeval with post-caldera basaltic and trachytic deposits. Not mapped where underlying units can be recognized.

**Qyp** Widespread airfall pumice deposits, from vents within Sete Cidades caldera. Consist mainly of trachyte pumice with minor xenoliths of dense trachyte and mafic rocks. Isopachs of the 12 subunits are given in Booth and others (1978), who designated them Sete A-L. In the Mosteiros area, includes accretionary lapilli deposited during Surtseyan eruptions that formed the Ilheu dos Mosteiros. Locally includes basaltic pyroclastic deposits from adjacent vents. Extensive human modification of the surface complicates identification of the separate pumice deposits away from their source vents. Qyp mantles all pre-existing and penecontemporaneous units, except the youngest Qal; it is not mapped where underlying units can be recognized.

**Qcr** Trachyte pumice ring of Caldeira Seca. Consists chiefly of fine-grained, unstratified, poorly sorted ash with scattered large (to 30 cm) fragments of pumice. $^{14}C$ age is 663 ± 105 years (Shotton and Williams, 1971). Coeval with part of Qyp.

**Qyac** Scoria cones of Pico das Camarinhas and Arrendamento. Consist of microcrystalline to glassy ankaramite with 10-20 percent olivine, 10-20 percent pyroxene, and 3-5 percent plagioclase phenocrysts. Scattered cumulate xenoliths of gabbro, pyroxenite, and hornblendite are present. Vents erupted along a west-trending fracture, radial to Sete Cidades caldera, that may have formed at the same time that caldera collapse occurred. $^{14}C$ age is 840 ± 60 years (M. Rubin, written commun., 1983). Thinly mantled by Qyp.

**Qyaf** Aa flows from Pico das Camarinhas and Arrendamento. Consist of microcrystalline ankaramite with 10-20 percent olivine, 10-20 percent pyroxene, and 3-5 percent plagioclase phenocrysts. Scattered cumulate xenoliths of gabbro, pyroxenite, and hornblendite are present.

**Qybc** Cones of Ferrarias and Pico do Carvão. Ferrarias cone consists of glassy basalt cinders and spatter with 4-8 percent olivine, 3-5 percent pyroxene, and less than 1 percent plagioclase phenocrysts. Scattered xenoliths of gabbro are present. Carvão cone consists of glassy to microcrystalline basalt cinders with 1-2 percent olivine and less than 1 percent pyroxene phenocrysts. $^{14}C$ age of Ferrarias spatter is 1,020 ± 60 years (M. Rubin, written commun., 1983). Thinly mantled by Qyp.

**Qybf** Aa flows from Ferrarias and Pico do Carvão. Ferrarias flow consists of microcrystalline basalt with 4-8 percent olivine, 3-5 percent pyroxene, and less than 1 percent plagioclase phenocrysts. Carvão flow consists of microcrystalline basalt with 1-2 percent olivine and less than 1 percent pyroxene phenocrysts. Thinly mantled by Qyp.

**Qybp** Airfall cinders from Ferrarias and Pico do Carvão. Consist of glassy basaltic cinders. Rare xenoliths of fused syenite are present. Thinly mantled by Qyp.

**Qryr** Younger pumice ring of Lagoa Rasa. Consists of trachyte pumice deposited during Plinian and sub-Plinian eruptions centered at Lagoa Rasa. Booth and others (1978) recognized the products of ten eruptions from Lagoa Rasa and the adjacent Lagoa de Santiago vents; all are younger than their arbitrary datum, the 4,600-year-old Fogo A deposit (Walker and Croasdale, 1970). The contact between Qryr and Qror is drawn on the basis of morphologic expression, which suggests that Qryr is nested within part of Qror. Coeval with part of Qyp.

**Qror** Older partial pumice ring of Lagoa Rasa. Consists of trachyte pumice deposited during Plinian and sub-Plinian eruptions at Lagoa Rasa. Coeval with part of Qyp.

**Qsr** Pumice ring of Lagoa de Santiago. Consists of trachyte pumice deposited during Plinian and sub-Plinian eruptions centered at Lagoa de Santiago and at the adjacent Lagoa Rasa vents. An unmapped tuff deposit that crops out at lake level may be responsible for water impoundment. Coeval with part of Qyp.

**Qsd** Trachyte dome of Lagoa de Santiago, discontinuously exposed inside the crater of Lagoa de Santiago and on the northeast flank of the pumice ring (Qsr). Probably emplaced during one of the early Plinian and sub-Plinian eruptions (Sete B-F; Booth and others, 1978) that formed Qsr. Subsequent eruptions that were partly phreatic pierced and partly destroyed the dome and mantled it with trachyte pumice. Consists of microcrystalline trachyte with 8-12 percent alkali feldspar and less than 1 percent biotite phenocrysts. Coeval with part of Qyp.

**Qsr** Pyroclastic ring of Caldeira de Alferes. Consists of dense trachyte scoria and minor pumice with 3-6 percent alkali feldspar and less than 1 percent biotite phenocrysts. Despite its size (about 1.5 km in diameter) and youthful appearance, Caldeira do Alferes does not appear to have been the source of any large post-caldera pumice deposit (Booth and others, 1978); a possible explanation is that Alferes trachyte was relatively degassed, a condition manifested by the relatively dense scoria that comprises much of the ring. Interbedded with Qyp.

**Qsc** Cone of Seara Cerrado da Ladeira. Consists chiefly of trachyte pumice deposited during Plinian and sub-Plinian eruptions. Cone was built around the vent that produced the Sete A deposit of Booth and others (1978). Qsc is the oldest major post-caldera cone inside the caldera; as noted by Booth and others (1978), the age of Sete A relative to the 4,600-year-old Fogo A deposit (Walker and Croasdale, 1970) is uncertain. Stratigraphic relationships on the northwest rim of the caldera and tentative correlation of a red soil that underlies the Sete A deposit with a similar-appearing soil that underlies Fogo A on the east flank of Sete Cidades Volcano suggest that the age of Sete A and Qsc is about 5,000 years. Coeval with part of Qyp.

**Qmac** Cinder and spatter cones, consisting of glassy to microcrystalline ankaramite and ankaramitic basalt with 15-25 percent olivine, 10-25 percent pyroxene, and 1-15 percent plagioclase phenocrysts. Eguas and Mafra cones contain abundant mafic and ultramafic xenoliths; many xenoliths in the Eguas cone are lherzolites. Vents commonly erupted along fractures, radial to Sete Cidades caldera, that may have formed at about the same time that caldera collapse occurred. Interbedded with Qyp.

**Qmaf** Aa flows from Qmac. Consist of microcrystalline ankaramite and ankaramitic basalt with 15-25 percent olivine, 10-25 percent pyroxene, and 1-15 percent plagioclase phenocrysts. Mafic and ultramafic xenoliths of generally cumulus origin are abundant in the flow from Mafra that forms the lava delta in Mosteiros. Interbedded with Qyp.

**Qmbc** Cinder and spatter cones; includes maar of Lagoa do Canario. Consist of glassy to microcrystalline basalt with 1-20 percent olivine, 0-10 percent pyroxene, and 0-20 percent plagioclase phenocrysts. Scattered mafic and ultramafic xenoliths of cumulus origin are present. Vents commonly erupted along fractures, radial to Sete Cidades caldera, that may have formed at about the same time that caldera collapse occurred. Interbedded with Qyp.

**Qmbf** Aa and pahoehoe flows from Qmbc. Consist of microcrystalline basalt with 1-20 percent olivine, 0-10 percent pyroxene, and 0-20 percent plagioclase phenocrysts. Interbedded with Qyp.

**Qmhc** Cinder and spatter cones, consisting of glassy to microcrystalline hawaiite that is either aphyric or contains less than 1 percent plagioclase and biotite phenocrysts. Vents commonly erupted along fractures, radial to Sete Cidades caldera, that may have formed at about the same time that caldera collapse occurred. Interbedded with Qyp.

**Qmhf** Aa flows from Qmhc. Consist of hawaiite that is either aphyric or contains less than 1 percent plagioclase and biotite phenocrysts. The $^{14}C$ age of one flow near Feteiras is 20,890 ± 240 years (M. Rubin, written commun., 1983). Interbedded with Qyp.

**Qmt** Domes and flows of the Ginetes area. Consist of microcrystalline trachyte with 2-4 percent alkali feldspar and less than 1 percent biotite phenocrysts. Domes were emplaced along a group of west-trending fractures, radial to Sete Cidades caldera, that may have formed at about the same time that caldera collapse occurred. Flows that rafted coeval trachyte scoria extend short distances from their vents. Interbedded with Qyp.

**Qfc** Cone of Cerrado das Freiras, on the east side of Lagoa Azul. Consists of dense trachyte scoria with 3-5 percent alkali feldspar and 1-2 percent biotite phenocrysts. Interbedded with Qyp.

**Qpf** Pyroclastic flows, locally welded and oxidized; includes minor blast deposits. Consists chiefly of partly welded trachyte pumice with 5-10 percent alkali feldspar and 1-3 percent biotite phenocrysts. Discontinuously exposed, mainly on the west and south walls of the caldera and in sea cliffs on the south coast of the volcano. Thickness ranges from about 5 to 60 m. Estimated volume is about 6 $km^3$, approximately the same as that of the caldera; ejection of Qpf was the principal cause of caldera formation. The eruption apparently was directed mainly southeast, as Qpf is not exposed on the north flank of the volcano. The deposit extends at least to the southeastern boundary of the map, about 13 km from its source. $^{14}C$ age of a late pyroclastic flow that immediately overlies the major welded unit is 21,160 ± 180 years (M. Rubin, written commun., 1983).

**Qoac** Cinder and spatter cone of Pico da Cruz, on the southeast rim of the caldera. Consists of glassy to microcrystalline ankaramitic basalt with 15-25 percent olivine and 10-20 percent pyroxene phenocrysts. Cone was partly truncated during formation of the caldera. Thickly mantled by Qyp.

**Qoaf** Aa flows, consisting of microcrystalline ankaramite and ankaramitic basalt with 5-25 percent olivine, 5-25 percent pyroxene, and 0-2 percent plagioclase phenocrysts. Locally includes unmapped trachyte pyroclastic deposits. Source vents, except for Pico da Cruz (Qoac), are buried beneath younger volcanic materials. Flows crop out chiefly in sea cliffs cut into the west and south flanks of the volcano.

**Qoad** Dikes on north and southeast walls of the caldera; the latter served as the feeding conduit for the Pico da Cruz eruption. Consist of glassy to microcrystalline ankaramitic basalt with 15-25 percent olivine and 10-20 percent pyroxene phenocrysts.

**Qobc** Cinder and spatter cones on the southeast caldera wall. Consist of glassy to microcrystalline basalt with 6-12 percent pyroxene, 6-12 percent plagioclase, and 2-4 percent olivine phenocrysts. Cones were partly truncated during formation of the caldera. Thickly mantled by Qyp.

**Qobf** Aa and minor pahoehoe flows that crop out chiefly in sea cliffs cut into the flanks of the volcano. Locally includes unmapped trachyte pyroclastic deposits. Consist of microcrystalline basalt with 5-15 percent plagioclase, 1-5 percent pyroxene, and less than 1 percent olivine phenocrysts. $^{14}C$ ages of two flows are older than 30,000 years (M. Rubin, written commun., 1983).

**Qobd** Dikes on southeast wall of the caldera and in the sea cliff on the north side of Ponta da Ferraria. Consist of glassy to microcrystalline basalt with 2-15 percent pyroxene, 2-10 percent olivine, and 1-12 percent plagioclase phenocrysts.

**Qohf** Aa flows, consisting of microcrystalline hawaiite that is either aphyric or contains 1-5 percent plagioclase, 1-4 percent biotite, less than 1 percent pyroxene, and less than 1 percent olivine phenocrysts. Locally includes unmapped trachyte pyroclastic deposits. Flows crop out chiefly on the caldera walls and in sea cliffs cut into the flanks of the volcano. $^{14}C$ age of one flow is older than 30,000 years (M. Rubin, written commun., 1983).

**Qohd** Dikes on the north and southeast walls of the caldera. Consist of microcrystalline hawaiite that is either aphyric or contains 1-3 percent pyroxene, 1-3 percent plagioclase, and 1-2 percent biotite phenocrysts.

**Qop** Trachyte pyroclastic deposits, chiefly pyroclastic flows, mudflows, and pumice deposited during Plinian and sub-Plinian eruptions; includes minor ash, blast deposits, and lacustrine sediments. Locally interbedded with thin ankaramite, basanite, basalt, hawaiite, and trachyte flows that are not mapped. Unit crops out chiefly in the caldera walls and in sea cliffs cut into the flanks of the volcano. $^{14}C$ ages from several different pyroclastic flows within Qop, including those at the base and top of the map unit, are older than 30,000 years (M. Rubin, written commun., 1983).

**Qot** Aa flows, consisting of microcrystalline trachyte with 1-8 percent alkali feldspar and 1-4 percent biotite phenocrysts. Flows crop out in the walls of the caldera. Charcoal in a pyroclastic flow (Qop) that immediately overlies a Qot flow on the south caldera wall has a $^{14}C$ age in excess of 30,000 years (M. Rubin, written commun., 1983).

**Qvu** Volcanic rocks of the northeast wall of Sete Cidades caldera, undivided. Unit is inaccessible but appears to consist of interbedded trachyte pumice of Qop and aa flows of Qoaf, Qobf, and Qohf.

**Qt** Domes and flows that crop out chiefly at the bases of the caldera walls and in sea cliffs cut into the west and south flanks of the volcano. Consist of microcrystalline trachyte with 1-15 percent alkali feldspar and 1-2 percent biotite phenocrysts. Includes minor older trachyte pumice and hawaiite flows in sea cliffs at Relva Velha and about 1.5 km southeast of Ponta da Fonte Grande. A flow at Ponta da Ferraria has a K-Ar age of 74,000 ± 6,000 years, and a flow at the base of the north caldera wall has a K-Ar age of 210,000 ± 8,000 years (E.H. McKee, written commun., 1983).

## GEOLOGIC MAP SYMBOLS

- Contact, approximately located
- Normal fault, ball on downthrown side; locally mantled by Qyp
- Eastern map boundary
- Caldera boundary, approximately located
- q/y Relatively older and younger units of same age classification, at location where relationship is demonstrable

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# PRELIMINARY GEOLOGIC MAP OF SETE CIDADES VOLCANO, SÃO MIGUEL, AZORES

by Richard B. Moore

1983

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