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Glacial dispersal of gahnite from the Izok Lake Zn-Cu-Pb-Ag VMS deposit, northern Canada

M.B. McClenaghan[1]*, R.C. Paulen[1], D. Layton-Matthews[2], A.K. Hicken[2] & S.A. Averill[3]

[1] Geological Survey of Canada, Ottawa, ON K1A 0E8, Canada
[2] Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, ON K7L 3N6, Canada
[3] Overburden Drilling Management Ltd., 15 Capella Court, Unit 107, Ottawa, ON K7E 7X1, Canada
* Correspondence: Beth.McClenaghan@NRCan-RNCan.gc.ca

Abstract: The Izok Lake Zn–Cu–Pb–Ag volcanogenic massive sulphide (VMS) deposit in the Arctic region of Canada is one of the largest undeveloped Zn–Cu VMS resources in North America. In 2009, the Geological Survey of Canada initiated a detailed glacial dispersal study of the deposit focused on documenting its associated indicator mineral and till geochemical signatures. Glacial dispersal from the deposit is fan-shaped and was formed by an older SW ice flow and younger NW ice flow phases. Till samples contain chalcopyrite, sphalerite, galena, and pyrite up to 1.3 km down-ice and gahnite at least 40 km down-ice. Gahnite ($ZnAl_2O_4$) is an ideal indicator mineral in till because of its visually distinctive bluish green colour combined with its high specific gravity (4–4.6) for recovery using density-based separation methods, moderate hardness (physical durability during glacial transport), chemical stability in oxidizing surficial environments (resistance to post-glacial weathering), and its occurrence in highly metamorphosed VMS deposits such as Izok Lake. Most gahnite grains in till down-ice are 0.25–0.5 mm in size. Coarser gahnite (0.5–2.0 mm) occurs only in till proximal to the deposit (<3 km down-ice) and thus is an indicator of proximity to a gahnite-bearing bedrock source. Ore (Cu, Pb, Zn, Ag) and pathfinder element (As, Cd, Bi, Hg, In, Sb, Sb, Tl) contents in the <0.063 mm fraction of till reflect glacial dispersal up to a maximum of 6 km down-ice. A 15–20 km till indicator mineral sample spacing is sufficient to detect a gahnite glacial dispersal train such as that from the Izok Lake VMS deposit.

Keywords: Izok Lake; dispersal train; gahnite; indicator minerals; till geochemistry; drift prospecting; volcanogenic massive sulphide deposit

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Till geochemistry has been used for more than 50 years to explore for volcanogenic massive sulphide (VMS) deposits in the glaciated terrain of Canada (McClenaghan & Peter 2013). Glacial dispersal trains derived from VMS deposits are usually short (<1 km long) and thus present small exploration targets that require the collection of closely spaced (<2 km) till samples. Also, if oxidized till is sampled, the distribution of the major ore elements, Cu, Pb, and Zn will reflect not only clastic glacial dispersal but also secondary dispersion and remobilization of metals (Shilts 1984; Kaszycki *et al.* 1996; Lett & Jackaman 2002; Hall *et al.* 2003). Few studies, however, have focused on the indicator mineral signatures of VMS deposits in glacial sediments, and the resultant size of glacial dispersal trains that could be detected using this method.

In 2009, the Geological Survey of Canada (GSC) initiated a detailed glacial dispersal study of the Izok Lake Zn–Cu–Pb–Ag VMS deposit focused on documenting its indicator mineral signature. This deposit was chosen as a test site because: (1) mineralization is present in subcrop and was therefore subjected to glacial erosion; (2) the local terrain is mostly till-covered; and, (3) this deposit is known to contain gahnite (Money & Heslop 1976), a Zn-spinel which is a potential indicator mineral of high-grade metamorphosed VMS deposits (e.g. Spry 1987*a*, *b*; Averill 2001; Heimann *et al.* 2005). This research was carried out as part of the GSC's Geo-Mapping for Energy and Minerals (GEM) Program (2008–2013) Tri-Territorial Indicator Mineral Project, in collaboration with Queen's University, and with the exploration company that holds the deposit, Minerals and Metals Group (MMG).

The objectives of this research were to document and better understand the geochemical and indicator mineral signatures of metal-rich till glacially dispersed from a VMS deposit. Bedrock and till samples for this case study were collected by the GSC and MMG between 2009 and 2012 as part of a local-scale (*c.* 100 km^2) till survey around the Izok Lake deposit (Hicken *et al.* 2012, 2013*a*,*b*; McClenaghan *et al.* 2012*a*, 2013; Paulen *et al.* 2013). In addition to these local samples, archived reconnaissance-scale till samples originally collected by the GSC in 1994 (Dredge *et al.* 1996*a*,*b*), up to 70 km down-ice from the Izok Lake VMS deposit, were re-examined (McClenaghan *et al.* 2012*b*). These archived samples provide a regional context for the interpretation of the local-scale indicator mineral data reported in this study.

Study area

Regional setting

The Izok Lake VMS deposit is inside the western boundary of the Canadian Territory of Nunavut (65°38'00"N, 112°4745"W) in the Point Lake National Topographic System (NTS) map sheet 86H, *c.* 400 km north of Yellowknife (Fig. 1). The deposit underlies Izok Lake, which is 5 km west of the northern arm of Itchen Lake and 30 km north of Point Lake. The Izok Lake area is within the Bear-Slave Upland of the Canadian Shield (Bostock 1970), north of the tree line, within the zone of continuous permafrost. The topography is generally undulating, with irregular, glacially streamlined bare bedrock knobs interspersed with glacial deposits and

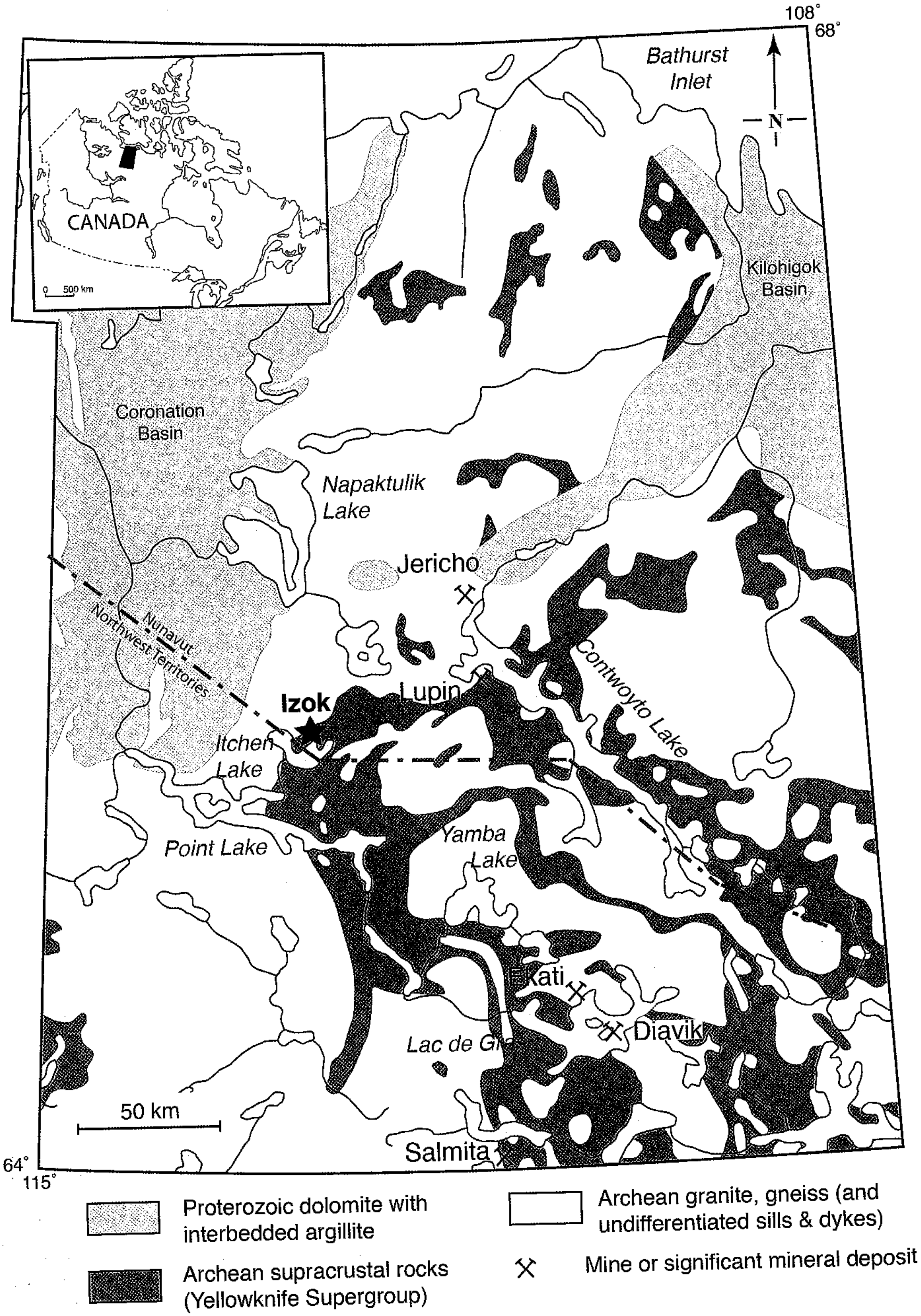

Fig. 1. Location of the study area in eastern Northwest Territories and western Nunavut (modified from Dredge *et al.* 1999, geology after Hoffman &

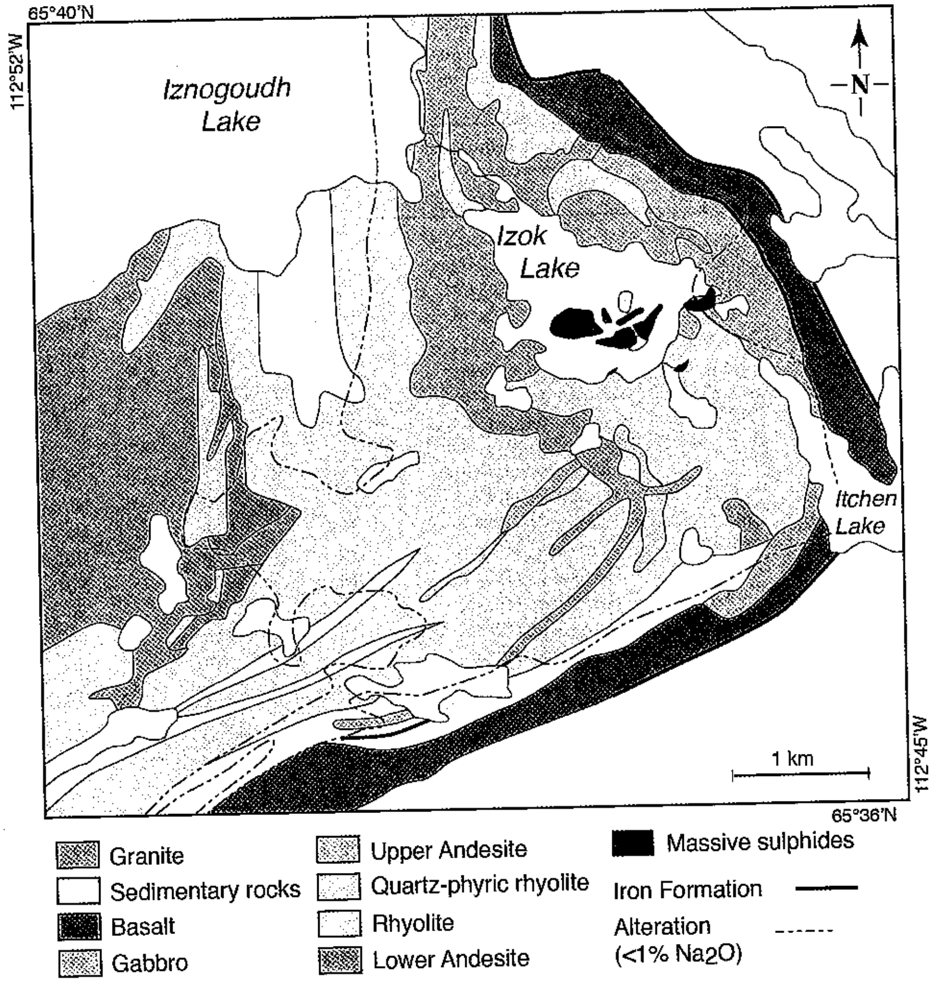

Fig. 2. Local scale bedrock geology map of the Izok Lake area showing the location of the massive sulphide lenses (modified from Morrison 2004).

numerous lakes. The exploration property is accessed by chartered aircraft or winter road.

Regional bedrock geology

The study area is in the central Slave Province, a granitic-greenstone terrane of folded, faulted, and metamorphosed Archean rocks containing belts of 2.67–2.70 billion year old metasedimentary and metavolcanic rocks of the Yellowknife Supergroup (Padgham & Fyson 1992; Bleeker & Hall 2007). The Yellowknife Supergroup has been locally divided into the lower Point Lake Formation and the upper Contwoyto Formation. Both formations were intruded extensively by synvolcanic to post-volcanic granitic plutons dated between 2.58 and 2.68 billion years (Bleeker *et al.* 1999) and were much later crosscut by north–NW-trending regional diabase dike swarms belonging to the 1.27 billion year Mackenzie swarm (LeCheminant & Heaman 1989; Buchan & Ernst 2013).

The Izok Lake VMS deposit is hosted within the Izok Lake volcanic belt of the Point Lake Formation (Morrison & Balint 1993; Morrison 2004). The belt forms an 18 km-long and approximately 1–5 km-wide arc that is dominated by felsic metavolcanic rocks, with lesser intermediate and mafic metavolcanic rocks and derived metasediments (Bostock 1980; Tremblay *et al.* 1980). The northern and central parts of the belt are metamorphosed to upper amphibolite-sillimanite grade with characteristic minerals assemblages consisting of hornblende, cordierite, and sillimanite (Thomas 1978). The rocks in the southern part of the belt are of greenschist grade, with a characteristic mineral assemblage of albite-epidote-chlorite.

The Izok Lake VMS deposit is one of the largest undeveloped Zn–Cu resources in North America (Morrison 2004), containing total indicated and inferred resources of 14.8 Mt grading 2.5% Cu, 12.8% Zn, 1.3% Pb, and 71 g/t Ag enclosed within a group of five near-surface sulphide lenses (Fig. 2). The three westernmost ore zones subcrop under Izok Lake. The deposit consists mainly of sphalerite, chalcopyrite, galena, and pyrrhotite with a variety of minor metallic minerals (Money & Heslop 1976; Cabri *et al.* 1984; Harris *et al.* 1984*a*,*b*, 1986; Morrison 2004). These minerals are listed in Table 1.

Host rocks of the deposit are highly deformed gneisses, with at least three distinct phases of deformation (Morrison 2004). Based on the metamorphic assemblage of gahnite, staurolite, garnet, cordierite, pyrrhotite, hornblende, quartz, feldspar, muscovite, and biotite, an upper amphibolite grade of peak metamorphism has been estimated (Money & Heslop 1976; Bostock 1980; Morrison 2004). The host rocks have been interpreted as meta-rhyolites, meta-dacites and meta-felsic tuffs with variable, primary hydrothermal alteration overprint (Fig. 2). In areas of hydrothermal alteration, Mg-enrichment is related to proximity to the deposit with the greatest Mg-enrichment located beneath the deposit lenses. This high-Mg enrichment is locally mapped in drill-core as a distinct chlorite-biotite-cordierite (CBC) unit. Stringer sulphide mineralization is well developed stratigraphically adjacent to the Central West lens in close association with the CBC unit, and has been intersected by drilling to a depth of 170 m beneath the footwall contact. In these stringer-mineralized areas, gahnite is common with a close association with quartz, feldspar, biotite, muscovite, sphalerite, chalcopyrite and pyrrhotite.

Glacial history

The present-day landscape of the Izok Lake area, due to the relatively thin drift cover (<3 m thick) and lack of deeply weathered

Table 1. *(a) Summary of metallic minerals in the Izok Lake deposit reported by Money & Heslop (1976), Harris* et al. *(1984*a,b*), Cabri* et al. *(1984), Harris* et al. *(1986) and Morrison & Balint (1993), compared to the ore minerals seen in samples in this study in polished thin section (PTS), bedrock or till heavy mineral concentrates (HMC) (modified from Hicken* et al. *2012, 2013*a,b*); (b) oxide and silicate indicator minerals of base metal massive sulphide deposits in glaciated terrain reported by Averill (2001) that were identified in samples of this study in polished thin section (PTS), bedrock or till heavy mineral concentrates (HMC)*

Mineral	Formula	Hardness	Specific gravity	Presence in bedrock reported by other sources	Found in PTS in this study	Found in bedrock HMC in this study	Found in till HMC in this study
(A) Metallic minerals							
Acanthite	Ag_2S	2.0–2.5	7.2–7.4	Harris *et al.* (1984*b*)	No	No	No
Allargentum	Ag1−*x*Sb*x* (*x*=0.009–0.16)	4.0	10.0	Harris *et al.* (1984*b*)	No	No	No
Arsenopyrite	FeAsS	5.0	6.07	Harris *et al.* (1984*b*)	No	Yes	Yes
Boulangerite	$Pb_5Sb_4S_{11}$	2.5	5.7–6.3	Harris *et al.* (1984*b*)	No	No	No
Bournonite	$PbCuSbS_3$	3.0	5.7–5.9	Harris *et al.* (1984*b*)	No	No	No
Breithauptite	NiSb	3.5–4.0	8.23	Harris *et al.* (1984*b*)	No	No	No
Chalcopyrite	$CuFeS_2$	3.5	4.1–4.3	Money & Heslop (1976), Cabri *et al.* (1984) and Harris *et al.* (1984*b*)	Yes	Yes	Yes
Cobaltite	CoAsS	5.5	6.33	Harris *et al.* (1984*b*)	No	No	No
Cosalite	$Pb_2Bi_2S_5$	2.5–3.0	6.4–6.8	Harris *et al.* (1984*b*)	No	No	No
Covellite	CuS	1.5–2.0	4.6–4.76	Harris *et al.* (1984*b*)	No	No	No
Cubanite	$CuFe_2S_3$	3.5	4.7	Harris *et al.* (1984*b*)	No	No	No
Digenite	Cu_9S_5	2.5–3.0	5.6	Harris *et al.* (1984*b*)	No	No	No
Dyscrasite	Ag_3Sb	3.5–4.0	9.4–10.0	Harris *et al.* (1984*b*)	No	No	No
electrum	AuAg	2.5–3.0	16	Harris *et al.* (1984*b*)	No	Yes	Yes
galena	PbS	2.5	7.2–7.6	Money & Heslop (1976) and Harris *et al.* (1984*b*)	Yes	Yes	Yes
Gudmundite	FeSbS	5.5–6.0	6.72	Harris *et al.* (1984*b*)	No	No	No
Izoklakeite	$(Cu, Fe)_2Pb_{27}(Sb,Bi)_{19}S_{57}$	3.5–4.0	6.47	Harris *et al.* (1986)	No	No	No
Jaskolskiite	$Cu_{0.2}Pb_{2.2}Sb_{1.2}Bi_{0.6}S_5$	4.0	6.5	Harris *et al.* (1984*a*)	No	No	No
Loellingite	$FeAs_2$	7.1–7.5	5.0–5.5	No	No	No	Yes
Meneghinite	$Pb_{13}CuSb_7S_{24}$	2.5	6.34–6.43	Harris *et al.* (1984*b*)	No	No	No
Molybdenite	MoS_2	1.0	5.5	Harris *et al.* (1984*b*)	No	Yes	No
Native Bismuth	Bi	2.0–2.5	9.7–9.8	Harris *et al.* (1984*b*)	No	No	No
Native silver	Ag	2.5–3.0	10–11	Harris *et al.* (1984*b*)	Yes	No	No
Nuffieldite	$Pb_2Cu(Pb,Bi)Bi_2S_7$	3.5-4.0	7.01	Harris *et al.* (1984*b*)	No	No	No
Polybasite	$[(Ag,Cu)_6(Sb,As)_2S_7][Ag_9CuS_4]$	2.5–3.0	4.6–5.0	Money & Heslop (1976) and Harris *et al.* (1984*b*)	No	No	No
Pyrargyrite	Ag_3SbS_3	2.5	5.9	Harris *et al.* (1984*b*)	No	No	No
Pyrite	FeS_2	6.5	5.0–5.2	Money & Heslop (1976), Harris *et al.* (1984*b*) and Morrison & Ballint (1993)	Yes	Yes	Yes
Sphalerite	(Zn,Fe)S	3.5–4.0	3.9–4.2	Money & Heslop (1976), Harris *et al.* (1984*b*) and Morrison & Ballint (1993)	Yes	Yes	Yes
Stannite	Cu_2FeSnS_4	3.5–4.0	4.3–4.5	Harris *et al.* (1984*b*)	No	No	No
Stephanite	Ag_5SbS_4	2.0–2.5	6.2–6.3	Harris *et al.* (1984*b*)	No	No	No
Sternbergite	$AgFe_2S_3$	1.0–1.5	4.22	Harris *et al.* (1984*b*)	No	No	No
Tennantite	$(Cu,Fe)_{12}As_4S_{13}$	3.5–4.0	4.6–4.7	Harris *et al.* (1984*b*)	No	No	No
Tetrahedrite	$(Cu,Fe)_{12}Sb_4S_{13}$	3.5–4.0	4.6–5.2	Money & Heslop (1976) and Harris *et al.* (1984*b*)	No	No	No
Valleriite	$4(Fe,Cu)S{\bullet}3(Mg,Al)(OH)_2$	1.0–1.5	3.09–3.14	Harris *et al.* (1984*b*)	No	No	No
(B) Oxide and silicate indicator minerals							
Anthophyllite§	$(Mg,Fe)_7Si_8O_{22}(OH)_2$	5.0–6.0	3.5	No	No	No	No
Barite§	$BaSO_4$	4.48	3.0–3.5	No	No	No	No
Cassiterite	SnO_2	6.0–7.0	6.8–7	Harris *et al.* (1984*b*)	No	No	No
Cr-Rutile§	$(Ti,Cr)O_2$	6.0–6.5	4.23	No	No	Yes	Yes
Dumortierite§	$Al_7(BO_3)(SiO_4)_3O_3$	7.0–8.5	3.3–3.4	No	No	No	No
Franklinite§	$(Zn, Mn,Fe)(Fe,Mn)_2O_4$	5.5–6.0	5.07–5.22	No	No	No	No
Gahnite§	$ZnAl_2O_4$	8	4–4.6	Money & Heslop (1976) and Morrison & Ballint (1993)	Yes	Yes	Yes
Kyanite§	Al_2SiO_5	4.0–7.0	3.61	No	No	No	Yes
Mg-Spinel§	$MgAl_2O_4$	8.0	3.64	No	No	No	No
Mn-Epidote§	$Ca_2(Al,Fe,Mn)_3Si_3O_{12}(OH)$	6.0–7.0	3.3–3.6	No	Yes	No	Yes
Orthopyroxene§	$(Mg,Fe)_2Si_2O_6$	5.0–6.0	3.4	No	No	No	Yes
Sapphirine§	$(Mg, Al)_8(Al, Si)_6O_{20}$	7.5	3.45	No	No	No	No
Sillimanite§	Al_2SiO_5	6.5–7.5	3.23	Morrison & Ballint (1993)	Yes	Yes	Yes
Spessartine§	$Mn_3Al_2Si_3O_{12}$	6.5–7.5	4.15	Morrison & Ballint (1993)	No	No	Yes
Staurolite§	$(Fe,Mg,Zn)_2Al_9(Si,Al)_4O_{22}(OH)_2$	7.0–7.5	3.65–3.77	No	Yes	Yes	Yes
Tourmaline§	$(Na,Ca)(Mg,Fe)_3Al_6(BO_3)_3(Si_6O_{18})(OH)_4$	7.0–7.5	3.06	No	Yes	No	Yes
Willemite§	Zn_2SiO_4	5.5	3.9–4.2	No	No	No	No
Magnetite	Fe_3O_4	5.5–6	5.1–5.2	Morrison & Ballint (1993)	Yes	Yes	Yes
Mn-axinite	$Ca_2MnAl_2(BO_3)Si_4O_{12}(OH)$	6.5–7	3.27–3.29	No	Yes	Yes	No

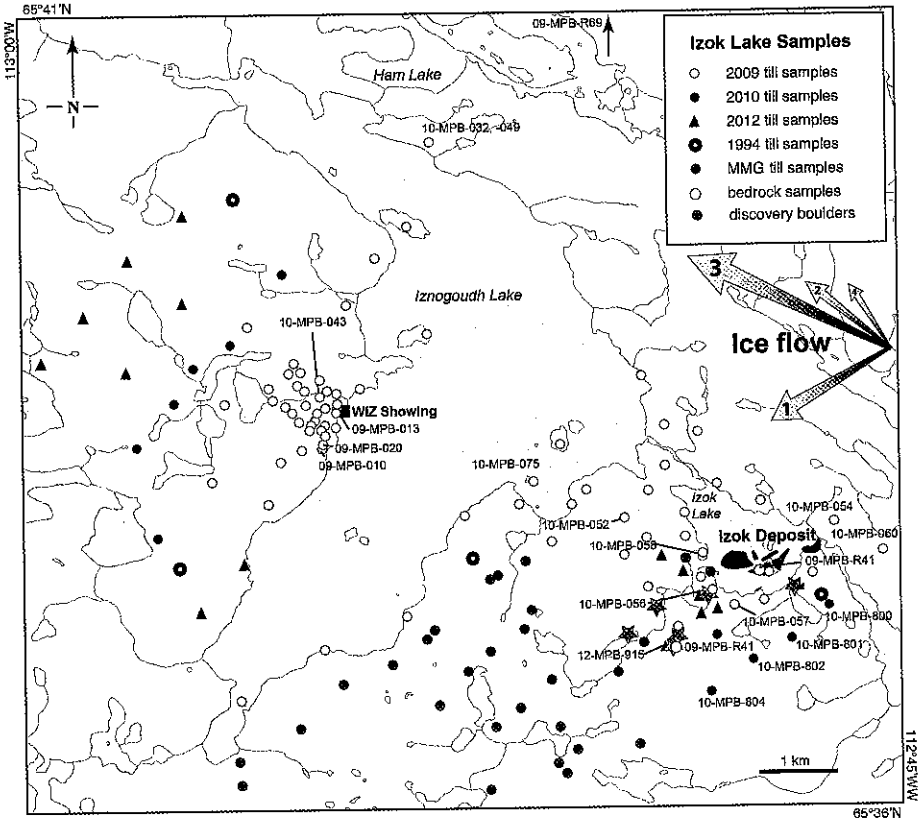

Fig. 3. Location of till samples and selected bedrock samples used in this study, and regional till samples collected by GSC in 1994 and by MMG as part of their exploration program. Arrows indicate relative ice flow chronology (1 = oldest) and vigor (arrow size) of flow events (Paulen *et al.* 2013). Till and bedrock samples mentioned in text are labeled. Locations of massive sulphide discovery boulders are shown by red dots, gahnite-bearing rocks are indicated by green stars, and massive sulphide ore bodies are indicated by solid red polygons (unpublished data, MMG). This figure is available in colour in the web version of this article.

bedrock, is assumed to be a product of the last glaciation, the Laurentide Ice Sheet (Dyke *et al.* 1982; Dyke & Dredge 1989; Dredge *et al.* 1999). Recent mapping of cross-cutting erosional relationships and depositional landforms by Paulen *et al.* (2013) builds on the earlier regional mapping of Dredge *et al.* (1996*c*) and Stea *et al.* (2009) as well as reconnaissance-scale reconstructions by Dyke & Prest (1987*a*,*b*) and Dyke (2004). All of this ice flow evidence indicates that the Izok Lake area was affected by four ice-flow phases. Of those, two dominant ice-flow phases are responsible for sculpting the landscape and striating bedrock surfaces: an older SW ice flow phase, and a younger WNW phase during the Late Wisconsin Laurentide glacial maximum. Locally, till thickness varies from outcrop with a till veneer of <1 m thick north and west of Izok Lake to thicker deposits >3 m thick in low lying areas east and south of Izok Lake (Dredge *et al.* 1996*c*). Till covers all parts of the deposit that subcrop on land; no massive sulphide is exposed at surface. Till in the area is relatively uniform in texture, containing an average of 48% sand, 51% silt, and 1% clay (Dredge *et al.* 1996*b*; Hicken *et al.* 2012).

Exploration history

The Izok Lake deposit was discovered in 1975 by following up the initial discovery of massive sulphide boulders containing >30% Zn along the SW shore (Fig. 3) of Izok Lake (Money & Heslop 1976). Detailed mapping, geophysics, soil geochemistry, and diamond drilling were used to locate the bedrock source of the mineralized boulders and a mineral resource was identified within a group of four near-surface sulphide lenses (Morrison 2004). Since the initial discovery, the deposit has been explored by various companies including Minnova, Inmet, Wolfden, and finally a series of companies that, through takeovers, led to the current property holder MMG.

During the early exploration activity in the Izok Lake area, a gossan containing sphalerite and chalcopyrite was identified on the west side of Iznogoudh Lake, *c.* 6 km NW of the Izok Lake deposit, which was later informally named the West Iznogoudh Lake (WIZ) showing (Heslop 1976; Money & Heslop 1976). To date, no significant base metal mineralization or gahnite has been discovered at the WIZ showing.

Previous surficial geochemical studies in the region

In 1975, Uranerz Exploration carried out a regional lake sediment survey in the Point Lake region but their results did not identify significant geochemical anomalies in the Izok Lake area (Reid 1975). In 1994, the GSC carried out a reconnaissance-scale (5–10 km sample spacing) till geochemical survey in the Point Lake region and reported geochemical data for <0.002 mm and <0.063 mm till fractions (Dredge *et al.* 1996*a*,*b*). Forty of their till samples were collected within a 20 km radius of the Izok Lake deposit, but the geochemical data did not reflect the presence of the Izok Lake Cu-Pb-Zn mineralization. At that time, the heavy mineral fractions of some of their reconnaissance till samples (10–15 km sample spacing) were also examined for gold grains and kimberlite indicator minerals, but no VMS indicator minerals were systematically searched for. As part of a student research project, a detailed till geochemical survey was conducted around the WIZ showing in 2009. In this detailed study, Oviatt (2010) reported elevated contents of Zn, Ag, Cu, Hg, and Bi in the <0.063 mm fraction of till samples proximal to the WIZ showing.

Methods

In preparation for the initial till sampling in 2009, the glacial flow history in the immediate vicinity around the Izok Lake deposit was mapped in detail by the GSC. These new ice flow data, combined with the known regional ice flow history (Kerr *et al.* 1995; Stea *et al.* 2009), have been described in detail by Paulen *et al.* (2013). The ice flow data guided the till sampling strategy used up- and down-ice of the deposit. In addition to the local-scale samples collected between 2009 and 2012, archived reconnaissance-scale till samples originally collected by the GSC in 1994 (Dredge *et al.* 1996*b*,*c*), up-ice and up to 70 km down-ice from the Izok Lake deposit were re-examined as part of this study.

Field sampling

In order to characterize the indicator mineral signature of the Izok Lake deposit, suites of bedrock samples from mineralization, alteration, and host rocks were collected. Twenty-three bedrock samples were collected from drill-core or outcrops to identify the indicator minerals associated with mineralization as well as minerals that could potentially be glacially eroded from background host rocks. Lithologies included Izok Lake ore, stringer zones, alteration zones, and background host rocks. Bedrock samples of mineralization and proximal alteration zones were collected from drill-core from various depths within the deposit because the subcropping surface was not exposed for sampling. These bedrock samples are typical of the mineralization and alteration that was exposed to glacial erosion. Additional mineralized bedrock samples were collected to compare with the Izok Lake deposit: weak sulphide mineralization 8 km to the north of the deposit (09-MPB-R091); the WIZ gossan 6 km NW of the deposit; and an iron gossan 1 km SW of the deposit (09-MPB-R115). Bedrock hand sample and petrographic descriptions, locations, and photographs of polished slabs are reported in McClenaghan *et al.* (2012*a*), Hicken *et al.* (2013*a*) and McClenaghan *et al.* (2013).

Till samples were collected in the summers of 2009, 2010, and 2012 from mudboils at a depth of 10 to 50 cm, at locations that are considered to be up-ice, proximal, and down-ice of the deposit. Large till samples (*c.* 10–20 kg) were collected for the recovery of indicator minerals from 75 sites. Small till samples (*c.* 3 kg) were collected at the same locations as the large samples as well as from 39 additional sites, for a total of 104 sites (Fig. 4) for matrix geochemistry. Field data and photographs of each sample site are reported in Hicken *et al.* (2013*b*).

Sample processing and indicator mineral picking

Till samples

A detailed description of sample processing procedures used in this study is reported in McClenaghan *et al.* (2012*a*, 2013). The average mass of till samples processed to recover heavy minerals was 11.1 kg. Briefly, the <2.0 mm fraction of each sample was processed at Overburden Drilling Management Limited (ODM) to produce a non-ferromagnetic heavy mineral concentrate (HMC) for selection of indicator minerals. Till samples were processed in a predetermined order from what was anticipated to be least metal-rich to most metal-rich, to limit the potential for significant cross-contamination (Plouffe *et al.* 2013). The <2.0 mm material was passed over a shaking table and the resulting HMC was recovered and micro-panned to recover and document gold and sulphide grains. These grains were counted and returned to the sample. Table concentrates were then refined using heavy liquid separation in methylene iodide at specific gravity (SG) of 3.2. After heavy liquid separation, the >0.25 mm ferromagnetic fraction was removed using a hand magnet. The non-ferromagnetic HMC was sieved into three size fractions (0.25–0.50, 0.5–1.0, 1.0–2.0 mm) and then examined by ODM for potential oxide and silicate indicators of massive sulphide deposits (Table 1), including ODM's magmatic/metamorphosed massive sulphide indicator mineral (MMSIM®) suite. This suite is used to explore for a broad spectrum of sulphide-associated deposits including VMS deposits (Table 1) and is based upon observations of indicator mineral suites in bedrock and surficial sediments near metamorphosed base metal deposits (Averill 2001). Other metallic minerals of interest were also picked. In addition to MMSIM® minerals, the abundance of gold, kimberlite indicator minerals (e.g. McClenaghan & Kjarsgaard 2007), and other unusual minerals were estimated for each sample and a selection of grains was set aside for further study. All raw indicator mineral abundance data are reported in McClenaghan *et al.* (2012*a*, 2013). The abundance of indicator minerals selected for this study (i.e. sphalerite, chalcopyrite, galean, and gahnite) in the 0.25–0.50 mm fraction of till samples normalized to a 10 kg sample mass of <2 mm material (table feed) is listed in Table 2 and all discussion of these results will refer to these normalized values. Field duplicates and other heavy mineral quality control measures are described in McClenaghan *et al.* (2012*a*), Hicken *et al.* (2012) and McClenaghan *et al.* (2013). As part of this Izok Lake study, 25 of the 1994 GSC archived heavy mineral concentrates were re-examined by ODM to recover indicator minerals characteristic of VMS deposits. Results of the re-examination are reported in McClenaghan *et al.* (2012*a*).

Bedrock samples

Polished thin sections (PTS) for each bedrock sample were examined to determine the minerals present and their size range. A separate split of each bedrock sample was disaggregated using an electric pulse disaggregator (EPD) to break apart the rock yet preserve natural grain sizes, textures, and shapes. The <2.0 mm disaggregated material was processed using heavy liquid separation at SG 3.2 to produce HMCs for examining and counting indicator minerals, according to the methods described in McClenaghan *et al.* (2012*a*). Bedrock samples were processed in a predetermined order from least mineralized to most mineralized to limit potential cross-contamination. Quartz 'blanks' were inserted into the sample batch (at the beginning, end and two in the middle of the sample batch) during processing to monitor, as well as limit, carryover contamination. Raw mass data and indicator mineral counts for the quartz blanks are also listed in McClenaghan *et al.* (2012*a*). Similar to till samples, the 0.25–0.50 mm non-paramagnetic and paramagnetic fractions, and the 0.5–1.0 mm and 1.0–2.0 mm non-ferromagnetic HMC fractions were then examined for indicator minerals that may be associated with VMS deposits (Table 1). The abundance of selected indicator minerals in the 0.25–0.5 mm HMC fraction of bedrock samples normalized to a 1 kg sample mass is listed in Table 3.

Geochemical analysis

A 2–3 kg split of each small till sample was oven dried at <30 °C and sieved to recover the <0.063 mm fraction as it is the most commonly used till size fraction for VMS exploration (McClenaghan & Peter 2013). A 1 g aliquot for each sample was digested in aqua regia and analysed by ICP-MS to determine base and precious metal contents. An additional 0.2 g aliquot was analysed by ICP-MS and ICP-ES following lithium metaborate/tetraborate fusion. Archived splits of the <0.063 mm fraction of 48 of the 1994 till samples were reanalysed with the 2011 GSC till samples and those results are reported in Hicken *et al.* (2012). Analytical accuracy and precision were monitored using certified reference standards, in-house standards, silicic acid blanks, and blind duplicates. Analytical results, along with data for standards, duplicates, and blanks are reported in Hicken *et al.* (2012). Aqua regia data for Cu, Pb, Zn, and Ag for 15 GSC till samples collected in 2012 (Paulen *et al.* 2015) and unpublished data for 15 MMG till samples analysed using the same geochemical methods, were combined with published GSC data for the 1994, 2009 and 2010 till samples and plotted on proportional dot map geochemical maps (Fig. 5).

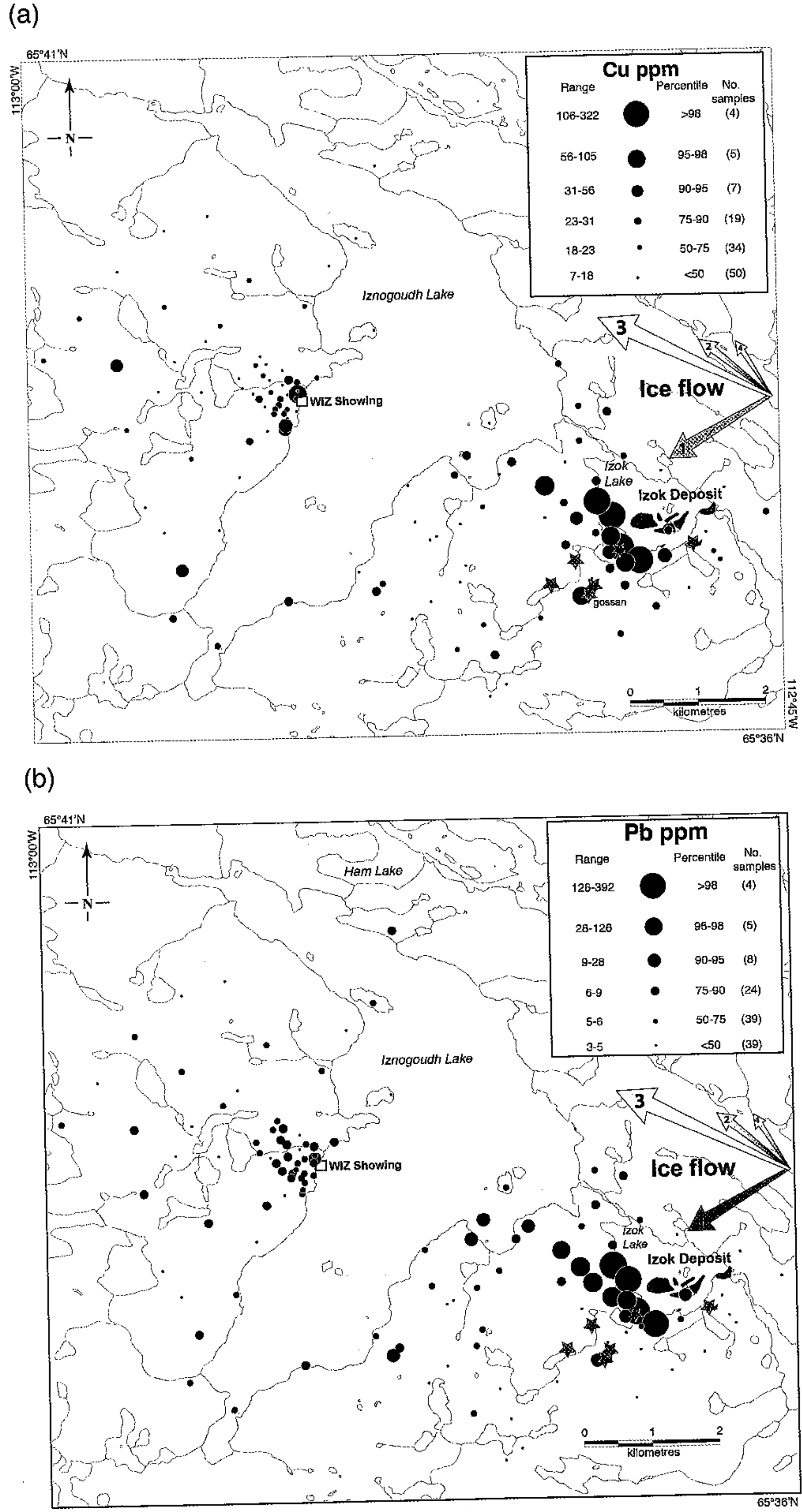

Fig. 4. Trace element content in the <0.063 mm fraction of till determined by aqua regia/ICP-MS around the Izok Lake VMS deposit ($n = 119$): (a) Cu ppm; (b) Pb ppm; (c) Zn ppm; (d) Ag ppb. Locations of gahnite-bearing rocks indicated by green stars and location of massive sulphide indicated by solid red polygons (unpublished data, MMG). This figure is available in colour in the web version of this article.

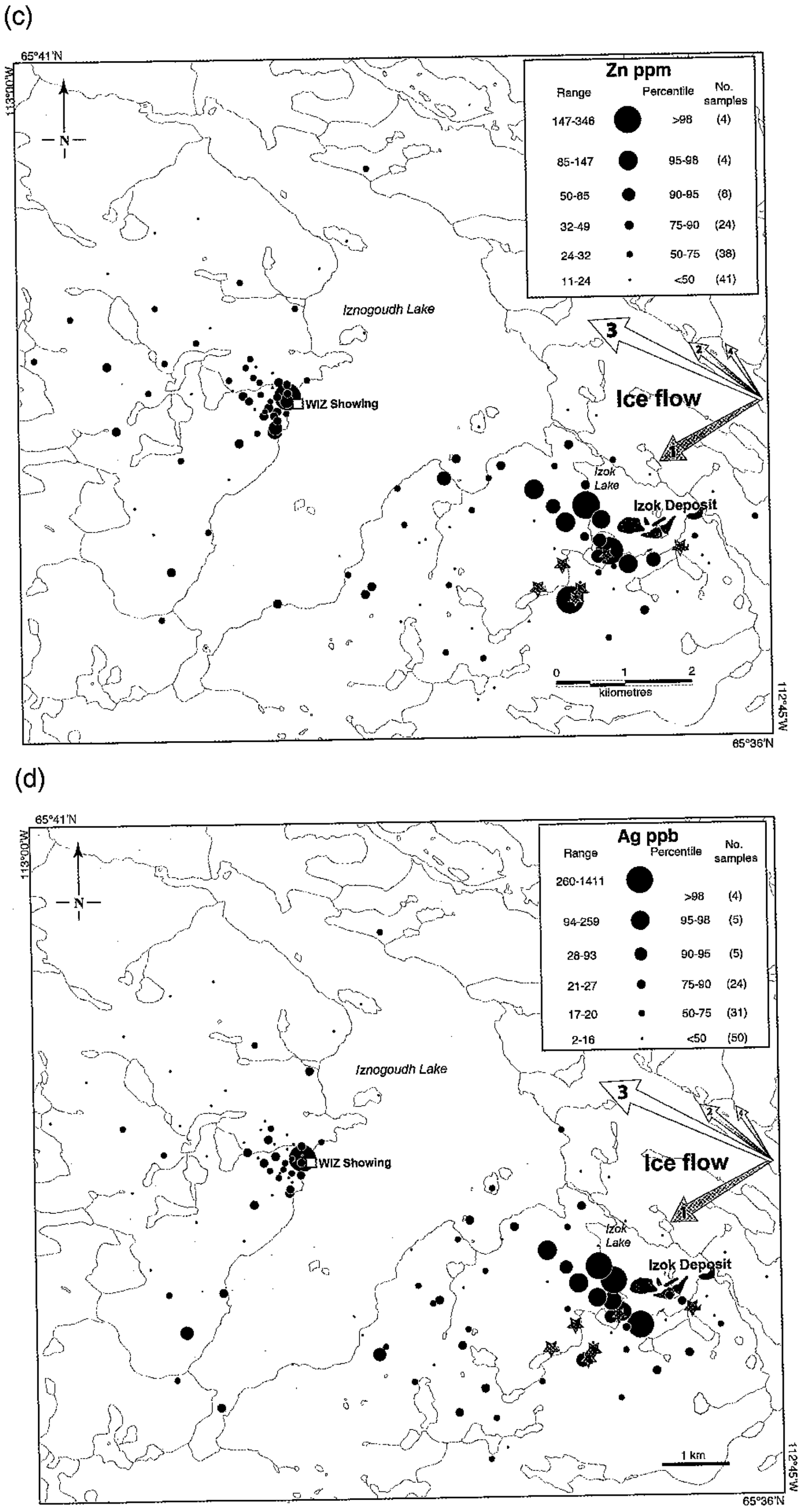

Fig. 4. (continued)

Table 2. *Abundance of sphalerite, chalcopyrite, galena, and gahnite in the 0.25–0.5 mm and 0.5–2.0 mm fractions of till (normalized to 10 kg sample mass) and bedrock (normalized to 1 kg) compared to contents of Cu, Pb, Zn, Ag, Cd, Sb, Bi, Hg, Se and In (aqua regia/ICP-MS) in the <0.063-mm size fraction of selected till samples at key distances up- and down-ice of the Izok Lake VMS deposit*

														Sphalerite		Chalcopyrite		Galena		Gahnite	
Sample	Material	Distance from Izok deposit (km)	Cu ppm	Pb ppm	Zn ppm	Ag ppb	Cd ppm	Sb ppm	Bi ppm	Hg ppb	Se ppm	Tl ppm	In ppm	0.25–0.5 mm	0.5–2.0 mm	0.25–0.5 mm	0.5–2.0 mm	0.25–0.5 mm	0.5–2.0 mm	0.25–0.5 mm	0.5–2.0 mm
09-MPB-R93	Massive sulphide	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	177,305	46,099	40,000	46,099	0	0	0	0
09-MPB-R41	Stringer zone	0.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	39	16	46	3	10	0	24,351	2597
09-MPB-R115	Gossan	1.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	154	8	231	15	771	123	96339	9249
09-MPB-060	Till	−0.8	21	4	30	15	0.04	<0.02	0.19	<5	0.1	0.07	<0.02	0	0	0	0	0	0	0	0
09-MPB-081	Till	0.0	28	12	23	27	0.06	0.03	0.26	<5	<0.1	0.08	<0.02	0	0	0	0	0	0	3	1
09-MPB-058	Till	0.3	132	303	109	1076	0.27	1.12	5.12	135	0.3	0.20	0.21	1271	127	9	1	0	0	77	9
09-MPB-059	Till	0.5	162	145	346	351	1.36	0.66	2.12	102	0.2	0.18	0.15	0	0	17	2	0	0	29	0
09-MPB-051	Till	1.3	27	28	84	49	0.19	0.13	0.54	11	0.2	0.10	<0.02	0	0	3	0	0	0	10	3
09-MPB-052	Till	1.5	68	55	120	187	0.48	0.20	0.58	55	0.3	0.13	0.25	4	0	42	3	3	0	15	0
09-MPB-053	Till	2.0	25	10	34	24	0.09	0.03	0.23	7	<0.1	0.08	<0.02	0	0	0	0	0	0	34	5
09-MPB-075	Till	3.0	24	9	39	22	0.10	0.03	0.36	15	<0.1	0.09	<0.02	0	0	0	0	0	0	64	6
09-MPB-021	Till	5.5	14	5	29	27	0.04	<0.02	0.14	<5	0.2	0.09	<0.02	0	0	0	0	0	0	20	2
09-MPB-038	Till	6.3	23	8	32	21	0.08	<0.02	0.18	<5	0.2	0.09	<0.02	0	0	0	0	0	0	25	4
09-MPB-022	Till	6.5	14	5	29	13	0.05	<0.02	0.18	<5	0.1	0.07	<0.02	0	0	0	0	0	0	35	0
09-MPB-002	Till	7.0	12	4	21	12	0.04	<0.02	0.14	<5	<0.1	0.06	<0.02	0	0	0	0	0	0	26	1
09-MPB-005	Till	7.0	20	4	23	9	0.03	<0.02	0.13	<5	<0.1	0.08	<0.02	0	0	0	0	0	0	14	0
12-MPB-906	Till	8.0	22	5	28	15	0.05	<0.02	0.17	9	<0.1	0.09	<0.02	0	0	0	0	0	0	17	0
12-MPB-902	Till	9.0	16	6	22	16	0.07	<0.02	0.21	<5	0.4	0.06	<0.02	0	0	0	0	0	0	38	1
94DU2588	Till	10.0	13	4	17	14	0.05	<0.02	0.17	6	<0.1	0.07	<0.02	0	0	0	0	0	0	45	0
94DU2614	Till	40.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	2	0	0	0	5	0
95th percentile			56	28	85	93	0.3	0.13	0.5	20	0		0.04								
Max value in 1994 regional samples		20 km radius	40	5	36	24	0.1	0.05	0.2	12	0		<0.02								

NA, not analysed.

Table 3. *Abundance of galena, sphalerite, chalcopyrite, pyrite, pyrrhotite, and gahnite in the 0.25–0.5 mm heavy mineral fraction of mineralized and unmineralized bedrock samples, normalized to 1 kg mass (disaggregated to <2 mm material)*

Sample Number	Lithology	Location	Galena	Sphalerite	Chalco-pyrite	Pyrite	Pyrrhotite	Gahnite	Mn-Axinite
09-MPB-R42	Iron formation	Up-ice	0	0	0	6	0	0	0
09-MPB-R90	Iron formation	Up-ice	0	0	0	9	0	0	0
09-MPB-R43	Metasediment	Up-ice	0	0	39	1640	8202	0	0
09-MPB-R45	Metasediment	Up-ice	0	0	0	0	0	0	0
09-MPB-R87	Clastic metasediment	Up-ice	0	0	0	4149	0	0	0
09-MPB-R47	Mafic metavolcanic	Up-ice	0	0	0	9792	0	0	0
09-MPB-R49	Diabase	Down ice	0	0	0	0	0	0	0
09-MPB-R51	Felsic metavolcanic	Up-ice	0	0	2	0	0	0	0
09-MPB-R88	Felsic intrusive	Izok deposit	0	0	2	0	0	0	0
09-MPB-R41	Stringer zone	Izok deposit	10	40	47	21710	16700	25050	0
09-MPB-R61	Sulphidic chert	Izok deposit	52	52	2064	6192	51600	361197	0
09-MPB-R62	Sulphidic breccia pipe	Izok deposit	419	387097	129032	194	0	0	387097
09-MPB-R65	Sulphidic breccia pipe	Izok deposit	235	293686	293686	294	14684	0	23892
09-MPB-R60	Massive sulphides	Izok deposit	0	958188	17422	871080	0	0	0
09-MPB-R64	Massive sulphides	Izok deposit	0	521739	35	347826	0	0	0
09-MPB-R93	Massive sulphides	Izok deposit	0	323834	518135	77720	64767	0	0
09-MPB-R69	Sulphidic alteration zone	north of Ham Lake	0	193	48243	1723	68918	137836	0
09-MPB-R91	Felsic metavolcanic	North of Ham Lake	0	0	6	955	0	0	0
09-MPB-R92	Metagabbro	Up-ice	0	0	0	15	197	0	0
09-MPB-R94	Felsic metavolcanic	Up-ice	0	0	0	0	0	0	0
09-MPB-R95	Metapelite	Up-ice	0	0	0	0	0	0	0

Results

Till matrix geochemistry

Concentrations of Ag, Bi, Cd, Cu, Hg, In, Pb, Sb, Se, Tl, and Zn for selected samples at key distances up- and down-ice of the deposit are summarized in Table 2. The thresholds between background and anomalous element concentrations were calculated for the full dataset of the reanalysed 1994 samples plus 2009, 2010, and 2012 samples using two methods, 95th percentile and probability plots/natural breaks, and are listed in Table 2. The highest contents of these elements are in till samples on the west and south shore of Izok Lake, and up to 3 km NW between Izok Lake and the east shore of Iznogoudh Lake (e.g. Fig. 4a–d). Elevated values of Cu, Zn, Ag, Cd, and Tl also occur in till samples 6 km to the NW, on the west side of Iznogoudh Lake, including sample 09-MPB-013 at the WIZ showing, and samples 09-MPB-010 and 09-MPB-020 that are 1 km SW of the WIZ showing (Fig. 4a and c). Till sample 12-MPB-915, 1 km SW of the deposit and immediately west of a gossan (bedrock sample 09-MPB-R115) (Fig. 3), contains high concentrations of Cu and Zn (Fig. 4a and c).

A correlation matrix for till samples collected in 1994, 2009, 2010 and 2012 samples was calculated in Table 4. Copper concentrations show variably strong ($r^2 > 0.8$) to statistically significant ($r^2 = 0.6$–0.8) correlations with Pb, Zn, Ag, Cd, Bi, and In (Table 4). Zinc concentrations show slightly different associations, with strong ($r^2 > 0.8$) positive correlations with Cd and Cu, and significant ($r^2 = 0.6$–0.8) correlations with Ag, Bi, Sb, and In. Lead concentrations shows strong ($r^2 > 0.8$) positive correlations with Ag, Sb, Bi, and In, and statistically significant ($r^2 = 0.6$–0.8) correlations with Cu, Zn, and Hg. Silver contents show strong positive correlations ($r^2 > 0.8$) with Pb, Bi, and In, as well as a statistically significant ($r^2 = 0.6$–0.8) correlation with Cu and Zn, Cd, Sb, and Hg.

Indicator mineral contents in bedrock and till

Table 2 lists the contents of sphalerite, chalcopyrite, galena, and gahnite in the HMC of till samples normalized to a 10 kg sample mass and Table 3 summarizes sulphide mineral and gahnite abundances in bedrock samples normalized to a 1 kg sample mass.

Thresholds between background and anomalous contents of indicator minerals in till in the Izok Lake area were established using till samples up-ice (east) of the deposit (samples 09-MPB-060, -054, 10-MPB-800 to -802, -804) and north of the deposit (samples 09-MPB-032, -049).

Pyrite

Pyrite occurs in mineralized rocks (thousands to hundreds of thousands of grains) and some felsic metavolcanic, mafic metavolcanic, and clastic metasedimentary rocks (ones to tens of grains) (Table 3). Most till samples contain zero pyrite grains and the background content is zero. Elevated counts occur in till samples on the west shore of Izok Lake, between 300 m (82–339 grains) and 1.5 km (24 grains) down-ice, and on the island directly overlying the deposit (56 grains).

Chalcopyrite

In the 0.25–0.50 mm fraction, thousands of chalcopyrite grains occur in massive sulphide-rich bedrock samples, whereas a few to tens of grains were recovered from felsic metavolcanic, metasediment, and felsic intrusive rocks (Table 3). In many of these samples, chalcopyrite is intergrown with sphalerite and pyrite. Most till samples contain zero chalcopyrite grains and background content is zero. However, chalcopyrite (2–42 grains) was recovered from the 0.25 to 0.50 mm fraction of till samples immediately down-ice (south and west) and up to 1.3 km down-ice (NW) of the deposit (Fig. 5).

Sphalerite

In bedrock samples in this study, sphalerite is the dark grey-black Fe-rich black variety (Fig. 6) and is commonly intergrown with pyrite and chalcopyrite. Hundreds of thousands of grains/kg are present in the 0.25–0.5 mm fraction of highly mineralized bedrock samples (Table 3) and no grains are present in unmineralized rocks. In till, the background content of sphalerite in the 0.25–0.5 mm fraction is zero grains. Only four till samples were found to contain sphalerite: sample 09-MPB-052 (4 grains in the 0.25–0.5 mm fraction) 1.3 km NW of the deposit, 09-MPB-058 (1271 grains in the 0.25–0.5 mm fraction) 300 m NW, 09-MPB-016 (14 grains in pan concentrate) 300 m NW, and

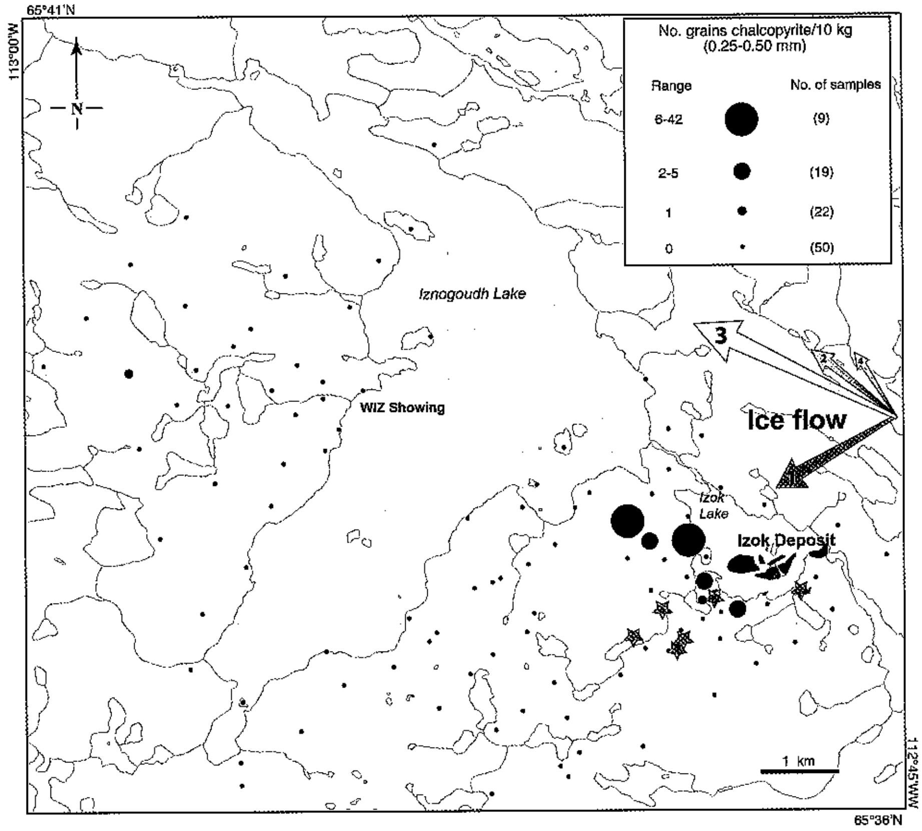

Fig. 5. Distribution of chalcopyrite in the 0.25–0.5 mm non-ferromagnetic heavy mineral fraction of till (normalized to a 10 kg sample mass) around the Izok Lake VMS deposit and the interpreted net glacial dispersal. Arrows indicate relative ice flow chronology (1 = oldest) and vigour (arrow size) of flow events (Paulen *et al.* 2013). Modified from Hicken *et al.* (2013*b*). Locations of gahnite-bearing rocks indicated by green stars and location of massive sulphide indicated by solid red polygons (unpublished data, MMG). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Table 4. *Correlation matrix for selected elements determined by aqua regia ICP-MS for the <0.063 mm fraction of 1996, 2009, 2010, 2012 till samples (n = 119). Numbers in bold are statistically significant (r^2 > 0.6) correlations*

	Cu	Pb	Zn	Ag	Cd	Sb	Bi	Hg	Se	In
Cu	1.00	–	–	–						
Pb	**0.76**	1.00	–	–						
Zn	**0.81**	**0.80**	1.00	–						
Ag	**0.79**	**0.91**	**0.79**	1.00						
Cd	**0.77**	**0.80**	**0.88**	**0.75**	1.00	–	–	–		
Sb	0.59	**0.86**	**0.63**	**0.79**	**0.68**	1.00		–		
Bi	**0.75**	**0.90**	**0.78**	**0.89**	**0.74**	**0.85**	1.00	–		
Hg	0.49	**0.66**	0.47	**0.71**	0.52	**0.72**	**0.66**	1.00		
Se	0.41	0.51	0.49	0.51	0.41	0.36	0.48	0.27	1.00	–
In	**0.71**	**0.83**	**0.68**	**0.86**	**0.70**	**0.79**	**0.80**	**0.72**	0.43	1.00

09-MPB-056 (9 grains in the pan concentrate) on the SW shore of Izok Lake.

Galena

Three to hundreds of galena grains/kg are present in the 0.25–0.5 mm fraction of some highly mineralized bedrock samples but not all (Table 3), and hundreds to thousands of galena grains, 15–100 µm in size, were observed in pan concentrates of mineralized bedrock samples (Hicken *et al.* 2013). Background galena content in the 0.25–0.5 mm fraction of till is zero grains. Till sample 09-MPB-052, 1.3 km to the NW, contained three galena (Fig. 6) grains in the 0.25–0.5 mm fraction and sample 09-MPB-057 on the south shore of Izok Lake contained a few grains of galena in the pan concentrate (25–50 µm). A few grains of galena were also recovered from the pan concentrate of sample 09-MPB-043 immediately NW of the WIZ showing.

Gold

No gold was observed in, or recovered from, bedrock samples in this study and no gold has been reported in the deposit (Harris *et al.* 1984*a*,*b*; Harris *et al.* 1986; Morrison 2004). Gold grain abundance in till varies between background values of 0–5 grains, to a maximum of 24 grains. Background concentrations in till are considered to be 0–5 grains based on abundances reported for gold grains in till overlying Archean greenstone belts in permafrost terrain of NWT and Nunavut (e.g. Kerr 2002; Dredge *et al.* 2005). The highest gold grain counts in till are located NE and SW of the WIZ showing (21–24 grains). The majority of till samples around the Izok Lake deposit contain 6–20 grains. Grains vary between 15 and 125 µm in size, with most between 15 and 50 µm and have been classified as 'reshaped' using the scheme of DiLabio (1990). Reshaped grains likely indicate a glacial transport distance of at least several km (Averill 2001).

Gahnite

Gahnite ($ZnAl_2O_4$) is a zincian spinel that occurs around or within metamorphosed VMS deposits (Spry 1982; Sheridan & Ray 1984; Spry & Scott 1986*a*, *b*; Spry 1987*a*, *b*; Heimann *et al.* 2005; Ghosh & Praveen, 2008; O'Brien *et al.* 2014). It has a high specific

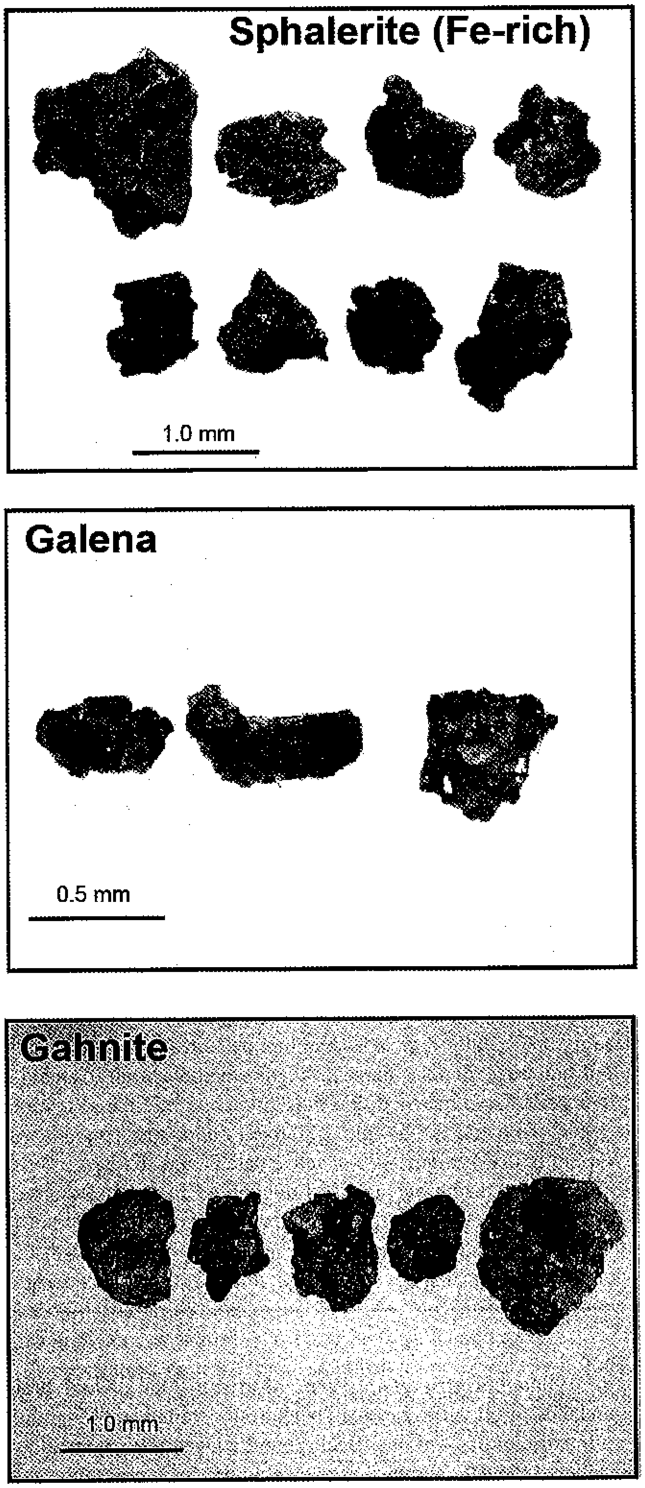

Fig. 6. Colour photographs of 0.25–2.0 mm indicator minerals recovered from the heavy mineral fraction of till: (a) sphalerite from sample 09-MPB-058 1.0–2.0 mm; (b) galena from sample 09-MPB-052, 0.25–0.5 mm; (c) gahnite from sample 09-MPB-057, 0.5–1.0 mm. Photos provided by Overburden Drilling Management Ltd.

gravity of 4–4.6 and thus is easily concentrated in HMC. Gahnite was visually identified in the HMC by its blue green and its euhedral crystal habit (Fig. 6). Gahnite recovered from the bedrock samples is commonly interlocked with quartz, muscovite, and biotite, and less commonly with Ca-amphibole, spinel, microcline, clinochlore, ripidolite, epidote, sillimanite, albite, corundum, dravite, apatite, spessartine, monazite, ilmenite, xenotime, magnetite, plagioclase, and titanite (Hicken *et al.* 2013*b*). Gahnite grains were recovered from samples of the sulphide stringer zone and at the contact between the sulphide stringer zone and host rocks in the Izok Lake deposit. Tens of thousands to hundreds of thousands of grains/kg of gahnite were recovered from the 0.25 to 0.5 mm fraction of bedrock samples 09-MPB-R69 (metamorphosed sulphidic alteration zone 8 km north of the deposit), 09-MPB-R61 (sulphidic chert) and 09-MPB-R41 (felsic volcanic) (Table 3). Tens of thousands to hundreds of thousands of gahnite grains/kg were also recovered in the coarser fractions (0.5–1.0, 1.0–2.0 mm) of samples 09-MPB-R41 (felsic volcanic), 09-MPB-R69 (metamorphosed sulphidic alteration zone), and 09-MPB-R61 (sulphidic chert) (Table 3). Tens to hundreds of thousands of gahnite grains/kg are also present in an exposed gossan zone (09-MPB-R115) 1 km SW of the deposit (Fig. 7a).

The gahnite content in the 0.25–0.5 mm fraction of till varies between 0 and 1739 grains (Fig. 7a). Background content in till samples up-ice (east) and north of the deposit ranges from 0 to 2 grains. Till collected immediately down-ice (SW and NW shorelines of Izok Lake) contains between 77 and 1739 grains. Further down-ice (NW), till contains tens of grains: 12 grains at 0.9 km, 34 grains at 2 km, 31 grains at 4 km, 42 grains at 5 km, to 26 grains at 7 km, 45 at 10 km and 8 grains at 40 km. Gahnite abundance is also above background WSW of the deposit on the east side of Iznogoudh Lake (Fig. 7a).

Coarse gahnite grains (0.5–1.0 mm) were recovered from till along the west and south shore of Izok Lake, between Izok and Iznogoudh lakes (NW), and 6–10 km down-ice (NW) on the west side of Iznogoudh Lake (Fig. 7b). Very coarse (1.0–2.0 mm) gahnite grains were recovered from three till samples, indicated by the encircled dots on Figure 7b, on the south and west shores of Izok Lake and from sample 09-MPB-075, *c.* 3 km down-ice (NW) of the deposit.

The gahnite content for the 0.25–0.5 mm fraction of the 1994 archived heavy mineral concentrates are plotted in Figure 8. Samples up-ice to the north and east of the deposit were used to define a background content of 0 to 1 grain. In contrast, archived till samples down-ice (NW) of the deposit contain between 2 and 45 grains at least 40 km down flow, as indicated by the shaded polygon in Figure 8.

Discussion

Till geochemistry

The term 'indicator element' is used here to refer to an element that is an economically valuable component of the ore being sought and may be used to detect an orebody (Rose *et al.* 1979). Indicator elements in the <0.063 mm fraction of till down-ice of the Izok Lake VMS deposit include Cu, Pb, Zn, and Ag and indicate the presence of metal-rich debris 500 km to the SW (older ice flow event) and 6 km to the NW (younger ice flow event). The term 'pathfinder element' is used here to refer to non-ore elements associated with the deposit that may be used to detect the orebody (Rose *et al.* 1979). Pathfinder elements for the Izok Lake VMS deposit include As, Cd, Bi, Hg, In, Sb, Se, and Tl. Elevated Cu, Ag, and Zn values in till sample 09-MPB-013 immediately west of the WIZ showing are likely related to dispersal from that local source. High contents of Zn and Cu in till samples 09-MPB-010 and 09-MPB-020, 1 km SW of the WIZ showing (Fig. 4a and c), combined with the presence of gahnite grains, suggest these high metal values are likely the result of NW ice flow (Phase 3) from the Izok deposit 6 km to the SE, and not older SW flow from the WIZ showing.

Sphalerite is a major mineral in the Izok deposit, and is likely the source of elevated Zn (100s of ppm), Cd, In, and Hg concentrations in till (aqua regia digestion) down-ice of the deposit. A second Zn-bearing mineral in the till at Izok Lake is gahnite. Gahnite

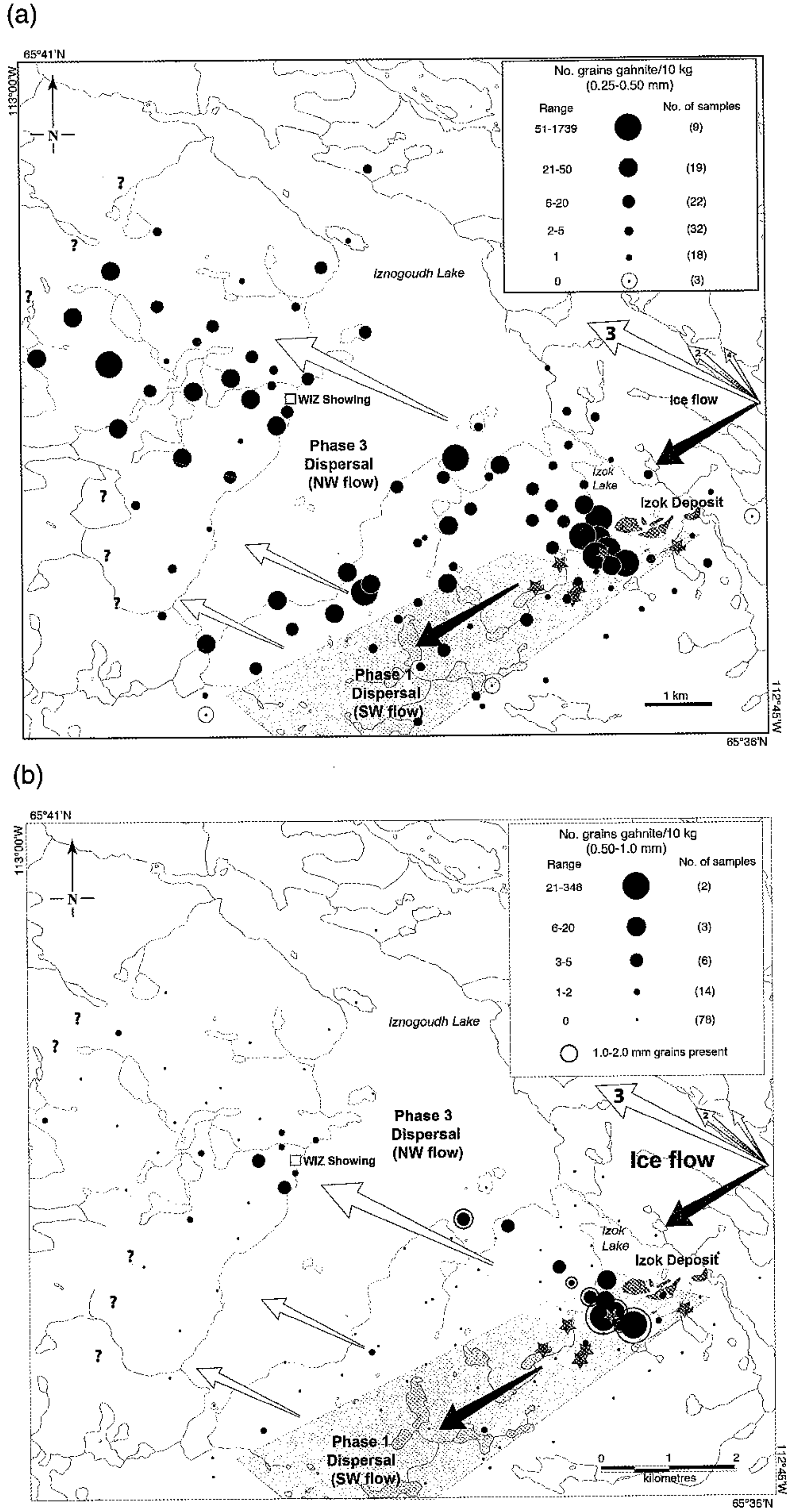

Fig. 7. Distribution of gahnite in the non-ferromagnetic heavy mineral fraction of till (normalized to a 10 kg sample mass) around the Izok Lake VMS deposit and the interpreted net glacial dispersal: (a) 0.25–0.5 mm fraction; (b) 0.5–1.0 and 1.0–2.0 mm fractions. Arrows indicate relative ice flow chronology (1 = oldest) and vigor (arrow size) of flow events. Yellow polygon represents dispersal by the NW ice flow; blue represents dispersal by older SW ice flows (modified from Paulen *et al.* 2013). Locations of gahnite-bearing rocks indicated by green stars and location of massive sulphide indicated by solid red polygons (unpublished data, MMG). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

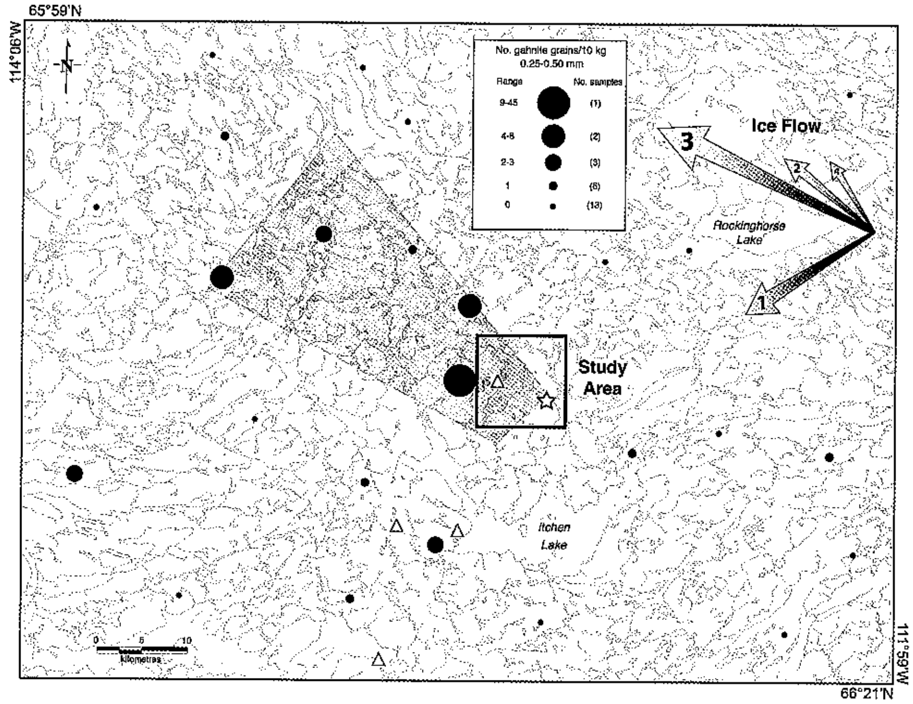

Fig. 8. Distribution of gahnite in the 0.25–0.50 mm fraction of till in the Izok Lake region in archived (1994) GSC till heavy mineral concentrates (Dredge *et al.* 1996*a*) re-examined in this study (McClenaghan *et al.* 2012*a*) normalized to a 10 kg sample mass. The net regional glacial dispersal fan boundaries are indicated by the grey polygon. Arrows indicate relative ice flow chronology (1 = oldest) and vigor (arrow size) of flow events. Modified from McClenaghan *et al.* (2012*b*). White star indicates the location of the Izok Lake VMS deposit; white triangles indicate locations of VMS showings.

is similar to other spinel group minerals in that it is not readily dissolved in aqua regia (Chao & Sanzolone 1992), thus Zn contents in the <0.063 mm fraction of till as determined by aqua regia ICP-MS do not reflect the gahnite content in till. Aqua regia digested an average of 71% of the total Zn content that was determined by borate fusion. This percentage increases to 86% for aqua regia Zn values that are >100 ppm. The distribution pattern of total Zn values in till is similar to that of Zn determined by aqua regia (Fig. 4c), indicating that in this study, borate fusion offered no advantage over aqua regia for determining Zn content in till at Izok Lake.

Elevated Cu values (100s of ppm) in till samples are accompanied by several grains to a few tens of chalcopyrite grains/10 kg in the 0.25–0.5 mm fraction, indicating that chalcopyrite is the main source of Cu anomalies in the metal-rich till. Galena is the major source of elevated Pb contents in till along with additional contributions from Pb-bearing ore minerals listed in Table 1. Chalcopyrite, combined with native Ag and other Ag-bearing minerals in the deposit listed in Table 1 (Harris *et al.* 1984*a*; Hicken *et al.* 2012), are the sources of Ag in the metal-rich till down-ice of the deposit. Elevated Bi content in till (10s of ppm) is likely derived from native Bi and cosalite as well as other Bi-bearing minerals in the deposit (Table 1). Antimony contents in till likely reflect the presence of the 13 Sb-bearing minerals listed in Table 1. Selenium in VMS deposits is present within sulphides and sulphosalts (e.g. Huston *et al.* 1995; Layton-Matthews *et al.* 2008), which are likely the source of elevated Se in till down-ice of the Izok Lake deposit.

Dredge *et al.* (1996*b*) collected 40 till samples within a 20 km radius of the Izok Lake deposit as part of their reconnaissance scale survey of the Point Lake region. They analysed the <0.002 mm fraction of these samples using aqua regia digestion, but not the <0.063 mm fraction as used in this study, preventing direct comparison of results with this study. Therefore, the <0.063 mm fraction of their till samples within a 20 km radius of the Izok Lake deposit were reanalysed as part of this study (Hicken *et al.* 2012). Maximum trace element values for these 1994 samples are reported in Table 3 and they are notably lower than the 95th percentile values reported for this study. These low contents of indicator and pathfinder elements in the reconnaissance samples are not unexpected. The sample spacing for the 1994 survey was at a reconnaissance scale (5–10 km), and sample sites may not have been close enough to the Izok Lake deposit or the WIZ showing to detect mineralized debris that may have been glacially dispersed down-ice. Dredge *et al.* (1996*b*) did note some higher contents of Cu, Pb, Zn, and Ag in the 86H NTS map sheet, but these did not correspond to the Izok Lake deposit or the WIZ showing.

Indicator minerals

Mineralized rocks in the Izok Lake deposit contain hundreds to thousands of grains of chalcopyrite, galena, and sphalerite. Of these three main ore minerals, chalcopyrite displays the most obvious glacial dispersal trending 1.3 km to the NW (Fig. 5). Other potential indicator minerals listed in Table 1 that were found in till include arsenopyrite, cassiterite, and gold. Rare single grains of arsenopyrite recovered from till are unrelated to mineralization. A single cassiterite grain (25 µm) was recovered from the pan concentrate of till sample 09-MPB-056, 300 m SW of the deposit. Gold grain content in till in the Izok Lake area is low (0–24 grains) and displays a distribution pattern that is unrelated to the Izok Lake deposit.

In contrast to the sulphide minerals, mineralized rocks contain tens of thousands of grains of gahnite. Till samples collected down-ice (SW and NW) to the deposit contain tens to thousands of grains. Background gahnite content in the 0.25–0.5 mm fraction of till up-ice and in areas away from the dispersal train is 0 to 1 grain. The glacial dispersal pattern detected using gahnite is the net effect of two dominant phases of ice flow. The oldest flow to the SW carried gahnite-rich debris from the deposit southwestward. A younger flow to the NW displaced the debris dispersed by the SW ice flow (purple polygon in Fig. 7a), as well as dispersed newly eroded debris northwestward (yellow polygon in Fig. 7a). This displacement of a dispersal train by a subsequent glacial flow phase is known as palimpsest dispersal (Parent *et al.* 1995; Stea *et al.* 2009; Paulen *et al.* 2013). Coarse gahnite grains (0.5–1.0 mm) were recovered from till up to 9 km down-ice (NW) and very coarse (1.0–2.0 mm) gahnite was recovered from till up to 3 km down-ice (NW) of the deposit. The coarser grains were rarely recovered from the Phase 1 (older) flow part of dispersal fan (blue polygon in Fig. 7b), possibly due to the additional mechanical wear of gahnite (entrainment, transport, and comminution) by multiple glacial flow phases.

At regional to reconnaissance scales, background gahnite content in the 0.25–0.5 mm fraction of till is 0–1 grain. Elevated contents in regional till samples extend at least 40 km NW of the Izok Lake deposit. The pattern shown in Figure 9 is interpreted to be the net effect of the two dominant phases of ice flow, the oldest flow to the SW and the younger flow to the NW. The gahnite abundance data for the archived till samples are significant for three reasons. First, the data indicate that, even at a reconnaissance scale of 15–20 km sample spacing, the presence of a gahnite-bearing source rock is detectable. Second, gahnite is a very robust indicator mineral (hardness of 8) capable of surviving long distance glacial transport. Third, the data show the value of archiving till heavy mineral concentrates and re-examining them when new indicator mineral(s) become available.

The presence of gahnite in highly metamorphosed VMS deposits is well documented (e.g. Spry 1982; Sheridan & Ray 1984; Spry & Scott 1986*a*,*b*; Bernier *et al.* 1987; Heimann *et al.* 2005; Ghosh & Praveen 2008; Spry & Teale 2009). The potential of gahnite as an indicator mineral of metamorphosed VMS deposits in glacial sediments has been reported by Stendal & Theobald (1994), Morris *et al.* (1997), and Averill (2001). Gahnite is easily recovered from surficial sediments because of its visually distinctive bluish green colour combined with its high specific gravity. These characteristics combined with its physical robustness (H = 8) and chemical stability in oxidizing environments (Morris *et al.* 1997) make it a useful indicator mineral. One of the challenges of using gahnite as an indicator mineral for VMS mineralization is that it is not unique to VMS deposits. It also occurs in pegmatites, aluminous metasedimentary rocks, skarns, marbles and metamorphosed banded iron formation (Heimann *et al.* 2005; Spry & Teale 2009; O'Brien *et al.* 2014).

Toverud (1977) and Peuraniemi (1990) were among the first to document the presence of gahnite in till down-ice of known VMS mineralization. Subsequently, Lalonde *et al.* (1994) reported gahnite in till up to 5 km down-ice of the Montauban VMS deposit in eastern Canada. Recently, McClenaghan *et al.* (2012*c*) reported the presence of gahnite in till around the Halfmile Lake VMS deposit in the Bathurst Mining Camp of eastern Canada. However, it is not yet clear whether the Halfmile Lake deposit is the source of the gahnite in the till. To date, the Izok Lake case study is the first detailed study of the glacial dispersal of gahnite from a VMS deposit known to contain gahnite using modern indicator mineral methods.

Glacial dispersal

Till geochemistry of the <0.063 mm fraction defines glacial dispersal of metal-rich debris from the Izok Lake deposit only at a local scale (maximum 6 km down-ice) (Fig. 4). At this scale, glacial dispersal patterns are the net effect of the two dominant phases of ice flow, the oldest SW and the main NW flows. Similar short glacial dispersal distances defined by till geochemistry were noted down-ice of other VMS deposits, including the Jameland (Shilts 1976), Hackett River (Miller 1979), Lar (Nielsen & Conley 1991), Lost Lake/Ghost Lake (Kaszycki *et al.* 1996), Samtosum (Paulen 2001), and Restigouche, C-4, and C-5 (Parkhill & Doiron 2003).

Gahnite distribution in till defines glacial dispersal at both the local and regional scales. At a regional scale, elevated gahnite contents in till extend at least 40 km down-ice (NW) of the deposit. At a local scale, dispersal patterns shown in Figures 7 and 8 reflect the two dominant phases of ice flow.

Many of the kimberlites in the Slave Craton NE and south of Izok Lake have well developed glacial dispersal trains (e.g. McClenaghan *et al.* 2002; Stea *et al.* 2009) that have been defined using the physically robust and the visually distinct kimberlite indicator minerals (KIM) Cr-pyrope, chromite, Mg-ilmenite, Cr-diopside, and olivine. Similar to the Izok Lake area, some of the KIM glacial dispersal trains are the product of multiple phases of ice flow (e.g. Stea *et al.* 2009). Many of the KIM trains are tens of km long (Armstrong 2000, 2003). Gahnite is similar to KIM in that it is physically robust and visually distinct. Thus it is not unexpected that gahnite dispersal from the Izok Lake deposit can be detected at least 40 km down-ice.

Conclusion

Till geochemistry has historically been used to explore for VMS deposits in glaciated terrain. In this study, glacial dispersal from the Izok Lake VMS deposit was detected up to maximum of 6 km down-ice using till geochemistry of the <0.063 mm fraction of closely spaced (500 m) till samples. Indicator elements for the deposit include Cu, Pb, Zn, and Ag, and pathfinder element include As, Bi, Cd, Hg, In, Sb, Se, and Tl. The 5–10 km sample spacing from the GSC's 1994 till geochemistry reconnaissance survey was too large to detect glacial dispersal from the Izok Lake deposit. In order for till geochemistry of the <0.063 mm fraction to be effective for detecting VMS mineralization in the region, a closer sample spacing of 1–2 km would have to be used.

The Izok Lake survey is the first case study to use modern indicator mineral methods to document the glacial dispersal patterns of sulphides and gahnite from a known gahnite-bearing VMS deposit. Till samples down-ice from Izok Lake contain tens to thousands of chalcopyrite, sphalerite, galena and pyrite grains/10 kg up to 1.3 km to the NW. Sulphides were recovered from the 0.25 to 0.5 mm fraction of till as well as the pan concentrate. Till down-ice also contains tens to thousands of grains of gahnite and the mineral is present in till at least 40 km down-ice (NW). Gahnite is an ideal indicator mineral because of its distinctive bluish green colour combined with its high specific gravity, hardness, and chemical stability in oxidizing surficial environments. The 10–15 km sample spacing originally used by the GSC for their 1994 reconnaissance-scale heavy mineral till survey was sufficient to detect the gahnite glacial dispersal from the Izok Lake deposit. Re-examination/re-picking of gahnite and other VMS indicator minerals, from archived GSC heavy mineral concentrates demonstrates the value of retaining heavy mineral concentrates after a project is finished, and of applying new indicator mineral suites to archived samples.

The size of indicator minerals in till is controlled primarily by the original size of the grains in the source rock and the durability of the mineral during glacial erosion/transport/deposition. Gahnite grains up to 2 mm in size were recovered from mineralized bedrock. Of the three till size fractions examined for gahnite in this study, most grains are in the 0.25–0.5 mm fraction. Gahnite grains 0.5–1.0 mm and 1.0–2.0 mm in size are found only in till proximal to the deposit, between 0 and 3 km down-ice (SW and NW). Thus, the presence of coarse (>0.5 mm) gahnite in till can be an indicator of proximity to a bedrock source.

The resultant indicator mineral dispersal train from the Izok lake VMS deposit is a large fan formed from the oldest ice flow phase to the SW (255°) and the main ice flow phase to the NW (292°). The identification of a fan-shaped glacial dispersal pattern at Izok Lake emphasizes the importance of thoroughly conducting field-based ice-flow indicator mapping to document all phases of glacial flow. This example provides a model for future exploration in the glaciated terrain of the north–central part of the Slave Province.

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