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Seismic tomography of Central São Miguel, Azores

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ABSTRACT

We determine the three-dimensional distribution of P- and S-wave velocities for Central São Miguel Island (Azores, Portugal) by tomographic inversion of local earthquake arrival times. We use P- and S-phases from 289 earthquakes recorded by a network of 20 seismometers. The model shows good resolution in the shallowest 5–6 km, as illustrated by different resolution tests. There are several velocity anomalies, interpreted as pyroclastic deposits, intrusive bodies, geothermal fields, and the effects of tectonics. A low Vp zone marks Furnas caldera, probably evidencing volcaniclastic sediments with development of intense geothermal activity. Another low Vp zone extends in correspondence of the highly fractured area between Fogo and the north coast. Conversely, strong positive anomalies are found south of Fogo and northwest of Furnas. They are interpreted in terms of high-density deposits and remnants of a plutonic intrusion. These interpretations are supported by the distribution of Vp/Vs, and are consistent with previous geological, geochemical, and geophysical data.

1. Introduction

The Archipelago of Azores consists of nine volcanic islands located at about 38°N–28°W, in the triple junction zone among the American, Eurasian, and African plates. The largest island is São Miguel (Fig. 1). The structure of São Miguel is characterized by fault systems mainly trending NW-SE and E-W. The most important volcanic complexes are located at the intersection of these tectonic lineaments (see Cruz, 2003 and references therein). In Central São Miguel, the main volcanic structures are those of Fogo and Furnas. Both are central volcanoes with a summit caldera and a dominantly trachytic composition. Furnas is the youngest volcano and consists of a steep-sided, 8 km ×5 km caldera complex formed during several collapses (Guest et al., 1999). In the last 3000 years, most eruptions were phreato-magmatic and occurred with an average recurrence interval of 320 years (Moore et al., 2001). The Fogo volcanic edifice rises to an elevation of ∼ 1000 m above sea level, and is composed by lava flows, domes and pyroclastic deposits over an older submarine lava basement. See, for example, Guest et al. (1999) for a detailed description of the geology of the area.

Although Central São Miguel volcanoes have not erupted since the 17th century, the area is restless. Geothermal manifestations are conspicuous and constitute one of the most important present day indications of volcanism. Geothermal exploration and research evidence two main active fields, in the Ribeira Grande-Fogo and Furnas regions. In these fields, local tectonics seem to control subsurface flow and the alignment of fumaroles and thermal springs (Ferreira and Oskarsson, 1999). The most intense thermal activity coincides with an E-W tectonic lineament in Furnas and a NW-SE fault system in Fogo (Cruz, 2003). At Ribeira Grande, the geothermal field is possibly connected to a reservoir between Fogo and the northern coast, hosted by highly fractured, pyroclastic rocks (Muecke et al., 1974; Gandino et al., 1985; Carvalho et al., 2006). The heat source, especially for deeper levels of the field, could be a regional heat anomaly (Silveira et al., 2006; Ritsema and Allen, 2003). At Furnas, the heat source is probably the plutonic remnants of the most recent volcanism below the center of the caldera, although there are no clear signs of direct magmatic contribution in the discharge composition (Cruz et al., 1999).

To study the structure related to the volcanic activity of the island, several investigations have been carried out. Camacho et al. (1997) performed a gravimetric study of São Miguel island to determine the density distribution in the first kilometers. At depths

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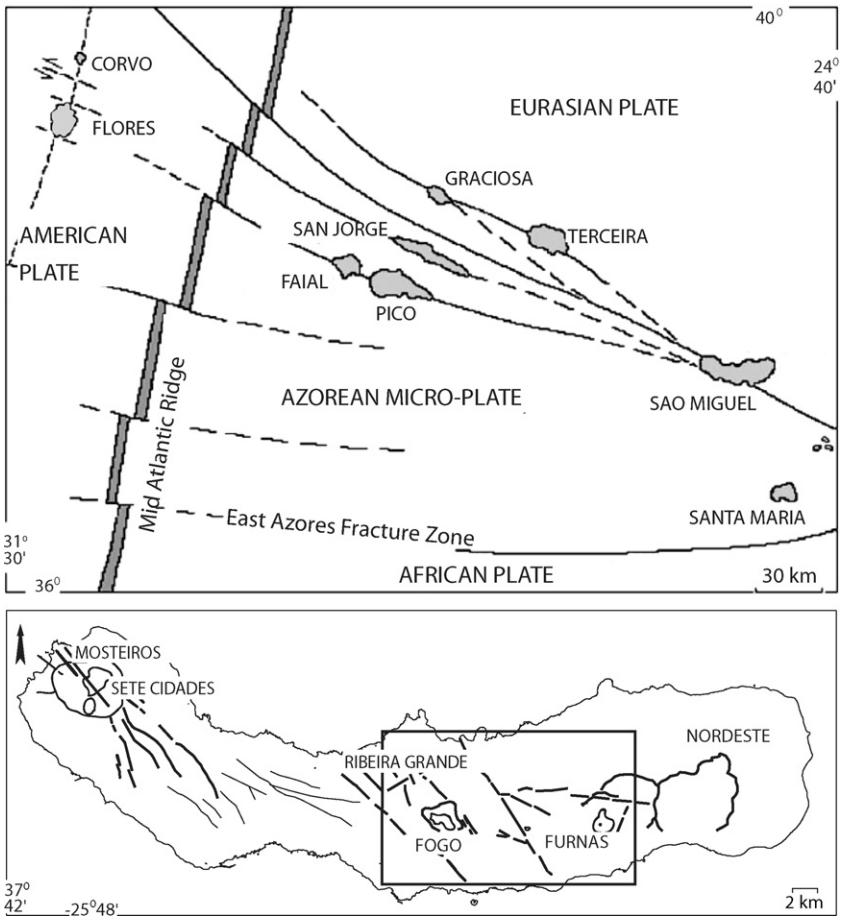

Fig. 1. (Top) Regional map showing the location and main tectonic features of the Azores Archipelago. (Bottom) São Miguel map with names of the most prominent regions. The box corresponds to the area selected for the study.

around 8 km, the areas around Fogo and Furnas show two density minima separated, in Congro zone, by a high-density region that shows a NE-SW trend. It extends to shallow depths (still present at 1 km) and has been interpreted as an old basaltic shield or a partly solidified magmatic body. Montesinos et al. (1999) focused on the gravimetric low-density anomaly of Furnas area. At shallow levels, this anomaly is interpreted as low-density silicic caldera infill, mainly due to collapse processes, and volcanic products from several eruptions which occurred after the formation of the main caldera from radial and concentric fractures. Deformation and GPS measurements performed at Central São Miguel have revealed a slight inflation of the Furnas area (Sigmundsson et al., 1995). An explanation refers to the presence of fluids within a deep hydrothermal system beneath the caldera, sealed by an impermeable zone and forced to growing pressures. At Fogo, GPS stations show displacements toward the caldera, indicating a slight deflation of the volcano (Jónsson et al., 1999). This deflation could be due to a pressure decrease in the magma chamber, or to the extraction of water and steam by a nearby geothermal power plant.

In the last years, thousands of earthquakes have been annually recorded and located around São Miguel island by the regional seismic network. Their origin is mostly related to the approximately WNW-ESE fault systems dominating the regional tectonics (e.g. Udías et al., 1976; Madeira and Ribeiro, 1990). Central São Miguel is crossed by different fault systems, trending NW-SE and E-W, and constitutes one of the most active seismogenic regions in the Azores (e.g. Gongora et al., 2004; Escuer, 2006). This observation is compatible with the focal mechanisms calculated in the area (Udías et al., 1976; Buforn et al., 1988) and the strike-slip faulting observed in the bathymetry (Lourenço et al., 1998).

The local seismic network evidences that a substantial number of the earthquakes are swarms of local, low-magnitude earthquakes located in the area between Fogo and Furnas (D. Silveira, personal communication). Although the tectonic control seems important, a recent work by Luis (2006) suggests that these swarms are not generated by a tectonic-driven mainshock/aftershock mechanism. The most likely explanation is that Central São Miguel earthquake swarms have a volcano-tectonic origin.

Inhabited volcanic areas, where even a small eruption could produce considerable losses, pose important problems in terms of hazards. This consideration motivated an European Union-sponsored project (named *e-Ruption*) intended to quantify the present-day seismicity of various quiescent volcanoes in populated regions (Saccorotti et al., 2004). One of the selected sites was Central São Miguel, where a seismic survey was carried out in April–July 2003. In this paper, seismic data recorded in that experiment are used to determine the three-dimensional (3D) velocity structure of the central region of São Miguel. This work represents a first attempt to establish the relationship between seismic velocity distribution and volcanic structures in São Miguel Island.

2. Instruments and data

Between April 4 and July 15, 2003, a temporary network including short-period and broad-band instruments, as well as three small-aperture seismic antennas, was deployed in São Miguel