Marine EM on Land: MT Measurements in Mono Lake

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SUMMARY

Long Valley Caldera and the Inyo-Mono Craters are manifestations of an active volcanic system on the eastern flank of the Sierra Nevada in California, USA. The United States Geological Survey has been using the MT method to study the hydrothermal and magmatic systems associated with this volcanism, but Mono Lake, at the northern end of the Inyo-Mono Crater chain, creates a 20×15 km hole in the land MT data set. This is particularly inconvenient considering that the most recent volcanic feature in the area is the lake's Paoha Island, which emerged only 350 years ago. In 2016, we tested two moored, lake-bottom MT receivers which are based on the ocean-bottom MT instrument developed by Scripps. After encouraging results, in 2017 we conducted a small campaign to collect 21 sites across the lake. Seven instruments were deployed and moved three times at 2-day intervals, and collected good quality data from 100 Hz (limited by sample rate) to 200–3,000 s periods. A preliminary 2D model that includes land stations along with the lake-bottom stations identifies a large conductor on the north side of the lake at a depth of 3 km and extending to 20–30 km deep. This conductor is consistent with a conductor observed on the edge of 3D inversions of the land data, and is probably a hydrothermal system, similar to a conductor seen beneath Long Valley Caldera to the south, underlain by a magmatic system.

Keywords: lake MT, magmatic, hydrothermal, marine MT

INTRODUCTION

Mono Lake lies in the Mono Basin, situated at the eastern edge of the Sierra Nevada in central California near the Nevada border (Figure 1). Mono Basin and Long Valley Caldera, to the south of the basin, are both volcanically active regions. Extending south from Mono Lake is a chain of recent volcanic features called the Inyo-Mono Craters, which which have erupted as recently as 650 years ago. Paoha Island in Mono Lake is the most recent edifice, having emerged from the lake only 350 years ago. Long Valley Caldera lies at the southern end of the string of craters, having erupted 600 km^3 of material 0.76 Ma ago, material which now forms the Bishop Tuff which can be identified over 2,000 km from the eruption. Long Valley Caldera continues to be active, with a resurgent dome, many earthquake swarms, and the release of considerable amounts of CO_2. These active volcanic systems are not only of geological interest, but pose a threat to the communities of Mammoth Lakes, Bishop, and Lee Vining. For these reasons the United States Geological Survey (USGS) has been collecting magnetotelluric (MT) sites in Long Valley and across the crater chain in order to image the magmatic and hydrothermal systems in this region (Peacock et al., 2015: Peacock et al., 2016). However, the 20×15 km area of Mono Lake is not accessible to routine MT data collection, and so Scripps Institution of Oceanography (SIO) and the USGS teamed up to collect data in the lake using a modified version of an ocean-bottom MT instrument.

INSTRUMENTATION AND DATA COLLECTION

The ocean-bottom MT instrument described in Constable (2013) consists of a custom, low power, 8-channel, 24-bit logging system that uses a temperature compensated crystal oscillator for timing. The timing oscillator is set using GPS time on deployment, and on recovery drift is measured against GPS time: drift is typically about 1 ms/day. Electric fields are measured across silver-silver chloride electrodes and magnetic fields are measured using standard multi-turn induction coils with mu-metal cores. Both electric field and magnetometer amplifiers are transformer-coupled chopper amplifiers designed to exploit the low input impedance of electrodes in the marine environment, or to load the output of the induction coils to flatten the open-circuit resonant peak. Orientation on the seafloor is carried out using external compasses that measure pitch, roll, and heading.

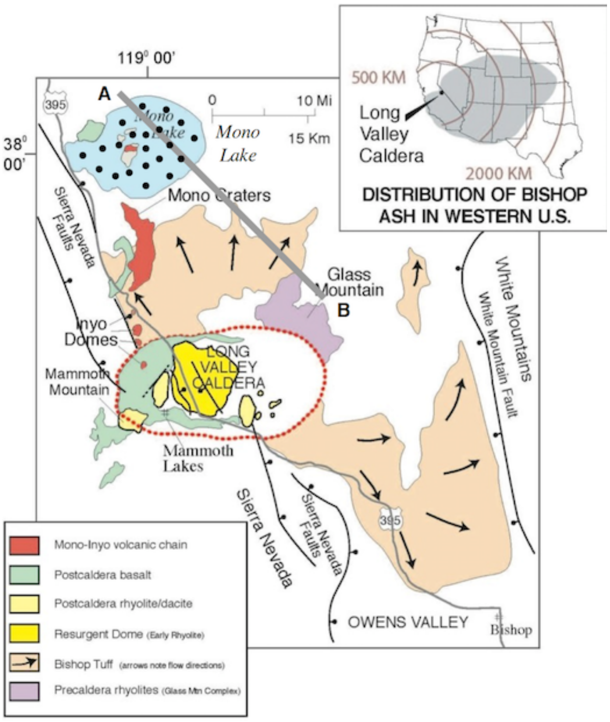

Figure 1: Simplified volcanic geology of Mono Basin and Long Valley Caldera, showing the extent of the Long Valley eruption. The approximate location of the lake-bed sites are shown as black dots, and location of the inversion transect shown in Figure 5 is given by **A-B**. Base figure from USGS via Wikipedia.

For the lake-bottom experiments, the deep-sea floatation was removed, along with the acoustic release mechanism. These were both replaced with 60 m of floating rope and a surface buoy to create a moored system that could be deployed and recovered by hand. (The maximum depth of Mono Lake is 48 m.) Motion of the surface buoy was decoupled from the instrument by attaching two 1.5 kg lead diving weights to the mooring rope about 2 m from the instrument. The 10 m electrode separation in the seafloor instrument was reduced to 3 m for the lake-bottom instrument to increase the ease of handling using small water craft. The seafloor instrument will record continuously for about 2 weeks from a pack of internal NiMH batteries, so the instruments could be moved from site to site without bringing them back to shore. The recording schedule of the external compass was modified to collect data every hour for the duration of the deployment, in order to record the changes in orientation when the instruments were moved. The instrument is shown in Figure 2.

Figure 2: Lake-bottom MT instrument, showing the various components. The electrodes, which need to be stored wet, have not yet been fitted.

In 2016, we deployed two prototypes of this instrument overnight in Mono Lake near the southern shore in order to test signal to noise ratios. The data were noisy but encouraging, given that the weather was poor (the lake was covered in whitecaps) and the deployment short. We reasoned that with more instruments, longer deployments, and better weather, the approach was viable, and so we returned in 2017 with seven instruments.

For initial deployment, the seven instruments were deployed by inflatable boat (Figure 3) across the lake. The instruments had been started the previous afternoon, and initial deployment only took half a day, taking two instruments out at a time in the boat. After two days, the instruments were recovered and moved to another location, one by one, which again only took half a day. The instruments were moved for a second time, to occupy 21 sites in all. Finally on the sixth day, the instruments were recovered and the data were downloaded. Two remote reference sites had been installed, using EMI BF-4 magnetometers and the same seafloor data logger, one on the south shore of Mono Lake and one in a quiet location close to the town of Mammoth Lakes.

At seven locations around the lake a conductivity-temperature-depth (CTD) probe was lowered to record water conductivity. There was a thermocline at about 5 m depth, with water conductivity about 7.25 S/m at the surface and 5 S/m below 20 m depth. Water conductivity structure was used in the inversion described below.

Figure 3: Two instruments about to be deployed.

Data and Inversion

Data were processed using the multi-station code of Egbert (1997), which works very well for seafloor instrument arrays similar to the one used here, with the addition of one of the land references included. In spite of only a 3 m dipole, the electric channels were excellent, and the noise is dominated by motion of the instrument on the magnetic channels. For about half the sites this created noise in the responses at around 2 Hz (Figure 4), which is probably a strumming frequency of the instrument or the mooring. In the worst cases, usable data only extend to 200 s periods, but in many cases, such as the site shown in Figure 4, usable data were processed to 1,000 s periods or longer. Two sites had large tilts (of order 45°), probably as a result of deploying on the tufa pinnacles for which Mono Lake is famous, and had to be discarded.

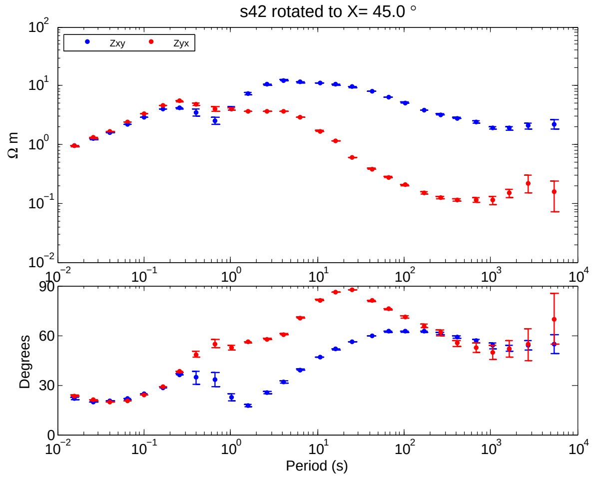

Figure 4: An example of the MT response functions from one site, better than average in terms of longest periods, worse than average in terms of motional noise around 2 Hz.

After inspecting polar plots, swift skew, and phase tensors, and considering the local geology, 9 lakebed sites and 13 land sites close to the line **A-B** shown in Figure 1 were rotated into the line and inverted with the MARE2DEM 2D inversion code of Key (2106). The result is shown in Figure 5. Data fit to RMS 1.4 with an error floor of 20%, with the TE resistivities excluded from the land stations to reduce the effects of 3D geology. A large conductor is evident, the top of which shallows to the north of Mono Lake to a depth of 3 km. The base of the conductor is around 25 km and the lowest resistivity about 0.3 Ωm. This conductor is consistent in position, depth, and resistivity with conductor "C3" which appears at the edge of the 3D inversion of Peacock et al. (2015), but the new data show that this conductor extends past the northern edge of the lake and puts a much better constraint on its shallowest depth. The top of the conductor is too conductive and too shallow to be a magmatic system, and is similar to a conductive body seen beneath Long Valley Caldera by Peacock et al. (2016), interpreted as a hydrothermal system. However, the Mono conductor extends to significantly greater depths, which may be a deep magmatic source for the recent volcanism in the area and the shallower hydrothermal systems.

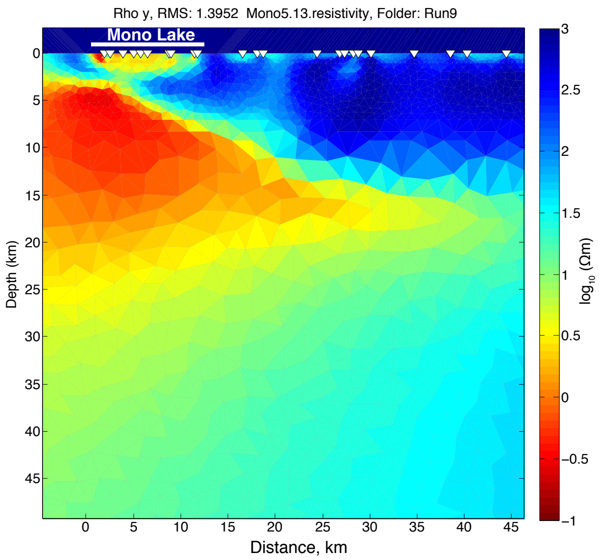

Figure 5: Inversion of land and lake-bed data from sites along the line **A-B** shown in Figure 1.

Conclusions

Moored versions of the Scripps seafloor electromagnetic receiver provide an effective and efficient method of collecting MT data in shallow lakes. Here, 21 MT sites were collected with an expenditure of 4 half-days of work spread out over 6 days of elapsed time. Such productivity for land MT is difficult to achieve. Our data clearly show that a conductive system identified in earlier 3D land MT inversions extends to the north side of Mono Lake, and is shallower than previously identified. Future work will involve collecting more data on the north side of the lake along with 3D inversion of the data.

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Figure 6: Mono Lake