Excerpts From USGS Sedona Magnetic Anomaly Survey:

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Preliminary Report
on Geophysical Data
in Yavapai County,
Arizona

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U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

1Menlo Park, California
2Tucson, Arizona
3Denver, Colorado

AEROMAGNETIC DATA, MAPS, AND DERIVATIVE PRODUCTS

About the Aeromagnetic Method

Geologic structures (such as faults or igneous intrusions) often produce small magnetic fields that distort the main magnetic field of the Earth (Fig. 3). These distortions, called anomalies, can be detected by measuring the intensity of the Earth's magnetic field on or near the surface of the earth. By analyzing magnetic measurements, geophysicists are able to learn about geologic structures, even though these structures may be buried beneath the Earth's surface (e.g., Dobrin and Savit, 1988; Blakely, 1995). Magnetic measurements are often made from airplanes (or helicopters) flown along closely spaced, parallel flight lines. Additional flight lines are flown in a perpendicular direction to aid in data processing. These measurements are then processed into a digital aeromagnetic map. Assisted by computer programs, the geophysicist builds a geologic interpretation from these data, incorporating geologic mapping, well information, and other available geophysical information (e.g., gravity, radiometric, electrical, seismic-reflection).

Magnetic Lithologies

Volcanic rocks are the most prevalent magnetic lithology of this region, and we expect high-amplitude, short-wavelength anomalies over volcanic terranes, especially in the Black Hills and the area between Page Springs and Sedona. Volcanic rocks in the area consist of (1) the Sullivan Buttes latite (24-26 Ma; also known as the andesite unit of Krieger, 1965), (2) an older sequence of basalts of the Hickey Formation, and (3) a younger section of basalts of the Perkinsville Formation. The basalts in this region typically include lava flows which individually may have a uniform direction of magnetization. Steeply dipping faults that offset subhorizontal units often produce magnetic anomalies that appear as linear trends on aeromagnetic maps (e.g., Bath and Jahren, 1984). The latites, on the other hand, often are extruded from volcanic plugs and thus tend to produce intense, somewhat circular magnetic anomalies (often as magnetic lows, because the latites are generally reversely polarized). The latites are exposed at Sullivan Buttes and are inferred to underlie parts of Little Chino Valley (Langenheim and others, 2000).

The magnetic properties of sedimentary rocks, such as the Paleozoic sequence of dolomite, limestone, and sandstone, are usually weak, such that the resulting magnetic anomalies are very small in amplitude or undetectable by airborne surveys. The Precambrian metasedimentary rocks are generally incapable of producing detectable magnetic anomalies, although there are some notable exceptions. Exceptions include an iron-rich metachert that forms a minor lithologic constituent exposed south of the towns of Prescott and Prescott Valley (Krieger, 1965) and metagraywacke exposed on the western side of Sullivan Buttes. Metavolcanic rocks, gabbros and some of the intrusive rocks can produce prominent magnetic anomalies. Magnetic susceptibility is a measure of how magnetic a rock becomes when placed in an external magnetic field and is mostly a function of the amount of magnetite in that rock. Magnetic susceptibility measurements of Precambrian metavolcanic rocks range from 2 (meta-rhyolite) to 8000 (metabasalt) 10-6 SI units (Ed DeWitt, written commun., 2000). Gabbros also show a high range in susceptibility for 29 samples, from 30 to 8000 x 10-6 in the SI system. Granodiorites and granites show a wide range in susceptibility, although individual granodiorite and granite plutons are characterized by narrower ranges in susceptibility. For example, the Prescott granodiorite has a range of 900 to 1600 x 10-6 for 6 samples (mean of 1100 x 10-6). The Minnehaha granodiorite, on the other hand, is less magnetic, showing a range in susceptibility of 10 to 350 x 10-6 for 5 samples (mean of 48 x 10-6).

Data Acquisition and Processing

Goldak Airborne Survey conducted the aeromagnetic survey under contract to Yavapai. County. Goldak is headquartered in Saskatoon, Sasketchewan, Canada, and has years of experience in acquiring and processing aeromagnetic data. Data acquisition and processing were accomplished under guidelines established by the U.S. Geological Survey over the last several decades.
The aeromagnetic data were acquired with a Piper PA-31 Navajo, a fixed-wing aircraft. The airborne magnetic sensor was a Geometrics G-822A cesium-vapor magnetometer located at the tip of a fiberglass stinger (boom). A theoretical flight surface, based on a digital topograhic model, was computed in advance of the survey, and a real-time, differentially corrected Global Positioning System (GPS) was used during flight to maintain this theoretical surface. Flight lines were oriented east-west and flown at a nominal altitude of 150 m (500 ft) above terrain, or as low as permitted by the Federal Aviation Adminstration and safety considerations. Figure 4 shows the height of the airplane above the ground measured by radar altimetry. The Prescott, Williamson Valley, and most of the Black Hills and Cottonwood blocks were flown at a flightline spacing of 200 m. The Upper Big Chino block and the northern parts of the Black Hills and Cottonwood blocks were flown at a spacing of 300 m. North-south control lines were spaced 3.0 km (1.83 mi) apart. Total flight distance was 21,691 km (13,478 mi).
Two base station magnetometers were deployed for this survey. The primary base station, a cesium-vapor magnetometer identical to the airborne sensor, was just east of Prescott. The secondary base station, a proton-precession magnetometer, was located at the Ernest Love municipal airport north of the city of Prescott. A base station magnetometer measures the time-varying magnetic field and has two important functions: (1) it records the normal daily changes of the external field (diurnal variation), which are subtracted from the aeromagnetic data and (2) it records the onset and dissipation of magnetic storms. Airborne operations were interrupted if magnetic storm activity exceeded the limits established by the U.S. Geological Survey. The limits were as follows: (a) 5 nanoteslas (nT) for monotonic changes during any 5 minute period, (b) 2 nT for pulsations with periods of 5 minutes or less, (c) 4 nT for pulsations with periods between 5 and 10 minutes, and (d) 8 nT for pulsations with periods between 10 and 20 minutes. Time between aircraft and base stations was synchronized with GPS time.
Post-survey data processing was performed by Patterson, Grant and Watson (PGW) of Toronto, Canada. This included removal of diurnal fields, subtraction of the International Geomagnetic Reference Field (e.g., Barton and others, 1996), navigational corrections, and adjustment of total-field values between crossings of flight lines and tie lines. A preliminary version of the completed survey was provided to the USGS for evaluation in September, 2001. Final data were delivered in November, 2001. Accuracy of the data is estimated to be on the order of 0.5 to 1 nT.

Aeromagnetic Map and Derivative Products

Figures 5a and 5b show the improved resolution of the new, high-resolution data compared to the preexisting, regional aeromagnetic data. Color scale in these maps indicates the intensity of the Earth's magnetic field relative to a global standard (the International Geomagnetic Reference Field updated to the date of the survey). The regional digital coverage (Sweeney and Hill, 2001) consists of east-west flightlines flown at a spacing of 1 or 3 miles and data from 3 higher-resolution surveys (Dempsey and Hill, 1963; USGS, 1981; USGS, 1982). We also incorporated the high-resolution aeromagnetic survey that covers the headwaters region of the Verde River (Langenheim and others, 2000). Figure 5b shows the new survey merged into the regional digital database.
As expected, volcanic regions produce distinctive magnetic anomalies, high in amplitude and short in wavelength. These anomalies are particularly evident over much of Lonesome Valley, the Black Hills and the area between Cornville and Sedona. For example, the preexisting regional coverage indicates only a broad magnetic high in the Page Springs area (Fig. 5a). Virtually all of the individual magnetic anomalies seen in the new high-resolution data (Fig. 5b) are absent in the pre-existing regional coverage.
Large magnetic highs are present over the weakly magnetic Paleozoic sedimentary rocks exposed on Big Black Mesa and in the vicinity of Sedona. Thus, the sources of these anomalies are likely concealed by Paleozoic units. Krieger (1967a) shows several small exposures of Precambrian granitic rocks along the Big Chino fault; these rocks are the most likely source of the Big Black Mesa magnetic high. The high is truncated by the Big Chino fault on its southwestern margin (Langenheim and others, 2000). Oil-test wells in the Sedona area encountered Precambrian granite beneath 300-500 m of Paleozoic sedimentary rocks (Peirce and Scurlock, 1972);

"Precambrian crystalline basement is the most likely source of the broad magnetic high in the Sedona area. The long-wavelength nature of the magnetic high indicates that the source of the anomaly is buried".

Subdued magnetic anomalies are present in the Verde Valley. The subdued nature of these anomalies is probably caused by two factors: (1) the increased height of the magnetic sensor above the ground surface in this region (Fig. 4) and (2) the increased thickness of relatively non-**magnetic** Verde Formation in the downdropped block of the Verde fault zone. To emphasize and sharpen the **anomalies** in this region, filtering of the data and comparison to the gravity data will be needed.

The new aeromagnetic data are of sufficient quality to permit the application of well-established processing and filtering techniques that emphasize subtle features. Figures 6 and 7 show the aeromagnetic data processed to enhance and define near-surface sources.

Figure 6 shows residual **magnetic** anomalies, a technique that emphasizes shallow **magnetic** sources. This residual **magnetic** map was computed by analytically continuing the aeromagnetic data to a slightly higher surface (100 m; Blakely, 1995), in other words, mathematically transforming the data as if they were collected at a higher altitude, and then subtracting that result from the original data. The **anomalies** that remain are commonly called residual **magnetic** **anomalies**. This method, essentially a discrete vertical derivative, emphasizes **anomalies** caused by shallow **magnetic** sources (approximately < 1 km) while subduing **anomalies** caused by deep sources. It is particularly useful in identifying shallow crustal faults that separate rocks of contrasting **magnetic** properties. Shallow sources produce short-wavelength **anomalies**, such as the **anomalies** present over exposed volcanic rocks.

Subtle **magnetic** **anomalies** that are not apparent in Figure 5b are accentuated in the filtered aeromagnetic data (Fig. 6). The **magnetic** field over the alluvial deposits of Lonesome Valley shows several northwest- and north-trending **anomalies**. Because alluvium is often weakly **magnetic**, some of these **anomalies** may originate from volcanic rocks concealed beneath the surface. Other possible sources are shallowly buried Precambrian basement, or alteration along buried fault zones. A linear, north-striking **magnetic** high extends from the town of Prescott Valley north towards Perkinsville. Its source probably resides within the Precambrian basement, because the **magnetic** anomaly can be traced onto Precambrian rocks.

Figure 7 shows magnetization boundaries, automatically computed from the aeromagnetic data (Blakely and Simpson, 1986). This calculation assumes that **magnetic** contacts are vertical; calculated positions will be shifted slightly over contacts that are not vertical. Figure 7 shows the magnetization boundaries plotted on the regional geology.

Langenheim and others (2000) used the magnetization boundaries to map the extent of the Big Chino Fault, as indicated by a lineament on the basin margin of Big Black Mesa. The new data extend the Big Chino fault to the north of the 1999 high-resolution aeromagnetic survey and are consistent with Kriegers (1967b) geologic mapping of the fault. The **magnetic** data can also be used to extend the Bear Wallow Canyon fault west of its mapped extent into the northern part of Verde Valley.

The magnetization boundaries also define structures related to buried volcanic rocks. For example, the magnetization boundaries in the northeast corner of the Upper Big Chino block delineate the extent of buried basalt (possibly a northeast-striking paleochannel filled with basalt?) on the upthrown side of the Big Chino fault. Future analysis should focus on establishing the depth, thickness, and geometry of the volcanic rocks beneath upper Big Chino, Lonesome, Verde, and Williamson Valleys.

SURFACE GEOPHYSICAL DATA

Gravity data and map

As part of this project, we compiled and reprocessed the existing gravity coverage of the region (National Geophysical Data Center, 1999; Frank, 1984; Smith, 1984; Langenheim and others, 2000) and added 628 new gravity stations using a global positioning system (GPS) to determine location and elevation. These data have been processed to provide information on subsurface density variations. The gravitational attraction at any point depends on many factors, including the latitude and elevation of the measurement, earth tides, terrain, deep masses that isostatically support the terrain, and variations in density within the Earth's crust and upper mantle. The last of these quantities is of primary interest in geologic investigations and can be obtained by calculating and removing all other quantities. The resulting field is called the isostatic residual gravity anomaly and reflects, to first order, density variations within the middle and upper crust (Simpson and others, 1986).

The gravity field is dominated by gravity highs along the northeastern part of the study area, with lower gravity values in the southwestern part of the study area (Fig. 8). Superposed on this regional field are local gravity lows in the valley areas. Big Chino Valley is characterized by a gravity low, bounded on the east by the Big Chino Fault. The deepest part of the basin, as suggested by the lowest gravity value within the valley (-24 mGal), is about 5 km from the southern edge of the Upper Big Chino aeromagnetic survey block. Gravity values increase to the southeast towards Sullivan Lake. The northern part of Lonesome Valley is characterized by higher gravity values than those over Big Chino Valley, suggesting that the basin fill beneath Little Chino Valley is less than 1 km (Langenheim and others, 2000). South of the town of Chino Valley is an east-west striking gravity gradient, with a large gravity low to the south. This low could be caused by a deep basin centered near the intersection of Highway 89 and alternate route 89, but a more likely explanation is a thick stock of Prescott granodiorite (Cunion, 1985). The gravity low extends over Precambrian rocks and Prescott granodiorite (and Granite Dells granite) is less dense than the some of the more mafic metavolcanic and gabbros within Precambrian basement.

A gravity feature of potential hydrologic interest is the gravity low over Williamson Valley. The gravity low may reflect either a relatively deep (1-2 km) sedimentary basin or a low-density pluton (Langenheim and others, 2000). The margins of the low are linear and strike northwest. The gravity low also coincides with a **magnetic** low (Fig. 5b, 6). The basin interpretation is preferred because the gravity low does not extend across

Precambrian outcrops exposed to the east of the gravity low. A drillhole recently (2002) completed for the city of Prescott supports the basin interpretation; the drillhole penetrated 460 m (1500 ft) without encountering basement rocks (T. Merrifield, oral commun., 2002; Fig. 8).

The Verde Valley is also characterized by a northwest-trending gravity low. Based on the amplitude of the gravity low (15-18 mGal) and assuming a reasonable density contrast between the basin fill and the basement rocks (-0.4 g/cm3), the basin fill may be as thick as 1 km. The low, approximately 35 km long and 8-10 km wide, lies within the western half of the valley. The western margin of the Verde Valley gravity low is nearly coincident with the southern part of the Verde fault zone, but lies 1-2 km east of the mapped trace of the northern part of the fault zone. The eastern margin of the basin is more linear, suggestive of a fault origin, and steps to the southwest near the intersection of I-17 and Hwy 260, dividing the gravity low into two parts. The lowest gravity values are northwest of the step. A smaller gravity low, about 8 km long, lies to the south of the step. The southern extent of this gravity low is poorly constrained by existing gravity data.

Another gravity feature of potential hydrologic interest is outside the study area, in the southwest corner of Figure 8, where the lowest gravity values lie northeast of the intersection of highways 89 and 96. Although the gravity feature is poorly constrained, the low appears to be caused by thick sedimentary fill. Two drillholes, 518 and 669 m deep (1700 and 2195 ft, respectively), did not penetrate basement (Oppenheimer and Sumner, 1980).

Surface Electromagnetic (EM) Surveys

Surface EM methods measure the apparent electrical conductivity of subsurface deposits, which help evaluate the approximate depth and extent of recent alluvium. The depth extent of these data is shallow (<75 m), which complements the generally more regional nature and deeper depth of investigation obtained from the gravity data. The apparent electrical conductivity of the deposits is a function of grain size, composition, and moisture content. Conductivity values for dry alluvium in the arid Southwest commonly are less than 10 millimhos per meter (mmhos/m) but can range from 20 to 50 mmhos/m when saturated; those of saturated clay and silt commonly are about 100 mmhos/m or greater. Paleozoic sandstones and limestones have conductivity values less than 20 and commonly less than 10 mmhos/m. Basalt units can be one of the least conductive rock units depending on degree of weathering and water content; generally, conductivity values are less than five mmhos/m.

Depth of investigation for the EM34-3 instrument used during these surveys (Fig. 9) ranges from about 7.5 to 60 m and is a function of transmission frequency, coil spacing, and dipole type (Table 1). Although depth of investigation for the electromagnetic-induction instruments extends to about 60 m, depth of the material contributing to the signal differs

Table 1. Depths of investigation using EM-34-3 instrument at various frequencies, coil spacings and dipole types (data from McNeill, 1980)

Frequency, in hertz	Coil spacing, in meters	Maximum depth of investigation, in meters	
		Vertical Dipole	Horizontal Dipole