Paper 65

Airborne Electromagnetic and Magnetic Surveys For Ground-Water Resources: A Decade of Study by the U.S. Geological Survey

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ABSTRACT

Since the first Exploration meeting in 1967, airborne surveys done by the USGS have evolved from regional surveys with broad geologic mapping goals to more detailed surveys with more specific project goals. These surveys have used increasingly sophisticated geophysical, geological, and hydrological modeling methods. This poster summarizes some of the advances that have taken place within the USGS for hydrologic studies in the decade since the last Exploration meeting in 1997. In particular, airborne magnetic and electromagnetic (EM) methods have focused on applications to new hydrologic problems and in development of integrated interpretation methods in 1) ground-water quality investigations of contamination from co-produced water from fossil fuel energy production and studies of watersheds containing abandoned mine lands, 2) ground-water resource studies in sedimentary terrains, and 3) geologic and hydrologic studies in karst terrains.

INTRODUCTION

The past decade of development and application of airborne geophysical methods for mineral exploration has been accompanied by increased applications to geologic and hydrologic studies. These investigations demonstrate successes in integrated interpretation of airborne geophysical data with a variety of geological and geochemical data. Though much of the research in airborne geophysics is motivated by the economy of mineral and energy exploration, non-mineral exploration airborne geophysical applications are important in advancing the state of the art. And in the coming decades water is likely to become the more precious commodity.

ACID MINE DRAINAGE STUDIES

Two projects focusing on acid mine drainage are located (Figure 1) in the Animas River Basin, Colorado (Church et al., in press), and the Boulder River Headwaters, Montana (Nimick et al., 2004). The ore deposits of the Boulder River area (Boulder mining district) are situated in the volcanic Boulder Batholith of Cretaceous age, whereas the deposits of the Animas River Basin (Silverton mining district) are within a Tertiary-age volcanic caldera. The projects have gathered geological, geochemical, and geophysical data on the distribution of rock types, mines and prospects, mine dumps, and active mine drainage sites necessary to characterize the watersheds and to prioritize sites within the drainage basins for remediation. Smith et al. (2000) have described the general aspects of the helicopter electromagnetic (HEM) and magnetic geophysical studies of these areas that that began in early 1995.

In the Boulder River study, the airborne electromagnetic data were used in structural and lithologic mapping and in the evaluation of a closed open-pit mine as a mine waste repository (Smith et al. 2004a). The locations of several ground-water monitoring sites were based on structures near the pit inferred from the airborne data. McCafferty et al. (2005) integrated geological and airborne geophysical data to construct geoenvironmental maps showing relative acid-neutralizing capacity (ANC) and net acid producing potential (NAPP) of surface and near-surface rocks.

HEM and magnetic surveys in the Animas River basin identify areas of near surface and subsurface electrical and magnetic physical property contrasts that suggest structural features. Geophysical maps show features that selectively emphasize specific lithology and structure that are important in understanding the ground-water regime. The geologic maps of the study area contain numerous structures and veins but only a few of these are associated with a distinctive geophysical signature. In addition the geophysical maps indicate structures that have not been previously mapped (Smith et al., 2004b). These structures possibly control ground-water flow.

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Regional propylitic alteration in the Animas River basin near Silverton, Colorado, has introduced mineral assemblages with varying degrees of ANC and NAPP that can be related to different rock magnetic properties (McCafferty et al., 2006). Where more intense alteration assemblages overprint the regional propylitic assemblage, magnetite is removed, magnetic susceptibility reduced, ANC minerals are eliminated, and NAPP is increased, although important exceptions may exist in some rocks. In general, our NAPP and ANC studies demonstrate that where rocks are propylitically altered, the units typically have higher ANC and high magnetite content. But where sericite has been introduced along with pyrite, then the ANC (and magnetite) is diminished and NAPP is enhanced (Yager et al., 2005).

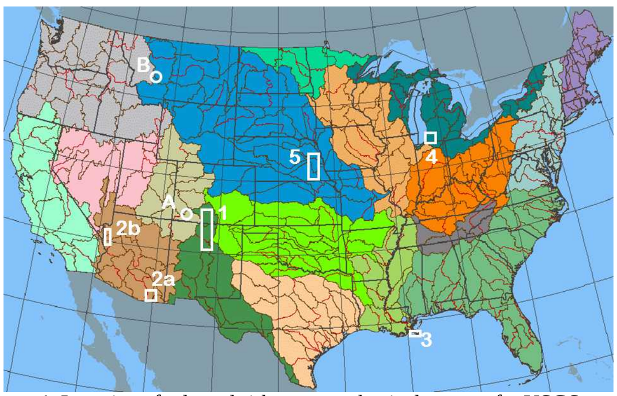

Figure 1: Location of selected airborne geophysical surveys for USGS abandoned mine land and alluvial aquifer studies in relation to regional watersheds (USGS National Atlas (http://www-atlas.usgs.gov/). Locations A and B (circles) are the Animas watershed and Boulder River studies, respectively. Alluvial aquifer studies general locations (boxes) are: 1) Rio Grande watershed (see below), 2a, b) Ground-water studies in Arizona basins (Pool et al. 2006), 3) Houma, Louisiana, an on-going coastal study, 4) Great Lakes project on-going geophysical studies, and 5) recently (2007) completed surveys in Nebraska.

ALLUVIAL AQUIFER STUDIES

Over the past decade, there has been a dramatic improvement in airborne magnetic and EM data acquisition through improved instrumentation and flight path recovery technology. These improvements have led to a revolution in airborne surveying applications in sedimentary terrains for energy and ground-water resources (Paine and Minty, 2005; Nabighian et al., 2005). The location of some of the ground-water studies carried out by the USGS that involve airborne electromagnetic and magnetic surveys are shown in Figure 1.

High-resolution airborne magnetic (HRAM) and fixed-wing time-domain EM surveys of the Rio Grande watershed in the Albuquerque Basin were first conducted by the USGS in 1996-1997 (Figure 1). The surveys were part of a multidisciplinary study to fill critical gaps in the understanding of ground-water resources for northern New Mexico's growing urban centers, which largely subsist on alluvial basin aquifers. The HRAM surveys were flown generally at a 1:1 ratio of line spacing to flight height (commonly 150 m). The resulting magnetic maps show remarkable expression of intra-basinal faults and buried igneous rocks (Grauch and Millegan, 1998; Grauch et al., 2001), providing new information on shallow structure and the distribution of aquifers within the basin (Bartolino and Cole, 2002). HRAM surveys benefiting water resource managers now cover over 12,000 square km in New Mexico and Colorado (Figure 1).

Fixed-wing time-domain EM surveys have been used in alluvial basins of New Mexico (Rodriguez et al., 2001 and in press) and Arizona (Bultmann et al., 1999; Pool et al., 2006) to map the 3D distribution of alluvial aquifers and major grain-size facies within the alluvium. The primary aquifer materials of sand and gravel are more resistive than fine-grained deposits of silt and clay, which are poor aquifers. Results of the geophysical investigations have been used to help estimate aquifer properties in ground-water models critical to water management (Bartolino and Cole, 2002; Pool and Dickinson, in-press).

GROUND-WATER CONTAMINATION RELATED TO ENERGY PRODUCTION

The first airborne electromagnetic survey to map contamination of shallow (less than 100 m) ground-water from saline-produced water disposal (in some cases >50,000 total dissolved solids; TDS) at oil fields near Brookhaven, MS (Figure 2) was carried out in 1987 (Smith et al., 1989). This was one of the first applications of helicopter frequency-domain EM methods to ground-water mapping. This survey successfully mapped pockets of shallow saline waters associated with produced water disposal ponds, some of which had not been documented before the airborne surveys. The EM data were used in one of the first conductivity-depth imaging algorithms developed by Peter Sengpiel (Smith et al., 1989); which greatly enhanced the mapping of conductivity anomalies not readily seen in the apparent resistivity maps plotted at individual frequencies. A repeat survey in 1997 showed changes in salinity caused by new point sources, some of which were documented by new monitoring wells drilled in the area (Smith et al., 1997). The success of the 1987 survey led to other surveys in Texas (Figure 2) funded by the Texas Railroad Commission and other state agencies to map saline waters in oil fields (Paine and Minty, 2005). These surveys successfully identified point sources of shallow ground-water contamination. By 2004, when the USGS contracted a HEM survey of part of the Poplar Oil Field on the Ft. Peck Indian Reservation (Montana) the analog system in the earlier surveys had been replaced by a broader band digital system (Smith et al., 2006). Current research on this project is developing conductivity depth sections that can be related to ground-water models to be used to predict movement of a saline water plume, several kilometers in aerial extent, caused by failure of an injection well.

Though most produced waters associated with energy production are saline, water co-produced from coal bed natural gas (CBNG) can have lower TDS than local ground water does. The rapid rise in production of natural gas from coal beds has raised environmental issues concerning proper disposal methods for the produced waters. Department of Energy and USGS studies of produced waters from CBNG development in the

Powder River Basin of Wyoming have included HEM surveys of selected areas (Sams et al., 2006). In some of the areas, the airborne surveys have helped to document how disposal of CBNG waters in ponds has led to dissolution of salts in the immediate area of the ponds. The result can be development of very high TDS plumes in some areas.

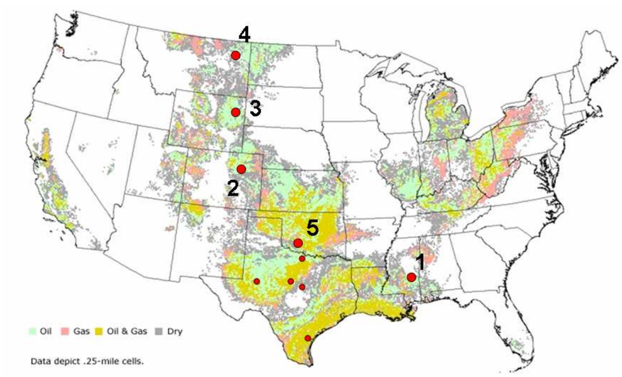

Figure 2: Location of airborne geophysical surveys done in conjunction with studies of ground water contamination related to energy production: 1) Brookhaven, 2) Denver-Julesburg Basin, 3) Powder River Basin and 4) Poplar Oil Field, Ft. Peck Indian Reservation. Studies in Texas were conducted from 1996 to 2005 by the Texas Bureau of Economic Geology. Studies outside of Texas were conducted as part of USGS programs. Studies in Wyoming were done as part of a cooperative project with the Department of Energy National Technology Laboratory.

KARST GROUND WATER

The first HEM survey of a karst terrain in the United States, done in 1996-97 at the Oak Ridge Reservation, (a national laboratory), Tennessee, was designed in cooperation with the USGS (Doll et al., 2000; Figure 3 area 1). Based on the success

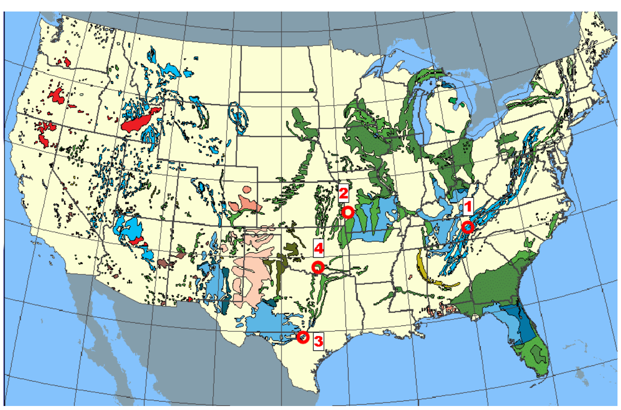

Figure 3: Location of airborne geophysical surveys done in support of studies of karst ground water resource studies. Base map is karstic terrains from the USGS National Atlas (http://www-atlas.usgs.gov/) Areas are: 1) Oak Ridge Reservation (National Laboratory; ORNL) 2) Camp Crowder military bas, 3) airborne surveys done as part of USGS studies of the Edwards and Trinity aquifers, and 4) flown in the spring of 2007 as part of new USGS studies of the karstic Arbuckle-Simpson aquifer.

of this survey in defining karst features, HEM was flown at Camp Crowder (Figure 3, area 2) in order to map possible path ways for contaminate flow in karst terrain. Epikarst was a critical feature in that study area.

The USGS has carried out HRAM and HEM surveys for karst ground-water studies of the Edwards aquifer, Texas (Figure 3). The HRAM survey revealed many circular magnetic high anomalies in the western part of the magnetic survey area, covering Uvalde and Medina Counties (Figure 3, inset), which are caused by igneous rocks intruding the aquifer (Smith and Pratt, 2003). Distribution of these intrusives is controlled by crustal structures that extend to a depth of several kilometers where the intrusives are rooted. These structures and the intrusives themselves may influence the regional ground-water flow.

Two HEM surveys were done in the Seco Creek area (west) in 2002 and in northern Bexar County (east) in 2004 (Smith et al., 2003; Smith et al., 2005). The Seco Creek survey demonstrated that the structure of the Edwards Aquifer recharge zone is much more complicated than mapped by traditional geologic methods. In addition, the HEM data established that the Edwards Limestone could be divided into upper and lower Devils River units based on relative electrical resistivity. More detailed airborne magnetic data than the fixed-wing HRAM survey from the Seco Creek helicopter survey provided the first evidence that some of the major structures in the Edwards Limestone might be associated with magnetic lows (Smith and Pratt, 2003). More detailed leveling of the larger HRAM data set suggests that major faults, many of which are covered by surficial deposits have a magnetic expression.

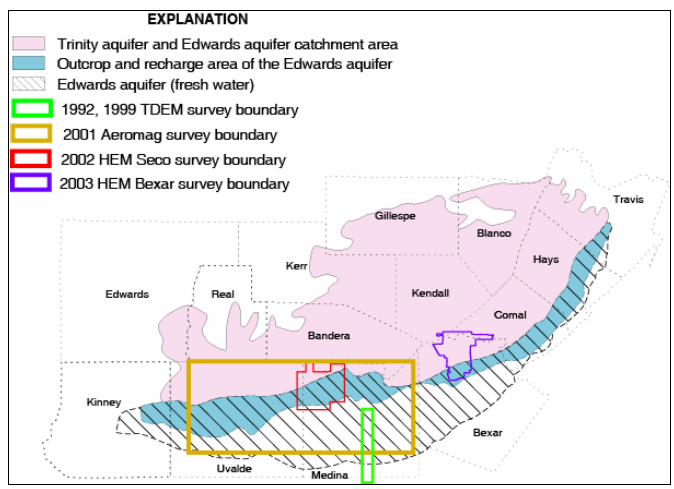

Figure 4: Location of airborne electromagnetic and magnetic surveys conducted from 1998 to 2003 as part of the USGS Edwards aquifer project (http://esp.cr.usgs.gov/info/edwards/index.html).

The HEM survey in northern Bexar County covered some of the older Glen Rose Limestone which composes the Trinity Aquifer north of the exposed Edwards recharge zone. This survey demonstrates that different hydrostratigraphic units of the Glen Rose Limestone can be defined on the basis of electrical signatures. These units are important in understanding recharge within the aquifer and its hydrologic relationship to the Edwards aquifer. The HEM survey also helped to improve structural maps where mapping is hampered by poor exposures.

CONCLUSIONS

The above studies show that airborne EM and magnetic data contributed significantly to development of new geologic and hydrologic interpretations in widely different geologic and hydrologic settings. Such airborne geophysical surveys are being increasingly used in quantitative modeling of geophysical, geological, and hydrologic properties of the earth. Integrating the rich physical-property information and spatial complexity provided by the airborne data into 3D earth and ground-water models is a focus of USGS research into the next decade.

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