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Investigation of the Potential for Concealed Base-Metal Mineralization of the Drenchwater Creek Zn-Pb-Ag Occurrence, Northern Alaska, Using Geology, Reconnaissance Geochemistry, and Airborne Electromagnetic Geophysics

Professional Paper 1784–B

U.S. Department of the Interior
U.S. Geological Survey

Cover
Photograph of the Drenchwater Creek study area. (USGS photograph by K.D. Kelley.)

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Abstract

In 2005, the U.S. Geological Survey, Bureau of Land Management, and State of Alaska cooperated on an investigation of the mineral potential of a southern part of the National Petroleum Reserve in Alaska, Howard Pass quadrangle, to provide background information for future land-use decisions. The investigation incorporated an airborne electromagnetic (EM) survey covering 1,500 mi^2 (~3,900 km^2), including flight lines directly over the Drenchwater Creek sediment-hosted Zn-Pb-Ag occurrence, the largest known base-metal occurrence in the survey area. Samples from the mineralized outcrop and rubblecrop contain metal concentrations that can exceed 11 percent Zn+Pb, with appreciable amounts of Ag. Soil samples with anomalous Pb concentrations are distributed near the sulfide-bearing outcrops and along a >2.5 km zone comprising mudstone, shale, and volcanic rocks of the Kuna Formation.

No drilling has taken place at the Drenchwater occurrence, so alternative data sources (for example, geophysics) are especially important in assessing possible indicators of mineralization. Data from the 2005 electromagnetic survey define the geophysical character of the rocks at Drenchwater and, in combination with geological and surface-geochemical data, can aid in assessing the possible shallow (up to about 50 m), subsurface lateral extent of base-metal sulfide accumulations at Drenchwater. A distinct >3-km-long electromagnetic conductive zone (observed in apparent resistivity maps) coincides with, and extends further westward than, mineralized shale outcrops and soils anomalously high in Pb concentrations within the Kuna Formation; this conductive zone may indicate sulfide-rich rock. Models of electrical resistivity with depth, generated from inversion of electromagnetic data, which provide along-flight-line conductivity-depth profiles to between 25 and 50 m below ground surface, show that the shallow subsurface conductive zone occurs in areas of known mineralized outcrops and thins to the east. Broader, more conductive rock along the western ~1 km of the geophysical anomaly does not reach ground surface. These data suggest that the Drenchwater deposit is more extensive than previously thought. The application of inversion modeling also was applied to another smaller geochemical anomaly in the Twistem Creek area. The results are inconclusive, but they suggest that there may be a local conductive zone, possibly due to sulfides.

Introduction

In 2005, the Alaska Division of Geologic and Geophysical Surveys (DGGS), funded by the United States Department of Interior, Bureau of Land Management (BLM), contracted Fugro Airborne Surveys to fly a helicopter-borne frequency domain electromagnetic (EM) survey of a 1,500 mi^2 area in parts of the remote Howard Pass and Misheguk Mountain quadrangles in the southern National Petroleum Reserve in Alaska (NPRA; fig. 1). The survey was a continuation of the BLM mineral-resource assessment program that began in the 1990s and was aimed at assessing the type, amount, and distribution of mineral deposits of the Colville mining district in the NPRA (Kurtak and others, 1995; Meyer and Kurtak, 1992, Meyer and others,1993). The area contains more than 20 documented mineral occurrences, some containing Zn-, Pb-, and Ag-rich sulfide minerals and/or barite. The NPRA is currently closed to mineral entry. A better understanding of the distribution of metallic resources will aid future land-use planning for the NPRA.

Within the NPRA, the Drenchwater Creek Zn-Pb-Ag occurrence is hosted in the Kuna Formation of the Lisburne Group (Mull and others, 1982), similar to several other Zn-Pb-Ag deposits, including the world-class Red Dog deposit, located approximately 160 km to the west (Kelley and Jennings, 2004). Although the spatial association of mineralization at Drenchwater with volcanic rocks in the Kuna

Formation has led to speculation that it could be a volcanogenic massive sulfide deposit (Werdon, 1996), the overwhelming textural, geochemical, and geological evidence suggests that it is a sediment-hosted or "Sedex" (sedimentary exhalative) deposit, similar to deposits in the Red Dog district (Lange and others, 1985; Kelley and Jennings, 2004; Werdon, 1996).

The initial discovery of Drenchwater was the identification of Zn- and Pb-bearing outcrop and rubblecrop along a ~5-km strike-length (Nokleberg and Winkler, 1982; Werdon, 1996). Geochemical anomalies were identified in surface rock, soil, and sediment samples collected in the area between False Wager and Drenchwater Creeks (Churkin and others, 1978; Nokleberg and Winkler, 1982; Theobald and others, 1978). The closure of the NPRA to mineral entry has precluded direct testing (for example, drilling and trenching) of the continuity or grade of base-metal mineralization at Drenchwater, so the extent of mineralized rocks can be assessed only by indirect methods, such as geophysics and geochemistry.

The 2005 airborne EM survey, which extends well beyond the mineralized surface exposures, is the most extensive geophysical coverage collected to date in the Drenchwater area. Previous ground-based gravity and magnetics surveys (Morin, 1997), and a VLF survey (Kurtak and others, 1995) identified possible faults, but were not extensive enough to adequately characterize the geophysical signatures of barren versus mineralized rock, or to constrain the extent of potential massive-sulfide mineralization.

In this paper, we combine geologic, geochemical, and geophysical data to estimate the possible distribution of base-metal mineralized rocks at the Drenchwater occurrence. Starting with a combined geological and geochemical framework, we use data from the 2005 EM survey to establish the general resistivity characteristics of the geologic units in the study area. Apparent resistivity anomalies are identified from apparent resistivity maps and are compared spatially to the known surface-mineralization and geochemical data in the occurrence area. Subsequently, we use data-inversion techniques to model subsurface electrical conductivity to indicate possible sulfide-rich conductive rock at Drenchwater. We also include a brief discussion on the application of inversion modeling to another smaller geochemical anomaly in the Twistem Creek drainage.

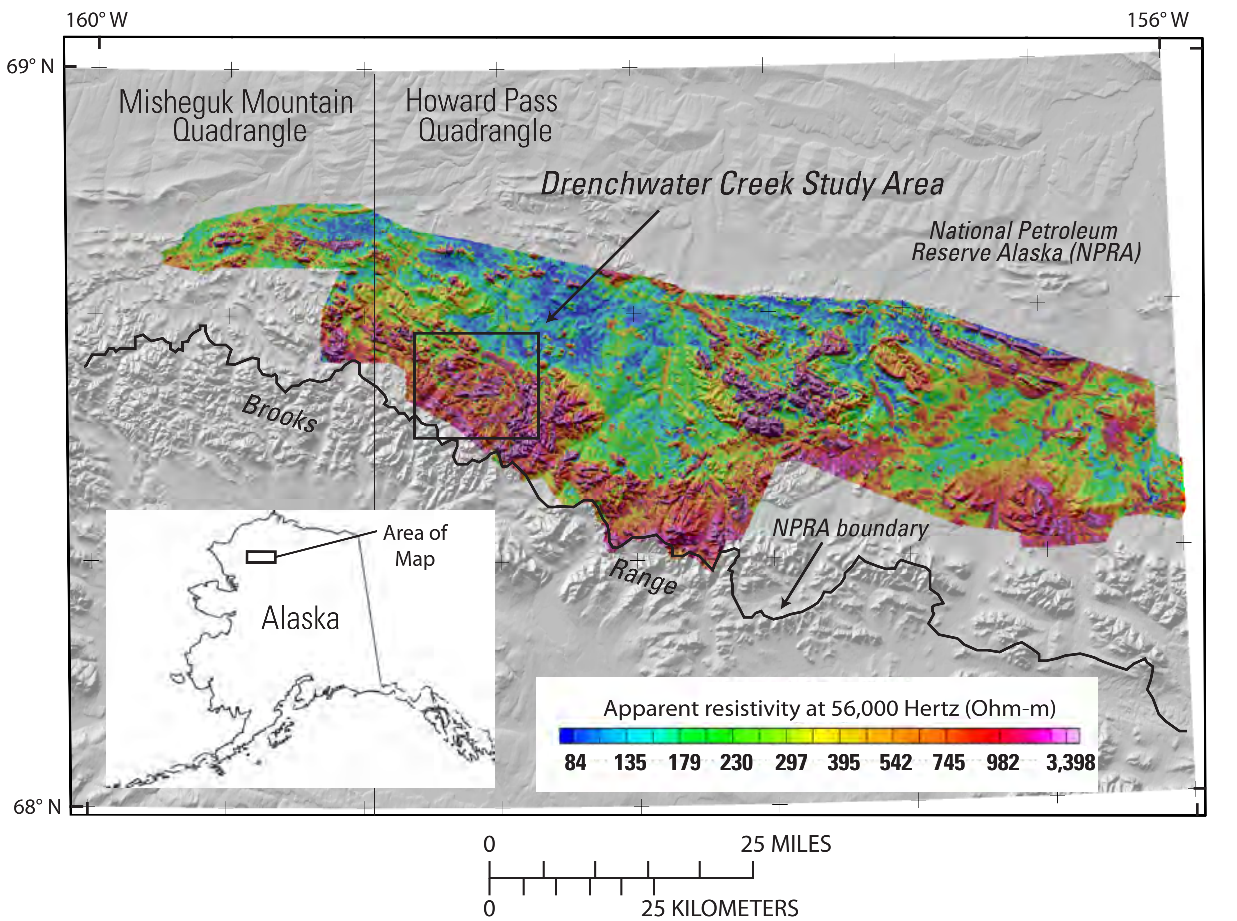

Figure 1. Location map showing the extent of the 2005 airborne geophysical survey and the Drenchwater Creek study area, northern Alaska. Color image is the 56,000 Hz apparent resistivity. Geophysical data from Burns and others (2006).

Physiography

The Drenchwater occurrence is located in northern Alaska in the C-5 1:63,360 sheet of the Howard Pass quadrangle, within the NPRA. It is approximately 7 km north of the Brooks Range crest (1,000–1,400 m elevation), in moderately sloping hills at approximately 650–700 m elevation. Relief ranges from approximately 140–220 m in the southern part of the study area to about 100 m in the north, and it becomes essentially flat 6.5 km northeast of the occurrence. The outcrop is largely restricted to ridge tops, isolated knobs, and areas along some stretches of stream banks. Much of the area, particularly in the northeast, is covered by vegetation underlain by permafrost. Vegetation includes low brush and tundra with willows and moss locally present along stream banks.

The area is remote and accessible only by helicopter; the nearest villages are Kotzebue, approximately 240 km to the southwest, and Umiat, approximately 280 km to the northeast. The Red Dog mine, located ~160 km west of Drenchwater, is the closest semi-permanent community. Climatic data from the Western Region Climate Center (2007a,b) shows average temperatures for Umiat and Kotzebue of approximately 11°C in July and –31 to –19°C in February. Total annual precipitation is between approximately 15 and 25 cm, including 84–132 cm of total snowfall.

Drenchwater Creek Geology

The northern Brooks Range is a north-vergent fold and thrust belt with a complex history (Moore and others, 1994; Young, 2004, and references therein). Seven different structural sequences or allochthons, have been identified in the Howard Pass quadrangle (Dover and others, 2004); these allochthons, which represent structurally dismembered segments of the Paleozoic Kuna Basin, were juxtaposed by the Jurassic to Cretaceous Brookian orogeny (Moore and others, 1994). Four of these allochthons [the Endicott Mountains (EMA), Picnic Creek (PCA), Ipnavik River (IRA), and Nuka Ridge (NRA)] are exposed at or near the Drenchwater stratiform Zn-Pb-Ag occurrence (figs. 2 and 3; Dover and

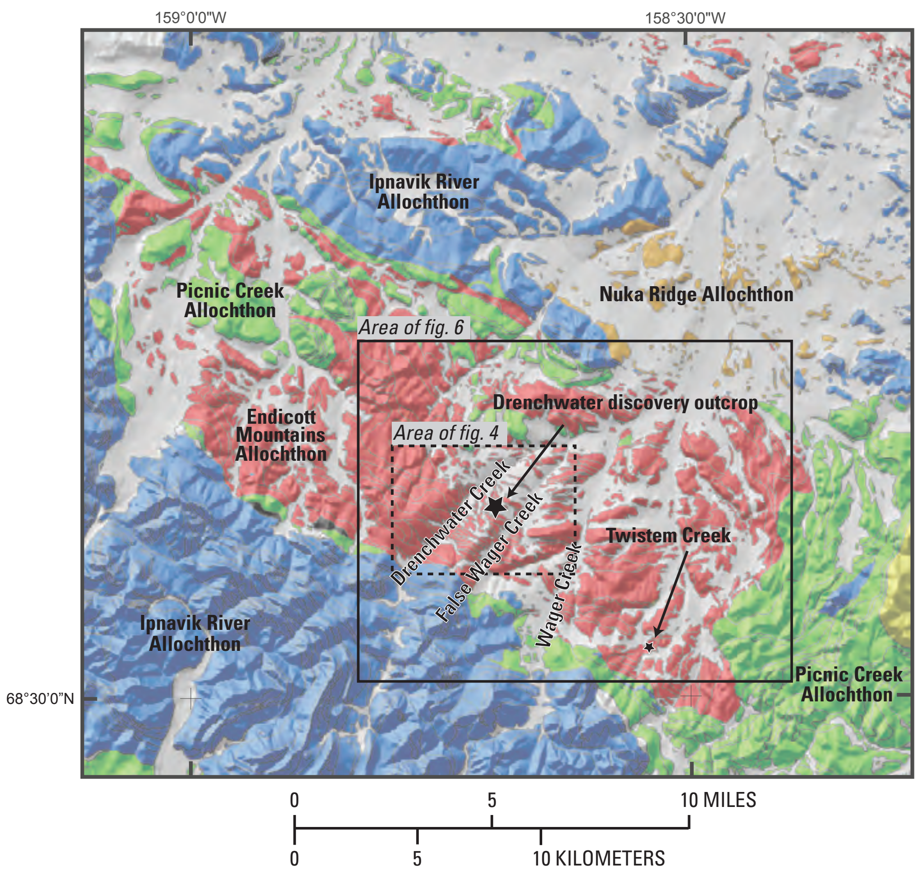

Figure 2. Map showing the allochthon distributions and the locations of the Drenchwater Creek discovery outcrop and the Twistem Creek stream-sediment geochemical anomaly, Drenchwater study area, northern Alaska. Gray areas in the figure represent covered areas. The black box shows the extent of the Drenchwater study area. Modified from Dover and others (2004).

others, 2004). The EMA, PCA, and IRA allochthons in the Drenchwater area contain deep-water facies that, like similar facies in the Red Dog district, formed as part of the Kuna Basin (Young, 2004; Dumoulin and others, 2004). In the Drenchwater area, deep-water facies include mudstone, shale, and associated volcanic rocks of the Kuna Formation of the EMA, the Akmalik Chert of the PCA, and the Rim Butte unit (limestone turbidites, siliceous mudstone, and chert) of the IRA (fig. 3; Dumoulin and others, 2004). These Carboniferous units are all part of the Lisburne Group; detailed descriptions of each unit are discussed by Dumoulin and others (1993, 1994) and Dover and others (2004). The Lisburne Group rocks are overlain by mixed shale and chert of the Etivluk Group, called Siksikpuk and Otuk Formations in the EMA, but Imnaitchiak Chert in the PCA and IRA (fig. 3).

The majority of the rocks in the immediate vicinity of the Drenchwater occurrence are within a fenster assigned to the EMA (figs. 2 and 4). Local slivers of Akmalik Chert (AC) of the PCA are found in the northernmost portion of the study area (fig. 4). The EMA rocks range in age from the Carboniferous Kuna Formation to the Cretaceous Okpikruak Formation. Nokleberg and Winkler (1982) subdivided the EMA fenster into five east-west striking thrust plates (north to south): Mother Bear (MBTP), Two Cubs (TCTP), Drenchwater (DWTP), Spike Camp (SCTP), and Gas Drum (GDTP) thrust plates (fig. 4). The rocks have undergone extensive folding and faulting, which has disrupted the geology; however, bedding generally strikes east-west, dipping 40–70 degrees to the south. The known prominent Zn-Pb-Ag-rich outcrops and rubblecrop discussed in this paper are restricted to the Kuna Formation and associated volcaniclastics of the Lisburne Group, mostly occurring in the Drenchwater thrust plate (fig. 4).The Kuna Formation in the Howard Pass area consists of dark gray to black carbonaceous and locally phosphatic shale, siliceous mudstone, and chert (Dumoulin and others, 2004). The unit has a maximum thickness of 100 m in the study area (Dover and others, 2004). Although black shale is commonly rich in metals, regional sampling indicates that the Kuna Formation has low concentrations of many elements, including As, Co, Cu, Pb, Sb, and Zn (Slack and others, 2004a). Low Fe contents of Kuna Formation rocks (average of 1.4 wt. % as Fe_2O_3) limited the generation of diagenetic pyrite to sparse cubes, framboids, and replacements of fossil fragments. Chert is abundant within several of the thrust sheets and locally contains disseminated pyrite (Nokleberg and Winkler, 1982). Barite is not a major constituent of the Kuna Formation rocks, and only one limestone bed is exposed, approximately 1 km east of False Wager Creek (fig. 4; Nokleberg and Winkler, 1982).

Submarine igneous rocks, dated at approximately 335–337 Ma (Werdon and others, 2004), are in direct contact with the Kuna Formation in the DWTP and consist mostly of light gray, medium to coarse grained, porphyritic felsic tuff and fine-grained layered tuff (Werdon, 1996). These tuffs are locally altered and pyritic. Thin, discontinuous tuffaceous beds occur in the MBTP and GDTP. At least three felsic to intermediate porphyritic domes occur within or near the felsic tuffaceous volcanic pile in the center of the study area. Three mafic units occur east of False Wager Creek—two in the DWTP and one to the north in the TCTP (Werdon, 1996).

Stratigraphically higher units are much more abundant in the thrust plates that flank the DWTP (fig. 4). The Pennsylvanian to Permian Siksikpuk Formation that overlies the Kuna Formation within the EMA consists of fine-grained sedimentary rocks. The lower portion contains pyrite-bearing orange chert, minor barite, gray shale, and local pyritic black shale (Nokleberg and Winkler, 1982). Chert, shale, and limestone comprise the Middle Jurassic to Triassic Otuk Formation.

The Cretaceous Okpikruak Formation caps the sedimentary succession and consists of lithic sandstone, siltstone, and mudstone flysch. The Siksikpuk, Otuk, and Okpikruak Formations are most abundant on the SCTP. Iron-staining from weathering of pyrite in all three rock units is prevalent along False Wager Creek (fig. 4; plate 2 of Nokleberg and Winkler, 1982).

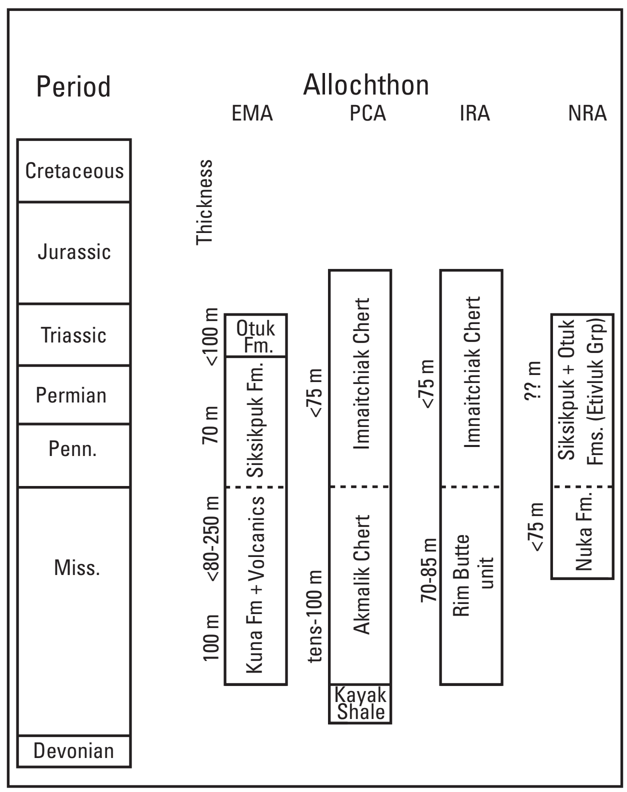

Figure 3. Stratigraphic section showing exposed units of the four local allochthons in the Drenchwater Creek study area, northern Alaska. EMA, Endicott Mountains Allochthon; PCA, Picnic Creek Allochthon; IRA, Ipnavik River Allochthon; NRA, Nuka Ridge Allochthon. The Kuna Formation, volcanic rocks, Akmalik Chert, and Rim Butte unit are all part of the Lisburne Group. The Siksikpuk and Otuk Formations make up the Etivluk Group. Modified from Dumoulin and others (2004).

The rock units comprising other allochthons (figs. 2 and 3) are described in detail by Dover and others (2004). The PCA units exposed in the study area consist of the Pennsylvanian to Mississippian Akmalik Chert and Jurassic to Pennsylvanian Imnaitchiak Chert, which are comprised of black and gray to greenish gray chert with shale partings or interbeds (Dover and others, 2004). Ipnavik River units include the basal Rim Butte unit of generally thin-bedded limestone turbidite and interbedded siliceous mudstone and lesser chert, overlain by Jurassic to Pennsylvanian Imnaitchiak Chert. The Pennsylvanian to Mississippian Nuka Formation includes arkose, arkosic limestone, and limestone beds that are sometimes glauconitic. These rocks are overlain by the chert-dominated Etivluk Group.

Base-metal Mineralization and Alteration

Mineral-resource assessment studies of the NPRA by the USGS and U.S. Bureau of Mines in the 1970's and 1980's (Churkin and others, 1978; Jansons and Parke, 1978; Nokleberg and Winkler, 1982) included geologic mapping that identified scattered exposures of base-metal sulfides and associated silicified rocks over a strike length of approximately 5 km within the Kuna Formation mudstone and carbonaceous shale, and locally within tuffaceous rocks of the DWTP (figs. 4 and 5). The most abundant sulfides in outcrop and rubblecrop occur in an area ~2.5 km long extending from Drenchwater Creek eastward to False Wager Creek. Alteration mapping and petrographic study of sulfide minerals by Werdon (1996) identified four textural variants of base-metal sulfides: (1) fine-grained, weakly disseminated sulfide (mostly sphalerite) in bleached and silicified gray shale/mudstone; (2) sphalerite and galena-rich, pyrite-bearing semi-massive sulfide; (3) chaotically laminated pyrite-sphalerite-galena semi-massive sulfide within shale: and (4) base-metal sulfides, quartz and fluorite, locally replacing or cementing clasts within volcanic rocks. Semi-massive sulfide is most common in the central area of known mineralization, cropping out in an area 64 m by ~15 meters (Area A and indicated by

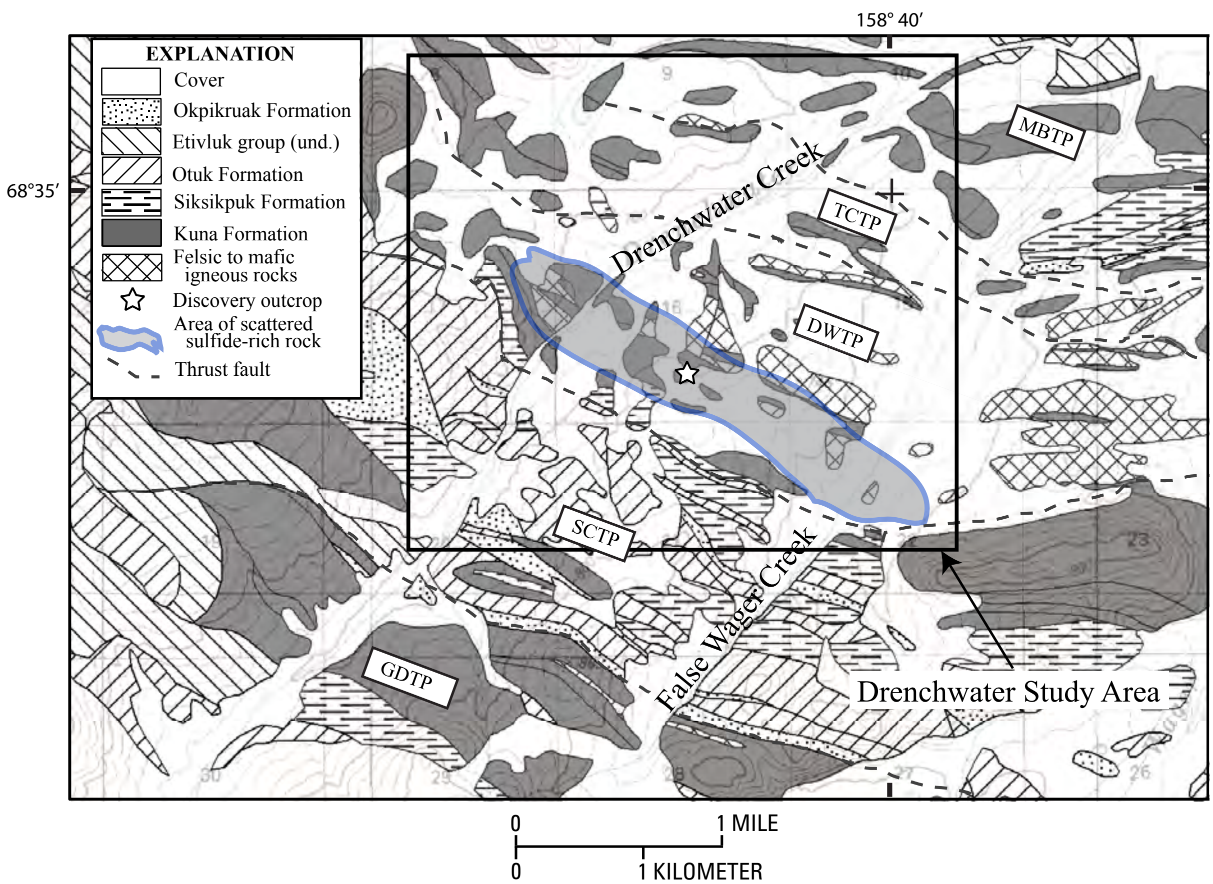

Figure 4. Simplified geologic map of the vicinity around Drenchwater Creek showing the general distribution of sulfide-rich rocks, Drenchwater study area, northern Alaska. The box shows the extent of data presented in figures 5 and 8 and the dashed box in figure 7. Structural plates identified by Nokleberg and Winkler (1982) in the Drenchwater area are, from north to south: MBTP, Mother Bear thrust plate; TCTP, Two Cubs thrust plate; DWTP, Drenchwater thrust plate; SCTP, Spike Camp thrust plate; and GDTP, Gas Drum Thrust Plate. Geology modified from Nokleberg and Winkler (1982) and Werdon (1996).

the star on figs. 5 and 6*A*). This locality is referred to as the "discovery outcrop" because it was the first zone of high-grade material that was observed in the area (Nokleberg and Winkler, 1982). This mineralized zone is bounded on its eastern and northern sides by faults, and exposures to the west are weakly disseminated sulfides (mostly sphalerite) in silicified mudstone. Approximately 900 m to the west, more pyritic (3–10+ percent pyrite), laminated base-metal sulfides (sphalerite and galena) crop out at water level, immediately adjacent to Drenchwater Creek (Area B on figs. 5 and 6B). The laminated sulfide-bearing rock is overlain by sparsely mineralized siliceous shale to the west, and its extent westward cannot be traced. Volcanic-breccia-hosted sulfides occur north and approximately 1 km east-southeast of the semi-massive sulfide outcrop (Area A on fig. 5); the eastern occurrence (Area C on fig. 5) marks the eastern extent of recognized exposed and potentially significant mineralization. Large variations in metal concentrations among rocks of differing textures are evident. A 102-kg bulk sample from the discovery outcrop contained 15.2 percent Zn, 3.23 percent Pb, and 59.9 g/t Ag (Meyer and others, 1993). A similar bulk sample from the laminated sulfides along Drenchwater Creek contained 10.5 percent Zn, 0.91 percent Pb, and 30.2 g/mt Ag (Meyer and others, 1993; Werdon, 1996). Representative grab samples of finely disseminated and volcanic breccia-hosted textures contain appreciably lower base-metal concentrations, commonly 1percent or less (combined Pb+Zn) (Meyer and Kurtak, 1992; Werdon, 1996).

Silicification is the dominant alteration associated with base-metal mineralization in the Kuna Formation (Werdon, 1996). Slack and others (2004b) show that silica is also the dominant alteration mineral in wallrocks of the Red Dog deposits, having formed at various stages of the deposit history, from early pre-sulfide hydrothermal fluids to post-mineralization silica that was introduced during the Jurassic to Cretaceous Brookian orogeny. Volcanic rocks at Drenchwater contain more varied alteration assemblages, ranging from silica-clay, to clay, to pyrite. Pyrite is locally abundant in tuffs

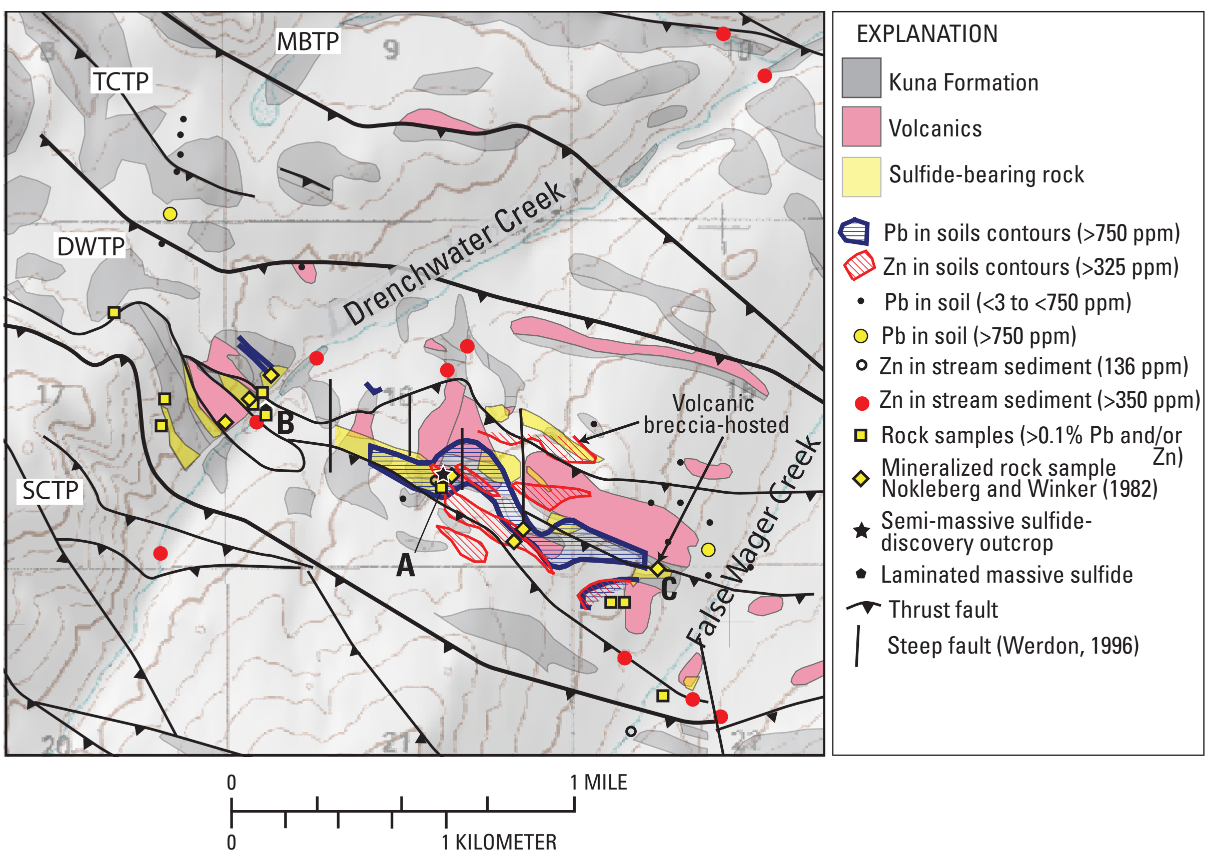

Figure 5. Distribution of selected outcrop, float, soil, and stream-sediment geochemical anomalies in the Drenchwater Creek study area, northern Alaska. A, massive sulfide of the discovery outcrop; B, laminated sulfide outcrop along Drenchwater Creek; and C, volcanic breccia-hosted sulfide. Soil geochemistry from Kurtak and others (1995) and Meyer and Kurtak (1992). Lowest-measured values for Pb and Zn were <2 ppm.

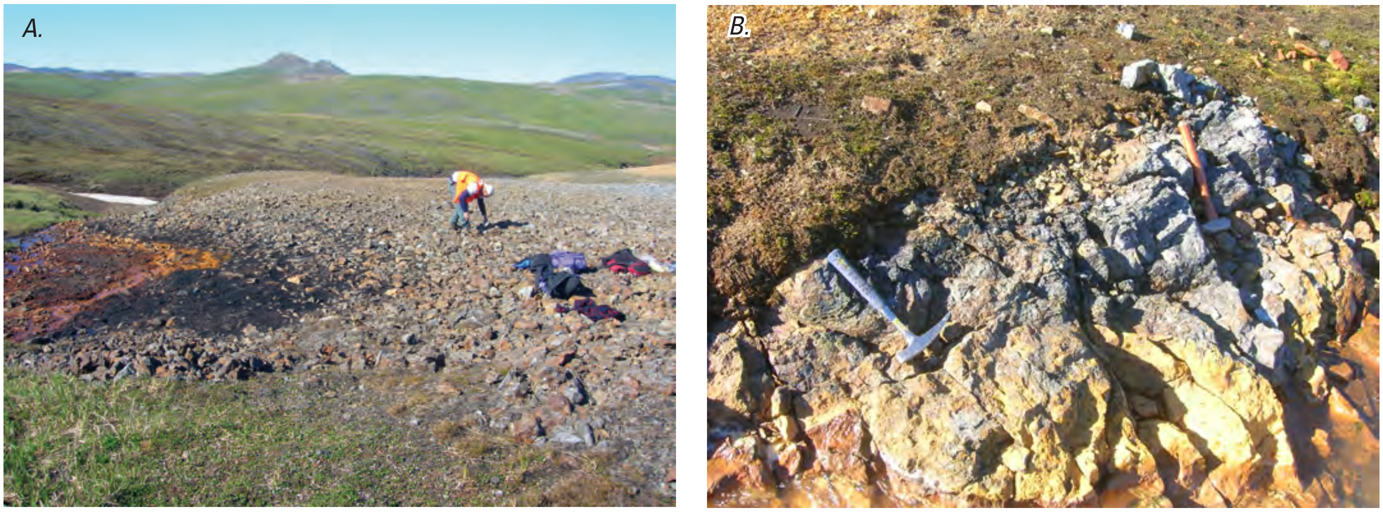

Figure 6. Photographs from the Drenchwater Creek study area, northern Alaska. *A*, Image looking approximately west over the prominent Drenchwater Creek discovery outcrop, consisting of silicified sphalerite- and galena-mineralized rubble. Strong iron staining in adjacent stream water is the product of sulfide oxidation. Note the low relief and abundant tundra cover in the background. *B*, Banded, highly pyritic sphalerite- and galena-rich mudstone exposure at the water level of Drenchwater Creek. Exposure is limited and covered by moss on the stream bank. (USGS photographs by K.D. Kelley.)

on the DWTP and in a tuff near the headwaters of False Wager Creek. Carbonate alteration is sparse-to-common in tuffaceous rocks (Nokleberg and Winkler, 1982; Werdon, 1996). The genetic relationship of the carbonate alteration to the base-metal sulfides is not known. Although carbonate is rare at Red Dog, it is a common alteration mineral in other Sedex-type deposits (Leach and others, 2005).

Geochemical Data

Early reconnaissance investigations of the NPRA involved collection of stream-sediment, heavy-mineral concentrate, and rock samples (for example, Churkin and others, 1978; Jansons and Parke, 1978; Theobald and others, 1978; Nokleberg and Winkler, 1982). Samples with high Pb and/or Zn concentrations in the Drenchwater Creek area led to more detailed sampling by the U.S. Bureau of Mines (Kurtak and others, 1995) and the USGS (Kelley and others, 1992, 1996). The most extensive sampling included a systematic soil survey (175 samples) completed by the U.S. Bureau of Mines using a line spacing of ~120 m and a sample spacing of 30 m (Kurtak and others, 1995; Meyer and Kurtak, 1992). Sample coverage was from False Wager Creek to ~800 m west of Drenchwater Creek primarily in the DWTP (fig. 5). Large Pb and Zn anomalies were delineated around the discovery outcrop in tundra-covered areas. The DWTP soils are characterized by elevated Pb concentrations (>50 ppm) relative to those collected in other thrust plates. Samples with concentrations of Pb in excess of 750 ppm define an elongate area that extends west and east of the semi-massive sulfide-discovery outcrop, projecting toward the laminated sulfide exposures on Drenchwater Creek and southeastward toward exposures of mineralized volcanic breccia near False Wager Creek on the eastern edge of the grid. A narrow zone of anomalous Pb concentrations in soils also occurs to the west of Drenchwater Creek. Zn anomalies locally overlap with, but largely occur outside of, the Pb-anomalous zones and are absent west of Drenchwater Creek. These soil anomalies generally coincide with the distribution of sulfide-bearing rock (figs. 4 and 5).

Rock samples with concentrations of >0.1 percent Zn and/or Pb, stream-sediment samples collected subsequent to the Bureau of Mines soil survey (U.S. Geological Survey and Bureau of Land Management, unpublished data), and rock samples in which sphalerite and galena were identified by Nokleberg and Winkler (1982) also are shown in figure 5. Stream-sediment samples with anomalous concentrations of Zn (350–1,000 ppm) are spatially associated with rocks of the Kuna Formation (fig. 5; Kelley and others, 1996; Graham and Kelley, 2009). The highest concentrations of metals in stream sediments occur downstream from laminated sulfides along Drenchwater Creek (locality B, fig. 5) and along False Wager Creek. Additional multi-element, stream-sediment point anomalies occur in Twistem Creek southeast of Drenchwater (fig. 2); Zn-only anomalies occur locally outside of the study area (discussed in detail later in this paper).

Geophysical Survey Data-Acquisition and Inversion Methods

From June 13 to August 18, 2005, an airborne geophysical survey was flown over a large area in the NPRA (fig. 1) using the Dighem V airborne system. Flight lines were oriented N25E and spaced .125 mile (200 m) apart in the immediate Drenchwater area, with tie-lines flown perpendicular to flight lines at 1.5 mile (2,400 m) spacings. Outside the Drenchwater area, the flight-line spacing was .25 mile (400 m) apart. This survey was intended to provide detailed, densely sampled electrical-resistivity data of the uppermost 100–150 m of the subsurface. For the purposes of this paper, only the data from the Drenchwater area are evaluated. The map of apparent resistivity at 56,000 Hz in the Drenchwater area is shown in figure 7.

We created conductivity-depth (25–50 m depth) sections along each flight line using inversion procedures based on calculations that find the best match between measured EM data and theoretical data calculated for an earth resistivity model. The inversions were carried out by using EM1DFM software developed by the University of British Columbia (Farquharson and Oldenburg, 2000). The one-dimensional

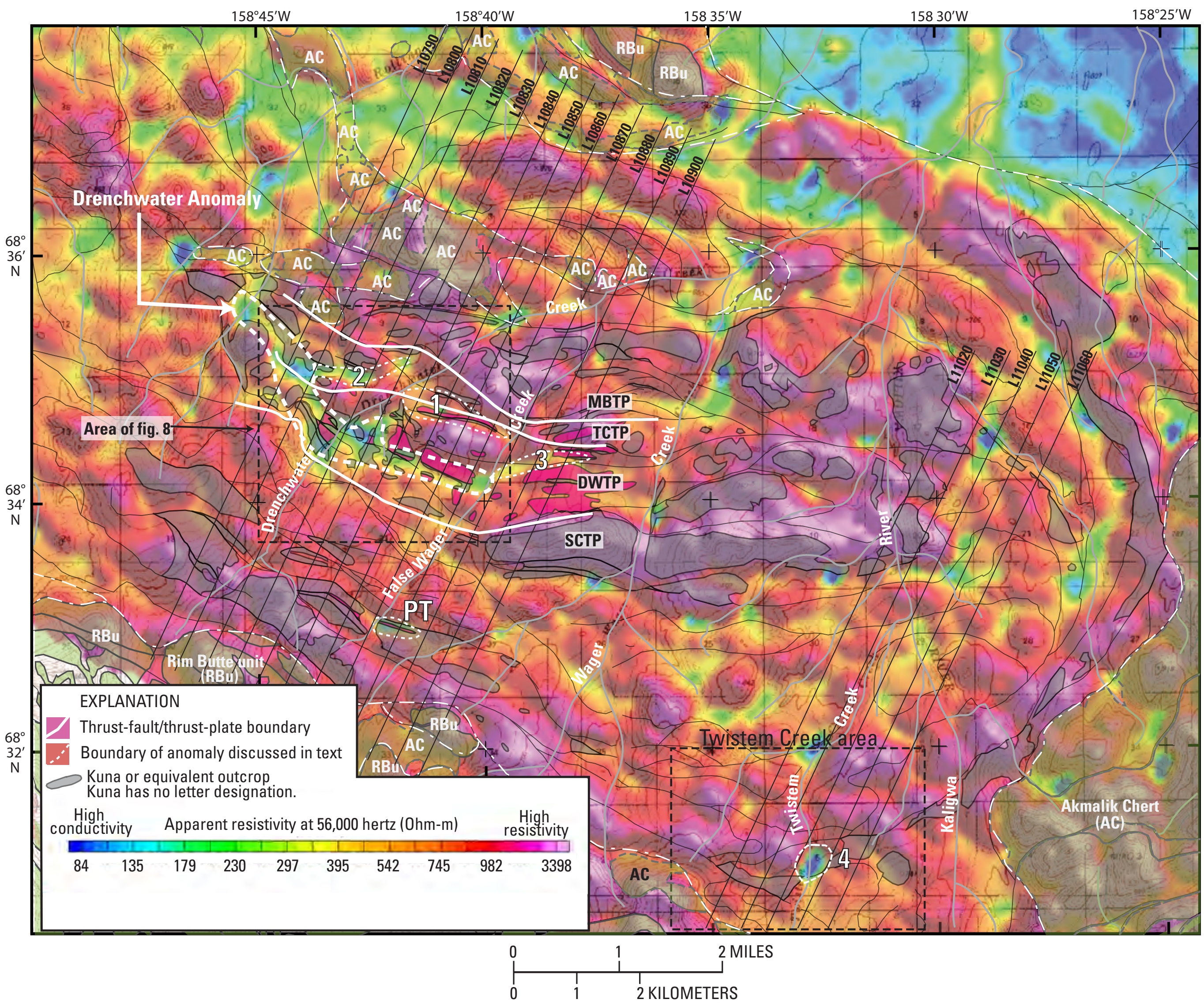

Figure 7. The 56,000 Hz resistivity survey showing contacts of selected units of each relevant allochthon, Drenchwater Creek study area, northern Alaska. Shaded units are: RBu, Rim Butte unit; AC, Akmalik Chert; unlabeled = Kuna Formation. Approximate allochthon boundaries are marked by white, long-short-dashed lines. Green and blue areas in the northern part of the figure are topographic lows. Note the Drenchwater anomaly (heavy white dotted line) and five other conductive areas (labeled 1, 2, 3, 4, and PT, for pyritic tuff). The significance of these anomalies is discussed in the text. Lines labeled with "L" as prefix are flight lines. 56,000 Hz resistivity data from Burns and others (2006).

inversion assumes that the layers are horizontal and of infinite extent. This approximation is most accurate providing dips of the strata are subdued (less than approximately 30 degrees) and lateral changes in conductivity are gradual. The inversions were carried out at every fiducial (that is approximately 3 m spacings along the flight lines). Detailed parameters of the inversion process are presented in appendix 1. The output of the inversions is presented as conductivity-depth sections, where the X-axis is the UTM northing, the Y-axis is the elevation above sea level (in meters); the conductivity values in each layer are shown as colors from blue (high conductivity) to red (low conductivity). The conductivity-depth profiles represent 25–50 m below ground surface.

Geophysical Survey Interpretation

Influences on Resistivity/Conductivity

The utility of the conductivity data from this survey is based on the observation that conductivity of materials is a function of the type, amount, and interconnectivity of conductive components within the materials. Differences in one or more of these parameters can lead to changes in measured conductivity, and therefore permit possible discrimination of different materials. Within the current study area, parameters that could cause high conductivity measurements include higher sulfide or carbon content, or wet cover. However, subtle variations may occur within a single parameter. For example, organic-rich shale is weakly conductive compared with highly conductive graphite, and among base-metal sulfide minerals, galena and pyrite are more conductive than sphalerite. Factors leading to lower conductivity include silicification, which destroys interconnectivity of conductive materials. Differences in conductivity may be inherent to the original rock and may characterize the entire stratigraphic interval (for example, organic-rich shale and pyritic shale), or be introduced locally within a unit, or by a feature that cross-cuts the stratigraphy (for example, silicification, hydrothermal sulfide formation, and graphite-bearing faulting).

Resistivity of Units and Anomalies

The data from the Drenchwater study area show significant variations in conductivity values (fig. 7). Generally, the deep-water units from the three allochthons—the Kuna Formation (unlabeled, shaded area), Akmalik Chert (AC), and Rim Butte unit on figure 7 (Dover and others, 2004)—have the lowest apparent conductivity (resistivity >2,000 Ohm-m). Each of these siliceous-to-chert-rich units commonly form prominent topographic highs, and therefore, these units tend to have only thin, dry soil/vegetative cover. The remaining units, including the tuff interbeds of the Kuna Formation, generally have intermediate conductivity ranges. Higher topographic expressions have slightly lower conductivity (similar to the deep-water units above), and rocks within lower relief regions have correspondingly higher conductivity. This trend indicates that moisture, along with mineral composition, significantly influences electrical resistivities of the underlying rock. The effect of water is prominent in the northeastern part of the study area, where bedrock is covered by wet tundra. The cause of the unusual, north-trending resistive zone in this covered area (northeast quadrant fig. 7) is not known.

There are many localized conductive zones and two larger, laterally extensive conductive zones within the EMA (fig. 7). Local conductive zones commonly occur immediately adjacent to or within streams and are only several hundred meters in maximum dimension. Some of these zones occur between flight lines and may be artifacts of gridding parameters (that is, gridded with an interval too small for data spacing). Larger anomalies that are defined by multiple flight lines are considered to be more robust.

The largest conductive zone is ~5 km long and is oriented normal to the general northeasterly stream drainage pattern and parallel to the strike of geologic units. This zone (hereafter termed the “Drenchwater anomaly” and delineated by the thick, dashed white line on figure 7) occurs primarily within the Kuna Formation and tuffaceous rocks of the Drenchwater thrust sheet of Nokleberg and Winkler (1982). A second parallel, more subtle anomaly (ellipse 1, fig. 7) is located northeast of the Drenchwater occurrence, where Kuna Formation shale and tuffaceous rocks are exposed immediately south of the thrust fault, with the TCTP to the north. The increased conductivity may be a product of increased tuff component and/or proximity to the thrust-plate boundary. Two additional weakly conductive zones are north and east-northeast from the Drenchwater anomaly. The first zone (ellipse 2) begins within the Drenchwater anomaly ~1 km northwest of Drenchwater Creek, extending >1.5 km to the east, following elevation contours. The second (ellipse 3) extends from the eastern end of the Drenchwater anomaly and cuts gradually across topography and the structural grain of the area up to the saddle that separates False Wager and Wager Creeks (fig. 7). A final narrow, weakly conductive zone occurs near the headwaters of False Wager Creek (ellipse PT) and is interpreted to identify the position of pyritic tuffs (Nokleberg and Winkler, 1982).

Comparison of the Drenchwater Anomaly to Surface-Sample Geochemistry

The base-metal-rich outcrops/rubblecrops at Drenchwater Creek, those at the discovery outcrop, and the mineralized volcanic rocks northeast of the discovery outcrop are aligned along a distinct 2.5-km-long linear portion of the Drenchwater anomaly (figs. 7 and 8). The moderately conductive zone (green and blue colors on fig. 7) corresponds spatially with the distribution of sulfide-bearing float and rubble-crop samples in this area (Nokleberg and Winkler, 1982; Werdon, 1996) and with elevated Pb concentrations in soils (775 to >3,200 ppm; Kurtak and others, 1995) in the 1-km-long, poorly exposed-to-covered area between the discovery outcrop and the volcanic breccia-hosted exposures (Area C on figs. 5 and 8). Width variations of the geophysical and Pb-geochemical anomalies correlate well. In contrast, there appears to be little correlation between elevated Zn concentrations in soils (>325 ppm) and conductive rock, with no elevated values west of Drenchwater Creek.

The Drenchwater geophysical anomaly extends at least 1.5 km west of Drenchwater Creek near the northern edge of the DWTP and southernmost TCTP near the apparent terminus of the thrust fault separating these plates and wholly within the DWTP farther to the east (fig. 7). Although only sparsely sampled, the western portion of the anomaly aligns with rocks containing anomalous concentrations of Pb (>0.1 wt percent; Kurtak and others, 1995). One soil sample containing elevated Pb (S1, 1,375 ppm Pb, fig. 8) is centered over the geophysical anomaly, approximately 1 km west of Drenchwater Creek. Less anomalous, but elevated Pb concentrations (>100 ppm) bracket this sample. A similar relationship exists along strike on the west bank of False Wager Creek. Here, a soil sample containing 805 ppm Pb (S2, fig. 8) coincides with conductive rock and marks the southeastern end of the Drenchwater geophysical anomaly. The weakly conductive east-northeast geophysical anomaly extends across False Wager Creek to the crest between False Wager and Wager Creeks (fig. 7), crosscutting faults mapped by Dover and others (2004). Two soil samples collected in the ridge saddle within this area contain slightly elevated Pb concentrations (110 and 320 ppm).

The narrow geophysical zone (ellipse PT, fig. 7) near the headwaters of False Wager Creek, and centered over pyritic tuff, is characterized by rock and stream sediments that have elevated Pb concentrations (70 and 104 ppm) and elevated Tl concentrations, but lack elevated Zn concentrations (Graham and others, 2009).

Inversion Subsurface Modeling

Inversions of electromagnetic data permit subsurface-conductivity modeling to depths of 25–50 m along individual flight lines (figs. 8 and 9). This shallow depth limits our ability

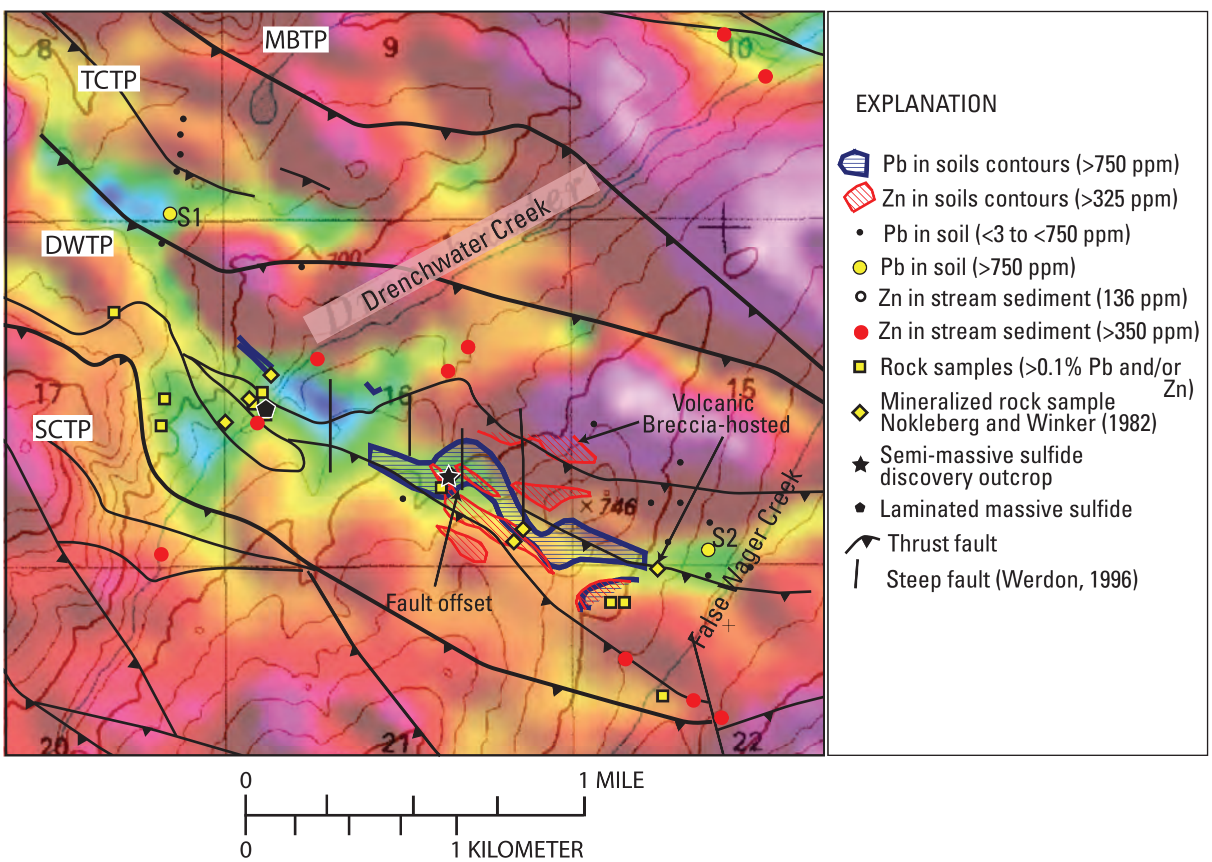

Figure 8. Map showing geochemically anomalous samples from figure 5 and the 56,000 Hz resistivity map in the immediate vicinity of the Drenchwater Creek anomaly, northern Alaska. 56,000 Hz resistivity data from Burns and others (2006).

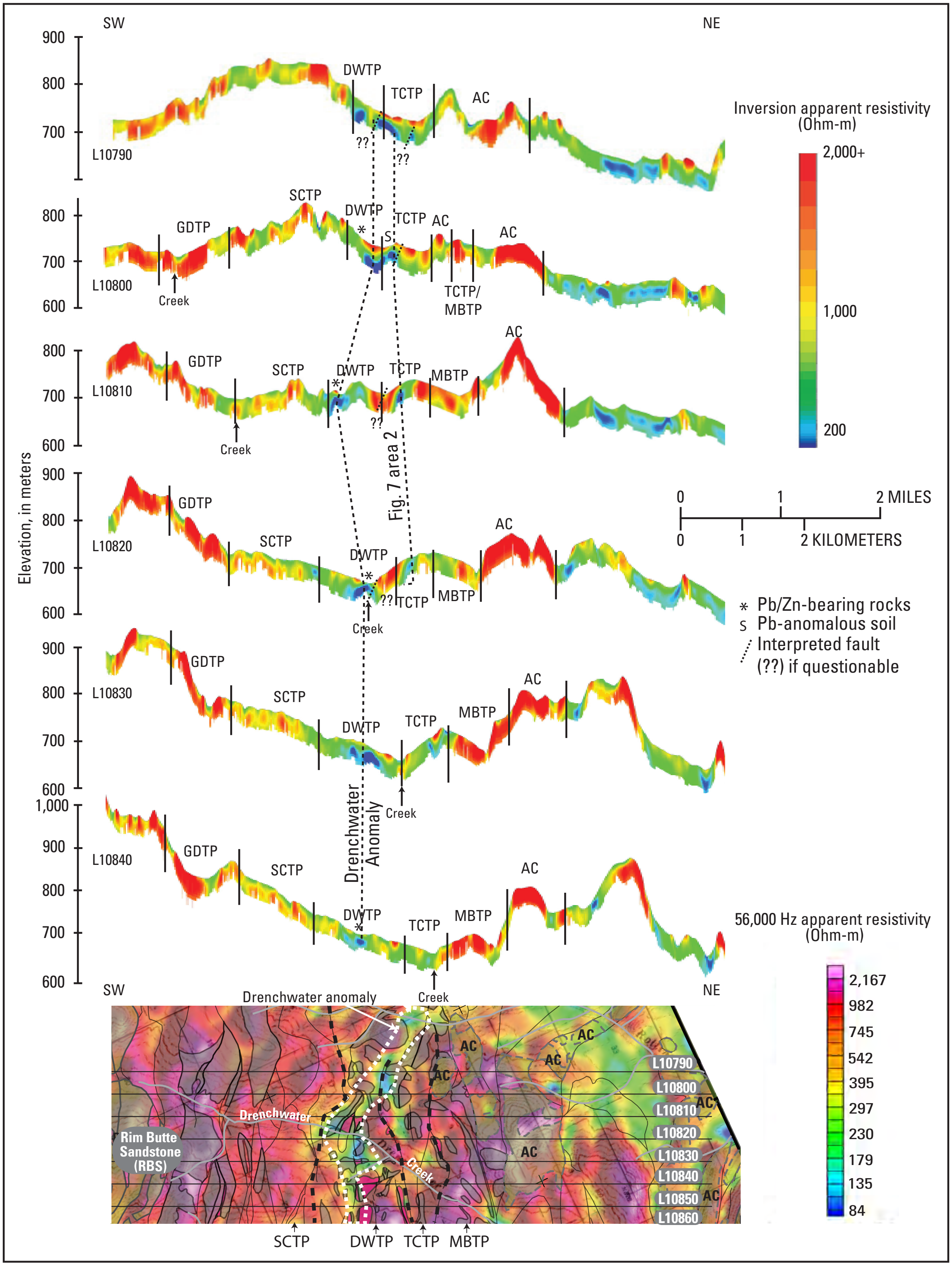

Figure 9. Western Drenchwater Creek area flight lines with inversion-model profiles, showing the Drenchwater thrust-sheet boundaries and the location of Akmalik Chert in the immediate vicinity of mineralization, Drenchwater study area, northern Alaska. MBTP, Mother Bear thrust plate; GDTP, Gas Drum thrust plate; SCTP, Spike Camp thrust plate; DWTP, Drenchwater thrust plate; TCTP, Two Cubs thrust plate; AC, Akmalik Chert; S, location of anomalous soil sample; *, mineralized outcrop location. 56,000 Hz resistivity data from Burns and others (2006).

to establish the true vertical extent of conductive zones in the subsurface; in some cases surface features (for example, streams and wet cover) also complicate our interpretation. Nevertheless, the modeling is consistent with the mapped geology and provides at least a lateral and vertical resolution of the Drenchwater conductive zone in shallow subsurface.

West of Drenchwater Creek (fig. 9, flight lines L10790 and L10800), multiple conductive zones (greens and blues on fig. 9) occur on the DWTP and on the TCTP. In the profiles, these zones have apparent widths of >200 m and appear as discrete bodies 10–15 m beneath more geophysically resistive material. Whereas these zones are, in part, spatially associated with the apparent near-terminus of the plate-bounding fault between the DWTP and TCTP, the large width of the zones, presence of an overlying resistive layer, and absence of spatial association of zones with faults farther to the east suggests a mineralogical control on the high conductivity. The highest Pb concentration measured in soils from this area occurred directly over the shallowest portion of the conductive zone (marked S on section L10800).

The geophysical anomaly is shallower and is near ground surface just west of Drenchwater Creek (flight line L10810) in an area of mixed Kuna Formation and tuff and, within Drenchwater Creek, the anomaly position coincides with outcropping sulfides (flight line L10820). The conductive zone does not correlate with pyritic felsic tuff, which has intermediate conductivity properties. The anomaly broadens out immediately east of Drenchwater Creek in an area with no geochemical data, and then forms a point anomaly (<200 m wide) directly beneath the Discovery outcrop (star, line 10840). Further east, the width and apparent vertical extent of the conductive zone decreases significantly (except L10870 in fig. 10). Elevated Pb concentrations in soils continue to correspond with higher measured conductivities (fig. 10).

Several shorter and/or less intense conductive anomalies are resolvable in the inversion-model profiles of the study area outside of the Drenchwater anomaly and are more distinct than in the apparent resistivity maps. The narrow (<50 m) anomaly coincides with thin outcrops of felsic tuff along the northern edge of the Drenchwater thrust sheet (ellipse 1 in figs. 7 and 10) and probably records the conductivity contrast between tuff (moderate) and the Kuna Formation (higher), possibly influenced by proximity to the thrust boundary. Farther south, a strong anomaly on False Wager Creek is coincident with a strongly pyritic tuff (figs. 7 and 10). Shallow conductive anomalies are evident in sulfide-bearing chert (pyritic chert) southeast of the pyritic tuff in flight lines L10880–L10900 (fig. 10; Nokleberg and Winkler, 1982).

Application to Twistem Creek

Twistem Creek flows through the southern-most exposure of the Kuna Formation, southeast of the Drenchwater prospect (fig. 7). Selected stream-sediment samples near exposures of the Kuna Formation contain elevated Zn concentrations (>500 ppm), and multiple stream-sediment samples and a single soil sample from the Twistem Creek area contain elevated Tl concentrations in addition to multiple base-metal anomalies, similar to those found in proximity to Drenchwater Creek (Kelley and others, 1992; Graham and others, 2009). Despite these geochemical similarities, no mineralized rock has been reported from the Twistem Creek area; sulfide mineralization may not have been fully exposed.

A small conductive zone occurs on Twistem Creek (ellipse 4 in fig. 7). The inversion model (Line 11040, fig. 11) indicates that the conductive zone is at the surface (within the creek) and within Etivluk Group rocks that conformably overlie the Kuna Formation (fig. 11). The anomaly does not extend to other flight lines, but does occur within the Kuna Formation, immediately upstream of a stream-sediment sample with anomalous Zn. These results are inconclusive, but suggest that while there may be evidence for a local conductive zone (possibly due to sulfides) at Twistem Creek, there is no large conductive zone in the shallow subsurface (up to 50 m?) analogous to that at Drenchwater Creek.

Discussion

Exposed sulfide-bearing rock along Drenchwater Creek and near the discovery outcrop (figs. 4 and 5) correlate strongly with conductive responses from the geophysical survey. By inference, conductive responses in covered areas are most likely due to the presence of sulfide minerals. Furthermore, the close spatial association of the geochemical and coincident geophysical anomalies with the Kuna Formation mudstones (and age equivalent tuffaceous rocks) suggests the presence of stratabound massive sulfides similar to the base-metal deposits at Red Dog. Elevated Pb with and without corresponding high Zn concentrations in soils may be a good indicator of underlying sulfide mineralization. The poor correlation between high Pb and high Zn concentrations in soil samples could be interpreted to preclude the presence of buried, Zn-rich rocks. Kelley and Hudson (2007), however, demonstrated that soil samples collected over similar Zn-dominated deposits hosted in the Kuna Formation in the Red Dog district contained high Pb concentrations (mostly hundreds to thousands of ppm) and low Zn concentrations (all but one value <400 ppm) with Pb/Zn ratios as high as 70 in shallow soil samples (top 30–40 cm). This disparity in base-metal contents is attributed to the fact that under acidic conditions generated during weathering of pyrite-bearing massive sulfide, sphalerite is preferentially dissolved and Zn is mobilized (Kelley and Hudson, 2007). Thus, the high concentrations of Pb (up to >3000 ppm) without corresponding Zn at Drenchwater does not preclude the presence of underlying base-metal sulfides and appears to be more effective than Zn in delineating the bedrock source of mineralization.

Morin (1997) interpreted the strong gradients in the gravity and magnetic surveys in the immediate vicinity and east of the discovery outcrop as support for the presence of a

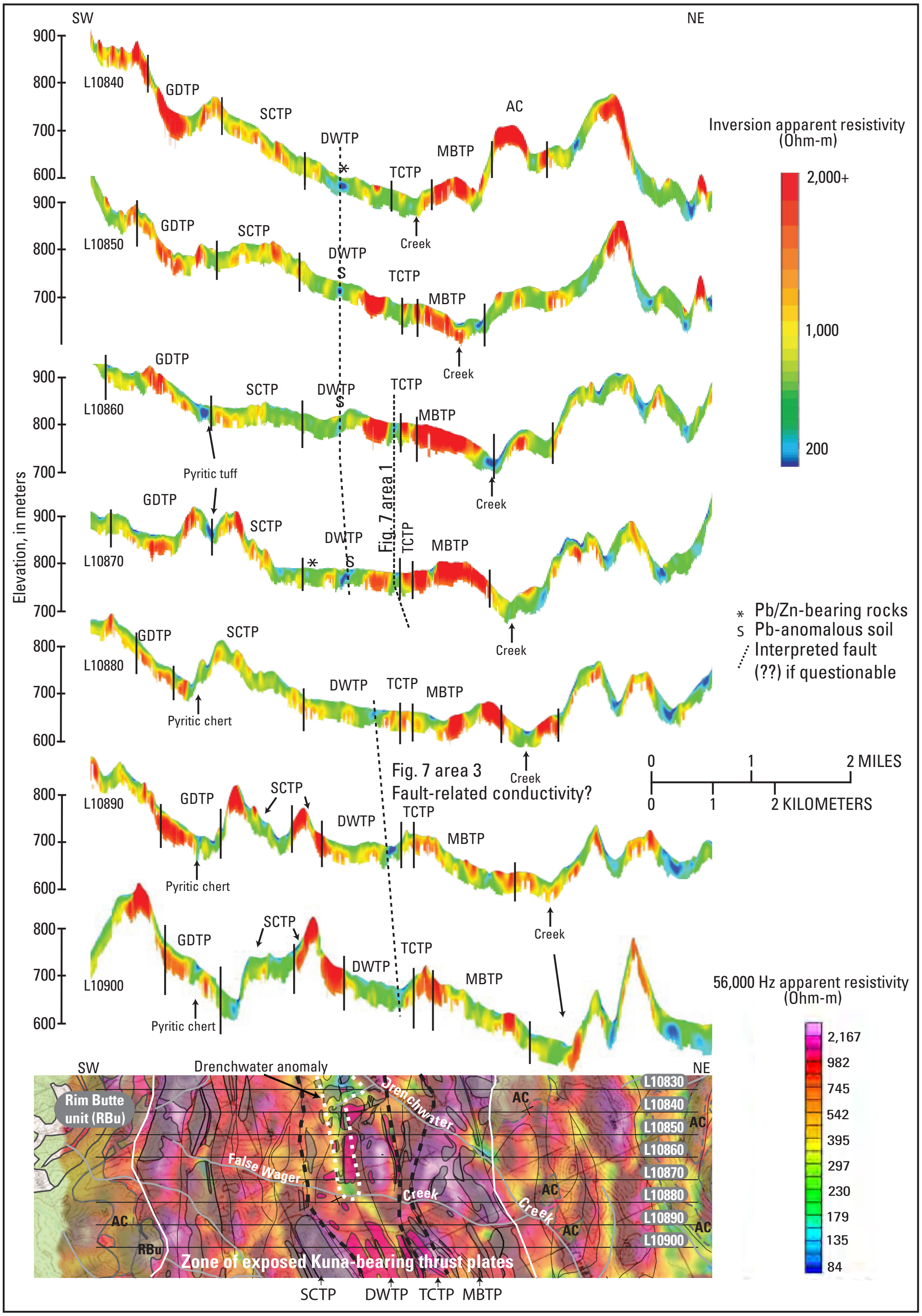

Figure 10. Eastern Drenchwater Creek area flight lines with inversion model profiles, Drenchwater study area, northern Alaska. MBTP, Mother Bear thrust plate; GDTP, Gas Drum thrust plate; SCTP, Spike Camp thrust plate; DWTP, Drenchwater thrust plate; TCTP, Two Cubs thrust plate; AC, Akmalik Chert; S, location of anomalous soil sample; *, mineralized outcrop location. 56,000 Hz resistivity data from Burns and others (2006).

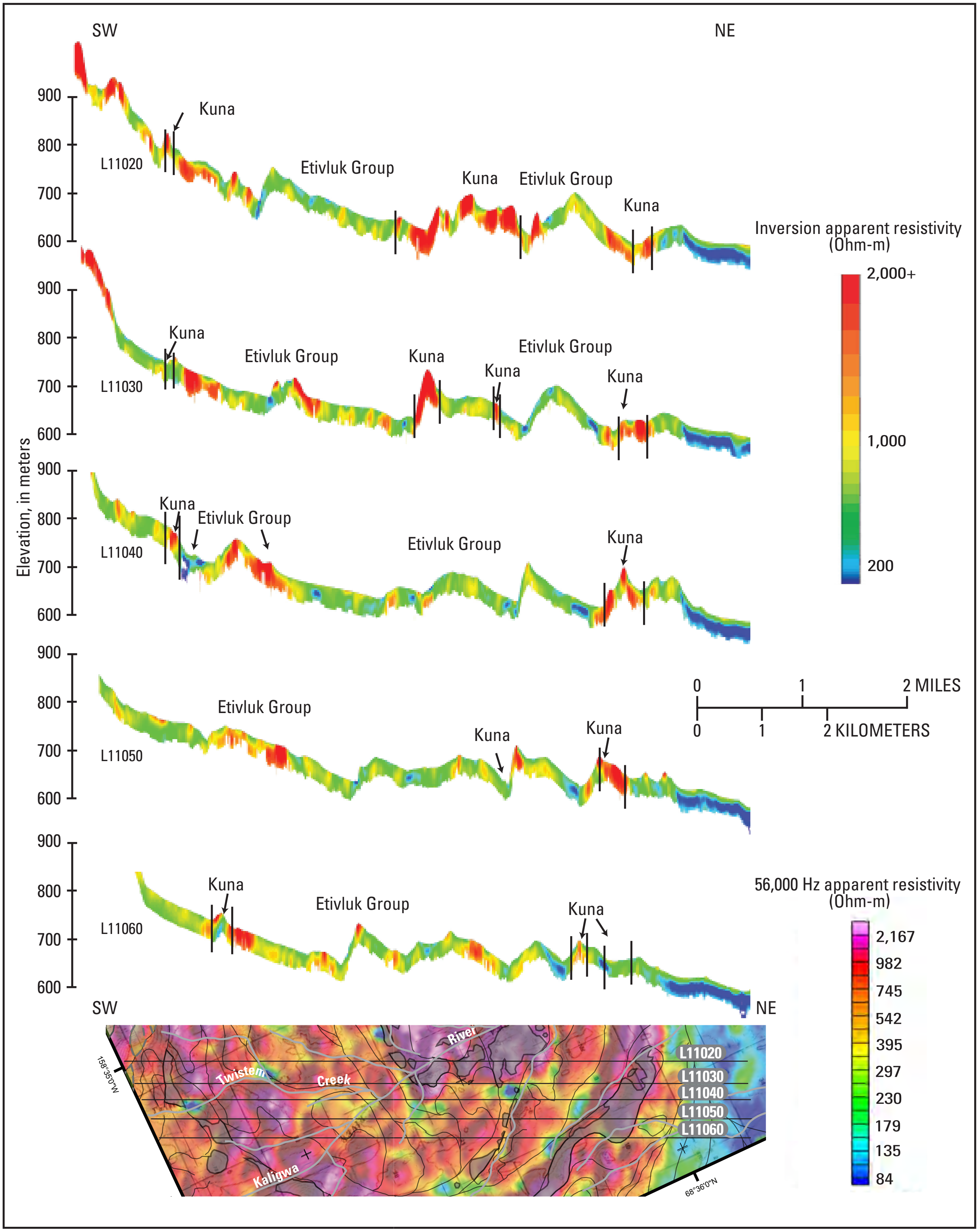

Figure 11. Twistem Creek area flight lines with inversion model profiles, Drenchwater Creek study area, northern Alaska. Note the inconsistent conductivity, which plots within the overlying light green Etivluk Group rocks (line L11040) and at the contact of Kuna and Etivluk Group rocks (line L11060). Intensity of conductive zone may be partially a product of wide line-spacing relative to anomaly size. 56,000 Hz resistivity data from Burns and others (2006).

north-oriented high-angle fault as mapped by Werdon (1996). He proposed an apparent offset of 150 m north for the eastern block. This geophysical signature is consistent with both the Pb values in soils and the weak conductivity gradients in the 2005 EM survey, which appear to deflect to the north in the general area of proposed faults (fig. 8).

Resistivity cross-sections from inversions provide important insights into the vertical position of the top of the conductive zones that are not obvious in the apparent resistivity plan-view map. Both map types illustrate the narrow conductive zone that links known mineralized outcrops, and the Pb-soil anomalies show that broader, higher conductivity zones in the shallow subsurface occur at and westward from the Drenchwater-discovery outcrop. Although indiscernible in plan view, the inversion models suggest that whereas east of Drenchwater Creek the zones are narrow and apparently reach the surface, to the west, the zones are overlain by at least several meters of less conductive (possibly unmineralized) rock (figs. 9 and 10). Rock samples adjacent to the geophysical anomaly that possibly represents weak mineralization contain slightly elevated Pb concentrations; the single soil sample from that area with anomalous Pb concentration was collected directly over the shallowest depth of the anomaly (L10800, fig. 9). Although inconclusive, these data are consistent with the interpretation of buried sulfide-mineralized rock west of Drenchwater Creek, outside of the focal area of previous studies.

Interpretation of other geophysical or geochemical anomalies is more precarious than the Drenchwater anomaly because of the lack of sufficient geochemical samples to corroborate the geophysical response. As previously noted, there are numerous “point” geophysical anomalies of small areal extent, commonly within or adjacent to stream beds and possible faults, which may simply be artifacts of data gridding, or may be because of saturation of the sediments and/or fracture zones. In the case of the Twistem Creek area, the stream-sediment and geophysical anomalies are small relative to the scale of the geophysical survey.

The anomalous geophysical signatures, like those at Twistem Creek that have corresponding nearby stream-sediment chemical anomalies, remain unexplained. Although there is no direct evidence of in-place base-metal sulfides at Twistem Creek, follow-up investigations in the area are warranted.

Conclusions

The 2005 airborne EM survey provides important information about the resistivity properties of the rocks of the Drenchwater area. Combined with geologic and geochemical data, the following conclusions can be made:

(1) The Kuna Formation, Akmalik Chert, and Rim Butte unit, Carboniferous deep-water strata that have been interpreted to be lateral temporal equivalents within the Kuna Basin, all have low conductivity. Younger rocks generally are more conductive. Intraformational variations in resistivity are likely due to lithologic changes (for example, changes in silica content that can correlate with topography; increase in diagenetic pyrite, with or without base metal sulfides; and saturation by surface and groundwater owing to proximity to streams and/or faults).

(2) A >3 km-long, generally east-west- trending conductive zone at Drenchwater coincides with scattered surface exposures of Zn-Pb mineralization and adjacent soils with anomalous concentrations of Pb and Zn and is interpreted to reflect the presence of sulfide mineralization. Lead, rather than Zn, is the more effective pathfinder element in soil samples over the anomaly, consistent with previous observations at sediment-hosted Zn-Pb-Ag deposits in Alaska. Delineation of the Drenchwater anomaly probably is enhanced by the high (topographically) and dry nature of the immediate area. A near-surface wet horizon might serve to mask subsurface mineralized zones.

(3) The highest conductivity along the Drenchwater anomaly occurs west of Drenchwater Creek, where inversion models to 25–50 meters below the surface indicate that the conductive zone is overlain by a thin resistive horizon. This western area, which accounts for nearly 50 percent of the length of the Drenchwater geophysical anomaly and is characterized by high conductivities, was outside of the main scope of previous studies and may have the highest potential for base-metal mineralization.

(4) The vertical extent of the Drenchwater anomaly is poorly constrained, and while the results presented in this paper provide a guide for testing for base-metal mineralization at Drenchwater, newer EM methods (for example, time-domain survey using HeliGEOTEM) might be more effective for inversion modeling to greater depths. Slightly deeper-buried sulfide mineralization, such as that potentially manifested at Twistem Creek, cannot be resolved by the methods we employed in this paper.

The conductive nature of the Drenchwater geophysical anomaly and its correspondence to the footprint of much of the mineralized rock at Drenchwater lends support to interpreting the EM data outside of these areas. The base-metal content of the rocks that produce the Drenchwater anomaly (and subsidiary anomalies) remains untested in the subsurface and can only be assessed by direct sampling (that is, drilling). However, the geophysical data indicate that mineralization may be considerably more extensive than the outcrop and geochemical anomalies suggest.

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Appendix. EM1DFM Inversions

Using the program EM1DFM, one-dimensional layered-earth inversions were done using these data. This program inverts for conductivities of a user-specified number of layers with fixed, user-specified thicknesses that are constant throughout the survey. The layers used for the Drenchwater area inversions were:

Upper depth(m)	Lower Depth(m)	Thickness(m)
0	-1.37709	1.37709
-1.37709	-2.93876	1.56167
-2.93876	-4.70975	1.77099
-4.70975	-6.71812	2.00837
-6.71812	-8.99568	2.27756
-8.99568	-11.5785	2.58284
-11.5785	-14.5076	2.92903
-14.5076	-17.8292	3.32163
-17.8292	-21.5960	3.76684
-21.5960	-25.8678	4.27174
-25.8678	-30.7121	4.84430
-30.7121	-36.2057	5.49361
-36.2057	-42.4356	6.22996
-42.4356	-49.5006	7.06500
-49.5006	-57.5126	8.01196
-57.5126	-66.5984	9.08585
-66.5984	-76.9021	10.3037
-76.9021	-88.5868	11.6847
-88.5868	-101.838	13.2509
-101.838	-116.865	15.0270
-116.865	-133.906	17.0412
-133.906	-153.231	19.3253
-153.231	-175.147	21.9156
-175.147	-200.000	24.8531
-200.000	-250.000	50.0000

Underlying the deepest layer is a uniform half-space.

The one-dimensional inversion assumes that the layers are horizontal and of infinite extent. This approximation holds quite well, providing that dips of the strata are relatively subdued (less than ~30 degrees) and lateral changes in conductivity are gradual.

The inversions were carried out at every fiducial (that is, ~3m spacings along the flight lines).

The output of the inversions is presented as conductivity-depth inversion (CDI) sections, where the X-axis is UTM northing (except UTM easting for Block D), Y-axis is elevation above sea level (in meters) and the conductivity values in each layer are shown colored from blue (low resistivity) to red (high resistivity).

Inversion Parameters

The data from frequencies (viz. 55,500, 7,323, 871, 1,115 and 5,660 Hz) were used in the inversion. The errors applied to the data during the inversion were 40, 20, 10, 10, and 10 ppm for the frequencies mentioned above or 4 percent relative error, with the higher of these applying in each individual frequency.

Other EM1DFM inversion parameters used were:
Model type—Conductivity only
Start model—0.001 S/m
Reference model—0.005 and 0.001 S/m (see below)
Background susceptibility model—0.0
Inversion type—Fixed trade off with B=10
Max iterations—15
Tolerance—0.001
acs—0.001
acz—1

Depth of Investigation

As the depth increases, there is less signal to constrain the inversion because the response diminishes by the cube of the distance from the conductive layer to the EM bird (~30 m above ground), and the computed conductivities trend more to the reference model. The reference model used was a constant conductivity for all layers (that is, a uniform half-space).

Two different start/reference models were used to investigate the depth of investigation of the EM survey, using the method described by Oldenburg and Li (1999). The uniform conductivity values used were 0.001 and 0.005 S/m, respectively. Near the surface the conductivities defined by the two inversions are similar, but at greater depths the conductivities diverge as the response becomes dominated by the reference model. The depth at which the calculated conductivities using the two reference models start to diverge, significantly provides a measure of the depth of investigation, or DOI.

A factor, *R*, was calculated to quantify the measure of divergence:

R=abs (Cond_Refp004-Cond_Refp001)/(Refp004+ Refp001)*100%,

where:
Cond_Refp005 is the conductivity of a layer calculated using reference model 0.004 S/m
Cond_Refp001 is the conductivity of a layer calculated using reference model 0.001 S/m
Refp005 is the conductivity of a first reference model: 0.005 S/m, and
Refp001 is the conductivity of the reference model 0.001 S/m g reference model 0.001 S/m.

Values where the above difference was higher than 30 percent were rejected. This formulation is different from the later method of quantifying the depth of investigation developed by Burke Minsley (USGS, oral commun.). The later estimate of the depth of investigation also was tested, but it resulted in a deeper section that seemed to obscure the interpretation.

References

Oldenburg, D.W., and Li, Y., 1999, Estimating depth of investigation in DC resistivity and IP surveys: Geophysics, v. 64, no. 2, p. 403–416.

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