Subsalt Exploration Using the Marine Magnetotelluric Method

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Abstract

We have developed instrumentation and techniques to collect magnetotelluric(MT) data on the continental shelves, allowing subsurface electrical resistivity to be mapped from the surface to depths of tens of kilometers. Electrical methods are particularly valuable in areas of poor seismic performance, such as sub-salt, sub-basalt, and sub-carbonate prospects. Our equipment was tested in 1997 over a deepwater, 3D salt sheet in the Gulf of Mexico. When inverted with modern 2-D interpretation packages, MT data yielded estimates of base salt depths that were within 10% of those obtained by state of the art 3-D seismic interpretation. We have worked with industry to make the methodology commercially available, and have conducted four proprietary surveys to date, both in the Gulf of Mexico and the Mediterranean.

Introduction

The magnetotelluric (MT) method is an established technique which uses measurements of naturally occurring electromagnetic fields to determine the electrical resistivity of subsurface rocks. Resistivity information may be used to map major stratigraphic units, determine relative porosity, or decide between two or more competing geological interpretations. When an MT survey is accompanied by seismic, gravity, or magnetic data, joint interpretation of all data leads to a more complete understanding of the subsurface than is possible through use of any one technique alone. The MT method can be used as a reconnaissance tool for basin characterization, or specifically to assist in regions of poor seismic performance and productivity. Typical of the latter are sediments buried under salt, basalt, or carbonate units which generate strong reflections and reverberations and make imaging the buried sediments difficult using acoustic methods alone.

Although salt has a high acoustic contrast with surrounding sediments, salt also has a high resistivity, making it a potential candidate for mapping by electrical methods. Modeling shows that given sufficient quality and quantity of MT data, salt structure, and in particular base of salt, can be

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resolved with accuracies approaching 5% of depth of burial (Hoversten et al., 1998). Electrical methods provide a data stream that is independent of seismic, gravity, and geological results, and so can greatly reduces risk when incorporated into the exploration program: Gravity models, intrinsically non-unique when used alone, can be tested for compatibility with constraints from an electrical survey. Seismic velocity models can be improved using both depth and porosity estimates obtained form resistivity models. And, ideally, preliminary structural information from electrical surveys could be used to design higher quality and more cost effective 3-D seismic surveys.

Early attempts to use the MT method in the marine environment (Hoehn and Warner, 1983) failed, mainly because the then current technology and methodology was not sufficient for the task. This situation has changed. Modern progress in land MT surveying such as remote reference data acquisition, robust data processing, multi-site acquisition, and multi-dimensional modeling and inversion have together made the MT method much more reliable than it was in the past. We have coupled these advances with the development of an effective marine instrument system based on strong existing programs in marine geophysics and instrumentation at Scripps Institution of Oceanography (SIO) (Constable et al., 1998).

Instrumentation

The SIO seafloor electromagnetic recorder (Figure 1) incorporates an acoustic navigation and release system, a modern digital data logger, custom electric field preamplifiers, low-noise electrodes designed for seafloor use, and commercial broad-band magnetic sensors in custom underwater housings. Logging electronics reside in a 15 cm inside diameter 7076-T6 aluminum tube which is anodized and painted to resist corrosion by seawater and terminated by two end-caps sealed with O-rings. One endcap has ports to start the computer, purge damp air from the instrument, and connect an external computer to the internal SCSI disk drive. The other endcap has high-pressure, underwater connectors for linking the sensors to the logger inputs. The entire system has a maximum operation depth of 6000 m.

The logger pressure case is supported in a polyethylene framework which protects the instrument form damage during handling and supports the five glass flotation spheres, acoustic release package, tow magnetometer coils, four 5 m electrode arms, and a concrete anchor. A magnetic compass, equipped with a timed release to lock the needle mechanically, records the orientation of the system after deployment on the seafloor. The acoustic release unit serves both to locate the instrument underwater and to release the package from the seafloor at the end of the recording period.

During marine operation, a concrete anchor is attached to the plastic frame by means of a release system actuated by acoustic command, releasing the anchor from the instrument and allowing the positively buoyant package to float to the surface for recovery. Data acquisition at remote reference sites can be effected with logger units identical to those used on the sea floor. By working with autonomous vehicles, rather than moorings, the instrument system is more compact (8 units, plus ancilliary equipment, fit into one wide-body air freight container), less susceptible to motional noise induced by mooring cables, and capable of being deployed and recovered in deep water in a timely fashion from a modest size ship.

Field Trials

During the summers of 1996, 1997, and 1998 we conducted marine MT field trials over the “Gemini” prospect in the Gulf of Mexico (Figure 2), a 3D salt sheet well mapped by 3D seismic data and containing a sub-salt discovery well (Figure 3). In 1996 instrument problems corrupted the seafloor magnetic data, and results relied on combining seafloor electric fields with magnetic reference data collected on land (so-called ‘hybrid’ data). Results were encouraging, but compromised by the absence of seafloor magnetic measurements. We returned in 1997 with improved equipment and a much more focussed objective to collect a single profile of high-quality, interpretable data as a demonstration of the method. Our survey profile was chosen on the basis of an experimental design study which assessed the success of 2-D modeling the 3-D structure and also the size of the expected signal. The water depth of the profile is almost constant at 950 m. A line of 9 high quality MT sites was obtained in over the deep, relatively thin, 3D saltstructure. Raw timeseries of seafloor electric and magnetic fields were remote reference processed to obtain MT responses in a 1 s to 1000 second period band.

Figure 4 shows the interpretation of these data using the Occam’s inversion 2-D MT code of deGroot-Hedlin and Constable (1990). This algorithm generates the smoothest model that fits the field data, based on the philosophy that only structure required by the MT responses is included in the final model. When the inversion is started from a featureless half-space, it generates a resistive region where the saltbody is known to be, showing that without any other information the MT method is sensitive to salt structure. The salt resistor is smooth, of course, reflecting the intrinsic resolution of the MT method when no other information is included.

The first additional information we can include in the inversion is the location of top-salt, obtainable from relatively inexpensive 2-D seismic profiling. We do this by relaxing the requirement that the model be smooth at the known location of the salt surface. Resolution of base salt improves only slightly, but the model begins to look more geologically realistic. Beneath stations 5 and 6 the salt is too thin to be detected by the MT method, and so the smooth inversion removes it.

Although smooth models are useful indications of MT resolution, we know that the contacts between salt and sediment are not smooth, but sharp. Recent developments in MT inversion technology (Smith et al.,1997) allow us to include this geological information in the interpretation, and invert for a salt body having sharp boundaries at both top-salt and base-salt surfaces. The result is shown in Figure 5. Again, the match between MT-determined base-salt and seismically-determined base salt is excellent except under stations 5 and 6, where the MT model salt is now too thick. The sharp boundary inversion is a regularized inversion similar to the smooth inversion, and in this case variations in salt thickness are penalized. Thus, the inversion makes the salt as thick as possible where there is no data constraint, in effect placing an upper bound on possible thickness.

Concluding Remarks

Mapping the base of thin, resistive salt is a challenging and difficult MT problem; electrical methods are not used to survey salt on land and perhaps could not be used for this purpose onshore. However, our offshore success results form the uniform electrical nature of seawater and the complete lack of cultural electrical noise, allowing us to produce quality Mt data free of static shifts and bias. After obtaining the results shown in this paper, we returned to the Gemini prospect in 1998 and collected the beginning of a 3-D set in order to test our capabilities over the more complex parts of the salt structure, and filled in the line collected in 1997 to examine issues of data density versus resolution (Figure 3). Since the inception of this project in 1994, SIO has assisted in creating a commercial marine MT capability, and in summer 1998 two proprietary surveys were conducted in the Gulf of Mexico, following earlier commercial operations in the Mediterranean.

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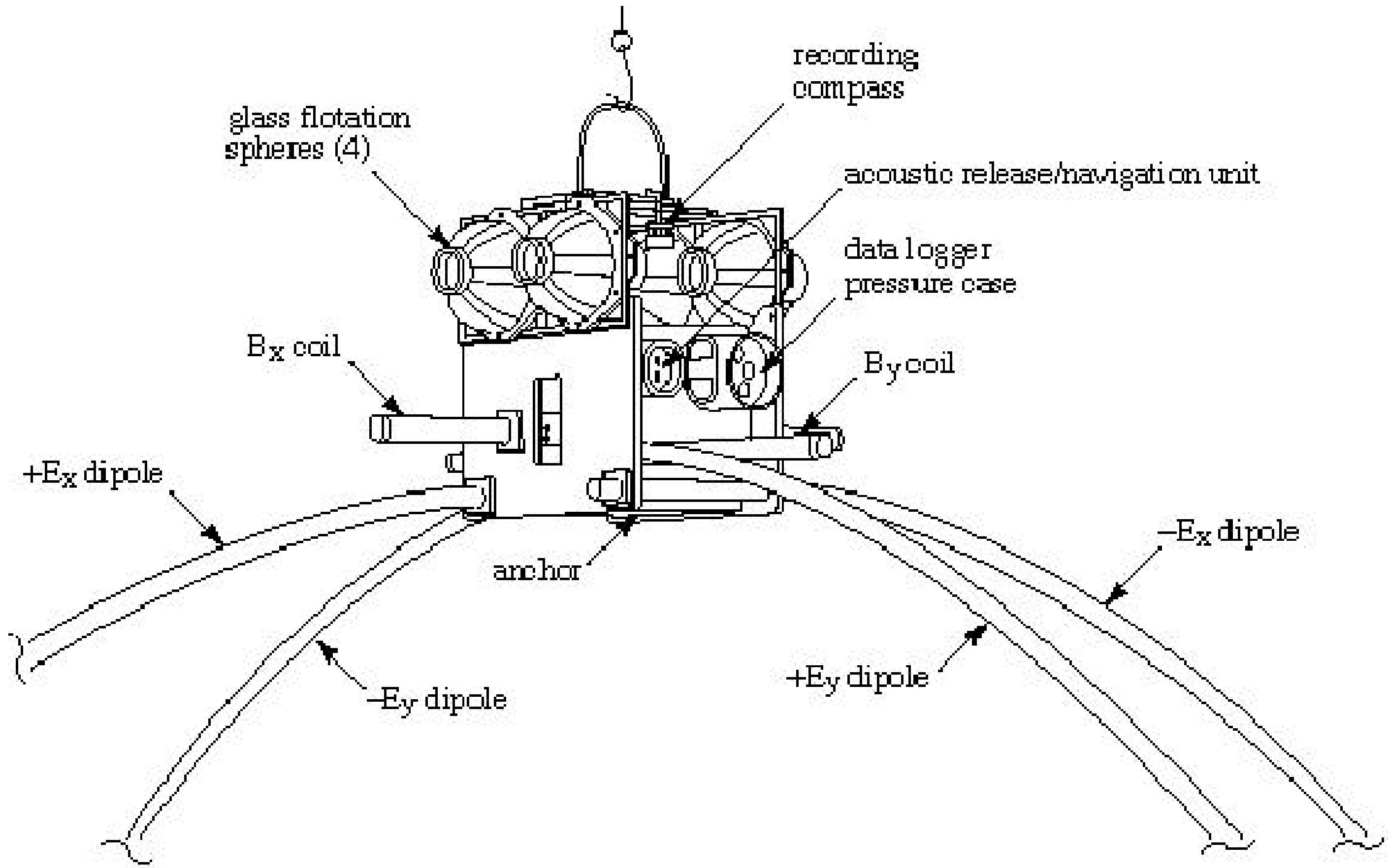

Figure 1: Line drawing of seafloor MT instrument. A concrete anchor sinks the device to the seafloor. The anchor is released by the acoustic unit on receipt of a command code, and the device rises to the surface with the help of the glass flotation spheres. The electric dipole arms are 5 m long pipes terminated with silver-silver chloride electrodes.

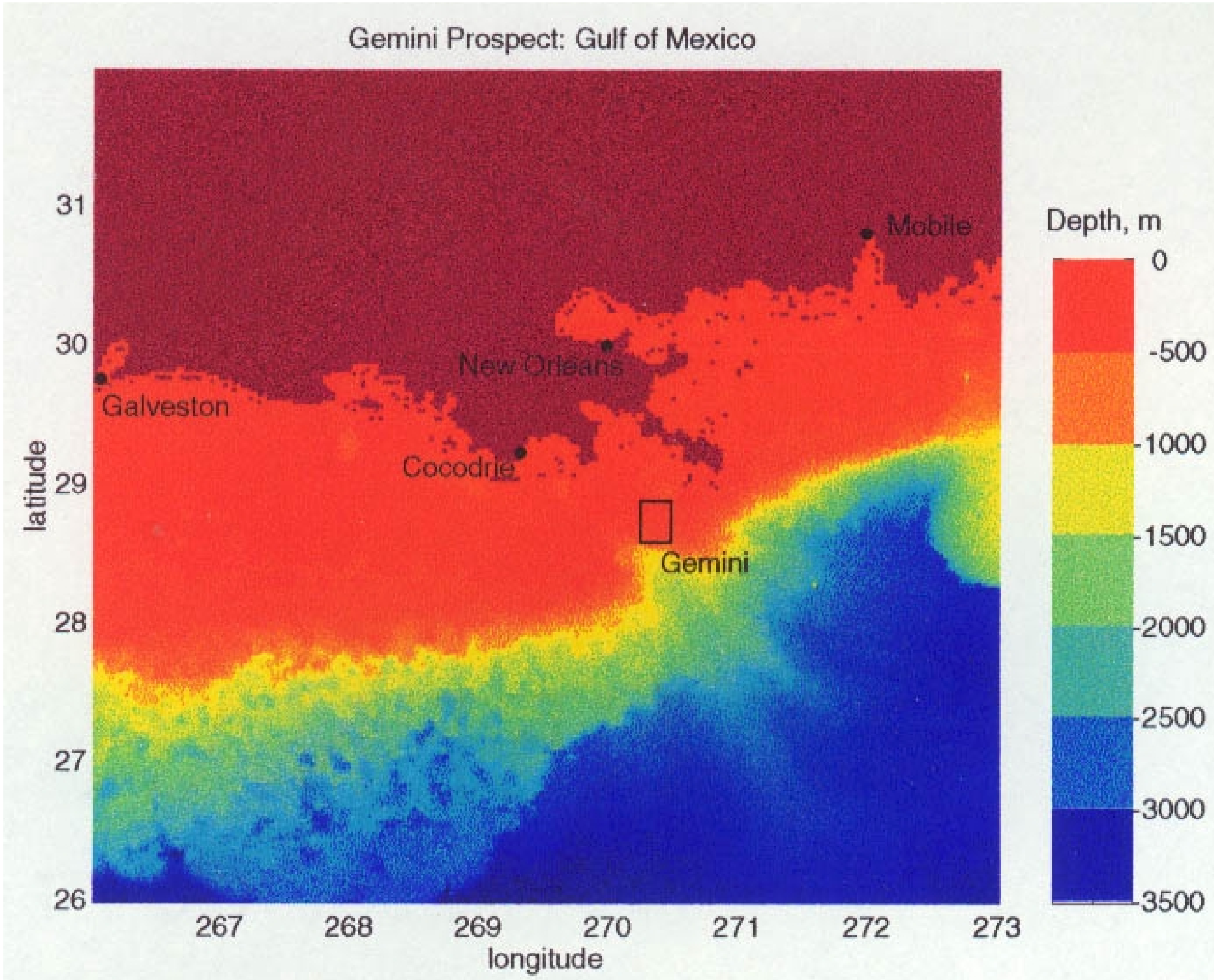

Figure 2: Bathymetry map of the Gulf of Mexico showing the location of the Gemini prospect in 1 km water off New Orleans.

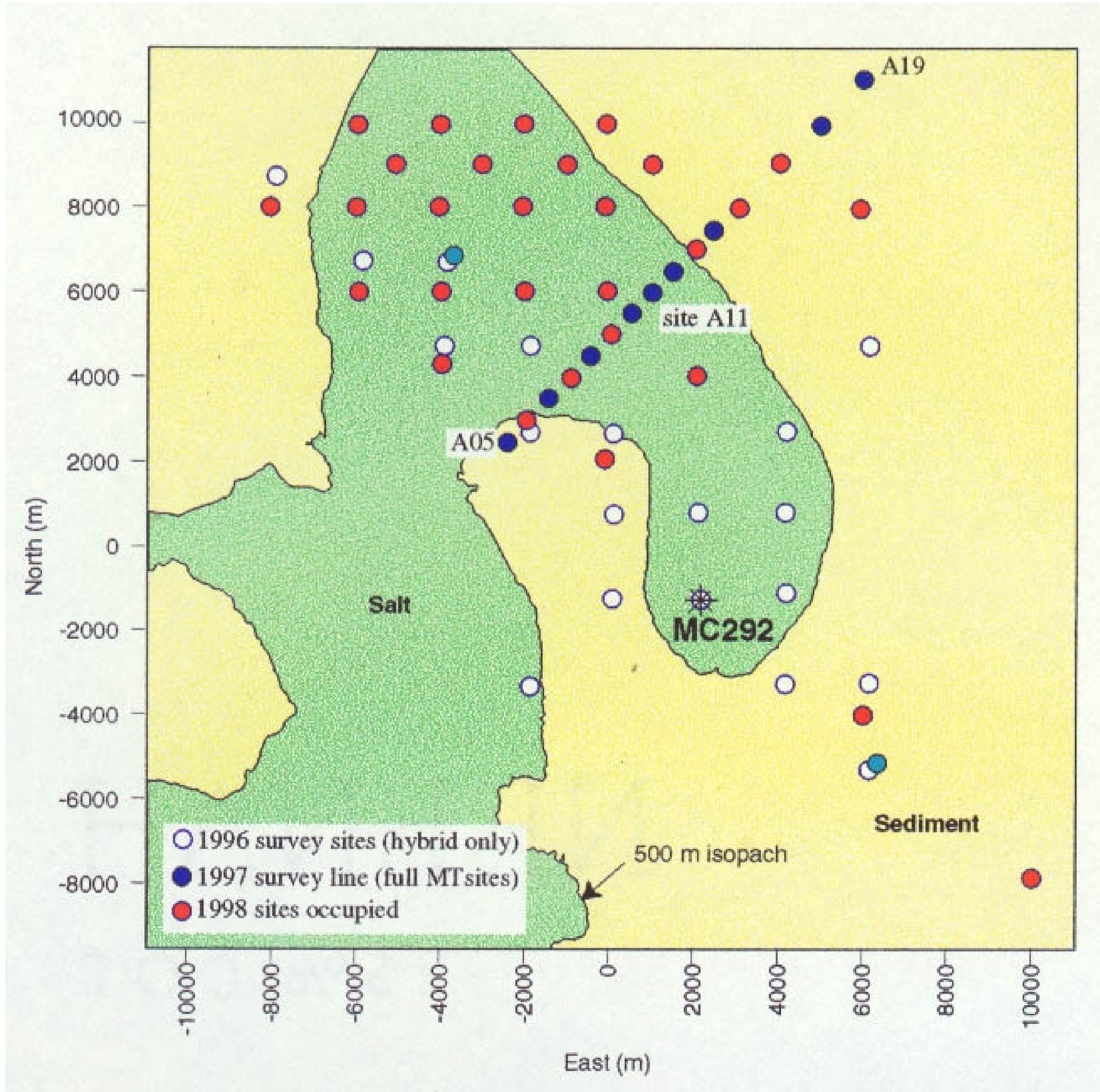

Figure 3: Footprint of the Gemini salt sheet, based on the 3-D seismic volume provided by sponsor companies, and the locations of MT sites collected during 3 summer field season. MC292 is Gemini discovery well.

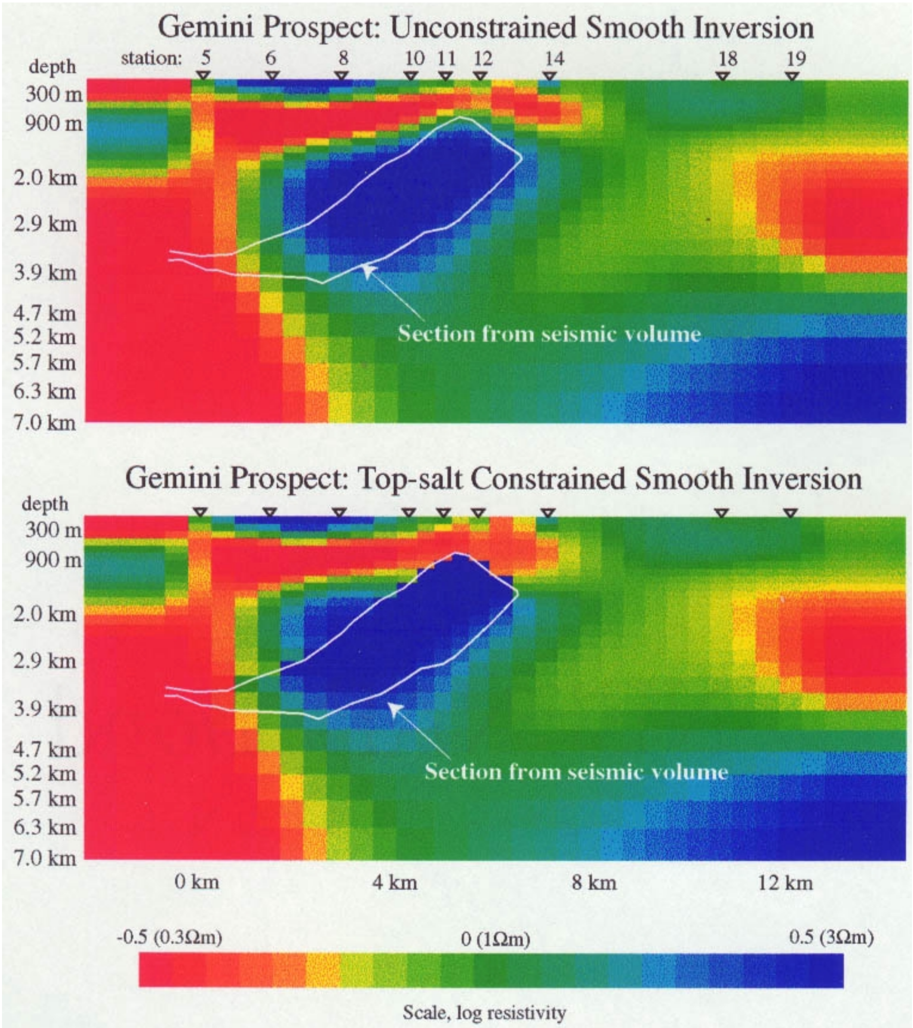

Figure 4: Inversion of the 1997 MT profile shown in Figure 3, using the regularized algorithm of deGroot-Hedlin and Constable (1990). In the upper panel, no constraints other than the data were applied to the inversion, which seeks the smoothest model compatible with the data. In the lower panel, the inversion was again started from a half-space, but in this case the smoothness penalty on the top of the salt was relaxed, allowing the inversion to place a sharp conductivity jump at this prescribed surface.

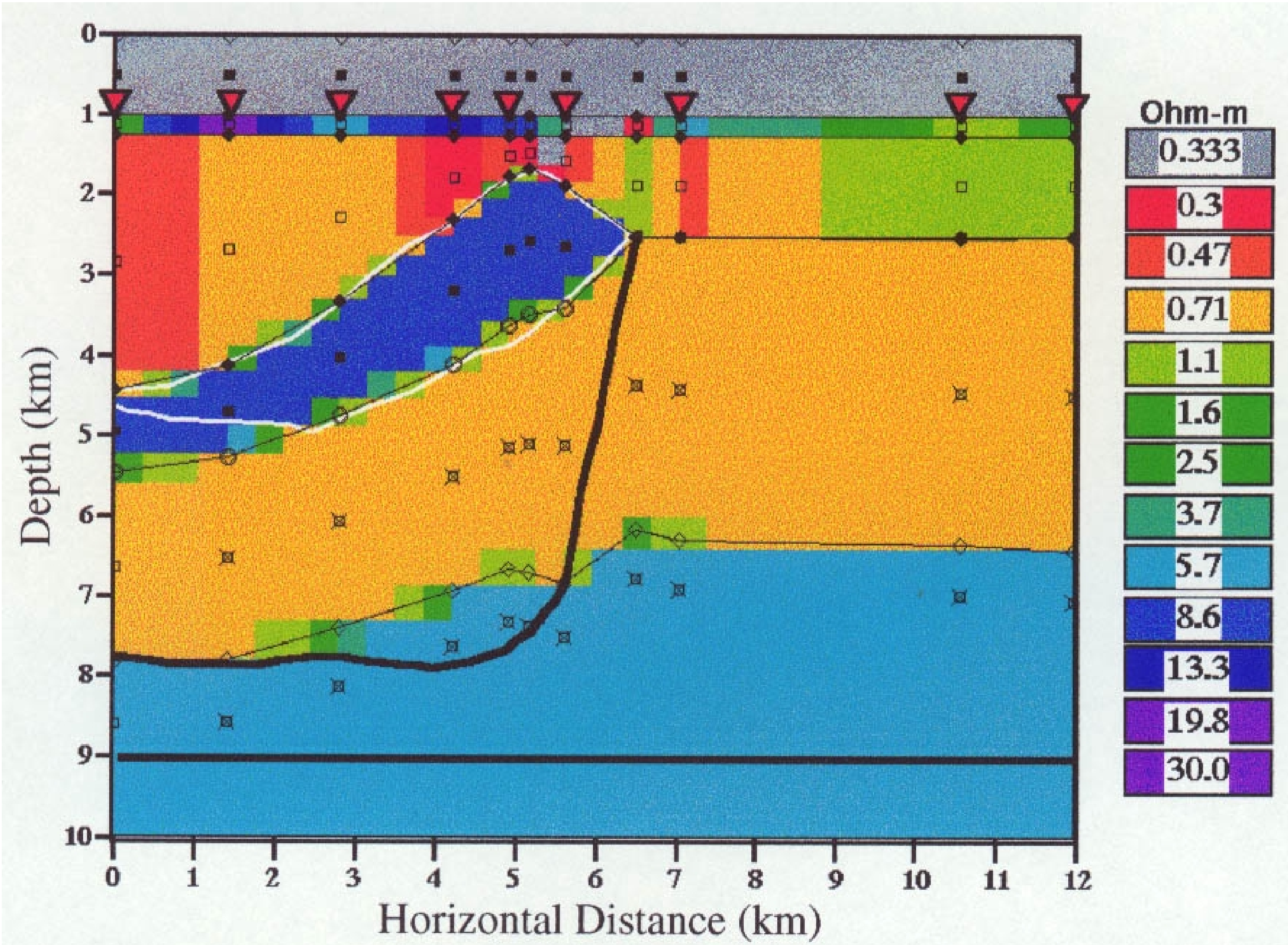

Figure 5: Inversion of the 1997 MT profile shown in Figure 3, using the sharp-boundary code of Smith et al. (1997) (Hoversten et al., 1999).As in the smooth inversion, top-salt is constrained to be at the seismically-determined depth, and base salt is defined by a sharp resistivity contrast. Again, the section through the seismic salt volume is shown by the white line. The heavy black line shows where the base-salt boundary was started during the inversion.