GS-28 PHYTOREMEDIATION AND PHYTOMINING IN MANITOBA: PRELIMINARY OBSERVATIONS FROM AN ORIENTATION SURVEY AT THE CENTRAL MANITOBA (AU) MINESITE (NTS 52L/13)

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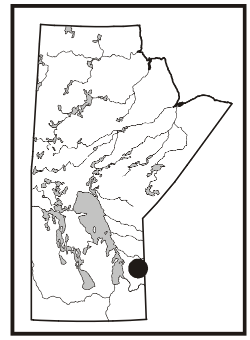

Renault, S., Sailerova, E. and Fedikow, M.A.F. 2000: Phytoremediation and phytomining in Manitoba: preliminary observations from an orientation survey at the Central Manitoba (Au) minesite (NTS 52L/13); *in* Report of Activities 2000, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 179-188.

SUMMARY

A new project to establish the trace-element content of abandoned minesite tailings and determine the potential for phytoremediation of these sites and production of bio-ores, through the identification of hyperaccumulator plant species, has been initiated at the Central Manitoba (Au) minesite in southeastern Manitoba (Fig. GS-28-1). The first phase of this project has established the trace-element characteristics of tailings at the minesite through multi-element analysis of samples collected from three 1 m deep, hand-augered profiles. Results indicate that a partial extraction at pH 2–3 liberates a wide range of base and precious metals from the tailings at the minesite, and that these metals provide the focus for the future development of a bio-ore. Ten plant species were planted on three experimental sites on mine tailings. The survival rate and amount of extracted base and precious metals should indicate plant species suitable for phytoremediation and phyto-extraction.

INTRODUCTION

Mining and mineral-processing activities contribute significant quantities of heavy metals to the environment and affect surrounding land, air and water quality. These effects cannot be reversed by nature and require aggressive application of planned restoration programs.

Metal mines throughout Manitoba and Canada contain variable amounts of sulphide minerals, either in the ore or in the surrounding host rocks. Leaching of heavy metals from tailings results from oxidation of pyrite under moist conditions. This oxidation leads to a decrease in pH, which increases the solubility of most heavy metals. Metal mobilization

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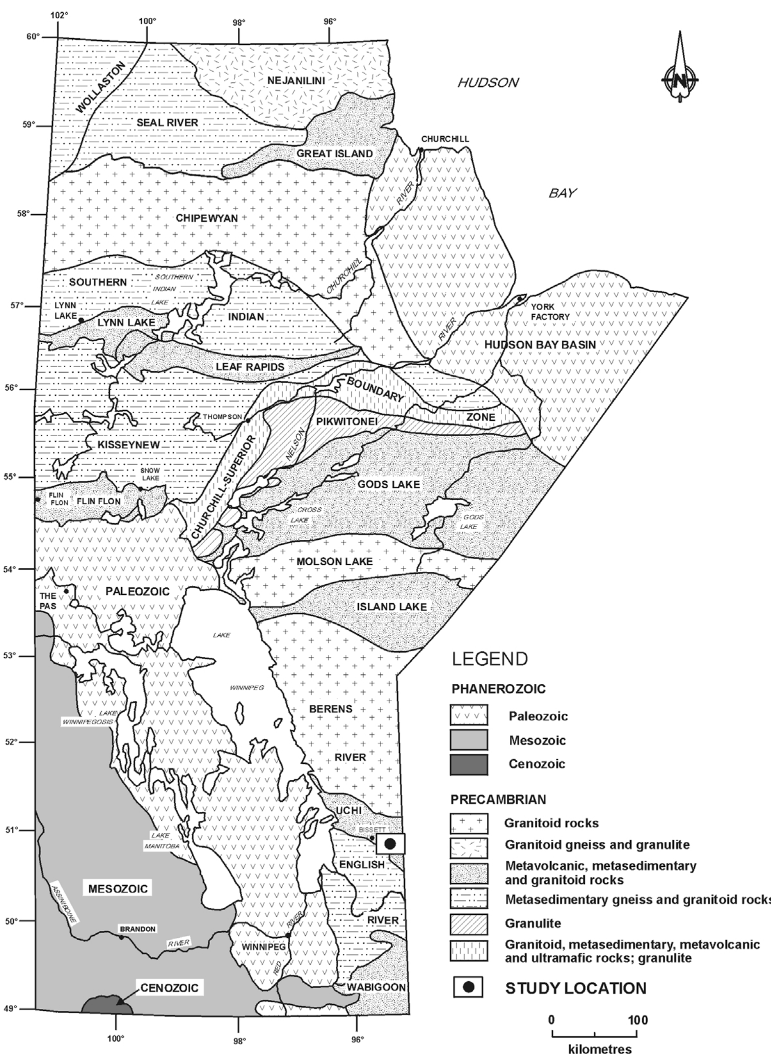

Figure GS-28-1: Location of the phytoremediation and phytomining study area, Central Manitoba gold mine, Bissett area, southeastern Manitoba.

from tailings can often be traced into watersheds downstream from active minesites.

Among the most promising and common approaches to preventing acid generation is to physically stabilize the waste by covering the acid-producing material with water. This forms an anaerobic environment, where sulphide minerals remain stable and dissolved metal concentrations are low. However, more than half of the existing tailings sites in Canada have been found to be unsuitable for water barriers (Ripley et al., 1996).

Pyrite oxidation can also be controlled by covering the surface tailings with soil and then usually revegetating the site. Establishment of a self-sustaining mat of vegetation is usually an important element in a rehabilitation program for waste-disposal areas. Vegetation stabilizes the soil, prevents new acid-generating material from being exposed, and decreases the amount of water available for deep percolation through transpirational water movement. Vegetation is established by controlling pH near the surface with addition of lime or limestone and by adding fertilizers where necessary. Plant species are usually selected from well adapted species generally growing in the region (Bradshaw, 1952). Nevertheless, revegetation alone does not stop acid drainage and does not remove heavy metals from the contaminated site.

Tailings are not the only cause of land contamination by heavy metals. Additional contamination is contributed by airborne pollutants, which are produced during mining and milling operations. Airborne pollutants are the major source of soil contamination in areas surrounding the mining operations. The distance from a source at which metals affect plants and soil has been documented. In Flin Flon, manganese was detectable for approximately 250 km from a base-metal smelter, and copper for up to 60 km. Affected soil cannot be used for agricultural purposes because of the high metal content, and other uses of these lands are also limited. The Subcommittee on Environmental Quality Criteria for Contaminated Sites of the Canadian Council of Ministers of the Environment has developed a set of interim criteria as part of the National Contaminated Sites Remediation Program. In some jurisdictions, these guidelines are being applied as limits for permitting purposes. Today's practices involve the expensive removal of contaminated soil (excavation; Giasson and Jaouich, 1998).

Phytoremediation of metals is being developed as a potential cost-effective remediation solution for thousands of sites contaminated by heavy metals in the United States and abroad (Salt et al., 1995, 1998; Cunningham et al., 1995; Comis, 1996). Plants, called hyperaccumulators, capable of accumulating 0.5 to 1% of their dry weight in metals have been identified. These include *Alyssum bertolonii* (1% or 10 000 mg/kg Ni) and *Brassica juncea* (Au). Anderson et al. (1999) provided a list of other hyperaccumulators.

Two basic strategies for phyto-extraction can be applied. The first of these is continuous phyto-extraction, which requires hyperaccumulators with high biomass production and the ability to grow in dense stands. Continuous phyto-extraction is also useful at sites where metals are already mobilized by low pH of the underlying soil, provided that the metals to be extracted are pH sensitive or contain high concentrations of metals in water-soluble form. The second approach is induced phyto-extraction (Blaylock et al., 1997). At the end of the plant-growth phase, the appropriate chelate, such as ethylene diamine tetra-acetic acid (EDTA), is applied to the area and plants are harvested within several days or a week. Chelate-assisted transport of metals to plant shoots appears to occur in the xylem via the transpiration stream. The metal appears to move to the shoots as a metal-chelate complex.

The technique of phytomining (Nicks and Chambers, 1998) involves growing a crop of a metal-hyperaccumulating plant species, harvesting the biomass, and burning it to produce a bio-ore. Up to 57 mg/kg Au (dry mass) can be accumulated by Indian mustard (*Brassica juncea*; Anderson et al., 1998) using induced hyperaccumulation by ammonium thiocyanate, which is biodegraded to ammonia, bicarbonate and sulphate.

Phytomining technology offers the possibility of exploiting ores or mineralized soils that are uneconomic by conventional mining methods. Bio-ores are virtually sulphur free, and their smelting requires less energy than sulphide ores. The metal content of a bio-ore is usually much greater than that of a conventional ore and therefore requires less storage space, despite lower density. Moreover, phytomining is an environmentally responsible approach to site remediation.

OBJECTIVES

The long-term goal of this study is to determine the optimal field conditions and define limiting factors for phytoremediation of sites contaminated with heavy metals. This field and laboratory study will guide the selection of suitable plant species for environmental conditions found in the boreal-forest region. The suitability of selected species for phytomining of base metals and gold will be tested in terms of the quality and costs of bio-ore production and economic effectiveness.

The initial experimental sites will be evaluated in terms of the degree and type of contamination, soil quality (including an estimation of soil pH and soil-layer thickness on revegetated areas), presence of other plant species, and soil drainage (Sailerova, in press). Furthermore, experimental sites must be evaluated for conditions that will enable the selected plant species to reach maximum biomass. Different plant species have different saturation irradiation levels and different requirements in terms of soil quality, mineral nutrition and water supply.

SIGNIFICANCE OF THE WORK

Soil contamination by heavy metals and metal leakage from sulphide tailings represent a significant and widely recognized ecological hazard. Phytoremediation offers the possibility of an ecologically acceptable and cost-effective solution. Phytomining, as a new technique for extracting metals from low–grade ore or sulphide tailings, is a promising new technique currently being developed for commercialization in the United States. Field experiments in phytomining in Manitoba could provide valuable information regarding the potential of this method to remediate sites contaminated with heavy metals.

GEOLOGICAL SETTING OF THE CENTRAL MANITOBA (AU) DEPOSIT

Tailings associated with the Central Manitoba gold deposit were selected for initial phytoremediation and phytomining studies. The deposit occurs within the Archean Rice Lake greenstone belt, in the Uchi Subprovince of the Superior Province in southeastern Manitoba (Fig. GS-28-1). The belt is flanked to the north by the North Caribou Terrane (Marr, 1971; Weber, 1971; Poulsen et al., 1996) and, to the south, is transitional with the English River gneissic belt (McRitchie and Weber, 1971; Weber, 1971; Poulsen et al., 1996). The Rice Lake belt is fault bounded on the north by the Wanipigow Fault and on the south by the Manigotagan Fault.

Host rocks to the deposit belong to the Bidou Lake subgroup (Poulsen et al., 1996) and comprise arkose, tuff and chert of the Dove Lake Formation. These sedimentary rocks have been intruded by gabbro sills. Gold-bearing quartz veins at the deposit are situated within en échelon shear zones at or close to the contact between the Dove Lake sedimentary rocks and an east-southeast-trending gabbro sill (Stockwell and Lord, 1939). Five veins contributed the bulk of production at the deposit. These were the Kitchener, Eclipse, No.1 Branch, Tene 6 and Hope veins. The quartz veins were mineralized with chalcopyrite, pyrite, pyrrhotite and free gold. Between 1928 and 1938, a total of 347 801 t of ore was milled and 4287 kg of gold produced.

GEOCHEMICAL CHARACTERIZATION OF TAILINGS

Geochemical analyses of 20 tailings samples collected from three hand-augered profiles, each approximately 1 m in depth, are presented in Tables GS-28-1, -2 and -3. The data in Tables GS-28-1 and -2 are total

Table GS-28-1: Instrumental neutron activation analysis (INAA) of tailings samples (-60 mesh) from three 1 m deep, hand-augered profiles. Negative values indicate less than the lower limit of determination.

Sample ID	Au	Ag	As	Ba	Br	Ca	Co	Cr	Cs	Fe	Hf	Hg	Ir	Mo	Na	Ni	Rb	Sb	Sc
	(ppb)	(ppm)	(ppm)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(ppb)	(ppm)	(%)	(ppm)	(ppm)	(ppm)	(ppm)
SITE 1: 0-15 cm	3430	-5	19	220	-1	-0.5	7	100	-0.5	5.49	1.5	2	-5	-5	0.58	-100	-20	0.9	12.2
SITE 1: 15-30 cm	1210	-5	16	180	-1	0.8	47	49	-0.5	3.6	1.7	-1	-5	-5	0.74	-100	-20	0.6	8
SITE 1: 30-45 cm	795	-5	10	230	-1	0.6	25	59	-0.5	3.47	1.8	-1	-5	-5	0.75	-100	-20	0.4	8.8
SITE 1: 45-60 cm	1040	-5	7	170	-1	0.9	34	32	-0.5	3.63	1.2	-1	-5	-5	0.46	-100	-20	0.3	8.2
SITE 1: 60-75 cm	352	-5	4	120	-1	-0.5	19	37	-0.5	3.11	1	-1	-5	-5	0.41	105	-20	0.4	7.9
SITE 1: 75-90 cm	727	-5	6	260	-1	1.2	28	47	-0.5	3.33	1.5	-1	-5	-5	0.56	-100	-20	0.4	9.1
SITE 1: 90-105 cm	780	-5	6	300	-1	1	25	14	-0.5	2.57	2	-1	-5	-5	0.43	-100	22	0.3	3.7
SITE 2: 0-15 cm	2290	-5	11	130	-1	1.1	8	75	-0.5	3.82	1	1	-5	-5	0.57	-100	-20	0.3	9.1
SITE 2: 15-30 cm	1530	-5	11	150	-1	0.8	16	110	-0.5	4.66	0.7	4	-5	-5	0.51	-100	-20	0.4	12.3
SITE 2: 30-45 cm	1490	-5	11	-100	-1	-0.5	22	84	-0.5	4.08	1	3	-5	-5	0.5	-100	-20	0.3	11.1
SITE 2: 45-60 cm	1810	-5	10	-100	-1	0.5	45	99	-0.5	4.32	0.7	2	-5	-5	0.39	-100	-20	-0.2	13.1
SITE 2: 60-75 cm	2640	-5	9	-100	-1	0.9	76	90	-0.5	4.04	0.9	-1	-5	-5	0.5	-100	-20	0.4	10.2
SITE 2: 75-90 cm	2390	-5	14	220	-1	1.5	83	85	-0.5	3.88	1.4	-1	-5	-5	0.63	-100	-20	0.4	9.5
SITE 2: 90-105 cm	1110	-5	20	220	-1	1.2	54	42	-0.5	3.4	2.8	-1	-5	-5	0.99	-100	-20	0.4	6.8
SITE 3: 0-15 cm	428	-5	6	190	-1	1.6	32	99	-0.5	4.06	1.8	-1	-5	-5	0.43	-100	32	0.3	10.6
SITE 3: 15-30 cm	569	-5	-2	190	-1	1.2	36	210	-0.5	4.92	0.5	-1	-5	-5	0.27	-100	-20	0.3	15.4
SITE 3: 30-45 cm	265	-5	4	-100	-1	1.5	29	178	1.5	4.35	-0.5	-1	-5	-5	0.21	-100	21	0.6	12.8
SITE 3: 45-60 cm	378	-5	3	-100	-1	0.7	29	194	-0.5	4.58	-0.5	-1	-5	-5	0.21	-100	-20	0.6	12.7
SITE 3: 60-75 cm	578	-5	4	-100	-1	1.3	31	260	-0.5	4.98	0.5	-1	-5	-5	0.25	-100	-20	0.4	15.6
SITE 3: 75-90 cm	958	-5	5	-100	-1	0.7	35	137	-0.5	4.79	0.7	-1	-5	-5	0.48	-100	-20	0.3	14.5

Sample ID	Se	Sr	Ta	Th	U	W	Zn	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Mass
	(ppm)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(g)
SITE 1: 0-15 cm	6	-0.05	-1	0.5	-0.5	6	40	1.5	4	-5	0.5	0.2	-0.5	0.8	0.11	1.485
SITE 1: 15-30 cm	3	-0.05	-1	1.1	-0.5	4	217	5.1	11	5	1.3	0.3	-0.5	0.8	0.13	1.803
SITE 1: 30-45 cm	-3	-0.05	-1	1.4	-0.5	4	110	3.7	8	-5	1.1	0.2	-0.5	0.9	0.14	1.484
SITE 1: 45-60 cm	-3	-0.05	-1	0.8	-0.5	4	187	3.5	8	-5	1	0.2	-0.5	0.8	0.12	1.597
SITE 1: 60-75 cm	-3	-0.05	-1	0.6	-0.5	-3	85	2.3	4	-5	0.7	0.2	-0.5	0.6	0.09	1.676
SITE 1: 75-90 cm	4	-0.05	-1	0.9	-0.5	4	128	3.3	8	-5	1	0.2	-0.5	0.8	0.14	1.435
SITE 1: 90-105 cm	-3	-0.05	-1	1	-0.5	5	79	5	11	5	1.2	0.2	-0.5	0.8	0.14	1.453
SITE 2: 0-15 cm	6	-0.05	-1	0.5	-0.5	5	65	1.5	4	-5	0.5	-0.1	-0.5	0.7	0.11	1.604
SITE 2: 15-30 cm	5	-0.05	-1	-0.5	-0.5	4	62	1.5	3	-5	0.5	0.2	-0.5	0.6	0.09	1.657
SITE 2: 30-45 cm	5	-0.05	-1	0.5	-0.5	4	69	1.2	3	-5	0.5	0.1	-0.5	0.6	0.1	1.57
SITE 2: 45-60 cm	5	-0.05	-1	-0.5	-0.5	3	103	1.6	4	-5	0.9	0.1	-0.5	0.8	0.12	1.605
SITE 2: 60-75 cm	6	-0.05	-1	0.6	-0.5	5	253	4.4	8	-5	1.1	0.2	-0.5	1	0.15	1.577
SITE 2: 75-90 cm	4	-0.05	-1	0.9	-0.5	4	259	4.8	9	-5	1.1	0.4	-0.5	0.9	0.15	1.362
SITE 2: 90-105 cm	-3	-0.05	-1	1.8	-0.5	6	234	7.5	15	7	1.7	0.5	-0.5	1.1	0.16	1.573
SITE 3: 0-15 cm	3	-0.05	-1	1	-0.5	4	117	3.9	9	-5	1.1	0.3	-0.5	0.9	0.14	1.833
SITE 3: 15-30 cm	5	-0.05	-1	-0.5	-0.5	3	156	1.6	5	-5	0.6	-0.1	-0.5	0.6	0.1	1.427
SITE 3: 30-45 cm	-3	-0.05	-1	-0.5	-0.5	3	75	0.9	-3	-5	0.4	-0.1	-0.5	0.5	0.07	1.372
SITE 3: 45-60 cm	-3	-0.05	-1	-0.5	-0.5	3	103	0.9	-3	-5	0.4	-0.1	-0.5	0.5	0.07	1.734
SITE 3: 60-75 cm	4	-0.05	-1	-0.5	-0.5	3	141	0.9	-3	-5	0.4	-0.1	-0.5	0.5	0.08	1.346
SITE 3: 75-90 cm	6	-0.05	-1	-0.5	-0.5	3	133	1.4	-3	-5	0.6	0.2	-0.5	0.7	0.11	1.532

Table GS-28-2: Geochemical analysis of tailings samples (-60 mesh) collected from three 1 m deep, hand-augered profiles. Analysis by ICP-MS following a lithium metaborate/tetraborate fusion. All values in ppm. Negative values indicate less than the lower limit of determination.

Sample ID	V	Cr	Co	Ni	Cu	Zn	Ga	Ge	As	Rb	Sr	Y	Zr	Nb	Mo	Ag	In	Sn	Sb	Cs	Ba
SITE 1: 0-15 cm	68	71	6	-20	834	153	8	-1	9	18	16	6	51	2	-2	6.0	-0.2	1	-0.5	-0.5	155
SITE 1: 15-30 cm	46	48	25	30	3640	82	9	1	10	20	23	8	70	2	-2	3.4	-0.2	1	0.5	-0.5	199
SITE 1: 30-45 cm	47	37	37	51	5740	183	9	-1	11	19	24	9	67	2	-2	4.0	-0.2	-1	-0.5	-0.5	177
SITE 1: 45-60 cm	40	25	31	36	3990	155	7	-1	-5	16	15	7	48	2	-2	3.9	-0.2	-1	-0.5	-0.5	150
SITE 1: 60-75 cm	42	30	17	24	3470	82	6	-1	-5	12	12	6	38	2	-2	2.8	-0.2	-1	-0.5	-0.5	120
SITE 1: 75-90 cm	46	32	26	29	3800	114	8	-1	5	19	18	8	59	2	-2	3.3	-0.2	-1	-0.5	0.5	198
SITE 1: 90-105 cm	23	-20	22	-20	3770	71	7	-1	10	19	17	7	72	2	-2	3.2	-0.2	-1	-0.5	-0.5	243
SITE 2: 0-15 cm	58	34	8	-20	1710	-30	7	-1	-5	16	18	6	46	2	-2	4.7	-0.2	-1	-0.5	-0.5	126
SITE 2: 15-30 cm	76	98	15	23	2890	43	7	-1	-5	13	13	7	30	1	-2	5.8	-0.2	-1	-0.5	-0.5	106
SITE 2: 30-45 cm	64	72	21	26	2370	44	6	-1	11	12	12	6	32	2	-2	5.2	-0.2	-1	-0.5	-0.5	106
SITE 2: 45-60 cm	64	81	35	53	10500	87	6	-1	9	11	12	6	26	1	-2	5.9	-0.2	-1	-0.5	-0.5	91
SITE 2: 60-75 cm	51	69	62	70	6560	178	7	-1	-5	15	19	10	43	2	-2	5.1	-0.2	-1	-0.5	-0.5	127
SITE 2: 75-90 cm	49	60	72	73	5860	211	8	-1	6	16	25	9	56	2	-2	4.8	-0.2	-1	-0.5	-0.5	149
SITE 2: 90-105 cm	37	29	51	44	6030	186	10	-1	9	23	37	11	101	3	-2	5.1	-0.2	-1	-0.5	-0.5	247
SITE 3: 0-15 cm	59	79	31	43	4510	111	9	-1	-5	22	21	9	65	2	-2	3.8	-0.2	-1	-0.5	-0.5	215
SITE 3: 15-30 cm	75	159	34	56	3490	93	7	-1	-5	17	10	6	24	1	-2	4.3	-0.2	-1	-0.5	-0.5	111
SITE 3: 30-45 cm	62	142	26	53	3150	68	5	-1	-5	10	8	5	13	-1	-2	4.2	-0.2	-1	-0.5	-0.5	69
SITE 3: 45-60 cm	58	141	24	50	3830	70	5	-1	-5	9	6	5	10	-1	-2	5.0	-0.2	-1	-0.5	-0.5	64
SITE 3: 60-75 cm	77	145	28	48	3510	78	6	-1	-5	15	7	5	13	-1	-2	4.7	-0.2	-1	-0.5	-0.5	89
SITE 3: 75-90 cm	72	114	30	43	4440	94	7	-1	-5	14	11	6	26	1	-2	4.8	-0.2	-1	-0.5	-0.5	121
Standards																					
Blank	-5	-20	-1	-20	-10	-30	-1	-1	-5	-2	-2	-1	-5	-1	-2	-0.5	-0.2	-1	-0.5	-0.5	-3
Standard MAG1	132	96	22	44	27	117	22	2	11	153	138	28	115	14	-2	-0.5	-0.2	3	0.9	8.5	482
Certified MAG1	140*	97*	20.4*	53*	30*	130*	20.4*		9.2	149*	146*	28*	126*	12	1.6	0.08	(0.18)	3.6	0.96*	8.6*	479*
Standard BIR1	310	392	51	163	125	76	16	2	-5	-2	107	16	14	-1	-2	-0.5	-0.2	-1	0.6	-0.5	7
Certified BIR1	313*	382*	51.4*	166*	126*	71*	16	1.5	(0.4)	0.25*	108*	16*	16	0.6	(0.5)	(0.036)		0.65	0.58	0.005	7
Standard DNC1	139	275	55	262	99	60	15	1	-5	3	138	18	37	2	-2	-0.5	-0.2	1	0.9	-0.5	113
Certified DNC1	148*	285*	54.7*	247*	96*	66*	15	(1.3)	(0.2)	(4.5)	145*	18*	41*	3	(0.7)	(0.027)			0.96*	(0.34)	114*
Standard GXR-2	49	34	7	-20	68	563	37	1	24	74	152	17	244	9	-2	17.0	-0.2	2	45.9	5.0	2300
Certified GXR-2	52	36	8.6	21	76	530	37		25	78.0	160	17	269	11	(2.1)	17	(0.252)	1.7	49	5.2	2240
Standard LKSD-3	75	85	28	45	31	138	15	1	26	76	246	30	162	8	-2	-0.5	-0.2	2	1.1	2.2	656
Certified LKSD-3	82	87	30	47	35	152			27	78	240	30	178	8	(<5)	2.7		3	1.3	2.3	680
Standard MICA-Fe	130	82	25	-20	-10	1300	97	3	3	2170	4	47	815	270	-2	-0.5	0.6	70	-0.5	179	145
Certified Mica Fe	135*	90*	23*	35*	5*	1300*	95*	3.2	3	2200*	5*	48*	800*	270*	1.2		0.60	70*		180*	150*
Standard GXR1	89	-40	9	44	1120	792	16	3	443	11	287	33	30	-2	18	31	0.8	53	122	3	772
Certified GXR1	80	12	8.2	41	1110	760	14		427	(14)	275	32	(38)	(0.8)	18	31	0.8	54	122	3.0	750
Standard SY3	49	-40	7	-40	-20	265	27	-2	20	218	308	723	302	164	-4	-1	-0.4	8	-1	3	449
Certified SY3	50	(11)	8.8	11	17	244*	27*	1.4	19	206*	302*	718*	320	148	(1.0)	(1.5)		(6.5)	0.31	3	450
Standard STM-1	-5	-20	-1	-20	-10	248	36	2	-5	112	695	45	1210	247	5	-0.5	-0.2	7	1.4	1.5	562
Certified STM-1	(8.7)	(4.3)	0.9	(3)	(4.6)	235*	36*	(1.4)	4.6	118*	700*	46*	1210*	268*	5.2	0.079*	(0.12)	6.8	1.66*	1.54*	560*
Standard IFG-1	-5	-20	31	-20	13	-30	1	23	-5	-2	5	11	-5	-1	-2	-0.5	-0.2	-1	0.8	-0.5	7
Certified IFG-1	2	4	29*	22.5	13*	20*	0.7	24	1.5	0.4	3	9*	1	0.1*	0.7		0.2	0.3	0.63	0.06	1.5

Table GS-28-2: Geochemical analysis of tailings samples (-60 mesh) collected from three 1 m deep, hand-augered profiles. Analysis by ICP-MS following a lithium metaborate/tetraborate fusion. All values in ppm. Negative values indicate less than the lower limit of determination. ***(continued)***

Sample ID	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Tl	Pb	Bi	Th	U
SITE 1: 0-15 cm	1.7	3.1	0.42	1.6	0.4	0.12	0.5	0.1	0.9	0.2	0.8	0.12	0.8	0.13	1.3	0.2	7	-0.1	33	127	0.8	0.2
SITE 1: 15-30 cm	3.4	7.5	0.89	3.9	1.0	0.25	1.1	0.2	1.3	0.3	0.9	0.14	0.8	0.13	1.8	0.2	7	-0.1	36	46.0	1.6	0.3
SITE 1: 30-45 cm	4.4	9.3	1.11	5.0	1.1	0.27	1.3	0.2	1.4	0.3	0.9	0.14	0.9	0.13	1.7	0.2	7	0.1	33	53.0	1.3	0.3
SITE 1: 45-60 cm	3.0	6.7	0.80	3.6	0.9	0.21	1.0	0.2	1.0	0.2	0.7	0.11	0.7	0.11	1.2	0.2	5	-0.1	18	42.0	1.0	0.2
SITE 1: 60-75 cm	2.0	4.5	0.56	2.5	0.6	0.16	0.7	0.1	0.9	0.2	0.6	0.10	0.6	0.09	1.0	0.1	3	-0.1	19	49.0	0.6	0.1
SITE 1: 75-90 cm	3.2	7.0	0.85	3.8	0.9	0.23	1.0	0.2	1.2	0.3	0.8	0.13	0.9	0.13	1.6	0.2	4	-0.1	31	44.0	1.0	0.2
SITE 1: 90-105 cm	4.3	9.3	1.10	4.6	1.0	0.24	1.1	0.2	1.1	0.2	0.7	0.12	0.7	0.12	1.9	0.2	9	-0.1	23	42.0	1.3	0.2
SITE 2: 0-15 cm	1.7	3.3	0.44	1.8	0.4	0.11	0.6	0.1	0.9	0.2	0.7	0.11	0.7	0.11	1.2	0.1	8	-0.1	16	61.0	0.5	0.1
SITE 2: 15-30 cm	1.7	3.2	0.44	1.9	0.5	0.12	0.7	0.2	1.0	0.2	0.8	0.12	0.7	0.11	0.8	-0.1	6	-0.1	30	92.0	0.5	0.1
SITE 2: 30-45 cm	1.4	2.9	0.41	1.8	0.5	0.12	0.7	0.1	0.9	0.2	0.7	0.11	0.7	0.10	0.9	0.1	5	-0.1	28	89.0	0.6	0.1
SITE 2: 45-60 cm	1.4	3.8	0.53	2.7	0.8	0.19	0.9	0.2	1.0	0.2	0.7	0.11	0.7	0.11	0.7	-0.1	4	-0.1	41	98.0	0.4	0.3
SITE 2: 60-75 cm	4.0	8.2	1.02	4.5	1.1	0.31	1.5	0.3	1.5	0.3	1.0	0.15	0.9	0.14	1.1	0.1	5	-0.1	18	94.0	0.7	0.2
SITE 2: 75-90 cm	4.3	9.0	1.08	4.8	1.1	0.29	1.4	0.2	1.4	0.3	0.9	0.14	0.8	0.14	1.5	0.2	6	-0.1	20	78.0	1.0	0.2
SITE 2: 90-105 cm	6.8	14.9	1.80	7.8	1.6	0.42	1.9	0.3	1.8	0.4	1.2	0.17	1.1	0.17	2.6	0.3	7	-0.1	31	41.0	1.8	0.4
SITE 3: 0-15 cm	3.7	8.1	1.03	4.4	1.0	0.26	1.2	0.2	1.4	0.3	0.9	0.15	0.9	0.14	1.7	0.2	6	-0.1	88	66.0	1.1	0.2
SITE 3: 15-30 cm	1.6	3.2	0.46	2.0	0.6	0.18	0.8	0.2	1.0	0.2	0.7	0.10	0.7	0.11	0.7	-0.1	4	-0.1	70	79.0	0.3	0.1
SITE 3: 30-45 cm	1.0	1.9	0.29	1.3	0.4	0.13	0.6	0.1	0.7	0.2	0.5	0.08	0.5	0.08	0.4	-0.1	4	-0.1	51	78.0	0.1	-0.1
SITE 3: 45-60 cm	1.1	1.9	0.29	1.3	0.4	0.11	0.5	0.1	0.8	0.2	0.5	0.08	0.5	0.07	0.3	-0.1	3	-0.1	51	89.0	0.1	-0.1
SITE 3: 60-75 cm	0.8	2.0	0.28	1.3	0.4	0.12	0.6	0.1	0.9	0.2	0.6	0.10	0.6	0.09	0.4	-0.1	3	-0.1	58	87.0	0.2	-0.1
SITE 3: 75-90 cm	1.3	3.0	0.39	1.9	0.5	0.13	0.7	0.1	0.9	0.2	0.6	0.11	0.7	0.11	0.7	-0.1	5	-0.1	43	62.0	0.3	-0.1
Standards																						
Blank	-0.1	-0.1	-0.05	-0.1	-0.1	-0.05	-0.1	-0.1	-0.1	-0.1	-0.1	-0.05	-0.1	-0.04	-0.2	-0.1	-1	-0.1	-5	-0.4	-0.1	-0.1
Standard MAG1	43.9	89.4	9.84	38.1	7.3	1.52	6.6	1.0	5.3	1.0	2.9	0.44	2.7	0.38	3.5	1.2	2	0.3	21	-0.4	12.1	2.9
Certified MAG1	**43***	**88***	**9.3**	**38***	**7.5***	**1.55***	**5.8***	**0.96***	**5.2***	**1.02***	**3**	**0.43***	**2.6***	**0.40***	**3.7***	**1.1**	**1.4**	**(0.59)**	**24***	**0.34**	**11.9***	**2.7***
Standard BIR1	0.8	2.1	0.40	2.5	1.1	0.56	1.8	0.4	2.6	0.6	1.8	0.28	1.7	0.28	0.6	-0.1	-1	-0.1	-5	-0.4	-0.1	-0.1
Certified BIR1	**0.62***	**1.95***	**0.38***	**2.5***	**1.1***	**0.54***	**1.85***	**0.36***	**2.5***	**0.57***	**1.7***	**0.26***	**1.65**	**0.26***	**0.6***	**0.04**	**0.07**	**(0.01)**	**3**	**(0.02)**	**0.03**	**0.01**
Standard DNC1	3.7	10.1	1.04	4.7	1.4	0.61	2.0	0.4	2.8	0.6	2.0	0.32	2.0	0.32	1.0	-0.1	-1	-0.1	6	-0.4	0.3	-0.1
Certified DNC1	**3.8***	**10.6**	**1.3**	**4.9***	**1.38***	**0.59***	**2**	**0.41***	**2.7**	**0.62**	**2***	**(0.33)**	**2.01***	**0.32***	**1.01***	**0.098***	**(0.2)**	**(0.026)**	**6.3**	**(0.02)**	**(0.2)**	**(0.1)**
Standard GXR-2	23.9	48.4	4.87	18.3	3.4	0.69	3.1	0.5	2.7	0.6	1.7	0.27	1.7	0.26	6.4	0.8	1	1.0	676	-0.4	8.1	2.7
Certified GXR-2	**25.6**	**51.4**		**(19)**	**3.5**	**0.81**	**(3.3)**	**0.48**	**3.3**			**(0.3)**	**2.04**	**(0.27)**	**8.3**	**0.9**	**1.9**	**1.03**	**690**	**(0.69)**	**8.8**	**2.9**
Standard LKSD-3	48.8	91.6	11.2	43.2	7.7	1.51	6.7	0.9	5.1	1.0	3.0	0.46	2.8	0.41	4.6	0.6	-1	0.2	27	-0.4	11.3	4.5
Certified LKSD-3	**52**	**90**		**44**	**8.0**	**1.50**		**1.0**	**4.9**				**2.7**	**0.4**	**4.8**	**0.7**	**(<4)**		**29**		**11.4**	**4.6**
Standard MICA-Fe	199	412	48.6	179	32.9	0.70	24.9	2.7	10.6	1.4	3.4	0.48	2.9	0.25	26.1	34.4	16	17.4	14	1.7	166	85.3
Certified Mica Fe	**200***	**420***	**49***	**180***	**33***	**0.7***	**21***	**2.7***	**11***	**1.6***	**3.8***	**0.48***	**3.5***	**0.5***	**26***	**35***	**15**	**16**	**13***	**2**	**150***	**80***
Standard GXR1	9.0	17	2.2	9.6	3.1	0.7	4.4	0.9	4.6	1.1	3.2	0.5	2.2	0.32	0.8	-0.2	168	0.5	702	1380	3.0	34.7
Certified GXR1	**7.5**	**17**		**(18)**	**2.7**	**0.69**	**4.2**	**0.83**	**4.3**			**(0.43)**	**1.9**	**0.3**	**1.0**	**0.175**	**164**	**(0.39)**	**730**	**1380**	**2.44**	**34.9**
Standard SY3	1340	2220	223	671	110	17.2	105	18.2	118	29.6	68.4	11.6	62.2	7.90	12.4	27.2	2	1.6	133	2.9	1000	650
Certified SY3	**1340***	**2230***	**223***	**670**	**109**	**17***	**105***	**18**	**118**	**29.5***	**68**	**11.6***	**(62)**	**7.90**	**9.70**	**30***	**1.1***	**1.50**	**133***	**(0.8)**	**1003***	**650***
Standard STM-1	147	256	20.9	76.3	11.7	3.54	10.1	1.5	8.0	1.5	4.4	0.67	4.3	0.58	27.6	19.0	4	0.2	18	1.5	31.4	9.0
Certified STM-1	**150***	**259***	**19***	**79***	**12.6***	**3.6***	**9.5***	**1.55***	**8.1***	**1.9**	**4.2***	**0.69**	**4.4***	**0.60**	**28***	**18.6***	**3.6***	**0.26**	**17.7***	**0.13**	**31***	**9.06***
Standard IFG-1	3.3	4.8	0.52	2.1	0.5	0.41	0.8	0.1	1.0	0.2	0.8	0.11	0.7	0.10	-0.2	0.2	219	-0.1	-5	-0.4	0.2	0.2
Certified IFG-1	**2.8***	**4***	**0.4***	**0.2**	**0.4***	**0.39***	**0.74***	**0.11***	**0.8***	**0.2***	**0.63***	**0.09***	**0.6***	**0.09***	**0.04**	**0.2**	**220**	**0.02**	**4**		**0.1**	**0.02**

*Recommended value.
( ) Information value.
All other values are proposed.

Table GS-28-3: Geochemical analysis of tailings samples (-60 mesh) collected from three 1 m deep, hand-augered profiles. Analysis by ICP-MS following an ammonium iodide extraction. Negative values indicate less than the lower limit of determination.

Sample ID	Li*	Be*	Cl*	Sc*	Ti*	V	Mn	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Rb	Sr	Y	Zr	Nb	Mo	Ru
SITE 1: 0-15 cm	6	-2	48384	-100	939	102	643	69	100	65055	126	12	2	40	25	6349	27	346	34	131	-1	7	1
SITE 1: 15-30 cm	396	4	46760	-100	460	60	50541	5529	2072	1691987	6479	21	5	127	45	6598	17	681	677	104	-1	25	-1
SITE 1: 30-45cm	32	-2	42286	-100	276	64	113460	10392	3373	1589745	34229	19	4	474	47	6528	19	1465	662	107	-1	51	-1
SITE 1: 45-60 cm	41	-2	46835	-100	244	38	58022	4647	1695	704168	24420	10	3	171	37	7387	14	1178	200	132	-1	32	-1
SITE 1: 60-75 cm	15	-2	47159	-100	195	42	33047	729	882	735417	5850	11	6	165	39	7388	8	1779	220	136	-1	22	-1
SITE 1: 75-90 cm	13	-2	47853	-100	516	79	50233	1796	1811	561936	8323	22	7	257	62	7293	11	2233	303	243	1	29	-1
SITE 1: 90-105 cm	7	-2	49338	-100	570	78	66712	390	799	149146	4260	31	11	188	54	7707	14	1837	220	220	1	24	-1
SITE 2: 0-15 cm	122	-2	53883	116	1995	174	12194	1026	1044	358362	1775	13	1	60	33	8066	133	904	133	130	2	6	1
SITE 2: 15-30 cm	314	4	52059	206	1603	435	48501	6717	3404	767980	4914	17	3	107	58	7977	189	919	311	110	1	9	-1
SITE 2: 30-45 cm	204	5	50391	228	369	276	55017	7087	3397	475237	4011	11	3	140	73	7580	110	535	176	98	-1	7	-1
SITE 2: 45-60 cm	232	24	45438	621	400	513	31700	5194	3337	999999	3681	19	9	140	92	6188	67	741	335	66	-1	9	-1
SITE 2: 60-75 cm	43	5	50442	147	505	401	257171	15623	6502	587436	35676	40	9	186	97	8639	64	2026	2082	180	1	57	-1
SITE 2: 75-90 cm	2082	4	52355	107	2952	288	185847	17540	7625	328337	39056	33	10	148	68	7988	48	1963	1090	172	2	73	-1
SITE 2: 90-105 cm	86	4	48230	108	950	164	154497	7183	3336	262740	32696	45	15	125	44	8553	22	2255	810	416	2	103	3
SITE 3: 0-15 cm	4	-2	43766	-100	264	99	64393	1661	1565	724289	5703	15	4	208	83	7902	32	1305	291	226	-1	26	-1
SITE 3: 15-30 cm	-2	2	44070	143	157	180	61800	1714	1499	700695	4877	11	3	98	121	8425	102	2057	424	92	-1	22	-1
SITE 3: 30-45 cm	3	-2	42244	119	126	155	47503	741	1155	613241	4052	9	2	55	70	8189	13	1835	351	39	-1	17	2
SITE 3: 45-60 cm	273	-2	40126	-100	154	172	36456	688	1003	647383	3627	9	3	62	67	7137	16	1389	294	47	-1	16	-1
SITE 3: 60-75 cm	6	-2	41281	103	171	262	38533	1127	1600	626482	4051	10	3	57	78	7499	22	1538	343	63	-1	9	1
SITE 3: 75-90 cm	10	-2	40266	-100	257	210	44879	1081	1113	323513	3544	13	4	65	63	7518	47	1729	307	87	-1	10	-1

Sample ID	Pd	Ag	Cd	In	Sn	Sb	Te	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta
SITE 1: 0-15 cm	1	492.2	7.0	2.7	13	2.9	15	2.1	-1	79.7	200.2	25.9	109.7	19.5	3.2	17.8	3.0	10.0	1.6	4.9	1.1	3.3	0.5	3.6	-0.1
SITE 1: 15-30 cm	1	276.7	129.7	5.7	12	5.4	90	1.7	168	599.4	1180.8	153.1	666.0	140.7	32.5	141.3	27.3	133.2	25.5	68.3	7.9	55.4	8.9	5.7	0.2
SITE 1: 30-45cm	2	133.2	339.3	7.5	22	8.5	295	1.2	280	471.7	857.4	107.4	453.5	98.3	25.9	109.2	21.6	112.8	22.7	63.3	8.6	53.4	9.4	5.0	0.3
SITE 1: 45-60 cm	3	107.6	262.5	9.9	18	4.6	215	0.6	271	117.7	236.1	28.8	126.6	29.7	7.5	31.9	6.0	34.4	6.9	20.2	2.7	19.0	4.1	5.1	-0.1
SITE 1: 60-75 cm	2	128.6	329.1	11.3	28	10.7	332	0.4	218	120.2	238.7	29.5	135.8	30.6	7.7	33.1	6.6	37.8	7.6	22.6	3.4	23.5	4.8	4.8	-0.1
SITE 1: 75-90 cm	3	152.2	311.9	12.5	44	29.3	649	0.8	296	214.2	445.7	52.9	246.7	55.3	13.9	55.7	10.2	55.6	10.9	32.1	3.9	30.1	6.0	8.3	-0.1
SITE 1: 90-105 cm	3	157.4	85.3	5.9	30	43.6	1653	0.5	516	232.8	481.8	56.0	238.8	51.9	13.2	50.2	9.1	45.0	8.2	23.6	2.7	19.5	3.1	6.2	-0.1
SITE 2: 0-15 cm	1	295.1	62.9	5.7	15	3.0	42	9.7	-1	132.9	332.8	43.1	185.3	33.3	6.8	33.1	6.6	27.5	5.3	15.7	1.7	11.1	1.7	3.3	-0.1
SITE 2: 15-30 cm	1	339.7	208.4	23.7	14	7.4	130	29.5	3	176.9	477.6	60.9	290.0	67.0	15.2	66.6	13.2	67.2	13.1	36.6	4.5	28.8	4.4	3.2	-0.1
SITE 2: 30-45 cm	-1	374.6	156.2	30.5	27	9.0	288	26.2	39	121.9	307.8	42.7	215.5	49.7	10.8	43.9	8.3	38.3	7.4	22.5	2.8	19.4	3.0	2.8	-0.1
SITE 2: 45-60 cm	-1	153.4	111.5	7.5	20	18.8	727	10.8	32	229.7	798.6	129.9	678.5	202.8	44.3	130.5	26.6	132.7	24.2	71.7	10.2	83.1	12.9	3.0	0.1
SITE 2: 60-75 cm	-1	157.0	1919.0	4.7	96	39.7	416	5.1	239	1044.4	2005.7	236.4	1099.0	274.4	79.3	327.7	69.2	372.7	73.5	208.1	26.7	178.7	29.7	8.4	0.5
SITE 2: 75-90 cm	-1	150.4	1282.1	3.0	43	38.3	313	4.5	274	758.9	1472.4	169.8	737.4	158.2	44.2	198.1	37.5	191.6	37.9	104.0	12.7	88.0	14.9	6.8	0.2
SITE 2: 90-105 cm	3	155.9	940.8	3.0	53	39.3	211	2.1	436	842.3	1882.0	221.7	897.8	151.7	46.7	219.3	39.2	184.3	33.8	95.9	11.8	80.0	13.9	14.3	0.3
SITE 3: 0-15 cm	1	137.7	228.0	11.8	44	9.3	613	2.3	517	203.8	409.0	49.9	229.1	54.0	13.5	53.9	10.6	53.6	10.9	30.3	5.0	29.5	5.6	8.1	-0.1
SITE 3: 15-30 cm	-1	157.1	479.6	10.7	18	10.4	167	2.2	387	149.2	313.2	40.9	199.2	52.5	16.7	57.3	12.3	71.2	15.6	45.8	6.7	44.4	8.5	3.6	-0.1
SITE 3: 30-45 cm	-1	181.8	386.3	10.9	40	10.5	71	1.9	230	110.2	230.0	28.8	153.7	40.8	14.4	45.9	9.9	58.3	12.6	35.4	5.3	36.1	6.9	1.4	-0.1
SITE 3: 45-60 cm	-1	213.8	259.7	13.1	19	14.1	90	1.9	217	91.3	188.9	28.4	131.3	35.7	11.5	38.9	8.2	49.2	10.5	31.6	4.2	31.0	5.8	2.1	-0.1
SITE 3: 60-75 cm	-1	236.5	297.7	10.3	51	21.4	96	2.6	273	105.9	224.3	29.1	148.2	42.2	13.7	45.3	9.7	59.9	12.3	37.5	4.9	34.9	6.6	2.5	-0.1
SITE 3: 75-90 cm	-1	234.8	197.6	6.5	32	20.0	199	5.3	517	139.7	304.9	39.7	197.4	51.3	13.4	50.4	10.2	55.3	11.3	34.5	4.0	31.8	6.1	3.6	-0.1

*Element determined semiquantitatively.
Values of 999999 indicate greater than the upper limit of detection.

Table GS-28-3: Geochemical analysis of tailings samples (-60 mesh) collected from three 1 m deep, hand-augered profiles. Analysis by ICP-MS following an ammonium iodide extraction. Negative values indicate less than the lower limit of determination. ***(continued)***

Sample ID	W	Re	Os	Pt	Au	S.Q.Hg	Tl	Pb	Bi	Th	U
SITE 1: 0-15 cm	3	-0.01	-1	-1	157.77	854	1.9	123	10018	8.8	1.8
SITE 1: 15-30 cm	7	0.07	-1	-1	129.79	328	-0.1	1808	6155	30.4	11.4
SITE 1: 30-45cm	10	0.03	-1	-1	175.99	319	3.4	1823	10612	16.0	9.5
SITE 1: 45-60 cm	9	0.04	-1	-1	125.37	128	-0.1	689	6718	11.0	7.0
SITE 1: 60-75 cm	8	0.10	-1	-1	48.96	101	-0.1	789	10690	10.1	6.4
SITE 1: 75-90 cm	21	0.34	-1	-1	43.42	107	3.7	2689	13731	28.4	9.5
SITE 1: 90-105 cm	100	0.19	-1	-1	22.69	66	6.6	4584	20620	37.1	5.3
SITE 2: 0-15 cm	6	0.14	-1	-1	163.27	702	-0.1	49	11129	9.1	2.0
SITE 2: 15-30 cm	12	0.31	-1	-1	196.75	1612	-0.1	232	22920	53.8	3.9
SITE 2: 30-45 cm	11	0.49	-1	-1	95.09	1100	-0.1	328	30381	31.3	4.3
SITE 2: 45-60 cm	17	0.49	-1	-1	35.04	216	-0.1	18972	28175	13.6	86.7
SITE 2: 60-75 cm	24	0.76	-1	-1	1.67	203	-0.1	8266	17087	18.8	23.4
SITE 2: 75-90 cm	16	0.65	-1	-1	2.60	225	-0.1	8151	9929	20.6	17.2
SITE 2: 90-105 cm	18	0.41	-1	-1	3.78	292	-0.1	13811	4502	51.2	11.0
SITE 3: 0-15 cm	26	0.06	-1	-1	48.08	351	-0.1	6878	9932	20.6	10.4
SITE 3: 15-30 cm	21	0.03	-1	-1	78.52	213	-0.1	3253	10202	5.9	14.6
SITE 3: 30-45 cm	8	0.02	-1	-1	40.65	139	-0.1	2904	12313	2.0	12.9
SITE 3: 45-60 cm	9	0.17	-1	-1	22.43	90	-0.1	2659	17144	2.1	11.8
SITE 3: 60-75 cm	8	0.25	-1	-1	6.07	131	-0.1	7068	14671	2.9	14.0
SITE 3: 75-90 cm	14	0.26	-1	-1	11.81	170	0.6	3153	9844	7.3	9.8

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Values of 999999 indicate greater than the upper limit of detection.

analyses based on instrumental neutron activation analysis (INAA) and inductively coupled plasma mass spectrometry (ICP-MS), respectively. Data in Table GS-28-3 were determined by ICP-MS following an ammonium iodide partial extraction and are therefore partial analyses. This analytical approach was undertaken to simulate a soil–plant root micro-environment with a pH of between 2 and 3. In this way, an initial estimate of bio-available metal could be obtained.

RESULTS

The INAA total data from Tables GS-28-1 and -2 indicate the relative base- and precious-metal enrichment in tailings at the minesite. In particular, Au is elevated in the upper 15 cm of the tailings profile at site 1 (3450 ppb), is consistently enriched throughout the profile at site 2 (1110–2640 ppb), and is somewhat lower but elevated at site 3 (265–958 ppb). Exceptional concentrations of Cu are documented from all three sites (834–5740 ppm at site 1, 1710–10 500 ppm at site 2 and 3150–4510 ppm at site 3; Table GS-28-2). Additional enrichments of Ag (up to 6 ppm) and Bi (up to 127 ppm) are documented at site 1. Arsenic is low (<2–20 ppm) at all three sites (Table GS-28-1).

The relative enrichment of base and precious metals is observed throughout the profiles, although the highest single-sample responses tend to be situated in the upper 15–30 cm. Despite some upward movement of metal-enriched waters through evapotranspiration or fluctuation of groundwater levels near surface, metal enrichment may be critical, since root access of hyperaccumulator species will likely not exceed 0.5–1.0 m. Interestingly, previous studies reported in the literature (Robinson et al., 1999) demonstrate that multiple crops of nickel-hyperaccumulator species could be removed from nickeliferous soils before any reduction of nickel could be documented in the soil. This probably argues for movement of metal from the base to the top of the nickel-enriched soil profile.

Simulation of a plant root–soil micro-environment (pH of 2–3) for this orientation survey was necessary because not all metal present in the substrate will likely be available for uptake by plants (bio-available). The differences in bio-availability in the tailings may be explained, in part, by the mineralogy and forms of the metals present. These differences probably account for some of the variations in the concentrations of metals extracted from the samples using total versus partial techniques (cf. Tables GS-28-1, -2 and -3). Neutron activation and ICP-MS analysis based on lithium metaborate/tetraborate fusion of the samples will reflect total amounts of metals regardless of mineralogy, whereas ammonium iodide extraction will liberate metals at pH 2–3. The ICP-MS analyses following ammonium iodide extraction (Table GS-28-3) indicate the numerous base and precious metals that are being liberated from the three tailings profiles at the Central Manitoba site. These include significant quantities of Cu, Zn, Ni, Co, Mo, Cd, In, Sb, Hg, Pb, Bi and, in particular, Au and Ag. The metals defined as bio-available by the ammonium iodide extraction would be the focus of phytoremediation and the production of a bio-ore in the next phase of this study. Bio-availability of gold and base metals can be substantially increased by application of thiocyanate (Anderson et al., 1999) and chelating agents (Blaylock et al., 1997), respectively.

Field Study: Plant Species

Seedlings of native plant species of the boreal forest were selected for study. In July 2000, the following species were planted on three different sites at the Central Manitoba tailings site: dogwood (*Cornus stolonifera*), yellow willow (*Salix lutea*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*), tamarack (*Larix laricina*) and bog birch (*Betula glandulosa*). Half of the plants were fertilized with 10-30-15-04 (nitrogen-phosphate-potash-sulphur) at a rate of 500 kg/ha. Seeds of the following species were also planted: *Cornus stolonifera*, Indian mustard (*Brassica juncea*), slender wheatgrass (*Agropyron trachycaulum*) and altai wildrye (*Elymus angustus*). In the fall, the seedlings will be evaluated for survival and degree of injury. Selected organs of some woody seedlings will be harvested for metal-content measurements and the remainder will be left on site for further survival studies. The remainder of the live herbaceous seedlings will be treated with thiocyanate and harvested to evaluate their base-metal and gold content.

Greenhouse Study: Germination Rates

Seeds of *Brassica jun*cea, *Sinapis alba* (white mustard*), Agropyron trachycaulum*, *Elymus angustus*, *Pinus banksiana* and *Picea glauca* were planted in trays on tailings collected from the top 15 cm of the three selected sites. The trays were sprayed with distilled water regularly to keep moisture level relatively constant. Germination rates were recorded regularly. Red-osier dogwood seedlings were planted in two-litre pots containing tailings collected from the top 15 cm of the three selected sites. The pots were placed in trays so that the plants could be bottom watered to avoid leaching. Four replicates per site were used for the studies.

Preliminary results show that seeds were able to germinate in tailings collected from sites 1 and 3 (Fig. GS-28-2). Indian mustard, white mustard and altai wildrye had a relatively high germination rate when planted on tailings from sites 1 and 3, both of which have high gold and copper concentrations. Relatively few altai wildrye seeds were able to germinate on tailings collected from site 2. These preliminary results suggest that some of the selected plant species can tolerate the high level of metals in this environment (Fig. GS-28-3 and -4).

FUTURE WORK

Future work will focus on the determination of metal content in the plants and the facilitation of metal uptake through plant and substrate remedial treatment. Additional plant species will be tested for their ability to acquire and store base and precious metals in this environment. Further experiments with *Brassica juncea*, the most promising plant species for gold phytomining, should establish the most effective experimental and field conditions for maximizing gold uptake in a bio-ore based on this species. The economics of commercial production of bio-ores will be determined.

REFERENCES

Anderson, C.W.N., Brooks, R.R., Chiarucci, A., LaCoste, C.J., Leblanc, M., Robinson, B.H., Simcock, R. and Stewart, R.B. 1999: Phytomining for nickel, thallium and gold; Journal of Geochemical Exploration, v. 67, p. 407–415.

Anderson, C.W.N., Brooks, R.R., Stewart, R.B. and Simcock, R. 1998: Harvesting a crop of gold in plants; Nature, v. 395, p. 55–56.

Blaylock, M.J., Salt, D.E., Dushenkov, S., Zakhartova, O., Gussman, C., Kapulnik, Y., Ensley, B.D. and Raskin, I. 1997: Enhanced accumulation of Pb in India mustard by soil-applied chelating agents; Environmental Science and Technology, v. 31, p. 860–865.

Bradshaw, A.D. 1952: Population of *Agrostis tenuis* resistant to lead and zinc poisoning; Nature, v. 169, p. 1068.

Comis, D. 1996: Green remediation: using plants to clean the soil; Journal of Soil and Water Conservation, v. 51, no. 3, p. 184–192.

Cunningham, C.D., Berti, W.R and Huang, J.W. 1995: Phytoremediation of contaminated soils; Trends in Biotechnology, v. 13, p. 393–397.

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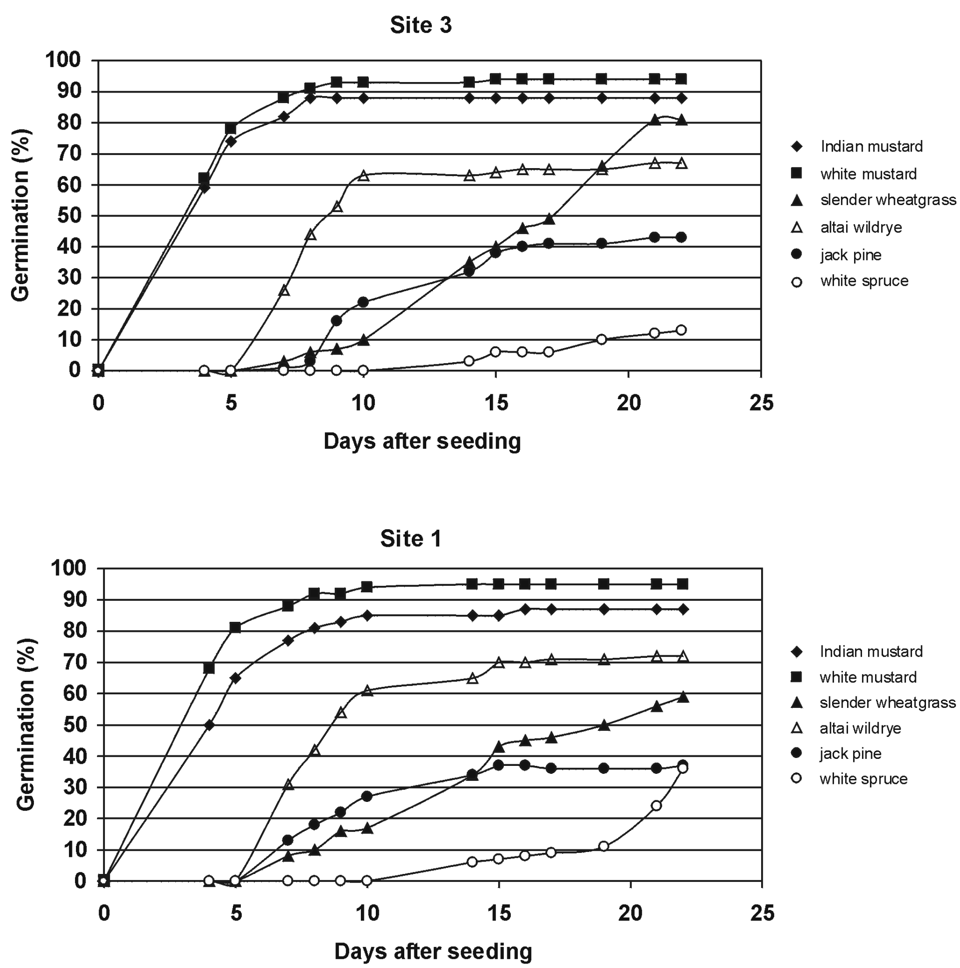

Figure GS-28-2: Germination profiles for sites 1 and 3, Central Manitoba (Au) minesite.

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REFERENCES

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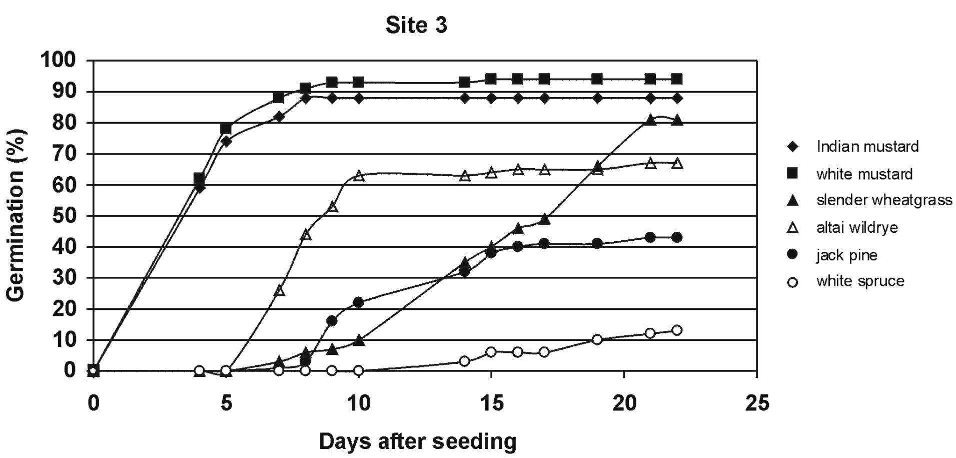

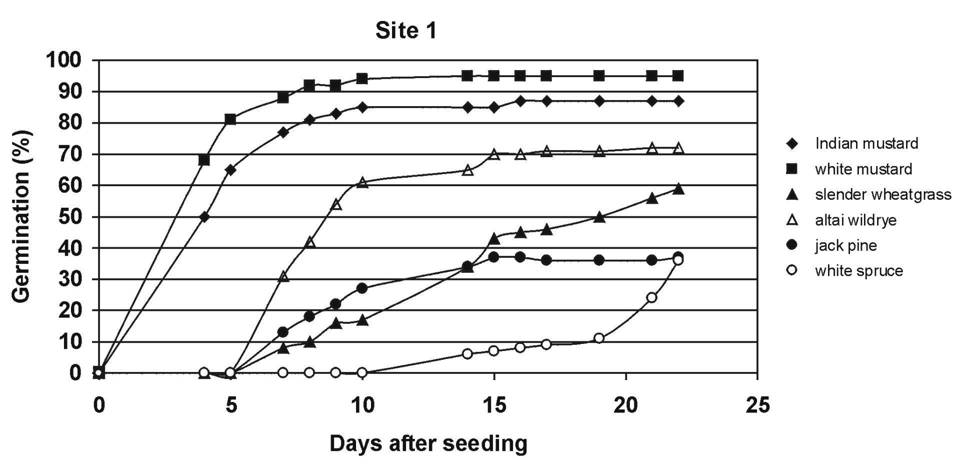

Figure GS-28-2: Germination profiles for sites 1 and 3, Central Manitoba (Au) minesite.

Figure GS-28-3: Seedlings of various species planted in July 2000 at site 2, Central Manitoba (Au) minesite.

Figure GS-28-4: Red-osier dogwood seedlings growing at the University of Manitoba greenhouse in tailings from the Central Manitoba (Au) minesite.

DEPOSIT

Tailings associated with the Central Manitoba gold deposit were selected for initial phytoremediation and phytomining studies. The deposit occurs within the Archean Rice Lake greenstone belt, in the Uchi Subprovince of the Superior Province in southeastern Manitoba (Fig. GS-28-1). The belt is flanked to the north by the North Caribou Terrane (Marr, 1971; Weber, 1971; Poulsen et al., 1996) and, to the south, is transitional with the English River gneissic belt (McRitchie and Weber, 1971; Weber, 1971; Poulsen et al., 1996). The Rice Lake belt is fault bounded on the north by the Wanipigow Fault and on the south by the Manigotagan Fault.

Host rocks to the deposit belong to the Bidou Lake subgroup (Poulsen et al., 1996) and comprise arkose, tuff and chert of the Dove Lake Formation. These sedimentary rocks have been intruded by gabbro sills. Gold-bearing quartz veins at the deposit are situated within en échelon shear zones at or close to the contact between the Dove Lake sedimentary rocks and an east-southeast-trending gabbro sill (Stockwell and Lord, 1939). Five veins contributed the bulk of production at the deposit. These were the Kitchener, Eclipse, No.1 Branch, Tene 6 and Hope veins. The quartz veins were mineralized with chalcopyrite, pyrite, pyrrhotite and free gold. Between 1928 and 1938, a total of 347 801 t of ore was milled and 4287 kg of gold produced.

GEOCHEMICAL CHARACTERIZATION OF TAILINGS

Geochemical analyses of 20 tailings samples collected from three hand-augered profiles, each approximately 1 m in depth, are presented in Tables GS-28-1, -2 and -3. The data in Tables GS-28-1 and -2 are total analyses based on instrumental neutron activation analysis (INAA) and inductively coupled plasma mass spectrometry (ICP-MS), respectively. Data in Table GS-28-3 were determined by ICP-MS following an ammonium iodide partial extraction and are therefore partial analyses. This analytical approach was undertaken to simulate a soil–plant root micro-environment with a pH of between 2 and 3. In this way, an initial estimate of bio-available metal could be obtained.

RESULTS

The INAA total data from Tables GS-28-1 and -2 indicate the relative base- and precious-metal enrichment in tailings at the minesite. In particular, Au is elevated in the upper 15 cm of the tailings profile at site

1 (3450 ppb), is consistently enriched throughout the profile at site 2 (1110–2640 ppb), and is somewhat lower but elevated at site 3 (265–958 ppb). Exceptional concentrations of Cu are documented from all three sites (834–5740 ppm at site 1, 1710–10 500 ppm at site 2 and 3150–4510 ppm at site 3; Table GS-28-2). Additional enrichments of Ag (up to 6 ppm) and Bi (up to 127 ppm) are documented at site 1. Arsenic is low (<2–20 ppm) at all three sites (Table GS-28-1).

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