Physical Properties of Carbonate-Hosted Nonsulphide Zn-Pb Mineralization in Southern (NTS 082F/03) and Central (NTS 093A/14E, 15W) British Columbia

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Introduction

Carbonate-hosted, nonsulphide base metal (CHNSBM) deposits form in supergene environments from sulphide deposits such as Mississippi Valley-type (MVT), sedimentary-exhalative (SEDEX), Irish-type and vein-type deposits and, to lesser extent, skarns. Carbonate-hosted sulphide deposits in the Kootenay terrane, adjacent Cariboo terrane and elsewhere in British Columbia (Figure 1), have near-surface Zn- and Pb-bearing–oxide gossans (Simandl and Paradis, 2009; Paradis et al., 2010, 2011). The metals, liberated during the weathering of sulphides, can be trapped locally, forming direct-replacement CHNSBM deposits or they can be transported by percolating waters down and away from the sulphide protore, forming wallrock-replacement CHNSBM deposits (Heyl and Bozion, 1962; Hitzman et al., 2003; Simandl and Paradis, 2009).

Neither direct-replacement nor wallrock-replacement CHNSBM deposits in BC have been comprehensively characterized. The characterization of these deposits is essential for the formulation of integrated exploration programs targeting CHNSBM deposits. Zn or Pb oxides, silicates and carbonates may also represent indirect indicator minerals in exploration for MVT, SEDEX, Irish-type and vein-type Zn-Pb deposits (i.e., Zn-Pb sulphide precursors to CHNSBM deposits).

Gravity, magnetic, electromagnetic, radiometric and seismic surveys all provide methods to determine the three-dimensional geometry of host rock, cover and exploration targets. To identify the sources of geophysical anomalies, it is necessary to identify the physical property fingerprints of each rock type and formation in the area.

Keywords: *zinc-lead deposits, nonsulphides, carbonate-hosted, geophysical surveys, physical properties, density, magnetic susceptibility, electrical resistivity, Salmo district, Quesnel Lake area*

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In the analysis of CHNSBM deposits, the physical properties of the host rocks, parent sulphide mineralization and the target nonsulphide deposits must all be characterized. A ground gravity survey of the Cariboo Zinc property (Luckman, 2008) revealed partial correlation between known Pb-Zn showings and positive Bouguer gravity anomalies, as well as some enigmatic small negative anomalies. In analyzing this survey, Paradis et al. (2010) stated "Knowledge of physical properties of nonsulphide mineralization in the Cariboo Zinc district would greatly improve the quality of the interpretation, but such data are not presently available."

This knowledge gap is addressed by presenting new measurements on the density, magnetic and electrical properties of a representative set of hand samples collected from one Pb-Zn mineralization camp (i.e., Salmo camp) in the Kootenay Arc of southern BC, and one mineral camp (i.e., Cariboo Zinc property) in the Quesnel Lake area of east-central BC. The study forms one part of Geoscience BC Project 2009-030: "Geology and mineralogy of carbonate-hosted nonsulphide Zn-Pb mineralization in southern (NTS 082F/03) and central BC (NTS 093A/14E, 15W)".

Carbonate-Hosted Nonsulphide Zn-Pb Deposits

Nonsulphide deposits were the main source of zinc prior to the 1930s, but following the development of differential flotation and breakthroughs in smelting technology, the mining industry turned its attention to sulphide ore. Today, most zinc is derived from sulphide ore (Hitzman et al., 2003; Simandl and Paradis, 2009). The situation is changing further, as evidenced by the successful operation of a dedicated processing plant to extract zinc metal, through direct acid leaching, solid-liquid separation, solvent extraction and electrowinning, from nonsulphide and mixed ores mined at the Skorpion mine, Namibia.

Wallrock-replacement deposits can be located in proximity to protore (primary ore) or several hundreds of metres away (Heyl and Bozion, 1962; Hitzman et al., 2003; Reichert and

Borg, 2008). The direct-replacement nonsulphide deposits are also known as 'red ores' because they consist commonly of Fe-oxyhydroxides, goethite, hematite, hemimorphite, smithsonite, hydrozincite and cerussite; they typically contain >20% Zn, >7% Fe and Pb±As. The wallrock-replacement deposits know as 'white ore' consist of smithsonite, hydrozincite and minor Fe-oxyhydroxides, and contain <40% Zn, <7% Fe and very low concentrations of Pb. Wallrock-replacement deposits are commonly rich in Zn and poor in Pb relative to the direct-replacement CHNSBM deposits (Simandl and Paradis, 2009) and, from a metallurgical and environmental perspective, white ores are simpler and preferable.

Historically, it was believed that BC did not have a significant potential to host economic CHNSBM deposits because it was subjected to several periods of glaciation. It is now convincingly established, that given favourable morphology and orientation, CHNSBM deposits can survive glaciations, making these deposits legitimate exploration targets in the province. Introductory papers on carbonate-hosted nonsulphide Zn-Pb deposits of the southern Kootenay Arc (Simandl and Paradis, 2009) and on the sul-

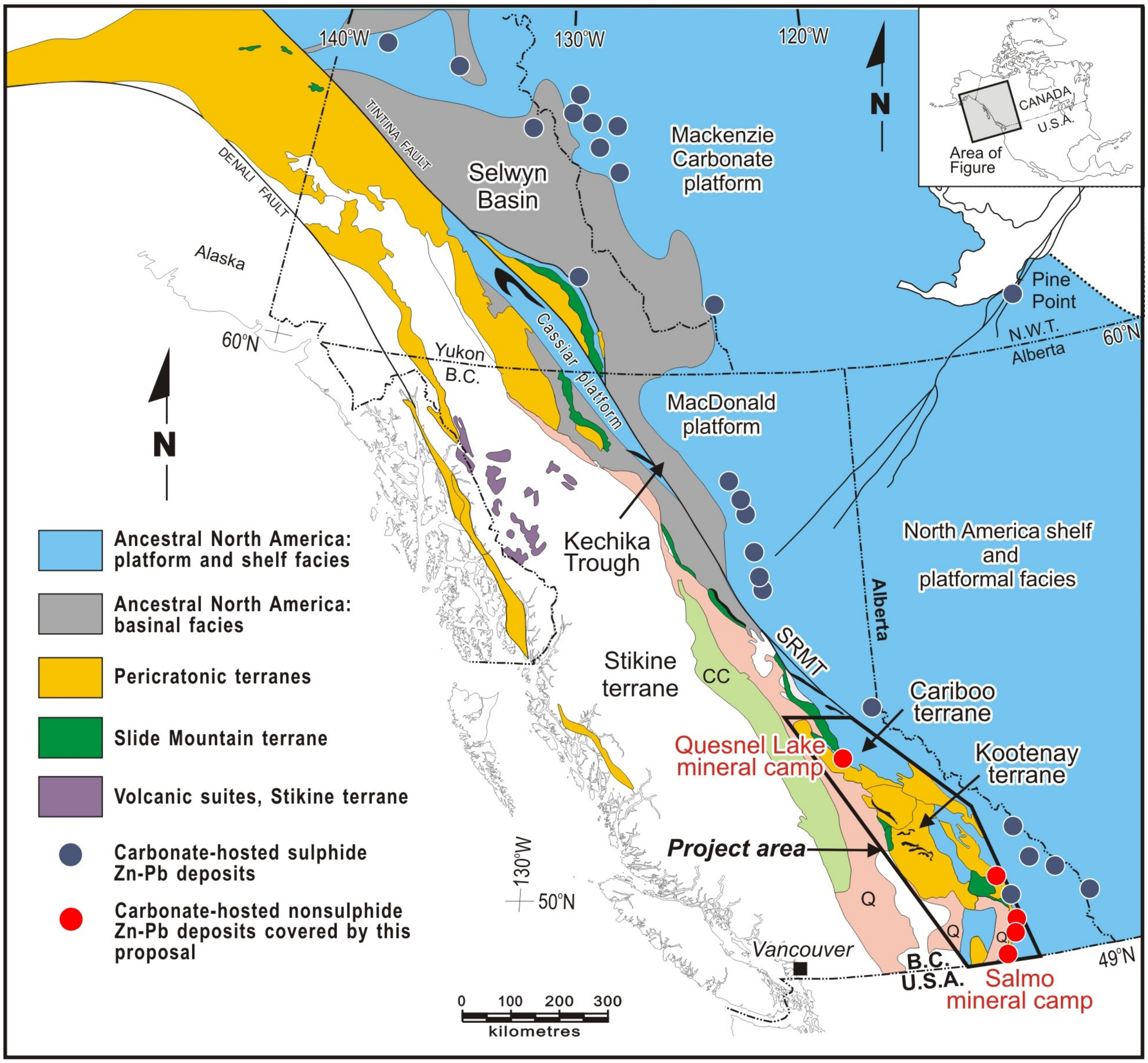

Figure 1. Location of the project area, south-central British Columbia, with respect to other significant carbonate-hosted sulphide and nonsulphide occurrences in the northern cordillera (modified from Nelson et al., 2002, 2006). Samples for this study were collected from the Salmo and Quesnel Lake mineral camps. Abbreviations: CC, Cache Creek terrane; Q, Quesnel terrane; SRMT, Southern Rocky Mountain Trench.

phide/nonsulphide Pb-Zn mineralization of the Quesnel Lake area (Paradis et al., 2010), describe examples of these deposit-types located in British Columbia, but detailed mineralogical and geochemical characterization of ore minerals was not done at the time. The companion paper (Paradis et al., 2011) discusses the complementary mineralogical and geochemical analyses of these same samples and places them in their geological context.

Regional Geology

The areas of interest are located in the Salmo camp of the southern Kootenay Arc of southeastern BC (NTS 082F/03) and the Cariboo Zinc property, Quesnel Lake area of east-central BC (NTS 093A/14E, 15W; Figures 1, 2). The Kootenay Arc is an arcuate belt of complexly deformed rocks extending at least 400 km from near Revelstoke to the southwest across the Canada–United States border (Fyles, 1964). The Kootenay Arc lies between the Purcell Anticlinorium in the Purcell Mountains to the east and the Monashee metamorphic complex to the west, and it is part of the Kootenay terrane. The arc consists of a thick succession of thrust-imbricated Proterozoic to Early Mesozoic miogeoclinal to basinal strata derived from sedimentary and volcanic protoliths (Brown et al., 1981). Colpron and Price (1995) outlined a regionally coherent stratigraphic succession in the Kootenay Arc. The lower part is composed of siliciclastic and carbonate rocks of the Eocambrian Hamill/Gog Group and Mohican Formation. These are overlain by the archaeocyathid-bearing carbonate rocks of the Early Cambrian Badshot Formation and its equivalent, the Reeves Member of the Laib Formation (Fyles and Eastwood, 1962; Fyles, 1964; Read and Wheeler, 1976), which host a number of Zn-Pb sulphide

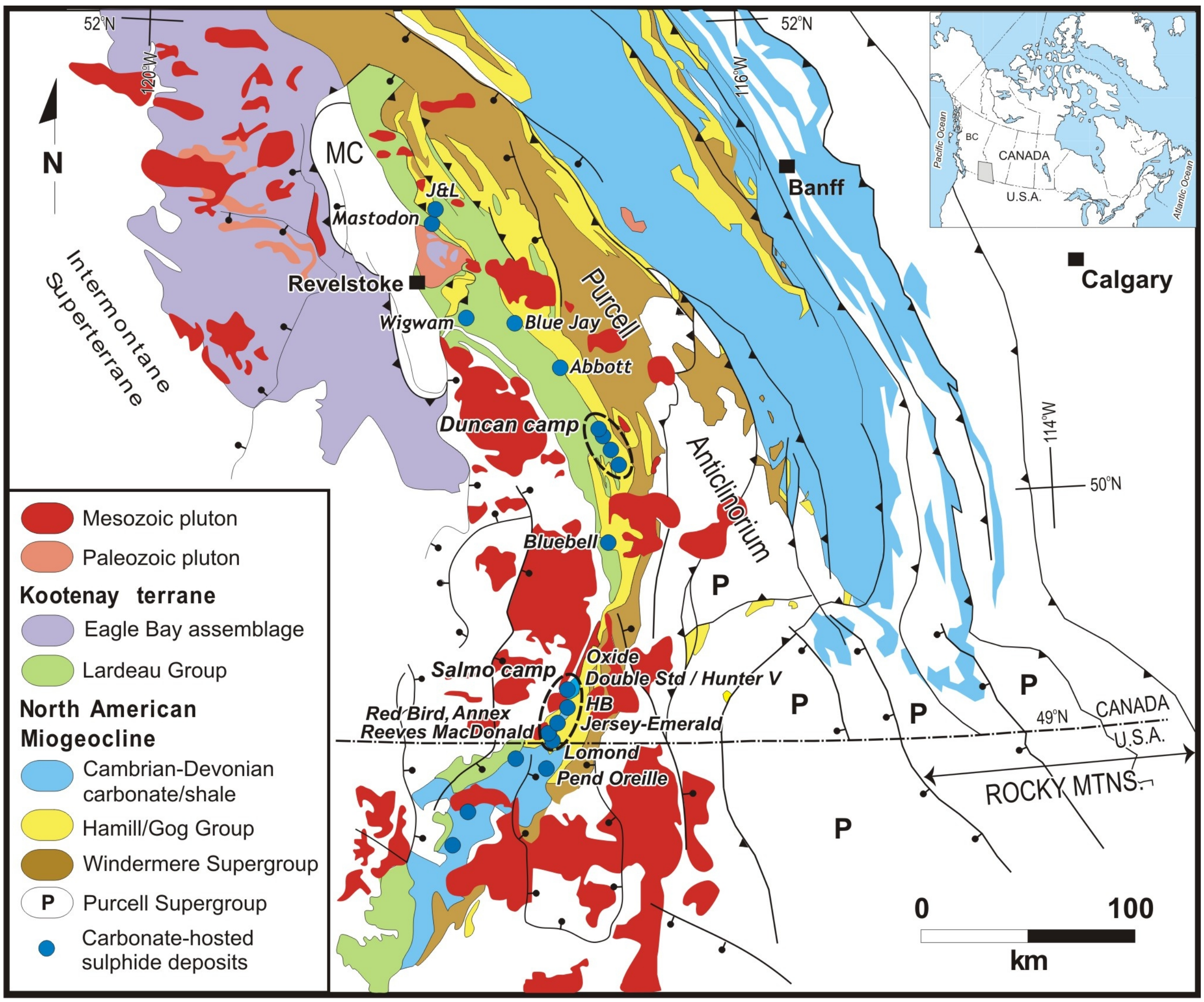

Figure 2. Simplified geological map of southeastern British Columbia and surrounding region, showing the Kootenay Arc and location of carbonate-hosted Zn-Pb deposits (modified from Wheeler and McFeely, 1991; Logan and Colpron, 2006; Paradis, 2007). The Cambrian-Devonian carbonates include the Early Cambrian Badshot Formation and its equivalent, the Reeves Member of the Laib Formation, which hosts the Zn-Pb sulphide and nonsulphide deposits. Abbreviations: MC, Monashee complex.

deposits. The Badshot Formation is characterized by calcitic to dolomitic marble. Schist is locally interlayered with the marble. In the southern part of the Kootenay Arc, the carbonate rocks are overlain by siliciclastic, basinal shale and mafic volcanic rocks of the Early Paleozoic Lardeau Group (Colpron and Price, 1995). Polyphase deformation has transposed bedding and locally obscured primary stratigraphic relationships (Colpron and Price, 1995).

The Quesnel Lake area in central BC is composed of rocks of the Cariboo terrane, North American miogeocline and the Barkerville subterrane. To the east, the Cariboo terrane is in fault contact with the western margin of the North American miogeocline along the Rocky Mountain Trench. To the west, it is in fault contact (along the westerly verging Pleasant Valley thrust) with rocks of the Barkerville subterrane, which corresponds to a northern extension of the Kootenay terrane.

The Cariboo terrane comprises thick sequences of Precambrian to Early Mesozoic siliciclastic and carbonate rocks that have similarities with rocks of the North American miogeocline. In the Quesnel Lake area, the Cariboo terrane is represented by the Late Proterozoic Kaza Group, the Late Proterozoic to Late Cambrian Cariboo Group and the Ordovician to Mississippian Black Stuart Group. The Cariboo Group includes argillite, slate and phyllite of the Isaac Formation; carbonate of the Cunningham Formation; argillite and phyllite of the Yankee Belle Formation; white quartzite of the Yanks Peak Formation; shale, phyllite and micaceous quartzite of the Midas Formation; carbonate of the Mural Formation; and slate, phyllite and minor limestone of the Dome Creek Formation (Struik, 1988). Sedimentary rocks of the Isaac, Cunningham and Yankee Belle formations correlate with like rocks of the Windermere Supergroup, and the quartzite of the Yanks Peak Formation correlates with that of the Hamill Group in southern BC (Struik, 1988). The archaeocyathid-bearing carbonate of the Mural Formation is biostratigraphically correlative with the Badshot Formation of the Kootenay Arc, which contains numerous stratabound carbonate-hosted Zn-Pb sulphide and nonsulphide deposits and polymetallic Pb-Zn (±Ag) veins (Struik, 1988; Paradis, 2007).

Sample Collection

Samples, collected during the 2007, 2008 and 2009 field seasons, were chosen to represent the range of rock types found within the CHNSBM deposit areas. In total, 47 samples were taken from the Salmo camp and 19 from the Quesnel Lake camp. Brief lithological descriptions are included in Table 1; to simplify analysis, however, the rock types have been grouped into the following classifications (with the number of samples studied):

Hostrocks:
- nonmineralized limestone (4)
- nonmineralized dolostone (9)

Sulphide (± nonsulphide)–bearing rocks:
- weakly mineralized limestone (1)
- weakly to moderately mineralized dolostone (some contain sulphides and nonsulphides) (13)
- semi-massive sulphides (protore) (9)
- skarn (1)

Nonsulphide (± sulphide, iron oxides)–rich dolostone:
- iron-oxides (16)
- nonsulphide-rich rock, i.e., rich in Zn-Pb carbonates or silicates (13)

Laboratory Methods

All samples were petrographically described. Some of the samples were investigated using X-ray powder diffraction (XRD) and scanning electron microscope (SEM) analyses. Most samples were sufficiently competent to permit extraction of 2.5 cm diameter, 2.2 cm long cylindrical cores. These drillcores were characterized in terms of skeletal and bulk density, porosity, magnetic susceptibility, magnetic remanence, Koenigsberger ratio and electric resistivity. Friable or unconsolidated samples were subject only to skeletal density and magnetic susceptibility measurements.

Density and Porosity

For all samples, the skeletal density (i.e., the density of the minerals not including the connected pore space) was measured using the ‘weight-in-air–weight-in-water’ method (Muller, 1967). The bulk density (i.e., the density of the whole rock including the pore space) was also measured on the samples that could be drilled, since the volume of a right cylinder can be measured geometrically. For six samples that were too friable to drill, yet competent enough to saw and grind into rough cubes, the hexahedral volume was determined using the tetrakis hexahedron volume formulation of Grandy (1997).

Porosity is calculated as the difference between the skeletal and bulk density measurements normalized by the skeletal density. In the authors’ experience, values below 2% are not significantly different from 0% porosity.

For powders, the skeletal volume was determined by measuring the mass of water needed to fill a graduated cylinder to a given level. The porosity of the powders was around 50%, but that is not necessarily representative of their in situ porosity.

Magnetic Susceptibility

Magnetic susceptibility was measured on friable or unconsolidated hand samples in the laboratory using a SM-20

Table 1. Physical properties of samples collected from the Salmo and Cariboo Lake mineral camps, south-central British Columbia.

Sample no.	UTM	Area/ Region	Deposit	Zone	Rock type	Hand sample description[1]	Coding	Bulk density (g/cm^3)	Skeletal density (g/cm^3)	Porosity (connected) (%)	Resistivity (ohm·m)	NRM (A/m)	MS (SI)	K_N
2009-SP-173	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	weathered weakly mineralized dolostone	dolostone with minor 5% Fe-Ox along microfractures and carb cleavages	w-Dol	2.234	2.485	10.11	6.67E+06	7.30E-05	1.96E-05	0.09
2009-SP-175	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	weathered weakly mineralized dolostone	dolostone with minor Fe-Ox along microfractures and carb cleavages	w-Dol		2.498				4.00E-06	
2009-SP-178	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	weathered weakly mineralized dolostone	dolostone with Fe-Ox and nonsulp filling fractures/veinlets, cavities and in carb groundmass (<10%)	w-Dol	2.496	2.632	5.17	2.44E+07	1.31E-04	4.22E-06	0.78
2009-SP-182	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	weathered weakly mineralized dolostone	dolomitic limestone with diss oxidized sph in groundmass and microfractures (~8%)	w-Dol	2.485	2.767	10.20	7.22E+06	2.40E-04	1.94E-05	0.31
2009-SP-184	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	weathered weakly mineralized dolostone	dolostone with ≤1% diss oxidized sph	w-Dol	2.352	2.571	8.52	3.88E+06	4.78E-04	2.36E-05	0.51
2009-SP-194a	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	weathered weakly mineralized dolostone	dolostone with ≤2% sphalerite in microfractures	w-Dol	2.687	2.786	3.57	3.80E+06	5.60E-04	4.10E-06	3.41
2009-SP-194b	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	weathered weakly mineralized dolostone	dolostone with sphalerite in microfractures	w-Dol	2.625	2.758	4.83	3.05E+06	1.60E-04	6.78E-06	0.59
2009-SP-221A	5853951N 641596E Z10	Quesnel Lake	Cariboo Zinc	Dolomite Flats	moderately mineralized dolostone	fg to cg dolostone with fractures filled by oxidized sulphides and cg white do; nonsulp along microfractures and walls of cavities; remnants of py enveloped by Fe-Ox	w-Dol	2.677	2.831	5.45	4.33E+07	4.38E-05	8.65E-06	0.13
2009-SP-221B	5853951N 641596E Z10	Quesnel Lake	Cariboo Zinc	Dolomite Flats	moderately mineralized dolostone	same as 221A	w-Dol	2.676	2.830	5.44	1.42E+07	2.99E-04	1.69E-06	4.42
2009-SP-224B	5853582N 641791E Z10	Quesnel Lake	Cariboo Zinc	Main zone	mineralized Dolostone	brecciated dolostone with nonsulp associated with Fe-Ox microfractures and replace carb groundmass; remnants of py, sph	w-Dol	2.805	2.901	3.29	2.33E+07	9.38E-05	1.47E-05	0.16
2009-SP-225A	5853400N 641939E Z10	Quesnel Lake	Cariboo Zinc	Main zone	weakly mineralized dolostone	fg dolostone with microfractures hosting tr sulph and nonsulp	w-Dol	2.732	2.847	4.05	2.00E+07	2.56E-04	2.30E-05	0.28
2009-SP-227	5852378N 643555E Z10	Quesnel Lake	Cariboo Zinc	Gunn zone	weathered mineralized dolostone	weathered dolostone with diss fresh and oxidized sph (~5%); nonsulp replace sph cx along borders	w-Dol	2.412	2.700	10.67	8.70E+06	5.81E-04	1.04E-05	1.40

Table 1 (continued)

Sample no.	UTM	Area/ Region	Deposit	Zone	Rock type	Hand sample description[1]	Coding	Bulk density (g/cm^3)	Skeletal density (g/cm^3)	Porosity (connected) (%)	Resistivity (ohm·m)	NRM (A/m)	MS (SI)	K_N
2009-SP-231C	5852188N 643413E Z10	Quesnel Lake	Cariboo Zinc	Gunn zone	quartz-galena vein	qz-ga vein in dolostone	w-Dol	2.548	2.779	8.32	1.46E+07	1.36E-04	-1.47E-06	-2.31
2007-SP-012-3	5430371N 474343E Z11	Salmo	BL		dolostone	foliated dolostone	Dol	2.715	2.825	3.89	2.55E+07	3.29E-04	4.61E-06	1.78
2007-SP-022-2	5430154N 4741109E Z11	Salmo	Reeves MacDonald		dolostone	fine-grained white dolostone	Dol	2.694	2.798	3.70	1.09E+07	5.25E-04	6.39E-06	2.05
2009-SP-170	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	weathered dolostone	dolostone with minor 5% Fe-Ox along microfractures and carb cleavages	Dol	2.638	2.746	3.92	1.75E+07	7.35E-05	1.06E-05	0.17
2009-SP-177	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	weathered dolostone	bleached dolostone; no sulph and nonsulp	Dol	2.660	2.765	3.79	8.36E+06	3.53E-04	5.42E-06	1.63
2009-SP-185	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	weathered weakly mineralized dolostone	fine-grained white dolostone	Dol	2.834	2.824	-0.35	1.08E+07	5.34E-04	6.27E-06	2.13
2009-SP-220A	5853965N 641517E Z10	Quesnel Lake	Cariboo Zinc	Dolomite Flats	dolostone	fine- to medium-grained massive dolostone	Dol		2.907				-1.60E-05	
2009-SP-231G	5852188N 643413E Z10	Quesnel Lake	Cariboo Zinc	Gunn zone	dolostone	fine-grained white dolostone	Dol	2.846	2.660	-7.00	1.01E+07	1.07E-04	1.30E-06	2.06
2009-SP-237B	5851520N 644120E Z10	Quesnel Lake	Cariboo Zinc	Que zone	dolostone	fine-grained white dolostone	Dol		2.670				-1.80E-05	
2009-SP-239A	5851304N 644197E Z10	Quesnel Lake	Cariboo Zinc	Que zone	dolostone	fine-grained white dolostone	Dol	2.742	2.820	2.78	1.65E+07		1.38E-06	0.00
2008-GS-15	5444589N 485465E Z11	Salmo	HB		iron-oxide gossan	nonsulp fill cavities, fractures and replace groundmass of Fe-Ox and carb	Fe-Ox		2.692				5.10E-05	
2008-GS-15A	5444589N 485465E Z11	Salmo	HB		iron-oxide gossan	Fe-Ox–rich sample with go layers; qz fill cavities	Fe-Ox	2.833	2.890	1.99			2.39E-04	
2008-GS-16A	5427797N 475327E Z11	Salmo	Lomond		iron-oxide gossan	go-rich sample	Fe-Ox	2.371	2.718	12.79			5.41E-04	
2008-GS-20C	5427906N 475494E Z11	Salmo	Lomond		iron-oxide gossan	go-rich sample	Fe-Ox	2.895	3.329	13.03	2.22E+07	2.83E-03	9.43E-04	0.08

Table 1 (continued)

Sample no.	UTM	Area/ Region	Deposit	Zone	Rock type	Hand sample description[1]	Coding	Bulk density (g/cm^3)	Skeletal density (g/cm^3)	Porosity (connected) (%)	Resistivity (ohm·m)	NRM (A/m)	MS (SI)	K_N
2008-GS-22A	5427787N 475355E Z11	Salmo	Lomond		iron-oxide gossan	massive hem, go with cavities partially filled by nonsulp	Fe-Ox		2.911				5.15E-04	
2008-SP-104A	5439662N 483892E Z11	Salmo	Jersey		iron-oxide gossan	oxidized layered massive py (minor sph) with occ nonsulp altering sph	Fe-Ox	2.442	2.833	13.81	2.97E+04	1.48E+00	6.87E-04	53.84
2008-SP-104B2	5439662N 483892E Z11	Salmo	Jersey		iron-oxide gossan	oxidized layered massive py	Fe-Ox	3.855	4.038	4.52	3.22E+03	2.92E-01	2.53E-04	28.81
2009-SP-176	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	iron-oxide gossan	friable hem and go-rich sample	Fe-Ox		2.690				5.06E-04	
2009-SP-181	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	iron-oxide gossan	semiconsolidated to unconsolidated iron-oxide–rich sample	Fe-Ox	1.369	3.370	59.37			2.23E-04	
2009-SP-183	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	iron-oxide gossan	porous, friable Fe-Ox–rich sample	Fe-Ox		2.181				2.81E-04	
2009-SP-186	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	iron-oxide gossan	unconsolidated iron oxides (li, go, hem)	Fe-Ox		1.781				1.28E-04	
2009-SP-197	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	iron-oxide gossan	unconsolidated iron oxides (li, go, hem)	Fe-Ox	1.471	3.417	56.94			4.00E-04	
2009-SP-200	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	iron-oxide gossan	semiconsolidated iron-oxide–rich sample (hem, go)	Fe-Ox		3.091				4.26E-04	
2009-SP-207	5429240N 471314E Z11	Salmo	Red Bird	Zone C, Trench C-2000-02	iron-oxide gossan	unconsolidated iron-oxide material	Fe-Ox	1.503	2.828	46.85			4.68E-04	
2009-SP-231Fa	5852188N 643413E Z10	Quesnel Lake	Cariboo Zinc	Gunn zone	iron-oxide gossan	Fe-Ox–rich sample with layers/ seams/fractures of nonsulp; few remnants of py surrounded by Fe-Ox	Fe-Ox	2.491	2.523	1.27			1.73E-04	
2009-SP-231Fb	5852188N 643413E Z10	Quesnel Lake	Cariboo Zinc	Gunn zone	iron-oxide gossan	Fe-Ox rich sample with layers/ seams/fractures of nonsulp; few remnants of py surrounded by Fe-Ox	Fe-Ox	2.133	2.081	-2.53			1.73E-04	
Skarn at Jersey	5438270N 483762E Z11	Salmo	Jersey		skarn	cg massive agg of diopside, garnet, hornblende, qz and cc	Sk	3.245	3.340	2.83	1.19E+07	1.14E-03	1.24E-03	0.02
2008-SP-97A	5453862N 487295E Z11	Salmo	Double Standard		limestone	cg white limestone.	Ls	2.414	2.759	12.49	1.24E+08	9.36E-05	-6.77E-06	-0.35

Table 1 (continued)

Sample no.	UTM	Area/ Region	Deposit	Zone	Rock type	Hand sample description[1]	Coding	Bulk density (g/cm^3)	Skeletal density (g/cm^3)	Porosity (connected) (%)	Resistivity (ohm·m)	NRM (A/m)	MS (SI)	K_N
2009-SP-179	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	dolomitic limestone	weathered dolomitic limestone with fine disseminated sph along microfractures	Ls	2.248	2.490	9.70	9.27E+06	7.96E-04	1.03E-05	1.93
2009-SP-188	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	argillaceous limestone	fg layered argillaceous limestone	Ls	2.671	2.674	0.11	1.61E+08	1.09E-04	-3.53E-06	-0.77
2009-SP-189	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	altered limestone	weathered medium-grained limestone with sulph and nonsulp(?) along microfractures	Ls	2.477	2.586	4.20	1.76E+07	9.90E-05	-3.30E-07	-7.50
2009-SP-190	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	weakly mineralized limestone	foliated limestone with tr of nonsulp between carb grains	w-Ls	2.378	2.588	8.12	9.40E+06	1.99E-04	4.84E-06	1.03
2008-SP-85	5457482N 489475E Z11	Salmo	Oxide		nonsulphide-rich dolostone	nonsulp fill cavities and replace carb groundmass	NS		2.615				1.10E-05	
2008-SP-88	5457365N 489966E Z11	Salmo	Oxide		nonsulphide-rich dolostone	massive replacement by he	NS	2.489	2.979	16.44	2.53E+07	4.81E-04	6.46E-06	1.86
2009-SP-174	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	nonsulphide-rich dolostone	nonsulp-rich dolostone; nonsulp (>50%) replaces carb groundmass and sulph	NS		2.356				-1.20E-05	
2009-SP-203	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	mineralized dolostone	weathered dolostone with nonsulp as fine acicular cx along Fe-Ox–filled microfractures (~10%); remnants of sph	NS	2.679	2.796	4.16	1.74E+07	1.52E-04	9.80E-06	0.39
2009-SP-204a	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	nonsulphide-rich dolostone	dolostone with nonsulp (50%) along Fe-Ox–filled microfractures and agg replacing carb groundmass	NS	2.497	2.683	6.93	3.29E+07	2.03E-04	2.51E-05	0.20
2009-SP-204b	5429388N 471447E Z11	Salmo	Red Bird	Zone C, Trench C-2000-01	nonsulphide-rich dolostone	nonsulp along Fe-Ox–filled microfractures and agg replacing carb groundmass; cavities filled by cg clear cc	NS	2.595	2.700	3.90	1.07E+07	1.68E-04	2.10E-05	0.20
2009-SP-225B	5853400N 641939E Z10	Quesnel Lake	Cariboo Zinc	Main zone	nonsulphides-ga-qz vein	nonsulphides-ga-qz vein; nonsulp are along cavity wall, fill cavities, grow along Fe-Ox and altered ga	NS		1.818				-9.00E-05	
2009-SP-230	5852259N 643479E Z10	Quesnel Lake	Cariboo Zinc	Gunn zone	nonsulphide-rich dolostone	nonsulp replace groundmass, fill cavites, and alter ga	NS	3.264	3.545	7.95	9.66E+06	2.61E-03	2.36E-06	27.65
2009-SP-237A	5851520N 644120E Z10	Quesnel Lake	Cariboo Zinc	Que zone	nonsulphide-rich dolostone	massive he replacement of carb and sulp	NS	2.425	2.764	12.26			-8.00E-06	
2009-SP-240B	5851503N 644162E Z10	Quesnel Lake	Cariboo Zinc	Que zone	mineralized dolostone	fg to cg dolostone crosscut by ga veinlets; nonsulp associated with ga	NS	2.799	2.995	6.52	1.22E+07	4.79E-04	1.19E-05	1.01

Table 1 (continued)

Sample no.	UTM	Area/ Region	Deposit	Zone	Rock type	Hand sample description[1]	Coding	Bulk density (g/cm^3)	Skeletal density (g/cm^3)	Porosity (connected) (%)	Resistivity (ohm·m)	NRM (A/m)	MS (SI)	K_N
2009-SP-242	5851843N 643242E Z10	Quesnel Lake	Cariboo Zinc	Que zone	nonsulphide-rich dolostone	nonsulp-rich dolostone; nonsulp (70%) replace carb and sulph	NS	2.568	3.150	18.48	2.37E+07	1.72E-03	4.86E-06	8.85
2009-SP-243	5851843N 643242E Z10	Quesnel Lake	Cariboo Zinc	Que zone	nonsulphide-rich dolostone	fg dolostone crosscut by fractures filled by Fe-Ox and nonsulp (40–50%); possible remnants of sph	NS	2.512	2.698	6.90	1.19E+07	7.72E-04	7.89E-06	2.45
Trench B 2000-1	5429240N 471314E Z11	Salmo	Red Bird	Beer Bottle, zone B, Trench B-2000-01	nonsulphide-rich dolostone	weathered dolostone with numerous microfractures filled by Fe-Ox	NS	2.700	2.821	4.30	3.37E+07	1.87E-04	9.32E-06	0.50
2007-SP-012-1	5430371N 474343E Z11	Salmo	BL		sulphide-rich dolomitic limestone	dolomitic limestone with fine diss py (<5%) and tr of sph, ga	SMS	3.391	3.443	1.52	5.08E+05	1.92E-04	4.28E-06	1.12
2007-SP-028-1a	5438270N 483762E Z11	Salmo	Jersey		semi-massive sulphides	bands and stringers of sph and ga (~45%) in dolostone	SMS	3.908	4.012	2.59	1.49E+07	1.56E-04	5.51E-05	0.07
2007-SP-028-1b	5438270N 483762E Z11	Salmo	Jersey		semi-massive sulphides	bands and stringers of sph and ga (~45%) in dolostone	SMS	3.056	3.137	2.60	2.79E+07	9.50E-05	7.00E-05	0.03
2007-SP-028-1c	5438270N 483762E Z11	Salmo	Jersey		semi-massive sulphides	bands and stringers of sph and ga (~45%) in dolostone	SMS	3.472	3.537	1.82	6.97E+07	5.80E-04	6.31E-05	0.23
2008-75-5	5438270N 483762E Z11	Salmo	Jersey		semi-massive sulphides	bands and stringers of sph (~30–40%) in dolostone	SMS	2.969	3.104	4.34		2.77E-02	1.04E-04	6.67
2008-SP-100A	5454065N 487981E Z11	Salmo	Jackpot	Jamesonite trench	semi-massive sulphides	cg limestone with sph-rich layers (≤40%)	SMS	2.917	3.000	2.76	1.27E+08	1.45E-04	3.47E-05	0.10
2008-SP-99C	5453790N 487902E Z11	Salmo	Hunter V area		semi-massive sulphides	agg of sph (≤10%) in cg siliceous dolostone	SMS	2.896	2.979	2.78	1.07E+07	7.19E-02	7.75E-05	23.20
2009-SP-227A	5852378N 643555E Z10	Quesnel Lake	Cariboo Zinc	Gunn zone	barite-galena vein	cg barite, ga and minor sph in vein	SMS	3.068	3.184	3.64	1.43E+07	3.12E-04	8.19E-06	0.95
HB	5444008N 485257E Z11	Salmo	HB		semi-massive sulphides	fine-grained layered sulphides (py, sph, tr ga) replacing layered dolomitic limestone	SMS	3.099	3.204	3.27	6.56E+05	3.84E-04	3.27E-05	0.29

[1]All percentages are visually estimated.

Abbreviations: agg, aggregates; anh, anhydrite; carb, carbonates; cc, calcite; cg, coarse grained; cx, crystals; diss, disseminated; do, dolomite; Dol, dolostone; Fe-Ox, iron oxyhydroxides; fg, fine grained; ga, galena; go, goethite; gyp, gypsum; hem, hematite; he, hemimorphite; K_N, Koenigsberger ratio; li, limonite; Ls, limestone; MS, magnetic susceptibility; nonsulp, nonsulphides; NRM, natural remanent magnetization; NS, nonsulphides-rich rock, i.e., rich in Zn-Pb carbonates or silicates; occ, occasional; qz, quartz; py, pyrite; Sk, skarn; sph, sphalerite; SMS, semi-massive sulphides; sulph, sulphides; tr, traces; UTM, Universal Transversal Mercator location; w-Dol, weakly mineralized dolostone; w-Ls, weakly mineralized limestone pocket magnetic susceptibility meter (GF Instruments s.r.o., Brno, Czech Republic), with a sensitivity of 10^{-6} SI volume units and a measurement coil with a 5 cm diameter. Approximately 90% of the measured responses came from the top 2 cm of samples tested. Susceptibility measurements on cores were taken with an SI2B susceptibility meter (Sapphire Instruments, Ruthven, Ontario), accurate to 10^{-7} SI units. These higher precision measurement techniques were used in preference to the SM-20 hand-sample measurements when the stability of the sample permitted.

Magnetic Remanence and Koenigsberger Ratio

Magnetic remanence was measured using an AGICO s.r.o. (Brno, Czech Republic) JR5-A spinner magnetometer (sensitivity 10^{-5} A/m). The three-dimensional vector was measured, but as the samples were not oriented, only the vector magnitude of the remanence is reported in the database. The Koenigsberger ratio (K_N) compares the relative strength of the natural remanent magnetization (NRM) to the induced magnetism in the geomagnetic field: K_N = NRM/(H_0 $_0$), where $_0$ is the magnetic susceptibility and the geomagnetic field strength (H_0) is approximated as a constant 40 A/m (or $_0H_0$ = 50 T = 50000 , where $_0$ is the permeability of free space). When K_N is above 1, then a quantitative model derived from a magnetic anomaly interpretation will be inaccurate if magnetic remanence is not taken into consideration.

Electrical Resistivity

Complex electrical impedance frequency spectra were measured using a Solartron Model 1260 Impedance/Gain-Phase Analyzer (AMETEK, Farnborough, United Kingdom), based on the method of Katsube (2001). Sample cylinders were vacuum impregnated in distilled water and allowed to soak for at least 24 hours, to allow original groundwater solutes precipitated in the sample porosity to dissolve and approximate original groundwater conductivity. The impedance was measured with 5 frequencies per decade from 1 MHz to 1 Hz. The scalar resistance was picked as the real impedance at the frequency which displays minimum imaginary impedance, typically around 1000 Hz. In doing so, we report the real resistance valid over the largest possible frequency range. Resistivity (ohm m) is this resistance times the sample geometric factor, the cross-section area divided by the length.

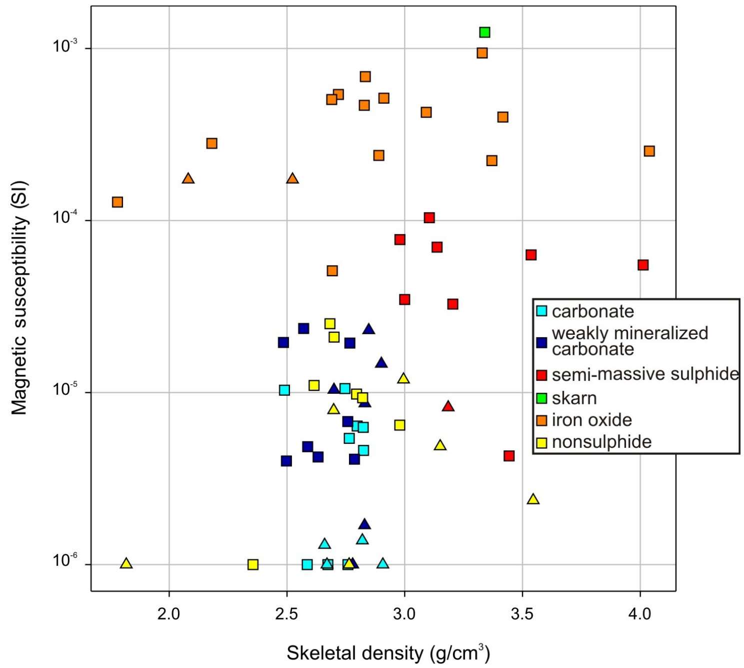

Figure 3. Relationship between skeletal density and magnetic susceptibility, samples from Salmo and Quesnel Lake camps, south-central British Columbia. Salmo camp samples are plotted as squares while Quesnel Lake samples are plotted as triangles. Note that diamagnetic samples (i.e., negative susceptibility) are plotted with susceptibility of $+10^{-6}$ SI, as negative values cannot plot on a logarithmic scale.

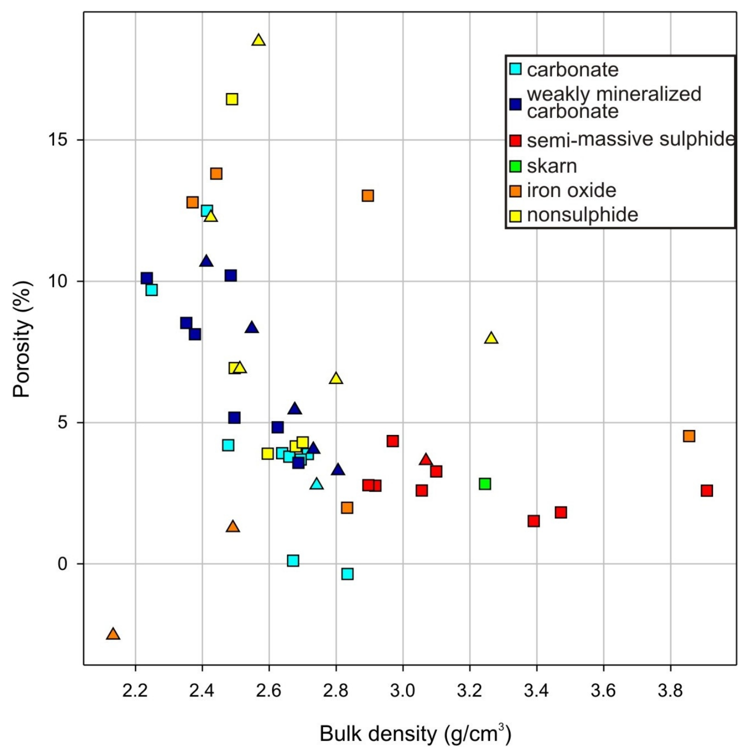

Figure 4. Plot of bulk density versus porosity, samples from Salmo and Quesnel Lake camps, south-central British Columbia. Salmo camp samples are plotted as squares while Quesnel Lake samples are plotted as triangles.

Results and Interpretation

The measurements taken from 66 samples collected in the Salmo and Quesnel Lake camps are compiled in Table 1. The only physical properties that could be measured on all samples were the skeletal density and the magnetic susceptibility. The different rock types lie in distinct regions of the density/susceptibility plot (Figure 3). The skarn and the iron oxides have the highest magnetic susceptibilities, as expected. They have a wide range of densities, with one sample (08-SP-104B2) denser than 4 g/cm^3. The semi-massive sulphides are distinguished by their high density, always near or above 3 g/cm^3. While the nonmineralized carbonates and weakly mineralized carbonates have skeletal densities between 2.5 and 2.9 g/cm^3, typical of carbonate rocks, strongly mineralized nonsulphide samples range from 1.8 to 3.5 g/cm^3. The low skeletal density nonsulphide samples (09-SP-225B and 09-SP-174) are diamagnetic, reflecting the dominance of dolomite in the mineralogy. The nonsulphide sample with highest density (09-SP-230) contains galena stringers (galena has density above 7 g/cm^3), and thus the anomalous density may be dominated by the sulphide component.

The bulk density is influenced by the porosity (as expected). The most porous samples (>8% porosity) have bulk density <2.5 g/cm^3 (Figure 4). Of the 45 samples for which magnetic remanence could be measured, a notable 20 have Koenigsberger ratios >1 (Figure 5), suggesting that magnetic survey interpretation involving quantitative modelling of the shapes of magnetic bodies can be misleading if only magnetic susceptibility is modelled. While most samples have very high resistivities (>10^6 ohm m), two iron-oxide samples and two massive-sulphide samples have low resistivities (Figure 6), which, if representing sufficiently large bodies, could produce significant electromagnetic anomalies.

Conclusion

This study is the first of its kind to determine and document physical properties of carbonate-hosted Pb-Zn nonsulphide mineralization and to compare these properties with those of surrounding country rock and sulphide protore. Based on the results of this study, gravity surveys probably hold the most promise for detection of this type of deposit, as both the sulphide protore and many of the nonsulphide rocks have densities above 3 g/cm^3. From a practical point of view, the inter-

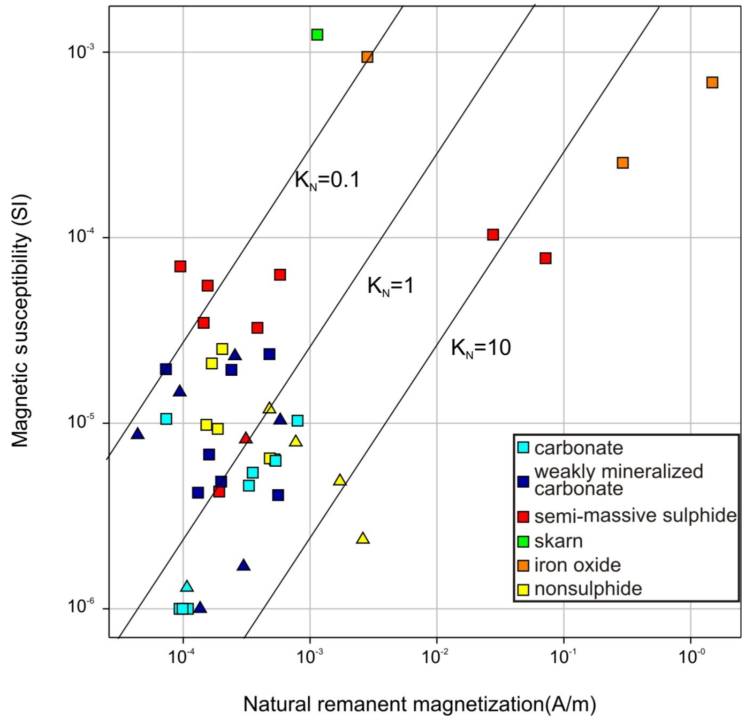

Figure 5. Plot of magnetic remanence versus magnetic susceptibility, with lines of equal Koenigsberger ratio (K_N) indicated, samples from Salmo and Quesnel Lake camps, south-central British Columbia. Note that nearly half the samples have K_N >1. Salmo camp samples are plotted as squares while Quesnel Lake samples are plotted as triangles.

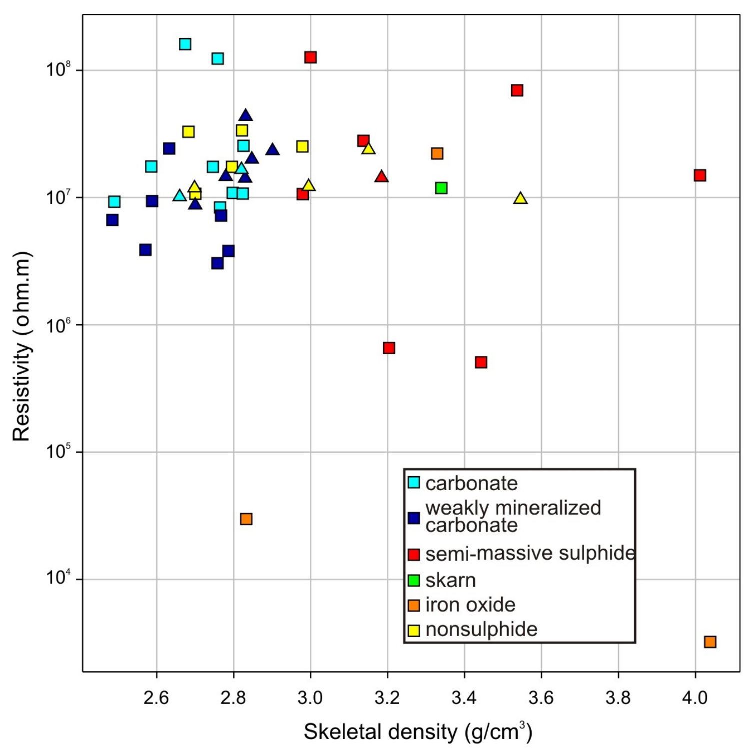

Figure 6. Plot of bulk density versus electrical resistivity, south-central British Columbia. Salmo camp samples are plotted as squares while Quesnel Lake samples are plotted as triangles.

pretation of the gravity data will not be straightforward; the density of nonsulphide mineralization can also be very low, which may explain the small negative gravity anomalies observed in the Cariboo Zinc property of the Quesnel Lake area. A full understanding of the significance of these rock property measurements requires further consideration of the correlation between a measured rock property and the mineralogy, texture and porosity of each sample. With the benefit of such an understanding, the next step of evaluating the significance of geophysical anomalies can proceed with a measure of confidence.

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