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GIS-Based Identification of Areas that have Resource Potential for Sediment-hosted Pb-Zn deposits in Alaska

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By Karen D. Kelley, Garth E. Graham, Keith A. Labay, and Nora B. Shew

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

Abbreviations

ADGGS	Alaska Division of Geological and Geophysical Surveys
AGDB	Alaska Geochemical Database
ARDF	Alaska Resource Data File
BLM	Bureau of Land Management
CD	clastic-dominated
EM	electromagnetic
GIS	Geographic Information System
HMC	heavy-mineral-concentrate
HUC	hydrologic unit code
MTV	median topsoil value
MVT	Mississippi Valley Type
NGDB	National Geochemical Database
NURE	National Uranium Resource Evaluation
ppm	parts per million
SEDEX	Sedimentary Exhalative
USBM	U.S. Bureau of Mines
USGS	U.S. Geological Survey
VMS	volcanogenic massive sulfide

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Abstract

A state-wide Geographic Information System (GIS) analysis was conducted to assess prospectivity for lead (Pb) and zinc (Zn) in sediment-hosted deposits in Alaska. The datasets that were utilized include publicly available geospatial datasets of lithologic, geochemical, and mineral occurrence data. Key characteristics of Pb-Zn deposits were identified in available datasets and scored with respect to relative importance. To evaluate resource potential, drainage basins of the smallest size were chosen, each of which covers approximately 100 square kilometers (km^2). Drainage basins are the most logical and efficient unit for evaluation because the most regionally robust dataset comes from stream sediment geochemistry.

Sediment-hosted Pb-Zn deposits in Alaska include those contained in carbonate rocks (similar to Mississippi Valley Type or MVT deposits) and those contained in clastic-dominated (CD) sequences (CD Pb-Zn), historically referred to as SEDEX (sedimentary exhalative). The latter include the deposits currently being mined in the Red Dog district in the western Brooks Range. Host rocks for the two subtypes are distinct: carbonate versus fine-grained clastic rocks for CD Pb-Zn deposits. However, there are exceptions: some CD Pb-Zn deposits are hosted in carbonate layers within a thick clastic-dominated rock sequence. The statewide geologic map database contains units that commonly include mixed carbonate-clastic sequences that cannot be subdivided. The most significant difference between the two deposit types is their respective depositional environments and tectonic settings, but at the reconnaissance level of mapping in most areas of the state, these distinctions are not possible. Furthermore, nearly all critical geochemical parameters (silver [Ag], barium [Ba], Pb, Zn) are common to both types, and therefore it was not possible to do separate assessments for carbonate-hosted and CD Pb-Zn deposits.

Areas identified that have moderate to high potential for sediment-hosted Pb-Zn deposits include the (1) western and central Brooks Range, referred to in this report as the Brooks Range zinc belt; (2) Seward Peninsula (and adjacent St. Lawrence Island); (3) Farewell terrane in Interior Alaska; (4) two spatially distinct belts in east-central Alaska; and (5) the central Alaska Range. All areas contain some known deposits, and that provides credibility to the scoring process. Some hydrologic unit codes (HUCs) that have high potential for sediment-hosted Pb-Zn deposits are located adjacent to areas of known deposits and indicate the potential for expansion of known Pb-Zn districts. There are a few areas that have high potential but contain no known sediment hosted Pb-Zn occurrences, prospects, or deposits. In such areas, future investigations could be focused on better defining and constraining prospectivity with additional data.

Introduction

On a global scale, stratabound and stratiform sediment-hosted Pb-Zn deposits contain the world's largest resources of lead (Pb) and zinc (Zn) and dominate world production of these metals. They are a diverse group of ore deposits hosted by a wide variety of carbonate, siliciclastic, and metasedimentary rocks that have no obvious genetic association with igneous activity (Leach and others, 2005). Classification of these deposits has traditionally included process-related, interpretive, and model-driven features. For example, as traditionally used, the term SEDEX indicates deposits formed by synsedimentary exhalative precipitation on the seafloor, whereas many deposits classified as SEDEX were formed by diagenesis, or epigenetic replacement of carbonates (for example, the Anarraaq deposit in Alaska; Kelley and others, 2004). The term SEDEX is replaced by "Clastic dominated Pb-Zn" or "CD Pb-Zn deposits" in this report because it is descriptive (Leach and others, 2010a) and refers to deposits that are hosted within a clastic-dominated sedimentary rock sequence without any implication of ore-forming processes.

Sediment-hosted Pb-Zn deposits in Alaska include two primary types: (1) CD Pb-Zn deposits, which are hosted in shale, sandstone, siltstone, or mixed clastic rocks, or occur as carbonate replacement within a clastic dominated sedimentary rock sequence (Leach and others, 2010a); and (2) carbonate-hosted deposits. Some of the sediment-hosted deposits are in metasedimentary rocks. For example, deposits on the Seward Peninsula were deformed and metamorphosed to blueschist facies and then retrograded to greenschist facies; however, geochemical and geologic characteristics of these occurrences are consistent with formation in a synsedimentary or early diagenetic environment (Slack and others, 2014; Till and others, 2014). Carbonate-hosted Pb-Zn deposits in Alaska lack spatially or genetically associated igneous rocks and are, in that sense, similar to classic Mississippi Valley Type (MVT) deposits, but they also differ in many aspects.

Sediment-hosted Pb-Zn deposits are a major contributor to Alaska's economy, largely through production from the CD Pb-Zn Red Dog mine, which began in 1990 and has continued to the present. Although carbonate-hosted deposits in Alaska have not had significant production, the moderate grades and large tonnages typical of global examples combined with Alaska's large areas of favorable or permissive host rocks make them an attractive exploration target in the state. This statewide data-driven Geographic Information System (GIS) analysis is designed to assess areas of known sediment-hosted Pb-Zn mineralized areas and to extrapolate to areas of cover. The analysis uses multiple data layers to evaluate the geologic setting, lithology, pathfinder element enrichments, and geochemical favorability of hydrologic units.

Purpose and Scope

The GIS analytical method is applied herein to identify areas with geologic potential for sediment-hosted Pb-Zn deposits in Alaska. It is not a comprehensive review of known mines, prospects, occurrences, or mineral deposits that contain these commodities. Instead, it is an evaluation of the locations of perspective areas based on geoscientific data and features such as geology (for example, lithology, mineralogy, known prospects) and geochemistry (of stream sediment and heavy mineral concentrate samples).

Sediment-hosted Pb-Zn deposits were chosen for evaluation because they are a major focus for exploration and development in Alaska and important to Alaska's economy. Data-driven, objective GIS analysis allows relative potential for Pb and Zn resources in geologic tracts to be modeled, and if integrated with other types of geospatial data, to inform land-use decisions from a practical and regional perspective. At the same time, this analysis can be useful for guiding exploration for these important commodities.

Based on similar dominant characteristics of the two subtypes of sediment-hosted Pb-Zn deposits (described below) and on recent research that suggests that both types of deposits formed from sedimentary brines with similar temperatures and ore depositional paths (Leach and others, 2010a), it is not possible to clearly separate these two deposit types in a statewide assessment. The most significant difference between carbonate-hosted and CD Pb-Zn deposits is their depositional environment, which is determined by their respective tectonic settings. In some poorly studied regions of Alaska, making such a distinction is not possible. Furthermore, the reconnaissance level of regional-scale geologic mapping and geochemical data collection typically provide insufficient detail to target one subtype versus the other. Therefore, this assessment of Pb-Zn deposits combines the two types. However, if sufficient evidence is present in a region (due to an abundance of known deposits of a specific subtype or to a known depositional setting) to suggest one subtype versus the other, distinctions are noted.

Sediment-hosted Pb-Zn Deposit Definitions

A strong understanding of the fundamental geologic and geochemical processes operating in individual geologic environments, the sources of fluids available, the host rock compositions, and the potential chemical and physical traps are necessary components of prospectivity analysis or resource potential modeling. These essential components are described below for carbonate-hosted and CD Pb-Zn deposits. Many of the Pb-Zn deposits in Alaska that are carbonate-hosted without spatially associated igneous rocks have been called MVT deposits in the literature, although they have characteristics that set them apart from typical MVT deposits, and the lack of study of most of the Alaskan occurrences precludes definitive classification as MVT deposits. Therefore, throughout the text, these are referred to as carbonate-hosted deposits, but comparisons to the MVT model are important for understanding their origin.

Carbonate-hosted Deposits

Carbonate-hosted Pb-Zn MVT deposits are found throughout the world but are most abundant in North America and Europe (Leach and others, 2005). The name derives from the fact that several classic districts are located within the drainage basin of the Mississippi River in the central United States. Early models for MVT deposits were diverse, calling upon ore formation by dilute meteoric groundwater, magmatic, or connate fluids, and invoking processes that ranged from synsedimentary-exhalative to supergene activity involving meteoric water. Early models assumed that MVT deposit formation had no connection to tectonic processes, but in the past 20–35 years, fluid inclusion, geochronologic, and other geologic studies showed that MVT ores form from basinal fluids derived from evaporated seawater that are driven into platform carbonates by large-scale tectonic events (Leach and others, 2010b). In particular, Leach and Rowan (1986) recognized that orogeny led to continental-scale flow systems critical in generation of MVT deposits in the Ozark region of the United States. The role of tectonism is further demonstrated in the abundance of Phanerozoic deposits (which comprise >80 percent of known MVT deposits globally) that formed during distinct time periods in Earth history. Two major periods include the Devonian to Permian (which corresponds to tectonic events during the assimilation of Pangea) and the Cretaceous to Tertiary, when microplate assimilation affected the western margin of North America (Leach and others, 2010a).

Nearly all MVT deposits are hosted in platform carbonate sequences and usually located at the flanks of basins, orogenic forelands, or foreland thrust belts inboard of the clastic rock-dominated passive margin sequences (Leach and others, 2010b). Deposits in dolostone are relatively more abundant than those hosted in limestone, and dolostone-hosted deposits are generally larger and contain higher Pb, Zn, and silver (Ag) grades (Leach and others, 2005). It is now widely accepted by most researchers of MVT deposits that there is no genetic association with igneous rocks (Leach and others, 2005; 2010b). Abundant evidence has shown that the ore fluids in MVT deposits were derived mainly from evaporated seawater and were driven within platform carbonates by large-scale tectonic events (Leach and others, 2010b). The most important ore controls were faults and fractures, dissolution collapse breccias, and lithologic transitions.

Most MVT deposits have a simple mineralogy, consisting primarily of sulfide minerals that are dominated by sphalerite, galena, and iron sulfides. Barite may be present in minor to trace amounts and fluorite is rare (Leach and others, 2005). The most common alteration associated with MVT deposits is dissolution and hydrothermal brecciation of the carbonate host rocks. Silicification is present in some deposits (Leach and others, 2005). Trace elements typically associated with these deposits include Ag, arsenic (As), barium (Ba), cadmium (Cd), cobalt (Co), gallium (Ga), germanium (Ge), indium (In), manganese (Mn), antimony (Sb), and thallium (Tl). Spatially associated deposit types include CD Pb-Zn, sandstone-hosted Pb deposits and fracture-controlled Pb-Zn and fluorite-barite deposits (Leach and others, 2010b).

Carbonate-hosted deposits in Alaska have characteristics similar to worldwide MVT examples, such as a simple mineralogy, low Fe sulfide content, no apparent igneous association, partial dolomitization or silicification of wall-rock limestone, and variable barite and fluorite contents (Schmidt, 1997b). The closest analogs to MVT deposits include the Reef Ridge deposit in the Medfra 1°×3° quadrangle and deposits in the Charley River and Livengood areas of east-central Alaska (Schmidt, 1997b). Other occurrences in the Brooks Range (for example, Powdermilk) lack well-developed karst or solution collapse features (brecciation), or they are Cu-rich (Frost and Omar) compared to many MVT deposits, and therefore, may not be MVT deposits strictly speaking. Known occurrences, prospects, and deposits of this class are listed in table 1, and more detail on Alaskan deposits will be provided in sections that follow.

CD Pb-Zn Deposits

Originally termed SEDEX deposits, CD Pb-Zn deposits (Leach and others, 2010a) are widely distributed worldwide but are most common in North America, Australia, and Asia. Early models for CD Pb-Zn deposits called upon formation by metalliferous fluids exhaling onto the ocean floor, depositing sulfide minerals in a brine pool, resulting in sulfides interbedded with euxinic marine black sedimentary rocks (Model 31a; Cox and Singer, 1986). The main distinction between CD Pb-Zn and MVT deposits in early models was in the timing of deposition and textural differences. However, the distinction between some CD Pb-Zn and MVT deposits can be subjective, because some CD Pb-Zn ores replaced sediments in an early or burial diagenetic environment, whereas some MVT deposits formed in an early diagenetic environment and display laminated ore textures (Leach and others, 2005). Furthermore, new literature has shown that CD Pb-Zn deposits may form in non-euxinic marine environments (Slack and others, 2017; Johnson and others, 2018). Recent research suggests that both MVT and CD Pb-Zn deposits formed from sedimentary brines with similar temperatures and ore depositional paths (Leach and others, 2010a). Therefore, the most significant difference between MVT and CD Pb-Zn deposits is their depositional environment, which is determined by their respective tectonic settings. CD Pb-Zn deposits form in passive margin settings, continental rifts, continental sag basins, and back-arc basins (Leach and others, 2005). The contrasting tectonic setting also dictates the fundamental deposit attributes that generally set them apart, such as host rock lithology, deposit morphology, and ore textures.

CD Pb-Zn deposits are hosted by a wide variety of rock types that include shale, carbonate, and organic-rich and calcareous clastic rocks such as siltstone and less commonly sandstone- and conglomerate-rich sequences (Sangster, 1990). The most important primary minerals are sulfides, carbonates, barite, and quartz (Leach and others, 2005). Pyrite can vary from rare or minor in abundance (for example, Red Dog, Howards Pass) to composing the most abundant sulfide mineral (for example, Cirque, Meggen, HYC). The main Pb-Zn minerals are galena and sphalerite. Most deposits are Zn-rich relative to Pb. Silver is reported in many CD Pb-Zn deposits (Leach and others, 2005). Alteration associated with these deposits is reflected by Fe-Mn carbonate alteration halos and silicate alteration halos that may extend along stratigraphy for a few hundred meters to tens of kilometers (Large and others, 2005). Important pathfinder elements for these deposits include Ag, As, Ba, bismuth (Bi), Ge, Mn, phosphorous (P), REE (present primarily in apatite), Sb, and Tl. Deposits that are spatially associated with CD Pb-Zn deposits include bedded barite (Kelley and others, 1993; Johnson and others, 2004), phosphate (Dumoulin and others, 2011; Dumoulin and others, 2014b; Slack and others, 2017), and MVT deposits.

Alaska contains several economically important belts of CD Pb-Zn deposits (Schmidt, 1997a). The best known and largest of these is the extensive belt in the western and central Brooks Range that includes the Red Dog deposit and others in the district (Kelley and Jennings, 2004). Some of the regions with CD Pb-Zn deposits are in metasedimentary rocks, such as the Seward Peninsula. The Alaskan occurrences contain either barite or base metal sulfides or both in the case of many deposits in the Red Dog district (Johnson and others, 2004). Known occurrences, prospects, and deposits of this class are listed in table 1, and more detail on Alaskan deposits will be provided in sections that follow.

Table 1. Sediment-hosted Pb-Zn mineral deposit types considered in this study, and their commodities, characteristics, and representative localities in Alaska.

[ARDF number refers to the Alaska Resource Data File; AGDB3, Version 3 of the Alaska Geochemical Data Base (Granitto and others, 2019); ND=no data; see plate 1 for Region and Quadrangle locations; Ag, silver; Ba, barium; Cu, copper; Pb, lead; Zn, zinc; Co, cobalt; Ge, germanium; Tl, thallium; In, indium; Mtns, mountains; Mtn, mountain; Fm, Formation]

Region	Quadrangle	Host lithology	Deposit name	ARDF number	Mineralization	Trace element enrichments in rock samples from AGDB3 (if available)[1]
			Carbonate-hosted Pb-Zn			
Brooks Range zinc belt	Baird Mtns	Baird Group carbonates or broadly coeval metacarbonate and carbonate units	Frost	BM011	Disseminated, vein, and carbonate breccia-hosted sulfides (primarily galena and sphalerite) +/- secondary smithsonite or hydrozincite; some contain barite; Omar and Frost contain significant Cu, and therefore may not be traditional carbonate-hosted Pb-Zn	Ag, Ba, Cu, Pb, Zn
			Powdermilk	BM010		Ag, Ba, Ge, Pb, Zn
			Deadfall	BM010		Ag, Ba, Pb, Zn
			Peak	BM022		Ag, Ba, Pb, Zn
			Omar	BM012		Ag, Co, Cu, Ge, Pb, Tl, and Zn
	Ambler River		Nanielik Creek	AR052		ND
East-central Alaska	Black River	Tindir Group; carbonate, quartzite, argillite	VABM Fort	BR001		ND
			Pink Bluff	BR003		ND
			Midnight Hill	BR005		ND
	Charley River	Funnel Creek Limestone	Step Mtn	CY030		ND
			VABM Casca	CY034		ND
			Casca Zinc	CY005		ND
			Three Castle Mountain	CY040		ND
		Tindir Group	Pleasant Creek	CY024		ND
Farewell Terrane, Interior Alaska	Medfra	Whirlwind Creek Fm	Reef Ridge	MD055		ND
			Spring Ridge	MD047		ND
			Bear Pass	MD044		ND
			Katy-O	MD051		ND
		Beaver Creek Dolomite	Hillside	MD049		ND
		Paradise Fork Fm	Lynn-Marie	MD042		ND
			Starship	MD043		ND
			Bermuda	MD045		ND
			Beaver	MD048		ND
			Big Gate	MD050		ND
			Atoll	MD053		ND
			Saddle	MD054		ND
			Soda Creek	MD056		ND
			Asmyrahha	MD080		ND
			Cache Creek	MD037		ND

Table 1. Sediment-hosted Pb-Zn mineral deposit types considered in this study, and their commodities, characteristics, and representative localities in Alaska.—Continued

[ARDF number refers to the Alaska Resource Data File; AGDB3, Version 3 of the Alaska Geochemical Data Base (Granitto and others, 2019); ND=no data; see plate 1 for Region and Quadrangle locations; Ag, silver; Ba, barium; Cu, copper; Pb, lead; Zn, zinc; Co, cobalt; Ge, germanium; Tl, thallium; In, indium; Mtns, mountains; Mtn, mountain; Fm, Formation]

Region	Quadrangle	Host lithology	Deposit name	ARDF number	Mineralization	Trace element enrichments in rock samples from AGDB3 (if available)[1]
			Clastic-dominated Pb-Zn (CD Pb-Zn)			
Brooks Range zinc belt	De Long Mountains	Lisburne Group (Kuna Fm); Black Mudstone/Shale/Carbonate	Red Dog Main	DL001	Galena, sphalerite, and pyrite in fine-grained clastic rocks, either as disseminations, layers, massive zones, or veins; many but not all contain barite in addition to sulfides	Ag, Ba, Co, Cu, In, Pb, Tl, Zn
			Qanaiyaq (Hilltop)	DL001		ND
			Aqqaluk	DL001		Ag, Ba, In, Pb, Tl, Zn
			Paalaaq	DL001		Ag, Ba, In, Pb, Tl, Zn
			Suds	DL006		Ag, Pb, Tl, Zn
			Su-Lik	DL005		Ag, Pb, Tl, Zn
			Fritz	DL010		ND
			Surprise	DL011		ND
			Competition Creek	DL012		ND
			Alvinella/Cub Creek	DL015		ND
			Anarraaq	DL016		Ag, Ba, Ge, In, Pb, Tl, Zn
			Aktigiruk	Not In ARDF		ND
			Moil	DL003	Bedded barite	Very little except Ba
			Gull Creek	DL003		
		Endicott Group; Clastic Rocks	Husky (Robinson Creek)	DL002	Sulfide-rich veins and breccias in coarse clastics	Ag, Co, Cu, Pb, Zn
			Grizzly	Not In ARDF		
			Weasel Creek	Not In ARDF		

Table 1. Sediment-hosted Pb-Zn mineral deposit types considered in this study, and their commodities, characteristics, and representative localities in Alaska.—Continued

[ARDF number refers to the Alaska Resource Data File; AGDB3, Version 3 of the Alaska Geochemical Data Base (Granitto and others, 2019); ND=no data; see plate 1 for Region and Quadrangle locations; Ag, silver; Ba, barium; Cu, copper; Pb, lead; Zn, zinc; Co, cobalt; Ge, germanium; Tl, thallium; In, indium; Mtns, mountains; Mtn, mountain; Fm, Formation]

Region	Quadrangle	Host lithology	Deposit name	ARDF number	Mineralization	Trace element enrichments in rock samples from AGDB3 (if available)[1]
Brooks Range zinc belt	Baird Mtns	Lisburne Group (Kuna Fm); Black Mudstone/	Ahua	BM017	Pyrite and minor base metals as concretions/ Massive layers	ND
	Misheguk Mtn	Shale/Carbonate	Ginny Creek	MU007	Sulfides in fine-grained clastics	Ag, Co, Cu, Pb, Zn
			Nimiuktuk	MU001	Bedded barite	Very little except Ba
	Howard Pass	Lisburne Group (Kuna Fm)	Drenchwater	HW004	Galena, sphalerite, and pyrite in fine-grained clastic rocks, or spatially associated volcanic rocks	Ag, Ba, In, Pb, Tl, Zn
		Lisburne Group (Akmalik Chert)	Longview	HW034	Bedded barite	Very little except Ba
			Lakeview	HW023		
			Abby	HW024		
			Bion	HW025		
			Stack	HW026		
			Tuck	HW027		
		Endicott Group; clastic rocks	Story Creek	HW015	Vein-breccia: sulfide-rich veins and breccias in coarse clastics	Undivided sedimentary rocks: Ag, Ba, Pb, Zn[2]
			Safari Creek	HW010		
			Whoppee Creek	HW016		
			Kivliktort Mtn	HW020		
			Koiyaktot Mtn	HW018		
	Killik River		Kady	KL007		
			Vidlee	KL008		
	Wiseman	Skajit limestone and schists	Frog	WI044	Stratiform sulfides, disseminated and layered	ND
			Tana	WI050		ND
East-Central Alaska	Big Delta	Chena slate belt; siliceous and carbonaceous black quartzite, slate, and phyllite	Teuchet Creek	BD050	disseminated and foliation-parallel sulfides in carbonaceous phyllite and quartzite	Ag, Cu, Pb, Zn
			Drone Creek	BD051		ND
			Mount Schwatka	BD050		ND
	Charley River	Argillite, Chert, Shale	Hard Luck Creek	CY017	ND; occurrence based on soil anomaly	ND
			Derwent	CY008		ND
	Eagle	Carbonaceous Quartzite	O'Brien Creek	EA075	Disseminated sulfides	ND

Table 1. Sediment-hosted Pb-Zn mineral deposit types considered in this study, and their commodities, characteristics, and representative localities in Alaska.—Continued

[ARDF number refers to the Alaska Resource Data File; AGDB3, Version 3 of the Alaska Geochemical Data Base (Granitto and others, 2019); ND=no data; see plate 1 for Region and Quadrangle locations; Ag, silver; Ba, barium; Cu, copper; Pb, lead; Zn, zinc; Co, cobalt; Ge, germanium; Tl, thallium; In, indium; Mtns, mountains; Mtn, mountain; Fm, Formation]

Region	Quadrangle	Host lithology	Deposit name	ARDF number	Mineralization	Trace element enrichments in rock samples from AGDB3 (if available)[1]
Seward Peninsula/ St. Lawrence Island	Bendeleben/Kotzebue	Marble/Schist	Inmachuk/Hannum	Bn056	Lenses and (or) veins of dis-seminated to semi-massive sulfides	ND
			Anugi	KZ003		ND
			Chaulk Mountain	KZ003		ND
			Independence	BN076		ND
			Omilak Creek	BN133		ND
	Solomon		Wheeler	SO117		Ag, Ba, Cu, Ge, Pb, Tl, Zn
	Nome	Nome Complex Meta-Sedimentary Rocks	Quarry	NM135		Ag, Ba, Pb, Zn
			Nelson	NM090		Ag, Pb, Zn
			Aurora	NM140		Ag, Ba, Cu, Ge, Pb, Zn
			Galena	NM130		
	St. Lawrence	Limestone, Chert, Shale, and Siltstone	Ongoveyuk River	SL019	ND; occurrence based on soil anomaly	ND
Farewell Terrane, Interior Alaska	Lime Hills	Shale, Siltstone	Gagaryah	Lh002	Bedded barite	Fine-grained clastics: Ag, Ba; Carbonate: Ag, Pb, Tl; Undivided Sedimentary Rocks: Ag, Ba, Co, Cu, In, Pb, Zn[2]
	McGrath	Post River Fm; Carbonaceous Shale, Siltstone, Carbonate	Windy Fork	MG074	Discontinuous lenses and lay-ers of sulfides in limestone, siltstone	
			West Fork of Post River	MG072		

[1]See appendix 1 for ranges of data; elements listed here are >7.5 times Clarke Values (table 5). Clarke Values are defined as a measure of the average concentration of an element in the Earth's crust (Fortescue, 1992).

[2]See appendix 1 for ranges of data; Data for individual deposits not available; Data are for sedimentary rocks in the area of known occurrences; Some rock descriptions include veins cutting sedimentary rocks, and these are what contain metals for the most part.

Analytical Process and Data Sources

In this GIS analysis, key quantifiable characteristics of Pb-Zn deposits were identified in available datasets and scored with respect to relative importance for indicating potential for resource occurrence. To evaluate resource potential for sediment-hosted Pb-Zn deposits in Alaska, drainage basins of the smallest size were chosen; these are designed using 12-digit hydrologic unit codes (HUCs) that are available in the National Hydrography Dataset (https://nhd.usgs.gov/), each of which covers approximately 100 square kilometers (km^2). A different areal unit of evaluation is possible, such as a square mile grid. However, data density sufficient to evaluate Pb-Zn deposits by a square mile grid is typically available only for selected, relatively small areas in Alaska, which could bias certain areas in a regional analysis. Furthermore, because the most regionally robust dataset is stream sediment geochemistry, sediment sources are the key target for resource analysis, and drainage basins are the most logical and efficient unit for evaluation.

The following geospatial datasets were assembled for analysis using ArcGIS: (1) bedrock geology from the digital Geologic Map of Alaska (https://doi.org/10.3133/sim3340); (2) known mineral deposits, prospects, and occurrences in the Alaska Resource Data File (ARDF) (https://ardf.wr.usgs.gov/); and (3) geochemical data for rocks, sediments, soils, and heavy-mineral concentrates from the Alaska Geochemical Database (AGDB) (Granitto and others, 2019), the National Uranium Resource Evaluation (NURE) geochemical database (https://mrdata.usgs.gov/nure/sediment), and the Alaska Division of Geological and Geophysical Surveys (ADGGS) geochemical database (https://doi.org/10.3133/ds1117).

Data scoring and ranking of each data type were conducted using key parameters for sediment-hosted Pb-Zn deposits. Datasets that were applied in the analysis, the parameters in the datasets that were queried, and the weighting of each parameter are listed in table 2.

In this report, “mineral resource potential” is defined as the relative probability for the occurrence of a concentration of a mineral(s) of interest (in this case carbonate-hosted and CD Pb-Zn-Ag accumulations or resource) but the term does not take into consideration economically viable development or extraction of the mineral resource. This study separates four levels of mineral resource potential based on the presence and number of favorable attributes. The product of the analysis is a map, which indicates the relative level (High, Medium, Low, Unknown) of potential, and the relative level (High, Medium, Low, Unknown) of certainty for all 12-digit HUCs within Alaska (plate 1; see discussion below regarding 12-digit HUCs).

Based on previous work (Taylor and Steven, 1983; Goudarzi, 1984), and as defined below, the four levels (High, Medium, Low, and Unknown) of resource potential are assigned as follows:

1. High mineral resource potential is assigned to areas where geological, mineralogical, geochemical, and mineral occurrence characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a high degree of likelihood for resource accumulation, where data indicate that mineral concentration has taken place, and evidence supports mineral deposit models of interest. Resources or deposits need not be identified for an area to be assigned high resource potential.

2. Medium mineral resource potential is assigned to areas where geological, mineralogical, geochemical, and mineral occurrence characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a reasonable likelihood of resource accumulation, and where an application of mineral deposit models indicates favorable ground for concentration of the specified type of minerals.

3. Low mineral resource potential is assigned to areas where geological, mineralogical, geochemical, and mineral occurrence characteristics define a geologic environment in which the existence of the specific resource is unlikely.

4. Unknown mineral resource potential is assigned in situations where information is inadequate to assign low, medium, or high levels of resource potential to the area.

Based on previous studies (Taylor and Steven, 1983; Goudarzi, 1984), the four levels (High, Medium, Low, and Unknown) of certainty are assigned as follows:

1. High certainty is assigned to areas for which available information from multiple sources provides a robust indication of the level of mineral resource potential.

2. Medium certainty is assigned to areas for which available information is sufficient to give a reasonable indication of the level of mineral resource potential.

3. Low certainty is assigned to areas for which available information is limited and only suggests minimal mineral resource potential.

4. Unknown certainty is assigned to areas for which available information is not adequate for determination of the level of mineral resource potential.

For the GIS analyses in this report, certainty for each HUC is quantified by the number of geoscientific data layers that contribute to the resource potential score of that HUC (table 3). A lack of stream sediment data or panned concentrate geochemical data, a lack of appropriate rock type, and a lack of ARDF records for a HUC yields an Unknown classification assignment (plate 1).

Table 2. Scoring template for analysis of sediment-hosted Pb-Zn deposit potential within each hydrologic unit code (HUC) in Alaska.

[NA, not applicable; ADGGS, Alaska Division of Geological and Geophysical Surveys database; AGDB3, Alaska Geochemical Database, version 3; ARDF, Alaska Resource Data File; HMC, heavy-mineral concentrate; NURE, National Uranium Resource Evaluation database; ppm, parts per million; Zn, zinc; Cu, copper; Ag, silver; Pb, lead; Ba, barium]

Category	Dataset/layer	Component	Selection and score
Lithology	Geologic map of Alaska (Wilson and others, 2015)	(LITHOLOGY_SCORE)	4 points if barite 4 points if sphalerite 5 points if carbonate 5 points if chemical 5 points if metasedimentary
ARDF records	ARDF	Sediment-hosted Pb-Zn model keywords[1]	5 points if keyword total score >21 3 points if keyword total score ≥14 *and* ≤21
Sediment-sample geochemical data[2]	AGDB3 + ADGGS + NURE	(SED_ZN_SCORE)	10 points if (Zn_ppm ≥914.5) and (Cu_ppm<51.8) 8 points if (Zn_ppm ≥442.5 *and* <914.5) and (Cu_ppm<51.8) 4 points if (Zn_ppm ≥206.5 *and* <442.5) and (Cu_ppm<51.8)
		(SED_AG_SCORE)	10 points if (Ag_ppm ≥4.18) and (Cu_ppm<51.8) 8 points if (Ag_ppm ≥2.02 *and* <4.18) and (Cu_ppm<51.8) 4 points if (Ag_ppm ≥0.945 *and* <2.02) and (Cu_ppm<51.8)
		(SED_PB_SCORE)	10 points if (Pb_ppm ≥275.9) and (Cu_ppm<51.8) 8 points if (Pb_ppm ≥133.5 *and* <275.9) and (Cu_ppm<51.8) 4 points if (Pb_ppm >62.3 *and* <133.5) and (Cu_ppm<51.8)
		(SED_BA_SCORE)	10 points if Ba_ppm ≥7936 8 points if Ba_ppm ≥3840 *and* <7936 4 points if Ba_ppm ≥1792 *and* <3840
Heavy-mineral-concentrate-sample data	AGDB3—HMC mineralogy	(HMC_SCORE)[3]	3 points if (Ag_ppm >30) and (Cu_ppm<150) 3 points if (Ba_ppm>1000) and (Cu_ppm<150) 3 points if (Pb_ppm >200) and (Cu_ppm<150) 3 points if (Zn_ppm >700) and (Cu_ppm<150)
		(MIN_SCORE)[4]	1 point if sphalerite and galena are present 1 point if barite is present

[1]See appendix 2 of Kelley and others (2020) for a list of sediment-hosted Pb-Zn model keywords and the scoring template for ARDF records.

[2]Sediment geochemical data scores are additive, for a possible total score of 40 for each HUC.

[3]Geochemistry scores from heavy mineral concentrate sample data are additive, for a possible total score of 12 for each HUC.

[4]Mineral scores from heavy mineral concentrate sample data are additive, for a possible total score of 2 for each HUC.

National Hydrography Dataset and Watershed Boundary Dataset

The National Hydrography and Watershed Boundary Datasets (NHD and WBD; https://nhd.usgs.gov/) delineate surface water networks and drainage basins throughout the United States using standardized criteria based on topography and hydrology. Relative drainage basin size, geographic location, and nested hierarchy are encoded within a string of digits known as HUCs. A classical hydrologic unit is a division of a watershed with a single discharging stream; accordingly, it corresponds to a physical watershed that is defined by topography. The United States is divided and sub-divided into successively smaller hydrologic units, which are classified into four levels: regions, subregions, accounting units, and cataloging units. The hydrologic units are arranged or nested within each other, from the largest geographic area (regions) to the smallest geographic area (cataloging units). Each hydrologic unit is identified by a unique HUC consisting of two to twelve digits based on the levels of classification in the hydrologic unit system. Numeric codes, names, and boundaries associated with each HUC provide unique identifiers useful for associating other geospatial data from multiple sources in a

Table 3. Mineral resource potential versus certainty classification matrix for sediment-hosted Pb-Zn deposits in Alaska.

[Color coding in this table corresponds with the color assignments in plate 1 representing Pb-Zn potential. HUC, hydrologic unit code; c, certainty; p, potential; Pb, lead; Zn, zinc]

Sediment-hosted Pb-Zn	Estimated certainty[1]				
	Low	**Medium**	**High**		
	Total score ≥18 (p) 2 datasets not null (c)	Total score ≥18 (p) 3 datasets not null (c)	Total score ≥18 (p) 4 datasets not null (c)	**High**	
Unknown (Total score = 0 *and* no sediment samples in HUC)	Total score 7–17 (p) 2 datasets not null (c)	Total score 7–17 (p) 3 datasets not null (c)	Total score 7–17 (p) 4 datasets not null (c)	**Medium**	**Estimated potential[1]**
	Total score 0–6 (p) 1-2 datasets not null (c)	Total score 0–6 (p) 3 datasets not null (c)	Total score 0–6 (p) 4 datasets not null *or* Total score = 0 (c)	**Low**	

[1]Abbreviations (p) and (c) in cells denote which components contribute to the assignment of *potential* and *certainty* classifications, respectively.

GIS. Twelve-digit HUC boundaries are used in this study as a geographic reference frame and sampling unit for evaluating mineral resource potential across Alaska. Datasets described below were scored for each twelve-digit HUC across the state as they pertained to sediment-hosted Pb-Zn deposits, and scores were analyzed and classified for mineral resource favorability following the methods described below.

Geochemical Data Sources

The geochemical dataset used for this report is a compilation derived from three geochemical databases; these sources represent samples of geologic materials collected across Alaska. The file structure and data format of each database is markedly different, which necessitated reformatting the geochemical databases for consistency and optimization for geochemical mapping and statistical evaluation.

The U.S. Geological Survey (USGS) AGDB3 was used in the prospectivity analyses. It includes new and historical geochemical analyses of rock, stream sediment, soil, and heavy-mineral concentrate samples from Alaska (Granitto and others, 2019). The AGDB3 includes analyses of 145,389 rock samples; 178,137 sediment samples; 8,433 soil samples; 7,560 mineral samples; 53,192 heavy-mineral concentrate samples; and 3,619 oxalic acid leachate samples. The AGDB3 is composed of data from the USGS National Geochemical Database (NGDB), the National Uranium Resource Evaluation (NURE) database, and the Alaska Division of Geological and Geophysical Surveys (DGGS) database that includes data from the U.S. Bureau of Mines (USBM) and Bureau of Land Management (BLM) work in Alaska. The AGDB3 samples were collected between 1938 and 2017 and prepared according to a variety of USGS standard methods (variously described in Miesch, 1976; Arbogast, 1990, 1996; Taggart, 2002), by NURE methods (described in Smith, 1997), or by DGGS, USBM, and BLM methods that, if recorded, can be obtained from publications linked to samples collected by those agencies and listed in the AGDB3.

The NGDB contains data derived from various USGS programs: chiefly the Alaska Mineral Resource Assessment Program (AMRAP) and the Heavy Metals Program. These data are derived from the analyses of 111,375 rock samples; 96,887 sediment samples; 7,201 soil samples; 48,328 heavy-mineral concentrate samples (mostly nonmagnetic fraction concentrates from stream sediments); 7,469 mineral samples; and 3,619 oxalic acid leachate samples. These samples were collected between 1938 and 2017.

The NURE database contains data derived from the NURE Hydrogeochemical and Stream Sediment Reconnaissance (NURE-HSSR) program that was overseen by the U.S. Atomic Energy Commission. Sediment samples for NURE were collected in Alaska between 1976 and 1979.

The DGGS geochemical database includes analyses of 34,015 rock samples; 15,264 sediment samples; 1,232 soil samples; 4,864 heavy-mineral concentrate samples; and 93 mineral samples collected between 1938 and 2017. These data were provided by the DGGS and are also available for download via the internet (https://doi.org/10.3133/ds1117).

Many samples in the AGDB3 and DGGS databases were analyzed by more than one method; consequently, some samples have concentration determinations by more than one method for some elements. To minimize the complexity inherent in multiple determinations for individual elements, a single best value concentration was identified for each element in each sample. The best values were chosen by considering (1) the mass of the sample that was analyzed, (2) the method of decomposition of the sample during preparation, (3) the sensitivity and accuracy of the instrument used for analysis, (4) the upper and lower limits of determination for a given element by a particular method, (5) the age of the method and stage of its development when a specific analysis was performed, and (6) the specific analytical laboratory and equipment used. Granitto and others (2019) provide a detailed description of these considerations and how they were used to determine best value concentrations.

Sediment and Rock Geochemistry

Sediment geochemical data represent the most comprehensive, evenly distributed, and highest-density dataset available for the analysis of mineral resource potential across Alaska. Bedrock is concealed in many areas by unconsolidated sediment and vegetation. However, sediment geochemical data portray elemental abundance patterns that reflect rock compositions in their respective drainage basins and, thus, provide clues about rock types in areas of poor exposure or where geologic mapping is lacking.

For the purpose of this report, geochemical data from the AGDB3, NURE, and DGGS datasets are combined into a single dataset. These data can be used in models of resource potential to determine concentrations of elements that are relatively high compared to a threshold value (and thus, that may be an indicator of proximity to mineral deposits containing those elements). In general, methods for determination of threshold values in datasets are varied, and it is critical to use a threshold that is best suited for the goal of assessing mineral potential. A common method involves calculating percentile values and assigning percentile groupings (for example, >90th percentile) as “anomalous” with respect to the complete dataset. Although samples represented by these >90th percentile classes contain element concentrations that are high compared to the total population, the absolute concentrations may not be high enough to be indicative of the presence of mineral deposits.

For this study, threshold values were chosen by a methodology that uses natural element abundance as the basis for classifying element concentrations. The median values for A-horizon soils (called Median Topsoil Values or MTV) determined from samples collected throughout the entire conterminous United States (Smith and others, 2013) were used to establish “background” values, and multiples of this background were chosen as threshold values. Table 4 lists the MTV for each element.

To display data in terms of ranges of values, the following scheme was used: background range was determined to be between 0.5 and 1.5× MTV. Low level anomalous concentrations were those between 3.5× and 7.5×, moderately anomalous between 7.5× MTV and 15.5× MTV, and highly anomalous were those values between 15.5× the MTV and the concentration of the maximum value in the dataset for any given element (Kelley and others, 2020).

The distribution of rock geochemical analyses is restricted to very select areas in Alaska and is far less representative compared to the distribution of sediment data in the state. Furthermore, many of the rock samples in the AGDB3 have only been analyzed for a few elements, which typically do not include the important pathfinder elements for sediment-hosted deposits. Therefore, the rock geochemical data were not used as a regional data layer in this assessment. However, the rock data were used to identify characteristic trace element concentrations in rocks from areas with known sediment-hosted deposits (table 1). In addition, 517 archived rock samples from regions with known deposits were retrieved and submitted for reanalysis for a full element suite by modern ICP-MS methods. The results are included in Granitto and others (2019). Threshold values for rock samples were determined in a manner similar to sediment samples; that is, threshold values were determined as multiples of Clarke values (Fortescue, 1992). These threshold values are shown in table 5. Some of the elements with >7.5× Clarke values are listed in table 1 and are displayed as boxplots in appendix 1.

Heavy Mineral Concentrate Mineralogy and Geochemistry

Mineralogical data that are based on visual identifications are available for more than 18,137 nonmagnetic bulk-panned-concentrate or heavy-mineral-concentrate (HMC) samples in the AGDB3 (Granitto and others, 2019). The HMC samples were derived from sediments, soils, or less commonly, from rocks. The minerals that were identified during visual examination include gold, galena, sphalerite, and other sulfide minerals (Granitto and others, 2019). Grain-count data are available for some samples. Abundances in other samples are qualitative or semi-quantitative (for example, “present,” “abundant,” “trace”), estimated percentages, or percentage ranges. Null values indicate that the mineral was not observed in a sample. Mineralogy data in the AGDB3 are presented as they were originally recorded and interpreted; data sources are listed in Granitto and others (2019). The AGDB3 also contains best-value geochemical data for 49,783 HMC samples across the state. The specific methods used to incorporate HMC mineralogy and geochemistry into the prospectivity analysis are more fully described in relevant sections below.

Although data from the AGDB3 dataset are not evenly distributed across the state, the heavy mineral concentrate geochemistry and (or) presence of specific minerals can provide evidence of Pb- and Zn-bearing sources within a HUC. The HMC data are divided into two components, mineralogy and chemistry in the AGDB3.

Alaska Resource Data File

The Alaska Resource Data File (ARDF; https://ardf.wr.usgs.gov/) contains 7,693 reports of mines, deposits, prospects, and mineral occurrences in Alaska. USGS Open-File Reports containing ARDF records for each USGS 1:250,000-scale quadrangle are available for download from the ARDF site separately or as part of a single composite ARDF database. ARDF records include a broad spectrum of mineral deposit types. For this study, mineral “deposits” are localities with reported inventory or past production of the mineral, whereas mineral “prospects” and “occurrences”

Table 4. Median Topsoil Values (MTV) of A-horizon soils determined from samples collected throughout the entire conterminous United States.

[To map abundances of sediment samples used in this report in terms of classified ranges, the following scheme was used: background range was determined to be concentrations between 0.5 times (×) and 1.5× the MTV abundance value; low level anomalous concentrations were those between 3.5× and 7.5×, moderately anomalous between 7.5× MTV and 15.5× MTV, and highly anomalous were those values between 15.5× the MTV and the concentration of the maximum value in the dataset for any given element. Values in parts per million (ppm) unless specified as percent (%)]

Element	MTV Value	Reference	0.5× MTV	1.5× MTV	3.5× MTV	7.5× MTV	15.5× MTV
Ag	0.27	Salminen and others (2005) Topsoil Median	0.135	0.405	0.945	2.025	4.185
Al%	4.71	Smith and others (2013) A-Horiz Median	2.355	7.065	16.485	35.325	73.005
As	5.2	Smith and others (2013) A-Horiz Median	2.6	7.8	18.2	39	80.6
Au	0.004	Fortescue (1992) Clarke Index	0.002	0.006	0.014	0.03	0.062
B	26	Shacklette and Boerngen (1984)	13	39	91	195	403
Ba	512	Smith and others (2013) A-Horiz Median	256	768	1792	3840	7936
Be	1.3	Smith and others (2013) A-Horiz Median	0.65	1.95	4.55	9.75	20.15
Bi	0.16	Smith and others (2013) A-Horiz Median	0.08	0.24	0.56	1.2	2.48
Ca%	0.74	Smith and others (2013) A-Horiz Median	0.37	1.11	2.59	5.55	11.47
Cd	0.2	Smith and others (2013) A-Horiz Median	0.1	0.3	0.7	1.5	3.1
Ce	51.7	Smith and others (2013) A-Horiz Median	25.85	77.55	180.95	387.75	801.35
Co	7.8	Smith and others (2013) A-Horiz Median	3.9	11.7	27.3	58.5	120.9
Cr	31	Smith and others (2013) A-Horiz Median	15.5	46.5	108.5	232.5	480.5
Cs	3.71	Salminen and others (2005) Topsoil Median	1.855	5.565	12.985	27.825	57.505
Cu	14.8	Smith and others (2013) A-Horiz Median	7.4	22.2	51.8	111	229.4
Dy	3.42	Salminen and others (2005) Topsoil Median	1.71	5.13	11.97	25.65	53.01
Eu	0.77	Salminen and others (2005) Topsoil Median	0.385	1.155	2.695	5.775	11.935
Fe%	1.99	Smith and others (2013) A-Horiz Median	0.995	2.985	6.965	14.925	30.845
Ga	11.2	Smith and others (2013) A-Horiz Median	5.6	16.8	39.2	84	173.6
Hf	5.55	Salminen and others (2005) Topsoil Median	2.775	8.325	19.425	41.625	86.025
Hg	0.02	Smith and others (2013) A-Horiz Median	0.01	0.03	0.07	0.15	0.31
K%	1.5	Smith and others (2013) A-Horiz Median	0.75	2.25	5.25	11.25	23.25
La	25.7	Smith and others (2013) A-Horiz Median	12.85	38.55	89.95	192.75	398.35
Li	20	Smith and others (2013) A-Horiz Median	10	30	70	150	310
Lu	0.3	Salminen and others (2005) Topsoil Median	0.15	0.45	1.05	2.25	4.65
Mg%	0.46	Smith and others (2013) A-Horiz Median	0.23	0.69	1.61	3.45	7.13
Mn	498	Smith and others (2013) A-Horiz Median	249	747	1743	3735	7719

Table 4. Median Topsoil Values (MTV) of A-horizon soils determined from samples collected throughout the entire conterminous United States.—Continued

[To map abundances of sediment samples used in this report in terms of classified ranges, the following scheme was used: background range was determined to be concentrations between 0.5 times (×) and 1.5× the MTV abundance value; low level anomalous concentrations were those between 3.5× and 7.5×, moderately anomalous between 7.5× MTV and 15.5× MTV, and highly anomalous were those values between 15.5× the MTV and the concentration of the maximum value in the dataset for any given element. Values in parts per million (ppm) unless specified as percent (%)]

Element	MTV Value	Reference	0.5× MTV	1.5× MTV	3.5× MTV	7.5× MTV	15.5× MTV
Mo	0.78	Smith and others (2013) A-Horiz Median	0.39	1.17	2.73	5.85	12.09
Na%	0.69	Smith and others (2013) A-Horiz Median	0.345	1.035	2.415	5.175	10.695
Nb	8.6	Smith and others (2013) A-Horiz Median	4.3	12.9	30.1	64.5	133.3
Nd	20.8	Salminen and others (2005) Topsoil Median	10.4	31.2	72.8	156	322.4
Ni	13.8	Smith and others (2013) A-Horiz Median	6.9	20.7	48.3	103.5	213.9
P%	0.055	Smith and others (2013) A-Horiz Median	0.0275	0.0825	0.1925	0.4125	0.8525
Pb	17.8	Smith and others (2013) A-Horiz Median	8.9	26.7	62.3	133.5	275.9
Rb	65.8	Smith and others (2013) A-Horiz Median	32.9	98.7	230.3	493.5	1019.9
Sb	0.57	Smith and others (2013) A-Horiz Median	0.285	0.855	1.995	4.275	8.835
Sc	6.1	Smith and others (2013) A-Horiz Median	3.05	9.15	21.35	45.75	94.55
Se	0.2	Smith and others (2013) A-Horiz Median	0.1	0.3	0.7	1.5	3.1
Sm	3.96	Salminen and others (2005) Topsoil Median	1.98	5.94	13.86	29.7	61.38
Sn	1.3	Smith and others (2013) A-Horiz Median	0.65	1.95	4.55	9.75	20.15
Sr	122	Smith and others (2013) A-Horiz Median	61	183	427	915	1891
Ta	0.68	Salminen and others (2005) Topsoil Median	0.34	1.02	2.38	5.1	10.54
Te	0.03	Salminen and others (2005) Topsoil Median	0.015	0.045	0.105	0.225	0.465
Th	7.7	Smith and others (2013) A-Horiz Median	3.85	11.55	26.95	57.75	119.35
Ti%	0.24	Smith and others (2013) A-Horiz Median	0.12	0.36	0.84	1.8	3.72
Tl	0.4	Smith and others (2013) A-Horiz Median	0.2	0.6	1.4	3	6.2
U	2	Smith and others (2013) A-Horiz Median	1	3	7	15	31
V	54	Smith and others (2013) A-Horiz Median	27	81	189	405	837
W	0.8	Smith and others (2013) A-Horiz Median	0.4	1.2	2.8	6	12.4
Y	14.5	Smith and others (2013) A-Horiz Median	7.25	21.75	50.75	108.75	224.75
Yb	1.99	Salminen and others (2005) Topsoil Median	0.995	2.985	6.965	14.925	30.845
Zn	59	Smith and others (2013) A-Horiz Median	29.5	88.5	206.5	442.5	914.5
Zr	180	Shacklette and Boerngen (1984)	90	270	630	1350	2790

Table 5. Geochemical data for rock samples and ranges considered anomalous based on multiples of Clarke values.

[All values in parts per million (ppm) unless otherwise indicated as percent (%). To map abundances in terms of classified ranges, the following scheme was used: background range was determined to be between 0.5 times (×) and 1.5× the Clarke abundance value; low level anomalous values between 3.5 and 7.5× Clarke value; moderately anomalous between 7.5× and 15.5× Clarke value, and highly anomalous between 15.5× Clarke value and the maximum concentration for the dataset]

Element	Clarke Value	Reference	0.5× Clarke	1.5× Clarke	3.5× Clarke	7.5× Clarke	15.5× Clarke
Ag	0.08	Fortescue (1992)	0.04	0.12	0.28	0.6	1.24
Al%	8.36	Fortescue (1992)	4.18	12.54	29.26	62.7	129.58
As	1.8	Fortescue (1992)	0.9	2.7	6.3	13.5	27.9
Au	0.004	Fortescue (1992)	0.002	0.006	0.014	0.03	0.062
B	9	Fortescue (1992)	4.5	13.5	31.5	67.5	139.5
Ba	390	Fortescue (1992)	195	585	1365	2925	6045
Be	2	Fortescue (1992)	1	3	7	15	31
Bi	0.17	Taylor (1964)	0.085	0.255	0.595	1.275	2.635
Br	2.5	Fortescue (1992)	1.25	3.75	8.75	18.75	38.75
Ca%	4.66	Fortescue (1992)	2.33	6.99	16.31	34.95	72.23
Cd	0.16	Fortescue (1992)	0.08	0.24	0.56	1.2	2.48
Ce	66.4	Fortescue (1992)	33.2	99.6	232.4	498	1029.2
Cl	126	Fortescue (1992)	63	189	441	945	1953
Co	29	Fortescue (1992)	14.5	43.5	101.5	217.5	449.5
Cr	122	Fortescue (1992)	61	183	427	915	1891
Cs	2.6	Fortescue (1992)	1.3	3.9	9.1	19.5	40.3
Cu	68	Fortescue (1992)	34	102	238	510	1054
Dy	5	Fortescue (1992)	2.5	7.5	17.5	37.5	77.5
Er	3.46	Fortescue (1992)	1.73	5.19	12.11	25.95	53.63
Eu	2.14	Fortescue (1992)	1.07	3.21	7.49	16.05	33.17
F%	0.0544	Fortescue (1992)	0.0272	0.0816	0.1904	0.408	0.8432
Fe%	6.22	Fortescue (1992)	3.11	9.33	21.77	46.65	96.41
Ga	19	Fortescue (1992)	9.5	28.5	66.5	142.5	294.5
Gd	6.14	Fortescue (1992)	3.07	9.21	21.49	46.05	95.17
Ge	1.5	Fortescue (1992)	0.75	2.25	5.25	11.25	23.25
Hf	2.8	Fortescue (1992)	1.4	4.2	9.8	21	43.4
Hg	0.086	Fortescue (1992)	0.043	0.129	0.301	0.645	1.333
Ho	1.26	Fortescue (1992)	0.63	1.89	4.41	9.45	19.53
In	0.24	Fortescue (1992)	0.12	0.36	0.84	1.8	3.72
Ir	0.000002	Fortescue (1992)	0.000001	0.000003	0.000007	0.000015	0.000031
K%	1.84	Fortescue (1992)	0.92	2.76	6.44	13.8	28.52
La	34.6	Fortescue (1992)	17.3	51.9	121.1	259.5	536.3
Li	18	Fortescue (1992)	9	27	63	135	279
Lu	0.54	Fortescue (1992)	0.27	0.81	1.89	4.05	8.37
Mg%	2.764	Fortescue (1992)	1.382	4.146	9.674	20.73	42.842
Mn%	0.106	Fortescue (1992)	0.053	0.159	0.371	0.795	1.643
Mo	1.2	Fortescue (1992)	0.6	1.8	4.2	9	18.6
Na%	2.27	Fortescue (1992)	1.135	3.405	7.945	17.025	35.185
Nb	20	Fortescue (1992)	10	30	70	150	310

Table 5. Geochemical data for rock samples and ranges considered anomalous based on multiples of Clarke values.—Continued

[All values in parts per million (ppm) unless otherwise indicated as percent (%). To map abundances in terms of classified ranges, the following scheme was used: background range was determined to be between 0.5 times (×) and 1.5× the Clarke abundance value; low level anomalous values between 3.5 and 7.5× Clarke value; moderately anomalous between 7.5× and 15.5× Clarke value, and highly anomalous between 15.5× Clarke value and the maximum concentration for the dataset]

Element	Clarke Value	Reference	0.5× Clarke	1.5× Clarke	3.5× Clarke	7.5× Clarke	15.5× Clarke
Nd	39.6	Fortescue (1992)	19.8	59.4	138.6	297	613.8
Ni	75	Taylor (1964)	37.5	112.5	262.5	562.5	1162.5
P%	0.112	Fortescue (1992)	0.056	0.168	0.392	0.84	1.736
Pb	13	Fortescue (1992)	6.5	19.5	45.5	97.5	201.5
Pd	0.015	Fortescue (1992)	0.0075	0.0225	0.0525	0.1125	0.2325
Pr	9.1	Fortescue (1992)	4.55	13.65	31.85	68.25	141.05
Pt	0.0005	Fortescue (1992)	0.00025	0.00075	0.00175	0.00375	0.00775
Rb	78	Fortescue (1992)	39	117	273	585	1209
Re	0.0007	Fortescue (1992)	0.00035	0.00105	0.00245	0.00525	0.01085
Rh	0.0002	Fortescue (1992)	0.0001	0.0003	0.0007	0.0015	0.0031
Ru	0.001	Fortescue (1992)	0.0005	0.0015	0.0035	0.0075	0.0155
S%	0.034	Fortescue (1992)	0.017	0.051	0.119	0.255	0.527
Sb	0.2	Fortescue (1992)	0.1	0.3	0.7	1.5	3.1
Sc	25	Fortescue (1992)	12.5	37.5	87.5	187.5	387.5
Se	0.05	Fortescue (1992)	0.025	0.075	0.175	0.375	0.775
Si%	27.3	Fortescue (1992)	13.65	40.95	95.55	204.75	423.15
Sm	7.02	Fortescue (1992)	3.51	10.53	24.57	52.65	108.81
Sn	2.1	Fortescue (1992)	1.05	3.15	7.35	15.75	32.55
Sr	384	Fortescue (1992)	192	576	1344	2880	5952
Ta	1.7	Fortescue (1992)	0.85	2.55	5.95	12.75	26.35
Tb	1.18	Fortescue (1992)	0.59	1.77	4.13	8.85	18.29
Te	0.004	Fortescue (1992)	0.002	0.006	0.014	0.03	0.062
Th	8.1	Fortescue (1992)	4.05	12.15	28.35	60.75	125.55
Ti%	0.632	Fortescue (1992)	0.316	0.948	2.212	4.74	9.796
Tl	0.72	Fortescue (1992)	0.36	1.08	2.52	5.4	11.16
Tm	0.5	Fortescue (1992)	0.25	0.75	1.75	3.75	7.75
U	2.3	Fortescue (1992)	1.15	3.45	8.05	17.25	35.65
V	136	Fortescue (1992)	68	204	476	1020	2108
W	1.2	Fortescue (1992)	0.6	1.8	4.2	9	18.6
Y	31	Fortescue (1992)	15.5	46.5	108.5	232.5	480.5
Yb	3.1	Fortescue (1992)	1.55	4.65	10.85	23.25	48.05
Zn	76	Fortescue (1992)	38	114	266	570	1178
Zr	162	Fortescue (1992)	81	243	567	1215	2511

describe localities where minerals of the commodity have no reported inventory. Mineral deposit “types” are recognized styles of mineralization described in published deposit models.

A list of keyword search terms that are unique to sediment-hosted Pb-Zn deposits was developed to distinguish these deposits from other Zn-Pb bearing deposit types. Keywords such as “VMS,” “porphyry,” “orogenic gold,” “carbonate-hosted Cu,” and “skarn deposits” that contain similar ore and gangue minerals and other characteristics were assigned sufficiently strong negative scores to eliminate them from consideration during the assessment. During the process of developing keywords, it was clear that most characteristics (such as ore and gangue minerals and main commodities) used to describe carbonate-hosted and CD Pb-Zn deposits were common among both types, and therefore, all sediment-hosted Pb-Zn deposits (CD Pb-Zn and carbonate-hosted Pb Zn deposits) were assessed as a single group. Keywords were weighted on a scale from 1 to 5 for their relevance. Complete lists of keywords and associated weights are given in appendix 2 of Kelley and others (2020).

Results of scores for the ARDF database are given in appendix 3 of Kelley and others (2020). Scores for each of the fields in ARDF were applied to each deposit or occurrence in the ARDF table. For example, if a deposit is listed as containing Ag as main commodities (5 points assigned – see appendix 2, column D of Kelley and others [2020]), Ba (4 points), Pb (5 points), and Zn (5 points), a score of 19 is assigned to that column (see COMMODITIES_MAIN_SCR – column D, appendix 3 of Kelley and others [2020]); conversely, if a deposit or occurrence is listed as having fewer main commodities, the score is less. This was done for all of the categories from the ARDF table, and subsequently the scores were added to produce a total score (see TOTAL, column N, appendix 3 of Kelley and others [2020]). The total scores were statisti-cally analyzed by the Jenks (1967) method to bin into groups. In areas with multiple relevant ARDF records, scores for all ARDF records within a HUC were not considered; only the highest scoring record was used as the representative ARDF score for any single HUC. The representative ARDF score was generated by assigning a score of 5 for high potential (if the keyword total score was >21), and 3 for lower potential (table 2). The maximum possible score of 5 was used in order to prevent known deposits from skewing the spatial distribution of deposit potential. This allowed other parameters such as rock type, geochemistry, and panned concentrate data to help identify undiscovered sediment-hosted Pb-Zn deposits.

In some cases, scrutiny of individual ARDF records revealed word misspellings and imprecise location information that hindered appropriate scoring. Records that contained errors were corrected in the database prior to final analyses. ARDF records are updated on a regular basis (on the website at https://ardf.wr.usgs.gov/), but future ARDF users are cautioned because the database may still contain unrecognized errors. However, the greater abundance of accurate ARDF records and other data utilized will likely outweigh and minimize the effects of spurious ARDF records.

Geologic Map of Alaska

The Geologic Map of Alaska portrays the distribution of diverse rock types across the state (Wilson and others, 2015). The associated catalog of lithology descriptions in the table “nsalith” of the geologic map geodatabase was searched to identify rock types most permissive for hosting particular deposit types. Lithology query results were used to develop derivative, generalized lithology map layers that show the distribution of rock types favorable for the occurrence of sediment-hosted deposits in Alaska. Specific lithologies considered favorable for the occurrence of each deposit group are summarized in appendix 4 of Kelley and others (2020).

Aerial Magnetic Surveys

A compilation of aeromagnetic data is available for the state of Alaska (Saltus and Simmons, 1997). Such a dataset can be used to distinguish intrusive rocks from other lithologies, which is important for identifying some types of mineral deposits. However, for sediment-hosted deposits that occur in fine-grained clastic or carbonate rocks that form without genetic association with igneous activity, magnetic signatures may be non-distinct. Therefore, the utility of aeromagnetic data is limited, particularly at the resolution of the statewide scale of the aeromagnetic data. For this reason, the aeromagnetic data were not used in the assessment.

GIS-Based Methods

The GIS process is based on the identification of key characteristics of sediment-hosted Pb-Zn deposits that have been determined from available datasets and scored with respect to importance. A data scoring and ranking process was implemented. Table 2 lists information such as which datasets were used, which parameters in the datasets were queried, and the amount each parameter could contribute to the estimate of prospectivity in each HUC. Additional data sources and geospatial data file sources (see Kelley and others, 2020) provide the scoring results and permit the user to analyze and query the findings in a spatial context on the final digital map product. A python script was used to combine individual parameter scores into cumulative scores for each HUC (Kelley and others, 2020).

Cumulative total scores from multiple parameters that characterize sediment-hosted Pb-Zn deposits were statistically divided into four levels of mineral resource potential for lead and zinc deposits using natural breaks (Jenks, 1967). As described above in the Analytical Process and Data Sources section, these include High, Medium, Low and Unknown potential categories. The “mineral resource potential” is defined as the relative probability for the occurrence of a concentration of a mineral(s) accumulation (Taylor and Steven, 1983; Goudarzi, 1984), but does not take into consideration whether the development or extraction of the mineral resource is economically viable. The GIS method used here separately qualifies the certainty of the mineral resource potential assignment based on the number of datasets that contribute to each score (table 3). The product of the analysis is a map that indicates the relative level of potential, represented by red, yellow, and green colors for High, Medium, and Low respectively, and the relative level of certainty, represented by dark, medium, and light shades of the colors for High, Medium, and Low, respectively, for all of the 12-digit HUCs within Alaska (plate 1; see discussion above regarding 12-digit HUCs). The Unknown class represents a lack of data and is colored gray.

Mineral Resource Potential Estimation Method

The method for estimating the potential for sediment-hosted deposits begins with evaluating datasets with respect to the most distinctive parameters. These parameters are weighted accordingly and contribute to total scores for each HUC, which are then statistically analyzed to assign the high, medium, and low classifications for Pb-Zn potential. The most robust parameters are the sediment geochemistry and the lithologic dataset from the digital Geologic Map of Alaska (Wilson and others, 2015), owing to their systematic statewide coverage.

The most distinctive parameters for identifying HUCs with elevated prospectivity for sediment-hosted Pb-Zn deposits are the presence of (1) galena and sphalerite with or without barite in panned concentrates and high concentrations of Pb, Zn, and Ba in panned concentrates and stream sediments, (2) carbonate, fine-grained clastic sedimentary, or metasedimentary rocks, (3) Ag as a pathfinder element in the panned concentrate and stream sediment dataset, and (4) known occurrences, prospects, or deposits (table 2). As stated previously, it was not possible to do separate assessments for carbonate-hosted and CD Pb-Zn deposits because nearly all of the critical parameters used in the assessment are common to both. However, based on known occurrences and rock geochemistry, it is possible to determine in some regions whether there is higher potential for one deposit type or the other, and these are discussed in following sections.

Lithology

Host rocks for the two subtypes are distinct: carbonate versus fine-grained clastic rocks for CD Pb-Zn deposits. However, there are exceptions: some CD Pb-Zn deposits are hosted in carbonate layers within a thick clastic-dominated rock sequence. The statewide geologic map database contains units that commonly include mixed carbonate-clastic sequences that cannot be subdivided. Broad categories of three units important for sediment-hosted deposits were broken out as follows: (1) mostly carbonate; (2) mostly chemical, which includes fine-grained clastic rocks such as shale, argillite, mudstone, or siltstone, or chemical sedimentary rocks (for example, chert), and (3) mostly metasedimentary rocks. It should be noted that all three of these broad categories may contain rocks of the other two in any given area.

All three of these broad units were assigned 5 points for their general association with sediment-hosted Pb-Zn deposits. The points for these lithologies are not additive; thus, any HUC containing one or more of these units was assigned 5 points (table 2). In some cases, the 'nsaunits' table of the geologic map geodatabase (Wilson and others, 2015) specifically contained the words "barite" or "sphalerite," so these were queried and assigned 4 points. However, less than 10 results were found across the entire state, so the impact of these scores proved negligible.

Alaska Resource Data File

In order to constrain the search to identify sediment-hosted deposits, keywords in the ARDF that were as unique as possible to sediment-hosted Pb-Zn deposits were scored (appendix 2 of Kelley and others, 2020). Keywords referring to sediment-hosted deposits in the Deposit Model field, such as "sedimentary exhalative," "southeast Missouri Pb-Zn," "sediment-hosted," or "lead-zinc massive sulfide" were given high weight (5). High weights were also assigned to key minerals and associations, including galena, sphalerite, barite, smithsonite, and other secondary Pb- and Zn-bearing minerals, and their constituent elemental symbols (Ba, Pb, Zn). Other common but non-unique gangue minerals associated with sediment-hosted deposits, such as quartz, siderite, or carbonate were also given high weight. However, many Pb- or Zn-bearing deposit types other than sediment-hosted deposits contain similar ore and gangue minerals and associated element symbols. For example, volcanogenic massive sulfide (VMS) deposits (Kuroko, Cyprus, Besshi), orogenic gold deposits, sediment-hosted Cu (Bornite, Kennecott-type) and porphyry deposits may all contain galena, sphalerite, barite, quartz, and carbonate minerals as major constituents. Therefore, sufficiently negative scores were assigned to terms such as "Kuroko," "Cyprus," "Besshi," or "VMS" when they appeared in the Deposit Model field, effectively eliminating them from the present assessment. Most sediment-hosted Pb-Zn deposits contain low or negligible gold (Au) and copper (Cu) as opposed to the other deposit types listed above. For this reason, if Au or Cu are listed in the "Other commodity" or "Main commodity" fields, or if associated gold or chalcopyrite (or other Cu-bearing minerals) are listed in the "Ore minerals" field, they were assigned negative values (appendix 2 of Kelley and others [2020]). Polymetallic veins and replacement Pb-Zn deposits were difficult to separate from carbonate-hosted or CD Pb-Zn deposits, and some that are described as such in the ARDF records may actually be more appropriately classified as sediment-hosted deposits. Therefore, most of these remain as high scores in the ARDF dataset. Keyword totals (column N, appendix 3 of Kelley and others, 2020) were binned into a representative ARDF score of 3 points for weighted totals between 14 and 21, and 5 points for weighted totals of >21 (table 2 and appendix 3 of Kelley and others [2020]).

Stream Sediment Geochemistry

High concentrations of Ag, Ba, Pb, and Zn in stream sediments coincide with regions containing known deposits. Therefore, elevated abundances of these elements in sediments elsewhere indicate additional permissive areas for sediment-hosted Pb-Zn deposits. The scoring rubric for sediments is outlined in table 2. Each element (Ag, Ba, Pb, and Zn) was scored individually. When the concentration in sediment samples from a HUC exceeded 3.5× background for an element, a score of 4 points was assigned. If an element exceeded >7.5× background, a score of 8 points was assigned, and for those elements with >15× background, a score of 10 was assigned (table 2). Following the logic described above that most sediment-hosted Pb-Zn deposits contain minimal Cu, only HUCs with the above listed Ag, Ba, Pb, and Zn concentrations and Cu less than 3.5× background were scored. The maximum composite score for sediment chemistry was 40. Limiting the scores only to sediments with high Ag, Ba, Pb, and Zn but containing low Cu effectively eliminated some areas of known VMS, porphyry, sediment-hosted Cu, and orogenic gold deposits that commonly contain many if not all of the same elements (Ag, Ba, Pb, and Zn) that are pathfinders for sediment-hosted Pb-Zn deposits.

Heavy Mineral Concentrate Data

Mineralogy and chemistry from HMC samples are incorporated into the mineralization potential scoring as a measure of the presence of barite, galena, and sphalerite in a HUC. HUCs with concentrate samples containing sphalerite and galena were assigned one point and HUCs containing barite were assigned 1 point. Therefore, the maximum score available for the HMC mineralogy is 2 points (table 2).

Panned concentrate geochemistry was also used in the scoring. HUCs were scored based on Ag > 30 parts per million (ppm) (3 points), Ba >1000 ppm (3 points), Pb >200 ppm (3 points), and Zn >700 ppm (3 points), if Cu concentration was low (<150 ppm), similar to that described for the stream sediments. The threshold values for Ag, Ba, Pb, and Zn are approximately equivalent to the highest percentile grouping (for example, >90th percentile) with respect to the panned concentrate geochemistry dataset. The maximum score for the panned concentrate geochemistry is 12 points. Availability of HMC data, regardless of whether the score was zero (that is, no minerals of interest present) or more (that is, minerals of interest identified), contributed one point to HUC *certainty* scores; a lack of HMC data for a HUC—a null value—contributed no points to the *certainty* score for a HUC.

Results and Discussion

Areas identified by the geospatial scoring process in this study that have moderate to high potential for sediment-hosted Pb-Zn deposits include the (1) western and central Brooks Range, referred to as the Brooks Range zinc belt; (2) Seward Peninsula (and adjacent St. Lawrence Island); (3) Farewell terrane in Interior Alaska (Medfra, Lime Hills, and McGrath quadrangles); (4) two spatially distinct belts in east-central Alaska (Charley River, Black River, and Eagle quadrangles, and Livengood, Circle, and Big Delta quadrangles) (figure 1, plates 1 and 2); and (5) the central Alaska Range. All areas contain some known deposits, and that provides credibility to the scoring process. Some HUCs that have high potential for sediment-hosted Pb-Zn deposits are located adjacent to areas of known deposits and indicate the potential for expansion of known Pb-Zn districts. There are a few clusters of HUCs that have high potential in areas that have no known sediment hosted Pb-Zn occurrences, prospects, or deposits. There are sporadic HUCs with high potential in southeast Alaska, but nearly all known occurrences in these areas are poorly described as polymetallic veins in metamorphosed sedimentary rocks, with no clear indication of a genetic association with sedimentary Pb-Zn deposits, and therefore, these areas are not discussed further.

Brooks Range Zinc Belt

The western and central Brooks Range contain many known sediment-hosted deposits that form a belt informally referred to as the Brooks Range zinc belt (plate 2). The largest are the stratabound Red Dog deposits (CD Pb-Zn) and others in the district (Kelley and Jennings, 2004), and numerous deposits occur in a belt that extends about 75 kilometers (km) eastward from Red Dog to the Drenchwater deposit in the central Brooks Range (Werdon, 1996). All of the stratabound deposits are hosted in carbonaceous mudstone and shale of the Mississippian Kuna Formation of the Lisburne Group (Dumoulin and others, 1993; 2004). Paleogeographic reconstructions imply that carbonate platforms flanked the deeper water Kuna basin on three sides (Dumoulin and others, 2004). Numerous small but high-grade veins and breccias occur stratigraphically below the Kuna Formation in clastic rocks of the Upper Devonian to Lower Mississippian Endicott Group (table 1) and are interpreted to represent fluid flow pathways for metalliferous brines that ultimately formed deposits like Red Dog when such fluids interacted with reduced sediments near the seafloor (Werdon, 1999; Werdon and others, 2004). The vein-breccia occurrences extend well into the Killik River quadrangle east of Drenchwater (Kelley and others, 1997; 2000), but Drenchwater is the easternmost known stratabound CD Pb-Zn deposit hosted in Kuna Formation rocks. Although the vein-breccia occurrences are unlikely to be economic, their

Figure 1. Location map showing 1°×3° quadrangles and primary geographic features of Alaska.

presence suggests that the geologic processes necessary to form stratabound deposits like Red Dog were clearly prevalent over a very wide area.

All HUCs that contain a known occurrence in the Red Dog region and east to the Killik River quadrangle have high scores that reflect high potential, and because both sediment and panned concentrate samples contain high Ag, Ba, Pb and Zn, and there is permissive lithology, most of these HUCs have high certainty (plates 1 and 2). Owing to the fact that elements such as Ge and In are not widely reported in analyses of sediment samples, these elements were not weighted in scoring of statewide sediment geochemical data. However, sediments that were analyzed in the Red Dog district and Drenchwater deposit area contain sporadic relatively high In contents (up to 0.62 ppm and 0.17 ppm, respectively; Granitto and others, 2019). Germanium, which is another common pathfinder for some sediment-hosted Pb-Zn deposits, either (1) was not analyzed or (2) the lower limit of determination was too high (10 ppm) to be useful in sediment samples.

Surrounding the HUCs with known occurrences, a very consistent band of HUCs also has high potential but occurrences have not been reported (for example, several HUCs in the western Misheguk Mountain quadrangle between Red Dog and Drenchwater); these high scores are derived largely from permissive lithology and high total sediment scores (with or without panned concentrate geochemistry). There are HUCs with indicated high potential as far east as the Philip Smith Mountains quadrangle (fig. 1, plates 1 and 2), at least 600 km east of Red Dog. In addition, a band of medium potential HUCs (low to medium certainty) surrounds the belt of high-potential HUCs across the entire Brooks Range zinc belt (plate 1).

Geochemistry of variably mineralized rock samples from known deposits in the Brooks Range (Slack and others, 2004a, 2004b; Granitto and others, 2019) show high concentrations of Ag and Ba in addition to Pb and Zn; a few deposits (Red Dog deposits) have isolated high Cu concentrations and some have high Ge, In, and Tl (table 1 and appendix 1). The Ge and In contents in particular are highly enriched (823 ppm Ge and 5.3 ppm In maximum values); these values are more than 15.5× average crustal abundances, also known as the Clarke Index, compiled by Fortescue (1992) (table 5). Furthermore, both Ge and In have been recovered as byproducts of zinc concentrate processing. It is reported that by-product In (Roskill, 1992) and most of the Ge produced at the Trail Metallurgical Operation likely comes from sphalerite concentrates from the Red Dog deposits (Foley and others, 2017).

The main carbonate-hosted Pb-Zn deposits in the Brooks Range occur in the Baird Mountains quadrangle and include Powdermilk, Omar, Deadfall, Peak, and Frost (table 1 and plate 2). All of the occurrences are hosted in carbonate rocks of the Ordovician through Devonian Baird Group (Dumoulin and Harris, 1994; Till and others, 2008). However, Proterozoic(?) through Devonian carbonate and metacarbonate rocks in the Baird Mountains quadrangle (Wilson and others, 2015) are also prospective for carbonate-hosted deposits. Nearly all of the HUCs in the northwest quarter of the Baird Mountains quadrangle contain scores indicative of high potential (with high or medium certainty). These high scores are due almost exclusively to the presence of favorable lithologies (carbonate or metamorphosed equivalent) and high Ag, Ba, Pb, and Zn concentrations in stream sediment and panned concentrates. Rocks from some of these occurrences show elevated Ag, Co, Cu, Ga, Ge, In, and Tl (table 1 and appendix 1).

High scoring HUCs in the eastern Ambler River quadrangle are the consequence of elevated concentrations of Ag, Ba, Pb, and Zn (but less than 51.8 ppm Cu) in sediment samples (tables 2 and 3). These HUCs are coincident with known VMS deposits, but the total HUC scores in this region are not influenced by ARDF scores (in other words, the ARDF scores in these HUCs are zero) because the impact that VMS deposits have on the total ARDF scores was minimized. Thus, only the high Ag, Ba, Pb, and Zn concentrations in sediments and panned concentrates and presence of barite, galena, and sphalerite contributes to HUCs with high potential. Unlike many VMS deposits that contain only minor barite, the Arctic and other VMS deposits in the eastern part of the Ambler quadrangle contain high barite contents (Schmidt, 1986), and therefore have similar geochemical fingerprints to sediment-hosted Pb-Zn deposits. Alternatively, many of these HUCs contain metasedimentary or carbonate rocks in addition to volcanic rocks, and thus, potential for sediment-hosted Pb-Zn deposits should not be discounted. There is one occurrence within a high scoring HUC in the eastern Ambler River quadrangle that is described as a polymetallic vein in limestone, but little additional information is available. Similar polymetallic vein or Pb-Zn replacement deposits as listed in the ARDF files are in the Wiseman quadrangle east of Ambler River and many of these coincide with HUCs that contain underlying metasedimentary rocks and rate as high potential, but the lack of descriptive information about the occurrences prevents conclusive evidence about their classification.

Seward Peninsula and Adjacent St. Lawrence Island

Stratabound base-metal sulfide deposits and occurrences (Aurora Creek, Galena, Quarry, Wheeler North, Nelson; plate 2) are present in metasedimentary rocks of the Neoproterozoic and Paleozoic Nome Complex on south-central Seward Peninsula (Nome quadrangle; plate 2). The protoliths of the Nome Complex were part of the same late Proterozoic to Devonian continental margin as weakly deformed rocks in the Brooks Range, with the Nome Complex protoliths representing a carbonate platform (and related rocks) that underwent incipient rifting, probably during the Ordovician, followed by an influx of siliciclastic detritus during the Devonian (Till and others, 2014). Together these rocks underwent ductile deformation and metamorphism at blueschist and subsequent greenschist facies during the Jurassic and Early Cretaceous Brookian orogeny.

Although some workers have classified the deposits as epigenetic veins, VMS, or carbonate-replacement deposits, recent field and laboratory data suggest that these deposits represent different levels of CD Pb-Zn systems, with stratiform deposits like Aurora Creek and Wheeler North having formed either on the seafloor or in the shallow subsurface. The deformed veins such as Quarry and Galena are interpreted to have formed deep in the subsurface, possibly as feeders to overlying CD Pb-Zn deposits (Slack and others, 2014).

The Solomon and Bendeleben quadrangles adjacent to the Nome quadrangle have additional known prospects, occurrences, and deposits (table 1 and plate 1). Some of these (for example, Hannum, Omilak Creek) are described as replacement sulfides in marble, others (for example, Anugi) are described as Paleozoic stratiform sulfide bodies remobilized during Cretaceous or younger tectonic or intrusive events. Very little is known about many of these occurrences and therefore definitive classification is not possible, but underlying lithologies (carbonate, metasedimentary rocks) are permissive for CD Pb-Zn deposits.

On St. Lawrence Island, permissive rocks for CD Pb-Zn deposits include Mississippian to Triassic limestone, chert, shale, and siltstone (Patton and Dutro, 1969). Some stream sediment samples collected from a tributary to the Ongoveyuk River contain high Ag, Ba, and Zn, and these were interpreted as possibly related to base metal sulfide mineralization (Patton and Csejtey, 1972).

All occurrences and deposits described on the Seward Peninsula and St. Lawrence Island are within HUCs that scored high or medium in terms of potential (plate 1), with high certainty owing to high scores for multiple data layers (ARDF, lithology, sediment or panned concentrates geochemistry, or any combination of them). Widespread distribution of permissive lithologies include metamorphosed carbonate rocks and fine-grained clastic rocks (Till and others, 2011, 2014; Dumoulin and others, 2014a). A few adjacent HUCs also have high scores, even though occurrences or deposits of CD Pb-Zn or carbonate-hosted Pb-Zn deposits are not known in these basins (plates 1 and 2). For example, the far northwest part of the Bendeleben quadrangle contains two large HUCs with high resource potential; these have underlying metasedimentary rocks and anomalous concentrations of Ag, Ba, Pb, and Zn in sediment and panned concentrate samples. The dominant metals in mineralized samples from most of the known occurrences include Ag, Pb, and Zn; but Ba, Co, Cu, Ge, and Tl are enriched in some samples (table 1 and appendix 1).

Farewell Terrane

The Farewell terrane of interior Alaska consists of a Proterozoic basement complex, a Neoproterozoic-Devonian passive margin sequence, and enigmatic Devonian-Jurassic rocks of the Mystic subterrane (Dumoulin and others, 2018). Barite (for example, Gagaryah) and several unnamed and poorly described Pb-Zn deposits are known in the southern McGrath and northern Lime Hills quadrangles (table 1). Most of the Pb-Zn occurrences are hosted in the Ordovician to Silurian Post River Formation consisting of shales and limestones and are assumed to be CD Pb-Zn deposits, but they have not been studied in detail. The Gagaryah barite deposit is at least 640 meters (m) long and up to 39 m thick and is hosted in Devonian siltstone and shale but it lacks base metal sulfide minerals (Bundtzen and Gilbert, 1991). The nearby KC occurrence is similarly lacking in base metal sulfide minerals (Schmidt, 1997b).

The Farewell terrane rocks also host numerous carbonate-hosted deposits, particularly in the Medfra quadrangle (table 1; Schmidt, 1997b). The economically largest deposit is the Reef Ridge deposit, hosted by the Lower–Middle Devonian Whirlwind Creek Formation and interpreted by Schmidt (1997b) as an MVT deposit formed between the Late Cretaceous and early part of the Tertiary. Weathering of mineralized rock has oxidized most of the primary sulfides (pyrite/marcasite and sphalerite), and therefore Reef Ridge may be a supergene deposit formed from an MVT deposit (Santoro and others, 2015). In the oxidation zone, smithsonite is the predominant mineral. Most of the other smaller occurrences in the Medfra quadrangle are similar to Reef Ridge, but their extent and characteristics have not been described in detail.

Skarn deposits are also widespread in the Farewell terrane. Although keyword terms specific to skarn deposits were assigned negative scores to minimize their impact on ARDF scores, Pb- and Zn-bearing minerals in streams or rock samples from skarn deposits could add to the sediment and panned concentrate scores.

All known occurrences (for example, the presumed CD Pb-Zn and carbonate-hosted) are within HUCs that scored as high potential, with moderate to high certainty (plate 1). The high scores are based on contributions from known deposits and underlying favorable lithologies (plate 2), as well as sediment and panned concentrate samples with high Ag, Ba, Pb, or Zn concentrations. A few sediment samples contain In concentrations up to 0.3 ppm, and Ge contents from 13.5 to 23.4 ppm (Granitto and others, 2019), but it is unclear whether these sediment samples reflect mineralized areas. Nonetheless, they are both common pathfinder elements for some sediment-hosted massive sulfide deposits. Multiple high-potential HUCs with favorable lithologies are also identified east of the Gagaryah barite deposit in the Lime Hills quadrangle and surrounding the known base metal occurrences in the southern McGrath quadrangle, even though there are no known barite or base metal occurrences. More difficult to explain are high-potential HUCs in the northeast quadrant of the Lime Hills quadrangle (outside of area identified as Farewell Terrane; plates 1 and 2) because these HUCs are underlain primarily by Tertiary intrusive rocks with very few sedimentary rock units exposed at the surface. The HUC scores in this area are based exclusively on sediment and panned concentrate geochemistry (Ag, Pb, and Zn without high Ba). As discussed above, many different types of deposits may contribute such metals to drainage basins. Although some known polymetallic veins and porphyry Cu-Mo deposits in the area were successfully minimized in terms of contributing ARDF scores to the total HUC score, the deposits nevertheless contribute base metal sulfide minerals to streams and add to the sediment and panned concentrate scores.

Geochemical data for rocks from specific known occurrences are not available. However, select sedimentary rocks from the Medfra, McGrath, and Lime Hills quadrangles (for example, Farewell terrane) described in the AGDB (Granitto and others, 2019) as mineralized fine-grained clastic rocks, carbonate, fine-grained clastic, and undivided rocks were retrieved from archives and resubmitted for geochemical analyses. Some of these samples contain very high Ag, Ba, Co, Cu, Ga, In, Pb, and Zn (appendix 1) and support the conclusion that the Farewell terrane has potential for sediment-hosted deposits.

East-central Alaska

Black River, Charley River, and Eagle Quadrangles

A remote region on the northeast side of the Yukon Flats basin in east-central Alaska (Charley River, Black River, and Eagle quadrangles) is underlain by a thick sequence of limestone as well as dolostone and calcareous shale and black chert originally assigned to the Porcupine River sequence (Churkin and Brabb, 1967). The oldest units are Neoproterozoic to Lower Cambrian rocks of the Tindir Group (Dover, 1994), overlain by a thick sequence of Paleozoic passive-margin sediments. The early Permian Tahkandit Limestone unconformably overlies the older units (Gehrels and others, 1999). The Devonian graptolitic shale, limestone, and chert in the Porcupine River area (Churkin and Brabb, 1967) are interpreted to have accumulated in a slope or basin environment and may correlate with the Ordovician to Early Devonian Road River Formation (Churkin and Brabb, 1965; Brabb and Churkin, 1969) that is prevalent in the Selwyn Basin area in Yukon and Northwest Territories, Canada, and which hosts many CD Pb-Zn deposits. Conodonts and megafossils in these Devonian rocks have chiefly Laurentian (North American) affinities (Oliver and others, 1975; Savage and others, 1985; Rohr and Blodgett, 1994).

Both carbonate-hosted Pb-Zn and CD Pb-Zn deposits are known in the region. One of the carbonate-hosted occurrences is Step Mountain, described by Schmidt (1997b) as primarily smithsonite in limestone breccia zones and lenses within the early Permian Tahkandit Limestone. Other occurrences (Three Castle Mountain, Pleasant Creek and Midnight Hill) occur in Neoproterozoic dolostones of the Tindir Group, or Early Cambrian Funnel Creek Limestone (for example, VABM Casca), and can include sphalerite as a primary phase. Some phosphate and uranium occur with the Zn mineralization at VABM Casca and Three Castle Mountain occurrences (Schmidt, 1997b).

The HUCs that contain these occurrences were rated as having moderate potential (medium certainty; plate 1). Lithology and ARDF scores contributed to total scores, and many of the HUCs contain sediment samples with high Zn concentrations, without Ag, Ba, or Pb, and thus the sediment scores are relatively lower than might be expected for occurrences that contain multiple base metal sulfides (for example, galena) or barite. Furthermore, panned concentrate data are not available for the area, thereby lowering total scores as well as level of certainty due to the lack of panned concentrate geochemistry or mineralogy layers available for the assessment. Several HUCs with high potential ratings (and high levels of certainty) are located immediately south of the known occurrences in the southern part of the Charley River and northern part of the Eagle quadrangle. These HUCs contain similar lithologies as those that host the known occurrences to the north, and sediment samples contain high Zn and Ba, resulting in overall higher scores contributed by the sediment geochemistry. However, there are no known carbonate-hosted deposits in these HUCs (plate 2).

Although most of the occurrences described above are best considered carbonate-hosted Pb-Zn deposits, a few have characteristics more aligned with CD Pb-Zn deposits. The Hard Luck Creek prospect (Charley River quadrangle) is hosted in a sequence of sedimentary rocks that includes the Road River Formation, although some of the mineralization is within Neoproterozoic to Lower Cambrian Tindir Group rocks. Similar to other occurrences discussed above, the Hard Luck Creek area is in a HUC that was rated as moderate potential (moderate certainty).

Similar to the Farewell terrane discussed above, geochemical data for specific known occurrences are not available. Carbonate, fine-grained clastic rocks, and undivided rocks from the Charley River, Black River, and Eagle quadrangles as described in the AGDB (Granitto and others, 2019) were retrieved and submitted for analyses. Barium and zinc concentrations are elevated in a few samples, but otherwise appear to be unmineralized (appendix 1).

Big Delta, Circle, and Livengood Quadrangles

Metasedimentary and metaigneous rocks of uncertain age and origin occur in parts of the Big Delta, Circle, and Livengood quadrangles of east-central Alaska (Menzie and Foster, 1978; (Dusel-Bacon and others, 2006). Stratigraphic relationships between assemblages in this part of the Yukon-Tanana Upland are difficult to decipher due to poor exposure and limited age control. The informal “Chena slate belt” is a roughly 75 km-long belt in the northern Big Delta quadrangle that contains the Blackshell unit of Late Devonian and Early Mississippian age (Dusel-Bacon and others, 1998; 2006). The Blackshell unit consists of siliceous and carbonaceous black quartzite, slate, and phyllite. Based on stratigraphic similarities and limited fossil ages and a U-Pb zircon age of 356 Ma, Mortensen (1992) interpreted that the rocks are similar to metamorphosed rocks in the eastern Alaska Range and western and southeastern Yukon, as well as unmetamorphosed rocks of the Selwyn Basin (Murphy and Abbott, 1995).

Several CD Pb-Zn deposits are known in the region. Carbonaceous black phyllite and quartzite host Pb-Zn occurrences near Teuchet Creek, Mount Schwatka, and Drone Creek (Dusel-Bacon and others, 1998; 2006). At Drone Creek, stream-sediment sampling defined a 30-km belt of anomalous Zn. In 1991, additional soil and rock geochemistry, gravity, and electromagnetic (EM) surveys delineated a Pb-Zn zone that was subsequently drilled. At the Teuchet Creek property, foliation-parallel and disseminated sulfides (primarily pyrite, sphalerite, and galena) occur in carbonaceous phyllite and quartzite (Dusel-Bacon and others, 2006).

The HUCs that contain these occurrences were scored as moderate or high potential (plates 1 and 2). Lithology, ARDF, sediment, and (or) panned concentrates with high Zn and Pb (or any combination of them) contributed to total scores. North of the Teuchet Creek and Drone Creek occurrences in the Circle quadrangle is a broad area that defines a zone from west to east, containing sediment and panned concentrates with base metal sulfide anomalies, and underlain by metasedimentary rocks. However, there are no known Pb-Zn occurrences in the region, and few exploration or detailed studies have been performed in the area. Therefore, it is not certain whether or not the geochemical anomalies reflect sediment-hosted occurrences or are related to other types of deposits, in particular VMS deposits that are known to occur.

Central Alaska Range

An extensive area in the central Alaska Range (Denali and Healy quadrangles) is characterized by medium- or high-potential HUCs that are underlain by permissive host rocks (plate 2). In addition to lithology, ARDF scores contributed to some of the HUCs. Sediment samples with high Ag, Pb, or Zn concentrations also contributed to some of the HUCs. However, most of the occurrences in this region are described as polymetallic veins in metamorphosed rocks. As stated earlier, these types of veins will generate many of the same geochemical anomalies (Ag, Pb, and Zn) as stratiform sulfide bodies. Therefore, many of the high-potential HUCs in this region may be unrelated to typical sediment-hosted deposits.

One exception is the Canyon Creek occurrence (plate 2), which is described as a possible CD Pb-Zn occurrence hosted in graphitic schist of the upper Precambrian Birch Creek Schist (Bundtzen, 1981). The graphitic schist is commonly weathered to an orange-red color and stream channels draining the unit are coated with iron oxide precipitate. Pyrite is disseminated in the graphitic unit, but sphalerite or galena has not been identified. However, zinc concentrations in streams collected below the graphitic schist are as high as 540 ppm with local high concentrations of lead (Bundtzen, 1981). Results of EM and aeromagnetic surveys are consistent with a response to a massive sulfide deposit; the result of the magnetic survey suggests that graphite is not the sole conductor (Thornsberry and others, 1984). Other occurrences near Canyon Creek are described as veins in graphitic schist or marble, but detailed information is lacking. The Busby occurrence (plate 2) is described as galena-bearing silver-rich veins and lenses in black schist and limestone, which are permissive host rocks, but zinc contents are generally low (Conwell, 1973), suggesting this is not a typical sediment-hosted Pb-Zn deposit.

In general, although large regions in the Central Alaska Range are rated as having high potential for sediment-hosted Pb-Zn deposits (plates 1 and 2), most of the geochemical anomalies in stream sediments appear to be caused by polymetallic veins and sulfide-bearing shear zones within metasedimentary rocks. Although some of the veins or sulfide lenses may in fact be stratabound sediment-hosted occurrences, it is not possible to definitely reach this conclusion without further investigation. Similarly, scattered high-potential HUCs in southeast Alaska and in the Anchorage quadrangle and further east in the McCarthy quadrangle most likely reflect polymetallic veins unrelated to sediment-hosted Pb-Zn deposits.

Summary and Conclusions

The state-wide GIS-based analysis of publicly available datasets included evaluation and scoring of key parameters unique to sediment-hosted Pb-Zn deposits (including carbonate-hosted and CD Pb-Zn deposits): (1) the presence of carbonate, fine-grained clastic sedimentary, or metasedimentary rocks; (2) the presence of galena and sphalerite with or without barite in panned concentrates and high concentrations of Ag, Pb, Zn, and Ba (with low concentrations of Cu) in panned concentrates and stream sediments; and (3) known occurrences, prospects, or deposits scored for keywords relevant to sediment-hosted deposits. Although data are sparse, some identified high-potential areas also contain sediment or rock samples with elevated concentrations of Ge and In. Both of these elements are known to be good pathfinder elements for sediment-hosted deposits.

The primary areas of interest identified in the analysis include (1) the Brooks Range zinc belt with multiple known CD Pb-Zn deposits in the Red Dog district and carbonate-hosted deposits in the Baird Mountains area; (2) the Seward Peninsula and adjacent St. Lawrence Island; (3) the Farewell terrane; (4) East-central Alaska; and (5) the Central Alaska Range. Most of the high-potential areas with known deposits within these broad belts contain medium to high prospectivity in areas that surround them, indicating strong potential for expansion of areas that may contain Pb-Zn deposits. The results also indicate a few areas that do not contain known sediment-hosted Pb-Zn occurrences. These areas warrant further evaluation with respect to data quality and favorability of depositional and tectonic setting. Other areas are clearly lacking in data and are poorly understood in terms of geology. Therefore, prospectivity is not well constrained.

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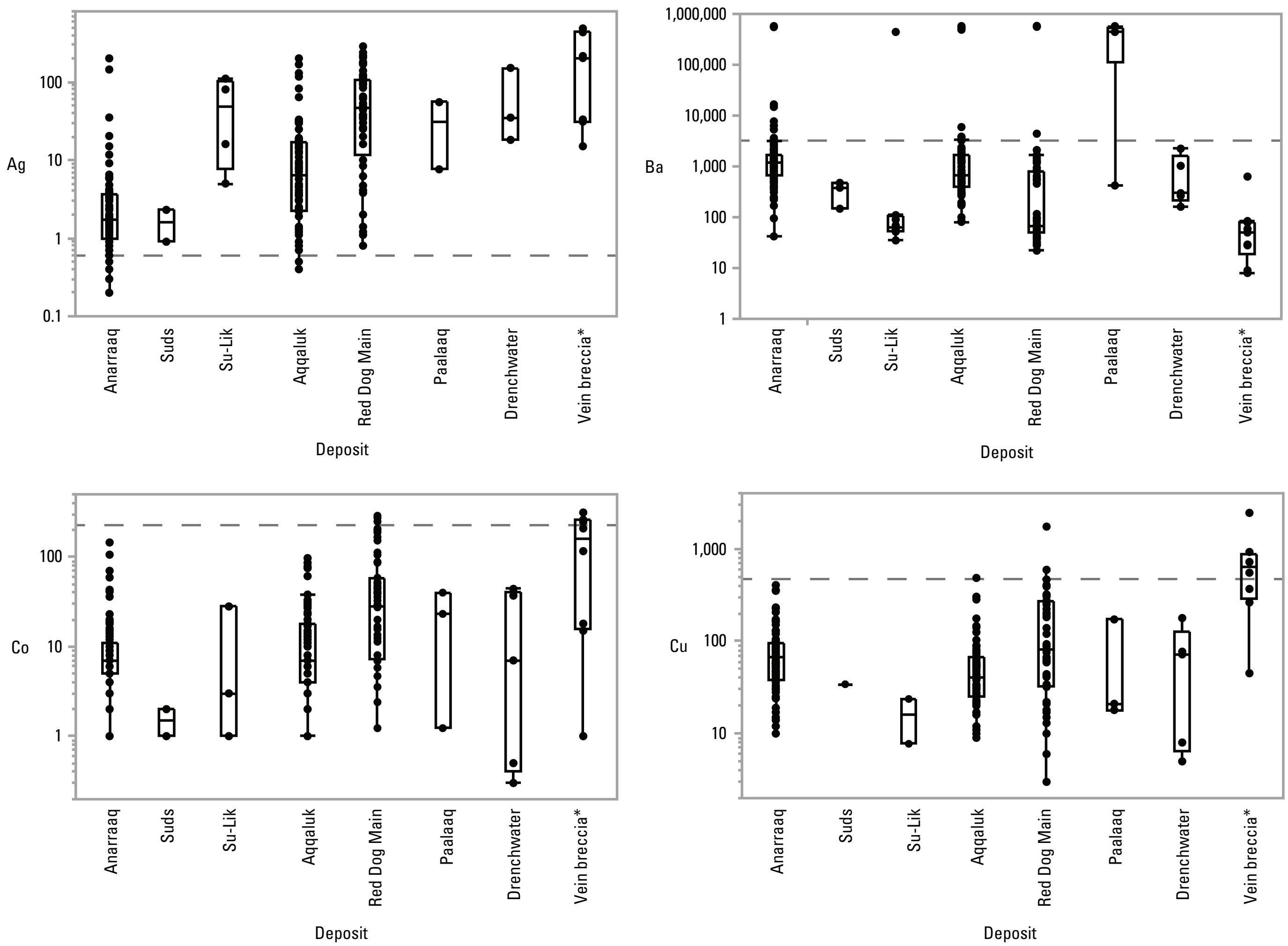
Appendix 1. Boxplots of select elements in rock samples from areas with high potential

Brooks Range zinc belt: CD Pb-Zn deposits (for location descriptions, see Table 1); *, includes all vein breccia occurrences from Table 1



Boxplot explanation

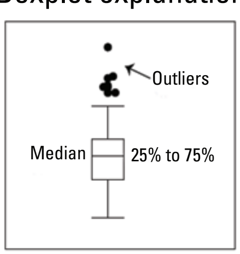


Figure 1.1. Brooks Range zinc belt—CD Pb-Zn deposits (for location descriptions, see table 1); *, includes all vein breccia occurrences from table 1; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.

Brooks Range zinc belt: CD Pb-Zn deposits (Cont)

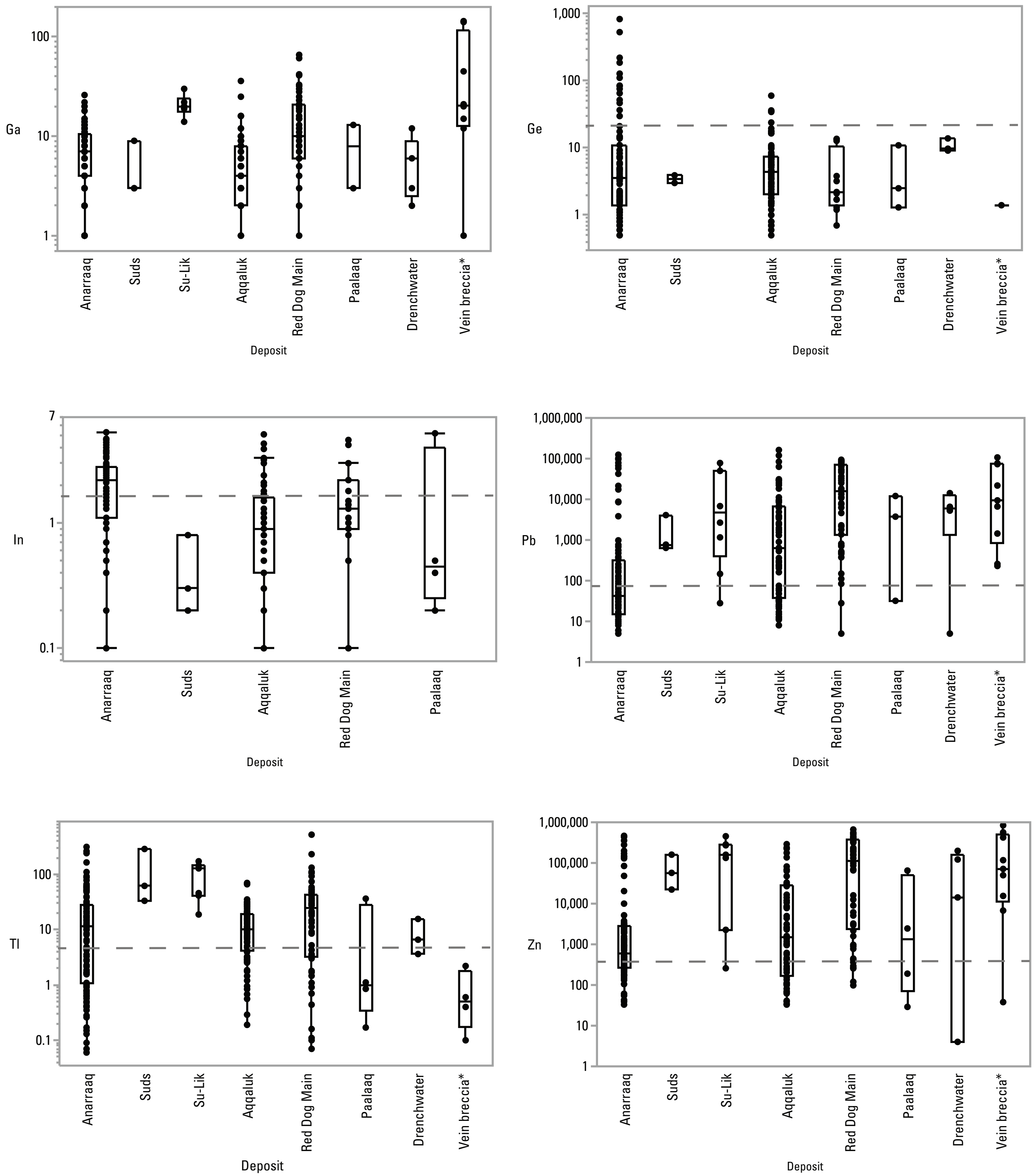


Figure 1.1. Brooks Range zinc belt—CD Pb-Zn deposits (for location descriptions, see table 1); *, includes all vein breccia occurrences from table 1; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot—Continued

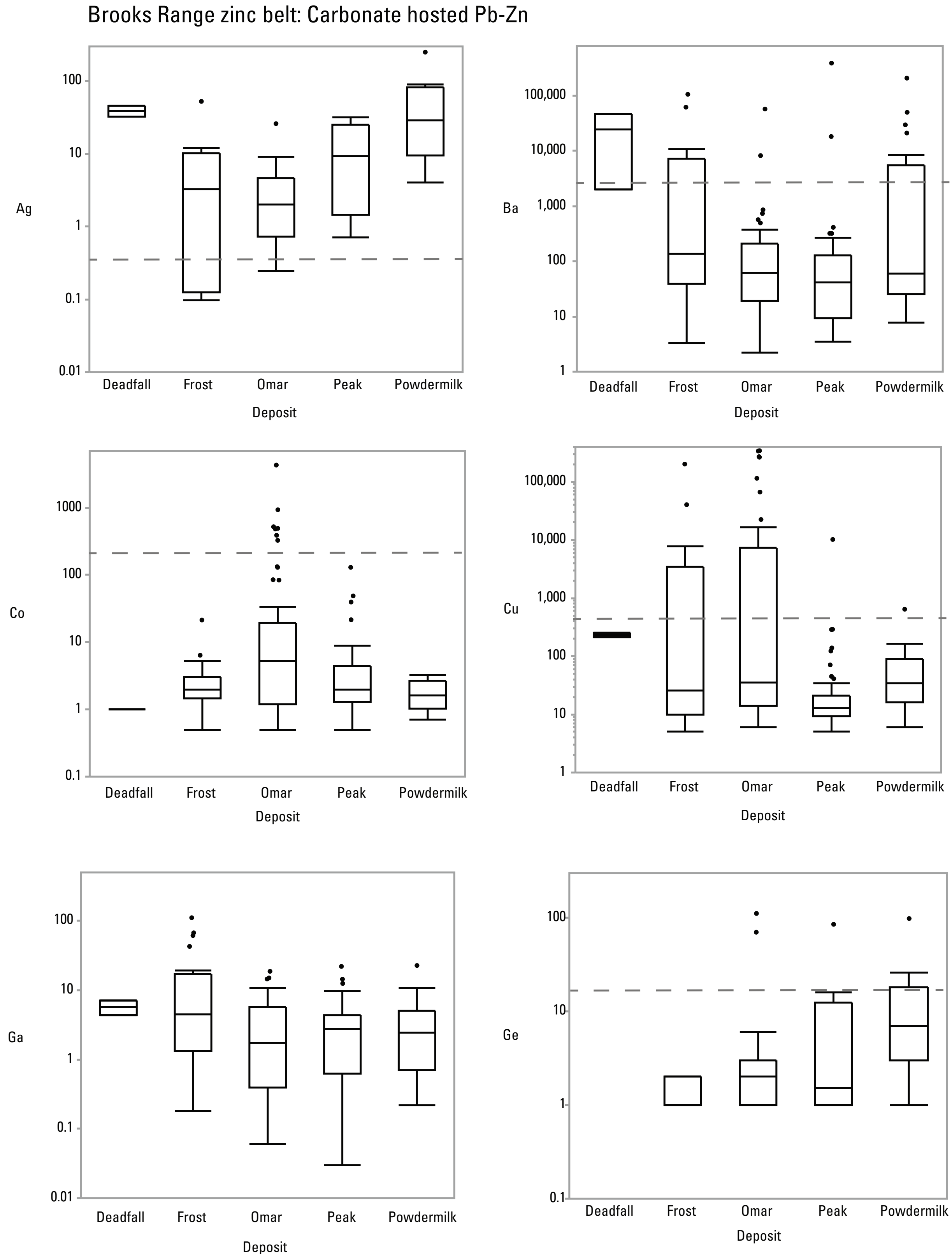


Figure 1.2. Brooks Range zinc belt—Carbonate hosted Pb-Zn; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.

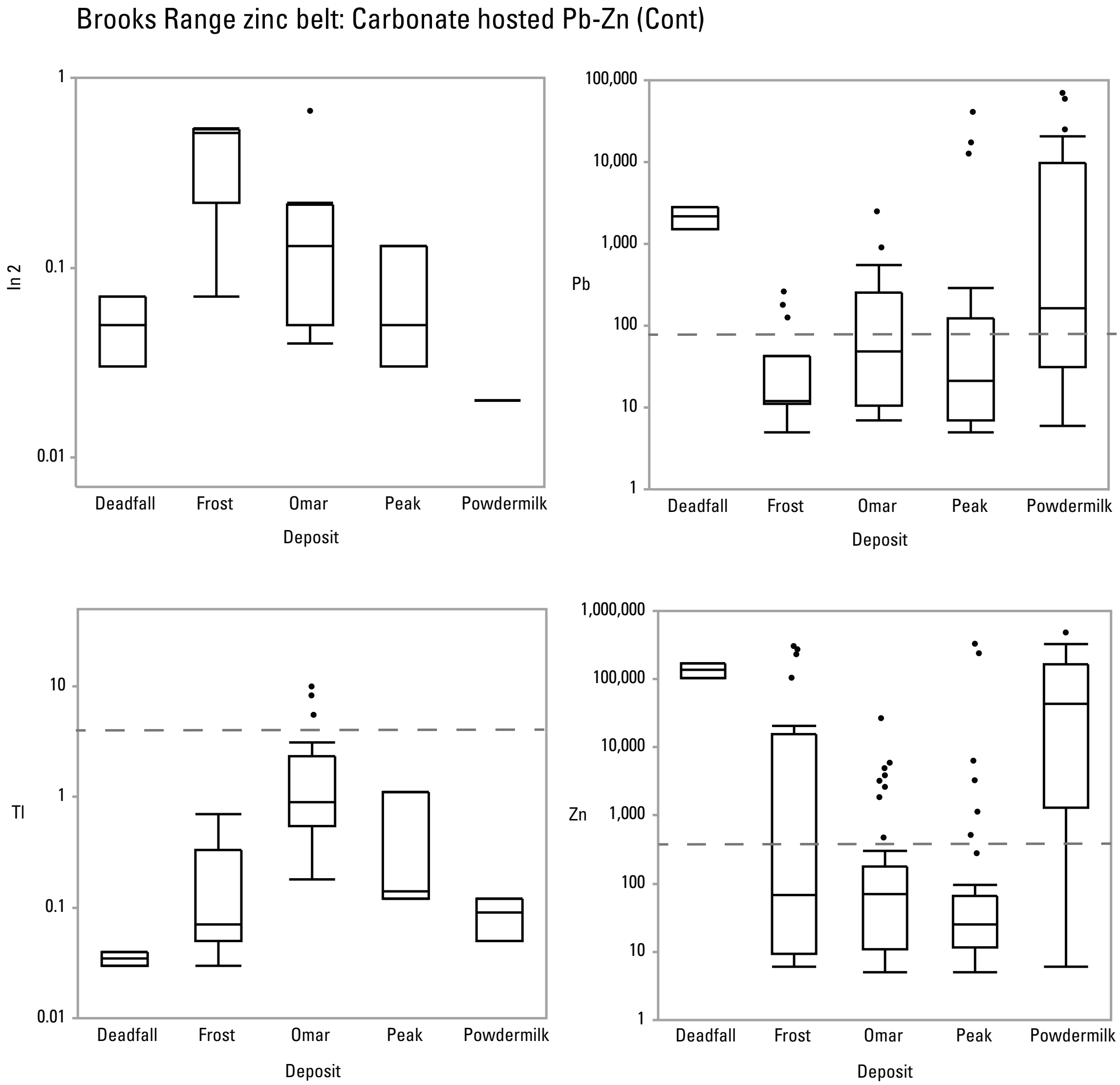


Figure 1.2. Brooks Range zinc belt—Carbonate hosted Pb-Zn; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.—Continued

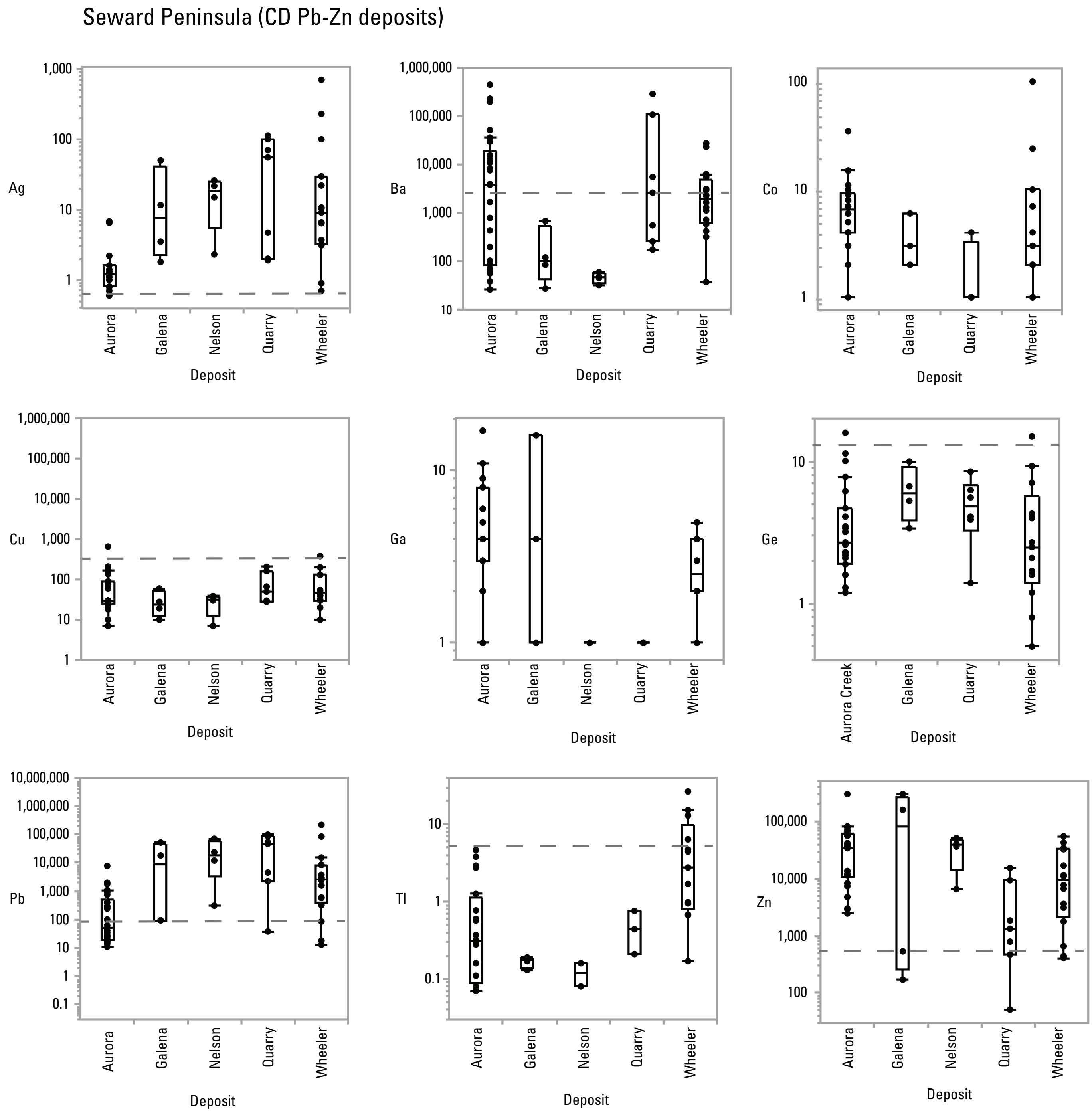


Figure 1.3. Seward Peninsula—CD Pb-Zn; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.

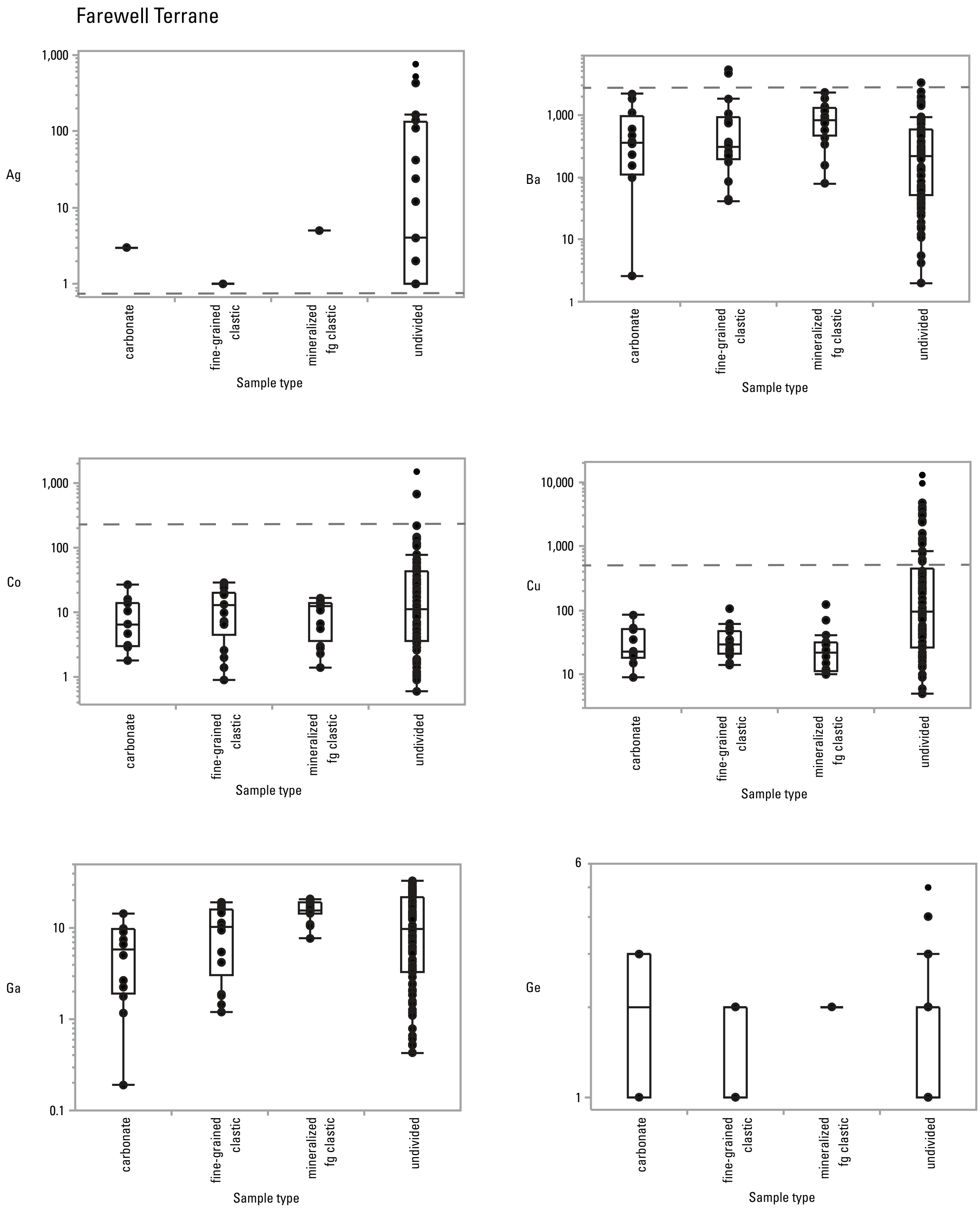


Figure 1.4. Farewell Terrane; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.

McGrath-LimeHills-Medfra

Farewell Terrane (Cont)

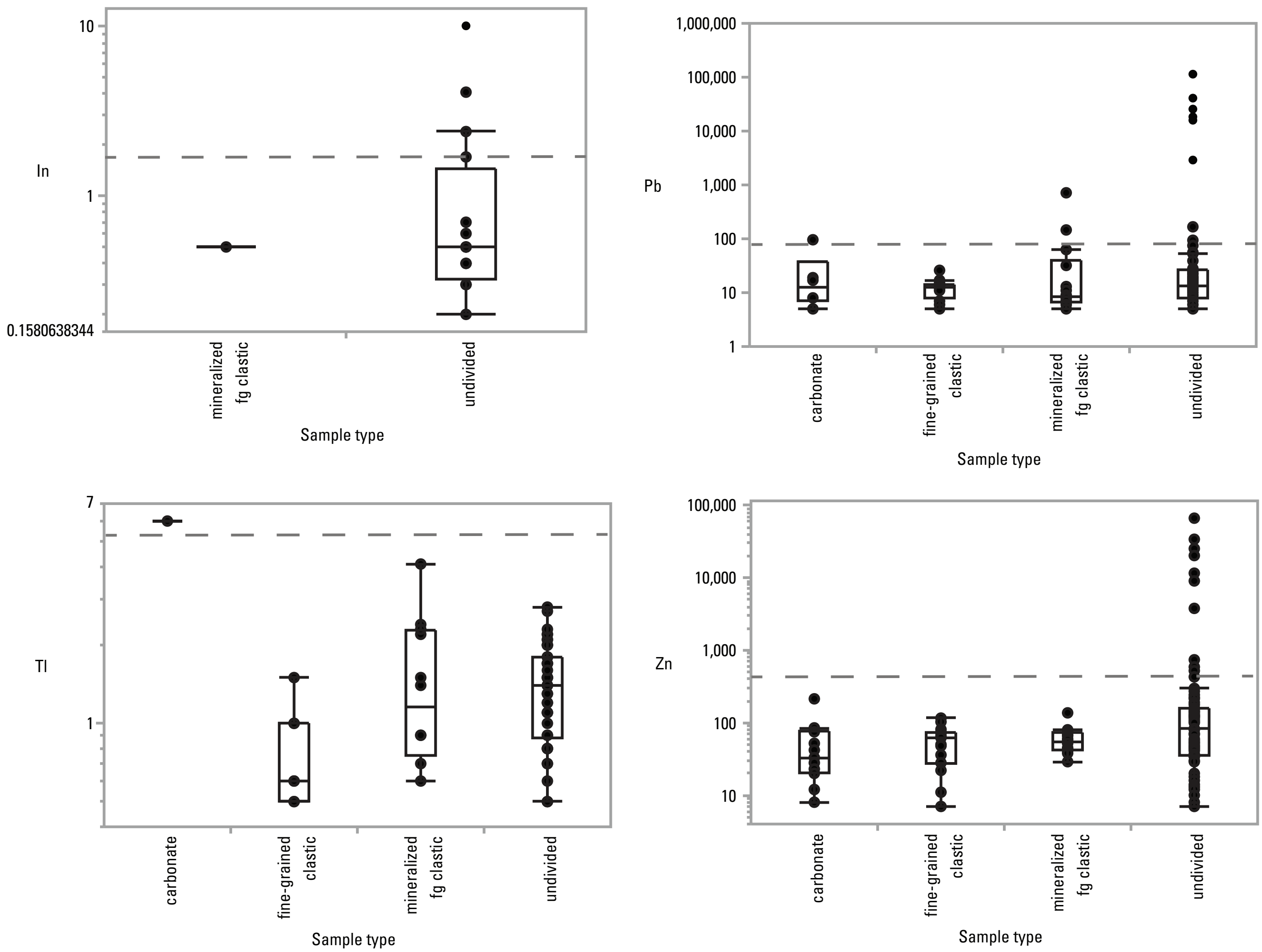


Figure 1.5. Farewell Terrane—McGrath-LimeHills-Medfra; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.

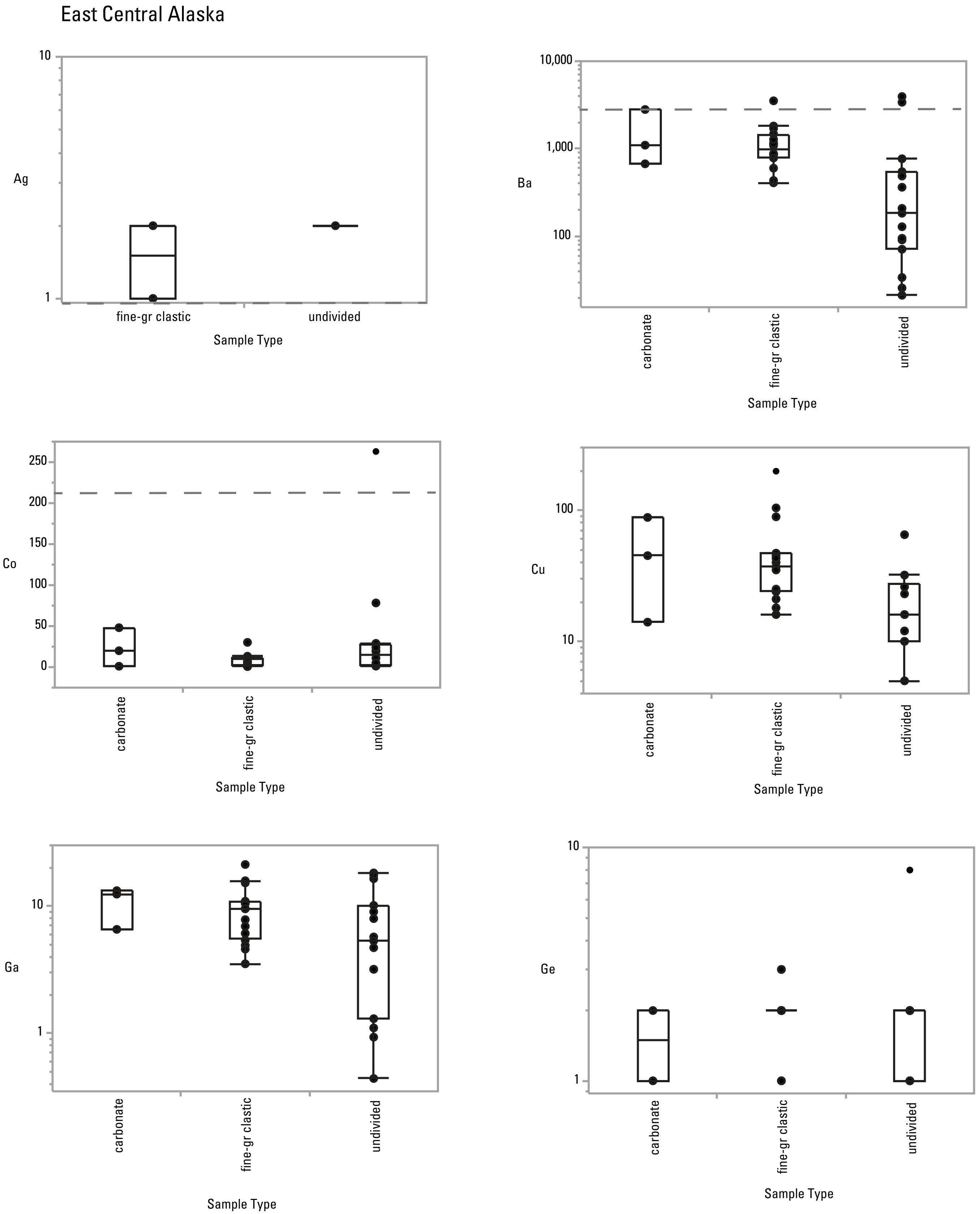


Figure 1.6. East Central Alaska; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.

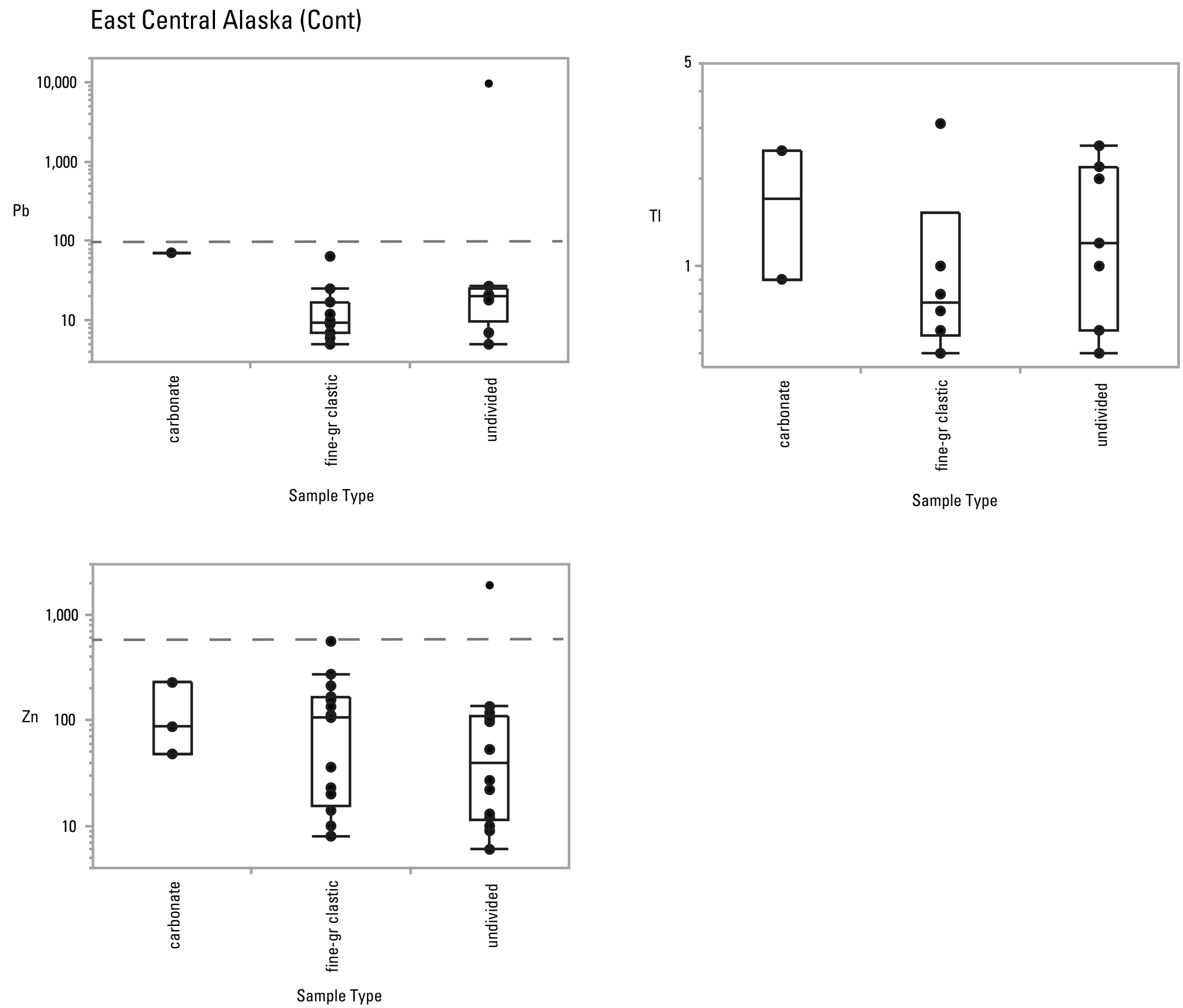


Figure 1.6. East Central Alaska; all element concentrations are in parts per million; the dashed horizontal line indicates 7.5 times Clarke value (Table 5). If dashed line is not shown on plot, the 7.5 times Clarke value is higher than the concentration range shown by the plot.—Continued

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