Legacy of Luiz Rijo in MT Exploration at the University of Utah and Beyond: Two-Dimensional Inversion and Frontier Solid-Earth Investigations

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Abstract

Among his many important research and educational contributions, one of the first developments of Professor Luiz Rijo (while still a graduate student) was a basic but powerful finite element algorithm for modeling two-dimensional inductive EM scattering from Earth resistivity structure. Following additional efforts by colleagues and peers, this code became the basis for generalized platforms widely used to simulate and invert land, marine and airborne plane-wave data. The author's experience in this technology emphasizes application to solid-earth and geothermal exploration field studies including the Great Basin, New Zealand and Antarctica where unique insights from resistivity structure have been possible.

Introduction

When I arrived as a new graduate student to the University of Utah in 1976, Luiz Rijo was in the later stages of his Ph.D research program. Despite his overflowing schedule, which included a young family, he quickly became the senior graduate student of Professor and Department Chair Stan Ward who perhaps mentored me most closely. They were rather heady days with a very talented EM research group including Ph.D graduate students Jim Klein, Bill Pelton, Bill Petrick, Don Pridmore, John Stodt and Al Tripp, along with Professors Ralph Shuey, Bill Sill and (soon Professor) Jerry Hohmann. Frequent visiting associates were Charlie Swift, Roger Phillips and Professor Francis Bostick. Probably the centerpiece of Rijo's research at Utah was the creation of a finite element program for simulation of two-dimensional (2-D) EM scattering from earth resistivity (Rijo, 1977). In this somewhat personal perspective, I briefly summarize subsequent developments from this code and its applications to some large-scale MT transect projects involving myself. Detailed emphasis is placed on frontier MT studies on the Antarctic continent.

Algorithm Beginnings and Progress

The original finite element code developed by Rijo (1977) implemented a purely rectilinear 2-D mesh having rectangular elements subdivided into four triangular elements (Figure 1) (see also Wannamaker et al., 1987). Mesh geometry was input in terms of element dimensions but in principle the element equations are general enough to allow unique positioning of each element corner in y-z space (x = strike) (see MacInnes and Raymond, 2006, for an adaptation). The field variation was assumed to be linear over each triangle, element equations derived with the Galerkin method, and the internal or fifth node eliminated via static condensation. The system matrix equation exhibits the well-known banded structure that is solved efficiently using a Modified Cholesky (LDL^T) direct algorithm. The original program was defined in terms of total E-field (TE mode) or H-field (TM mode) along strike with Dirichlet boundary conditions.

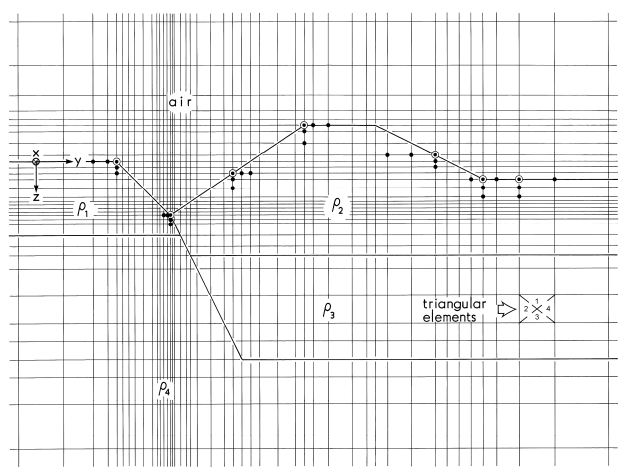

Figure 1. Schematic of finite element mesh with rectilinear elements subdivided into triangular elements. Modified from Wannamaker et al. (1986).

One of my first projects was using this program to model profiles of MT data taken across the Roosevelt Hot Springs geothermal area (Wannamaker, 1978). This acquainted me with capabilities and limitations of the 2-D assumption when working with natural MT responses. Pretty quickly it became clear that the nominal TE mode of the field data showed abundant effects that we now refer to as static shifts and other boundary charge (finite strike) phenomena over the localized hydrothermal alteration zones. The characteristic persistence of TE ρ_a anomalies over truncated conductors to arbitrarily low frequencies cannot be fit with TE algorithms where the E-field is assumed continuous, and can lead to unbounded depth extents of model conductors with only partial data fits. At the time it was noted that these TE data had TM mode-like characteristics (cf, Swift, 1967). A corollary pursued by Wannamaker et al. (1980, 1984) and Wannamaker (1999) based on quantitative 3-D simulations using an integral equations algorithm was that finite strike effects were relatively limited in the TM mode and thus the 2-D assumption could be robust for it with proper survey design and awareness of limitations (e.g., Berdichevsky et al., 1998).

Shortly after Luiz Rijo left Utah and returned to Brazil, John Stodt reviewed the element equations and corrected an error in the integration by parts step for deriving the TM mode equations when the four interior triangular elements are of unequal resistivity (Stodt, 1978). This affected simulations of sloping boundaries including topography. My own experience with the total field version of the program revealed certain ill-conditioning issues especially toward lower frequencies and larger element aspect ratios that were greatly reduced by moving to a secondary field formulation with an arbitrary 1-D background structure (Wannamaker et al., 1987). Mesh flexibility with triangular elements was subsequently exploited to allow forward modeling of 2-D MT responses that included topography, which mainly consisted of nodal bookkeeping and shifting to define the auxiliary (cross-strike) fields by local spatial differentiation (Wannamaker et al., 1986). In this approach, topography is defined by building it from triangular elements within the rectilinear context, rather than by deforming the mesh. That program has been used to derive resistivity cross sections incorporating topography by trial-and-error fitting over several geothermal and orogenic domains (e.g., Wannamaker et al., 1991; 1997).

Interest emerged in advancing the program to perform inversion. I derived parameter sensitivities (jacobians) using an analytic perturbation approach similar to Oristaglio and Worthington (1980) except that the source vector for each parameter was defined at the Helmholtz equation stage rather than later with the matrix equation. The perturbation method is best-suited to an overdetermined inversion problem and was applied as such to refine media resistivities in a geometrically constrained earth model such as at Valles Caldera (Wannamaker, 1997). Code with the forward problem and these sensitivities was supplied to the Scripps research group about two weeks before the 1988 EM Induction workshop in Sochi which they were able to incorporate with a parameter smoothing matrix and present there as the prototype Occam-2 underdetermined inversion program, published by deGroot-Hedlin and Constable (1990). Subsequently, reciprocity was exploited to reduce the jacobian source vectors from parameter-rank to receiver-rank which reduced computation time of that step by typically an order of magnitude. This method together with the parameter Helmholtz equations and the nodal manipulations for topographic simulation are described in deLugao and Wannamaker (1996).

The code for jacobians via reciprocity was provided to the Scripps group also in 2001 and greatly improved the efficiency of the Occam-2 algorithm as well. This code is freely available on the Scripps marine EM website. One of its major uses has been to image sub-seafloor resistivity structure in both hydrocarbon prospecting and tectonic research (e.g., Key et al., 2006; Key and Constable, 2011). Employing the same forward problem and jacobians, I have constructed a similar inversion program; it invokes a somewhat more general smoothing and a priori adherence utilising a model covariance matrix (Tarantola, 1987; Mackie et al., 1988) but uses a single user-specified damping value that is varied to test model robustness. A modified version of this code is used by Geotech Inc. to invert airborne ZTEM and AirMt responses (Legault et al., 2009). Although alternative 2-D MT modeling approaches using unstructured meshes are argued to be better suited to complex heterogeneity and topography/bathymetry (e.g., Key and Weiss, 2007), the simplicity, effectiveness and long history of testing of the rectilinear mesh platform that Luiz Rijo began at the University of Utah has established it as an enormously powerful and popular MT interpretation tool.

Frontier MT Transect Investigations of Solid Earth Processes: The Antarctic Experience

Much of my application of the MT method has been toward understanding orogen-scale geological processes and their controls on resource generation or societal hazards starting with active subduction zones (Wannamaker et al., 1988, 1989). Generating well-resolved resistivity models from transect data is an essential component of such projects and depends upon effective 2-D inversion capability. One recent example has been MT profiling across the central and northern South Island of New Zealand where oblique convergence of the Pacific and Australian plates is expressed as by continuum compression and crustal thickening (central) and by regional strike slip faulting and incipient subduction (northern) (Wannamaker et al., 2009). In the central portion, 2-D inversion using the above in-house code revealed a U-shaped conductor in the crustal root zone representing prograde metamorphic fluid formation whose extrema rose surfaceward and connected to zones of actively forming mesothermal gold occurrences. Toward the north, conductive structures denoted fluids derived from >100 km deep in the subduction zone rising to the upper-middle crust and triggering enigmatic large-magnitude earthquakes on high-angle thrusts unfavorably oriented for failure under dry conditions.

The finite element inversion algorithm can handle relatively large station numbers as exemplified by a good fit obtained to transect data of nearly 300 MT sites across the extensional U.S. Great Basin province (Wannamaker et al., 2011). Resistivity contrasts approach 10^4 across the horst-graben morphology and volcanic features. The section reveals numerous active magmatic underplating and fluid release zones in the deep crust connecting through steep crustal-scale fault zones toward the surface, ending in numerous instances at known high-temperature geothermal systems. Magmatic input to such systems is corroborated by He^3 anomalies. Characteristic depth to top of the deep crustal conductors corresponds approximately to a 500 C isotherm, and a shallowing of these features in western Nevada and western Utah is in keeping with enhanced extension rates and heat flow there. Regional MT thus provides a means of establishing deep, high-enthalpy potential for next-generation geothermal resources.

One of our most prominent efforts in MT research is to investigate the deep interior of Antarctica. Ice and snow cover 95% of this continent so that earth state and composition must be deduced geophysically. The continent is divided into West and East Antarctic subcontinents by the massive Transantarctic mountain (TAM) chain (Figure 1). West Antarctica is a distributed rift regime somewhat analogous to the U.S. Great Basin (Bentley, 1991). East Antarctica is a largely intact, Precambrian shield terrain with the TAM serving as an uplifted rift shoulder superficially resembling the Utah Wasatch Mtns. Deep structure is hard to deduce with passive seismology due both to lack of earthquakes and sparse seismometer placement, and generally has just distinguished that the West has slower speeds and higher deep temperatures than the East (Wannamaker et al., 2004). Our research group has participated in three MT field projects in Antarctica aimed at establishing thermal regime in those three principal physiographic divisions.

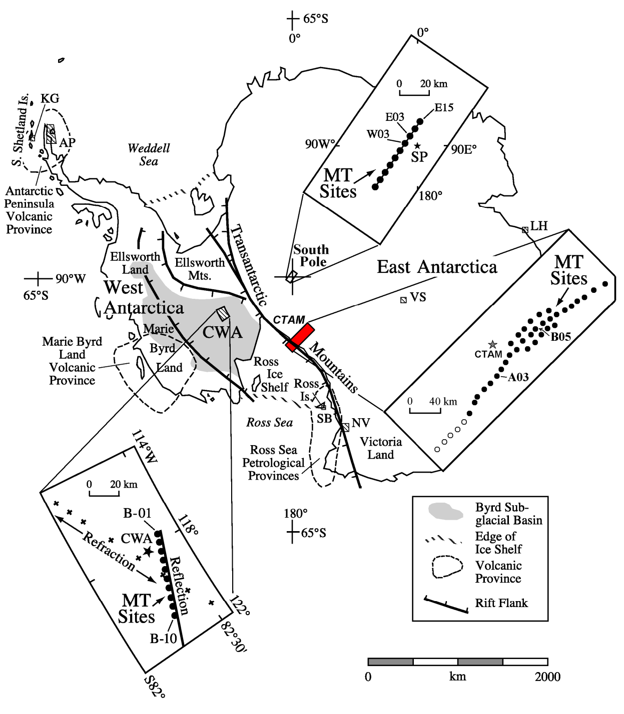

Figure 1. MT surveys of the Antarctic interior by University of Utah. CTAM project is ongoing at this writing.

MT measurements are a challenge here due to the high contact impedance with the snow (firn) at the electrodes (0.5 – 2 M-ohms) relative to land values typically in the k-ohm range. The high contacts required novel instrumentation designed largely by John Stodt in the form of buffer preamplifiers placed at the electrodes to present a low-impedance output down the bipole line to the receiver at site center (Figure 2) (see Wannamaker et al., 2004, for a circuit diagram). The magnetic coil measurements and receiver recording presented no special challenges other than power delivery in cold conditions.

Figure 2. Laying bipole in central Transantarctic Mtns via harnessed, paired travel. Ti sheet metal electrode with high impedance buffer pre-amp shown in inset.

The first application was to profiling over the Byrd subglacial basin of central West Antarctica (CWA) (Wannamaker et al., 1996). Ten sites over frequencies 100 – 0.002 Hz at 6 km intervals were achieved in a line parallel to companion seismic reflection profiling (Figure 1). Finite element 2-D modeling via trial-and-error data fitting was carried out with ice thickness constrained between 1.35 km and 2.1 km according to the reflection results (Figure 3). Most of the sub-ice section to > 100 km depth is resistive (>1000 ohm-m) with some tightly bounded conductive bodies embedded. Such dike conductors have appeared in fossil compressional regimes, but correspond typically to metasedimentary graphite or sulfides when followed to outcrop. Low resistivity of broad regional extent (10's of ohm-m over 100's of km) due to released fluids in the middle crust as is common to extensional regimes was not exhibited in CWA. Ours is recognized as the first work to quantitatively argue for a dormant state of rifting in this area of CWA (e.g., Winberry and Anandakrishnan, 2004).

Ten sites at 6 km intervals were obtained also across the South Pole station area in a second campaign (Wannamaker et al., 2004). The data have been reinverted here using the 2-D finite element code and damping model slope relative to that of a 1-D a priori model (Figure 4). The model shows a thick sedimentary section beneath the 3 km of ice which explains the lack of seismic refraction energy returns in previous studies. Somewhat surprisingly, the lowermost crust and uppermost mantle are conductive suggesting a moderately elevated thermal regime, although this is consistent with presence of sub-ice lake water in this region just inside East Antarctica. The finding is consistent with independent interpretations that thermal activity in Antarctica appears restricted to occasional localized conduits perhaps fed from deep plume sources.

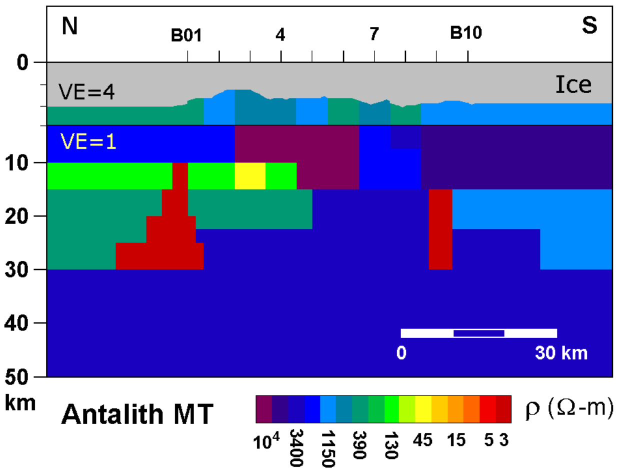

Figure 3. Trial-and-error 2-D forward resistivity model fitting TM and TE data of MT profile in central West Antarctica. This is a tiff replot of graphic in Wannamaker et al. (1996).

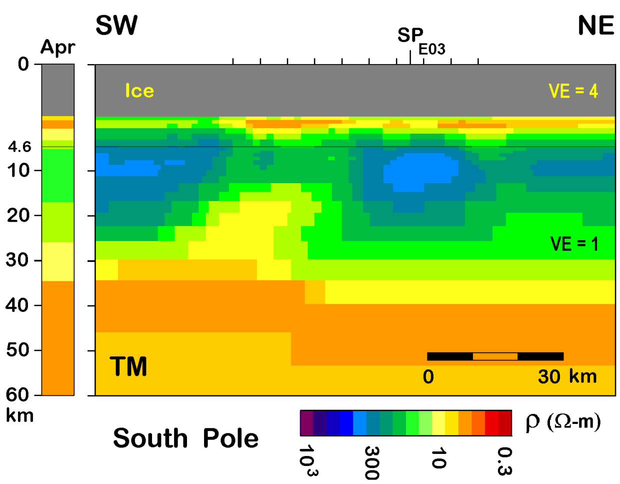

Figure 4. 2-D damped-slope resistivity section from joint TM mode inversion of South Pole MT profile data.

A much more ambitious MT transect program is ongoing through the central TAM (CTAM). The TAM is the world's largest rift shoulder and a generic tectonic question is the source of its support, whether thermal like the Wasatch or alternatively compositional only. In December and January previous, we brought a group of eleven professionals, students and post-docs from four countries to CTAM and accomplished a transect some 230 km in length (Figure 1) funded in the U.S. by the National Science Foundation. The team deployed up to ten Phoenix V-5 receivers at once with three MTC-50 coils each, owned by the New Zealand Geological and Nuclear Sciences and Tokyo Institute of Technology, with electrode buffer pre-amplifiers as above. We recorded up to one week to ensure data down to at least 3000 s period (0.00033 Hz) with system battery power backed by solar panels. The team acquired 33 high-quality sites with an average station spacing of 10 km, including some local 3-D control over a suspected metasedimentary belt.

Deployment mainly was by helicopter with some distant sites on the polar plateau east of the TAM accessible by Twin Otter (Figure 5). Crevasse hazards were a constant consideration in the project. Site selection with that in mind was initially by high-res satellite views, then Twin Otter recon over the field area, and then final pinpointing by helicopter. Landing sites were probed immediately by our accompanying, Antarctic experienced mountaineers, and we routinely utilized harnessed, roped, paired walking for electrode installation (Figure 2).

Figure 5. Final stages of deployment of Phoenix MT system by colleague John Stodt and U Utah post-doc Virginia Maris at site near TAM-Ross Sea transition. Phoenix receiver in gray crate by Maris; tall cardboard box to left used to carry Ti sheet electrodes.

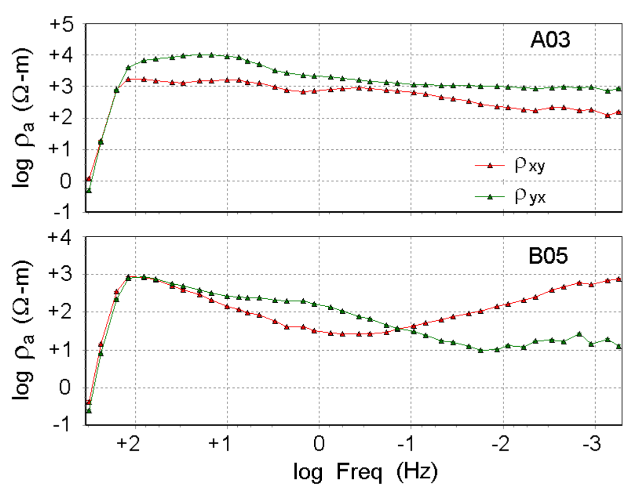

Figure 6. Two example soundings from the CTAM project showing generally very high apparent resistivities.

Signal was steady and environmental noise (e.g., charged blowing snow) was low, and so the quality of the soundings generally is excellent (Figure 6). While it is premature to offer firm conclusions from the data before inversion, the long period ρ_a values tend to remain high to the longest periods suggesting that the TAM at least in this region is held up by compositional buoyancy causes rather than thermal causes such as at the U.S. Great

Basin margin. The most pronounced ρ_a minima occur at middle periods over the metasediments, where most of the obvious 3-D effects lie also. A second season is on planning to extend the profiling mainly onto the extensional Ross Sea and onto East Antarctica.

Conclusions

Rigorous tools such as the finite element forward code written by Luiz Rijo together with advancements over following decades have enabled well-resolved resistivity models from appropriately designed field surveys which in turn have provided insight to Earth structure and processes not available by other methods. Successful developments are underscored by perseverance, an awareness of real-world data needs, and endless testing. This technology has met many applications, and in the field of solid earth studies MT transects designed and inverted rigorously are revealing controls on societal hazards, magma-geothermal connections, and driving mechanisms of orogenesis. MT has an important role to play in frontier Earth exploration; with successful deployments at central West Antarctica, South Pole, and now at greater scale across the central TAM, MT can become a standard tool for geophysical investigation of the Antarctic interior.

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