HIGH-RESOLUTION MAGNETIC AND GAMMA-RAY AIRBORNE SURVEY
AT SOCORRO ISLAND, MEXICO
V. Paoletti\textsuperscript{1}, M. D’Antonio\textsuperscript{1}, R. Supper\textsuperscript{2}, S. Gruber\textsuperscript{2}, K. Motschka\textsuperscript{2}
\textsuperscript{1} Dipartimento di Scienze della Terra, dell’Ambiente e delle Risorse, University Federico II, Naples, Italy
\textsuperscript{2} Geological Survey of Austria, Vienna, Austria

Introduction. The Island of Socorro (Fig. 1) is located 700 km off the western coastline of Mexico at the northern Mathematicians Ridge, an abandoned mid-ocean ridge spreading centre. Together with several other islands (e.g., San Benedicto and Clarion) and numerous seamounts, the so called Revillagigedo archipelago represents post-abandonment alkaline magmatism [e.g., Taran \textit{et al.} (2002) and references therein]. The last volcanic event in the area of Socorro took place in 1993 (e.g., Siebe \textit{et al.}, 1995), when a submarine basaltic eruption threatened the small settlement on the island. Until today, due to the remote location of the island, little knowledge is available concerning the subsurface structure of the volcanic edifice.

In support of plans of the Mexican government to enlarge the settlement on the island, a combined geophysical survey was conducted in February 2009 to open up new resources for local groundwater supply. Investigations were focused on determining the resistivity structure of the shallow subsurface of the volcanic edifice, as this parameter is directly related to the water content of subsurface structures. However other parameters such as clay content, fluid conductivity and temperature control the subsurface resistivity and these parameters normally show significant variations in volcanic areas. Thus, we conducted other investigations/analyses over the island, such as airborne magnetic, electromagnetic and gamma-ray measurements in order to have an overall view of the main structural/lithological features of the island.

The aim of this work is to retrieve information about the surface and subsurface geology of the island based on the analysis and interpretation of magnetic and gamma-ray airborne data, integrated with available geo-volcanological information.

Fig. 1 – Geologic sketch-map of Socorro Island (Carballido-Sanchez, 1994).
**Geo-Volcanological Outlines of Socorro.** Socorro Island is located in the eastern Pacific Ocean at 18°47’N and 110°58’W, 700 km off the coast of mainland Mexico at the intersection of the Clarion Fracture Zone and the Mathematician Ridge System. With an extent of 130 km² it is the largest island of the Revillagigedo Archipelago, which consists of the four islands Socorro, Clarión, San Benedicto and Roca Partida, all of them being volcanic in origin. These four islands as well as a group of several seamounts make up the Mathematician Ridge, an abandoned mid-ocean ridge spreading centre which was active from 6.5 Ma to 3.15 Ma before present (Siebe et al., 1995).

Socorro Island is the emergent portion of a large shield volcano, Volcán Evermann, which rises from the seafloor at a depth of about 3 km to the summit of the volcano at 1050 m above sea level (Carballido-Sanchez, 1994) and has a submarine slope of a little less than 10 degrees (Siebe et al., 1995). With a basal radius of 24 km and the assumption that the volcano is a perfect cone, the total volume of the volcano makes up approximately 2400 km³. Hence the subaerial portion of Volcán Evermann makes up about 2 vol. % of the total edifice.

Volcanism in the Revillagigedo Archipelago produced primarily alkali olivine basalts, followed by eruptions of soda-rich rhyolite (Siebe et al., 1995). Therefore, Volcán Evermann could be better described as a composite volcano, with an early shield-building stage, characterized by basaltic effusive eruptions, and late extensive pyroclastic peralkaline eruptions (Carballido-Sanchez, 1994). The domination of subaerial silicic peralkaline eruptions makes Socorro Island virtually unique in the Pacific Ocean. Peralkaline volcanic rocks show a molar excess of (Na₂O + K₂O) over Al₂O₃ whereas the opposite characteristic is usual in the Earth’s crust (Carballido-Sanchez, 1994). Samples from Socorro Island have a peralkalinity index, i.e. molar (Na₂O + K₂O)/Al₂O₃, of 1.1 – 2.2 (Bohrson and Reid, 1998). According to Carballido-Sanchez (1994), almost 90% of the peralkaline products on Socorro Island are of pantelleritic composition. It is supposed that peralkaline rocks make up 80-90% of the total subaerial volume of rocks exposed on Socorro Island. With the assumption that the submarine portion of the volcano is composed mainly of basalts, peralkaline rhyolitic rocks make up only 1.5 vol. % of the volcanic edifice. Only little is known about the submarine part of the volcano.

The eruptive history of Socorro Island has been divided into pre-, syn- and postcaldera stages (Bohrson et al., 1996), whereas the postcaldera stage has been subdivided by Bryan (1966) into Cerro Evermann eruptives and Lomas Coloradas eruptives. A geological sketch-map of the island (Carballido-Sanchez, 1994) is shown in Fig. 1.

The bulk of the volcanic edifice, which is submarine, erupted before the formation of a small caldera and is basaltic in origin. The precaldera units on Socorro Island erupted in two episodes of activity. The first episode of eruptions was mainly effusive. The volcano built up from the seafloor, which corresponds to the shield-building stage of volcanism. The second stage of precaldera activity was dominated by explosive eruptions and deposition of peralkaline pyroclastics (Carballido-Sanchez, 1994). The oldest subaerially exposed units of Socorro Island are precaldera alkaline basalts to comendites, which are confined to the base of a sea cliff at the eastern part of the island (Bohrson and Reid, 1998; Taran et al., 2002). Most of the subaerially exposed pre- and syncaldera rocks are silicic peralkaline ignimbrites, which are commonly holocrystalline non-vesicular lava-like deposits that lack inclusions or lithic fragments (Bohrson et al., 1996). These authors found some evidence that silicic pre- and syncaldera phases on Socorro Island were dominated by explosive eruptions with low eruption columns. The products of pre- and syncaldera activity range in age between 540 and 370 ka.

The remainder of a former caldera wall can be found on the southeastern side of the summit at approximately 600 m elevation. The size of the steep escarpment is consistent with a former caldera dimension of about 4.5 x 3.8 km, which is typical for peralkaline volcanoes (Bohrson

---

1 Pantellerite: peralkaline rhyolite, FeO-richer than comendite
2 Comendite: peralkaline rhyolite less FeO-rich than pantellerite
et al., 1996). Caldera formation occurred probably around 370 ka and was followed by up to 200 kyr of quiescence. The presence of a small summit caldera on Socorro suggests that the silicic magma reservoir was shallow, probably located within the volcanic edifice or the upper oceanic crust. Caldera formation was followed by a change in eruptive style from predominantly explosive to predominantly effusive (Bohrson et al., 1996).

Rocks of the postcaldera stage had been subdivided into the Cerro Evermann Formation and Lomas Coloradas Formation, which erupted between 180 and 15 ka (Cerro Evermann) and 150 and 70 ka (Lomas Coloradas), respectively (Bohrson et al., 1996). Rocks of the Cerro Evermann Formation are pyroclastics, lava flows, and lava domes of peralkaline composition, exposed in the caldera and at the northern, western and southern flanks of the volcano. These are primarily trachytes, comendites and pantellerites (Carballido-Sanchez, 1994). The lava flows and cinder cones of the Lomas Coloradas Formation are exposed at the south-eastern part of the island and are composed of basalt, hawaiite and mugearite (Carballido-Sanchez, 1994). Eruption of peralkaline-rhyolitic and basaltic magmas during the same time interval of post-caldera phase has been explained by a stratified magma chamber composed of soda-rhyolite overlying basaltic magma (Siebe et al., 1995).

Morphologically, the subaerially exposed rocks on Socorro Island can be classified as lava-flows, domes, pyroclastic flows, air-fall pyroclastics and cinder cones. The lava-flows on Socorro Island can be of both basaltic and peralkaline composition, whereas the pyroclastic flows are exclusively peralkaline (Carballido-Sanchez, 1994). Cinder cones are generally basaltic in composition (except for one) and are confined to the Lomas Coloradas unit. The domes, on the other hand, are exclusively peralkaline. Air-fall pyroclastics are both peralkaline and basaltic, whereas the basaltic ash, cinder, spatter and bomb deposits are all (except for one deposit in the Bahia Academy area) restricted to the Lomas Coloradas area (Carballido-Sanchez, 1994).

Bryan (1966) identified three major zones of fractures that intersect on Socorro Island. One zone has a north-south orientation and extends from the summit of Volcán Evermann to Bahia Academy, which is located in the northern part of the island. A second zone is orientated in east-west direction and extends from the western coast of the island (Cabo Henslow, Punta Tosca, Caleta Grayson) to the summit area of Volcán Evermann. The third zone is located in the southern part of the island and shows approximately NW-SE orientation.

Bohrson and Reid (1997) found three different conditions that are required for the formation of silicic peralkaline magmas: a mildly extensional tectonic setting, a shallow magma reservoir and availability of parental transitional to mildly alkalic basalt. The formation of silicic peralkaline magmas can be explained by three different mechanisms: fractional crystallization of transitional to mildly alkalic basalt, partial melting of mafic intrusive rock and volatile complexing and transport in association with one of these (Bohrson and Reid, 1997). According to these authors, the most likely mechanism of silicic peralkaline magma formation for Socorro Island is a moderate degree of partial melting of intrusive alkalic basalt and associated crystal cumulates followed by crystal fractionation.

Calculation of eruption rates for submarine and subaerial parts of the volcanic edifice suggests that either subaerial eruption rates are less than submarine eruption rates, or the growth of the volcano has continued to be dominantly submarine. Comparison of eruption rates of other isolated ocean islands suggests that the source of alkaline magmatism associated with Socorro may be consistent with a mantle plume (Bohrson et al., 1996).

Volcanic activity on Socorro Island has continued to the present. The first historically reported eruption took place in 1848, but no detailed description of the event exists. Another eruption was observed in 1896, but also no further information on the eruption is available. Further small eruptions were reported in 1947 and 1951. The so long last eruption occurred in 1993 and was submarine. At the moment, fumarolic activity can be observed near the summit of Volcán Evermann (Carballido-Sanchez, 1994).
Siebe et al. (1995) carried out a geochemical study on the 1993 submarine eruption near Socorro Island. Further work was done to investigate the genesis of silicic peralkaline magmas (Bohrson et al., 1996; Bohrson and Reid, 1998). In 1999, a seismic survey was carried out in the south-eastern part of Socorro Island with the use of five portable broadband seismometers (Valenzuela et al., 2005). The intention was to install a seismic T-phase station on Socorro, as part of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). The geochemistry of hydrothermal fluids on Socorro was investigated by Taran et al. (2010).

The airborne geophysical and ground geoelectric survey of the Geological Survey of Austria (GSA) in 2009 was the first detailed geophysical survey on Socorro Island.

**Airborne and Gamma-ray Survey at Socorro.** Airborne geophysics has been intensively applied for exploration of raw materials within the last decades, however so far it was hardly ever used to investigate the groundwater resources of volcanic islands. One of the big advantages of airborne geophysical measurements is that large areas can be surveyed within relatively short survey times. Furthermore, airborne geophysics is the only remote sensing method yielding information not only about the surface but also about the subsurface structures.

To perform the airborne measurements we used the complex airborne system of the Austrian Geological Survey (Motschka, 2001). Its instrumentation consists of a frequency domain electromagnetic bird operating at four different frequencies, a magnetic sensor and a gamma spectrometer. Positioning was performed using the data of a laser altimeter, two differential GPS sensors and flight path recordings from a downward looking digital video camera. For correction of altitude raw values for variations in vegetation thickness we employed advanced algorithms. The survey covered an area of 200 km², with an average line spacing of 100 m. The use of the electromagnetic system required the distance between terrain and sensor (“bird”) to be less than 100 m, in order to yield a reliable subsurface resistivity mapping.

**Airborne Magnetics.** With this methodology the total intensity of the Earth’s magnetic field is measured. Deviations from a reference earth magnetic field (IGRF) are considered as anomalies and assist e.g. in the discovery of differently magnetized bodies (i.e. ore bodies, young volcanic rocks, metallic contents of waste repositories) or fracture zones. The results are given in Fig. 2, which shows a high resolution map of the magnetic field anomalies reduced

![Fig. 2 – Preliminary interpretation of the pole-reduced magnetic data: magnetic lineaments and structures.](image)
to the pole. Interestingly, the central part of the map, corresponding to the of the summit of the island, shows a very large negative anomaly which is extended to the eastern part of the island. A preliminary DEXP analysis of magnetic data (Fedi, 2007) pointed out the presence of a low magnetization volume, which may be connected to: may be connected to: a high temperature (above the Curie temperature) in the deeper part of the volcano, a low total remanent magnetization of pyroclastic caldera sediments due to non-aligned sedimentation, and/or the influence of hydrothermal alteration within the caldera. In the latter case the caldera structure would extend further to the southern part of the island than assumed before.

Gamma-ray spectroscopy. This methodology determines the natural and artificial radioactivity, which depends on the content of radioactive minerals within the first decimeters of the subsurface. Natural gamma radiation is essentially derived from three sources: the radioactive elements thorium (energy peak: 2.62 MeV), uranium (energy peak: 1.76 MeV) and potassium (energy peak: 1.46 MeV). These elements occur in different rocks and soils at various concentration levels. The measuring sensor consists of several sodium-iodide crystals, which convert gamma radiation into flashes of light. Appropriate survey instruments determine their energies. With conventional measuring systems the energy spectrum between 0.2 to 6.0 MeV is resolved in 256 channels.

Since the air layer between helicopter and ground is absorbing gamma radiation (depending on the physical condition of the air), the exact flight altitude, air pressure, air temperature as well as air moisture have to be taken into consideration when correcting survey data.

Prior to processing, data were inspected for incorrect values and in particular all samples which were taken at altitude higher than 400 m were deleted.

The following calibration constants and coefficients were used for the processing of gamma-ray data of Socorro Island (Tab. 1):

<table>
<thead>
<tr>
<th>Aircraft Background</th>
<th>K40</th>
<th>U238</th>
<th>Th232</th>
<th>TC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic Background</td>
<td>0.083</td>
<td>0.043</td>
<td>0.059</td>
<td>1.9</td>
</tr>
<tr>
<td>Attenuation by air</td>
<td>-0.0057333</td>
<td>-0.0058056</td>
<td>-0.0070921</td>
<td>-0.0061463</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>47.2</td>
<td>7.3</td>
<td>3.4</td>
<td>29.5</td>
</tr>
<tr>
<td>Stripping Coefficients</td>
<td>0.2</td>
<td>0.26</td>
<td>0.74</td>
<td>0.05</td>
</tr>
<tr>
<td>SC altitude increase</td>
<td>0.00049</td>
<td>0.00065</td>
<td>0.00069</td>
<td>0</td>
</tr>
</tbody>
</table>

Processing was performed both with and without the use of PCA smoothed spectra. Radon removal was first run with the full-spectrum method, but this seemed to remove too much and so radon removal was run for a second time with the spectral-ratio method.

The best gridding results could be achieved with the gridding-method kriging. Since flight line spacing at Socorro was approximately 100 m, the grid-node spacing was also chosen to be 100 m, with a search radius of 150 m. The results for potassium, shown in Fig. 3, provide valuable information for geological and volcanological research. They show a good correlation between the maxima of the potassium map and the peralkaline trachytes dated approximately at 15 ka (Bohrson et al., 1996) belonging to the Felipe member (Fig. 1).

Interpretation of gamma-ray data of Socorro Island is being performed with the combined use of radioelement maps, ternary maps, a detailed satellite image and several pre-existing geological maps.

Conclusions. Through this work we aim at retrieving information about the surface and subsurface geology of the volcanic island of Socorro based on the analysis and interpretation
of high-resolution magnetic and gamma-ray airborne data. The data were measured in 2009 in the frame of a combined geophysical survey including also EM and ground resistivity data. A comparison of these data with available geological information and rocks composition is being carried out in order to put some constrain on the surface and subsurface geology of specific areas of the island.

A preliminary analysis of magnetic data (Fig. 2) performed through the DEXP method shows the presence of a low magnetization volume below the surface of the island, possibly connected to high temperatures in the deeper part of the volcano, a low total remanent magnetization of pyroclastic caldera filling due to non-aligned sedimentation, and/or the influence of hydrothermal alteration within the caldera. The airborne gamma-ray data (Fig. 3) show a good correlation between the maxima of the potassium map and the 15 ka old peralkaline trachytes of the Felipe member (Fig. 1).

References
Fedi M.; 2007: DEXP: a fast method to determine the depth and the structural index of potential field sources. Geophysics, 72, 1–11.


