USING ANALYTIC SIGNAL ANALYSIS ON AEROMAGNETIC DATA TO CONSTRAIN AMT INVERSIONS, SONORA SAN PEDRO BASIN, MEXICO

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Abstract

Airborne geophysical studies on the American side of the San Pedro Valley of Arizona and Mexico have allowed us to map depth to crystalline basement in this area where groundwater is critically important (Alley and others, 1999; Leake and others, 2000; Wynn and others, 2000; Wynn, 2000/2003). This basin, whose head lies in northern Mexico, hosts a major US-Mexico migratory bird fly-way. A desire to preserve the surface water in the San Pedro River led to the creation of the San Pedro National Riparian Conservation Area in 1988. To preserve the surface water, one must know something about the aquifer underlying it. On the American side of the basin, time-domain airborne geophysical methods were used to map the relatively conductive groundwater typical of an arid region to depths of 150 - 400 meters in the absence of human cultural interference. In order to better understand the hydrology of the basin as a whole, geophysical surveying has been extended southward into the Sonoran San Pedro Valley of northern Mexico. An airborne magnetic survey in northern Mexico has been processed to depth-to-magnetic-source, and concatenated to a magnetic data set from southern Arizona to show depth to basement for the San Pedro Valley drainage. We then conducted a scalar Audio-MagneTotelluric (AMT) survey over four different lines in the Sonoran San Pedro basin, and processed these data using a smooth-model inversion to conductivity-vs-depth profiles. As we view the conductivity inversion results, we are in fact visualizing the highly conductive water typical of an arid climate - in effect, we broadly image the saturated sediments. We then used an analytic signal depth-to-source algorithm on magnetic data along the same profiles to constrain the AMT inversion. The result is a unique set of geophysical profiles that clearly show basement structure beneath the Sonoran San Pedro basin to depths of up to 800 meters. These constrained profiles help resolve basement controls on groundwater flow in northern Mexico leading to the US frontier. It is impossible to understand the groundwater regime except in the context of the volcanic and sedimentary history of the region, and neither the geology nor the geophysics can be carried out independently of the other, but the whole together contribute substantially more than the parts.

Background

Major north-south trending river systems (like the San Pedro) in the Sonoran Desert are important corridors for migratory birds, which travel as far south as Argentina and as far north as the Arctic (figure 1). As many as 75 percent of the more than 500 bird species in the Sonoran bioregion breed, overwinter or migrate in north-south riparian corridors. According to Nabhan and Holdsworth (1999) “it is fair to day that in terms of breeding bird diversity and productivity, the Sonoran biome’s riparian habitats are among the richest in all North America”. However, pressures from development, groundwater pumping, agiculture, overgrazing, channelization and other human-related activities have reduced riparian gallery corridors in the southwest U.S. by 90 percent since the beginning of the 20th century. Conserving and restoring the remaining riparian corridors are considered essential to reverse some of this loss.

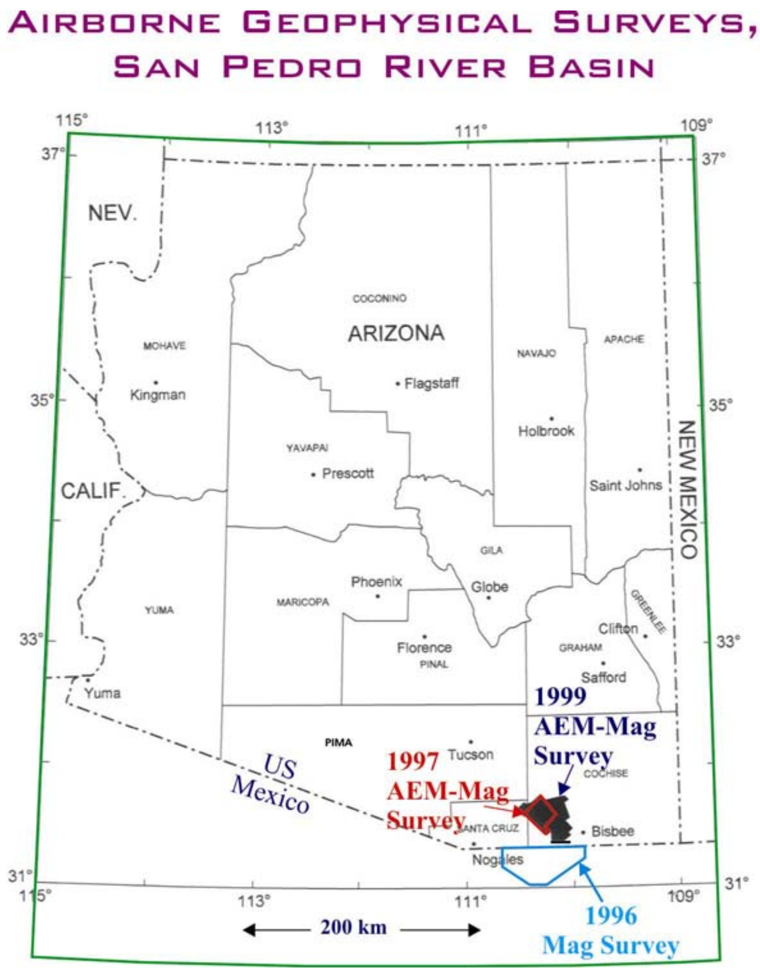

Figure 1. Index map showing locations of the airborne geophysical surveys referred to in the text.

In 1988 the US Congress declared the Arizona segment of the San Pedro River a National Riparian Conservation Area (narrow zone labeled “San Pedro River” in figure 2). This river comprises a key element of a major North American migratory bird fly-way, and was considered under serious threat due to an historical decline in surface water. Initial investigations suggested this might be due to extraction of ground water that exceeded annual recharge by the nearby city of Sierra Vista and the US Army base at Fort Huachuca (Pool and Coes, 1999). Other earlier work using gravity data (Gettings and Houser, 2000) suggested that the basement was a smoothly-varying surface beneath the modern Quaternary alluvium. A 1,000-square-kilometer airborne electromagnetic/magnetic survey (Wynn, 2000/2002), using higher-resolution magnetic data, showed that this basement contact is in fact quite complex (Wynn and others, 2000; Wynn, 2000/2003). The airborne EM component of the survey mapped the groundwater in the northern (American) part of the region in three dimensions, but did not extend across the Mexican border into the Sonoran San Pedro basin to the south. It is unreasonable to expect that the impact of various human activities on the groundwater of the San Pedro basin can be understood if only half of the basin has been analyzed. In an attempt to rectify the disparity in geophysical coverage, a scalar AMT survey was conducted on the Mexican side in cooperation with SEMARNAT, the Mexican environmental agency. In addition, a large airborne magnetic survey covering the region south of the border was obtained from a private mining company and processed for depth-to-magnetic-source.

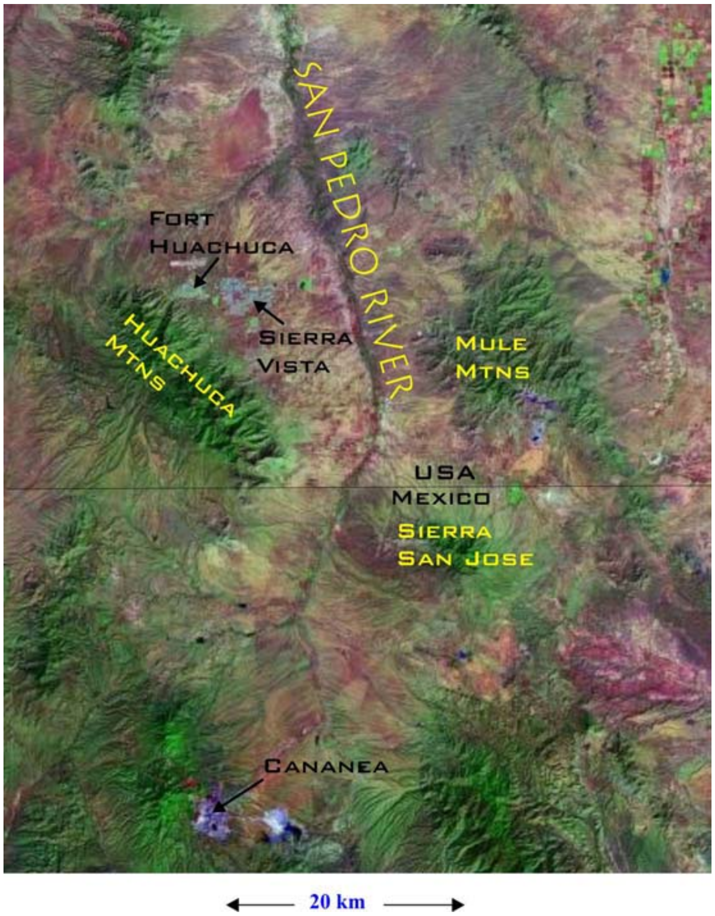

Figure 2. LANDSAT image showing the San Pedro basin, southern Arizona and northern Sonora State, Mexico. The San Pedro National Riparian Conservation Area is approximately the zone labeled in yellow as "SAN PEDRO RIVER".

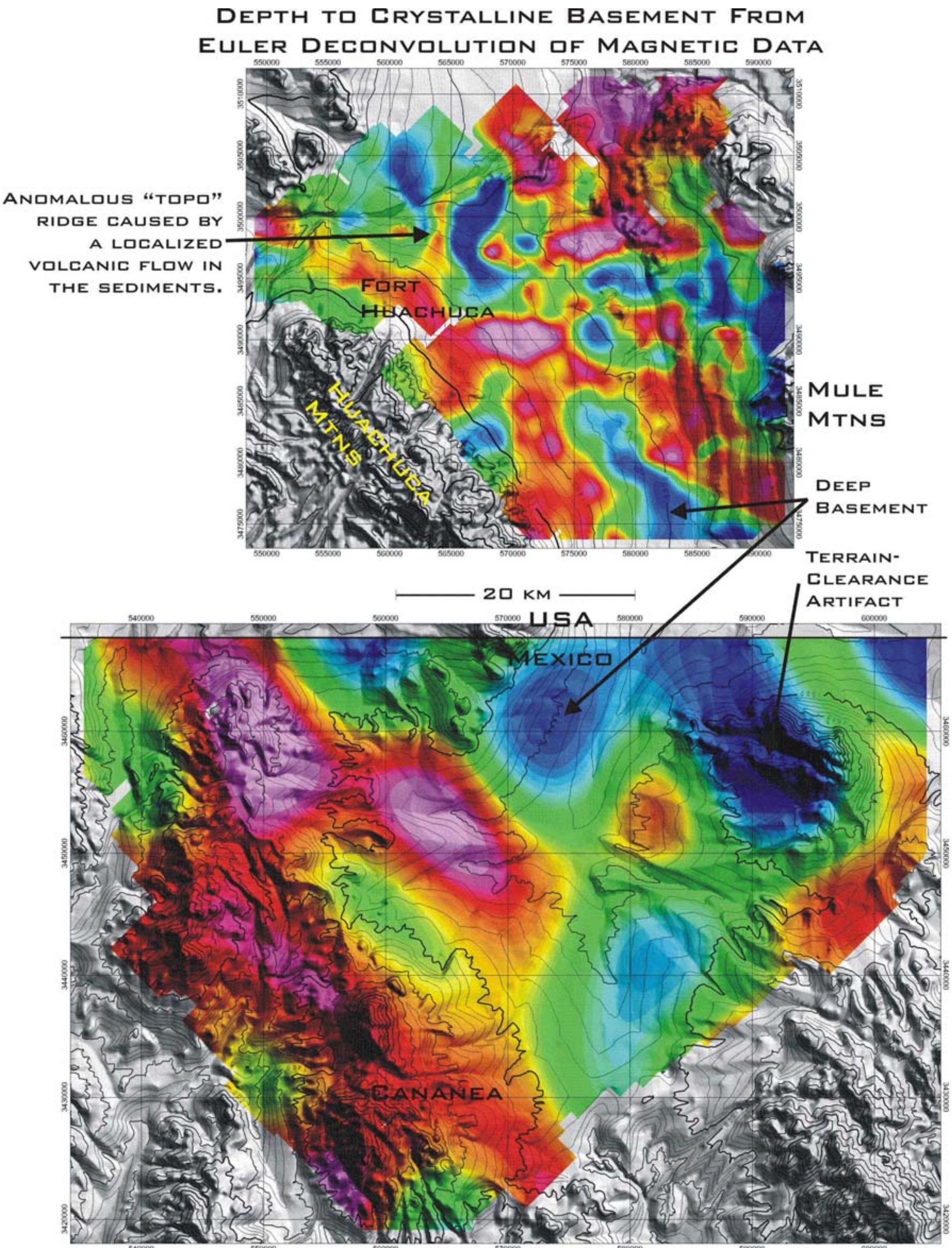

Figure 3. Figure showing depth-to-source derived from aeromagnetic data by using Euler deconvolution, San Pedro River Valley, southern Arizona and northern Sonora State, Mexico.

Magnetic Data

An aeromagnetic survey on the Mexican side of the international frontier was carried out in 1996, using both helicopter and fixed-wing platforms, a 250-meter spacing, and with flight-lines oriented approximately N70^{o}E (see figure 3). The data were provided to the USGS by Cyprus Mining company (now part of Phelps-Dodge, Corp.), and the acquisition and subsequent processing are described in detail in Wynn (2001). An Analytic Signal algorithm (Blakely, 1995), marketed commercially by Northwest Geophysical Associates as part of their "P-Depth" software system, was applied to individual profiles on the gridded aeromagnetic data. The Analytic Signal solution (using a structural index of 1 that emphasizes geologic contacts and faults) provides discrete depth-to-source information at a limited number of points along the line of interest. These points depend on where there is an inflection in the magnetic data that signal a change in the subsurface source. An extensive body of geologic work in the region was crucial for interpreting these results. Exposed bedrock, and the known structure and stratigraphy available to us, were then extended to the parts of the basin covered with Quaternary sediments.

AMT Data

AMT data was acquired in four different segments aggregating 20 line-kilometers around the southern margins of the Sonoran San Pedro basin (see figure 4). These data were processed using a method called smooth-model inversion (Wannamaker and others, 1986; MacInnes and Zonge, 1999), which provides a smoothly-varying, 2-D conductivity-vs-depth profile. Unfortunately, non-uniqueness doesn't allow a clear pick of where the crystalline basement lies in these profiles. In an effort to better define this contact between more conductive porous sediments and the presumably more resistive underlying basement rock, the P-Depth analytic signal depth-to-source software was applied to the aeromagnetic data along the four AMT profiles. Depth-to-source solutions can normally be obtained only where there is some variation in the magnetic properties of the source rocks, so the number of depth-solutions over a sedimentary basin is often limited - the data are generally smooth (in effect they are low-pass filtered by the depth). Nevertheless, the solutions that were obtained were sufficient to allow us to tie the crystalline basement to a particular contour interval in each AMT smooth-model inversion. This permitted us to map the sediment thickness with confidence along and beneath each of the four AMT profiles. While not the same as the 3-D conductor inversion obtained by the airborne geophysical survey conducted north of the border (Wynn, 2000/2003), these results do provide resistivity information to depths up to a kilometer, whereas the CDT inversions for the airborne EM data acquired north of the US-Mexican frontier can resolve interfaces only to a maximum depth of 400 meters.

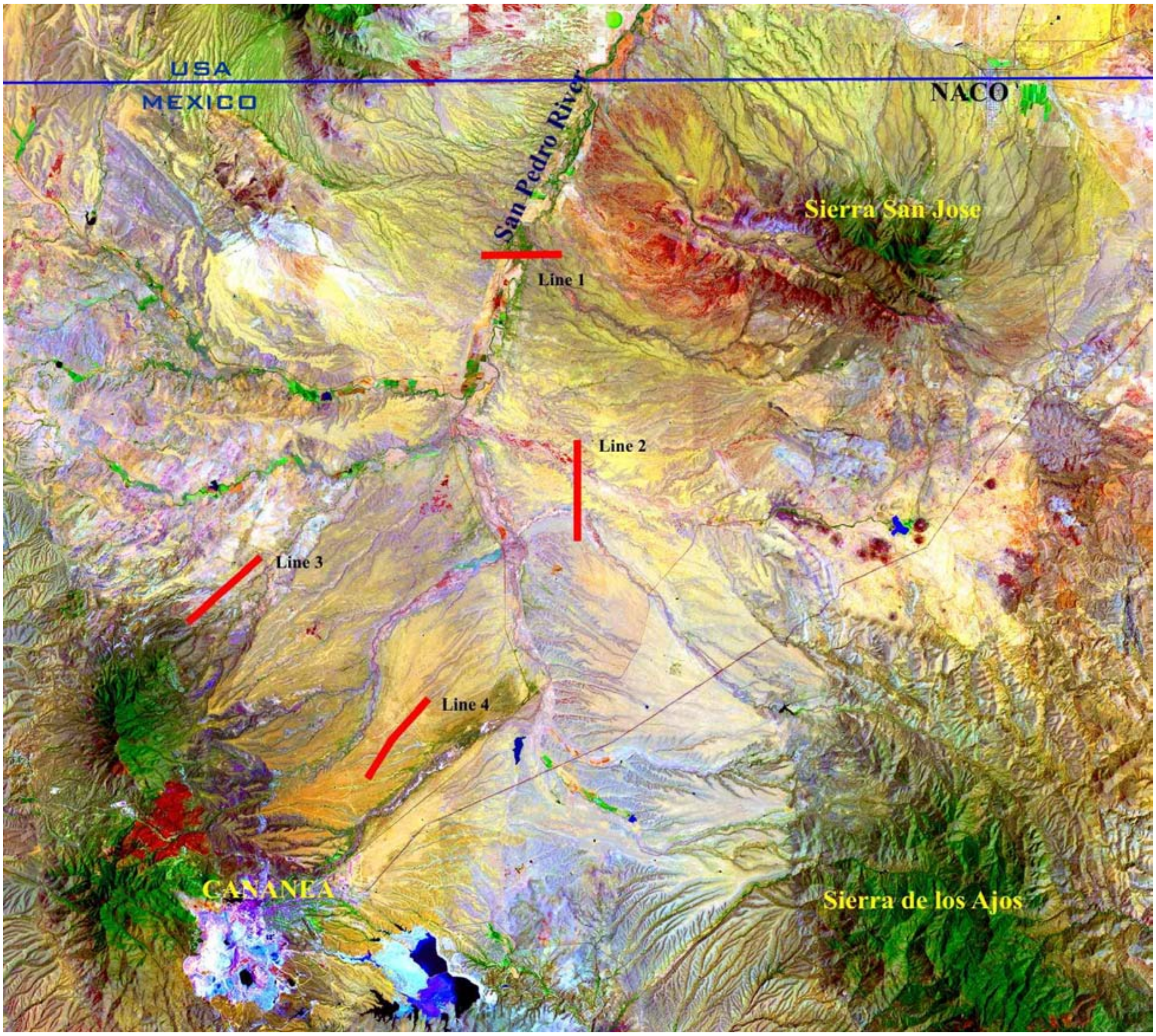

Figure 4. LANDSAT image showing the locations of the four AMT profiles acquired in northern Sonora State, Mexico.

Analytic Signal Solutions Constrain AMT Inversions - Examples

Figure 5a shows an example of the smooth-model AMT result for Line 1, located just west of the slopes and on strike with Sierra San José, and crossing the main San Pedro River channel on the eastern margin of the Sonoran San Pedro basin. As expected, the resistivity increases with depth along the profile, implying that the basement crystalline rock has lower porosity and therefor higher resistivity than the overlying sediments. The overlying sediments are quite conductive in this image, ranging from 6 to 12 ohm-meters, and in fact the San Pedro River exposes surface water intermittently between stations 1500 and 2000, suggesting the upper conductivity signal (the top 200 meters or so) probably represents a water saturated zone. Figure

5b shows the Analytic Signal depth-to-source inversion for the aeromagnetic data. Individual "picks" from the AS solutions can then be compared with the smooth-model AMT result, and this allows us to draw a solid line on the former (figure 5a) where we believe the contact between sediment and underlying basement rock lies. In this case there is a relatively smooth increase in depth to crystalline rock as one progresses westward along the profile. This is consistent with the nearby presence to the east of outcropping elements of the Sierra San José mountain range. In effect, the aeromagnetic data have been used here to constrain the smooth-model AMT inversion to fix the basement contact depth along the profile.

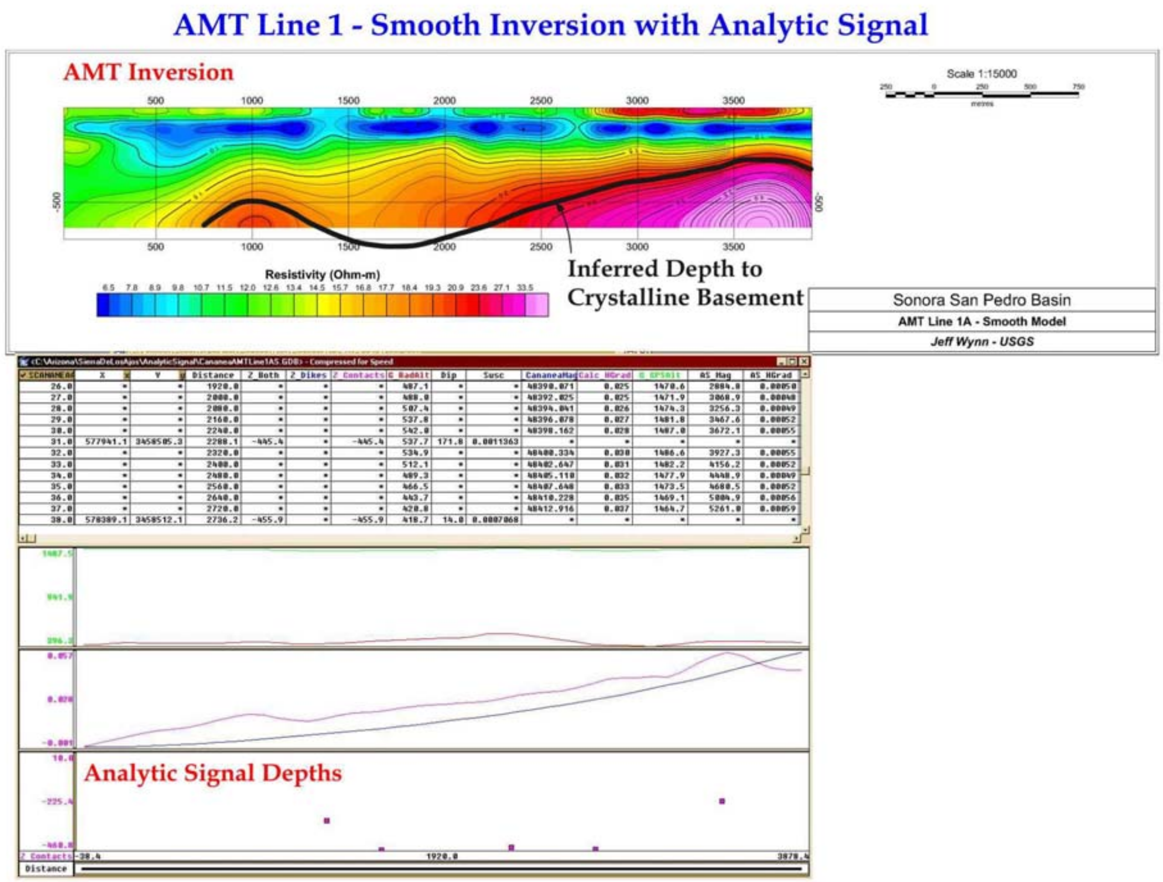

Figure 5. The AMT inversion (a) plotted against the Analytic Signal depth-to-source (b) for Line 1. The dark line in the top of the figure (5a)represents the inferred true depth to basement beneath overlying sediments.

Figure 6a shows another example, this time from the southwest margin of the Sonoran San Pedro basin just north of the town of Cananea, Sonora (refer again to figure 4). Because of the lack of outcrop or gravity data, the basin margin here was not known at all; even the magnetic data were not particularly helpful on initial visual examination. The results suggest an abrupt, normal-faulted transition from relatively shallow basement to much deeper basement as one progresses northeast along the profile. Figure 6b shows that Analytic Signal depth-to-source inversion can be used to constrain actual depths along the shallow-basement portion of the profile, but the normal faulting drops the basement northeast beyond the resolving depth of the AMT data (here about 600 meters maximum). A single Analytic Signal solution farther east suggests something rising back up towards the surface, a contention supported by the AMT smooth-model inversion, but without drill control we are unable to speculate as to the source of this anomaly. Geologic interpretation of the structural framework suggest that line 4 might intersect a strong trend of northwest-trending Basin-and-Range-related normal faults buried beneath alluvium in the upper San Pedro basin.

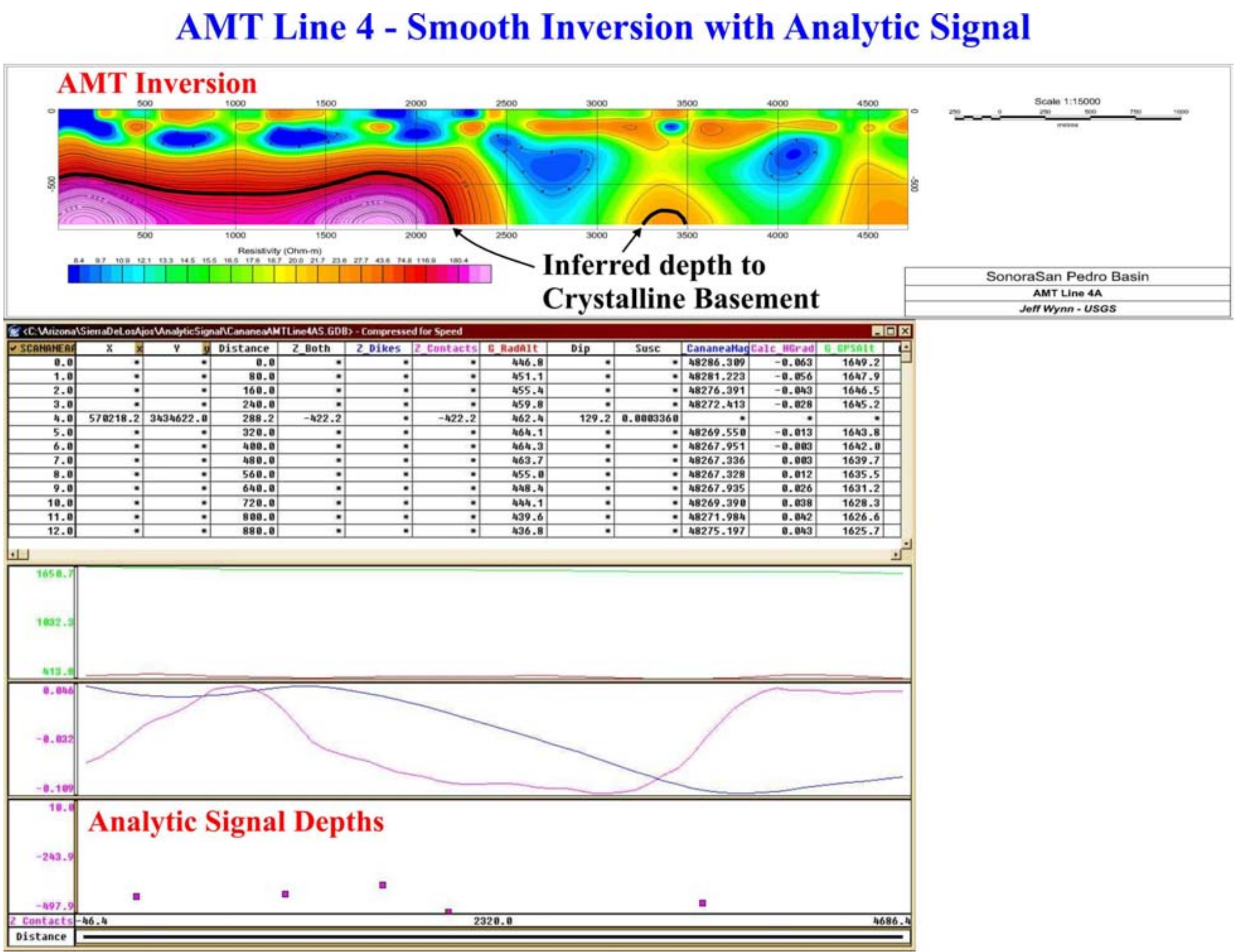

Figure 6. The AMT inversion plotted against the Analytic Signal depth-to-source for line 4. The dark line in the upper part of the figure (6a) represents the inferred true depth to basement beneath overlying sediments.

Conclusions

The use of two unrelated physical properties (magnetic susceptibility and resistivity) allows us to resolve inherent non-uniqueness in smooth-model inversion of the raw AMT data acquired in the Sonoran San Pedro Valley. New 2-D combined AMT-and-Analytic-Signal inversion profiles now allow geologists and hydrologists to work with realistic depths of sediments to model the distribution and movement of the groundwater in the Sonoran San Pedro drainage and understand the larger basin as a whole.

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