Mapping Groundwater in Three Dimensions: An Analysis of the Airborne Geophysical Surveys of the Upper San Pedro River Basin, Cochise County, Southeastern Arizona With an Interpretation of Where the Groundwater Lies

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ABSTRACT

This report summarizes results of two airborne geophysical surveys conducted in the upper San Pedro Valley of southeastern Arizona in 1997 and 1999. The combined surveys cover about 1,000 square kilometers and extend from the Huachuca Mountains on the west to the Mule Mountains and Tombstone Hills on the east, and from north of the Babocomari River to near the Mexican border on the south. Part of the survey included acquisition of high-resolution magnetic data, which were used to map depth to the crystalline basement rocks underlying the sediments filling the basin. The magnetic inversion results show a complex basement morphology, with sediment thickness in the center ranging from ~ 237 meters beneath the city of Sierra Vista to ~1,500 meters beneath Huachuca City and the Palominas area near the border. Another part of the survey included acquisition of 120-channel time-domain electromagnetic data. Extensive QA/QC analysis of these data, including inversion to conductivity-vs-depth (conductivity-depth-transform or CDT) profiles and comparisons with electrical well-logs, show that this electrical conductor maps the underlying water over most of the basin. In a few places (notably the mouth of Huachuca Canyon) the reported water table lies above where the electrical

conductor places it. These exceptions appear to be due to either older, 1970's-era water-table depths in a zone through which the recharge must pass, or to a subtle calibration issue with the CDT algorithm apparent only in areas of highly resistive overburden. In either case, the electrical conductor may indicate that water is located up to tens of meters below the water-table of record. These occasional disparities appear in less than 5% of the surveyed area. It has been observed, however, that wells drilled in the thick unsaturated zone along the Huachuca Mountain front eventually intersect water, at which point the water rapidly rises high into the unsaturated zone within the well-bore, which may explain these apparent discrepancies. This implies some sort of confinement below the thick unsaturated zone, but this is not clear from the available literature. The occasional disparities notwithstanding, maps of the electrical conductor derived from the airborne EM system appear to provide a synoptic view of the water underlying the Upper San Pedro Valley, including its three-dimensional distribution, and the data even show faults previously only inferred from geologic mapping.

The magnetic and electromagnetic data together appear to show the thickness of the sediments, the water in the saturated sediments down to a maximum of about 400 meters depth, and even places where the main water body is not in direct contact with the San Pedro River. However, the geophysical data cannot directly say anything about hydraulic conductivity or ground-water flow. These require new hydraulic modeling based in part on the information presented here. One issue of concern to reviewers of this report is the effect that clays may have on the electrical conductor mapped with the airborne geophysical system. However, the water in the basin is unusually conductive, averaging 338 μS/cm, and reasoning cited below suggests that the contribution of clays to the overall conductivity would be relatively small. Basic principles of sedimentary geology suggest that silts and clays should dominate the center of the basin, while sands and gravels would tend to dominate the margins. While clay-content may increase the amplitude of the observed electrical conductors somewhat, they will not affect the depths to the conductor derived from depth-inversions. Further, fine-grained sediments generally have higher porosity and tend to lie towards a basin center, a fact in general agreement with the observed geophysical data.

INTRODUCTION AND BACKGROUND

The upper San Pedro Valley in southeastern Arizona is an area of concern for ground water resources, in part due to its natural aridity and in part due to multiple competing land uses. These land uses include commercial development, ranching, military base activities, and the San Pedro National Riparian Conservation Area (SPNRCA), established by Congress in 1988, which established a Federal reserve water right, with a priority date of the Act, for minimum flows in the river. In early 1997 an airborne electromagnetic survey was flown at the request of the US Army over the Fort Huachuca Military Reservation and immediate surrounding areas (Wynn and Gettings, 1997; and Bultman, Gettings, and Wynn, 1999). This survey was designed and flown to provide detailed 3-dimensional information on the regional aquifer of the Upper San Pedro River drainage. Due to its initial success, in early 1999 a follow-up survey was carried out over three adjacent tracts of land (see index map, figure 1). In addition, an experimental line was flown east-west across the San Pedro valley near the Mexican border to help document structure and stratigraphy of the sediments, and also to locate the aquifer in the vicinity of the international boundary (survey outlines are shown in figure 2; note that in this and subsequent figures the coordinate system used is UTM Zone 12).

The objectives of these surveys (results of the four separate survey segments are merged here in this report) were to gather resistivity data from the upper 150-400 meters of the subbasin which could be used to help map the regional aquifer, and the geologic structures which might control ground-water flow. In addition, the survey acquired magnetic data which was used to develop a map of the magnetic field strength. This map can be used to help define the location of faults and fractures in the crystalline rocks forming the basement beneath the sediments (and in some cases volcanic rocks within the basin fill). The magnetic data can also be used to estimate depth-to-source of the crystalline basement rocks, and thus provide another set of estimates (in addition to the existing, relatively coarsely-spaced gravity data) of the sediment fill of the basin. The thickness of sediments bears significantly on the hydrology of the basin, since shallow crystalline basement may interfere with water-flow.

Brown and others (1966) identified two different basin fill units that comprise the regional aquifer: the relatively more porous upper basin fill (UBF) and the more consolidated, less porous underlying lower basin fill (LBF). Recharge to the regional aquifer in the Sierra Vista subwatershed of the Upper San Pedro groundwater basin (defined as the part of the San Pedro drainage bounded by the Mexican border on the south and the northern extents of the Babocomari River and Walnut Gulch drainages on the north, and by the Huachuca Mountains on the west and the Mule Mountains on the east) is estimated to be about 12,500 to 15,000 acre-feet a year, primarily from the Huachuca Mountains on the west of the basin, and to a lesser extent from the Mule Mountains and the Tombstone Hills on the east of the basin (figure 2 - see Freethey, 1982; Pool and Coes, 1999). In addition, there is up to 3,500 acre-feet per year of ground-water flow from Mexico (Freethey, 1982).

Current groundwater withdrawal from the Sierra Vista subwatershed was probably less than 11,000 acre-feet per year in 1991 (Corell and others, 1996). It peaked at around 15,000 acre-feet per year in the early 1980's, but has declined since then due in part to conservation measures, but principally due to the retirement of irrigation pumping. In addition, there is evapo-transpiration along the San Pedro River by phreatophyte vegetation (e.g., cottonwoods, mesquite, and willow trees that use ground water) that is estimated to be about 6,200 acre-feet a year (Freethey, 1982; Pool and Coes, 1997). In addition, ground-water discharge to the San Pedro River is about 5,900 acre-feet per year (Freethey, 1982). Total input to the ground-water system is about 18,000 acre-feet per year. Total outflow from the system of about 11k + 6.2k + 5.9k = 22,100 acre-feet per year results in depletion of ground-water storage. More importantly, ground-water withdrawals intercept the flow of ground-water to the river and riparian area. Significant interception of the flow will affect river flow, and will lead to an inevitable reduction in riparian vegetation. The ground-water deficit varies from year to year depending on climate, withdrawals, recent conservation measures, and consumption by large mines and Ehidos in Mexico.

Extensive fine-grained silt and clay layers have been identified in the regional aquifer (Pool and Coes, 1999). These fine-grained sediments tend to dominate the center of the San Pedro valley, consistent with being more distal from their weathering origins in the Huachuca and Mule Mountains, and they influence the ground-water flow and interactions between the regional aquifer and the San Pedro River. The fine-grained sediments are overlain and underlain by saturated sands and gravels (W. Steinkampf, USGS Water Resources Division, Tucson, AZ, written comm., 2000). Water level data from wells and several springs to the west of the San Pedro River indicate that the water table becomes increasingly shallow toward the San Pedro River, and ground water discharges as spring flow in places west of the river (Pool and Coes, 1999). Conductivity maps, and Conductivity-Depth-Transform (CDT) images discussed later suggest that parts of the San Pedro river in the vicinity of the Tombstone volcanic rocks (as mapped by Moore, 1993) are not in direct hydraulic contact (defined as saturated flow between aquifer and river) with the Sierra Vista sub-watershed of the Upper San Pedro Basin ground-water system.

This report describes the airborne geophysical survey, the operating parameters for the airborne geophysical system, and outlines the steps taken to assess quality control of the merged data-sets. It includes a section describing calculations of depth-to-source from the magnetic data (primarily addressing the depth to the crystalline basement underlying the San Pedro basin sediments). The report then shows several ways in which the combined 1997-1999 airborne electromagnetic (EM) data can be viewed to understand the 3-D aspects of the regional aquifer in the Sierra Vista sub-watershed. Water-table depths (Arizona Department of Water Resources, GWSI database, 2001, http://www.water.az.gov/hydrology/dload.html; see also the USGS Ground Water Survey Investigations database) are then compared with the shallow electrical conductor derived from the airborne electromagnetic survey. The water-table information dates from the 1970's through the 1990's; only the most recent value for a given well was used, but some have not been measured for several decades. Finally, a section discusses the issue of inversion of the electromagnetic data into Conductivity-Depth-Transform profiles (CDTs, or conductivity-vs-depth), what these tell us about the aquifer, and how reliable these inversions might be. A second method of doing inversions from the AEM data was tested and compared with the CDT results. Estimation of depth to water from these inversions was generally quite good, especially when compared to electrical well-logs. With a few exceptions discussed later, the CDTs for the entire survey area show maximum amplitude of the conductor at the water.

These surveys were designed and carried out under US Geological Survey supervision, at the request of the Environmental and Natural Resources Division at the Fort Huachuca US Army Garrison, which funded them. Fort Huachuca also provided funding to assist with the analysis and interpretation of these data in this and previous reports, provided logistical support to the flight crews, and provided copies of previous data and reports. Fort Huachuca's goal in assisting with these studies was to provide an objective, state of the art body of subsurface knowledge to those agencies and organizations trying to plan and manage water resources in the region.

NOTE: In the following discussion, the electrical properties of sediments are described in terms of conductivities, specifically in units of micro-Siemens per centimeter (µS/cm). This is done to make viewing the EM maps easier for the reader: red/purple in images shown later represents higher conductivity and shows where the water is located, as verified by comparison later on to e-logs. In general, it is expected that higher clay content would give an increased conductor amplitude, represented by the darker purple colors. The blue in the images represents lower conductivity, generally unsaturated zones and crystalline rock. Keep in mind that most ground geophysical measurements are reported as resistivity values (in ohm-meters). The relationship between the two is very straightforward: conductivity = 1/resistivity; for instance, 200 µS/cm = 50 ohm-meters.

PREVIOUS HYDROLOGICAL, GEOLOGICAL, AND GEOPHYSICAL STUDIES:

A number of hydrologic studies of the Upper San Pedro River basin have been produced over the years, one of the earliest being Brown and others (1966). This report described an Upper Basin Fill (UBF), a Lower Basin Fill (LBF), and an underlying, older Pantano Formation lying on crystalline basement. The UBF and LBF are lithologically similar; the main difference between them being relative porosity. The original ground-water model, on which all subsequent models have been based, was provided by Freethey (1982). The most recent studies include detailed hydrologic models, including one developed by the Arizona Department of Water Resources (Corell and others, 1996). Previous conceptual and numerical models assumed a fairly simple basin structure (in a subsequent section the reader will encounter a more complex basement configuration derived from aeromagnetic data in these two surveys).

The most recent hydrologic study of the San Pedro regional aquifer is by Pool and Coes (1999). They identified extensive fine-grained units in the regional aquifer, and provided detailed hydrogeologic sections of the sediments in the Sierra Vista sub-watershed of the Upper San Pedro River basin, based on well-data and a number of vertical electrical soundings. Pool and Coes define the primary regional aquifer as including "upper and lower basin fill, described by Brown and others (1966), that accumulated in the structural depression between mountain ranges during the Miocene through early Pliestocene ages" (Pool and Coes, 1999). Figure 8 of their report is particularly helpful as an overview of the sedimentary package hosting the regional aquifer.

A regional geologic and tectonic map completed by Drewes (1980) was supplemented in part by wilderness maps of the Coronado National Forest (Drewes, 1996; Kneale and others 1997). A 1:50,000-scale geologic map by Moore (1993) outlines a newly-discovered volcanic complex, and shows that parts of a large collapse caldera margin (part of what is now generally designated the Tombstone Caldera) underlie the eastern margins of the Fort Huachuca Military Reservation near the San Pedro River, including land covered by the airborne geophysical surveys. Together, these reports forced a fundamental reconsideration of the sub-basin structure. Reports by Halvorson (1984), Gettings and Houser (1995) and Gettings and Gettings (1996) provide an approximate map of the depth to bedrock beneath the Tertiary-Quaternary basin fill underlying the Upper San Pedro River drainage (compared later in this report with depth-to-source maps derived from the airborne magnetic data). These earlier studies revealed a depression in the bedrock as much as a kilometer deep beneath Huachuca City, and shallow crystalline rock underlying parts of the City of Sierra Vista. This latter structural high appears to be an uplifted basement block, and is supported by a driller's log of well **D(21-20)35abb**, where crystalline basement was encountered (237 meters or 770 feet deep) near Fry Blvd in downtown Sierra Vista. Euler deconvolution of aeromagnetic data (later in this report) also supports and augments information on these structures in the underlying crystalline basement. A seismic reflection study designed to map the water table and the aquifer (Environmental Engineering Consultants, 1996) gave inconclusive results.

There are no previous airborne electromagnetic surveys over the area known to exist. Pool and Coes (1998) have collected and analyzed ground-based electric soundings and profiles at selected sites in the area, and the area is included in earlier regional aeromagnetic surveys at 1 mi. spacing between flight lines (Andreasen and others, 1965) and proprietary mining company data at 1/3 mi. spacing. Geophysical logs of nine test wells on the Fort Huachuca Military Reservation are available (U.S, Army Corps Of Engineers, 1972, 1974) and were used for evaluation of the airborne data in the 1997 airborne geophysical survey covering the center of the study area (Wynn and Gettings, 1997; Bultman, Gettings, and Wynn, 1999). The Arizona Department of Water Resources provided a digital dataset of water-well locations and depths to water measured within the last few years for comparison to the electromagnetic data interpretation (also available in the USGS GWSI database). Gettings and Gettings (1996) collected and interpreted a detailed ground magnetic profile from the Dragoon Mountains southwest across the valley to the East Gate of Fort Huachuca. Halverson (1984) conducted the first gravity survey to map the depth to basement in the San Pedro Valley. Gettings and Houser (2000) have collected, compiled, and interpreted gravity anomaly, water resources, and exploration borehole geologic logs, and surface geologic data to model the depth and shape of the basin in the Sierra Vista to Huachuca City area. Significant amounts of proprietary geologic, geophysical, and geochemical data collected by mineral exploration companies exists for areas of bedrock outcrop, but were not available to the author.

DATA-ACQUISITION FOR THE 1999 AIRBORNE GEOPHYSICAL SURVEY:

The 1999 airborne geophysical survey (referred to elsewhere as the "Tombstone Survey" to distinguish it from the 1997 "San Pedro Survey") was conducted from 22 February to 1 March, 1999, and acquired both electromagnetic and magnetic data. Three discrete areas were flown, designed to supplement coverage from the 1997 (San Pedro) airborne geophysical survey of Fort Huachuca and surrounding areas (reported in Wynn and Gettings, 1997; Bultman, Gettings, and Wynn, 1999). These areas are labeled 1999-1, 1999-2, and 1999-3 (see Figure 2), and extended from Lyle Canyon to the city of Tombstone in the north, to the Mule Mountains and Greenbush Draw on the east, and over to the Huachuca Mountains on the south about 5 miles from the Mexican border. In addition a single 6-mile (10 km)-long profile was flown parallel to, but approximately 2 miles or 3 kilometers north of, the Mexican border to monitor ground water between the headwaters of the Upper San Pedro Drainage in Mexico (see figure 3) and the regional aquifer in the US part of the study area. The data were flown so as to be seamlessly merged with the 1997 survey, with the exception of this single experimental profile (analyzed in some detail at the end of this report). A total of 849 line-miles of data were acquired, including 385 line-miles in Area 1, 176 line-miles in Area 2, and 282 line-miles in Area 3. Line-spacing in Areas 1 and 2 was 0.25 miles (~400 meters); in Area 3 it was flown at 0.5 miles (~800 feet) spacing in order to fit within survey contract specifications but also maximize the areal coverage on the southern margin of the survey. Figure 3 shows the flight-line spacing (1/8th mile or 400, and 1/4th mile or 800 meters), the flight- line orientation for each segment flown, and the total line-miles covered in each section. Figure 4 shows the line-coverage superimposed on the local roads and topography for reference.

The survey utilized a CASA[1] C-212 twin turbo-prop aircraft, with nominal survey flight-speed of about 125 knots (145 mph, or 65 meters/sec), flown at a nominal terrain-clearance of 120 meters (~400 feet). A Rosemount[1] 1241M barometric altimeter was used to control survey aircraft elevation; this unit has a sensitivity of about 1 foot/0.3 meters in a 1-second recording interval. The radar altimeter was a TRT[1] AHV-8 model with a 2% accuracy over a 0 to 2,500 foot (0 to 800 meter) range; it also had a 1 second recording interval. A Panasonic[1] Super VHS camera model WV-CL302 was used to aid navigational recovery and help identify cultural interference, and electronic navigation was maintained to a horizontal precision of +/- 10 meters by using a Sercel[1] differential GPS receiver model NR103. This GPS system sampled location once every second to a resolution of 0.00001 degrees.

The magnetic data were acquired using a Scintrex[1] CS-2 single-cell cesium-vapor magnetometer, which was trailed in a towed sonde called a "bird" behind the aircraft sampling at 0.1 second intervals; this gives a magnetic data-density along lines of about one sample per 6.5 meters or every 20 feet. Nominal sensor height was 73 meters (240 feet) above ground. The noise envelope for this survey was estimated by the contractor to be about +/- 0.5 nano-Teslas (nT). A base station magnetometer was also operated at the Fort Huachuca airport to provide data for the diurnal magnetic field correction. The contractor completed corrections to the magnetic field data for diurnal drift, for sensor-lag (sensor distance behind GPS antenna), for leveling (tie line intersections), and subtraction of the International Geomagnetic Reference Field computed at an altitude of 1431 m (4,700 feet) above mean sea level. The contractor also supplied the magnetic field data as digital files of data along the flight lines, and on a grid with an interval of 50 m.

The GEOTEM[1] Airborne ElectroMagnetic (AEM) System is a proprietary EM exploration system only available from Geoterrex/Dighem[1]. It uses a transmitter coil of 232

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[1]Use of manufacturer's names and equipment designations is for descriptive purposes only and does not imply endorsement by the US Geological Survey or US Department of the Interior.

square meters with 6 turns, flown at a nominal height above ground of 120 meters (400 feet). The transmitter signal-current was an unusual time-domain signal (a 4080 microsecond half-sine followed by a 12,486 microsecond flat off-time) with an amplitude of 500 amperes. The dipole moment was 6.96×10^5 Amp-Meters^2 The multi-coil (3-axis: x, y, and z) receiver system was towed behind the aircraft in a bird maintained about 70 meters above the ground surface and approximately 125 meters behind the transmitter coil center. In order to have maximum penetration of the underlying sediments, the system was set to operate with a base frequency of 30 Hz; this provides a transmitter pulse width of 4080 microseconds.

The x-axis (in-line) and y-axis (side-looking) receiver components are optimally coupled for detecting vertical conductors (for instance vertical-sheet massive sulfide deposits or vertical/subvertical water-filled faults oriented perpendicular and parallel to the flight-path respectively). The z-axis (transmitter and receiver both having vertical-axis co-planar) component signal is optimally coupled for measuring the conductivity of horizontal layers beneath the ground surface, and is the coil orientation focused on in this report as being most useful for mapping shallow horizontal conductors, e.g., conductive ground-water. All three components will report anomalies over power lines, pipelines, and grounded fences. The transmitter by virtue of its horizontal layout is geometrically configured to induce (primarily) horizontal-plane eddy currents in the ground; the vertical (z-axis co-planar) receiver coil is thus optimally coupled to detect a secondary field from these eddy currents as deep as 400 meters in some cases.

The GEOTEM transmitted waveform is a unique half-sine-wave-followed-by-an-off-period signal that can be lengthened for maximum depth of penetration or shortened for maximum near-surface resolution. For the purposes of this survey the waveform was lengthened to near its maximum for the deepest possible penetration: a 30 Hz repeat-rate and a 4 millisecond sampling rate were used. The output "channels" consist of sampling windows taken at increasing time gates (one can translate these increasing time-gates as correlating with increasing depth below the surface) in the received secondary waveform for each of three coil orientations. In addition to 120 EM channels (20 time-windows each, times the three orientations, with an in-phase and a quadrature component each) the GEOTEM system also acquires data from a separate magnetic sensor, plus an additional 60-Hz monitoring channel to help distinguish man-made, grounded metallic structure anomalies (such as pipelines and power lines) from geologic anomalies. These signals are location-corrected during post-flight data-processing for the distance-lag caused by the retarded position of the two detector birds trailing behind the aircraft on their respective cables.

The GEOTEM system also acquires Differential Global Positioning System (DGPS) location signals as well as continuous videotape of the ground (used to resolve any remaining man-made-vs-geologic-source issues, and as backup to the DGPS location information). The differential GPS reference beacon was located at the Sierra Vista airport during the survey. The EM channels are calibrated periodically by flying over a well-characterized homogeneous target such as seawater, and also calibrated daily by flying the aircraft at the beginning and end of each survey at approximately 8,000 feet AGL (about 2,500 meters above the earth), so any possible conductors are well beyond the reach of the rapid-fall-off dipolar transmitted signal, and thus ground contribution is negligible). The data are also corrected for any residual signal caused by interaction of the transmitted pulse with the body of the aircraft (this is referred to as "compensation"). Barometric elevation and radar-altimetry channels are also acquired to verify the vertical position of the aircraft.

Since the transmitted signal from an alternating electromagnetic dipole such as the GEOTEM transmitter antenna falls off rapidly as one over the distance cubed, it is critically important to maintain the aircraft as close as possible to the ground for maximum penetration of signal. During the 1997 San Pedro River and 1999 Tombstone surveys the aircraft was "drape-flown" over the terrain at 400 feet AGL (about 125 meters above the ground surface), with the exception of a zone flown at 500 feet (about 155 meters) over the populated areas such as the City of Sierra Vista and Fort Huachuca. This local exception was a flight requirement to conform to FAA regulations. While flying at 400 feet AGL the magnetometer is nominally 120 feet (about 40 meters) below the aircraft and the EM bird is about 160 feet (slightly more than 50 meters) below the aircraft.

The GEOTEM system is a time-domain EM system; this means that data were sampled at certain defined time-gates, some before but most after the transmitter signal is switched off. These time-gates are sampled for each of the 3 components of the received EM signal detected at the towed bird. As indicated above, the base frequency was 30 Hz; that is, the transmitter was switched on and then off again 30 times per second. The channels used to sample the received signal are listed in Table 1. In this table, the delays indicate the start of the gated window in microseconds from the end of the transmitted pulse for the given channel. Negative delays indicate that the window was started before the end of the transmitted pulse; this is necessary in order to gather sufficient information to do inversions to conductivity vs. depth.

Table 1. EM time-domain gates.

Channel #	***Window starting-point: delay in microseconds from the end of the transmitted pulse.***
1	-3906 *(Transmitter-on data is*
2	-3169 *important in order to*
3	-1975 *precisely characterize*
4	-782 *the transmitted signal)*
5	-44
6	195
7	391
8	630
9	911
10	1215
11	1541
12	1931
13	2409
14	2995

15	3733
16	4665
17	5837
18	7313
19	9136
20	11306 microseconds

Between the 1997 and 1999 surveys the GEOTEM system was modified slightly; primarily, the channel designations were changed to order them in a more logical numerical sequence. In order to spline data-blocks from both surveys it was necessary to use the same time-gates so the system was measuring approximately the same conductivity at the same depth. Since the transmitter sets up eddy currents in any conductors in the ground, the secondary signal received (i.e., the signal received at the towed bird after the primary transmitter signal is turned off) from deeper depths would arrive later than a secondary response from shallower depths. There is an averaging effect going on also, so there is not a direct linear relationship between gate-times and depths. As a rule of thumb, however, the longer the time-delay in the sample-gate, the deeper the detected signals are coming from. For this reason we can use different time-gates to effectively sample different depths. The correlation between sampled channels between 1997 and 1999 surveys is listed in Table 2. These channel-equivalencies are presented with their relative depth of penetration indicated. Note that depth of penetration varies significantly all over the target area, and is controlled by variables such as aircraft elevation (increased flying elevation decreases depth penetration), degree of electrical interference (greater electrical interference reduces S/N and thus reduces depth of effective penetration), and ground resistivity (the greater the resistivity the greater the depth of penetration), among others. The CDT inversions discussed later compensate for the most of the fluctuations in elevation.

Table 2. Channel equivalencies between the 1997 and 1999 AEM Surveys.

1997 AEM Survey Channel #	1999 AEM Survey Channel #	*Relative Depth Penetration§*
2	10	Shallow

6	14	Intermediate
10	18	Deep

§See comments in the paragraph above.

Finally, using the Geosoft[1] Grid-Knit[1] software, the original 1997 dataset and the three 1999 data-sets, for the magnetic field as well as the three EM channel grids that we were interested in, were spliced together. The splicing was seamless for the magnetic data, and generally excellent for the EM channels except for an imperfect splice made difficult by an area of high topographic relief in the Tombstone Hills in Area 1.

QUALITY CONTROL ANALYSIS:

The GEOTEM airborne geophysical system is advanced and very complex, and as a result there are many variables that can affect data-quality. These include the relative locations of the towed birds with respect to the aircraft, among others. The transmitted signal is dipolar in form, which means that there are significant changes in detected signal strength for only small changes in geometry -- even if absolute coil-to-coil separation is unchanged. The relative position of the birds has been shown to have a significant effect on the data, both in signal-strength (fluctuations could thus look like changes in subsurface resistivity), and signal-to-noise (the noise threshold can exceed the signal, especially for secondary signals from deeper conductors). If the aircraft moves up and down significantly while draping rough terrain, then there will be fluctuations in apparent resistivity detected by the system (there is a lesser, but still non-zero, effect of these fluctuations on the magnetic data). Extensive engineering work has gone into compensating for this elevation-fluctuation effect, i.e., procedures to correct for these inevitable fluctuations, but they can never be perfect. The GEOTEM system was designed, however, to hold these signal-strength fluctuation effectss down in the part-per-million range for most flying conditions.

In addition to structural "flex" in the aircraft-bird geometry, there can be short-wavelength errors in the radar altimetry data (from electrical interference such as regional lightning or airport radar transmissions) and long-wavelength errors in barometric altimetry data (from weather systems moving through the area), both of which affect the signal strength and thus the apparent resistivity of the local subsurface sediments. There is also the theoretical potential for temperature-controlled or vibration-caused changes in the GEOTEM electronic systems. Much of the work done by flight engineers and post-processing technicians is devoted to compensating for these potential errors.

The survey target areas, especially Area 1, have significant topographic relief that the aircraft must try to drape over. In addition, there is always some degree of air turbulence due to rising heat from the desert floor, especially in the afternoons. Twice during the 1999 survey the aircraft was forced to return to base early when turbulence began to affect data-quality. In order to check these various effects on the data that was finally reported out by the contractor, I generated several comparison figures.

The contractor carried out altimeter calibration by making a series of level overflights over the Sierra Vista airport runway, whose elevation is well-known. Results of these calibration flights are shown in figure 5, which shows barometric elevation fluctuations of less than 15 feet (~5 meters). The GPS elevation noise is also shown in this figure for comparison. However, because GPS systems cannot take advantage of satellite geometry both above and below the aircraft (the Earth is in the way), the GPS elevations are always much noisier than horizontal position (therefore the GPS elevations were not used in the survey except as a rough data-check).

Figure 6 (View #1) shows a superposition of measured radar altimeter variations (in color) on shaded-relief topography (gray textures), with contour-lines of the shallow (1999 EM channel 10) z-axis conductivity. In this figure we can see correlation between both flight-line directions as well as topographic relief and the radar altimetry. Subtle fluctuations in the contours of the conductivity correlate closely with the slight "herringbone" effect in the radar altimetry. These fluctuations are within contract specifications however (some lines were re-flown when the fluctuations exceeded contract specifications). In the 1997 survey, some of the coverage over occupied areas such as Fort Huachuca and Sierra Vista had to be flown at a 500-ft terrain clearance because of FAA flight rules; non-habitation areas in the 1997 and 1999 surveys were flown at an optimal terrain clearance of 400 ft to maximize penetration of the EM transmitted signal while minimizing risk to the aircraft.

Figure 7 (View #2) shows the radar altimetry (this time as line-contours) superimposed on the 1999 EM Channel 10 z-axis conductivity (in color). Both are laid out over shaded-relief topography (digital USGS elevation data in gray-tones) for reference. This figure much more clearly shows that subtle wiggles on the edges of the conductivity anomalies in Area 1 of figure 3 are caused by radar altimeter fluctuations, which in turn are caused by the aircraft attempting to drape some of the more rugged topography. This figure shows that the affects of uncompensated aircraft motion are relatively small, especially considering the non-flat topography of the target area..

Finally, figure 8 (View #3) shows the radar altimetry fluctuations superimposed on the contoured-shaded-relief topography. From this it is clear that the fluctuations are almost all due to changes in the topography that the aircraft is attempting to negotiate. See, for example, the western parts of the Babocomari River (located around UTM Coordinates 3,500,000N, and 550000E to 555000E) where topographic relief caused larger than average variations in radar altimetry. All these figures indicate that the data returned by the contractor at least met (and generally exceeded) the survey contract specifications.

These comparisons are self-consistency checks based on data released by the contractor. During the 1999 survey the author served on-site as the Contracting Officer's Representative, working with flight-engineers and the data-reduction team to assure quality-control procedures were strictly adhered to. In addition, for several months after the data were released, correspondence was carried out between the author and the contractor to obtain all the data in useable formats. For instance, the "Mexico Line" was missing from the initial data-release; this does not reflect culpability on the part of the contractor, because the data were being released as fast as they were being processed (in piecemeal stages), to assist the USGS in starting work on the data analysis as soon as possible. Minor problems observed during the early data-checking phase were always corrected by the contractor within a day or two of request by the author; none of these problems required re-acquisition of data, however. Consequently, the data included as appendices of this report should be considered as the complete data-set for the 1999 survey. For convenience, the 1997 data are also included as part of the merged data-sets in this report. The 1997 data have already been released separately (Bultman, Gettings, and Wynn, 1999).

MAGNETIC DATA AND DEPTH-TO-BASEMENT:

Figure 9 shows the shaded-relief color-contoured magnetic data as a merged set of the 1997 and 1999 airborne surveys. The data are dominated in the center by a large magnetic high caused by the Tombstone volcanic field. There are small magnetic-noise anomalies caused by Fort Huachuca and Sierra Vista. In the northwest there is a magnetic high thought to be caused by Tertiary volcanic rocks. There are only small volcanic outcrops observed on the surface in the northwest part of the survey area (Kneale and others, 1997), and most of the mapped volcanics are off the map to the north and northwest. This anomaly implies that a significant amount of Tertiary volcanic material underlies the Tertiary-Quaternary sediments near Huachuca City (**Tv** outcrops in several places north of Fort Huachuca before the Mustang Mountains, and also along the Babocomari River; see Drewes, 1980). The data represented in this figure aren't particularly useful unless we have an interest in the geology of the volcanics or the basement rocks, something beyond the scope of this report. Magnetic contour maps generally show relatively little of the total information available in the magnetic data they are contoured from. In this case this is due to the dynamic range of the data being saturated by the strong magnetic high caused by the Tombstone volcanic field.

There is additional information hidden in subtle variations in the magnetic data which we can extract to provide ***depth-to-magnetic-source*** information. Wherever there is a small lateral change in the magnetic field strength (in most cases changes that are smaller than the contour intervals on these maps) we can calculate the depth to that source -- presumably from a geologic contact between two different lithologies with slightly different magnetic-mineral (usually magnetite) content. Usually, these changes are caused by geologic and fault contacts in crystalline basement rocks beneath a basin such as this. However, with the presence of Tertiary volcanic rocks (Drewes, 1980; Gettings and Houser, 2000) we must deal with the possibility that there could be volcanic flows with magnetic minerals intercalated in the sediments above the crystalline basement.

One method for calculating depth-to-source from magnetic data is called Euler deconvolution (Reid and others, 1990; Blakeley, 1995, p. 242-245). In simplest terms this method for calculating depth-to-source can be explained as follows. In an area with many subtle variations in magnetic field strength (each caused by a change in magnetite-content in the underlying lithology), a model can be theoretically constructed that breaks the anomaly source into many small prism-shaped sources. An analytic model that calculates the effect of each simple prism-shaped source can be incorporated into an "inversion" system, that is, an algorithm that continually compares the aggregate model solutions for a segment of the magnetic map, and modifies the model source until a "best fit" is obtained. In fact, the inversion effort (i.e., going backwards from the magnetic data to the geologic source) is best carried out as a non-linear process, since experience has shown that the comparison-and-modification part of the process can quickly become unstable. If the algorithm thus developed is passed along a profile it can calculate depth-to-source for multiple sources very quickly. These results vary widely in quality, however, depending on noise in the original data, and must be "windowed", that is, selected for sensitivity of the result to slight variations in horizontal and vertical changes in the small prism model sources.

Euler deconvolution was carried out on the merged 1997-1999 magnetic data-set. The results can be represented in several different ways, each of which has advantages and disadvantages. Figure 10 shows a map of the Upper San Pedro drainage with numerous circles on it. Each circle represents a windowed (i.e., acceptable quality or low-noise) solution for a small change in the magnetic field strength. The larger the circle, the deeper the source; also, warmer colors indicate a deeper source. This kind of presentation allows the geophysicist to see both the quality of the data (by the coherence of the solution-circles) and - equally important - where there is little information available (i.e., the absence of solution-circles in low-gradient zones). In addition, some structural information can be gleaned from this type or presentation: circles that lie along a line represent either a geologic contact or a fault-offset in the crystalline basement. However, they could also represent geologic contacts between non-magnetic sediments and thin layers of magnetic volcanic rock interleaved within the sediments. Finally, when small circles appear to stack on increasingly larger circles but with an offset with size, this implies a dip or non-vertical tilt in the geologic or fault contact.

We can also represent the results of the magnetic depth-to-source calculations as a color-shaded grid in figure 11. This is intuitively easy to visualize; deeper basement is represented by cooler colors, and shallower basement is represented by warmer colors. For reference, figure 12 shows the contours of depth-to-basement derived from gravity data (Gettings and Houser, 2000). These gravity contours are based on a much sparser gravity station dataset. The magnetic data, in contrast, show a much more complex basement than the gravity map of figure 12. Most of the differences can be ascribed to either the greater density of magnetic data or to "geologic noise". An example of "geologic noise" could be different depth-solutions caused by magnetic rocks lying at two different depths, one over the other.

Near Huachuca City, there is an apparent "ridge" in the basement that is almost certainly caused by a narrow channel filled with volcanic material from the Tertiary volcanic rocks that are now intercalated in the sediment stack in the northwestern part of the survey area. This apparent ridge is located at UTM coordinates 3500000N, 564000E in figure 11. The San Pedro River, with one or two small exceptions in the study area, runs over parts of the basin underlain by shallow crystalline rock and relatively little sediment. The electrically conductive aquifer discussed later correlates rather well with the deeper sections of the basement lying to the west of the river. In the northeastern quadrant of the study area the San Pedro River, Walnut Gulch, and the Babocomari River intersect and are underlain by large sections of shallowly-buried-to-surficial exposures of the Tombstone volcanic field. The relationship between the basin sediments and the bedrock in the Tombstone Hills area is complex and may be both stratigraphic (Cenozoic basin sediments unconformably overlie the Cretaceous volcanic rocksintercalated volcanic flows in the sedimentary stack) and fault bounded. This region lies in the mapped Tombstone caldera margin (Moore, 1993).

One can see a roughly east-west deep basement feature (the blue feature extending from the figure's right side to around UTM coordinates 3495000N, 380000E in the middle of the figure) passing south of Tombstone, and it apparently intersects another northwest-southeast deep basement zone that roughly parallels the Huachuca Mountain front but lies to the east of it (the NNW-SSE blue zone on the left-center of figure 11).

The magnetic depth-to-source map in figure 11 agrees remarkably well with the gravity depth-to-basement map, figure 12. There is a structural high (probably a horst or uplifted fault-block) underlying the city of Sierra Vista centered around UTM coordinates 3490000N, 570000E. This has been verified by a drillers log of well D(21-20)35abb, which encountered crystalline basement at 237 meters (770 feet) beneath the city. There is also a north-south fault (roughly along UTM Longitude line 565,000E) that extends from the Whetstone Mountains to the north just beyond the northwest corner of the study area to the Huachuca Mountains on the south (referred to in Houser and Gettings, 2000, as the "Range-Front Fault"). The deep (at least 1000 meter-deep) basin beneath Huachuca City (UTM coordinates 3505000N, 562000E) appears in figure 11 to be more than one basin, but the apparent ridge in the middle is likely a stringer of volcanic materials in the middle levels of the sediment-stack– from the Tertiary volcanic rocks just off the northwestern corner of the map and tiny outcrops in Babocomari River (Houser and Gettings, 2000). There is support in the depth-to-magnetic-source map for east-west faulting and uplift of basement rocks (probably related to 16-20 million-year-old Basin-and-Range faulting, though an east-west orientation is unusual in B&R faulting). There is some geologic evidence that these faults have been recently active (Gettings and Houser, 2000). There is also support in this map and from geologic mapping to the north of the study area (Gettings and Houser, 2000) for north-south faulting of indeterminate character.

The results obtained from the Euler deconvolution of the magnetic data should enable hydrologists to better assess the thickness of the Upper San Pedro drainage sediments that lie deeper than the airborne electromagnetic system can penetrate (depending on the degree of human electrical cultural interference present locally, this maximum direct depth of water detection by the AEM system discussed in the following section could be anywhere from 100 to 400 meters deep). However, structures deeper than 300-400 meters are of little hydrologic significance because there is generally less ground-water flow with depth, and the sediments at great depth have reduced porosity due to consolidation and compaction (Ingebritsen and Sanford, 1998, page 274). The CDTs discussed later appear to support this by showing closure (termination) of many of the electrical conductors at depth.

THE AIRBORNE EM DATA AND WATER IN THE SAN PEDRO BASIN:

In this part of the report I have chosen not to discuss the X-axis and Y-axis airborne EM data because in the Upper San Pedro basin they are very similar to the Z-axis EM data to be analyzed in detail below. I have chosen to focus the following interpretation almost exclusively on the Z-axis imagery because it is an optimally-coupled signal for mapping horizontal and sub-horizontal conductors. This approach is just the opposite of airborne EM investigators searching for mineral resources, where complex vertical and sub-vertical structures are generally the key to understanding the mineralization process.

Figure 13 is presented here as another form of index, or reference map. This image is taken from part of a larger Landsat Thematic Mapper image (Dohrenwend, 1999). The bright colors were deliberately enhanced to show subtle differences in surface rocks and soils that could be attributed to hydrothermal alteration, a process closely related to mineralization. The figure is used here, however, to provide a recent (1997) reference to the outlines of the growing population of Sierra Vista and surrounding areas. Airborne EM data are strongly influenced by human cultural interference such as power lines and pipelines.

Figures 14, 15, and 16 show the airborne EM images acquired using the Z-axis coil in the GEOTEM[1] system; they represent channel 10 (shallow), channel 14 (intermediate), and channel 18 (deep) respectively. The channels referenced here are from the 1999 survey, but the results hold for the entire survey area. The redder or "hotter" colors represent zones of higher conductivity caused by the occurrence of water with some additional contribution from clays. In these figures the San Pedro River, Babocomari River, and Walnut Gulch are represented as thick blue lines for easy reference; these features were digitized from the US Geological Survey 1:250,000-scale topographic map.

The San Pedro Basin lies in a relatively arid zone, and the ground-water has a generally higher conductivity from less extensive flow-through than experienced in wetter, more temperate regions of the US. Rainwater normally has very low conductivity, but when it rests in an aquifer over an extended period of time it will take on dissolved ions from the surrounding rocks and soils and become more conductive unless flushed by recharge and ground-water flow. Ground-water in the regional aquifer is potable, considered good quality in comparison to other nearby arid basins (Pool and Coes, 1999). However, conductance of ground water in the regional aquifer ranges from about 200 μS/cm to 1,200 μS/cm and averages 338 μS/cm (this latter is the same as a resistivity of 30 ohm-m; these values are taken from Pool and Coes, 1999, plate 3). Most geophysicists consider even 200 μS/cm to be conductive groundwater (Ken Zonge, Zonge Engineering & Research, Tucson, AZ, oral comm., 1999; also personal experience of the author). Slightly lower conductivity values in the Sierra Vista subwatershed in comparison to the nearby Tucson basin suggest a more recent age since time of recharge of the system. Well-water in the Tucson basin is reported to range between 300 μS/cm and 500 μS/cm. The presence of clays may further enhance conductivity values, but conductivities of ground-water in the San Pedro River basin are already quite high.

The most electrically conductive parts of the aquifer (more than 800 μS/cm, or less than 12.5 ohm-m resistivity) probably correlate with saturated silts and clays, and also with conductive sediments in electrical well logs, particle size logs (wells TW1, TW3, TW5, TW8, TW9, and MW7), and several vertical electrical soundings used to define the extent of the fine-grained sediments (Pool and Coes, 1999). Moderately electrically conductive sediments in the aquifer (200 μS/cm to 800 μS/cm) generally correlate with saturated sand and gravel. Less conductive materials (less than 200 μS/cm) are generally non-aquifer materials such as crystalline rocks. Fine-grained parts of the Pantano Formation, a poor aquifer, and Cretaceous Morita Formation, a mudstone deposit, can also be weakly to moderately electrically conductive if water-saturated, and could potentially be confused with fine-grained parts of the aquifer. These sediments are likely to occur in the near surface near the Huachuca Mountains (Kneale and others 1997).

The clay-contribution-to-conductivity issue bears some discussion. Based on several hundred laboratory sample electrical measurements made while working for an engineering firm in Tucson, plus several hundred line-miles of resistivity/IP surveys measured and interpreted in southeastern Arizona and other arid environments, the author believes that clays have a relatively minor effect on the already high conductivities observed in the AEM data in the San Pedro Valley. Clays may affect the amplitude of airborne EM conductors, but not where they are located horizontally or vertically in the inversions. Further, the effect of clays is not particularly significant in areas like the San Pedro Valley where ground water is already so highly conductive (about 338 μS/cm or 30 ohm-meters on average, and in a few cases above 800 μS/cm). Keller and Frischnkecht (1966, page 449) show that above about 5% clay content, cation exchange capacity becomes saturated. In other words, the contribution to conductivity from clays remains constant (and even declines) for clay-content above 5%. In work in a similar arid environment in Saudi Arabia (Flanigan and Wynn, 1979), wadis were found to be conductive only down-drainage from mineral deposits, whereas the clay content was uniform along the entire length of the wadi. Thus, from the Huachuca Mountain front to the center of the basin there is probably not much of a contribution by clays to the conductivity, no matter how much the clay content may increase. In consequence of this, the airborne geophysical data cannot reliably show the variation in clay-content over the basin, but CAN tell us where water is present. By inference, this means it can also tell us something about the porosity of the sediments.

Examination of figures 14-16 shows deep blue colors in the northeast part of the survey area that correlate closely with the Tombstone volcanic field. However, extensions of the blue areas to the west beyond where the volcanic rocks are shown on the geology map make it clear that these volcanic rocks extend under the more recent sediments beyond and west of where they are shown on the geologic map. The San Pedro River cuts through the Tombstone Hills volcanic rocks in the northern part of the survey area, and the AEM data make it clear that there is no significant shallow water present beneath the river there. An extension of the large, central high-conductivity zone (the red and purple colors in the figures) through the Tombstone Hills correlates with a zone of denser vegetation north of Graveyard Gulch, roughly northwest of Charleston, and east of Huachuca City, and extends into the western reaches of Walnut Gulch. Not surprisingly, the area where the Babocomari River and Walnut Gulch intersect the San Pedro River coincides with a zone of higher conductivity (red) that represents the southern end of another component of the regional aquifer lying north of the study area. A subtle offset in the warm colors in all three figures around 3459000N and 575000E coincides with the Sawtooth Canyon Fault of Drewes (1980; 1996). The geophysical data imply a left-lateral throw that geologic mapping by itself could not demonstrate.

Examination of figure 16 shows much stronger interference from power lines and pipelines in the survey area than we can see in figure 14. On the face of it, this is counter-intuitive, since figure 16 represents the output of EM channel 18 (Z-axis), the most deeply-penetrating EM channel. In fact, the deeper-penetrating (or longer time-lag) EM signals are attenuated more than the shallower signals by the overlying, conductive water-saturated layers, so the "speckling" or human cultural "noise" from the power lines and pipelines is more strongly represented when the gains are adjusted up to bring out the deeper signals. Even though the power lines and pipelines are at the ground surface, they therefore appear more strongly in the data representing the deeper conductive sources.

Referring back to figure 14, it is clear that the "speckled" areas west of the main low-resistivity zone are caused by power lines and pipelines above and beneath Fort Huachuca and Sierra Vista. Speckled zones in the south-southwest of the survey area correlate well with more recent extensions of human settlement to the south towards Garden Canyon and Ramsey Canyon. These cultural zones appear more prominent in the deeper (Em channel 18) conductor because they are relatively stronger vis-a-vis the deeper, weaker EM signal.

The large, high-amplitude high-conductivity zone in the extreme west of the survey area suggests a western extension of the regional aquifer around Lyle Canyon and Turkey Creek. There are mesquite bosques and springs in this area (Brenda Houser, USGS-Tucson, AZ, oral comm., 16 March 2001). This is conductor is probably caused by water present in parts of the Pantano or Morita Formations or pre-Tertiary sedimentary rocks which crop out near the Huachuca Mountains and along the Babocomari River (Drewes, 1980; Kneale and others, 1997). The conductivity anomaly can only occur if there is water present, however. In the author's experience with hundreds of laboratory resistivity measurements from samples throughout Arizona, dessicated clay-bearing samples are not conductive. If the clay-bearing samples are hydrated with distilled water, they become mildly to moderately conductive, but they must be saturated. The relatively high electrical conductivity of the ground water in the area (Pool and Coes, 1999, plate 3) makes it clear to the author that high-ion-content water dominates the conductivity anomaly observed here in the airborne geophysical surveys. This is especially true as porosity is usually higher in fine-grained sediments near the center of a valley (Driscoll, 1986, p. 67). This conductor should be investigated further to define its character and extent beyond the airborne survey boundaries.

Close to the Huachuca Mountain front (the deep blue colors on the southwestern edge of figures 14-16) there appear to be some small electrical conductors (narrow fingers of red color parallel to the mountain front) that may be small shallow buried water outliers. Fragments of fine-grained Pantano Formation, in general overlain by sand and gravel basin fill, have been mapped in this area, and Pantano Formation also shows up in test wells. The Pantano is not a particularly good aquifer, however (Brown and others, 1996). These small electrical conductors in the Huachuca Mountain front area do not appear to correspond to any powerlines or pipelines, so they must be caused by the presence of subsurface water.

Figures 14-16 are in effect depth-slices of the regional conductor. They appear to suggest a mountain-front-paralleling gap between these small electrical conductors and the huge conductor (interpreted as the regional aquifer) towards the east. This apparent gap is not real however, but shows up in inverted conductivity-vs-depth profiles (discussed in detail later) and in water-table depths as a thick, mountain-front-following unsaturated zone. The electrical conductor is continuous below this thick unsaturated zone between the narrow electrical conductors along the mountain front to the west and the large electrical conductor to the east interpreted as the main regional aquifer. Well draw-down has been documented locally to a maximum of about 70 feet (22 meters) in the area near the Fort Huachuca East Gate well-field, but elsewhere it is more typically less than 50 feet (15 meters) and well-draw-down becomes nearly insignificant (less than 10 feet) near the San Pedro River (Pool and Coes, 1999).

Geologic mapping (Houser and Gettings, 2000) has shown that there is a listric fault tilting sedimentary rocks to the southwest along the Huachuca Mountain front. Called the Nicksville fault, it is probably related to Basin-and-Range faulting (Brenda Houser and Mark Gettings, USGS-Tucson, AZ, oral comm., 1999). However, Don Pool (USGS-Tucson, AZ, written comm., 2001) feels that this fault may be early- to mid-Miocene in age because listric faulting is not common in mid to late Miocene Basin and Range deformation. This faulting has in effect down-dropped the less-hydraulically-conductive Pantano Formation more in the southwest than in the northeast. However, the younger Upper Basin fill sand and gravel sediments are not tilted. This southwestern tilting may explain the thick, mountain-front-following sand-and-gravel zone, but not why it is unsaturated, nor why the electrical conductor which apparently represents the presence of water lies deep beneath it. Wells drilled into this unsaturated zone encounter water at depth which then rises in the wells, as if it had been confined, to what is then recorded as a water table (Brenda Houser, USGS-Tucson, AZ, oral comm., 16 May 2001). The underlying Pantano Formation is an older, pre-Basin-and-Range basin fill unit (Tertiary age) with deformed and tilted bedding. It has widely-varying electrical properties (Pool and Coes, 1999), but is generally well-consolidated. It is also a poor aquifer (Brown and others, 1966). There is probably some ground water discharge from this area north to the Babocomari River near Huachuca City (M. Gettings and D. Pool, both with USGS-Tucson, oral comm., 1999).

Near the Huachuca Mountain front there are significant variations among nearby wells in the thickness of unsaturated resistive sands and gravels (basin fill) overlying the Pantano Formation. These variations suggest block-faulting between the Huachuca Canyon Fault and the Sawmill Canyon Fault of Drewes (1980) around the mouth of Huachuca Canyon. Detailed examination of data in this area (Mark Bultman, USGS-Tucson, AZ, oral comm., 14 March 2001) show differences between water table and electrical conductor depth of 10 - 20 meters in a narrow window near the mouth of Huachuca Canyon. These are among the largest deviations between the electrical conductor and the water table in the survey area. It is possible that this is an artifact in the conductivity-depth-transform calculations (discussed in detail later), but may also be due to seasonal variations in water-recharge in this canyon-mouth area. The water table data used in this report were acquired as much as several years prior to the airborne EM survey.

Examination of figures 14-16 shows an electrical conductor, interpreted here to be the regional aquifer, underlying (and therefore in hydraulic contact with) much of the San Pedro River. In the northern part of the study area however, (north of 3495000N), where the river passes over and through the western margins of the Tombstone volcanic field, there is little in the way of the electrical conductivity that we associate with ground water in any of these airborne EM channels. Some of this area is covered with limestone, but according to the magnetic survey this is a thin veneer that is underlain by volcanic rocks. The lack of an electrical conductor here implies that over at least the southern two-thirds of the survey area (south of 3495000N), the aquifer discharges directly to the San Pedro River, but not in the northern third.

The Landsat image (Figure 13) supports Pool and Coe's (1999) observation that significant water is lost to evapo-transpiration through local vegetation. The light purple zones immediately west of the San Pedro River correlate with significant vegetation and several springs. These springs appear to be caused by relatively insignificant ground-water flow reaching the surface as it moves eastward above silt and clay layers in the basin fill unit. The water table between Fort Huachuca and the San Pedro River becomes increasingly shallow as it approaches the river (see figure 17). The amount of discharge from these springs is very small, however, and cannot account for the vast majority of the ground-water flow from the aquifer. The perennial water seen in the eastern reaches of the Babocomari River in the north of the study area must come from the Upper San Pedro aquifer in this area.

Figure 17 (***also Plate 1***) represents an overlay of water table depths (numbers in black) onto the shallow electrical conductor (warm underlying colors) from EM channel 10. The water table data are from Tatlow, 1998; well-data can be accessed at http://www.water.az.gov/hydrology/dload.html and are also available from the US Geological Survey Ground Water Site Inventory). In general, there is good agreement between these two different kinds of data: the deeper water table (50 ft. to 175 ft. range) just east of Fort Huachuca and the Huachuca Mountains coincides with the green (weak electrical conductor) zones on the map. This has already been identified as a deep unsaturated zone where the conductive water lies much deeper than farther east in the central part of the valley. Where the shallow electrical conductor (the red color in the figure) is strongly manifested, the water table depths fall in the 20 ft. - 50 ft. range. In the northeast where the Tombstone Hills outcrop (the deep blue zone in the upper right of the figure), there are very shallow water table depths but this is a zone where there is almost no water present. Shallow (EM channel 10) aquifer extensions are also apparent on the east side of the San Pedro River where they correlate closely with drainages that channel runoff westward to the main regional aquifer from the Mule Mountains in the east.

The "deep conductor" (the deepest, purple-colored low-resistivity zone seen in the EM channel 18 data of figure 16) is apparently a deep, silt-and-clay-rich, high porosity basin-center deposit. This clay-rich zone is also seen in the shallower channels. This is a water-saturated unit that accumulated in the San Pedro basin during late Miocene to Pliocene time (about 10 to 2 MY ago). Weathered-out clays tend to concentrate more distally from their source rocks than do the sands and gravels, and thus they tend to predominate in the centers of basins. The colors suggest the deep conductor is less electrically conductive than the shallow aquifer above it (bright purple in the CDTs discussed later). From a later discussion in this report it is apparent that this is a subtle artifact of the airborne CDT inversion below about 150 to 200 meters. It is likely that the higher clay content in the central parts of the San Pedro Basin (but west of the San Pedro River) probably has lower hydraulic conductivity. This may cause at least some water flow in the Upper San Pedro Basin aquifer in a more northerly direction before discharging into the San Pedro River (for instance, via the Babocomari River).

In summary, the airborne EM survey appears to map where the water lies in the Sierra Vista sub-watershed down to depths of 300-400 meters. Because overlying-sediment lithostatic pressure tends to reduce porosity with depth, the majority of the water lies in this depth range. Figures 14-16 by themselves cannot explain how the water from the Huachuca Mountains reaches the main regional aquifer, but CDT cross-sections (discussed later) suggest there is a deeper hydraulic connection beneath the mountain-front-following thick unsaturated zone. To draw reliable conclusions about ground-water flow requires hydraulic data from wells in the area.

CONDUCTIVITY DEPTH TRANSFORMS (*"CDTs"*):

CDTs (Conductivity Depth Transforms) are a proprietary product provided at extra cost by the airborne survey contractor. They are calculated conductivity-vs-depth sections derived by a mathematical transform (technically not an inversion process) of the 120-channel airborne electromagnetic in-phase/quadrature data acquired by the GEOTEM geophysical survey system, using an infinite half-space assumption. In earlier reports (Wynn and Gettings, 1997; Bultman, Gettings, and Wynn, 1999) CDT sections were compared first with Vertical Electrical Soundings (VES) carried out in the upper San Pedro Basin and reported in Pool and Coes (1999), with available water-table data, as well as with short and long normal electrical logs from test wells on the Fort Huachuca military reservation. In general we found good agreement between the CDT information and the VES and particularly with electrical well-logs for the first 150 meters below the Earth's surface. We also found good agreement between the CDTs and other sources of San Pedro Basin water information [for instance, Corell and others, 1996).

Figure 18 shows an example of a CDT with an interpretation by Don Pool (USGS-Tucson, written comm., 1999) superimposed; this was taken from 1997 survey line #122, and was chosen because it crossed close to Test Well #5 discussed in Pool and Coes (1999). This geoelectrical section covers nearly 20 miles (30 km) horizontally from southwest to northeast, and up to 400 meters vertically (see figure 3 for location). Blue colors indicate low conductivity, and warm colors represent high conductivity; in this area the warm colors appear to map the water of the Upper Basin Fill and Lower Basin Fill (described in Brown at all, 1966, and Pool and Coes, 1999) as well as some of the Pantano Formation. The figure is topographically correct in that the elevations on the southwest (the left side, or Fort Huachuca side) are higher than the elevations at the San Pedro River to the northeast.

Note the shallow blue zone beneath and just east of Fort Huachuca; this is the thick unsaturated zone discussed earlier, also described in Pool and Coes (1999). Note the red colors beneath it in this CDT section; this is apparently water, probably saturated Pantano Formation sediments. Note the continuity between the airborne EM conductor near the Huachuca Mountains on the left and the electrical conductor interpreted to be the regional aquifer in the center. This continuity or link was not apparent in the depth-slices in figures 14-16, but the CDTs incorporate data from the longest time-gates (deepest penetration) of the airborne EM data. Note that the airborne EM system is mapping a conductive (water-saturated) unit beneath the thick unsaturated zone, showing apparent hydraulic connectivity at depth along the profile.

Just to the right of the blue, thick unsaturated zone, there is a thin red-purple area with white below it; this is a high electrical conductivity zone that comes very close to the surface, perhaps reflecting the presence of effluent-recharge ponds found here. The US Army NEPA Coordinator (Gretchen Kent, Fort Huachuca US Army Garrison, oral comm., 1999) has indicated that there is significant water-loss (up to 50%) in these ponds that cannot be explained by evapo-transpiration. A possible interpretation is that some of this water must therefore be recharging the regional aquifer in this area. A major highway crosses here, however, so the possibility of cultural influence in the data at this point cannot be discounted. The white color underneath is caused by the presence of human electrical interference (pipelines and power lines) - the CDT algorithm cannot reliably calculate the deeper resistivities because the electrical noise from this cultural interference overwhelms the data below about 50-100 meters.

Farther northeast (the center and right parts of the figure) there is a long, shallowing-to-the-right electrical conductor (deep red and purple) and a deeper, second red zone (red and orange). The shallow zone is likely water in the fine-grained UBF part of the aquifer. The lower purple zone is what we know to be the LBF that is still part of the aquifer. The UBF and LBF are not separate, they are parts of the same single aquifer. Farther to the northeast we see a shallow blue zone (labeled "Bedrock") with a very thin, barely subsurface red conductivity zone above it. These are the Tombstone Hills volcanic rocks, with a veneer of probably damp silt-clay making up a thin overlying layer of basin fill.

Figure 19 shows a comparison of a Conductivity-Depth-Transform with a resistivity log for Test Well #5 (see also Pool and Coes, 1999). Note that the horizontal axes in this and the following figure are in units of resistivity. Most ground geophysical measurements are reported in resistivity units, whereas the strength of EM conductors is usually reported as conductivities. The two units are simply related: conductivity = 1/resistivity. The short and long normal lateral E-log shows resistivities that closely parallel the CDT results, but the CDT shows consistently higher resistivity (the CDT curve lies to the right) of the electrical log of the well. Below about 150 meters, the CDT resistivity values continue to increase. This means that the CDT gives approximately quantitative resistivity values (different by a small multiplicative factor) down to about 150 meters depth, and qualitative values (a slow, roughly linear increase) below this. On the face of it, it would seem that we should be able to "tune" the CDT algorithm to more perfectly match the actual E-log resistivities over the entire survey area. This issue will be discussed in further detail below.

Note that the first resistivity low of the CDT appears to mark the water-table in this example. In fact, while this is generally the case over most of the San Pedro Basin, there are some areas where the CDTs don't exactly pick the water table, for instance in a narrow zone near the mouth of Huachuca Canyon. Figure 20 (adapted from Bultman, Gettings, and Wynn, 1999) shows a series of 9 CDTs converted to resistivity-vs-depth curves, correlated to the reported water-table in nearby test wells. Six of the CDTs mark the water table closely, two mark the water table somewhat lower than where it was measured, and one (the worst example we encountered, in the Huachuca Canyon outflow area) seems to show the water-table a full 100 meters below where it was measured. There is some question about the veracity of this water-table value (discussed previously). Some of the water table values were older measurements taken when the water table was higher, so we could perhaps explain these few apparent discrepancies as either horizontal location imprecision between the CDT vertical section and the nearby well it is compared to, or to older water-table measurements where the water is now in fact further drawn down. The water table values used for this report were always the most recent ones available.

There is also some suggestion (Bultman, written comm., January 2001) that the CDT algorithm may calculate the conductor above where it may actually lie in cases of highly resistive (i.e., dry) overburden, again raising the question of whether we can tune the CDT algorithm better. Efforts are on-going to resolve these occasional discrepancies, but they account for less than 5% of the surveyed area.

Figure 21 has been placed here to show another quality-control check of the data, in this case the CDT inversion process. In this figure, a 1997 profile (97 Line 101) is compared to a nearly-coincident 1999 profile (99 Line 214). The agreement is remarkable, considering that the position of the aircraft in three dimensional space could never be made to coincide exactly.

Figure 22 (***also Plate 2***) was generated to assist the reader to visualize where the main electrical conductor (which the author believes generally correlates with the presence of water) lies in three dimensions; this is ***a CDT "Fence Diagram"***. For selected airborne survey lines, entire CDTs have been scaled and laid down along the profile line. Remember, however, that these CDTs are topographically corrected, i.e., the white zone above a CDT on this fence diagram is compensation for the fact that one end of the line may lie at a higher elevation. In these cases, the colored zones must be moved up to the surface in the viewer's mind (if this is done, it corrects for a few apparent discrepancies, for instance where the Babocomari River should coincide with a low-resistivity zone on the CDT that crosses - or parallels - it). This fence diagram thus might be considered a broad-brush 3-D map of the water underlying the San Pedro Valley in the survey area, with the caveats enumerated above.

Some interesting structural information can be derived from the CDTs shown on this diagram. One example is a north-dipping conductor extending down and north from the Babocomari River - the northward-dipping conductor beginning at the river on line L203. This is almost certainly a water-filled, north-dipping fault system that controls the Babocomari. Another example can be seen in line L97-138 (and even better in figure 16): the Sawmill Canyon Fault that dashed through the basin fill on Drewes (1980) map can be seen as a left-lateral offset in the conductor (figure 14) and an angled offset in the conductor in the middle of line L97-138.

In Bultman, Gettings, and Wynn (1999), some interesting relationships between the digital CDTs, the well resistivity logs, and the water tables were observed, and these observations appear to be applicable to the entire 1997-1999 dataset:

1. The digital CDTs consistently demonstrate a slightly higher resistivity at a given depth than the short and long normal well logs. Part of this difference may be due to the elevation problem that was discovered and reported in the 1997 digital CDTs, and part of it may be due to parameters selected by the contractor in the CDT algorithm. The elevation problem has been corrected in the 1997 data and did not appear in the 1999 data.

2. The shape of the CDTs matches the general shape of the well logs in most cases for the first 150 meters depth.

3. For most of the test wells, the CDT-derived upper conductivity maximum/resistivity minimum seems to correlate well (within the vertical resolution of the CDTs) with the water table. In a few cases, notably near the mouth of Huachuca Canyon, the conductivity maximum suggests that the water table is lower than the water table in nearby wells. This may be due to the significant horizontal displacement between the wells and the CDT soundings, or to outdated water table information, or even to a calibration issue with the CDT algorithm in zones of highly resistive overburden. The author believes it is likely a combination of all three.

4. The CDT resistivity profiles when converted to conductivity-vs-depth seem well correlated with actual well-log resistivity to depths of about 150 meters. At depths below 150 meters, resistivities reported in the CDTs increase with increasing depth over the resistivities measured by well-logging. This led the author to consider the possibility of "tuning" the CDT algorithm to match the well-logs down to 400 meters depth; this is discussed in detail below.

CONDUCTIVITY VS. DEPTH CONVERSION SYSTEMS-- THE INVERSION "TUNING" ISSUE:

One product of the AEM survey is a conductivity-vs-depth section derived by a mathematical calculation of the 120-channel airborne electromagnetic data acquired by the geophysical survey system. These calculations are referred to as "Conductivity Depth Transforms" or CDTs by the airborne geophysical contractor, Geoterrex. The mathematical technique used to obtain the CDTs is described by Wolfgram and Karlik (1995), however the actual algorithm is considered proprietary by Geoterrex. While not technically a true inversion, the technique produces results similar to a true inversion based on the diffusion equation, yet requires much less computation because it is a forward, or "analytical" calculation.

Earlier, we observed the generally good correlation between well-logs and the CDT resistivity values; this would appear to establish the veracity of the CDT algorithm. Nevertheless, because of the apparent close correlation between CDT resistivities and E-logs in wells down to 150 meters - yet the increasing disparity or difference below 150 meters - the USGS purchased an EM inversion software package from ENCOM[1] called "EM Flow[1]". ENCOM is an Australian government/private-industry geophysical consortium; the inversion method is documented in MacNae and others (1991). Approximately a person-month was spent reformatting the 1999 airborne EM data and getting this software package operational, to invert data from parts of the 1999 airborne geophysical survey.

The line chosen for comparison was a separate 10-km-long (6 mile) profile flown parallel to the Mexican border and south of the combined 1997-1999 survey coverage, called here the "Mexico Line." The Mexico Line is important because a large part of the San Pedro Basin drainage lies south of the border in Mexico. This line provides some sense of the continuity between the aquifer surveyed in this report and that part of the San Pedro aquifer lying south of the international frontier. It is reasonable to assume that there is ground water flowing across the border, down-drainage towards the north. The extent to which an estimated volume of formerly Mexican ground water contributes to stream flow in the American side of the San Pedro River cannot at this time be quantified, however. The occurrence of perennial flow in the San Pedro River north of the border will be influenced by the geometry of the channel alluvium and the volume of bank storage present.

A considerable amount of water in the Upper San Pedro drainage is withdrawn by Cananea, the large porphyry copper mine that lies in the Upper San Pedro drainage in Mexico. The mining company Grupo Mexico has acknowledged on-going withdrawal from the Upper San Pedro aquifer of more than 15 million cubic meters of water per year (about 12,000 acre-ft) for the Cananea mine and its local operations (José María Guerra-Limón, Reserva Forestal Nacional y Refugio de Fauna Silvestre "Ajos-Bavispe", Hermosillo, Mexico, oral commun., 2000). The withdrawal apparently began in the 1940's and accelerated during the 1950's and 1960's to its present level. It is reasonable to assume that this withdrawal could have a significant effect on the ground-water system on the American side of the border. Note that the Cananea mine is but one of many entities withdrawing water from the Upper San Pedro aquifer in Mexico, including large communal farms ("Ehidos") and towns.

Figure 23 shows a comparison of Geoterrex CDTs (**"Conductivity Depth *Transforms*"**) vs. the Encom CDI (**"Conductivity Depth *Inversion*"**) for the Mexico Line. There are four parts to this figure. From the top, these are (a) the original EM Flow inversion of the normal off-time-gates that the software was configured to deal with. These time-gates are well-suited to defining details in the upper section, but do not sample far out into the late-time windows acquired by the GEOTEM system. The second part (b) is the original EM data, channel-by-channel, for reference. The third part (c) is the EM Flow result when the sampling time-gates are extended back into the on-time of the transmitter (for a closer reference to the transmitted signal strength) and as far down the off-time window as the software could deal with. This was done to sample as deeply beneath the ground surface as possible for a better comparison to the Geoterrex CDT profile, a powerful, proprietary analytical forward solution provided by the airborne geophysics contractor. The Geoterrex CDT profile constitutes the fourth part (d) of the figure.

Several things can be observed in this comparison between Geoterrex CDTs and the EM Flow Conductivity-Depth-Inversions (CDIs):

1. The EM Flow inversion for a single profile takes quite a long time to complete - up to 10 minutes on a fast Pentium-III computer (plus, it generally requires several runs, then color-scaling to reduce color-saturation and bring out details), vs. the few seconds that the CDT analytical calculation (i.e., a forward calculation) requires. Due to this and other inherent limitations, the EM Flow software as constituted in 1999 is an interesting research tool, but poorly-suited to production processing of large airborne EM surveys.

2. The EM Flow inversion provides quite a bit of fine resistivity detail in the upper 50-70 meters below the Earth's surface, substantially more detail than the Geoterrex CDT.

3. The EM Flow inversion, when extended to include early and late time-gates (figure 23, part C), agrees well with the CDT analytical conversion of the EM data (figure 23, part D).

There are some disparities, but they are minor, and are caused by the relative strengths of the two conversion methods.

4. The EM Flow results do not reach as deep as the Geoterrex analytical CDT solution. In figure 23, part D we can see a second, deeper conductive unit, possibly another deeper water body, on the left (west) side of the profile. We can see only a hint of this deeper, second water body in the EM Flow inversion. The reason this is not clearly seen on the EM Flow CDI is because the longest time-gates in the data could not be utilized by the EM Flow software.

5. As a generalization, silts and clays generally tend to collect distally from the source rocks from which they weathered. Along the Mexico Line this would suggest that the clays tend to collect in the middle of figure 23 near the San Pedro River (between reference UTM coordinates 580000W and 586000W in the figure). Sands and gravels on the other hand would likely predominate on the edges of a basin. One could then infer that both the shallow and deeper electrical conductors seen on the left side of figure 23, part D probably both represent accessible bodies of water. An observer using the CDT would thus understand that any water well located in this area should be extended below the first (shallow) electrical conductor, through the apparent aquiclude separating it from the underlying electrical conductor, and into the apparent second, deeper water body. This guidance would not be available if the interpreter used only the EM Flow CDI inversion results.

6. The apparent offset in the high-conductivity layers (warm colors) around location 582000E on the Mexico Line (this is the east component of the UTM coordinates) is a previously unknown feature, and probably represents a normal fault here. The fault probably influenced the accumulation of alluvial materials, and the apparent offset may simply reflect an increase in the thickness of the basin fill on the east side.

SUMMARY OF INTERPRETATIONS:

A - Interpretations related to the hydrology of the Upper San Pedro drainage derived from the airborne EM and the airborne magnetic data:

The combined 1997 and 1999 airborne geophysical surveys provide sufficient information, when combined with the hydrologic analysis of Pool and Coes (1999), to draw the following conclusions:

1. The EM conductivity maps (figures 16-18) and the CDT profiles (figures 24, 27, and Plate 1) show subsurface conductivities over about 1,000 square kilometers. This kind of subsurface imaging is possible because the local groundwater is quite conductive (Pool and Coes, 1999, Plate 3). While clays are also known to contribute to an increased conductivity, they cannot be the dominant factor in the conductivity images we see in these figures for reasons explained above. Nevertheless, for conductivities above 300 - 500 μS/cm they definitely have some contribution to the values measured. Consequently, the airborne-EM-derived conductivity maps provide a broad-brush image of the presence of ground water in the Sierra Vista sub-watershed of the Upper San Pedro regional aquifer, especially when combined with existing lithologic and hydrologic information. The parameters for the airborne EM surveys were optimized for maximum penetration in the San Pedro Valley -- about 400 meters. In the absence of human cultural interference, the CDT profiles appear to image most of the underlying water in most of the CDT profiles (one can usually see closure, i.e. the bottoms of the electrical conductors, in the CDTs).

2. The airborne EM data provide a static image of the subsurface electrical conductor, inferred generally to be the regional aquifer. Figures 14 - 16 effectively provide three depth-slices of this electrical conductor beneath the study area. The AEM images and CDTs do not directly provide information about groundwater flow, though some educated inferences may be drawn from these images by an experienced hydrologist.

3. In many cases the CDTs provide structural information about the subsurface, such as the north-dipping, water-saturated fault system controlling the Babocomari River (the

northward-dipping electrical conductor beginning at the Babocomari River on line L203 in figure 22 and Plate 2).

4. The airborne EM conductivity images suggest substantially reduced porosity beneath the Tombstone Hills volcanic field, over which the San Pedro River flows for about 30% of its length in the northern part of the survey area. In this zone at least, hydraulic communication is substantially reduced between the San Pedro River and the regional aquifer.

5. The Upper Basin Fill sediments in the center of the San Pedro Valley appear to be water-saturated. The apparent offset of the main conductor to the west of the river, combined with basic sedimentary principles that place the silts and clays more in the center of a basin, would suggest that there is a large silt-clay body present just to the west of the river. This is supported by both the CDTs and well-log data. This electrically conductive unit, which roughly parallels the river but lies to its west, has sands and gravels both overlying and underlying it, and significantly influences the ground-water flow in the regional system (Pool and Coes, 1999).

6. About 3,000 acre-feet of ground water has been estimated to flow from Mexico into the Arizona part of the basin each year (Freeythey, 1982). Withdrawal of more than 12,000 acre-feet of water each year by the Cananea Mine complex in Mexico must necessarily have a significant impact on water flowing in the San Pedro River in Arizona. A further increase in withdrawal in Mexico will almost certainly affect the San Pedro National Riparian Conservation Area.

7. According to the magnetic depth-to-source maps generated as part of this study, there are several deep sections of the Upper San Pedro Basin in the study area, for example beneath Huachuca City and beneath the Palominas area near the Mexican border (figures 11 and 12). These deep zones are filled with sediment, and in places saturated with water. Because of overlying lithostatic pressure which generally reduces the porosity, the bulk of the regional aquifer probably lies within the 400 meter depth-range of the airborne EM system. Nevertheless, the large volume of sediment represented by these huge "potholes" in the

crystalline rock basement must contribute substantially to the volume of bank storage in the Sierra Vista sub-watershed.

8. The magnetic depth-to-source map of figure 11 also shows that most of the San Pedro River in the southern 70% of the study area (south of the Tombstone Hills) has only 100 to 200 meters of sediment underlying it. This relatively thin, silt-and-clay-rich section of alluvium implies lower transmissivity in the immediate vicinity of the river in this segment south of 3493000N. Lines L323, L319, and L314 of figure 22 and Plate 2 appear to support this by showing only a thin electrical conductor (i.e., a thin, shallow water body) on the east side of each profile. "This feature likely also influences the movement of ground water in the system" (Don Pool, USGS-Tucson, AZ, written comm., January 2001).

B - Observations about the Geology of the Upper San Pedro drainage derived from the airborne EM and airborne magnetic data:

Some general geologic observations can be drawn from the combined 1997 and 1999 airborne geophysical surveys:

1. The upper San Pedro Basin is bounded on the southwest by the Nicksville Fault (Drewes, 1980), a high-angle basin-margin fault marking the eastern edge of the Huachuca Mountains that is apparent in the magnetic data. The Sawmill Canyon Fault (Drewes, 1980, 1996) can be seen in the airborne EM data (figures 14 - 16) as a subtle left-lateral offset in the shallow conductor in the middle of the basin. The Babocomari River appears to coincide with a north-dipping fault evidenced as a narrow conductor in the CDT data for line L203.

2. There is a bedrock high in the Sierra Vista area that extends eastward about 10 kilometers from the Huachuca Mountains into the basin. This feature can be seen in the inverted magnetic data (figure 11), and can also be seen in the CDT data as a rise in the near surface low-

resistivity zone. The presence of this high has been verified by well ***D(21-20)35abb***, located near Fry Blvd. in Sierra Vista (Gettings and Houser, 2000).

3. South of the Sierra Vista bedrock high the basin is complex, but includes a large basin-and-range-following basement low that appears to extend south into Mexico from the Palominas area. The gravity-based model is in close agreement with the magnetic model, but has much lower resolution because of fewer data-points. See also Halvorsen, 1984.

4. To the east of the basin bounding fault near the Huachuca Mountains and east of the Sierra Vista bedrock high, the basin remains deep until it approaches the Tombstone Hills. The relationship between the basin sediments and the bedrock in the Tombstone Hills area is complex and may be both stratigraphic (intercalated volcanic flows in the sedimentary stack) and fault bounded. This region correlates to the mapped Tombstone caldera margin (Moore, 1993).

C - Observations about the geophysical methods including the CDT conversion process:

The following observations about the CDT algorithm and the conversions released by Geoterrex can be made:

1. The Geoterrex CDT conductivities appear to map the presence of water to about 150 meters depth over most of the survey area. Keep in mind, however, that the CDT vertical resolution is on the order of about 10 meters. Below roughly 150 meters depth, the CDT conductivities increasingly diverge with increasing depth (towards lower conductivities) from values measured in well logs. In this zone the CDTs still appear to provide at least qualitative data on the presence or absence of water. In a few areas the water-table depths diverge from what the CDTs seem to show, notably a narrow zone near the mouth of Huachuca Canyon. This may be due to (a) out-of-date water-table information in a sharply-fluctuating recharge channel, (b) horizontal registration errors between wells and the CDT profile, or (c) a subtle calibration issue with the CDT algorithm only apparent in areas of highly resistive overburden. The available evidence suggests it is likely a combination of all three.

2. The bedrock under the basin sediments is generally visible in the EM data only where it outcrops or is overlain by less than about 300 - 400 meters of alluvium. The crystalline bedrock, however, is easily mapped by the airborne magnetic data converted through the Euler deconvolution algorithm. In a few cases, magnetic volcanic flows and volcano-sedimentary units deposited in the middle of the sediment stack above the crystalline basement make the basement appear to be locally shallower, for instance the apparent ridge in the middle of the Huachuca City basement low (which according to the gravity data is a single, deep subbasin in the San Pedro Valley).

3. The CDI inversion process (the EM Flow solutions) appears to verify the CDT analytical conversion process. The veracity of the CDTs and the conductivity maps of figures 14 - 16 generally are supported by well-log information.

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San Pedro Airborne Geophysical Survey
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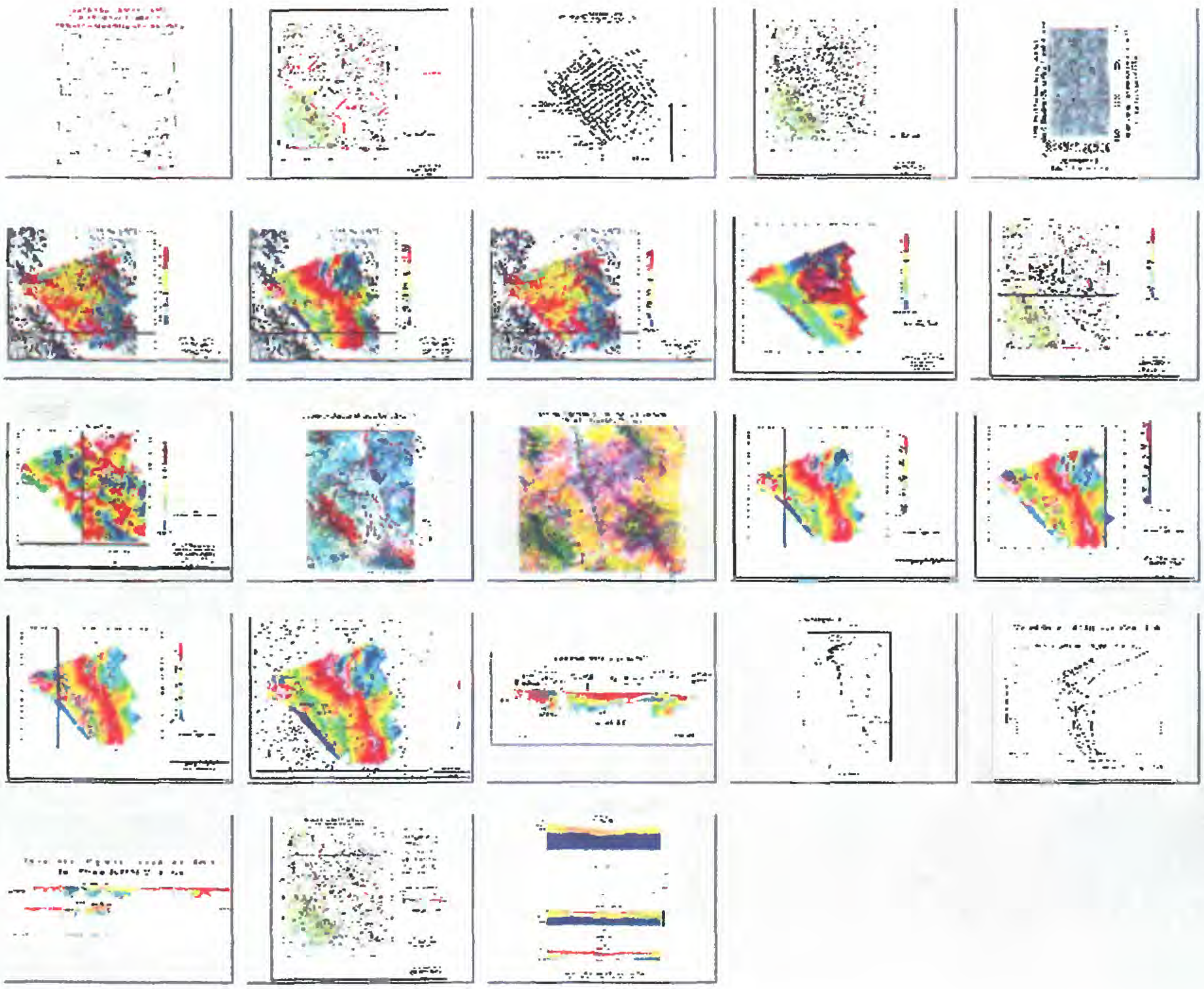
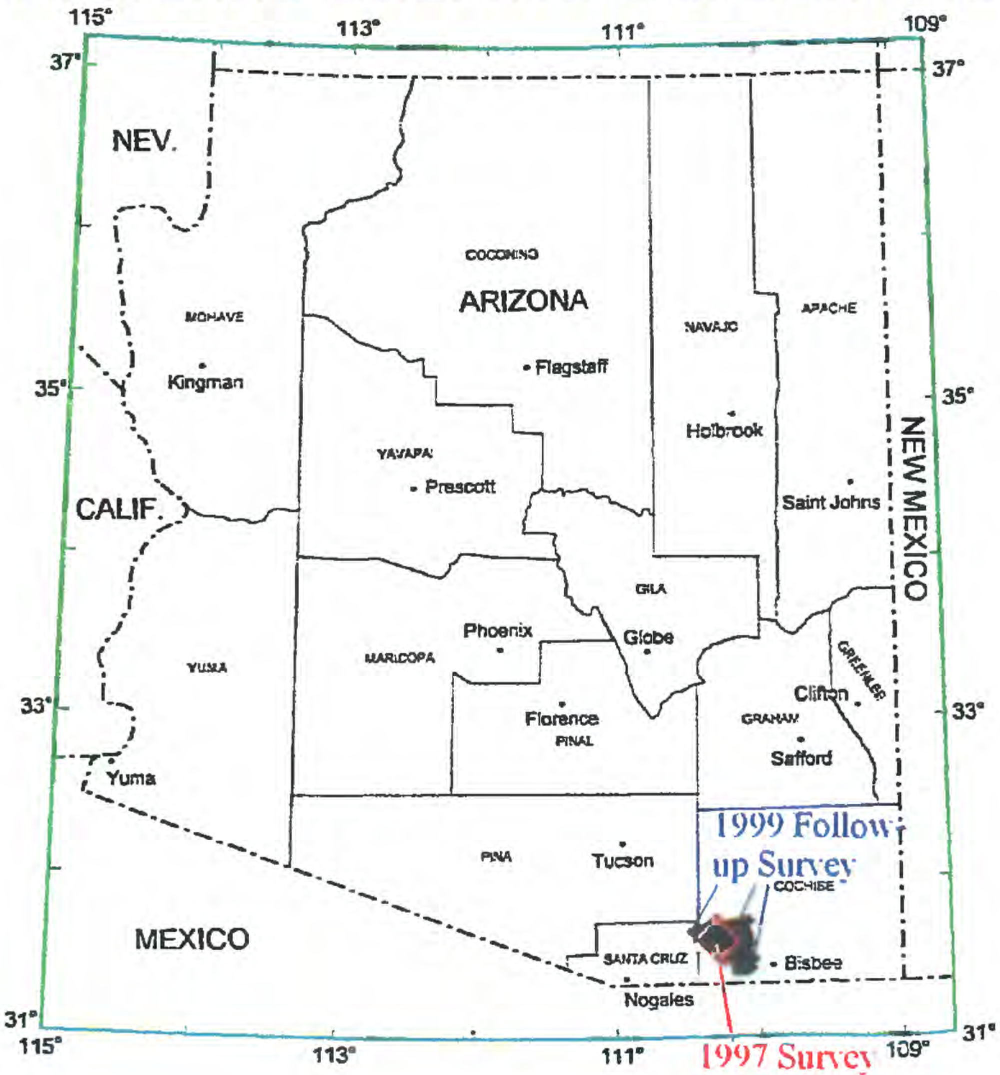
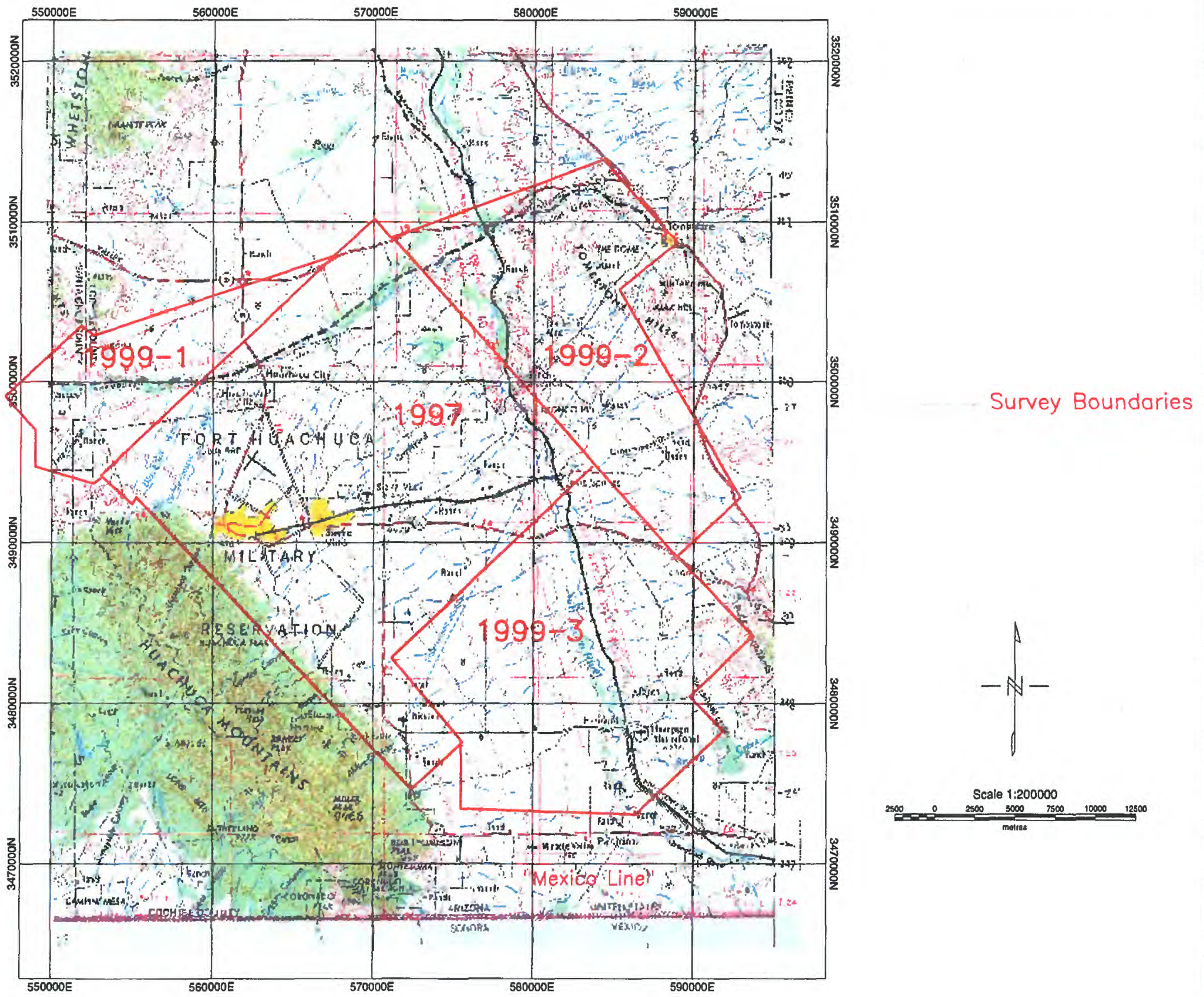


Combined 1997 - 1999
San Pedro & Tombstone
Airborne Geophysical Surveys

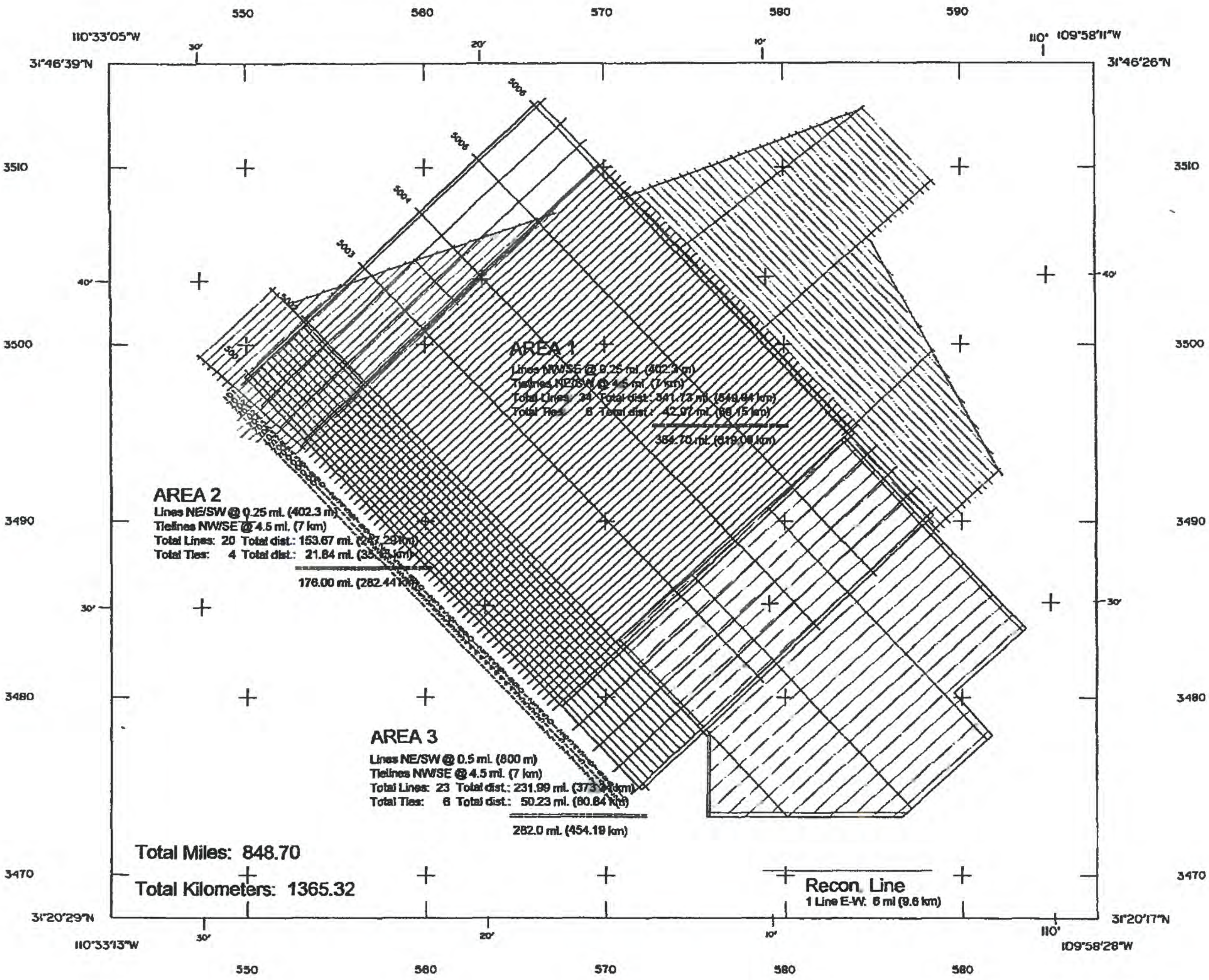


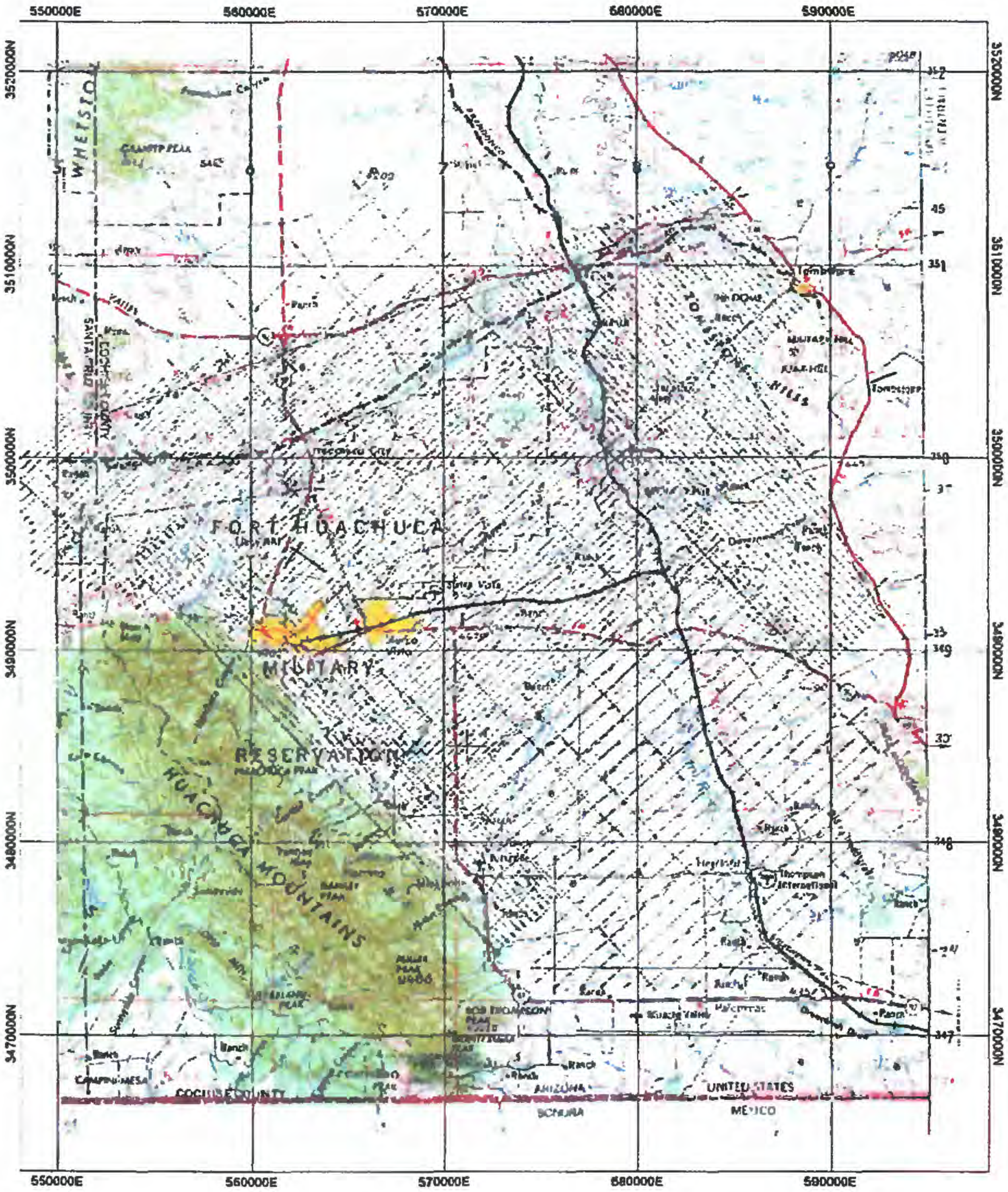


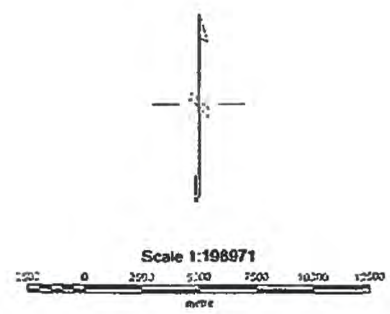
US Army Ft. Huachuca Garrison

Index Map of the 1997 and 1999 Airborne Geophysical Surveys

U.S Geological Survey
GEOTEM Electromagnetic / Magnetic Survey
Fort Huachuca area, Arizona



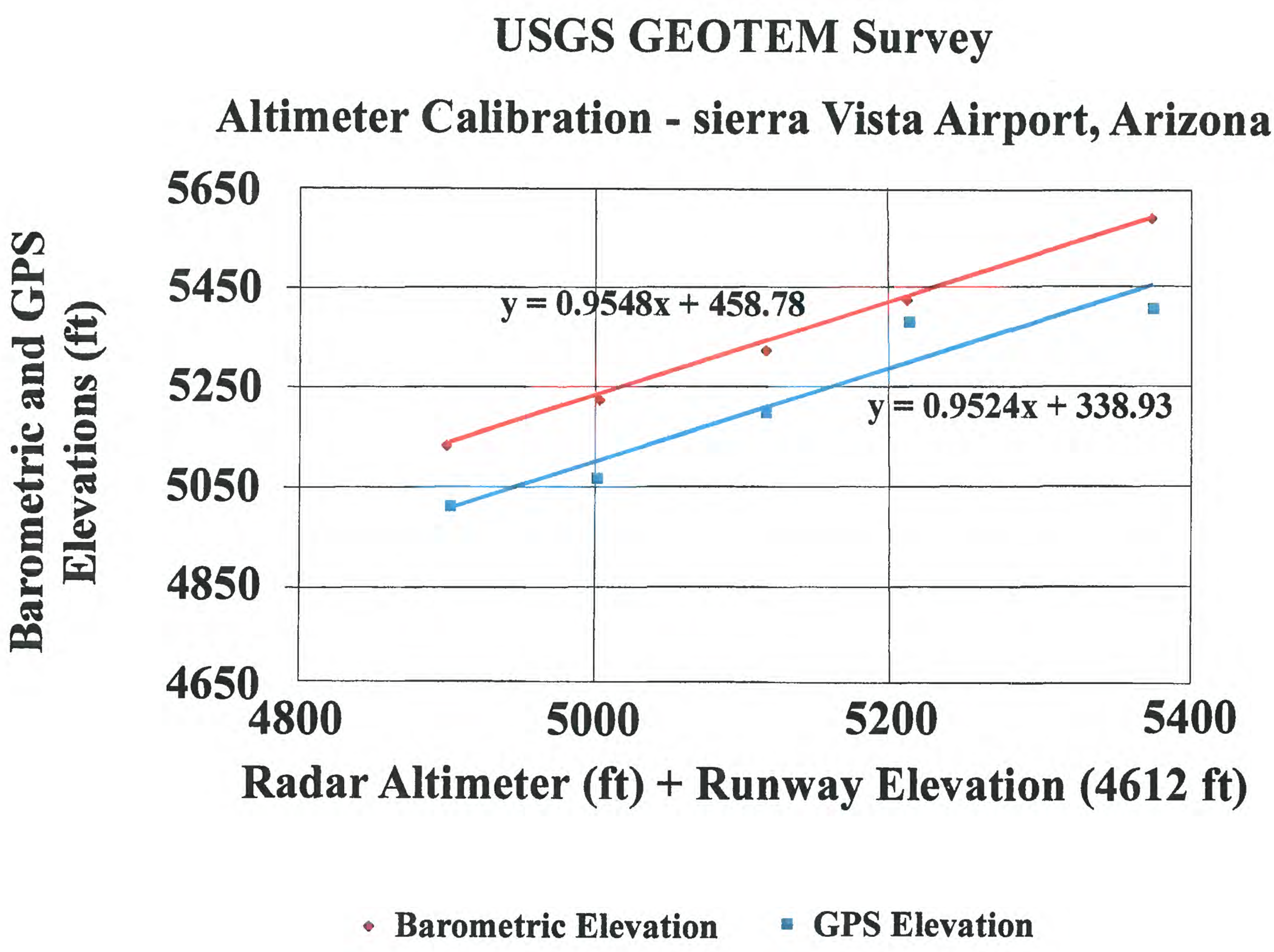


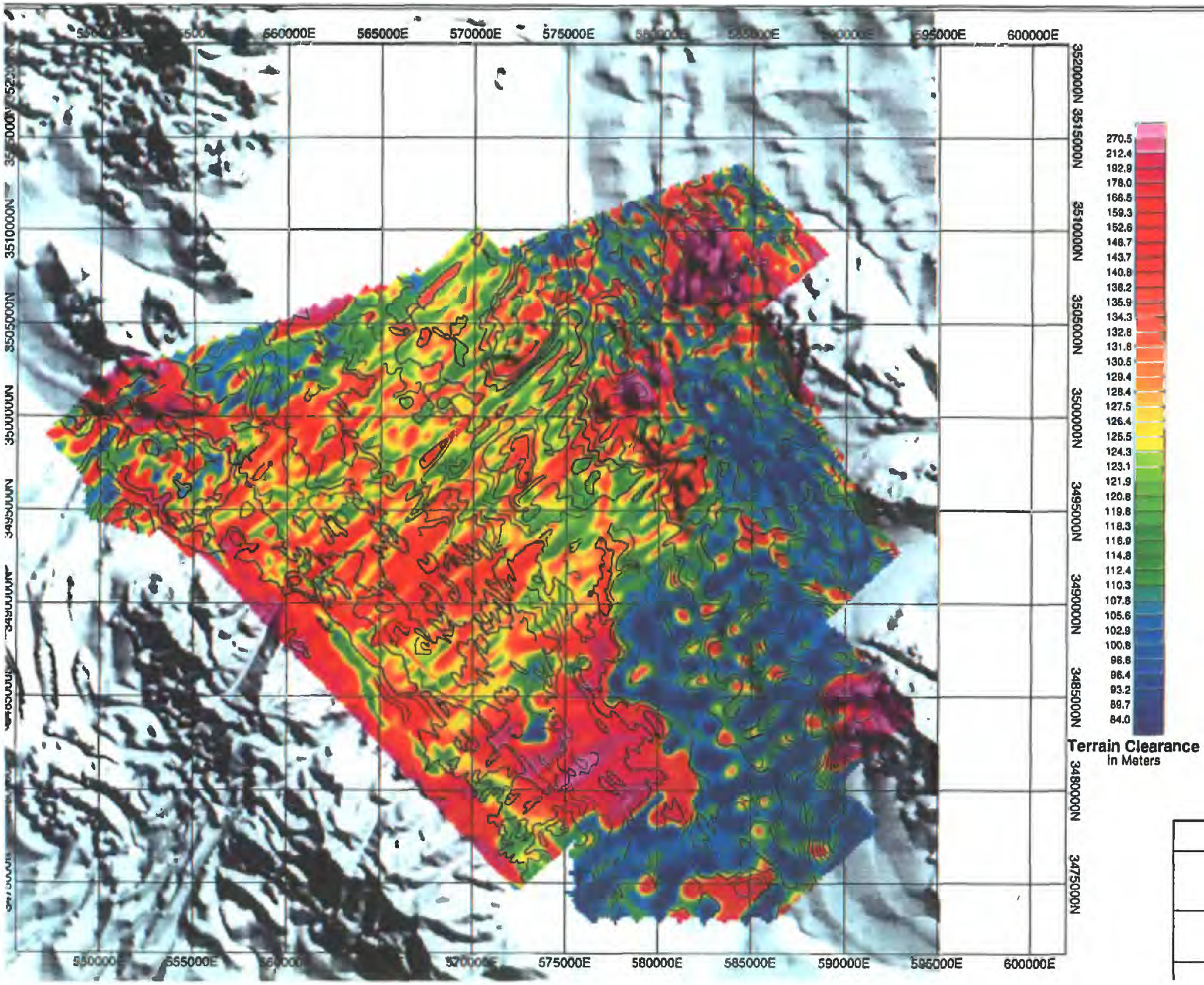


US Army Ft. Huachuca Garrison

Flightline Map on Topography
San Pedro (1997) and Tombstone (1999)
Airborne Geophysical Surveys

Jeff Wynn - USGS


USGS GEOTEM Survey
Altimeter Calibration - sierra Vista Airport, Arizona
5650
5450
5250
5050
4850
4650
4800
5000
5200
5400
y = 0.9548x + 458.78
y = 0.9524x + 338.93
Barometric and GPS Elevations (ft)
Radar Altimeter (ft) + Runway Elevation (4612 ft)
Barometric Elevation
GPS Elevation

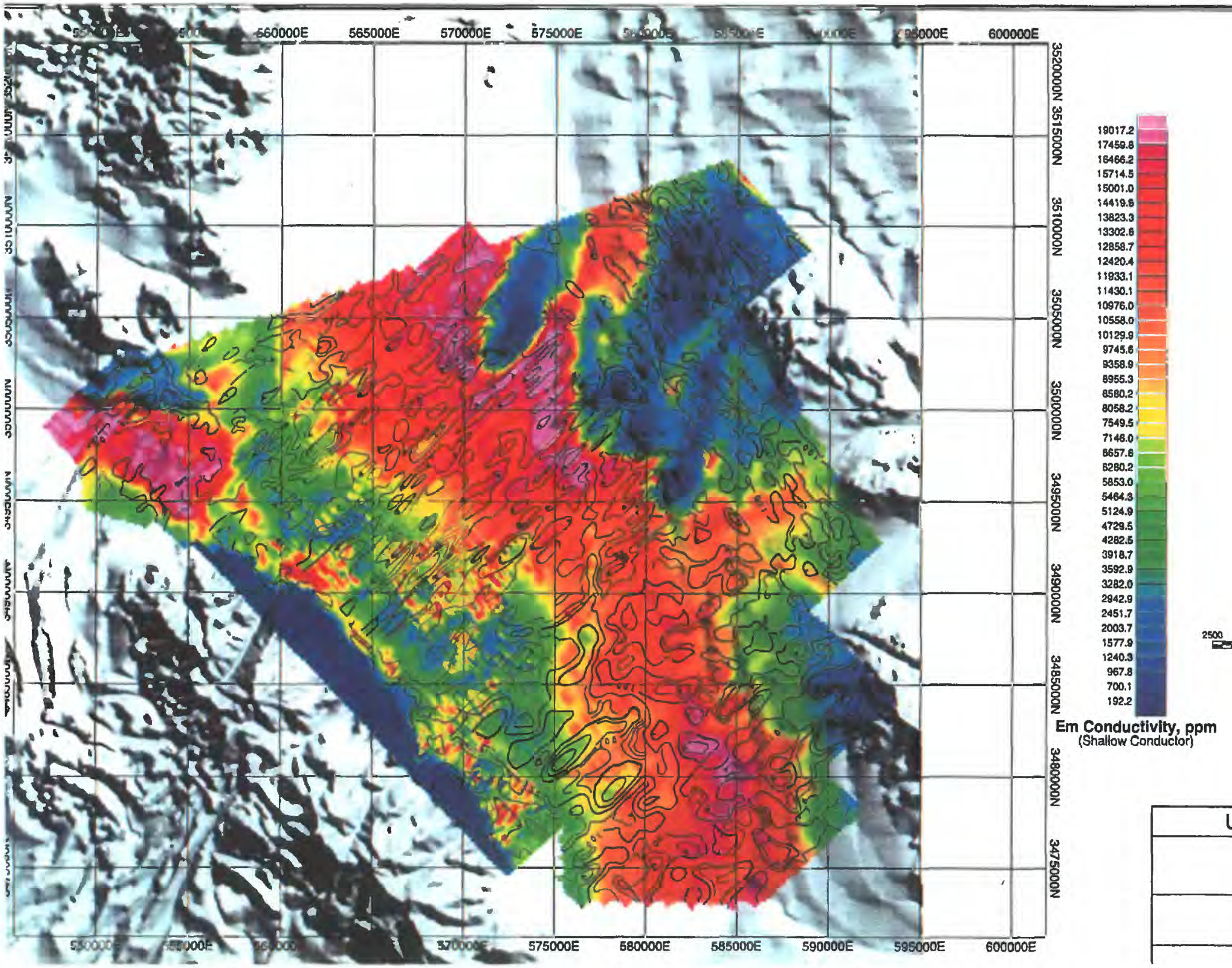


US Army Ft. Huachuca Garrison

1997 - 1999 Airborne EM Surveys
DATA-QUALITY CHECK
(View #1)

Superposition of Radar Altimeter Variations over Shaded-Relief Topography, with Superimposed Contours of EM Channel 10 (Z-Axis)

Jeff Wynn - USGS

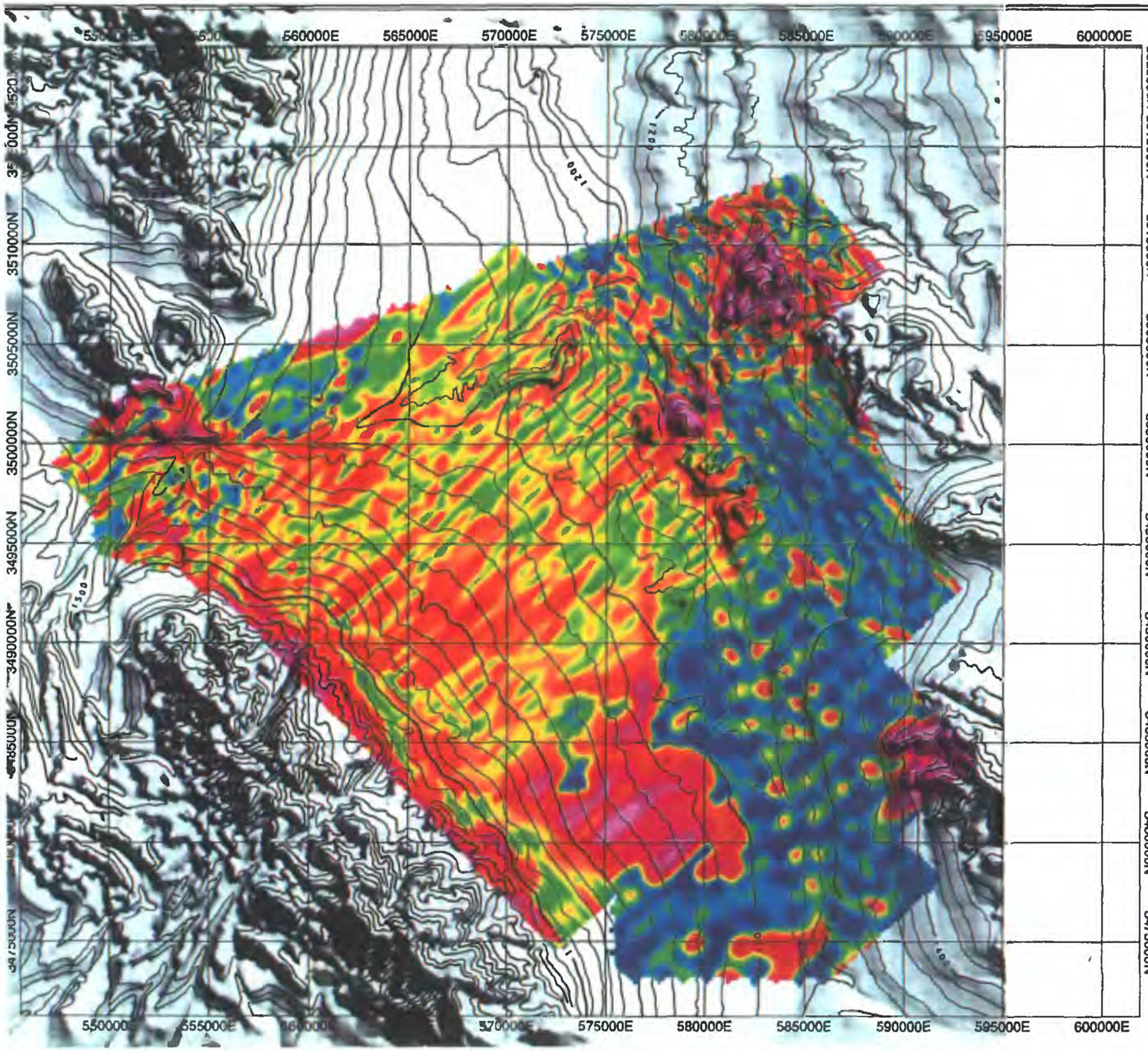


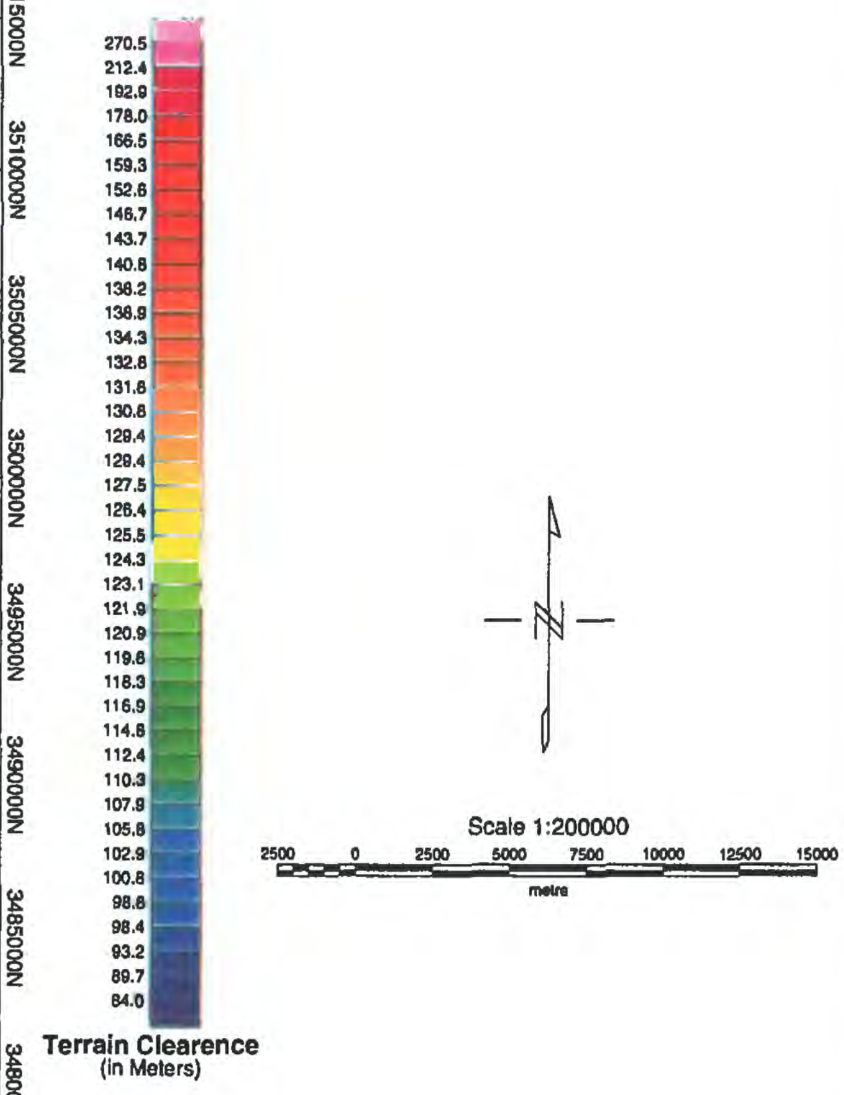
US Army Ft. Huachuca Garrison

1997 - 1999 Airborne EM Surveys
DATA-QUALITY CHECK
(View #2)

Superposition of Radar Altimeter Variations as CONTOURS on the Colored EM Channel 10 (Z-Axis), all over Shaded-Relief Topography

Jeff Wynn - USGS



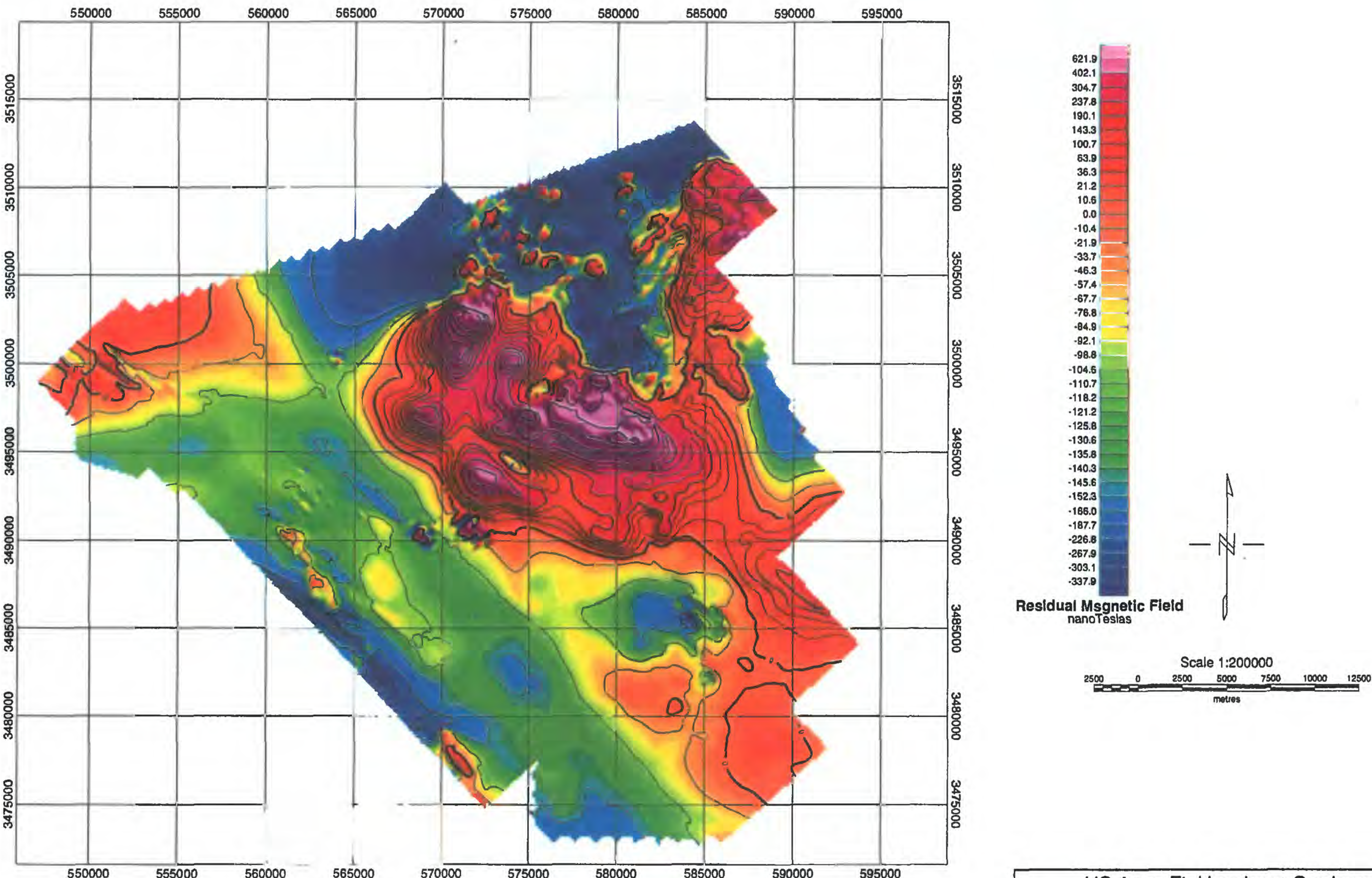


US Army Ft. Huachuca Garrison

1997 - 1999 Airborne EM Surveys
DATA-QUALITY CHECK
(View #3)

Superposition of Radar Altimeter Variations over Contoured, Shaded-Relief Topography

Jeff Wynn - USGS



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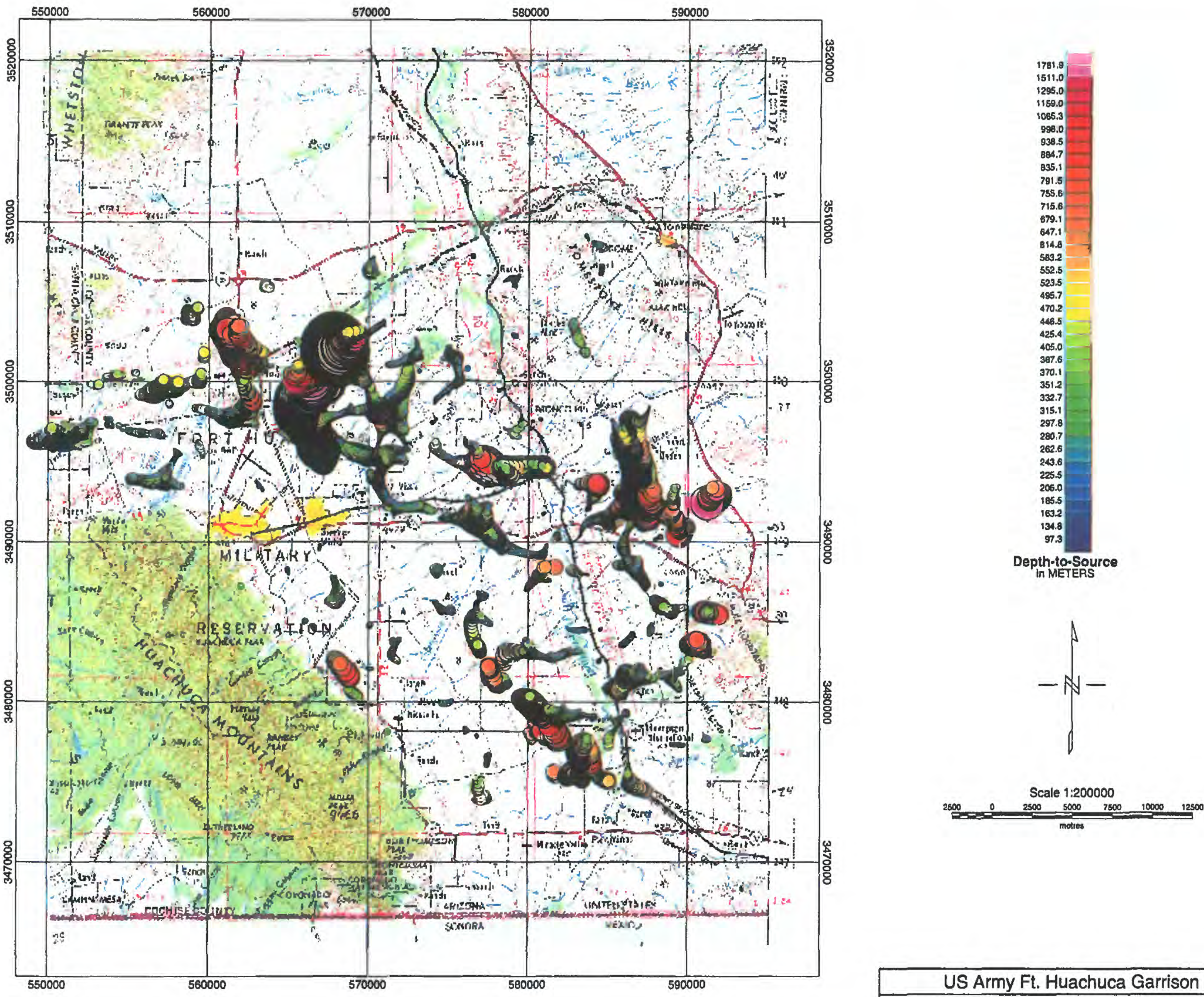
Merged Msgnetic Grids from the San Pedro (1997) and Tombstone (1999) Airborne Geophysicsl Surveye

Shaded-Relief Magnetic Map

Jeff Wynn - USGS

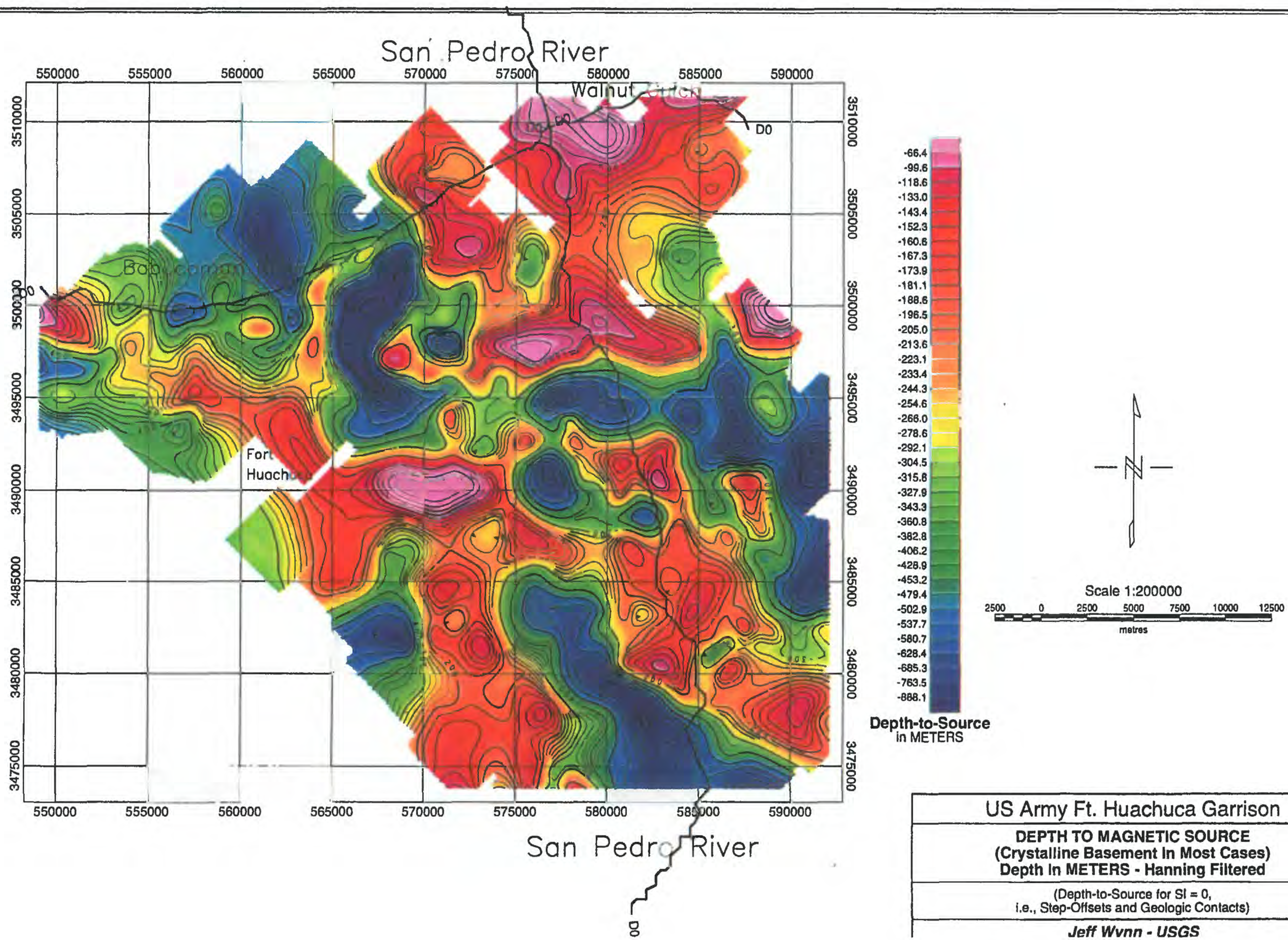


US Army Ft. Huachuca Garrison

Euler Solutions Superimposed on the Topo Map
The size and colors of the circles correlates with depth to magnetic basement.

The locations of individual solutions show magnetic gradients or geologic contacts.

Jeff Wynn - USGS



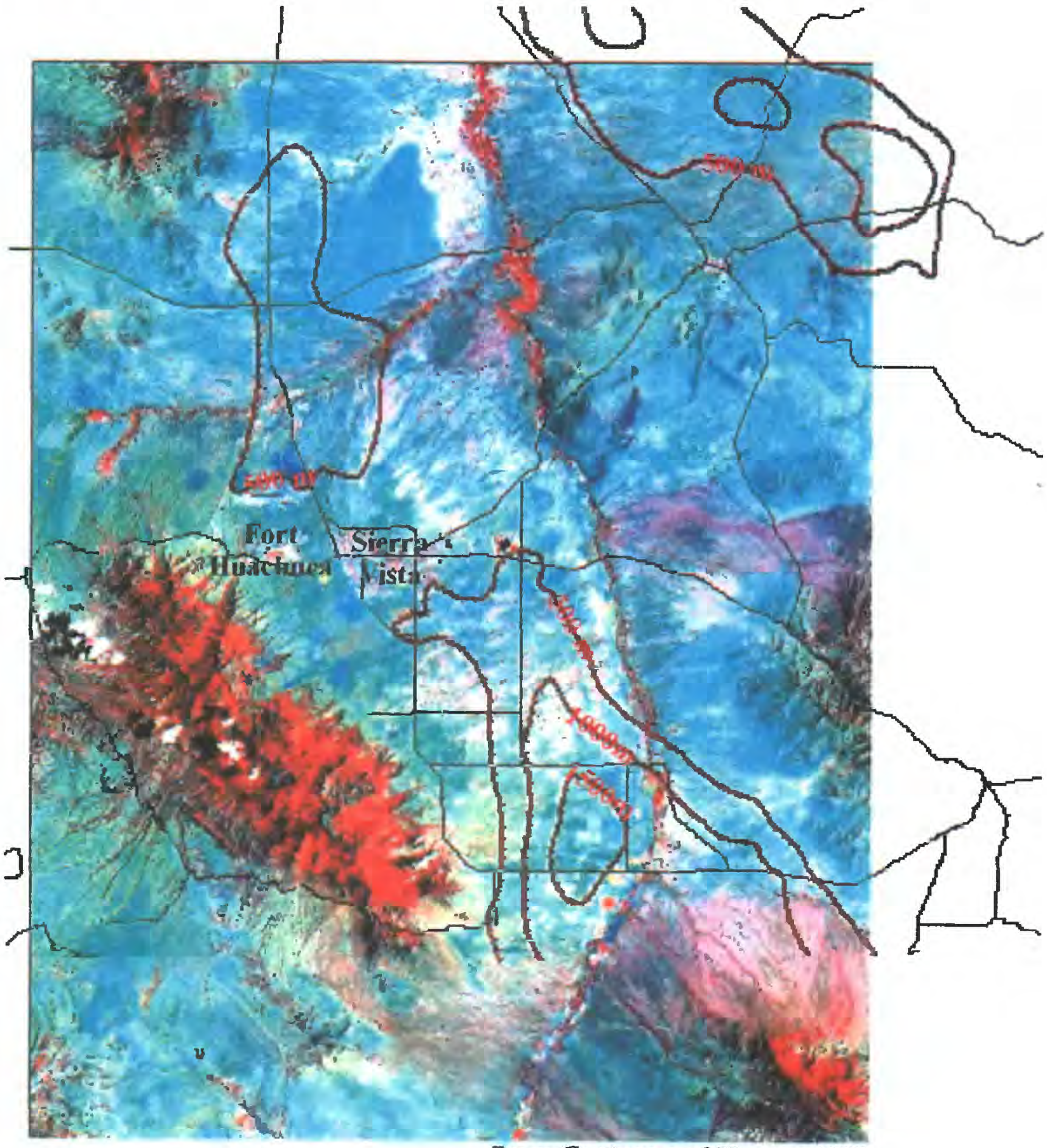
US Army Ft. Huachuca Garrison

DEPTH TO MAGNETIC SOURCE
(Crystalline Basement In Most Cases)
Depth In METERS - Hanning Filtered

(Depth-to-Source for SI = 0,
i.e., Step-Offsets and Geologic Contacts)

Jeff Wynn - USGS

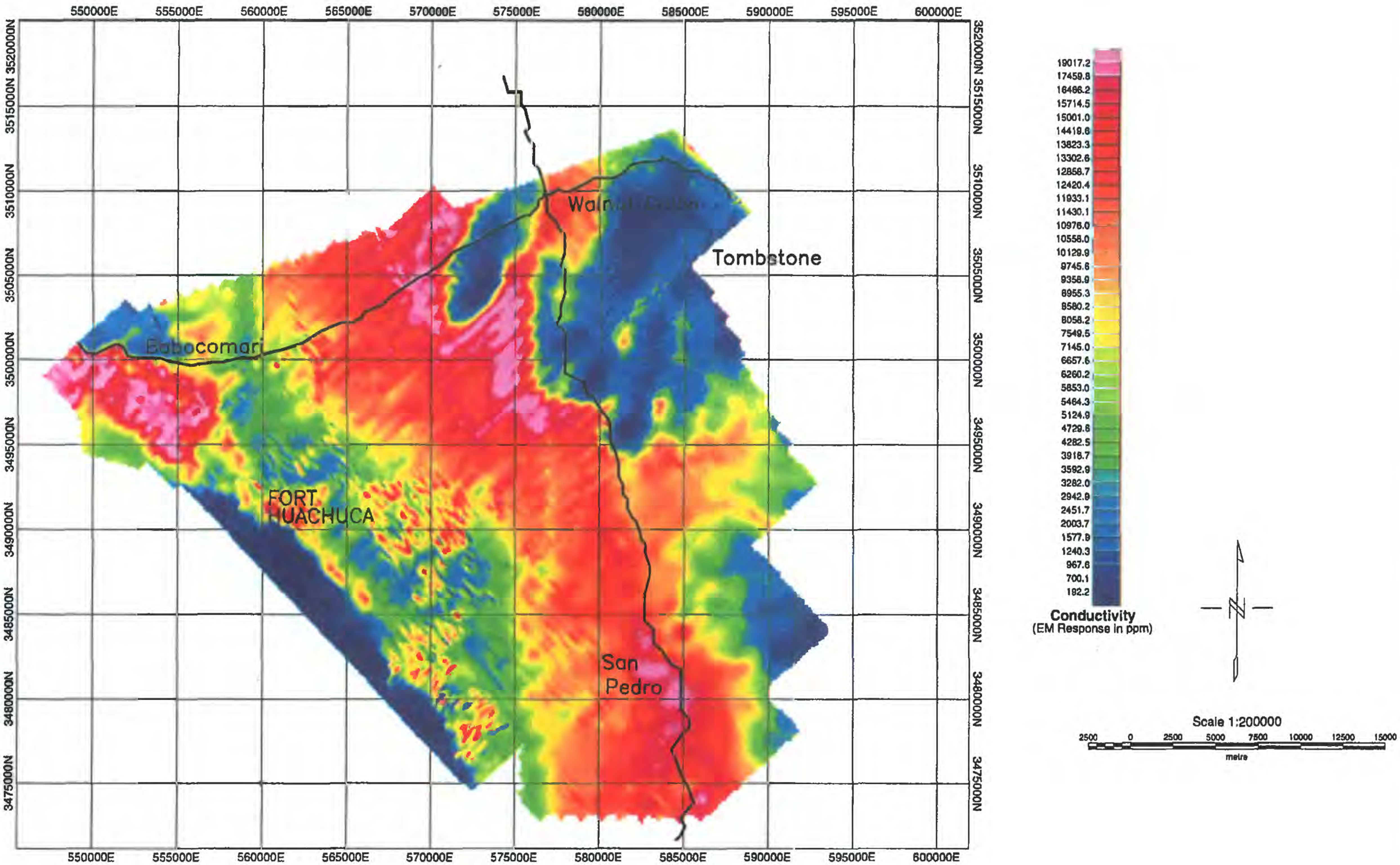
Depth-to Basement from Gravity Data



From Gettings and Houser, 1999

Thematic Mapper Image of the Sierra Vista Subbasin
Upper San Pedro River Drainage

Adapted from John Dohrenwend, 1999

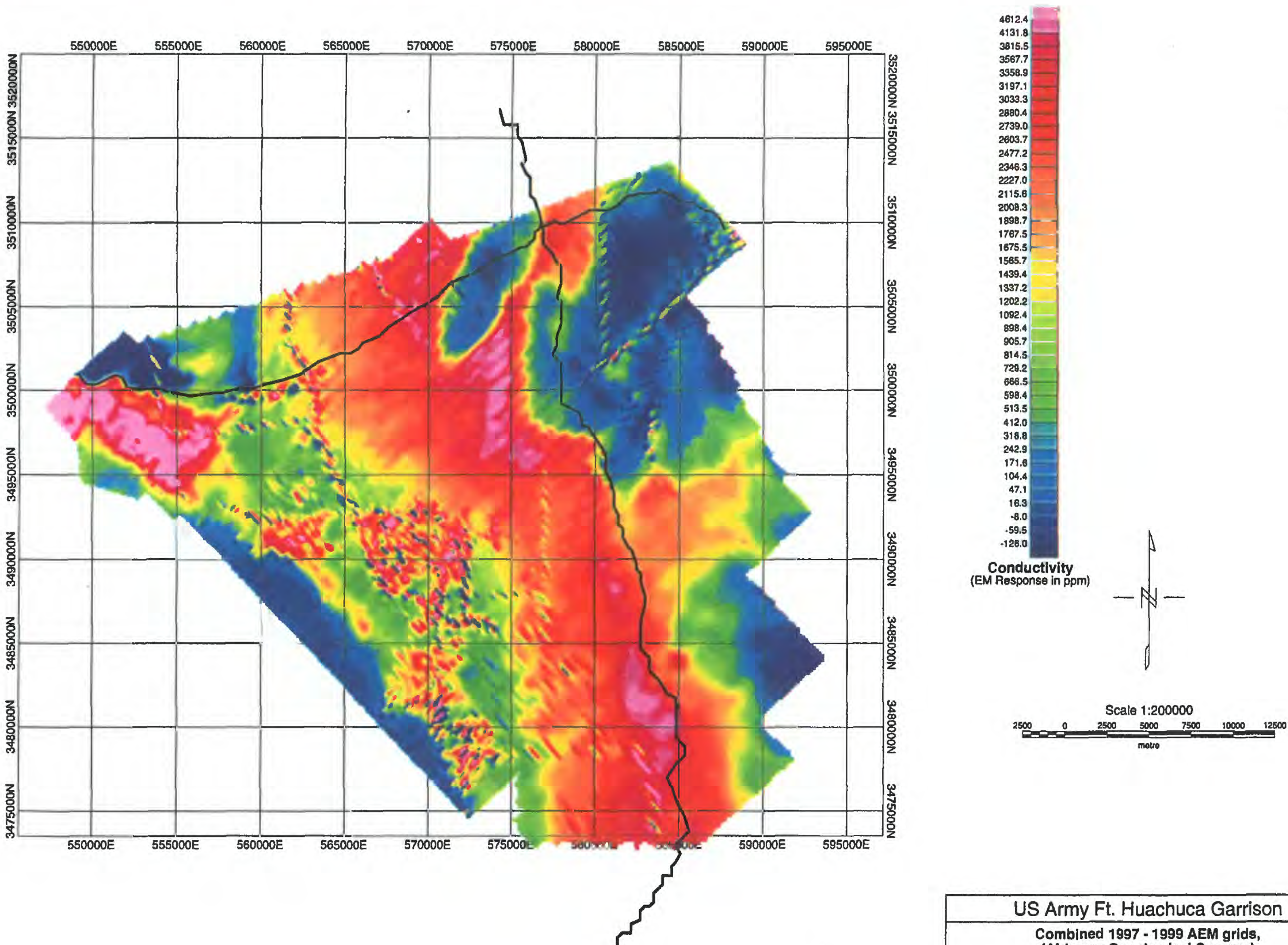


US Army Ft. Huachuca Garrison

Combined 1997 - 1999 AEM grids, (Airborne Geophysical Surveys) Z-Component Channel 10 (Shallow)

(Emphasizes a horizontal conductor- i.e., a view of the shallower part of the upper aquifer)

Jeff Wynn - USGS

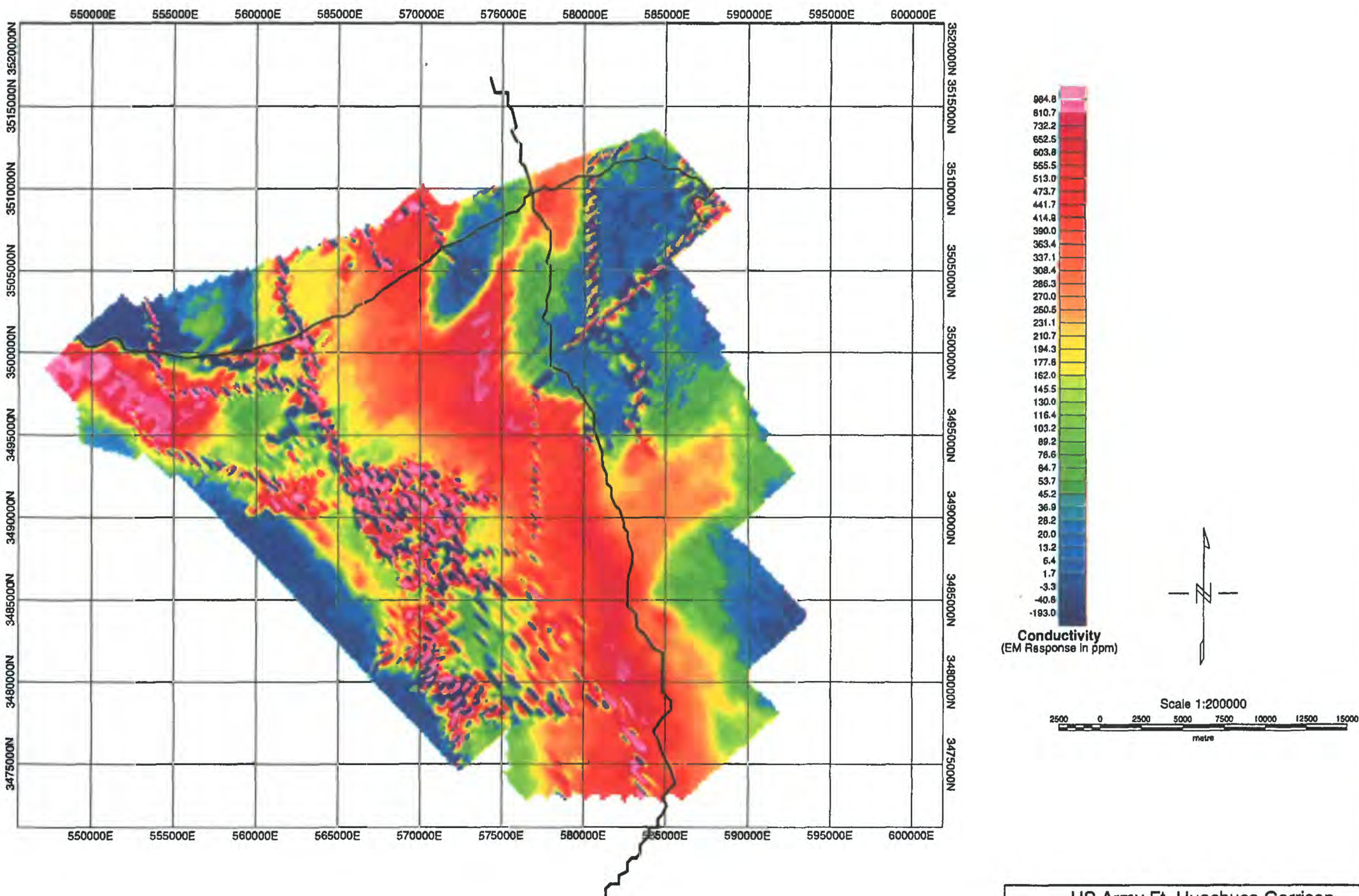


US Army Ft. Huachuca Garrison

Combined 1997 - 1999 AEM grids, (Airborne Geophysical Surveys) Z-Component Channel 14 (Intermediate)

(Emphasizes a horizontal conductor- i.e., a view of the intermediate aquifer)

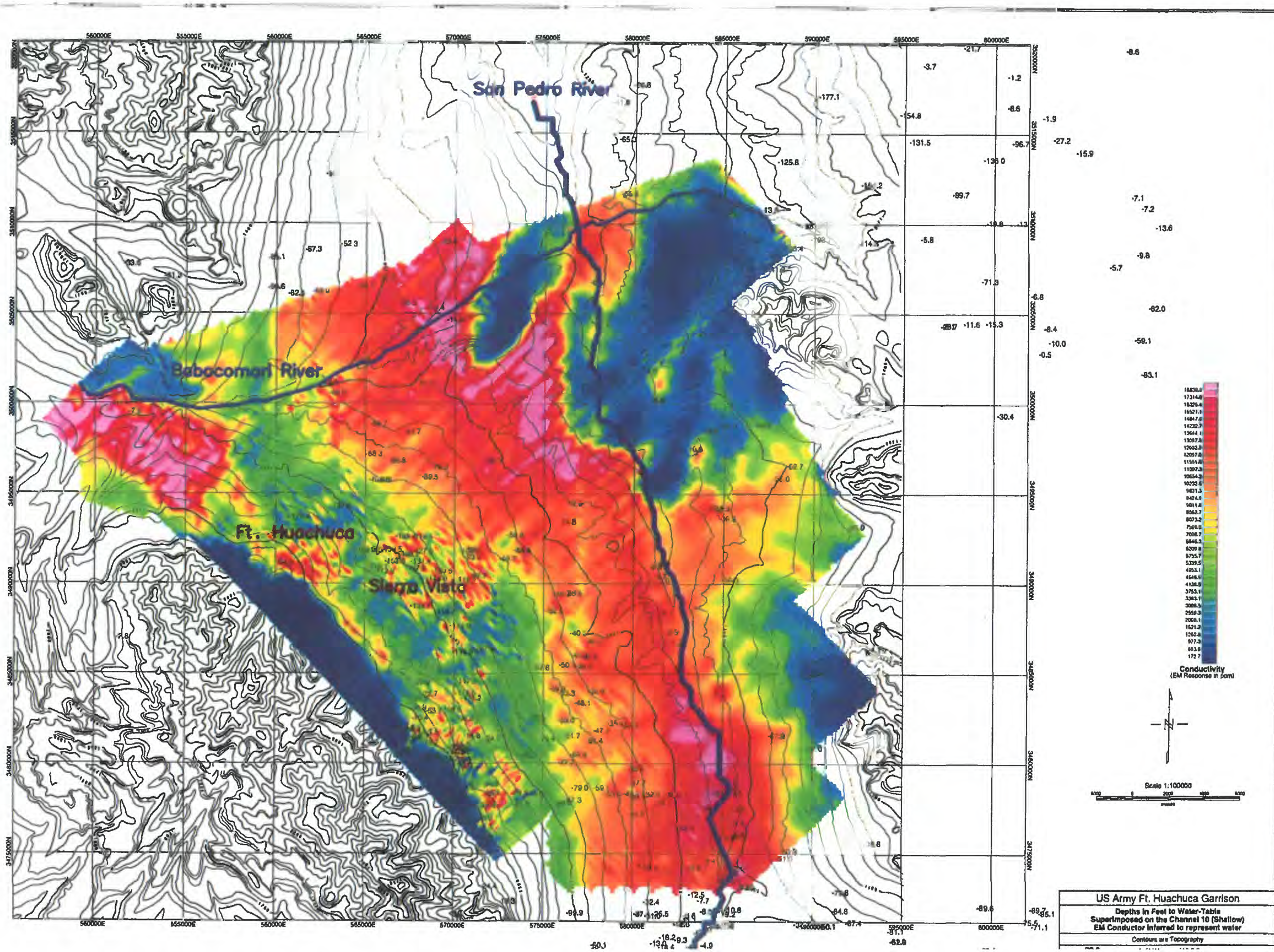
Jeff Wynn - USGS

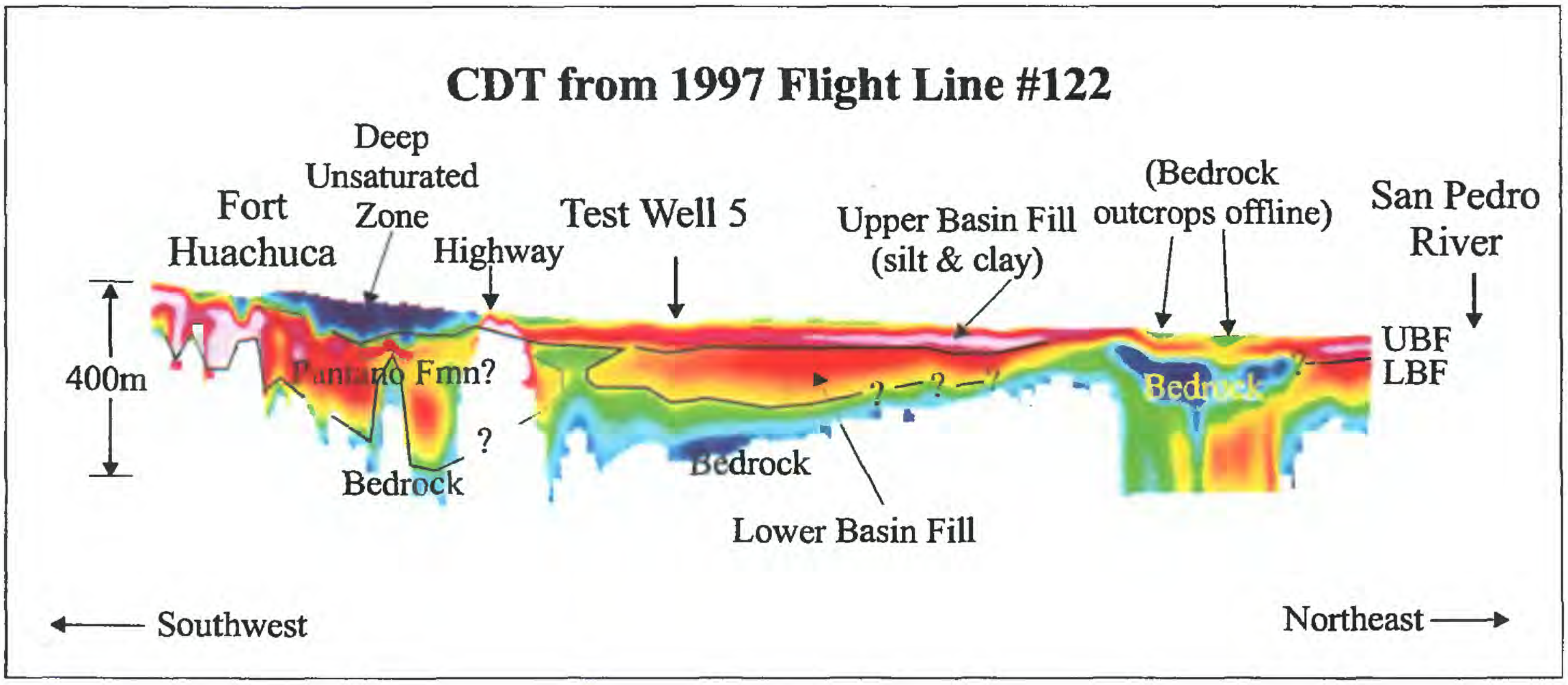


US Army Ft. Huachuca Garrison

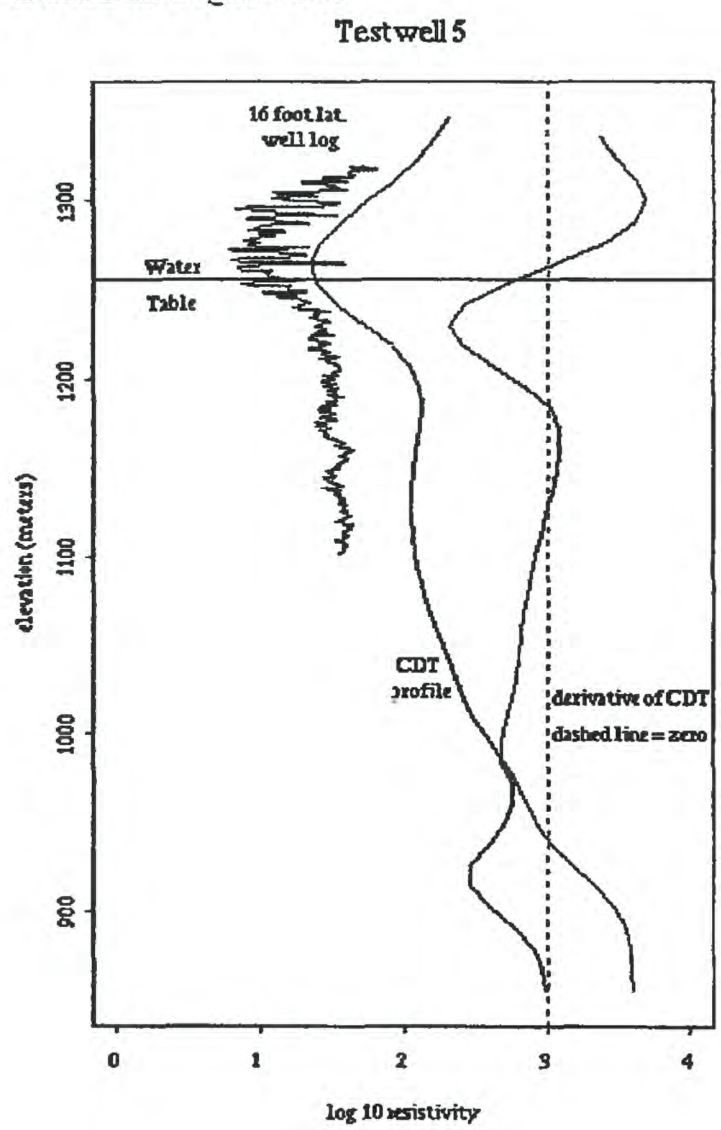
Combined 1997 - 1999 AEM grids,
(Airborne Geophysical Surveys)
Z-Component Channel 18 (Deep)

(Emphasizes a horizontal conductor- i.e., a view of the deeper part of the upper aquifer)

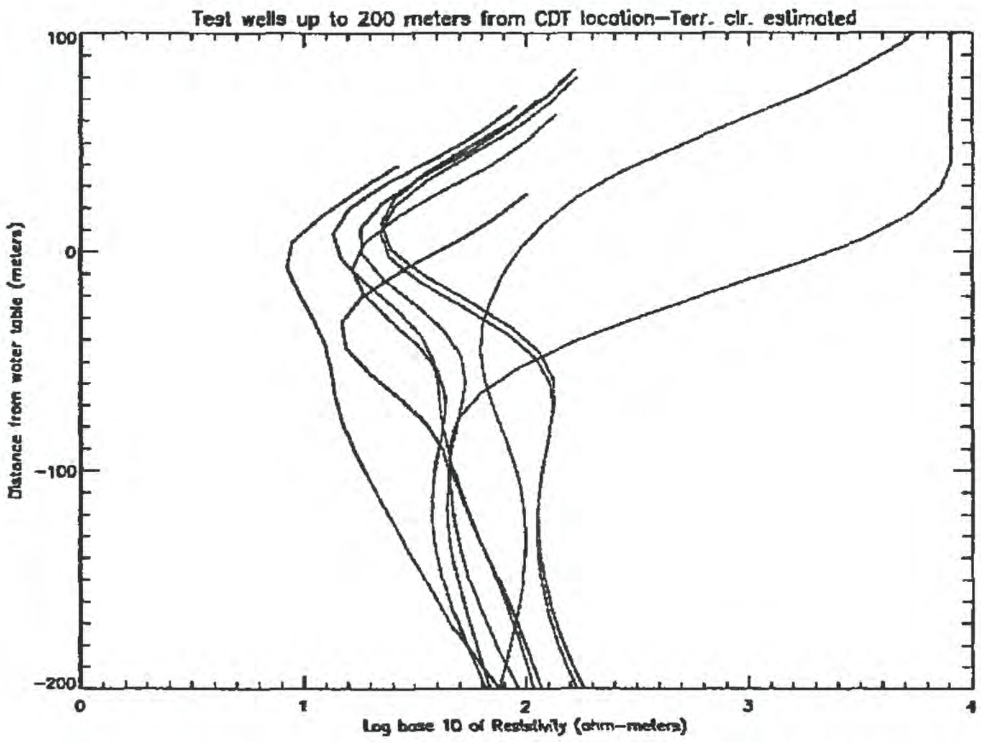

San Pedro River
Babocomari River
Ft. Huachuca
Sierra Vista
Conductivity
(EM Response in ppm)
Scale 1:100000
US Army Ft. Huachuca Garrison
Depths in Feet to Water-Table
Superimposed on the Channel 10 (Shallow)
EM Conductor Inferred to represent water
Contours are Topography


CDT from 1997 Flight Line #122
Fort Huachuca
Deep Unsaturated Zone
Highway
Test Well 5
Upper Basin Fill (silt & clay)
(Bedrock outcrops offline)
San Pedro River
400m
Pantano Fmn?
Bedrock
?
Bedrock
Lower Basin Fill
Bedrock
UBF
LBF
Southwest
Northeast

Bultman Figure 3.8

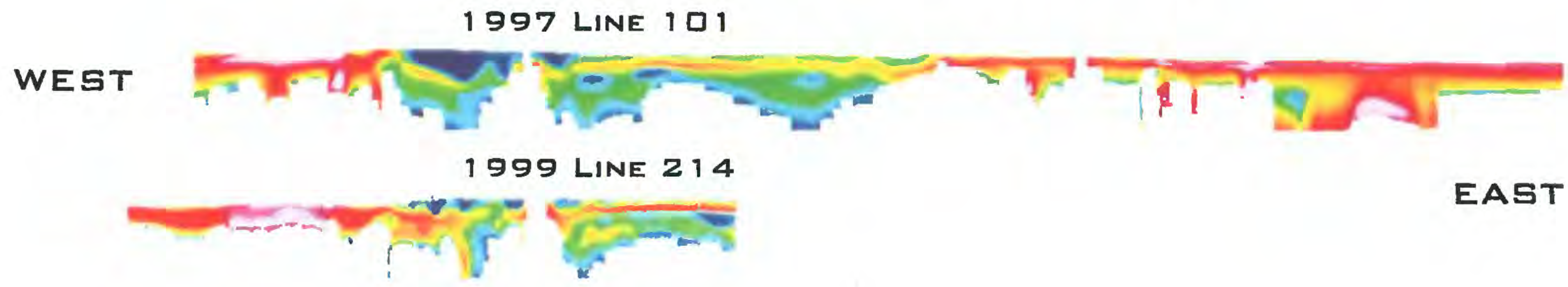


Vertical Sections of CDTs vs. the Water Table



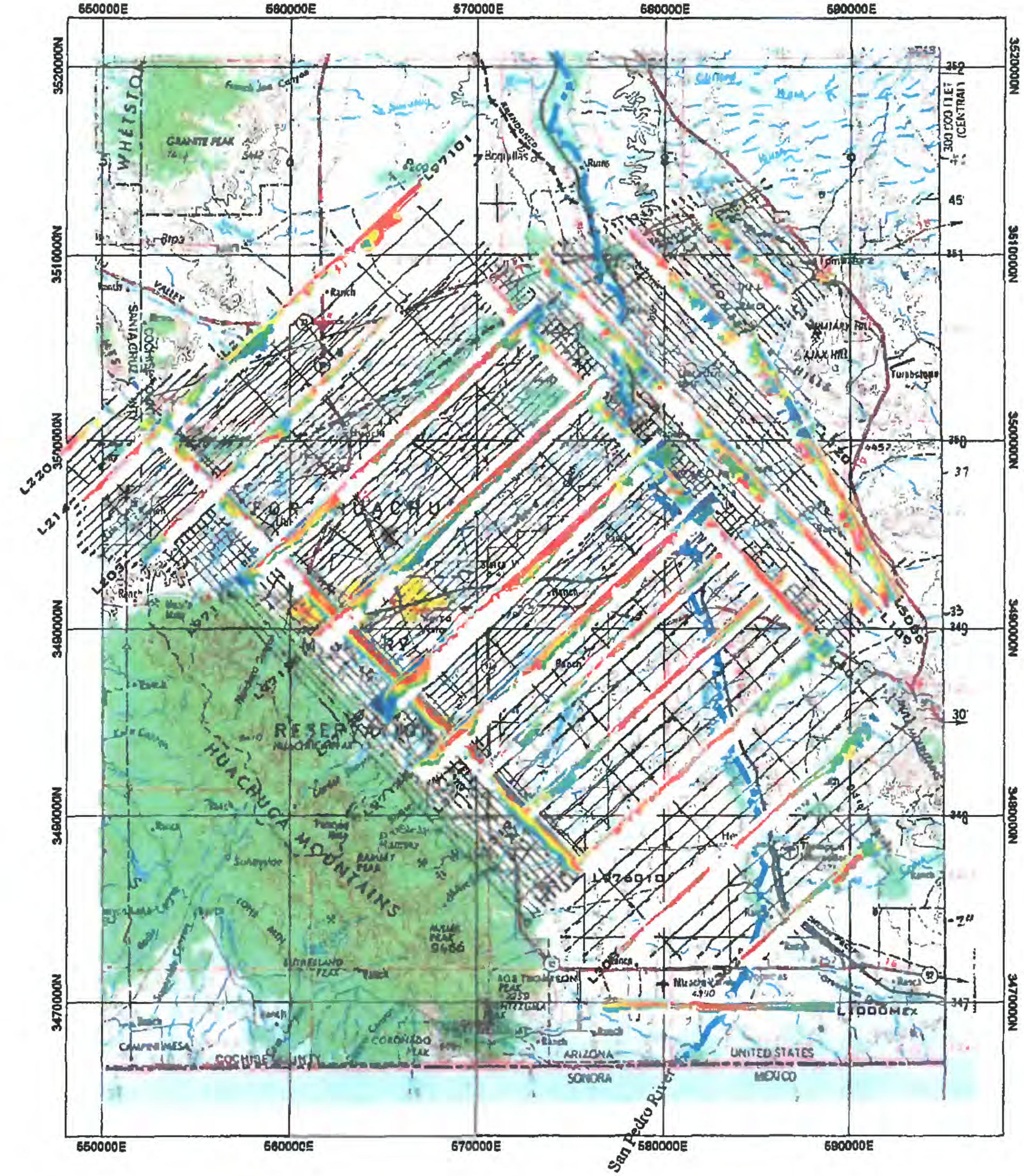
From Bultman, Ch. 3, Figure 3.13

Quality control: Repeatability comparison between the 1997 and 1999 AEM surveys



Note: lines are close to each other, but not coincident.

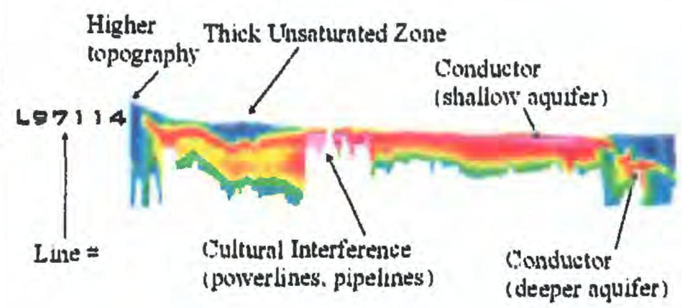
Conductivity vs. Depth Fence-Diagram
1997 and 1999 Airborne EM Surveys

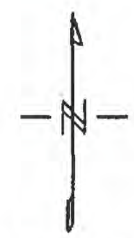


EXPLANATION:

Conductivity-Depth Profiles (CDTs) are mathematical inversions of the 60-channel airborne Electromagnetic signal acquired by the Geoterrex GEOTEM system. Inversion means simply conversion of data from signal in pico-volts per square meter to conductivity as a function of depth. Data are reliable down to about 150 meters depth, and generally meaningful down to about 400 meters depth. In this fence-diagram we generally see red where there is water, the depths are only approximate, but the deepest part of each CDT section is about 400 meters deep. We can use this fence-diagram to get a good idea of where the water in the Upper San Pedro Basin is, and how it deepens (towards the west) and shallows (towards the San Pedro River on the east)

LEGEND: A TYPICAL CDT:
(VERTICALLY EXAGGERATED)



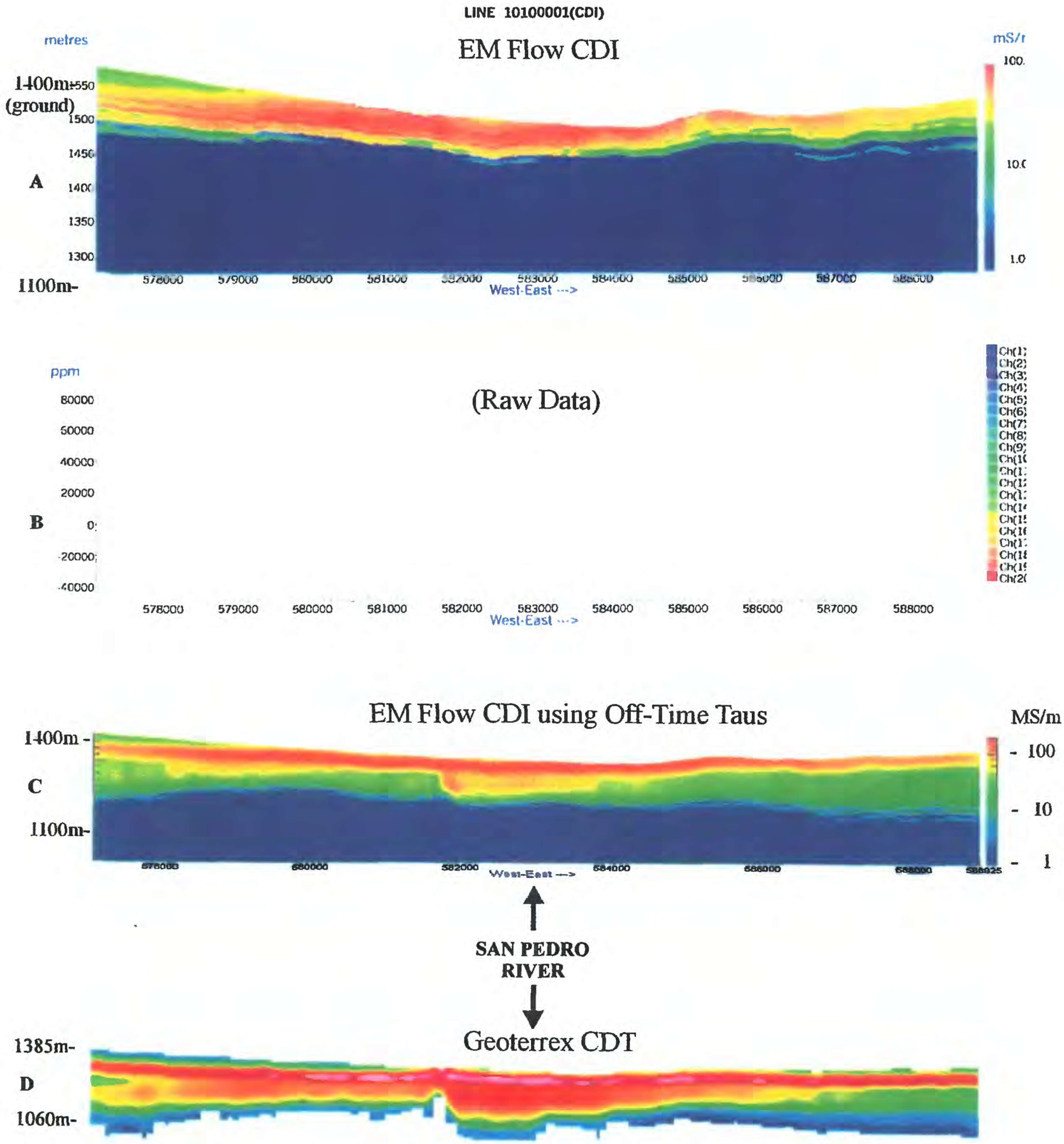


SCALE: 1:200,000

US Army Ft. Huachuca Garrison

Flightline Map on Topography
San Pedro (1997) and Tombstone (1999)
Airborne Geophysical Surveys

Jeff Wynn - USGS



Comparison of the Encom EM-Flow inversion (CDI's)
vs. the Geoterrex proprietary inversion (CDT)