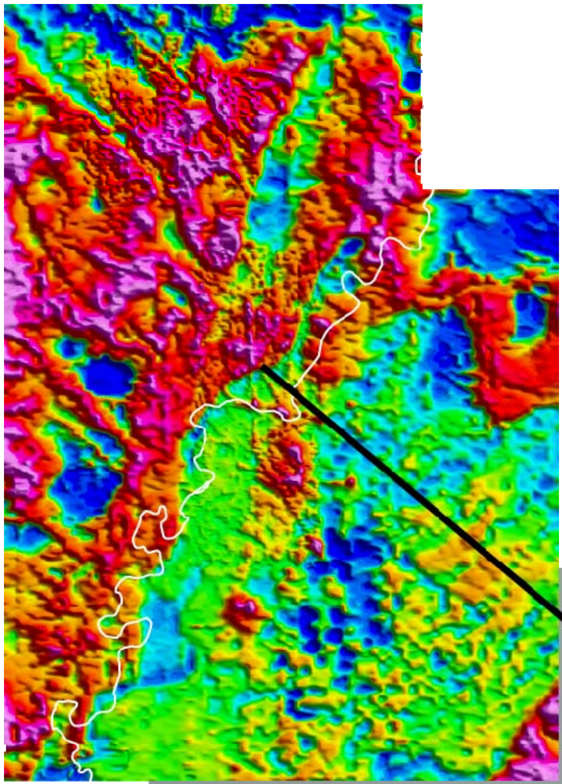
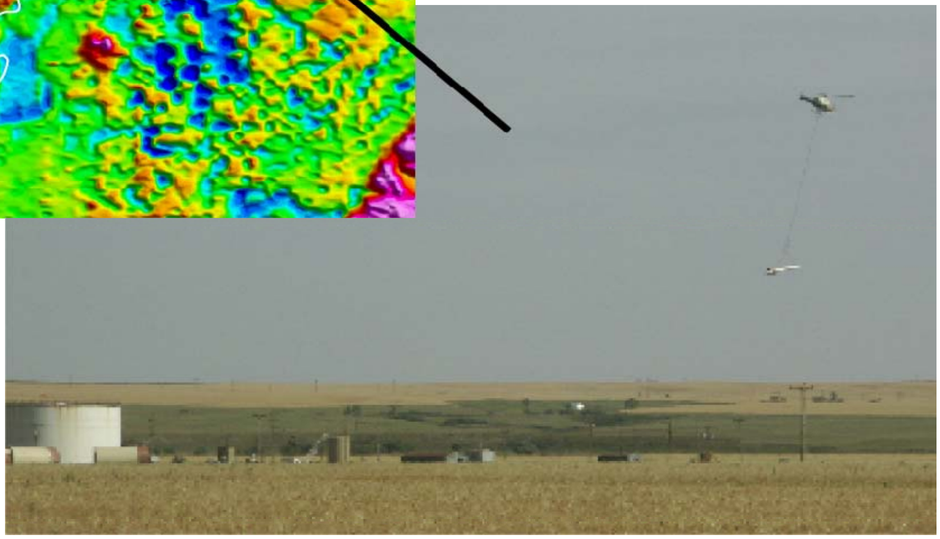
In cooperation with the Office of Environmental Protection of the Fort Peck Tribes

Helicopter Electromagnetic and Magnetic Survey Maps and Data, East Poplar Oil Field Area, Fort Peck Indian Reservation, Northeastern Montana, August 2004

By Bruce D. Smith, Joanna N. Thamke, Michael J. Cain, Christa Tyrrell, and Patricia L. Hill





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Front Cover: Photo shows helicopter EM system flying over part of the East Poplar oil field infrastructure (photo: B. Smith, 2004). The color map shows apparent conductivity at 8200 Hz. White line is the Poplar River. The black line shows the approximate location of photograph on geophysical map. The photo is taken east, facing across the Poplar River valley.

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Conversion Factors, Datum, and Acronyms

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	247.1	acre
liter (L)	0.2642	gallon (gal)
nanotesla (nT)	1	gamma
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F=(1.8\times°C)+32$

Vertical coordinate information is referenced to the "North American Vertical Datum of 1988 (NAVD 88)"
Horizontal coordinate information is referenced to the "North American Datum of 1927, Universal Transverse Mercator Zone 13 (NAD 27 UTM Zone 13N)"

ACRONYMS USED IN THIS REPORT:
GPS Global Positioning System
HEM Helicopter Electromagnetic
RTP Reduced-to-Pole
USGS U.S. Geological Survey
UTM Universal Transverse Mercator

ABBREVIATIONS USED IN THIS REPORT:
Hz hertz
kHz kilohertz

Helicopter Electromagnetic and Magnetic Survey Maps and Data, East Poplar Oil Field Area, August 2004, Fort Peck Indian Reservation, Northeastern Montana

By Bruce D. Smith[1], Joanna N. Thamke[2], Michael J. Cain[3], Christa Tyrrell[4], and Patricia L. Hill[1]

Abstract

This report is a data release for a helicopter electromagnetic and magnetic survey that was conducted during August 2004 in a 275-square-kilometer area that includes the East Poplar oil field on the Fort Peck Indian Reservation. The electromagnetic equipment consisted of six different coil-pair orientations that measured resistivity at separate frequencies from about 400 hertz to about 140,000 hertz. The electromagnetic resistivity data were converted to six electrical conductivity grids, each representing different approximate depths of investigation. The range of subsurface investigation is comparable to the depth of shallow aquifers. Areas of high conductivity in shallow aquifers in the East Poplar oil field area are being delineated by the U.S. Geological Survey, in cooperation with the Fort Peck Assiniboine and Sioux Tribes, in order to map areas of saline-water plumes. Ground electromagnetic methods were first used during the early 1990s to delineate more than 31 square kilometers of high conductivity saline-water plumes in a portion of the East Poplar oil field area. In the 10 years since the first delineation, the quality of water from some wells completed in the shallow aquifers in the East Poplar oil field changed markedly. The extent of saline-water plumes in 2004 likely differs from that delineated in the early 1990s. The geophysical and hydrologic information from U.S. Geological Survey studies is being used by resource managers to develop ground-water resource plans for the area.

Introduction

Studies conducted by the U.S. Geological Survey (USGS) of the Fort Peck Indian Reservation (fig. 1) beginning in 1976 have focused on the assessment and mapping of ground-water resources. Results of these studies have demonstrated that ground-water quality has been adversely affected by various land-use practices in some areas of the Reservation (Levins, 1984; Thamke and Midtlyng, 2003). Ground-water plumes of saline water were identified by Thamke and Craigg (1997) based on water well sampling, ground geophysical surveys, and borehole logs. The source of these plumes is related to oil production from the East Poplar oil field and the East Poplar Unit (Thamke and Craigg, 1997; fig. 1). In August 2004, a helicopter electromagnetic (HEM) and

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magnetic survey was conducted over the oil field in order to better define possible subsurface plumes.

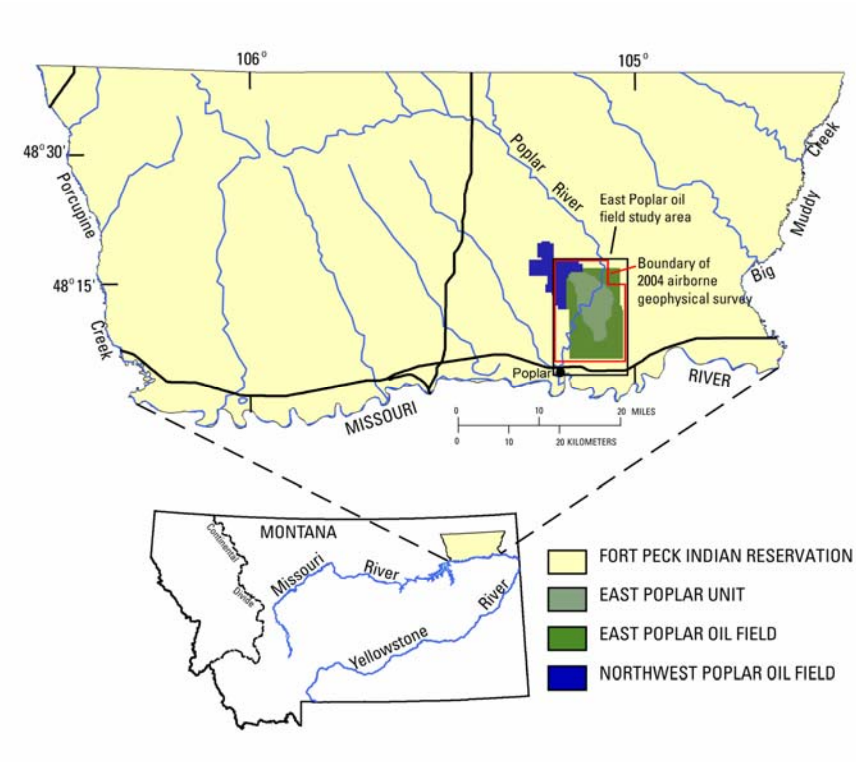

Figure 1. Location of study area and helicopter electromagnetic and magnetic survey.

Purpose and Scope

This report presents HEM and magnetic maps and data that were collected by the U.S. Geological Survey during August 12-14, 2004, in the East Poplar oil field study area. The survey covered about 275 square kilometers and included two smaller detail areas (fig. 2). Flight lines were spaced 200 meters apart, except in detail areas where flight lines were spaced 100 meters apart.

Description of Study Area

The East Poplar oil field study area includes the City of Poplar, the East Poplar oil field, and most of the Northwest Poplar oil field (fig. 1). The Poplar River flows generally southward through the study area. Throughout most of the study area, shallow Quaternary deposits (up to 30 meters thick) directly overlie the relatively thick (about 300 meters) Upper Cretaceous Bearpaw Shale and are the sole developed source of ground water for residents of the study area. Land uses in the study area include dry-land farming, livestock ranching, oil production, and residential development. Thamke and Craigg (1997) summarized previous investigations on geologic structure, stratigraphy, and hydrogeology in the East Poplar oil field study area.

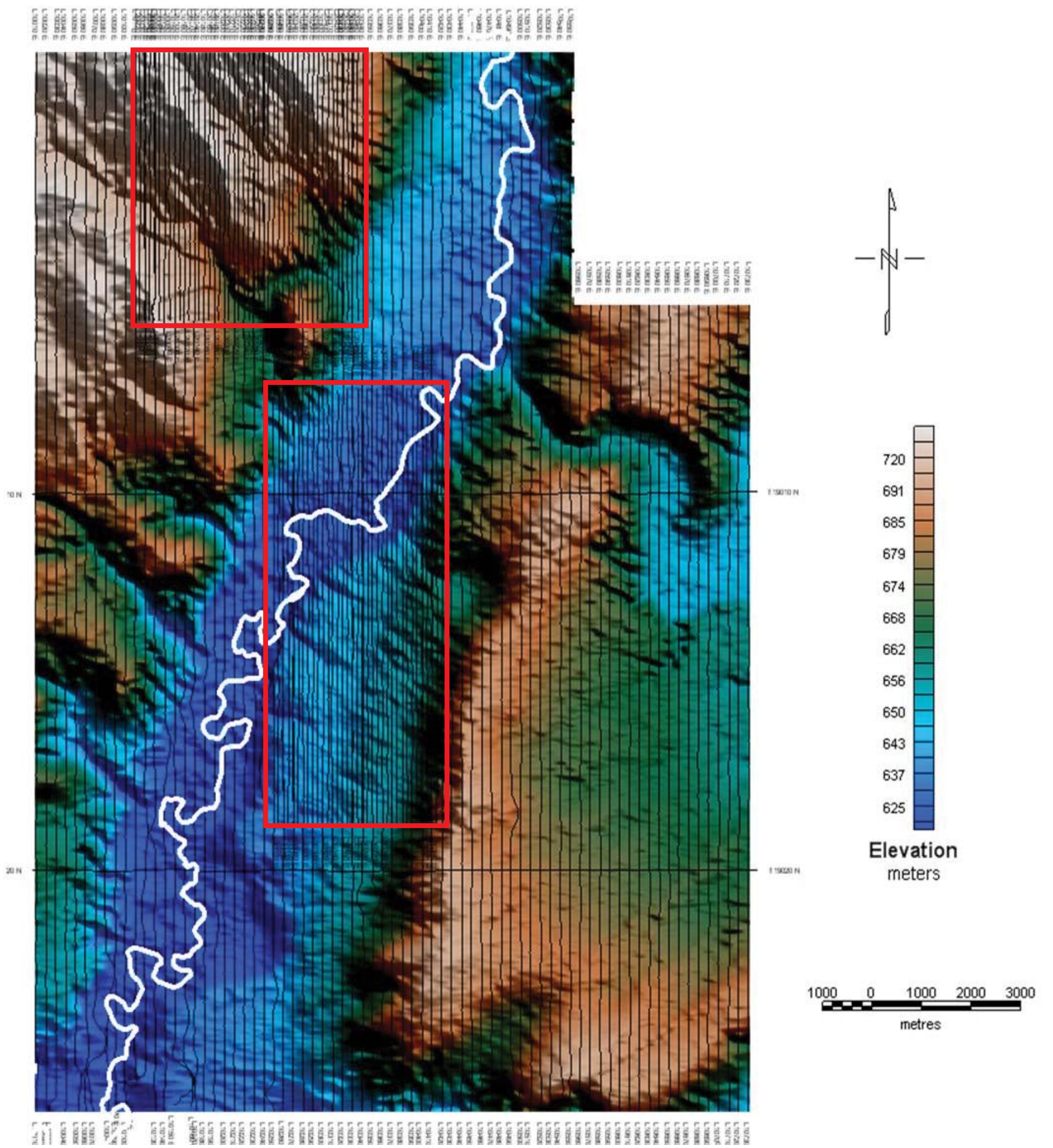

Figure 2. Generalized location of flight lines, East Poplar oil field area, overlain on digital topographic data. Two smaller areas where in-fill flight lines were flown are outlined in red.

Geologic Setting

Regionally, the study area is located near the western edge of the Williston Basin (fig. 3), a broad, northwest-trending structural depression in eastern Montana, western North Dakota, northwestern South Dakota, southwestern Manitoba, and southeastern Saskatchewan. The Williston Basin, one of the largest structural basins in North America, is about 800 kilometers long and 500 kilometers wide, and encompasses an area of about 347,000 square kilometers (Hamke and others, 1966, p. 5). The basin also is one of the oldest structural basins in North America; it was subsiding and affecting sedimentation patterns throughout most of Paleozoic and early Mesozoic time. The basin ceased subsiding and exerting control on sedimentation by Cretaceous time (Rice and Shurr, 1978, p. 267). Present structural configuration and structural features of the Williston Basin (domes, anticlines, and synclines) are a result of the Laramide Orogeny, during latest Cretaceous and early Paleocene time (Thamke and Craigg, 1997).

The study area lies atop the Poplar Dome (also referred to as the Poplar Anticline). The dome trends northwest and is about 50 kilometers long and 40 kilometers wide. As reported by Hamke and others (1966, p. 24), the dome consists of a principal domal structure with a structural closure of about 90 meters, and a smaller subsidiary dome with a structural closure of about 30 meters. When super-imposed on the broad, regional structure of the Poplar Dome, the structural framework of the smaller East Poplar oil field study area is not complex. Geologic units essentially are flat-lying and no faults have been mapped (Colton and Bateman, 1956; Colton, 1963a, 1963b).

Geologic units underlying the East Poplar oil field study area range in age from Precambrian through Cenozoic. Precambrian units consist solely of crystalline igneous and metamorphic rocks. Paleozoic through Cenozoic units consists of various sedimentary units; combined thickness of this sedimentary section probably is about 3,000 meters. Detailed basin-wide geologic descriptions of these units were given by Hamke and others (1966). The principal geologic units exposed in the study area are the Upper Cretaceous Bearpaw Shale, Hell Creek Formation, and Fox Hills Sandstone; Tertiary Flaxville and Fort Union Formations; Quaternary glacial and related deposits; and Quaternary alluvial deposits.

Colton (1963a, 1963b) mapped and described the geologic units exposed in the vicinity of the study area (fig. 4). Detailed discussion of all geologic units is beyond the scope of this report; however, units that are most relevant for the purposes of this geophysical survey are described in general terms below.

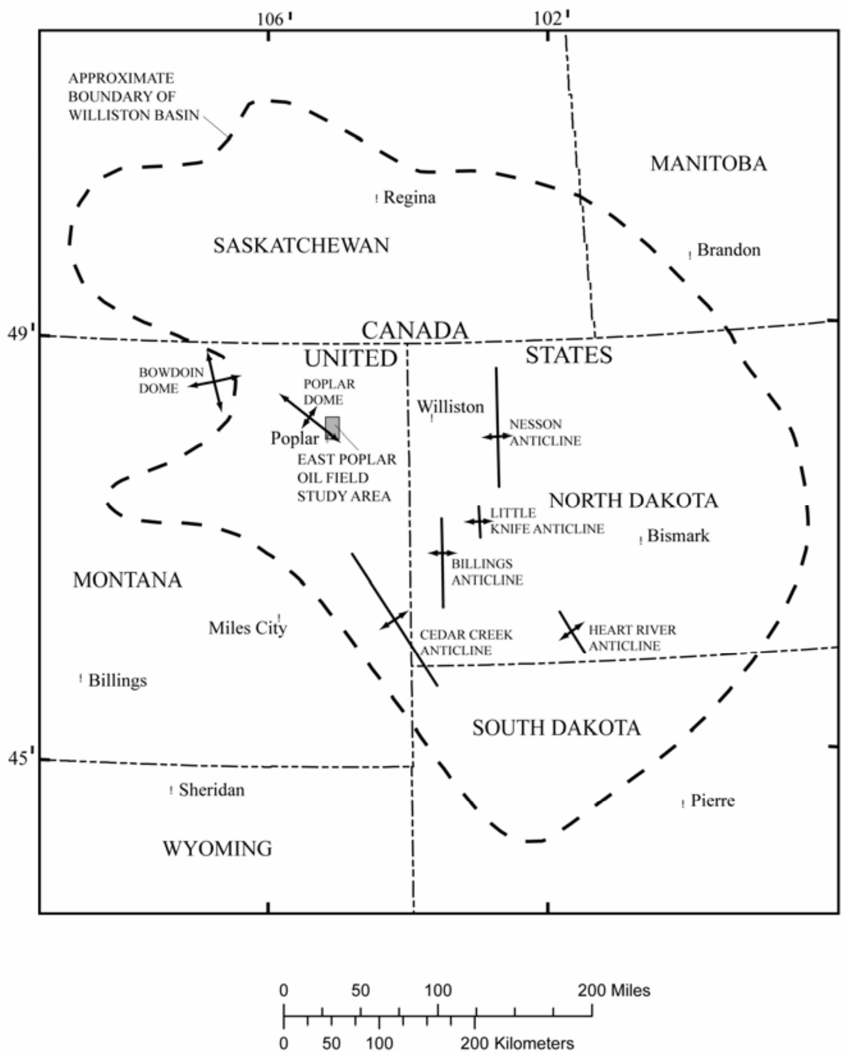

Figure 3. Location of Williston Basin, major structural features, and East Poplar oil field study area (modified from Thamke and others, 1997, fig. 1, and Gerhard and others, 1982).

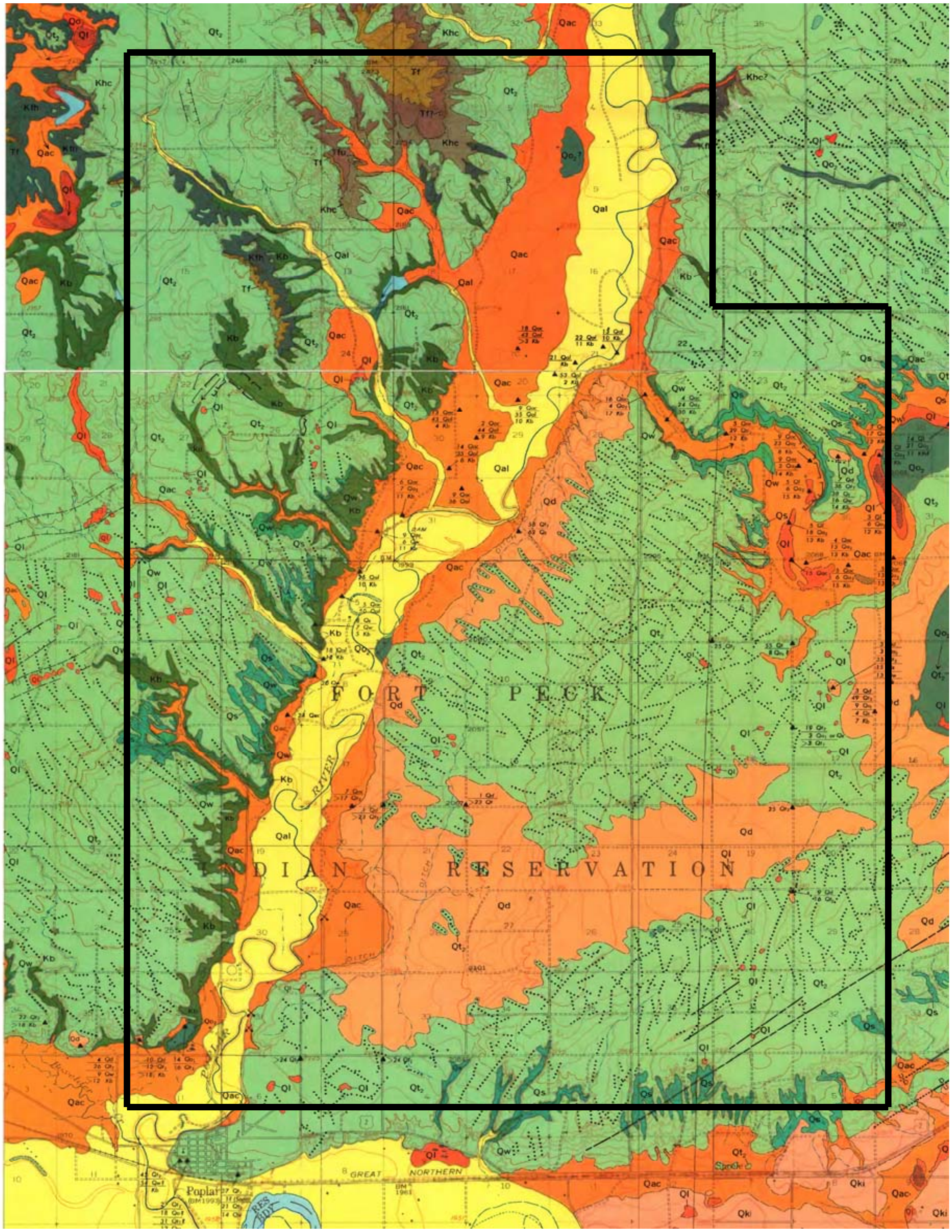

Figure 4. Generalized geology of the East Poplar oil field area (modified from Colton, 1963a, 1963b). Geologic units are described in report text. Dotted lines show locations of ice-crack moraines. Thick black line is approximate boundary of HEM and magnetic survey, August 2004.

Cretaceous Rocks

Cretaceous rocks exposed in the study area are the Bearpaw Shale, Hell Creek Formation, and Fox Hills Sandstone. General characteristics of these three units are given below; descriptions of other Cretaceous rocks are provided in Donovan (1988).

The Upper Cretaceous Bearpaw Shale (shown as Kb in fig. 4) consists mainly of dark-gray marine shale and claystone and is 200-300 meters thick. Bentonite is present as thin beds and also is disseminated throughout some shales zones; the upper part of the formation contains some beds of sandy shale (Colton, 1963a, 1963b; Hamke and others, 1966, p. 22). Colton and Bateman (1956) also reported that the Bearpaw Shale contains ironstone nodules and hard ellipsoidal concretions; many concretions may contain marine fossils. Minor fractures are present in the upper, eroded surface of the Bearpaw Shale, as noted during field observations by Thamke and Craigg (1997). The depth to the top of the Bearpaw Shale ranges from zero in outcrop areas to 37 meters (Colton, 1963a, 1963b). The subsurface top of the formation lies between about 590 meters and 650 meters above sea level. The top surface of the Bearpaw Shale east of the Poplar River appears to slope gently towards the west; the apparent trough beneath the Poplar River valley probably represents stream erosion concurrent with deposition of alluvium, rather than a geologic structure.

The Bearpaw Shale crops out mainly along low hills west of the Poplar River; only about the upper 37 meters of the Bearpaw is exposed in the study area (fig. 4). On the basis of lithologic descriptions of USGS monitoring wells, the depth to the top of the Bearpaw Shale in the study area has a range of about 8-17 meters (USGS92-14 and USGS82-11, respectively) beneath alluvial deposits of the Poplar River valley, and about 17-30 meters (USGS93-3 and USGS93-5, respectively) beneath glacial deposits east of the river (Levings, 1984, table 3; Thamke and others, 1997, table 3).

The Upper Cretaceous Fox Hills Sandstone (shown as Kfh in fig. 4) consists of an upper sandstone unit 11-18 meters thick underlain by a transitional marine shale about 18 meters thick (Colton, 1963a, 1963b). The upper sandstone unit contains numerous concretions. The lower unit consists of thin-bedded, well-laminated shale grading to silt toward the top (Colton and Bateman, 1956). The upper parts of the formation were removed by erosion in many places before deposition of the Hell Creek Formation. The Fox Hills Sandstone crops out mainly along several plateaus in the northwestern part of the study area (fig. 4).

The lower part of the Upper Cretaceous Hell Creek Formation (shown as Khc in fig. 4) consists of a well-stratified greenish-gray sequence of shales, siltstones, sandstones, and carbonaceous shales about 85 meters thick (Colton and Bateman, 1956). The lower 15-30 meters is predominantly medium-tan sand, locally cemented to sandstone. Basal conglomerate lenses in the lower Hell Creek Formation contain a few quartzite pebbles (Colton, 1963a, 1963b). The lower Hell Creek Formation overlies, and in some places is channeled into, the Fox Hills Sandstone (Donovan, 1988). The sandstone beds of the lower part of the Hell Creek Formation and the Fox Hills Sandstone generally are hydraulically connected (Thamke, 1991). The Hell Creek Formation crops out mainly along several plateaus in the northwestern part of the study area (fig. 4).

Tertiary Units

The Tertiary units most relevant to this study are the Fort Union and Flaxville Formations. General characteristics of these two units are given below; descriptions of other Tertiary units are provided in Donovan (1988).

The Tertiary Fort Union Formation (shown as Tfu in fig. 4) consists of interbedded gray clay, buff silt, lignite, buff calcareous sandstone, brown carbonaceous clay, olive-gray sand, gray bentonitic clay, and silty limestone concretions (Colton and Bateman, 1956; Colton, 1963a, 1963b). The Fort Union Formation conformably overlies the Hell Creek Formation and has limited exposure in the northern part of the study area (fig. 4). The lower 180 meters of the Fort Union Formation are reportedly present in the study area (Colton, 1963a, Colton b). However the unit thickness is likely much less than that.

The Tertiary Flaxville Formation (shown as Tf in fig. 4) consists primarily of sand and gravel, 90 percent of which is brown and red quartzite and argillite (Colton and Bateman, 1956). The Flaxville Formation also contains minor amounts of marl and volcanic ash and is locally cemented (Colton, 1963a, 1963b). Fossil fragments from a variety of mammals and fish have been found in the Flaxville Formation (Collier and Thom, 1918). The Flaxville Formation lies unconformably on Fort Union Formation strata (Hardie and Arndt, 1989). The Flaxville Formation is usually less than 30 meters thick and forms the caps of even-topped plateaus and benches (Collier and Thom, 1918; Thamke, 1991). Elsewhere the Flaxville Formation is buried beneath thin glacial deposits and is exposed only in the northwestern part of the study area (fig. 4).

Quaternary Deposits

Quaternary units in the study area include Wiota Gravel, Sprole Silt, glacial till, fan alluvium and colluvium, and alluvium. Minor thicknesses and extents of glacial outwash, lake deposits, and dune sand also are present, but are not discussed separately in this report (dune sand, however, is shown as Qd in fig. 4).

Pleistocene Wiota Gravel (shown as Qw in fig. 4) consists of unconsolidated deposits of clay, silt, and quartzitic sand and gravel. Thickness in the study area is uncertain, but Colton (1963a, 1963b) reported a maximum thickness of 17 meters to the south of the study area. The Wiota Gravels overlies the Upper Cretaceous Bearpaw Shale east of the Poplar River and north of the Missouri River.

Pleistocene Sprole Silt (shown as Qs in fig. 4) overlies the Wiota Gravel and consists of poorly bedded to massive deposits of silt. Colton (1963a, 1963b) reported a maximum thickness of 30 meters for the Sprole Silt in the southern part of the study area.

Pleistocene glacial till (shown as Qt in fig. 4) is a complex, unstratified, and heterogeneous admixture of clay, silt, gravel, and boulders deposited by glaciers. Colton (1963a, 1963b) reported that thickness generally is about 5 meters but locally may be as much as 76 meters. Glacial till is present throughout the study area, but the thickest deposits are beneath the topographic bench east of the Poplar River (fig. 4).

Pleistocene and Holocene fan alluvium and colluvium (shown as Qac in fig. 4) underlies flood plains and consists of slope-wash deposits derived from topographically higher deposits; lithologically the slope-wash deposits are similar to Holocene alluvium (described below). These deposits are not vertically extensive; Colton (1963a, 1963b) reported that the maximum thickness is 6 meters. Laterally these deposits can be more than two kilometers wide, although the average width is much narrower. The fan alluvium and colluvium are located primarily along the edges of the Poplar River and Missouri River valleys (fig. 4).

Holocene alluvium (shown as Qal in fig. 4) consists of stream-deposited clay, silt, sand, and gravel. The sand and gravel deposits typically occur as lenses of varying thickness. Deposits of Holocene alluvium are located along the Poplar River and Missouri River valleys (fig. 4).

Water Quality

The quality of water in Quaternary deposits in the East Poplar oil field study area is highly variable and is dependent on location relative to sources of saline water, chemical characteristics of the saline water, quantity of saline water, and ground-water flow characteristics in the area. Saline-water plumes were delineated using data collected during the early 1990s (Thamke and Craigg, 1997; Thamke and Midtlyng, 2003). Four principal water types (table 1) in the study area also were described by Thamke and Craigg (1997). Ground-water quality in the study area can vary substantially (table 1), and vary both spatially and temporally.

Table 1. Characteristics of water types in the East Poplar oil field area (Thamke and Midtlyng, 2003, and Thamke and Craigg, 1997)

Concentration ranges for water types			
Water type	**Domestic water use**	**Dissolved solids (milligrams per liter)**	**Chloride (milligrams per liter)**
Type1—Uncontaminated ground water	Suitable for most domestic purposes	427-2,870	4-260
Type 2—Moderately contaminated ground water	Suitable for some domestic purposes; generally not used for drinking water	1,170-9,250	330-4,800
Type 3—Considerably contaminated ground water	Unsuitable for any domestic purposes	9,640-91,100	5,200-58,000
Type 4--Brine (from oil production)	Unused	47,700-201,000	27,000-120,000

The dissolved-solids and chloride-concentration ranges of these water types were updated by Thamke and Midtlyng (2003, table 1) using data collected between September 1993 and September 2000. Well distribution and interpreted plume locations are shown in figure 5. The interpreted plume location is based on hydrologic and ground-geophysical data acquired in 1991 and 1992 (Thamke and Craigg, 1997; Thamke and Midtlyng, 2003).

Comparisons of past to more recent concentrations of dissolved solids and chloride in water from wells can be used to indicate temporal changes in water quality, and thus, also indicate if saline-water plumes in the study area have moved. Recently, plume movement has been documented for the southern part of the East Poplar oil field (Land and Water Consulting, Inc., 2003; 2004; 2005). Time estimates of saline-water plume movement to the City of Poplar range from two years (Montana Department of Environmental Quality, 2002) to more than one hundred years (Land and Water Consulting, Inc., 2003).

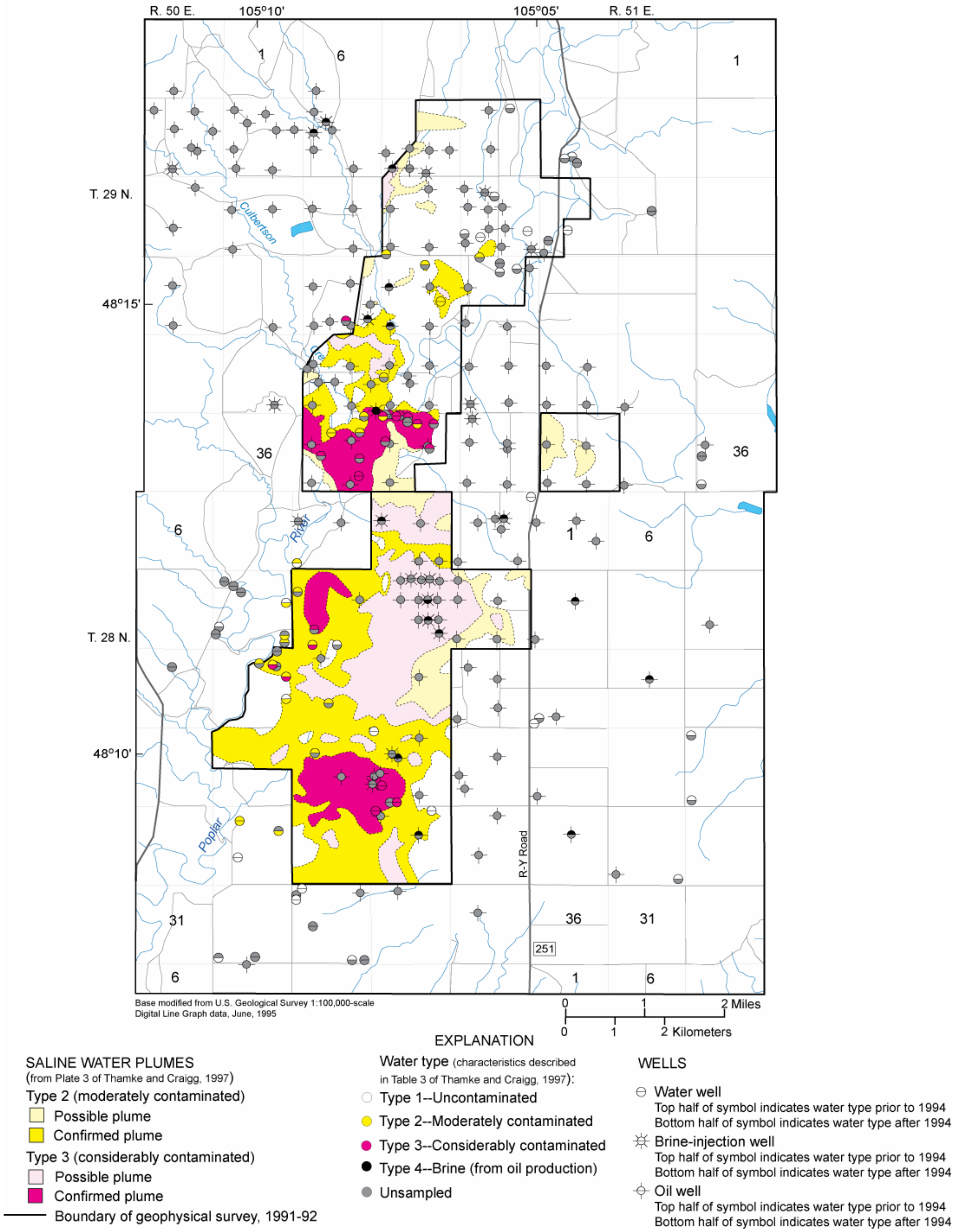

Figure 5. Locations of saline-water plumes in the East Poplar oil field study area, 1991-92 (Thamke and Craigg, 1997, also Table 1, this report).

Helicopter Electromagnetic and Magnetic Survey

Method

The RESOLVE© HEM system flown by Fugro Airborne consists of six coil pairs that measure resistivity at separate frequencies from about 400 hertz (Hz) to about 140,000 Hz (140 kHz). Five of the coil pairs were oriented in a horizontal, coplanar position and one of the coil pairs was oriented in a vertical, coaxial position. The system also includes a total-field magnetometer, differential kinematic GPS, and laser altimeter. The helicopter carried a separate differential GPS system, barometric and radar altimeters, and a video camera. Electromagnetic noise from power lines and natural sources (such as lightning) were also measured. The survey was flown with north-south flight lines and a nominal line spacing of 200 meters. The sensor was flown about 30 meters above the land surface except as required for safety considerations.

The magnetic system measured the Earth's total field to an accuracy of 0.01 nanoTesla (nT). The magnetic field consists of the Earth's main magnetic field and the local magnetic field due to sources within the crust and ferromagnetic metallic sources at the surface.

Detailed descriptions of equipment, calibration, quality control, and processing are provided in Appendix 1. Background information about a variety of geophysical topics, flight logs, tests and calibrations, processing logs, and a glossary are also included in Appendix 1.

Maps

In addition to digital location information (northing and easting), the global positioning systems used in the survey recorded accurate altitude information. Barometric, radar, and laser altimeters provided addition altitude information (Appendix 1). Data from the laser altimeter have been processed to produce a digital-altitude map for the study area (map a, plate 1). The altitude accuracy is on the order of 3 meters (Appendix 1).

The electromagnetic sensor of the HEM system measures the electrical resistivity (or the reciprocal, conductivity) of rocks. Apparent resistivity is the resistivity of a homogeneous isotropic volume that would give the same electromagnetic signal as measured by the HEM system. Fugro Airborne, as part of the contracted data processing, computed the apparent resistivity for each frequency. The computation is based on the pseudo-layer model (Fraser, 1978). Apparent conductivity (the reciprocal of resistivity) maps for the frequencies measured by the five co-planar coil pairs are show in maps b-f, plate 1.

The color scales indicate the maximum (red) and minimum (blue) values of apparent conductivity measured by co-planar coil pairs at the indicated frequencies. The apparent conductivity range for particular color scales are unique to each map in plate 1. The color scales have been used to emphasize comparative high and low conductivity areas within each map (at each frequency) rather than between maps.

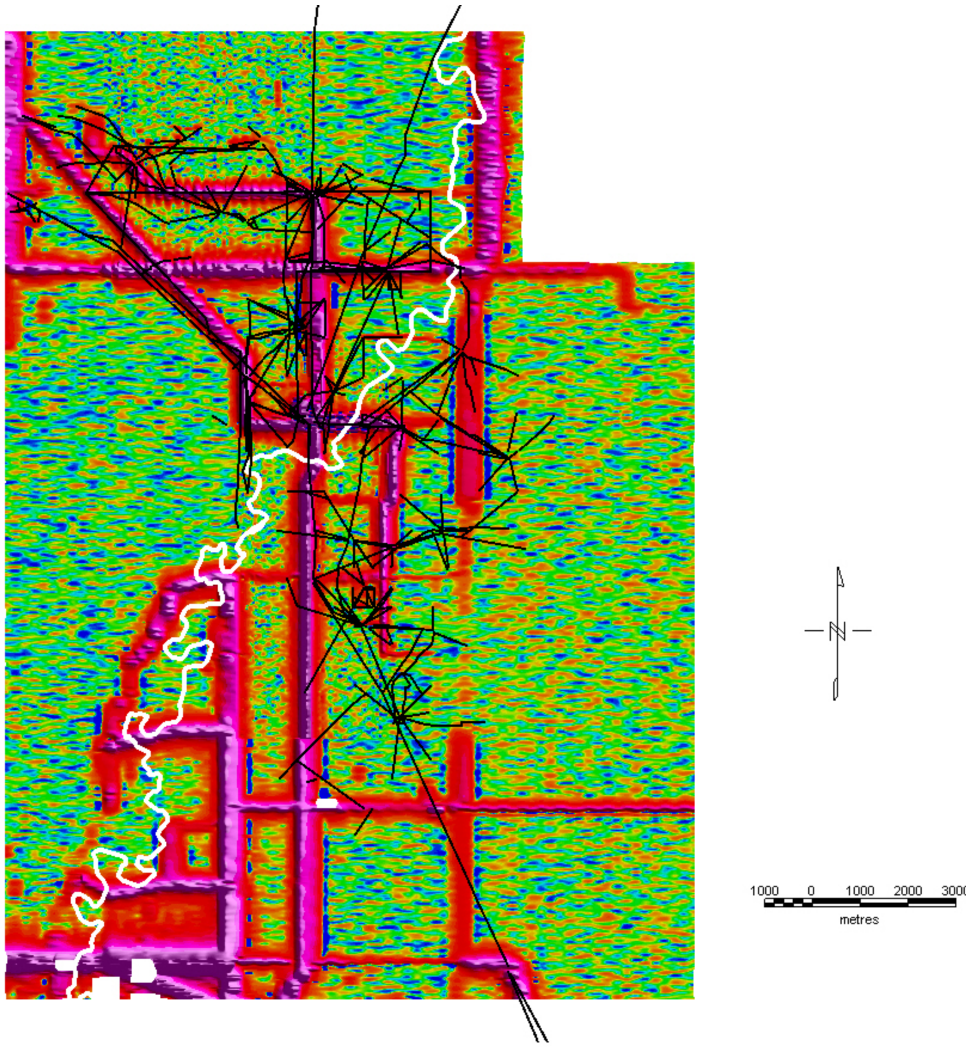

Figure 6. Gridded powerline monitor data from the electromagnetic sensor, East Poplar oil field area. Powerlines produce linear areas of high radiation (shown in red and pink hues) and were monitored by coaxial and coplanar coil pairs at 60 Hz. Subsurface pipelines are shown in black (U.S. Geological Survey, written commun., 2005).

In general, each apparent conductivity map shows progressively deeper sections (plate 1, maps b-f) of the earth. Also, the volume of the subsurface that is sampled increases as a frequency decreases. Consequently, the resolution of subsurface features decreases with depth. The effects of powerline noise also increases as a function of decreasing frequency. Examination of the lower frequency apparent conductivity maps (map f, plate 1) in comparison to the powerline monitor map (fig. 6) shows that most of the powerlines produce linear areas of high apparent conductivity (red hues). In contrast, the apparent conductivity measured at the highest frequency (140 kHz) appears to be little affected by the powerlines.

Magnetic field measurements and processing are described in appendix 1. The processed total-magnetic-field intensity has been corrected for the International Geomagnetic Reference Field to remove the local variations due to the Earth's main magnetic field. Two additional processing steps have been applied to these magnetic-field data. The first step is to reduce the main magnetic field to the pole, which shifts magnetic highs directly over the causative body instead of being shifted slightly to the south. Figure 7 shows the reduced-to-pole (RTP) magnetic field for the study area. The second step is to remove a regional magnetic field. This step was accomplished by fitting a third-order polynomial surface to the RTP magnetic data using Oasis Montaj software (Geosoft, Inc., 2006). This surface then was subtracted from the RTP map to produce the residual map (fig. 8).

The long spatial wavelength features in (fig. 8) are due to deeply buried magnetic sources. Short wavelength linear features are correlated, in part, with linear glacial features (fig. 4) and in part with cultural features. The small circular magnetic high and low anomalies are due to steel tanks and drill casing. In some places, the drill hole locations may represent unknown abandoned wells.

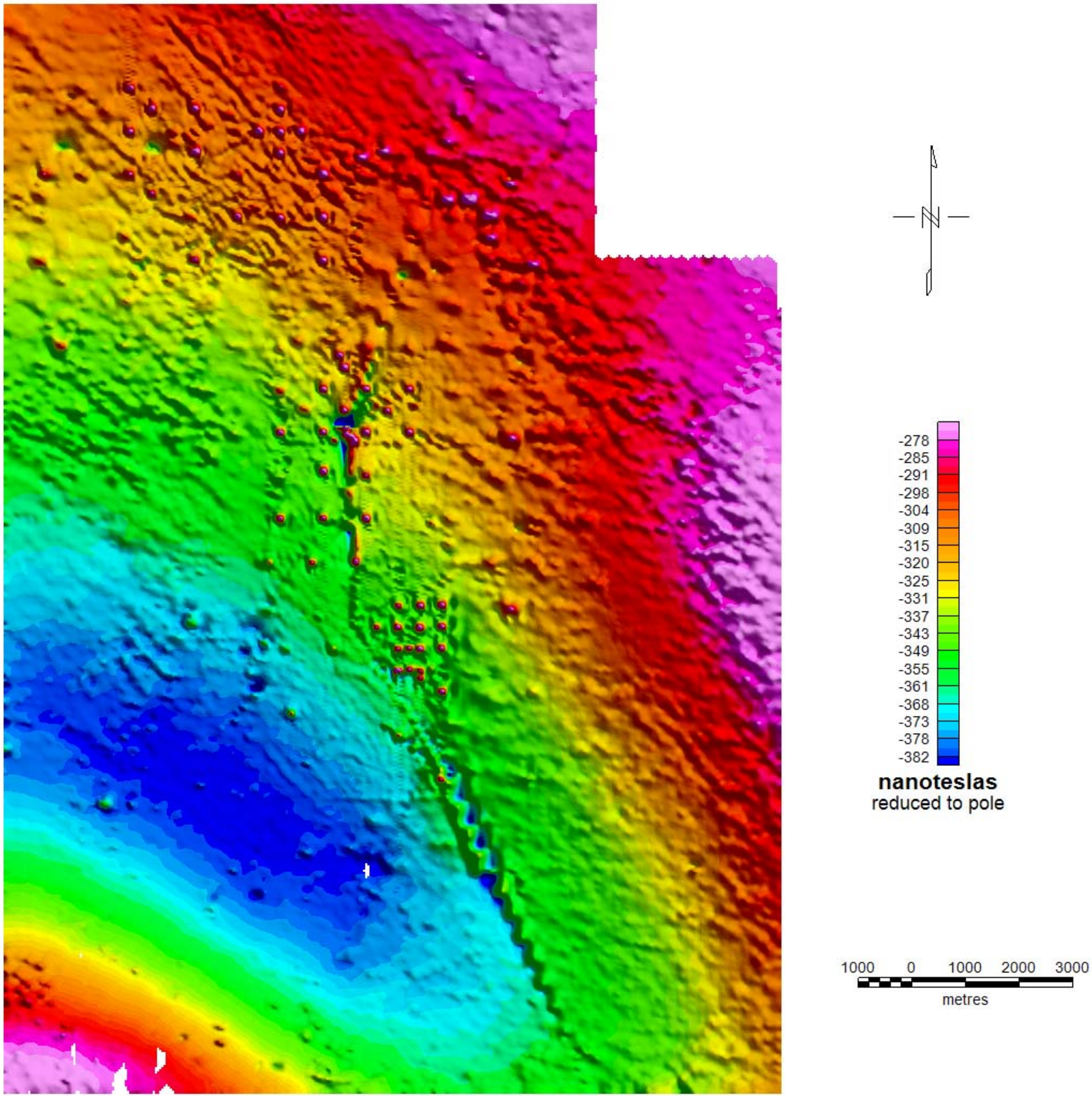

Figure 7. Reduced-to-magnetic pole total-field-magnetic data, East Poplar oil field area. Magnetic field parameters used are 10.78^{0} declination and 73.37^{0} inclination.

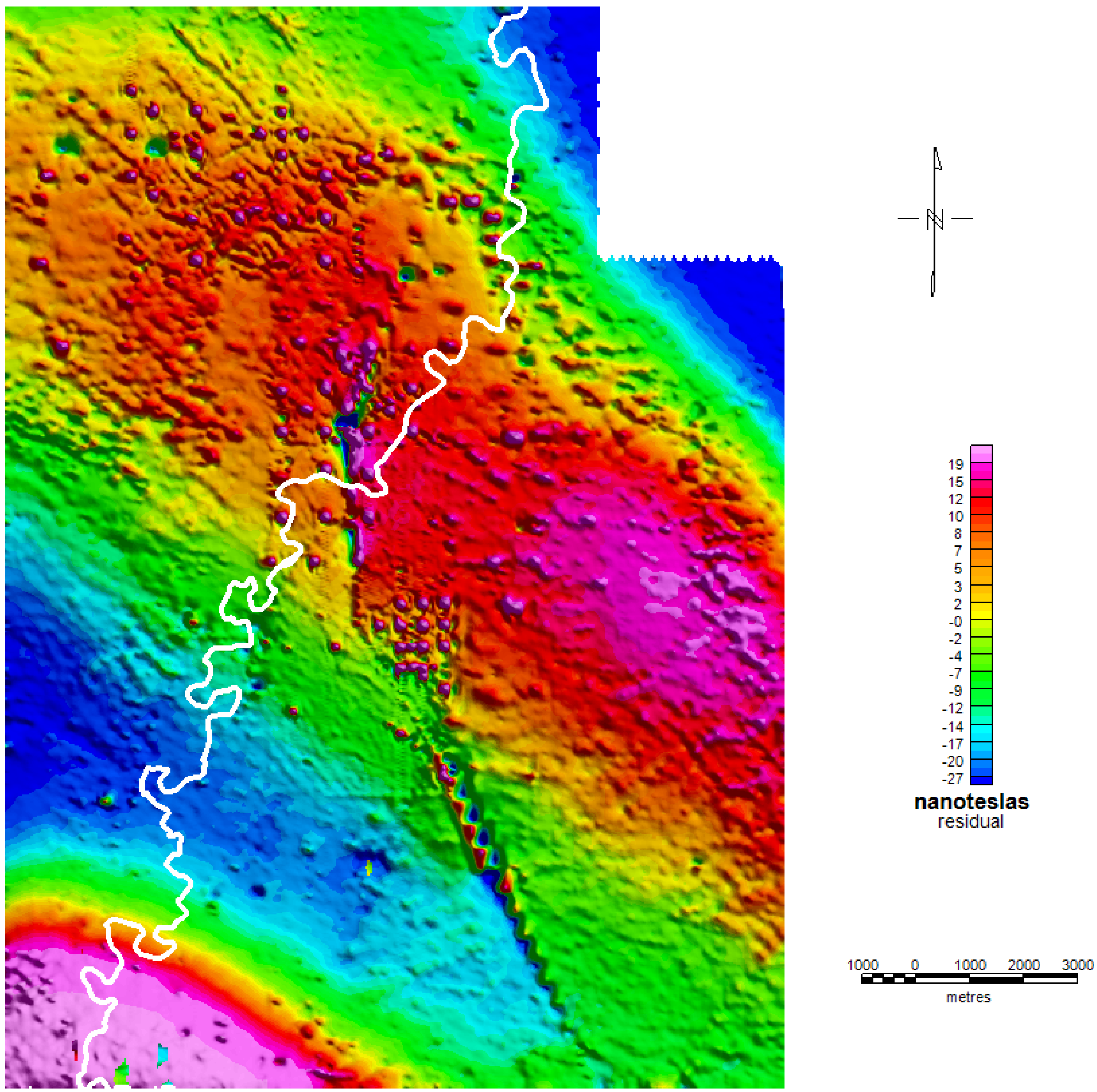

Figure 8. Residual total-field-magnetic data, East Poplar oil field area. A second-degree polynomial was fited to the data of figure 7 and then subtracted to produce the above map.

Digital Data

Digital data and other information are provided in six directories with contents as described:

Directory	Description
GIS	Geographic information such as topographic map.
GRIDS	Grids of the electromagnetic and magnetic field data for the horizontal coplanar coil pairs are in this directory. Grid cell size is 50 meters, which is large in comparison to the measurement spacing of 3 meters along flight lines because the spacing between flight lines is larger than the measurement interval. The grids are in Geosoft OASIS MONTAJ (***http://www.geosoft.com/***) format, a 'standard' of the geophysical industry used in many map display programs. Programs are included with this data release to view, export, and import the grid files in ARCVIEW.
LINEDATA	Flight-line data are in a Geosoft OASIS MONTAJ (***http://www.geosoft.com/***) database in this directory. This database can be read and converted to other formats by the OASIS Viewer program included in the ***SOFTWARE*** directory (see also below). The position is given in latitude and longitude as well as UTM coordinates. The raw GPS positioning data for the survey is in NAD83 (zone 13N) but has been reprocessed to NAD27 (zone 13N) in the database. The description of the header for each channel is given in the ".txt" file in the directory. Each channel is described in appendix 1.
IMAGES	Geotiff (UTM13N. NAD27 projected ".tif" files) of the grids are in this directory. Each file has an associated world file (".tfw"). The digital version of plate 1 can be found in this directory. The original images of the airborne apparent resistivity maps generated by the contractor are included in the IMAGES/CONTRACTOR_PDF_MAPS.
REPORT	This report and appendix 1 are in this directory as ".pdf" files.
SOFTWARE	The programs needed to read GEOSOFT and ERMAPPER images and data are in this directory.

Each directory contains a "readme.txt" file that describes the contents of the directory.

Acknowledgments

The Office of Environmental Protection of the Fort Peck Tribes is acknowledged for their support extended to the USGS throughout this investigation. The authors thank individual landowners and the various oil-field companies in the study area for their cooperation extended throughout this and previous investigations. Steven D. Craigg, USGS, deserves special mention as the original primary author of much of the "Geologic Setting" section this report.

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Appendix: Fugro Geophysical Report

The contractors report is given in the following link ***FUGRO REPORT***.