Airborne Detection of Magnetic Anomalies Associated with Soils on the Oak Ridge Reservation, Tennessee¹

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INTRODUCTION

Reconnaissance airborne geophysical data acquired over the 35,000-acre (18,000 hectare) Oak Ridge Reservation (ORR), Tennessee, between December, 1992 and February, 1993 (Doll and others, 1993) show several magnetic anomalies over undisturbed areas mapped as Copper Ridge Dolomite (CRD). The CRD is exposed on three ridges on the ORR. On Copper Ridge, near the southern border of the ORR, the exposure is widest (up to 1.25 mi, 2 km) because the dips approach horizontal. Figure 1 is a vertical magnetic gradient map of a portion of Copper Ridge from the southwestern portion of the ORR. The anomalies of interest are most apparent in magnetic gradient maps where they exceed 0.06 nT/m (Figure 1) and in some cases exceed 0.5 nT/m. Anomalies as large as 25nT are seen on residual magnetic anomaly maps (Figure 2). Some of the anomalies correlate with known or suspected karst, or with apparent conductivity anomalies calculated from electromagnetic data acquired contemporaneously with the magnetic data (Beard and others, 1994).

Because the anomalies persist from one flight line to another (Figure 1), we are confident that they are not caused by instrument noise, bird swing, or flight height variations. Some of the anomalies have a strong correlation with topographic lows or closed depressions. Many occur on hillsides, neither at the crest nor at the bottom of the slope. The topographic lows have dimensions on the order of a few hundred feet, and even though the survey was flown in a "draped" manner (maintaining constant altitude above ground level), the actual altitude was greater above the depressions than over adjacent terrain. Thus, large anomalies can occur where the altitude is greatest, opposite what one would anticipate if flight altitude variations were the cause of the magnetic anomalies. Finally, surface magnetic data have been acquired over some of these sites and have confirmed the existence of the anomalies. These data will be discussed in more detail later. We conclude that the anomalies are not caused by system noise or systematic errors in data acquisition.

In most of the ORR airborne reconnaissance data, magnetic anomalies are associated with man-made metallic wastes. We cannot exclude this as the cause of the anomalies in Figures 1 and 2, but believe that it is unlikely. Ground inspections in the vicinity of several of the anomalies has not led to any discoveries of manmade surface materials of sufficient size to generate the observed anomalies. Test data acquired in conjunction with the reconnaissance survey provide an estimate of the amount of metal required to produce anomalies. These data show that a pickup truck will generate a magnetic anomaly of approximately 35 nT from 65 ft (20m) altitude. The reconnaissance data discussed in this paper were acquired at a nominal magnetometer altitude of 200 ft (60m). If we apply a $1/r^3$ reduction in the anomaly, we would expect an anomaly of approximately 1 nT for a pickup truck from 200 ft altitude. Typical residual magnetic anomalies in Figure 2 have magnitudes of 5-10 nT, and some are as large as 25nT. The absence of roads or other indications of culture (past or present) near the anomalies and the modeling of anomalies in data acquired with surface instruments indicate that man-made metallic objects are unlikely to be responsible for the anomaly, particularly when the large volume of metal that would be required to cause the anomaly is considered.

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Figure 1. Measured vertical magnetic gradient map of a portion of the Oak Ridge Reservation, Tennessee south of Oak Ridge National Laboratory. Northing and easting are in administrative grid coordinates, which are rotated 34.2 degrees counterclockwise from true north. Helicopter magnetic profile lines which were used for modeling are indicated as H1 and H2; ground-based measurements were acquired along lines G1 and G2; and soil samples were collected at locations S1 through S14. Geologic contacts are also shown: Ccr is the Copper Ridge Dolomite, Cmn is the Maynardville Limestone, and Cn is the Nolichucky Shale. Data were not acquired over the Tower Shielding Facility (TSF). Arrows point to linear trends in the data that are discussed in the text.

Figure 2. Residual magnetic anomaly map of the area shown in Figure 1. North-south flight lines are superimposed in white. Designations for helicopter and ground magnetic profiles are the same as in Figure 1.

GEOLOGY OF THE COPPER RIDGE FORMATION

The Cambrian age CRD is exposed on several ridges in East Tennessee, including Copper Ridge, which trends in a northeast direction for tens of kilometers, passing through the southern portion of the ORR. Copper Ridge forms a topographic high on the ORR with more than 600 ft (180m) of relief.

The CRD is described by Hatcher and others, 1992, as a massively bedded cherty dolomite, commonly forming ridges in the Valley and Ridge province of the Appalachians, and characterized by the presence of bedded oolitic chert. It has a thickness of 800-1100 ft (250-350m). Quartz sandstone beds up to 8 in (20 cm) thick occur in the upper part of the formation, but no lithologies which might contain significant quantities of magnetic minerals have been reported.

Although it is presently a topographic high and source area for erosional materials, it is believed that the CRD was a topographic low at an earlier time in its geologic history. Evidence that the CRD was once a topographic low includes indications of high flow in the nearby Cherokee Caverns (Paul Rubin, personal communication with Peter Lemiszki, 1994) which could not be explained if it were a high. Models which explain the occurrence of ancient alluvium (discussed below) require that the CRD was a topographic low at some point during the Quaternary period.

Measurements of the magnetic susceptibility, κ , of rock core samples from the 2000-ft Joy-2 core and ten shorter core samples, using a Bartington MS2 meter with 3.15 in. (80mm) diameter MS2C core sensor, are consistent with the reported lithology of the CRD (Helm, in preparation). These cores cross several formations, and include much of the CRD section. Measured susceptibilities from the entire set of cores, which were acquired within a few miles of the study area, vary between 0 and 80×10^{-5} (SI units). The lowest values are associated with massive limestones and dolomites, and the higher values associated with shales, siltstones, sandstones, and shaley limestones. Core samples from the CRD have a mean susceptibility of less than 1×10^{-5} (SI units).

Surficial Features over Copper Ridge Dolomites

Features of weathered CRD are also described by Hatcher and others, 1992. Depth to bedrock is difficult to define because of the gradation from soil to saprolite to unweathered bedrock. It is typically given to be about 20 ft (7m) over most of the CRD. Pinnacles, ledges, sinkholes, and other karstic features are common in the CRD. Some parts of the CRD have a higher density of sinkholes than others, and the larger sinkholes generally occur on crestal landforms or at relatively high elevations, and appear stable. A small cave occurs in our study area at location S10, Figures 1 and 2.

The magnetic susceptibility of soil samples from several field locations was determined by packing augered soils in plastic tubing and passing these through the Bartington system. Most of the samples were acquired by hand augering with a 2-1/4 inch stainless steel bucket auger using plastic liner tubes. While this is less rigorous than taking measurements from undisturbed oriented samples, it provided a gross determination of soil properties, and yielded susceptibilities ranging from 15×10^{-5} to 500×10^{-5} (SI units) (Helm, in preparation). These values are shown in Table 1, and their numbered site locations are shown in Figure 1. The numbers in Table 1 are average values for susceptibility to about 2 ft (60 cm) depth. We have not yet acquired undisturbed cores of the entire soil profile, or collected in situ measurements of susceptibility in order to determine the relationships between susceptibility and soil horizons.

The high susceptibility values for soils may be explained by recrystallization or phase transformation of iron from dissolved carbonates or layer silicates in cherts and siltstone cements. Soils, referred to as "ancient alluviums", have been reported on Copper Ridge on the ORR (Kopp and Lee, 1985). These soils were mined for their iron content years ago. Analysis of ancient alluviums on the ORR has demonstrated that they contain the ferromagnetic mineral maghemite, which has presumably formed by iron replacement in oolitic limestones (Kopp and Lee, 1985). The maghemite occurs throughout the thickness of the ancient alluvium, which typically

Table 1. Magnetic Susceptibilities of Soil Samples

Soil Identification	$\kappa \times 10^{-5}$, SI units	Soil Identification	$\kappa \times 10^{-5}$, SI units
S1	192.4	S8	76.1
S2	73.2	S9	97.6
S3	216.2	S10	252.4
S4	158.5	S11	152.8
S5	342.2	S12	125.9
S6	263.7	S13	66.7
S7	410.8	S14	548.4

ranges from 6 to 10 ft. Because the mineral occurs in relatively thick, localized alluvial deposits on the ORR, rather than as a thin, continuous layer, and because it elsewhere occurs in association with mafic igneous rocks, the occurrence of maghemite is thought to be unusual. Maghemite is typically found in thin shallow soil layers (perhaps less than a foot) which may have been thermally altered by burning (Kopp and Lee, 1985), e.g., by forest fires, but this process is inconsistent with the thickness and discontinuous distribution of ancient alluvium. Measurements of maghemite nodules with the Bartington system yielded a susceptibility of about 10^{-1} (SI units). Since the nodules are smaller than the core diameter, the instrument does not accurately measure the mineral's susceptibility, but it does demonstrate that maghemite is highly magnetic.

Soil maps for Copper Ridge show agreement between the locations of some ancient alluviums and some of the magnetic anomalies, but many mapped ancient alluvium deposits have no magnetic signature, and large anomalies occur where there is no mapped ancient alluvium. Of the samples in Table I, only S7 is mapped as ancient alluvium. The lack of agreement may indicate that some of the mapped ancient alluvium deposits are too thin or small to have an anomalous magnetic signature, that ancient alluvium may be buried beneath recent soils at some sites, or that existing soil classifications do not effectively represent their magnetic properties. It appears that soils other than ancient alluvium can be highly magnetic, but the minerals responsible for this magnetism are not identified.

SURFACE MAGNETIC DATA ACQUISITION AND MODELING

To confirm the existence of anomalies identified in the airborne data and to improve understanding of the character of the anomalies, surface magnetic data were acquired along five profile lines using an OMNI-PLUS system with two proton precession magnetometers at 1m vertical separation. The locations of two of the five lines are shown as G1 and G2 on Figures 1 and 2.

Figure 3 shows the total field data (open circles) that were acquired along profile line G1 after subtracting an assumed constant regional field of 54,063nT. The line crosses a steep-sided depression south of the crest of Copper Ridge. Measurements were made at 16 ft (5m) increments along the 1450 ft (450m) line, and every other point is shown in Figure 3. The largest peak has an amplitude of about 150nT and a width of about 950 ft (300m). The peak of the anomaly correlates with the bottom of a closed topographic depression with irregular blocky exposures of CRD at the bottom. The topographic profile of the depression is shown by the locations of the measurement points in the lower part of Figure 3. The position and elevation of measurement points were not surveyed, but were estimated from the 1:24,000 topographic map of the area which has a 20-ft contour interval. Distances between measurement points were measured with a tape measure, and azimuth of the profile

Figure 3. Forward model for ground magnetic data, assuming a susceptibility of 15×10^{-5} (SI units). The body extends 50 ft in and out of the section. Elevations were approximated from the 20 ft. contours on the base map.

Figure 4. Thickened soil layer model which fits airborne magnetic data for line H1. The soil layer, has a susceptibility of 200×10^{-5} (SI units). The shape of the body is assumed to extend 500 feet in and out of the plane of the profile.

was maintained by shooting from station to station with a Brunton compass. The starting point for the profile was determined with a global positioning system. Although positioning errors are certain to occur, they are not large, because the bottom of the depression which was observed during data acquisition matched the position of the depression on the topographic map.

The workstation computer program HYPERMAG (Saltus and Blakely, 1993) was used for two-and-a-half-dimensional forward modeling of the surface data described in the previous paragraph. Because no indications of man-made wastes were found during surface data acquisition, and because core measurements indicated that bedrock magnetism was unlikely to cause the observed anomaly, we began modeling with the assumption that soil, either in filled depressions or subsurface voids, is responsible for the anomaly. Figure 3 shows a model consisting of a thickened soil layer which would produce the anomaly shown by the continuous line in the top half of the figure. The susceptibility which was assumed for the soil layer is 15×10^{-5} (SI units). This is approximately an order of magnitude smaller than observed susceptibilities for the soils. Measured susceptibilities of approximately 200×10^{-5} (SI units) were tested, but the models were very sensitive to small changes in the geometry of the soil layer. The magnitude of the observed anomaly could be approximated using the measured susceptibilities if soil layer thicknesses were an order of magnitude smaller. The shape of the model body shown in Figure 3 is a good match to observation if the soil layer is thinned by an order of magnitude and its susceptibility is increased by an order of magnitude. Thus, increases in soil layer thickness of 0 to 5 ft are appropriate to model the observed anomaly.

Background surface magnetic measurements were collected along Line G2 (Figures 1 and 2) after soil susceptibility measurements and airborne magnetic data indicated that anomalies were small near the center of the line. Surface measurements along the southern 1000 ft (300m) of the line vary over an 18 nT range, except when crossing a paved road. At the northern end of the line, surface data indicate an anomaly of up to 100 nT, in agreement with the airborne data.

MODELING OF AIRBORNE MAGNETIC DATA

Airborne magnetic data were modeled along two traverses as shown in Figures 1 and 2. Figure 4 shows a forward model for Line H1 which coincides with a high conductivity anomaly in the airborne electromagnetic data (Beard and others, 1993) and lies along a creek drainage with ridges that are approximately 75 ft (25m) higher on either side. Altitudes of measurement points are from the laser altimeter located on the bird, with 65 ft (20m) added to account for the position of the magnetometers further up the tow cable. These altitudes will have errors caused by variations in the lateral offset of the magnetometers relative to the bird, reflections of the laser altimeter from tree tops, and spatial averaging or non-vertically incident reflection of the laser beam. True elevation, which includes topography, is not shown in the model, and might account for some errors in the model. The model indicates that a narrow filled void or depression, about 100 ft wide and six feet deep can account for the 30nT peak anomaly. This is very likely a collapse feature since irregular blocks of CRD are observed at the surface near this site.

Modeling along airborne line H2 was conducted to provide a comparison with surface profiling along line G1. Since the lines are orthogonal, models for the two lines must differ, and cannot be compared directly. Modeling along line H2 is consistent with the models for line G1 which show a thin soil layer with a susceptibility of about 200×10^{-5} (SI units) with its thickness varying from 0 to 5 feet.

CONCLUSIONS

We have shown that observed anomalies in the CRD can reasonably be associated with thickening of the soil layer. The occurrence of the anomalies in areas where evidences of karstification are seen (e.g. blocky irregular outcrops along Line H1 or closed depressions along lines G1 and H2) would follow because sediment deposition would occur in topographic lows. Many of the anomalies in Figures 1 and 2 occur in areas where there are no indications of karst processes. When the anomalies occur in such areas, it might suggest a stable void or collapse structure which has completely filled with sediment. Linear groups of anomalies on the maps (e.g., along the arrows on Figure 1) may be associated with fracture zones which were eroded more than

adjacent rocks and were subsequently covered with a thicker blanket of sediment. The arrows are orthogonal to the mapped contact between the CRD and the Maynardville Limestone, and could be fracture zones related to tension during thrusting of an irregular interface, or to nonuniform thrusting. Fracture zones are important as possible contaminant transport pathways elsewhere on the ORR. This study indicates that airborne magnetic data may be of use in other sites where fracture zones or buried collapse structures are of interest. This may be particularly true in those portions of East Tennessee where magnetic soils occur over non-magnetic bedrock.

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