Overview of tungsten indicator minerals scheelite and wolframite with examples from the Sisson W-Mo deposit, Canada

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These short course notes provide an overview of published literature on the use of scheelite and wolframite as indicator minerals for W, Mo, and Au exploration. The use of scheelite and wolframite in stream sediments is well documented for mineral exploration but less so for using glacial sediments (Table 1). The Geological Survey of Canada has recently conducted a glacial till and stream sediment indicator mineral case study around the Sisson W-Mo deposit in eastern Canada. Preliminary indicator mineral results from this ongoing study are reported here.

SOURCES OF SCHEELITE AND WOLFRAMITE IN BEDROCK

Scheelite and wolframite are the main ore minerals of tungsten deposits, which form due to either magmatic-hydrothermal processes associated with felsic magmas (i.e. granite, pegmatite) or metamorphic processes (i.e. orogenic veins), with the former being by far the dominant in past and current production globally (see Kwak (1987) for review). Tungsten, more specifically scheelite, is also known to occur, albeit rarely, in stratiform/stratabound and commonly tourmaline-rich horizons associated with submarine basic volcanic rocks and clastic and chemical (i.e. carbonate) rocks. This mineralization model is, however, very controversial, one such example being the large Felertal scheelite deposit of Austria (Cheilletz 1988). In granite-related deposits, wolframite occurs in both greisen and veins, either within the intrusion or the surrounding country rock. The large Panasqueira, Portugal (Kelly & Rye 1979) and Pasto Buena, Peru (Landis & Rye 1974) deposits are good examples of granite-hosted, vein wolframite mineralization. The Mount Pleasant deposit in New Brunswick, Canada, is an example of a more complex system, both in terms of elements (W-Mo-Sn-Bi-Zn-In) and style, where greisen and stockwork mineralization occur (Kooiman *et al.*1986).

Where the surrounding country rock is dominated by carbonate, scheelite is the main tungsten mineral and occurs as part of a hydrous assemblage (i.e. amphibole-biotite-sulphides) that overprints an earlier higher temperature garnet-pyroxene assemblage (Meinhert *et al.* 2005). The Cantung and Mac Tung deposits in northwestern Canada, which are among the western world's largest resources of W, are examples of such scheelite mineralization (Dick & Hodgson 1982). As noted above, in vein and greisen settings, other elemental associations

Table 1. List of regional surveys and case studies conducted around the world in which scheelite and/or wolframite in surficial sediments have been used as indicator minerals.

Mineral	Media	Location	Source of Information
scheelite	stream sediments	Pakistan	Asrarullah (1982)
wolframite	stream sediments	Burma	ESCAP Scretariat (1982)
scheelite, wolframite	stream sediments	USA	Theobald & Thompson (1960)
scheelite	stream sediments, soil	Thailand	Silakul (1986)
scheelite	stream sediments	Greenland	Hallenstein *et al.* (1981)
scheelite	stream sediments	Spain	Fernández-Turiel *et al.* (1992)
scheelite	stream sediments	India	de Smeth *et al.* (1985)
scheelite	stream sediments	Canada	Maurice (1986)
scheelite	till	Finland	Lindmark (1977)
scheelite	till	Sweden	Brundin & Bergström (1977)
scheelite	till	Finland	Johansson *et al.* (1986)
scheelite	till	Finland	Nikkarinen & Björklund (1976)
scheelite	stream sediments	Turkey	Özcan & Çağatay (1989)
scheelite	stream sediments	Norway	Petersen & Stendal (1987)
scheelite	till	Finland	Peuraneimi (1992)
scheelite	till	Finland	Salminen & Hartikainen (1986)
scheelite	till	Ireland	Steiger (1977)
scheelite	till	Sweden	Toverud (1984)
scheelite, wolframite	stream sediments	Malaysia	Rajah (1982)
scheelite	stream sediments	Norway	Stendal (1978)
scheelite, wolframite	eolian sediment	Saudia Arabia	Salpeteur (1985)
scheelite, wolframite	till, stream sediments	Canada	McClenaghan *et al.* (2013a, in press)

can occur; thus W-Mo endo- and exo-skarn deposits have been noted, the large Logtung deposit being one example (Noble *et al.* 1984). As is discussed below, the presence of other elements, in particular Mo, is an important feature of W deposits as the presence of Mo in scheelite can affects its properties (e.g. fluorescence). Tungsten deposits are often associated with Sn, in addition to Mo mineralization. Varying combinations of pyrrhotite, chalcopyrite, sphalerite, arsenopyrite, galena, native Bi, and bismuthinite (Horsnail 1979; Hosking 1982) may also be associated with tungsten deposits.

Scheelite

Scheelite ($CaWO_4$) can be used as an indicator mineral because it is chemically robust, hard (H=4-5), dense (SG 5.9–6.12), and has blue-white fluorescence under UV light, which means that it is relatively insoluble in the natural pH range of surface water, survives moderate distances of glacial or fluvial transport, and can be easily identified (Horsnail 1979; Hosking 1982; Ottensen & Theobald 1994). Scheelite, however, is brittle and thus it does not survive long distance transport as com-

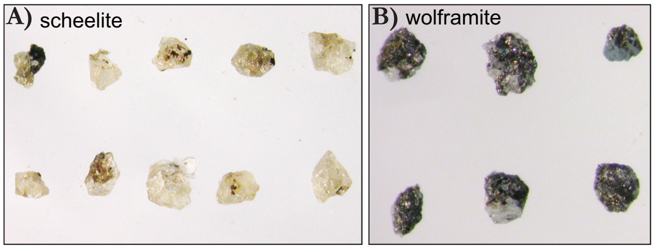


Fig. 1. Colour photographs of indicator minerals in bedrock heavy mineral concentrates from the Sisson W-Mo deposit: **A)** scheelite in sample 11-MPB-R07, 0.5–1.0 mm; **B)** wolframite in sample 11-MPB-R06, 0.25–0.5 mm (modified from McClenaghan *et al.* in press).

pared to other indicator minerals such as gold. Scheelite can be identified in heavy mineral concentrates (HMC) by its pale yellow colour (Fig. 1), cleavage, and its bright blue-white-yellow fluorescence under shortwave UV light (Fig. 2), which can vary due to Mo content (i.e. powellite substitution). Pure scheelite fluoresces strong blue, which with increasing Mo content changes from white at 0.5–1.0 wt% Mo, to yellow at >1 wt% Mo, to a deep orange-yellow at >4 wt% Mo (Hosking 1982). Zircon, another common fluorescent mineral in heavy mineral concentrates, can be distinguished from scheelite by its yellow-green-orange fluorescence under both short- and longwave ultraviolet light.

The angularity (and other features) of scheelite grains collected from streams can provide indications of relative distance of transport. For example, in southwest Poland, Mikulski & Wierchowiec (2013) compared the shape of scheelite grains in bedrock versus those collected from fluvial sediments downstream(Fig. 3); they also compared scheelite, adamantine luster, and intergrowths of other minerals (e.g. quartz and titanite), and fluid inclusions. Scheelite in alluvial sediments ~1 km downstream of the bedrock source were subangular to subrounded, contained fluid inclusions that matched the bedrock source, but lacked intergrowths of other minerals. Scheelite grains transported >2.0 km from the source had a matte luster instead of glassy, and the surfaces of larger scheelite grains had coatings of clay minerals. In another study, Wildon & Hotz (1955) noted that the presence of quartz intergrown with scheelite in stream sediments could be indicative of transport distance as well as the type of bedrock source (i.e. quartz-vein hosted).

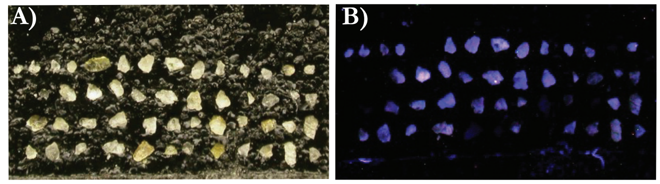


Fig. 2. Scheelite grains (0.25–0.5 mm) from till sample 11-MPB-504 mounted on a scanning electron microscope stub under **(A)** normal and **(B)** shortwave ultraviolet light (modified from McClenaghan *et al.* in press).

Several studies have noted that scheelite grain size decreases with increasing distance of transport, both in stream sediments

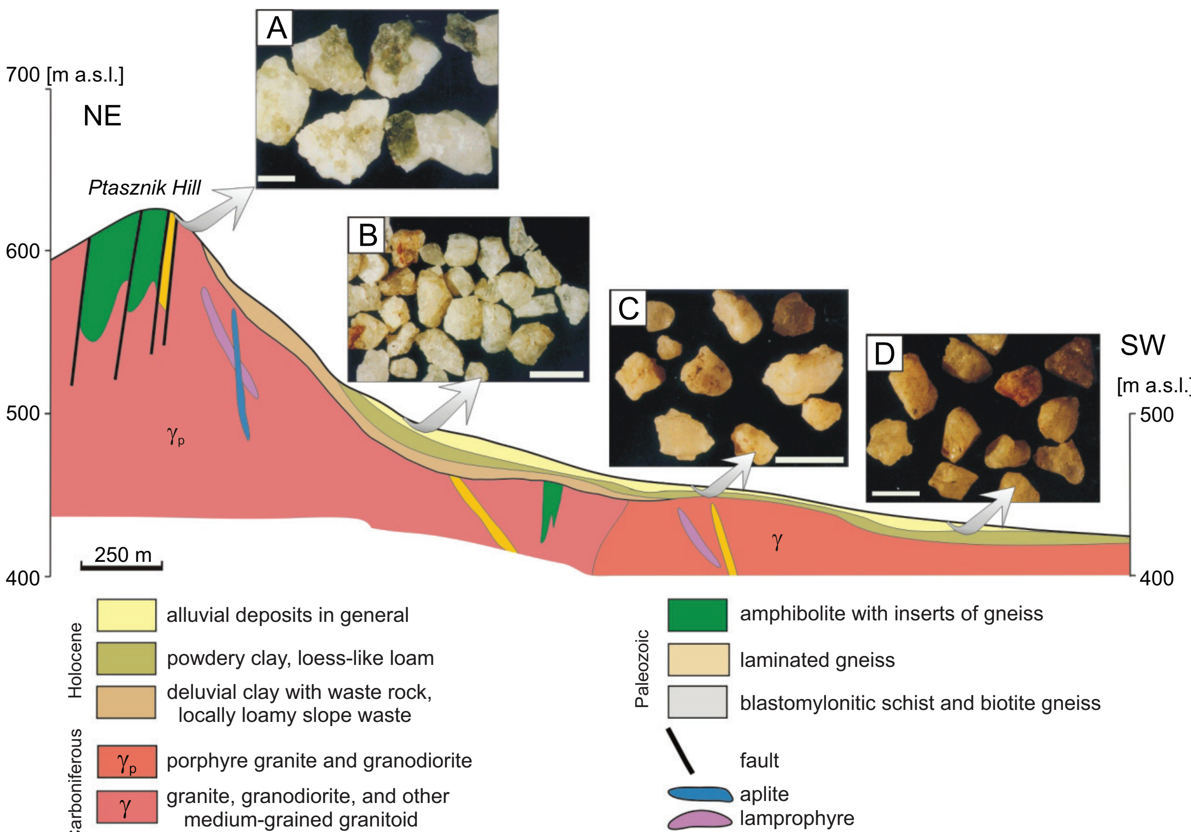


Fig. 3. Colour photographs of scheelite grains from bedrock **(A)** versus stream sediments **(B,C,D)** at increasing distances downstream from source in southwest Poland. Note the presence adamantine luster and intergrowths of other minerals on scheelite grains from bedrock sample A. Scheelite grains ~1 km downstream are subangular to subrounded with no intergrowths. Scheelite grains in alluvial sediments more than 1.5 km from source (C & D), have a matte luster and clay mineral coatings. Modified from Mikulski & Wierchowiec (2013).

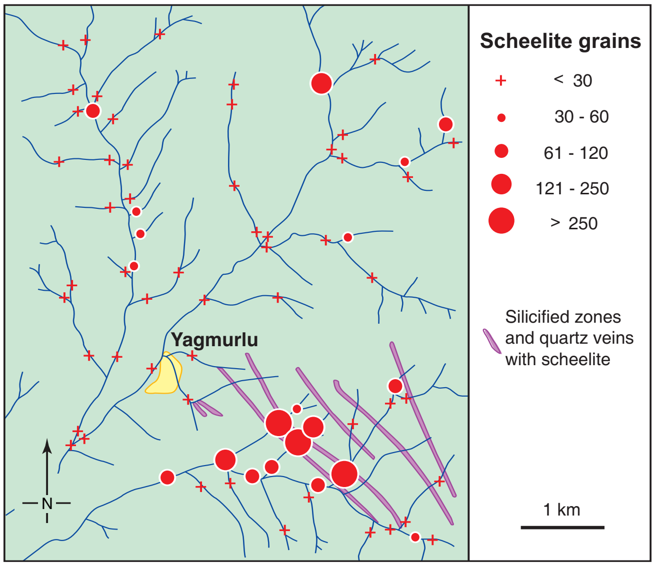


Fig. 4. Abundance of scheelite in <1.0 mm fraction of stream sediment concentrates from the Yagmurlu area of the Central Anatolian massif, Turkey (modified from Özcan & Çağatay 1989). Abundances are greatest overlying silicified zones and quartz veins with scheelite.

(e.g. Zeschke 1961; Stendal & Theoboald 1994) and till (e.g. McClenaghan *et al.* 2013b).

Mainly due its fluorescence, scheelite is easy to visually identify, and thus is globally one of the most commonly used indicator minerals in stream sediment surveys (Table 1) (e.g. Zeschke 1961) in support of W, Sn and Au exploration, including Turkey (Fig. 4) (e.g. Özcan & Çağatay 1989), Spain (e.g. Zantop & Nespereira 1979; Fernández-Turiel *et al.* 1992), Pakistan (e.g. Zeschke 1961; Asrarullah 1982), Malaysia (e.g. Rajah 1982), Somalia (Frizzo & Hassan 1983); USA (e.g. Theobald & Thompson 1960), and India (e.g. de Smeth *et al.* 1985). Scheelite has also been recovered from stream sediments in glaciated terrain, for example in Norway (e.g. Stendal 1978), Greenland (e.g. Hallenstein *et al.* 1981; Steenfelt 1987), and Canada (e.g. Maurice 1986; Allen *et al.* 1999). In some areas, scheelite content in stream sediments is sufficient for the sediments to be characterized as placer W deposits (e.g. Hess 1917; Wildon & Hotz 1955). Scheelite is used in soil surveys in some parts of the world in support of mineral exploration (e.g. Petersen & Stendal 1987; Özcan & Çağatay 1989; Surya Prakash Rao *et al.* 1989).

Recovery of scheelite from glacial sediments was first reported by Lindmark (1977) and Brundin & Bergström (1977) in the glaciated terrain of Fennoscandia. Lindmark (1977) described one of the first till sampling programs specifically designed to recover scheelite in till (Fig. 5), which was carried out as far back as the 1960s in Finland. Again, due to its fluorescent properties, it was easily identified in bulk till. In 1970, Brundin & Bergström (1977) were among the first to develop systematic methods for identifying indicator mineral in till in Sweden, including scheelite. They evaluated various sample weights (2.5 kg versus 25 kg), preconcentration methods (panning versus sluice box), and heavy liquid separation densities (SG 2.96 versus 3.3). In the 1970s and 1980s, several studies compared W contents of till to its scheelite abundance (e.g. Nikkarinen & Björklund 1976; Steiger 1977; Stea & O'Reilly 1982; Toverud, 1984; Johansson *et al.* 1986; Salminen & Hartikainen 1986; Petersen & Stendal 1987; Snow & Coker 1987; Peuraniemi 1992). It was often noted that scheelite in till formed larger anomalies than those outlined using W content. These early studies involved simply noting the presence scheelite and counting the number of scheelite grains in till heavy mineral concentrates under UV light.

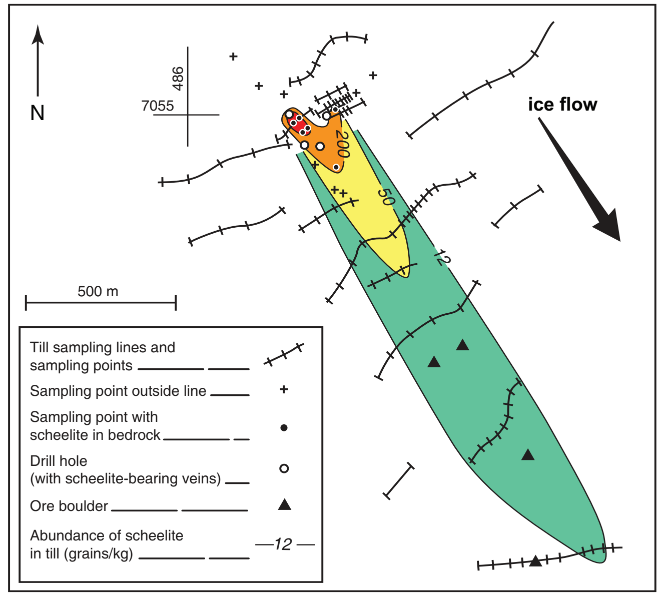


Fig. 5. Glacial dispersal train in west-central Finland defined by scheelite-bearing boulders (ore boulder in legend) and scheelite grains recovered from till samples by panning heavy minerals and examination under shortwave ultraviolet light (modified from Lindmark 1977).

Wolframite

The other common W-bearing indicator mineral is wolframite ($(Fe,Mn)WO_4$), which includes the solid solution series between hubnerite ($MnWO_4$) and ferberite ($FeWO_4$). Wolframite is by far the most commonly used indicator mineral of the series. It is a useful indicator mineral because it is relatively insoluble in the natural pH range of surface water (Horsnail 1979). Wolframite is identified in heavy mineral concentrates (HMC) by its black colour (Fig. 1B), prismatic crystal form, hardness (H=4.5, can be scratched with a needle), reddish brown streak, and lack of fluoresce under UV light. When rounded, it can be difficult to distinguish from other visually similar heavy minerals (e.g. hornblende, tourmaline, ilmenite) that can be abundant in stream sediments and till. Because of its brittle nature and perfect cleavage, wolframite breaks apart more readily than scheelite and thus tends to be rarer and, when present in stream sediments, is recovered in the finest fraction from within 2 to 3 km downstream of its bedrock source (ESCAP Secretariat 1982; Hosking 1982; Meizhong 1982).

Wolframite has been recovered in stream sediments surveys around the world (Table 1), including Spain (Zantop & Nespereira 1979; Fernández-Turiel *et al.* 1992), as well as from placer deposits (Hess 1917), such as those in Thailand (e.g. Pungrassami 1986), Burma (e.g. ESCAP Secretariat 1982), and the USA (e.g. Johnson 1910). The presence hubnerite in stream sediments in the southwest USA has been reported by Theobald & Thompson (1960). Recovery of wolframite from glacial sediments is occasionally noted when it occurs in association with scheelite (e.g. Brundin & Bergström 1977).

MINERAL CHEMISTRY

In addition to indicator mineral abundance, size, and shape, mineral chemistry can provide key information about the lithology or grade of a bedrock source. The best known example of this is the use of chemistry of kimberlite indicator grains in till for the preliminary evaluation of the diamond potential of an area or a kimberlite body (e.g. McClenaghan & Kjarsgaard 2007). Scheelite mineral chemistry has been reported by several authors (e.g. Hsu & Galli 1973; Sylvester & Ghaderi 1997; Ghaderi *et al.* 1999; Brugger *et al.* 2000a,b; Roberts *et al.* 2006; Dostal *et al.* 2009). Wolframite mineral chemistry has been reported by Nakashima *et al.* (1986) and Ferenc & Uher (2007).

Ongoing research into scheelite compositional criteria that can be used to characterize grains recovered from indicator mineral surveys includes the work of Poulin *et al.* (2013). Using scheelite grains recovered from a range of deposit types (W-bearing skarns, intrusion-related gold systems or orogenic, Au-bearing quartz-carbonate-sulphide veins), these authors are developing discrimination criteria based on scheelite composition and luminescence characteristics that are associated with a specific types of mineralization in bedrock. In turn these criteria may serve to identify potential bedrock sources of scheelite grains recovered from stream sediments or till.

SISSON W-Mo DEPOSIT CASE STUDY

The Sisson W-Mo deposit in west-central New Brunswick is a large, structurally controlled, intrusion-related W-Mo deposit consisting of four wide and steeply dipping zones of vein- and fracture-controlled W and Mo mineralization (Nast & Williams-Jones 1991; Marr 2009; Fyffe *et al.* 2010; Rennie 2012). Lang & Zahovskis (2013) reported resource estimates for the deposit of 383 Mt at 0.067% WO_3 and 0.021% Mo (measured and indicated) and 178 Mt 0.051 WO_3 and 0.021% Mo (inferred), making it one of the largest tungsten deposits in the world. In addition to W, the deposit has elevated concentrations of Cu, Zn, Pb, Bi, and As, which are directly related to late-stage quartz-scheelite and sulphide-rich veins and their sericite-sulphide envelopes. Scheelite ranges from <100 μm to 1 cm in size and overall wolframite is a minor mineral in the deposit. Bedrock outcrop on the Sisson property and surrounding area is rare due to the extensive till cover, which averages 8 m in thickness (Marr 2009). During the last glacial event, the subcropping surface was glacially eroded, mainly by southeast-flowing ice, resulting in metal-rich glacial debris (till) being deposited both overlying and down-ice (southeast) of the deposit (Seaman & McCoy 2008).

Methods

Methods and preliminary results presented here for the Sisson study are summarized from McClenaghan *et al.* (2013a,b, in press). Large (~15 kg) surface till samples up-ice, overlying, and up to 14 km down-ice (southeast) of the deposit along with mineralized bedrock samples were collected to document indicator mineral signatures of the deposit in till down-ice (southeast). Small bags of till were tested for their W and Mo content using a portable bench-top XRF to help guide sampling. Large (15 kg) stream sediment samples were collected up and down stream of the deposit to compare scheelite and wolframite abundance, size, and shape to those in till. Bedrock samples were collected from mineralization and host rocks to determine which minerals were indicative of W-Mo mineralization in the Sisson deposit. All samples were processed using a combination of shaking table, panning, and heavy liquids (SG 3.2) to produce heavy mineral concentrates for picking. Pan concentrates, as well as the 0.25–0.5, 0.5–1.0, and 1.0–2.0 mm non-ferromagnetic fractions of samples were examined and potential indicator minerals of W-Mo mineralization counted/selected, which included scheelite, wolframite, molybdenite, and other sulphide minerals. All heavy mineral concentrates were systematically examined inside a black box using shortwave ultraviolet light to identify and count scheelite grains. Sample processing methods and indicator mineral abundance data for all samples are reported in McClenaghan *et al.* (2013a).

Indicator mineral species

The primary ore minerals recovered from till and stream sediments at the Sisson deposit include scheelite, wolframite (Fig. 1), and molybdenite. Secondary ore minerals associated with mineralization and from bedrock and sediment samples include chalcopyrite, Bi-rich minerals (joseite, native Bi, bismutite, bismuthinite), galena, sphalerite, arsenopyrite, pyrrhotite, and pyrite (Table 1). These secondary minerals though much less abundant are useful indicators of the polymetallic nature of the Sisson deposit.

Indicator mineral size

The size of W-Mo indicator minerals in till at Sisson is controlled primarily by the size of the grains in the source rock and the durability of the mineral during glacial and subsequent fluvial transport.

Scheelite recovered from bedrock, till, and stream sediments is most abundant in the pan concentrate (25–200 μm) and the 0.25–0.5 mm size fractions. Scheelite is also present in the 0.5–1.0 mm size fraction, and least abundant in the 1–2 mm size fraction (Table 2). Similar to scheelite, wolframite is present in the coarser fractions but most abundant in the 0.25–0.5 mm fraction of bedrock, till, and stream sediments (Table 2).

Indicator mineral abundance

Mineralized bedrock processed to recover indicator minerals was found to contain 10,000s grains/kg of scheelite. Till and stream sediment samples overlying and immediately down-ice of the deposit contained 1000s to 100s of scheelite grains/10 kg in the 0.25–0.5 mm fraction. Background scheelite content in till and stream sediments varies from 0 to 2, and 0 to 9 grains, respectively. Elevated contents of scheelite are present in till at least 10 km down-ice (southeast) of mineralization (Fig. 6), whereas only one till sample (overlying the deposit) contains wolframite. In stream sediments, elevated contents of both scheelite (Fig. 7A) and wolframite (Fig. 7B) are present at least 4 km directly downstream and at least 5.5 km southeast in streams that transect the deposit's glacial dispersal train.

Wolframite, which is rare in till, was recovered from only 1 of the 56 till samples. It is more common in stream sediment samples and was recovered from 4 of 16 samples. Its low abundance in both till and stream sediments (100s grains) reflects its low content in the deposit. Few till and stream sed-

Table 2. Comparison of the abundance of indicator minerals in mineralized bedrock from the Sisson W-Mo deposit (normalized to 1 kg) to till and stream sediments (normalized to 10 kg) at varying distances, up-ice or upstream, overlying, and down-ice or downstream of the deposit. Data are reported for four size fractions. Pan concentrate counts are not normalized.

Sample Media	Sample	Interpretation	Distance from Deposit (m)	Scheelite				Wolframite				Molybdenite	Chalcopyrite	Arsenopyrite	Sphalerite	Bi minerals	Pyrite
				pan conc	0.25-0.5 mm	0.5-1.0 mm	1.0-2.0 mm	pan conc	0.25-0.5 mm	0.5-1.0 mm	1.0-2.0 mm	0.25-0.5 mm	0.25-0.5 mm	0.25-0.5 mm	0.25-0.5 mm	0.25-0.5 mm	0.25-0.5 mm
bedrock	11-MPB-R05	mineralized quartz vein	0	10000	22026	3671	140	0	11013	587	95	0	13216	0	2203	0	367
till	11-MPB-520	background up ice	-4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11-MPB-521	background up ice	-2250	0	2	0	0	0	0	0	0	0	0	0	0	0	0
	11-MPB-507	overlying mineralization	0	150,000	4706	0	0	0	0	0	0	0	0	0	0	0	0
	11-MPB-568	overlying mineralization	0	50	450	0	6	0	0	0	0	4	7	1	1	1	18
	11-MPB-567	overlying mineralization	0	50	261	0	7	0	0	0	0	87	8	0	0	2	217
	11-MPB-573	overlying mineralization	0	5,000	1852	0	0	0	0	0	0	4	0	0	0	4	2
	12-MPB-1026	overlying mineralization	0	200	280	105	2	0	112	38	0	0	2	1	0	0	1
	11-MPB-574	proximal down ice	20	50	5	0	1	0	0	0	0	0	1	7	0	0	29
	11-MPB-502	proximal down ice	50	0	40	2	0	0	0	0	0	0	6	0	0	2	1200
	11-MPB-562	proximal down ice	100	200	404	0	1	0	0	0	0	0	1	0	0	1	10
	11-MPB-511	proximal down ice	400	0	36	0	2	0	0	0	0	0	2	0	0	0	0
	11-MPB-544	proximal down ice	1100	0	49	0	1	0	0	0	0	0	1	0	0	0	0
	11-MPB-519	proximal down ice	1100	0	6	0	0	0	0	0	0	0	0	0	0	0	0
	11-MPB-546	distal down ice	2500	0	2	0	1	0	0	0	0	0	2	0	0	1	0
	11-MPB-526	distal down ice	3600	0	2	0	0	0	0	0	0	0	0	0	0	0	0
	11-MPB-531	distal down ice	4000	0	3	0	0	0	0	0	0	0	0	0	0	4	0
	11-MPB-525	distal down ice	4300	0	8	0	0	0	0	0	0	0	0	0	0	0	0
	11-MPB-539	distal down ice	10000	0	7	0	0	0	0	0	0	0	0	0	0	0	0
	11-MPB-540	background down ice	13000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stream	21J06-2012-2006	background up stream	-4000	0	9	1	0	0	0	0	0	0	0	0	0	0	0
sediments	21J06-2012-2004	background up stream	-4500	0	3	0	0	0	0	0	0	0	0	0	0	0	0
	21J06-2012-2005	background up stream	-4500	0	2	3	0	0	0	0	0	0	0	0	0	0	2
	21J06-2012-2011	background up stream	-1500	0	2	0	0	0	0	0	0	0	1	1	1	0	2475
	21J06-2012-2018	overlying	0	200	150	50	1	0	1	0	0	0	0	0	0	0	0
	21J06-2012-2007	overlying	0	500	2000	250	40	2	153	82	22	2	2	2	0	0	0
	21J06-2012-2019	overlying	0	50	300	57	3	0	5	0	0	0	0	0	0	0	0
	21J06-2012-2016	proximal downstream	100	0	0	0	0	0	0	0	0	0	0	0	0	0	5
	21J06-2012-2017	downstream	4000	0	80	17	1	0	13	4	2	0	4	0	0	0	8
	21J06-2012-2015	background	4000	0	5	3	0	0	0	0	0	0	0	0	0	0	1
	21J06-2012-2010	downstream of glacial dispersal train	4500	0	15	0	0	0	0	0	0	0	0	0	0	0	0
	21J06-2012-2012	downstream of glacial dispersal train	5500	0	80	7	0	0	0	0	0	0	3	0	0	0	1
	21J06-2012-2002	background	6500	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	21J06-2012-2013	background	8000	0	7	1	0	0	0	0	0	0	2	0	0	0	19
	21J06-2012-2003	background	9500	0	0	0	0	0	0	0	0	0	0	0	0	0	0

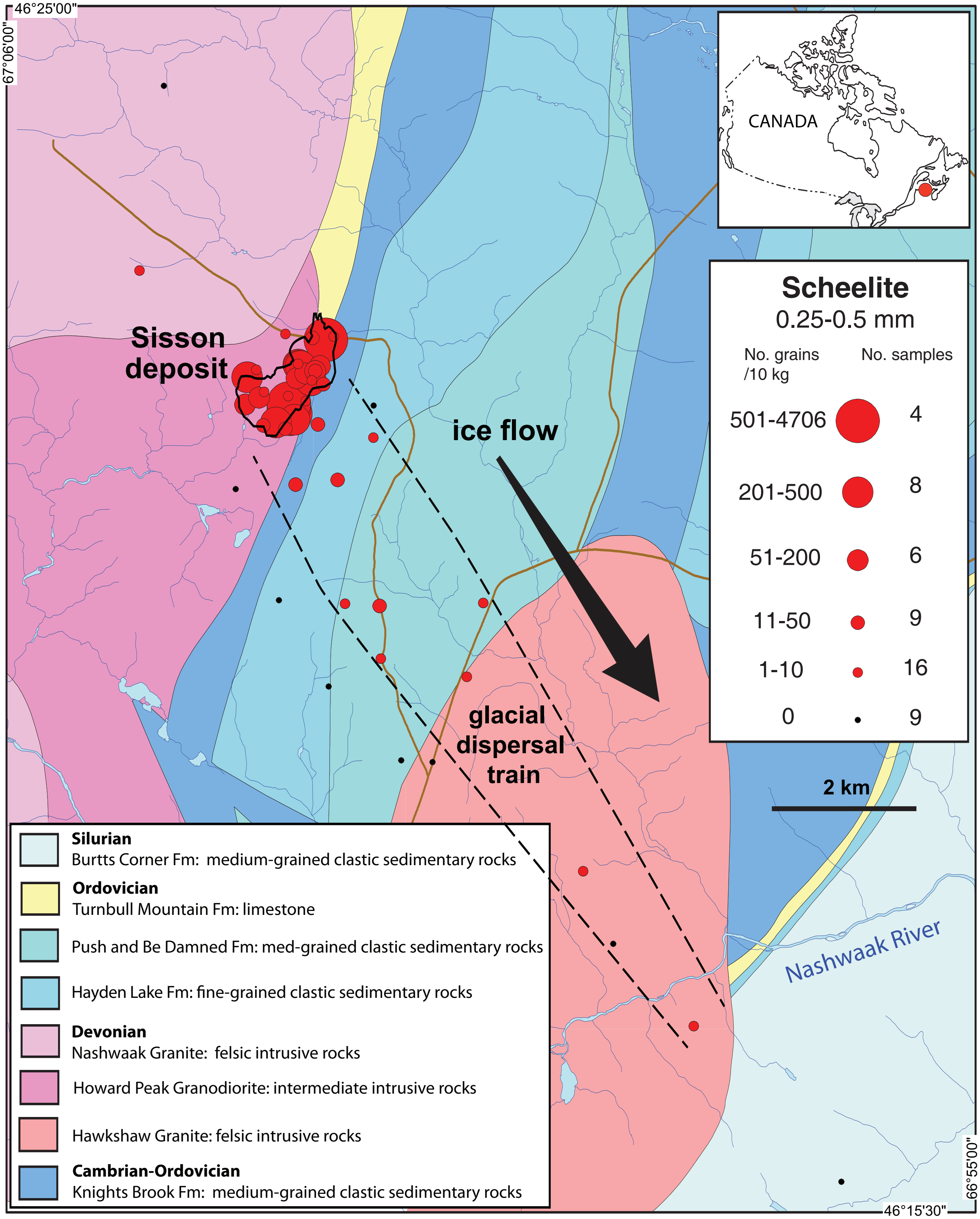
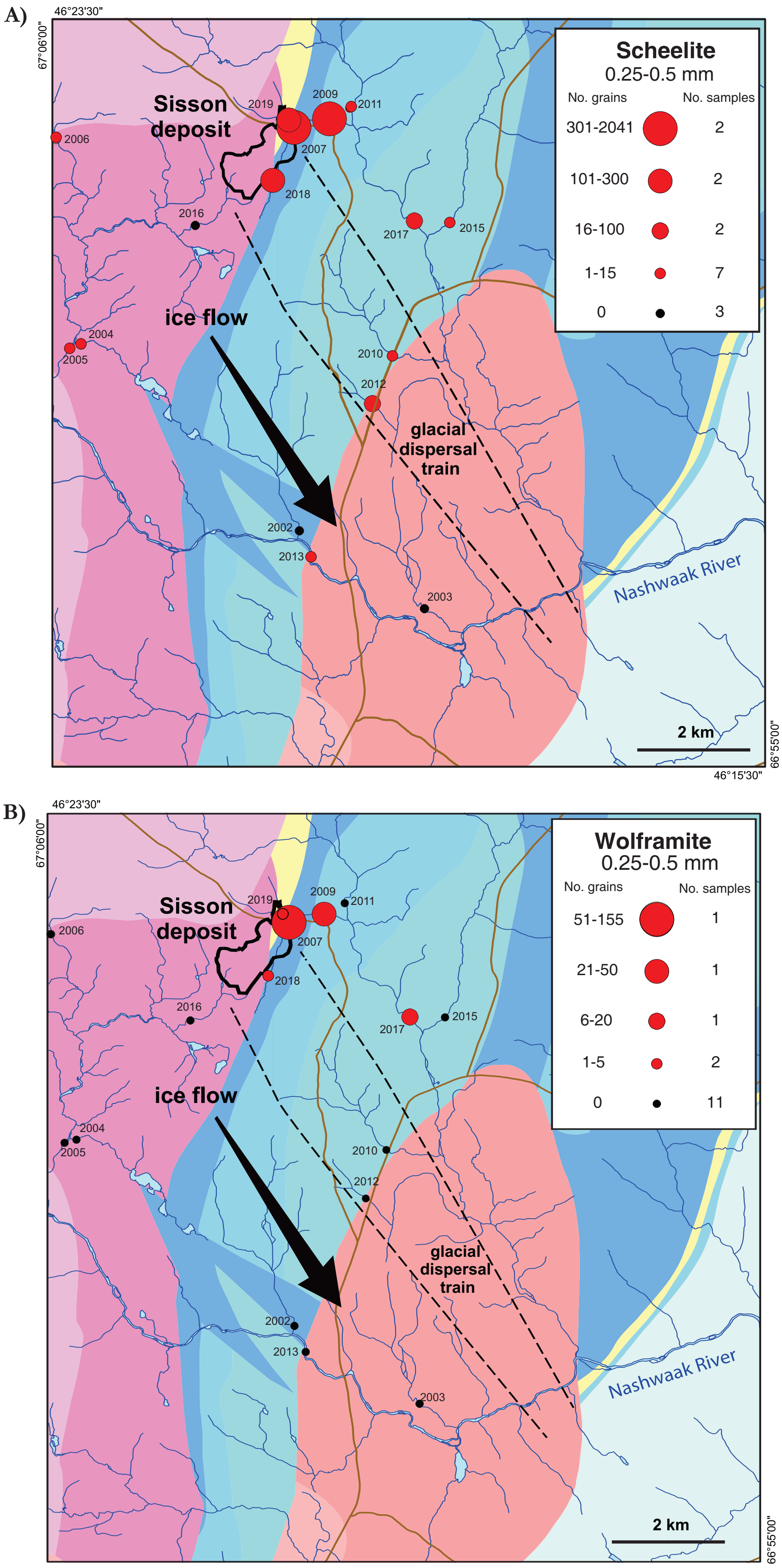


Fig. 6. Location of the Sisson area in eastern Canada (inset map), and the distribution of scheelite grains in the 0.25–0.5 mm fraction of till normalized to 10/kg plotted on the local bedrock geology of the Sisson W-Mo deposit area. The outline of the glacial dispersal train down-ice (southeast) of the deposit was first identified by Seaman and McCoy (2008). Bedrock geology modified from Smith and Fyffe (2006a-d). Deposit subcrop outline in black from Rennie (2012). Modified from McClenaghan *et al.* (in press).



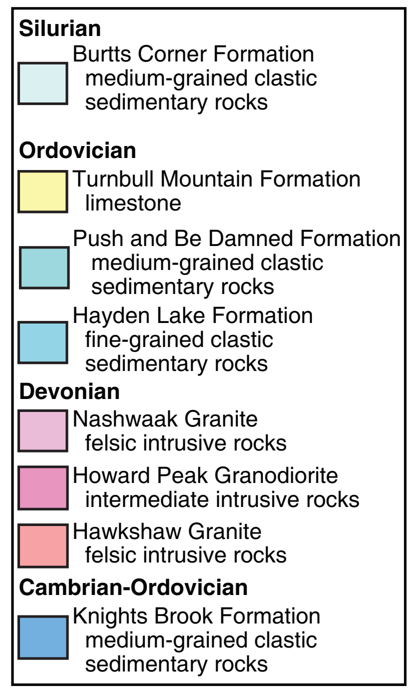


Fig. 7. Local bedrock geology of the Sisson W-Mo deposit area and distribution of **(A)** scheelite and **(B)** wolframite grains in the 0.25–0.5 mm fraction of stream sediments normalized to 10 kg. Bedrock geology modified from Smith & Fyffe (2006a-d). Deposit subcrop outline in black from Rennie (2012).

iment samples contain molybdenite (Table 1), reflecting its extreme softness and thus its inability to survive glacial or fluvial transport. The other indicator minerals present also occur in very low (trace) amounts (1 to 10 grains/10 kg).

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