Re-Os SYSTEMATICS OF Cr-PGE MINERALIZED ZONES IN THE PARTRIDGE RIVER AND SOUTH KAWISHIWI INTRUSIONS AND THE LAYERED SERIES AT DULUTH, DULUTH COMPLEX, NORTHEASTERN MINNESOTA

By

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INTRODUCTION

This report is a portion of a project on the relationship between chromium and platinum-group elements (PGEs) in the Duluth Complex (Fig. 1). The rhenium-osmium and oxygen isotope data in this report were produced from the magnetic fraction of samples in Table 1, where possible. These data are used to evaluate origin of chromium and related PGEs from various parts of the basal zone of the Duluth Complex (Fig. 1).

Chromium mineralization associated with PGEs in the Duluth Complex was first recognized by Sabelin and Iwasaki (1985, 1986) and Sabelin (1985, 1987) in drill hole Du-15 from the Birch Lake area (BLA). The presence of chromium spinels was noted earlier by Weiblen and Morey (1976) at the Spruce Road deposit. Severson (1995) identified chromium and platinum mineralization in drill hole SL-19A northeast of the Water Hen deposit. Also, Severson (1991) identified Cr-rich spinels in the Local Boy ore zone of the Babbitt deposit. Hauck et al. (in prep.; Hauck unpubl. data; Hauck et al., 1998) have identified a variety of Cr-rich spinels, e.g., Cr-magnetite, Cr-hercynite, Cr-Ti-magnetite, in the BLA, not all of which are directly associated with PGE mineralization. Cr-Ti-magnetite + Cr-pleonaste was identified by Sassani (1992) in the Fish Lake area of the Layered Series at Duluth. In addition, Heine et al. (1998) reported 1.64 % Cr_2O_3 in saprolite in drill hole 265 3/1 P2 in a Keweenawan-age (?) ultramafic body in Stearns County in central Minnesota.

Samples for this study were collected from oxide-bearing, semi-massive, and massive oxide zones or layers to answer some fundamental questions about the origin of the Cr-PGE mineralization within the Duluth Complex. Results of the sample from Stearns County are not discussed in this report.

GEOLOGY OF THE WESTERN MARGIN OF THE DULUTH COMPLEX

The portion of the Duluth Complex investigated in this study extends north from Duluth to Hoyt Lakes and then northeast to Spruce Road. Samples from this study (Table 1; Appendix 1) come from the: 1) Layered Series at Duluth; 2) Partridge River intrusion; and 3) South Kawishiwi intrusion (Fig. 1). Miller et al. (2002) summarize the geology of the various intrusions of the Duluth Complex. These three intrusions (out of eleven) are stratiform troctolitic to ferrogabbroic cumulate intrusions within the Duluth Complex, which Miller and Severson (2002) consider to have been emplaced during the main stage of Midcontinent rift magmatism. There are several other intrusions along the western margin of the Duluth Complex, e.g., Boulder Lake and Western Margin intrusions, that were not sampled due to the lack of exposed or drilled Cr-PGE-bearing samples.

The Layered Series at Duluth (DLS) is a 3-4.5 kilometer-thick, east-dipping, sheetlike mafic intrusion that extends about 60 km north to the contact of the Boulder Lake intrusion (Miller and Severson. 2002); the northern contact of the DLS is defined based on aeromagnetic data. The footwall of the DLS consists of Ely Peak Basalts, which are early rift-related basalts, but to the north the footwall becomes the slates and argillites of the Thomson Formation of the Paleoproterozoic Animikie Group (Miller and Severson, 2002). The DLS consists of five major zones based on primary rock type. The samples in this study are from drill holes in the basal zone, and consist of coarse-grained, taxitic olivine gabbro, augite troctolite, and hornfels inclusions (Miller and Severson, 2002; Severson, 1995). However, Miller et al. (1993) did not recognize iron-rich rocks in the basal or other zones of the Duluth area.

No.	Sample Number/ Drill Hole - Footage (ft.)	Location	Unit/ Rock Type	Type of Sample	Re-Os Analysis (Y/N)	Oxygen Isotopes (Y/N)	Whole Rock Cr/Cr_2O_3 (ppm/%)	Pt+Pd (ppb)	Re (ppb)	Os (ppb)
1	B1-211-2060.3-2063.0	Babbitt	Cr-Sill	Rock	Y	Y	2 B Analyzed			
2	B1-301-1723.0-1725.0	Babbitt	Cr Sill	Rock	Y	Y	2 B Analyzed			
3	B1-131-1909.0	Babbitt	Cr Sill	Rock	N	N	800	23.49	0.35	<0.93
4	BL-90-1-2372.5	Birch Lake	U3 - Mass Ox.	Rock	Y	Y	671	1,514		
5	BL-90-1-2383.0	Birch Lake	U3 - Mass. Ox.	Rock	Y	Y	297	957		
6	BL-90-1-2393.2	Birch Lake	U3 - MT-ORT	Rock	Y	Y	457	1,320		
7	BL-95-1-1432.7	Birch Lake	U3 - ORT w/ Ox.	Rock	Y	Y	14,389	434		
8	BL-95-1W-1339.8	Birch Lake	PEG - Mass Ox.	Rock	Y	N	>20,000	2,634		
9	Du-9-2591.3-2592.1	Birch Lake	PEG - PEG AT	Pulp	Y	N	1.60%	3,350		
10	Du-9-2593.7-2596.7	Birch Lake	PEG - Ox. T/AT	Pulp	N	Y	420	1,650		
11	Du-9-2634.1	Birch Lake	U3 - SM Oxide	Rock	Y	Y	400	1,470		
12	Du-9W-2631.0	Birch Lake	U3-SM Ox/Ox MT	Rock	Y	Y	Agua R 1,445	60		
13	Du-15-2354.0-2359.0	Birch Lake	U3 - Mass. Ox.	Coarse Rejects	Y	Y	1.22%	911		
14	Du-15-2411.0-2412.0	Birch Lake	U3 - SM-Mass Ox.	Rock	Y	Y	5.23%	8,163		
15	Du-15-2413.0-2414.0	Birch Lake	U3 - Mass. Ox.	Rock	Y	Y	6.62%	9,123		
16	Du-15-2419.0-2420.0	Birch Lake	U3 - Ox, MT	Rock	Y	Y	0.57%	1,090		
17	Du-15-2434.0-2438.0	Birch Lake	U3 - MT + SM Ox.	Pulp	Y	Y	1.10%	1,650		
18	FHL-2-319.4-324.3	Fish Lake	Semi-Mass. Ox.	Pulp	Y	Y	27,000			
19	FHL-2-324.3-325.4	Fish Lake	Semi-Mass Ox.	Pulp	Y	Y	48,000			
20	FHL-2-325.4-327.0	Fish Lake	Altered Chl Zone	Pulp	N	Y	2,100	572.3		4.5
21	SL-19A-446.0-446.7	Water Hen	Plag-Ox.-Ol Rock	Pulp	Y	Y	46,000	801	0.66	16.7
22	W-12-561.3	Wetlegs	Unit II - MT	Pulp	Y	Y	1.20%	140		
23	W-14-585.5-586.0	Wetlegs	Unit III - TA ?	Pulp	N	N	2.34%	27		

Table 1. Re-Os and Oxygen Isotope Sample List (abbreviations: Mt= melatroctolite; ORT= olivine-rich troctolite; SM=semi-massive; Mass=massive; plag=plagioclase; ol=olivine).

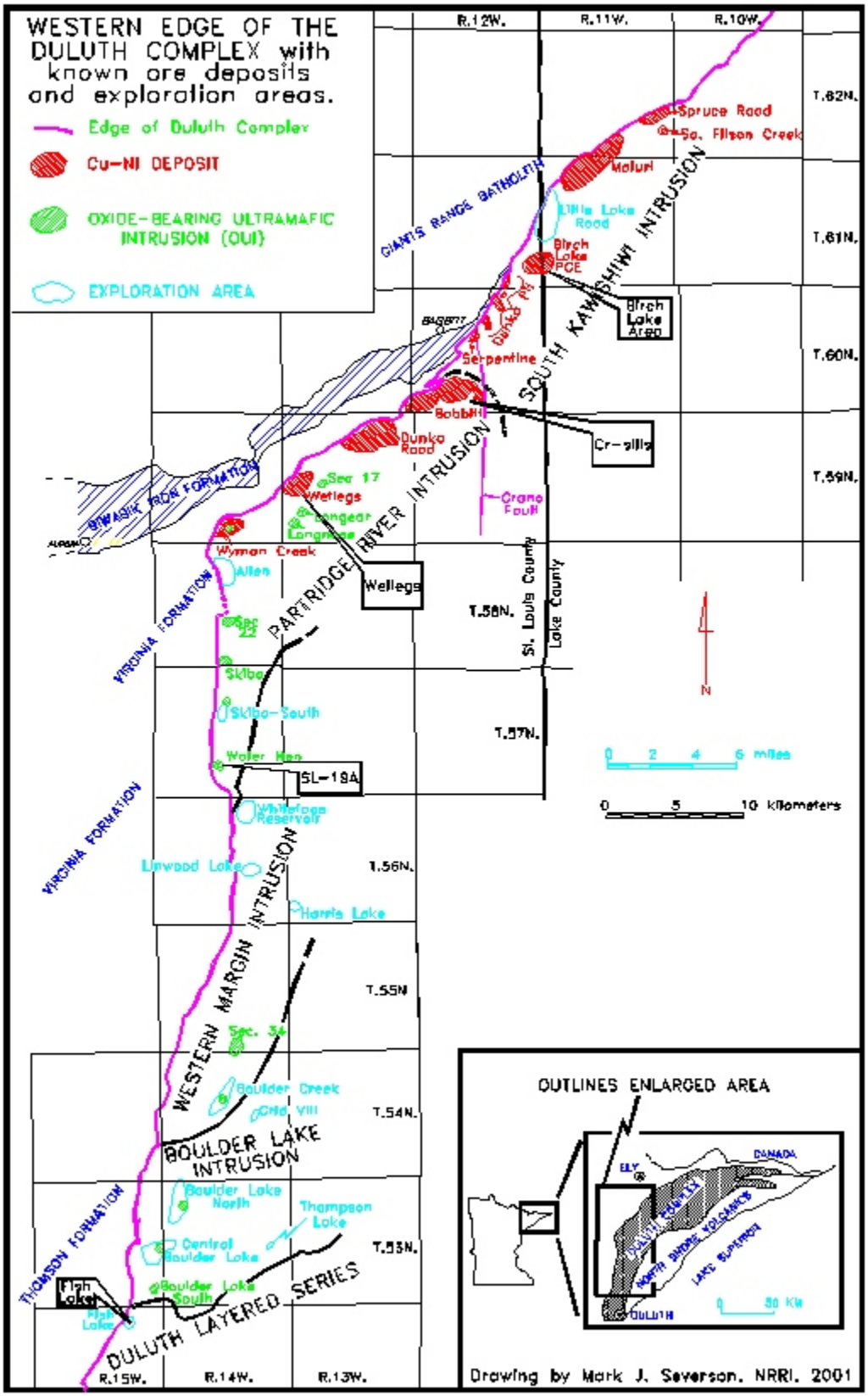

Figure 1. Location of areas where Re-Os and oxygen isotopes samples were collected. See Appendix 1 for drill hole locations.

The igneous stratigraphy of the Partridge River intrusion (PRI; Fig. 2) is described by Severson and Hauck (1990, 1999), Severson and Miller (1999), and summarized in Miller and Severson (2002). The PRI consists of eight troctolitic stratigraphic units along the marginal or contact zone of the PRI with the footwall graywackes of the Paleoproterozoic Virginia Formation. The samples in this study (Table 1) are from: 1) the Wetlegs Layered Series (WLS) in Unit II, which consists of repeated, thin cyclic units that internally grade upward from ultramafic to troctolitic rocks (Miller and Severson, 2002); 2) the top of Unit III; 4) an unnamed layered ultramafic series (in only one drill hole) near, but not associated with, the Water Hen Oxide-Bearing Ultramafic Intrusion; and 4) from pre-Complex Cr-bearing sills in the footwall of the PRI beneath the Babbitt Cu-Ni deposit. The latter are included here because the majority of these sills occur in the footwall beneath the PRI.

The igneous stratigraphy of the South Kawishiwi intrusion (SKI; Fig. 3) is described by Severson (1994) and Miller and Severson (2002). Severson (1994) divides the SKI into 17 different lithological units that occur over the 31 km of the SKI. Severson (1994) called this package of lithological units the South Kawishiwi Troctolitic Series, which was recently redefined as the South Kawishiwi Marginal Zone by Miller and Severson (2002). Sulfide mineralization is primarily confined to the bottom units, i.e., BH, BAN, U3, and UW. These lowest units are "compartmentalized," which suggests a complicated intrusive history (Miller and Severson, 2002). The Birch Lake area (BLA) is in such an area, and Hauck et al. (in prep.) suggest that the BLA mineralization is related to a local magma source, i.e., a feeder zone. Within the bottom units in the BLA, the U3 Unit contains most of the PGEs and Cr mineralization in various forms.

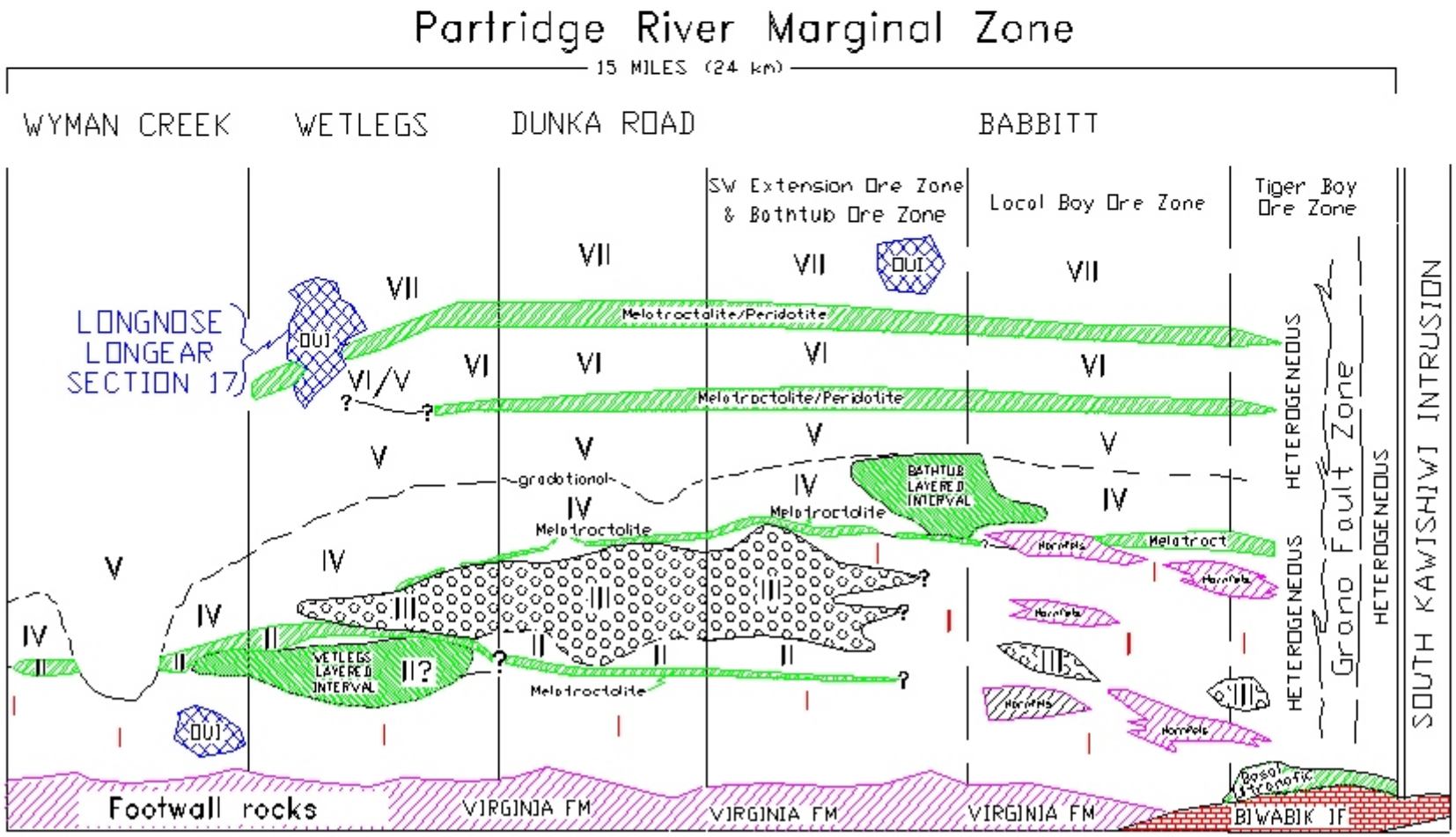

Figure 2. Igneous stratigraphy of the Partridge River Marginal Zone. Re-Os samples were collected from the Wetlegs Layered Interval and the Cr-Sills in the footwall Virginia Formation beneath the Local Boy Ore Zone (from Miller and Severson, 2002).

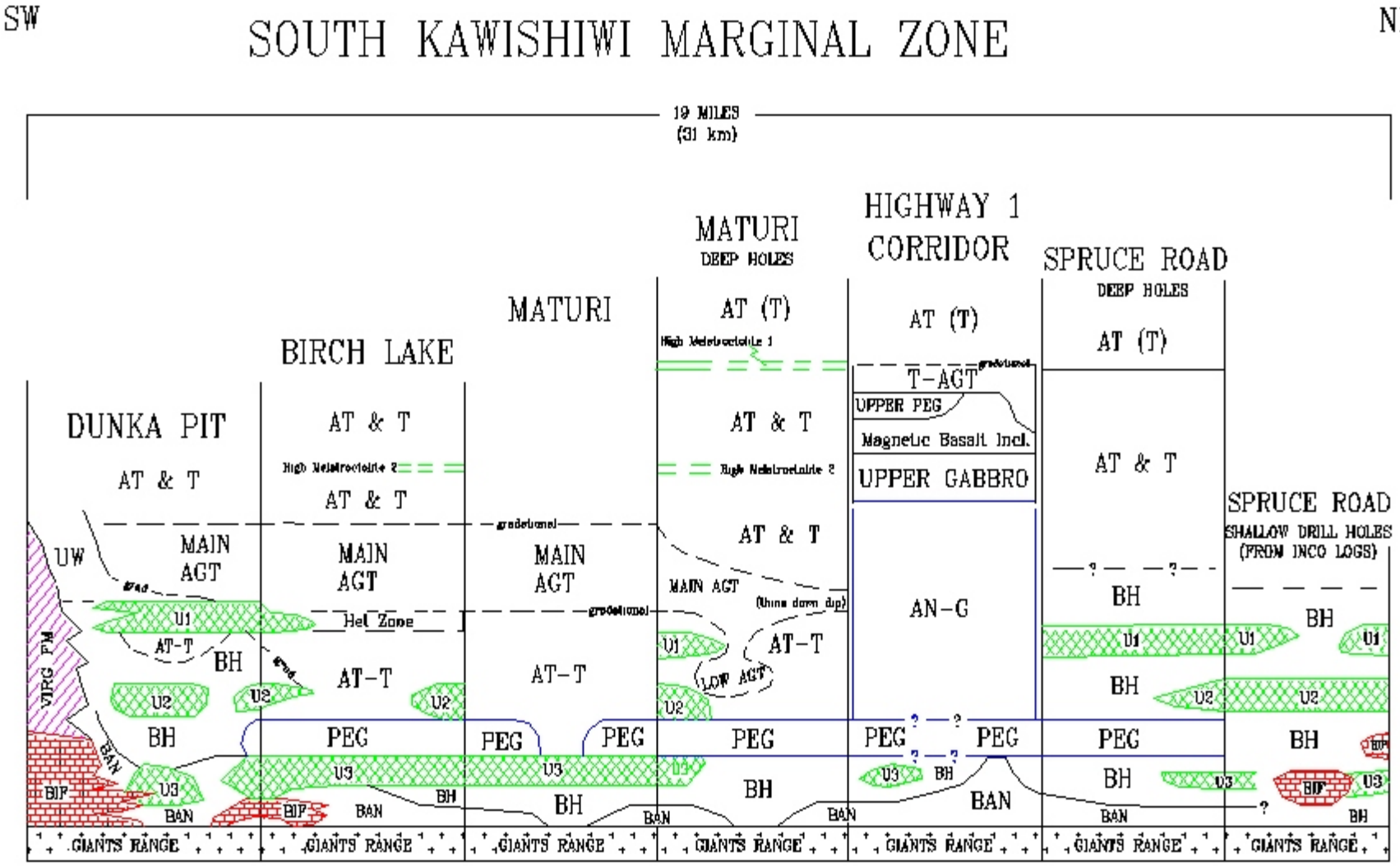

Figure 3. Re-Os samples were collected in the Birch Lake area of the South Kawishiwi Marginal Zone in the U3 and PEG Units (after Miller and Severson, 2002).

SAMPLE DESCRIPTIONS

BIRCH LAKE PGE PROSPECT- SOUTH KAWISHIWI INTRUSION

PGE-Cr mineralization in the Birch Lake PGE prospect was first identified by Sabelin and Iwasaki (1985, 1986) and Sabelin (1985, 1987) in drill hole Du-15 (Figs. 4, 5). Drill hole Du-15 was wedged (D15-W1) in 1986. Additional drill holes were drilled in 1988, 1990, 1995, and 1998-2002. A variety of Cr-magnetites, Cr-Ti-magnetites, and Cr-hercynites were identified in some drill holes using microprobe techniques (Hauck unpubl. data; Hauck et al., in prep.; Sabelin and Iwasaki, 1985). In almost all cases, PGEs were associated with Cr-spinels. While Cr and PGEs occur within all basal units, they occur primarily: 1) in melatroctolites and oxide-bearing rocks within the top 10-20 feet of the U3 Unit; 2) associated with some, but not all, oxide-bearing (>10% iron oxides) rock types, semi-massive oxides (10-80% iron oxides), and massive oxides (>80% iron oxides) irregularly scattered throughout the remainder of the U3 Unit; and 4) in U3 Unit xenoliths (? ; Hauck et al., in prep.) in the PEG Unit.

The basal units in the Birch Lake area contain trace to ore grade concentrations of PGEs, Cr, Cu, and Ni. The basal units (from the base upwards) are: 1) BAN Unit, which consists of a heterogeneous mix of troctolite, gabbro, and variably assimilated iron-formation; 2) U3 Unit, which consists of a heterogeneous mixture of melatroctolite, troctolite, pegmatoids, oxide-bearing rocks, semi-massive to massive iron oxide units (iron-formation restites); 3) PEG Unit, which consists of heterogeneous mix of medium- to very coarse-grained troctolite and anorthositic troctolite, with U3 Unit xenoliths (?; Hauck et al., in prep.). The questionable xenoliths consist primarily of oxide-bearing, semi-massive, and massive iron oxides. Where the BAN Unit is thin or non-existent, the BH or basal heterogeneous unit occurs, and it consists primarily of troctolitic rock types.

Samples for Re-Os and oxygen isotope analyses were selected from four drill holes (Table 1, nos. 4-14; Figs. 4, 5; Appendix 1) to assist in determining the origin of the various Cr-spinels and the rocks in which they occur. These samples include: 1) massive oxides in the U3 Unit; 2) semi-massive oxide xenoliths (?) in the PEG and U3 Units; 3) massive oxides in the PEG Unit; and 4) oxide-bearing olivine-rich troctolites and melatroctolites in the U3 Unit.

BL-90-1

Three samples were collected from drill hole BL-90-1 (Fig. 2, samples 4-6). Two of these three samples come from a massive oxide zone at the top of the U3 Unit in the Birch Lake area. The third sample was collected from a melatroctolite beneath the massive oxide zone. The three samples (sample nos. 4-6, respectively) had Pt+Pd assays of 1,514 ppb, 957 ppb, and 1,320 ppb and Cr assays of 671 ppm, 297 ppm, and 457 ppm, respectively.

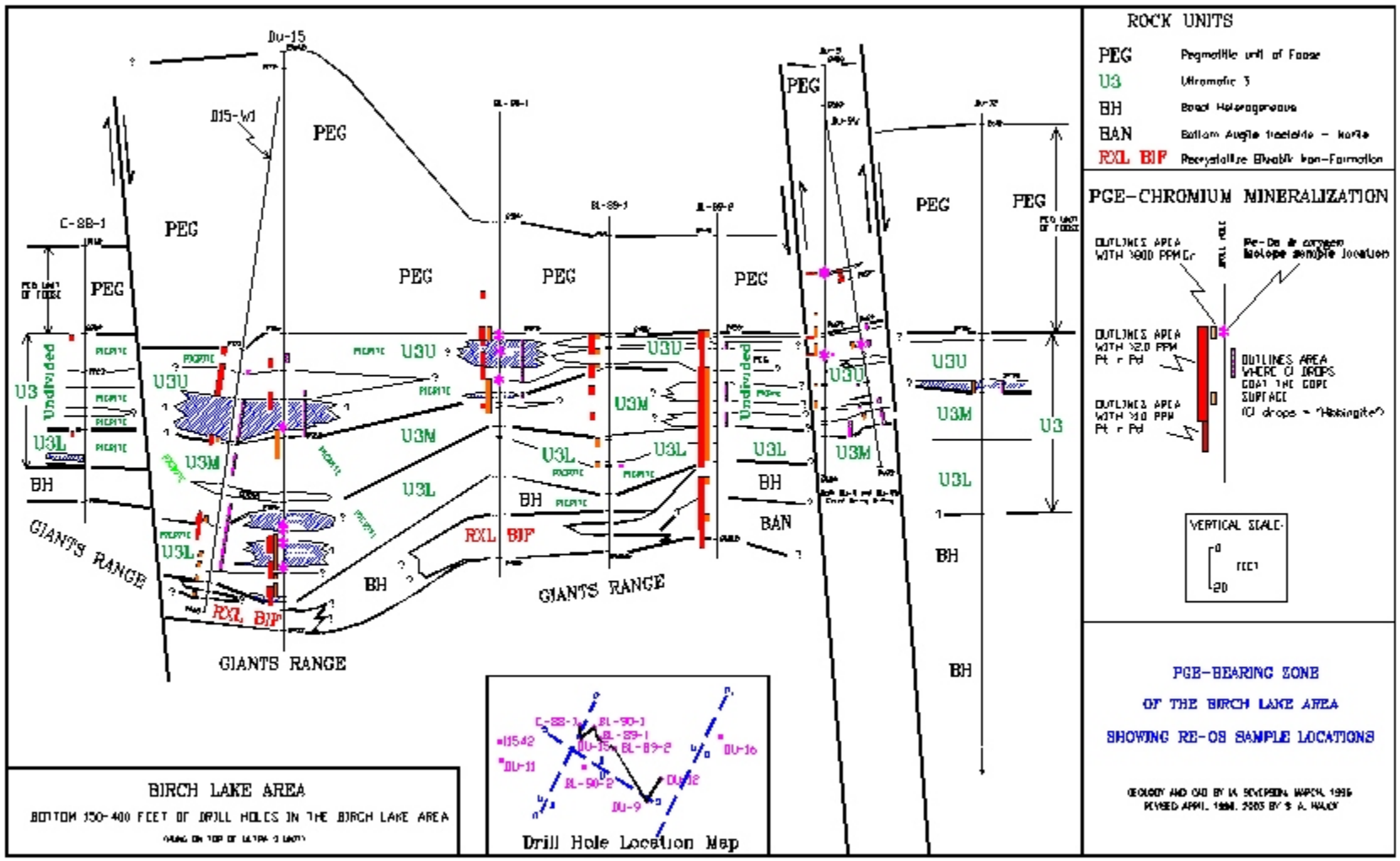

Figure 4. NE-looking cross-section of drill holes in the Birch Lake area illustrating igneous stratigraphy, structure, massive oxide zones (blue hatch), Re-Os and oxygen isotope sample locations (*), anomalous PGE and Cr zones, and the presence of chlorine-rich droplets on drill core. Drill holes are generally hung on the top of the U3 Unit.

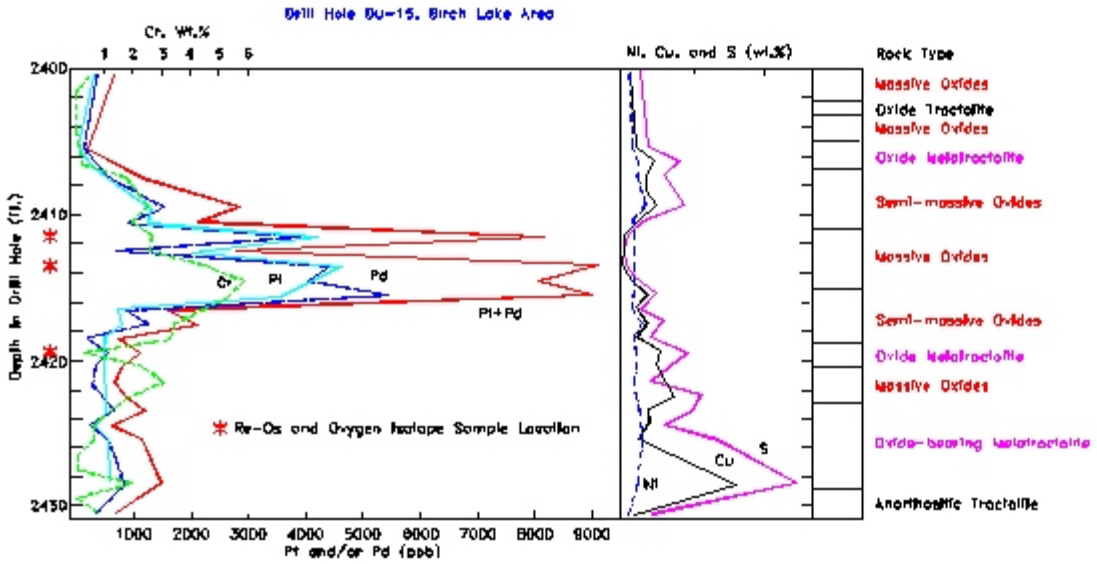

Figure 5. Re-Os and oxygen isotope locations in relationship to Pt-Pd-Cr-Cu-Ni-S mineralization in drill hole Du-15 (Modified after Sabelin and Iwasaki, 1986, and Hauck et al., 1997a). Note: Of the two samples not shown, one sample is above and one is below the footage shown on this figure.

BL-95-1 and BL-95-1W

Two samples were selected drill hole BL-95-1 and its wedge, BL-95-1W, based upon geochemistry (Fig. 6). The BL-95-1W sample (no. 8 in Table 1) was collected from a small massive oxide zone at the lower contact of a pegmatite in the PEG Unit. The Pt+Pd content was 2,642 ppb and the Cr content was >20,000 ppm. This massive oxide does not occur in the main drill hole, BL-95-1, less than one foot away. Microprobe data on this sample indicated that the chromium is in Cr-magnetite (Hauck, unpubl. data, 1996). The BL-95-1sample (Table 1, no. 7) is an oxide-bearing, olivine-rich troctolite that occurs near the top of the U3 Unit. This whole rock sample has 14,389 ppm Cr and 434 ppb Pt+Pd.

Du-9 and Du-9W

The samples (Table 1, nos. 9-12; Fig. 4) from Du-9 and Du-9W were collected from: 1) an iron oxide-rich, U3 Unit xenolith (?; nos. 9-10; Hauck et al., in prep.) in the PEG Unit; and 2) from iron oxide-rich rocks from the top of the U3 Unit (samples 11-12). One sample (no. 9) from the PEG Unit has elevated Cr_2O_3 (1.60%) and Pt+Pd (3,350 ppb) while the other PEG Unit sample has only elevated Pt+Pd (1,650 ppb). This same relationship exists in the samples (nos. 11-12) from the top of the U3 Unit.

Du-15

Five samples come from drill hole Du-15. One sample is from a massive oxide (Table 1, no. 13; Fig. 5) that occurs about 20 ft. from the top of the U3 Unit. Four samples (Table 1, nos. 14-17) also from the U3 Unit are from oxide-bearing melatroctolites and semi-massive to massive oxides near the bottom of the drill hole. Previous work (Severson, 1995; Hauck et al., in prep.) suggest that the massive oxide is a restite of partially melted Biwabik Iron Formation. Within one massive oxide zone, there is a 12 foot zone with 4.1 ppm Pt+Pd+Au and 4.83 wt. % Cr_2O_3, including three feet of 8.9 ppm Pt+Pd+Au and 7.19 wt. % Cr_2O_3 (Fig. 5). The origin of this sample is complicated by the fact that these elevated Cr and PGE values do not occur in similar rock types located less than ~20 ft. away in the adjacent wedge, D15-W1. Stable isotopes (13 samples), PGEs-Au-Ag-Cu-Ni assays (10 samples), and Sm-Nd, Pb-Pb, and Rb-Sr data (5 samples) are available in Hauck et al. (1997a) for samples from Du-15's wedge. Additional data on the occurrence and origin of the PGEs is discussed in Hauck et al. (1997b, 1998) and Komppa (1998). Most of these samples display “2 in 1" texture, or ameboidal to subhedral iron oxides that are poikilitically enclosed by plagioclase oikocyrsts.

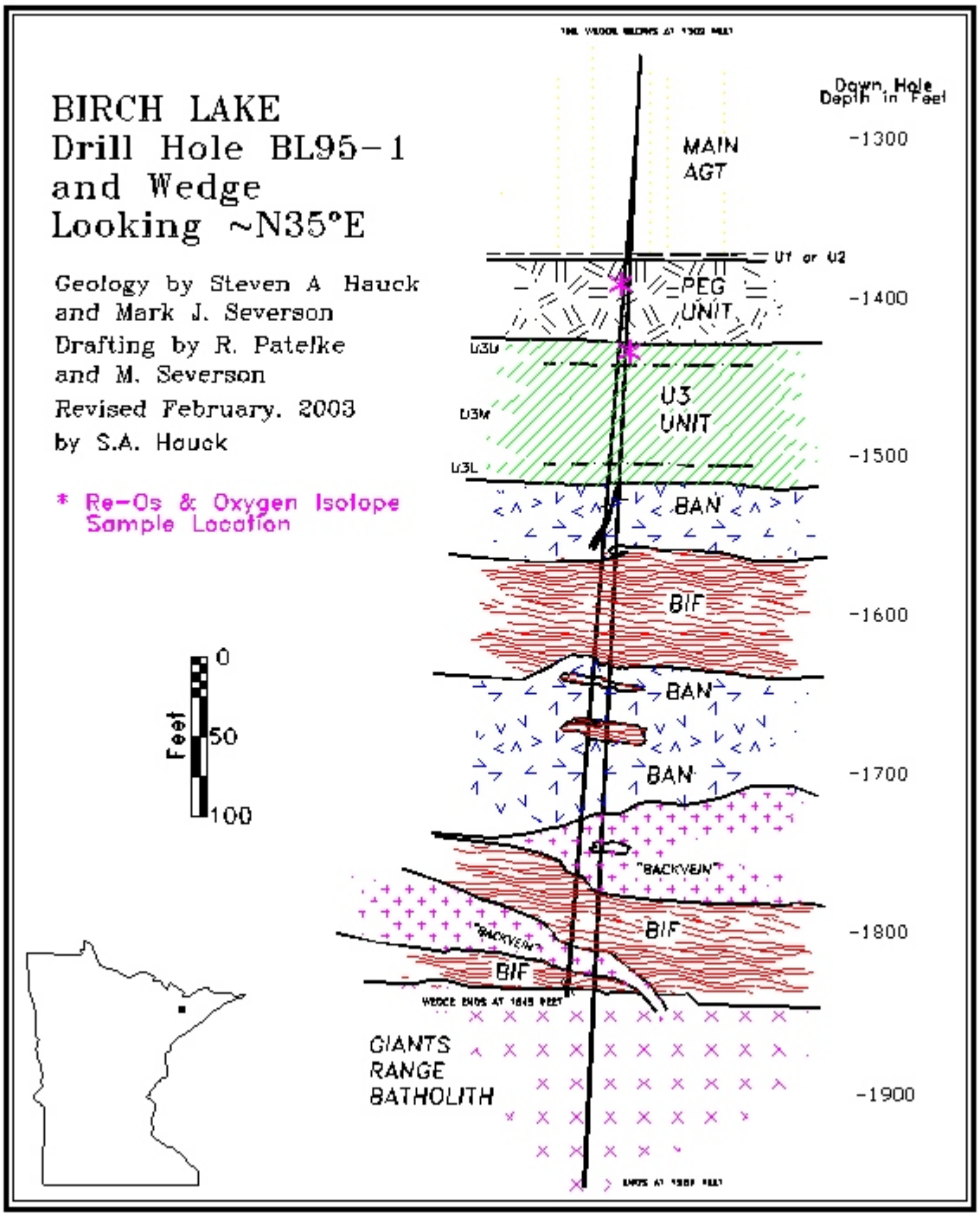

Figure 6. Location of Re-Os and oxygen isotope samples in drill hole BL-95-1 and its wedge BL-95-1. Note presence of a fault beneath the U3 Unit.

CR-SILLS (FOOTWALL OF BABBITT DEPOSIT) - PARTRIDGE RIVER INTRUSION

Two Keweenawan sills emplaced before the main mass of the Duluth Complex were originally described by Grout and Broderick (1919). Severson (1991) describes the sills and recognizes two different types of sills, one near the base of the Paleoproterozoic Virginia Formation and the other near the top of the Paleoproterozoic Biwabik Iron Formation (Fig. 7). Hauck et al. (1997a, b) and Peterson and Severson (2002) describe these sills as Cr-sills (in the Virginia Formation) and Logan-type sills (in the Biwabik Iron Formation). Severson et al. (1996) and Park et al. (1999) subdivided the Cr-sill into two types: 1) a chill zone or border phase; or 2) a coarse-grained, olivine- and hornblende-bearing interior. Microprobe data (Hauck, unpubl. data, 1996) indicates that the very fine-grained iron oxides in the sills contain 36-42% wt. Cr_2O_3. The Cr-sill has also undergone contact metamorphism by the Duluth Complex. Whole rock, stable, and radiogenic isotopic analyses are only available on sample B1-131 (Table 1, no. 1; Hauck et al., 1997a; Park et al., 1999). The three samples (Table 1, nos. 1-3) come from drill holes that penetrate the base of the Duluth Complex in the Babbitt Cu-Ni deposit.

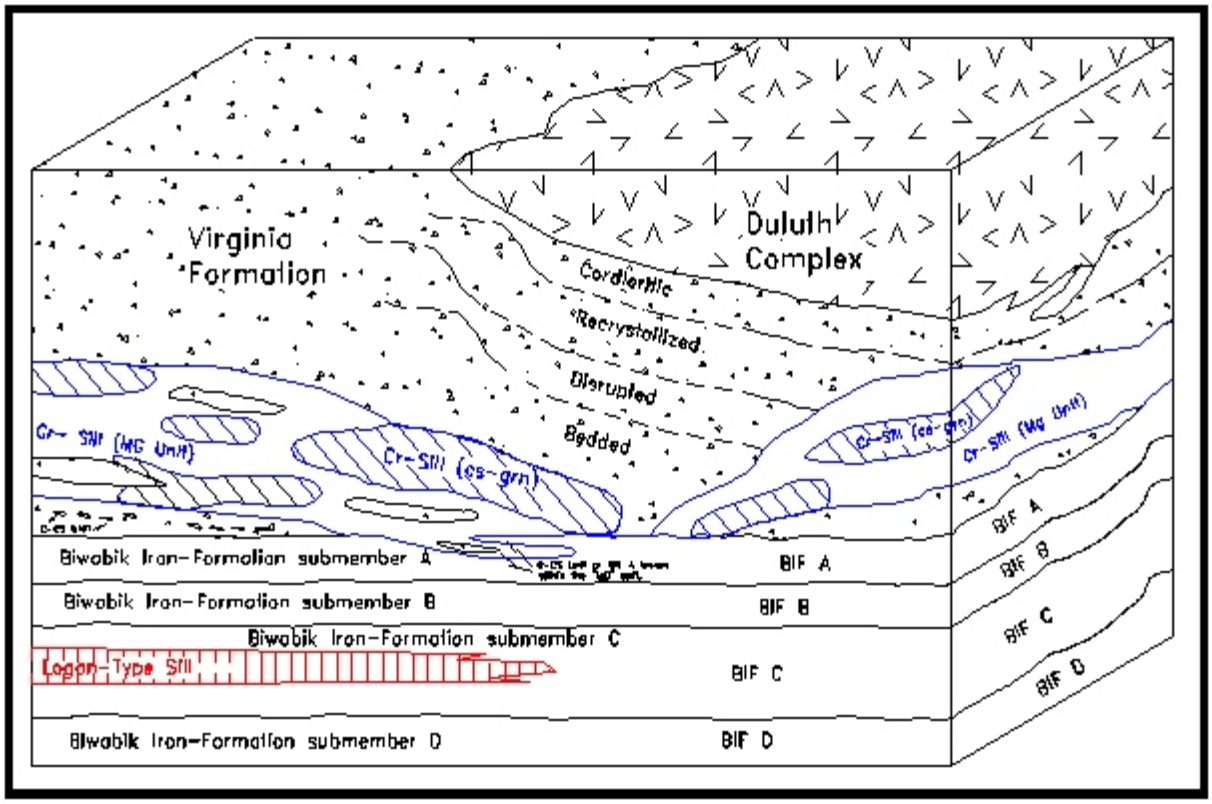

Figure 7. Schematic drawing showing the relationship of the pre-Complex Cr-Sill (in blue - cs-grn = coarse-grained, green colored portion; MG Unit = massive, gray colored portion) and Logan-type Sill (in red) in the Babbitt Cu-Ni deposit area (after Miller and Severson, 2002). Samples were collected from the coarse-grained portion of the Cr-Sill.

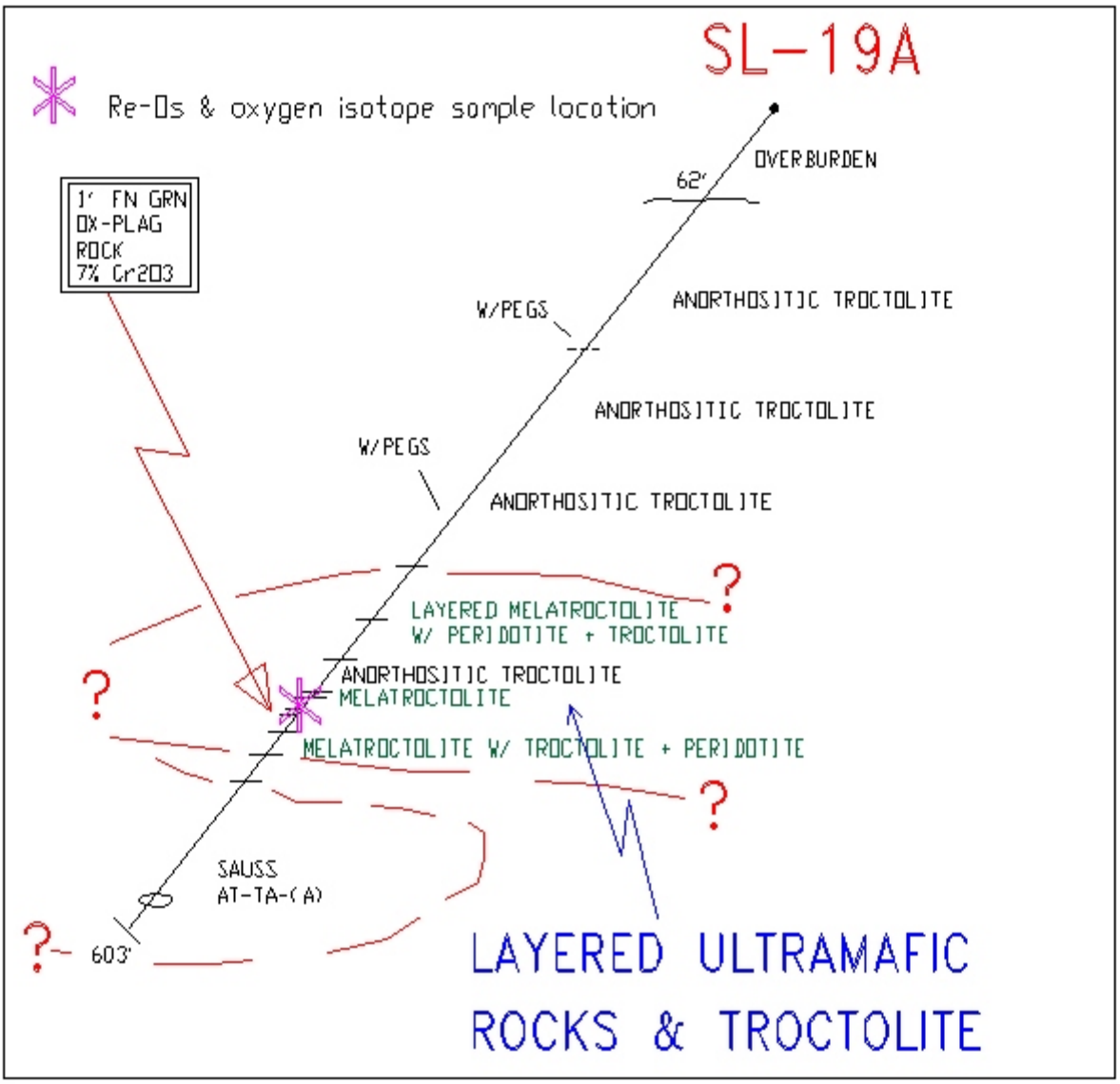

Figure 8. Location of Re-Os and oxygen isotope sample in drill hole SL-19A in the Water Hen OUI area (after Severson, 1995).

WATER HEN OUI DEPOSIT AREA- PARTRIDGE RIVER INTRUSION

Severson (1995) describes a semi-massive iron oxide horizon well north of the Water Hen OUI (oxide ultramafic intrusion) in drill hole SL-19A (Figs. 1, 8). Severson (1995) indicates that this iron oxide horizon is texturally similar to other iron oxide horizons in Du-9 and Du-15 at Birch Lake (sample nos. 9-12 and 13-17, respectively, Table 1) and in FHL-2 at Fish Lake (sample nos. 18-20, Table 1). The sample contains 801 ppb Pt+Pd and 46,000 ppm Cr (sample no.18, Table 1). Microprobe data (Severson, 1995) indicates that the Cr-spinels are chromium titanomagnetites (14.2-19.6 wt. % Cr_2O_3; 11.4-16.6 wt. % TiO_2) and chromium pleonaste (17.4-31.1 wt. % Cr_2O_3; 30.8-40.7 wt. % Al_2O_3). Severson (1995) indicates that this iron oxide horizon is between two ultramafic layers, and is unrelated to the Water Hen OUI.

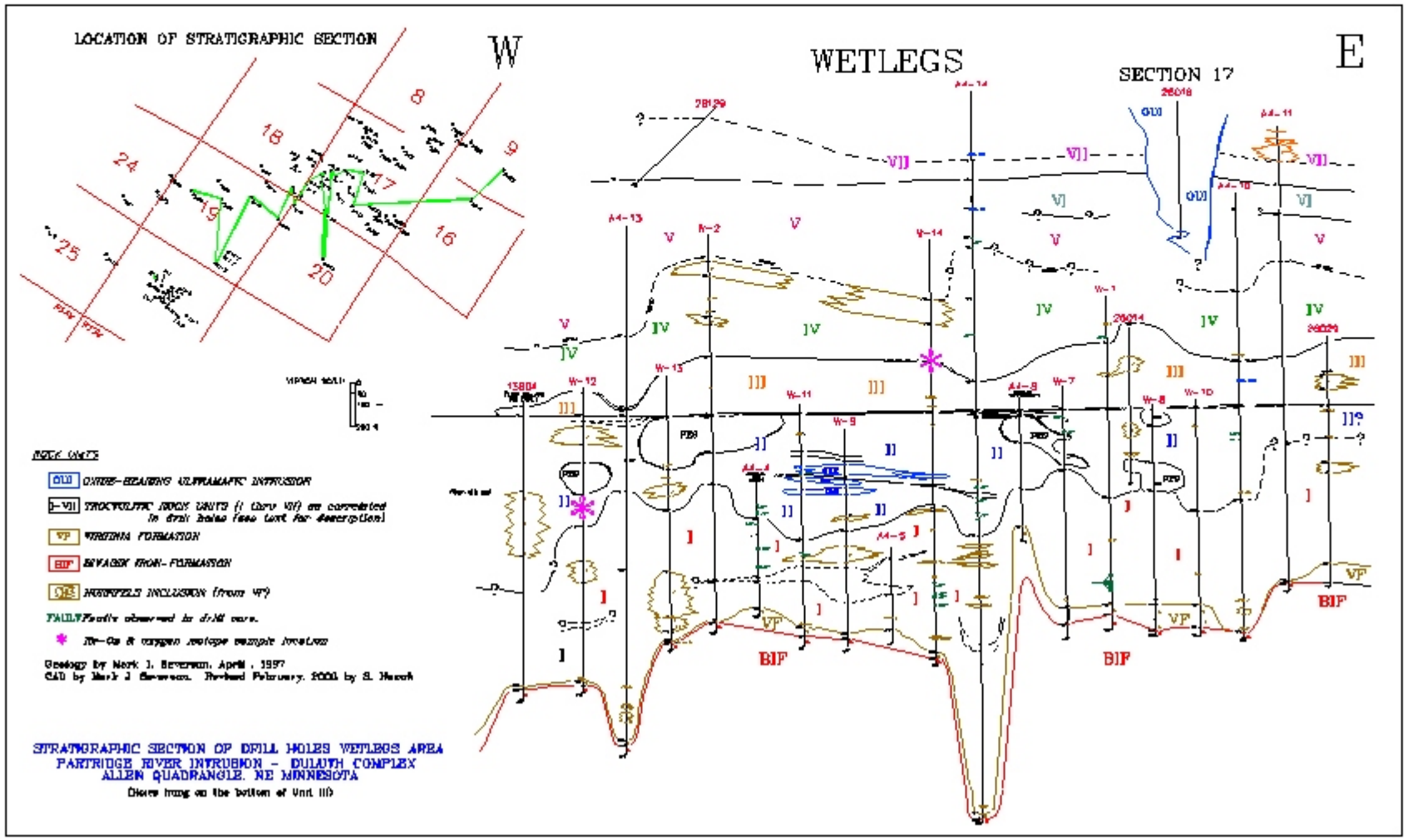

Figure 9. Location of Re-Os and oxygen isotope samples in the Wetlegs area. Note the different locations in the different units (after Severson and Hauck, 1997).

WETLEGS DEPOSIT - PARTRIDGE RIVER INTRUSION

Two different samples come from the Wetlegs deposit area, i.e., from Unit II/WLS (Wetlegs Layered Series; Fig. 9; Table 1, sample nos. 22), and from the top of Unit III at the contact with Unit IV (Table no. 1, sample no. 23). The latter sample (W-14) is one of several oxide-rich zones at the top of Unit III that is intersected in six additional Wetlegs drill holes (see Table 1 in Severson and Hauck, 1997). The oxide zone varies in thickness, but is mostly unassayed for PGEs and Cr (3 out of 7 drill holes have been assayed). This zone also displays "2 in 1" texture, i.e., fine-grained, round to subround oxide grains in poikilitic plagioclase, which is medium- to coarse-grained (Severson and Hauck, 1997). This zone is unrecognized outside of the Wetlegs area (Severson and Hauck, 1997). The W-12 sample (Table 1, no. 23) occurs within the WLS, and it contains 1.20 wt. % Cr_2O_3. This zone is not recognized in other drill cores in the WLS. More recently, a 2-3 cm zone with 15% oxides (25,745 ppm Cr) and 2,460 ppb Pd=Pt are report at the top of Uni II in drill hole W-1 by Severson and Hauck (in prep.). This oxide zone is not included in this report.

FISH LAKE OCCURRENCE - LAYERED SERIES AT DULUTH

Sassani (1992) conducted a detailed petrochemical investigation of drill holes FHL-1 and FHL-2. Severson (1995) reinterpreted the geology of these drill holes and assigned them to the basal zone of the Layered Series of Duluth, instead of the Partridge River intrusion (Sassani, 1992). According to Severson (1992), drill hole FHL-2 had a subhorizontal ultramafic layer from 252 ft. to 319 ft. (Fig. 10). At the bottom of this layer was a six foot zone of semi-massive oxide with "2 in 1" texture, i.e., iron oxides in poikilitic plagioclase. Sample nos. 18-19 in Table 1 were collected from this semi-massive oxide zone (319.4-325.5 ft.). This iron oxide zone had high Cr (27,000 ppm and 48,000 ppm, respectively). Beneath this iron oxide zone is an anomalous PGE zone in an altered troctolite (Table 1, no. 20) with 572 ppm Pt+Pd and 2,100 Cr. The iron oxides consisted of chromium titanomagnetite and chromium pleonaste (Sassani, 1992).

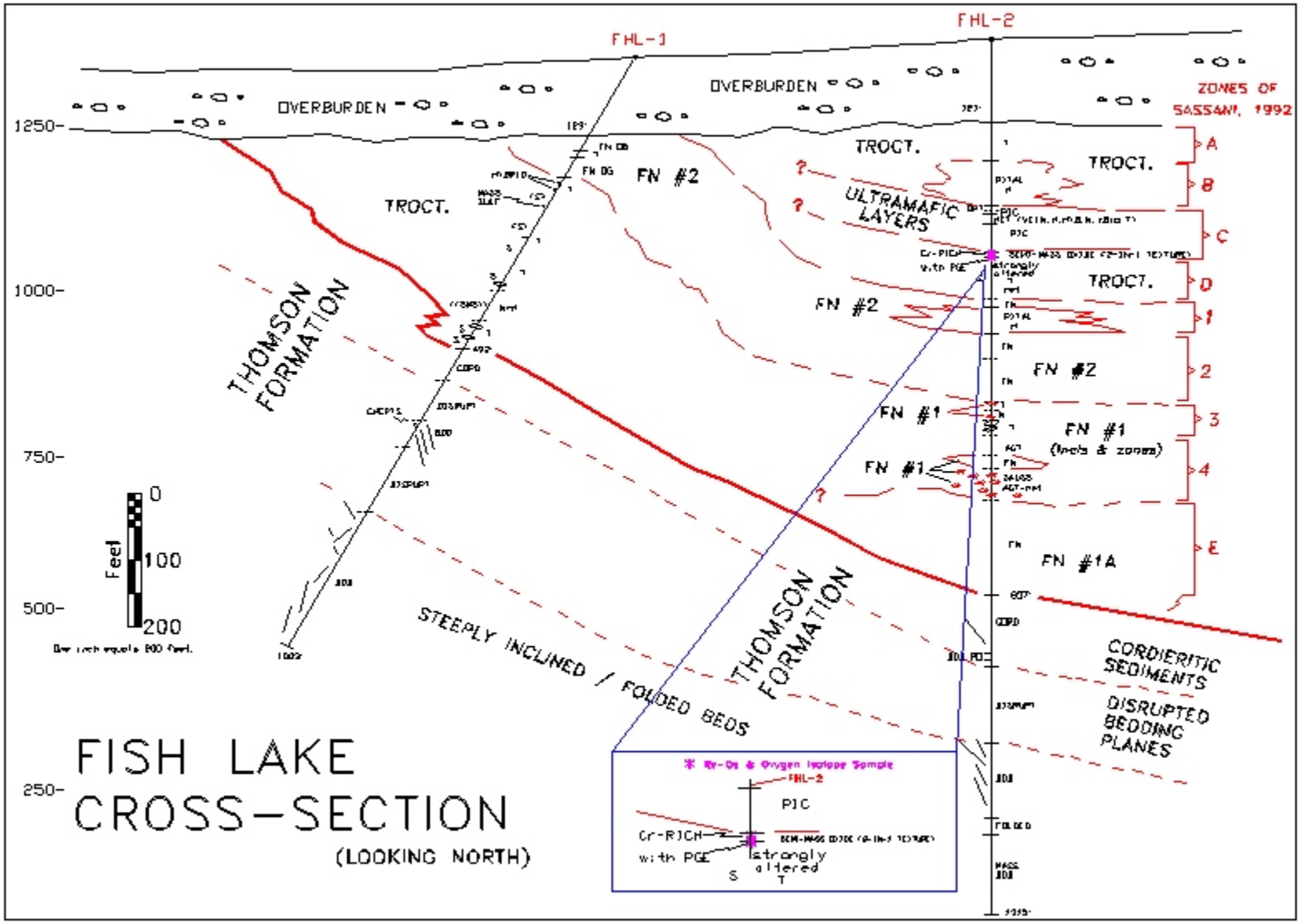

Figure 10. Location of Re-Os and oxygen isotope samples in drill hole FHL-2 in the Layered Series of Duluth (after Severson, 1995).

Re-Os BACKGROUND INFORMATION

Osmium is a PGE, and therefore, it is particularly useful when studying PGE deposits or prospects. Re-Os isotopic systematics are frequently applied to rock units of indeterminate source because of the osmium isotopic contrast between the crust and the mantle; Re and Os are concentrated in the mantle, while rhenium can be found in small concentrations in the crust. Osmium is an incompatible element and will remain concentrated in mantle-derived magma. Rhenium is a compatible element, meaning that it readily goes into sulfide and oxide mineral phases in a melt, and into the crust. Once in the crust, ^{188}Re will decay into ^{187}Os. The Os isotopic values (radiogenic versus non-radiogenic) give the γOs value, or the percentage of deviation from chondritic standard ($\gamma Os = 0$). Sulfide minerals act as a sink for both Re and Os, but oxides can have relatively high (ppb range) concentrations of each (Faure, 1986).

METHOD

Pulp and rock samples were sent to Paula Shafer at Indiana University for preparation prior to chemical analyses. Both Re-Os and oxygen isotope analyses require fine-grained sample powders to be used, so the samples were powdered using a ball mill with an agate vessel. The powders then underwent heavy liquid separation to concentrate the oxide fraction. Magnetic separation was not used due to the inefficiencies of attempting to separate a fine powder using this method. The only samples that were not separated were the three samples from the Cr sills, as requested by Steve Hauck.

Rhenium-osmium analyses were carried out at University of Maryland-College Park, using the standard isotopic dilution technique described in Shirey and Walker (1995). This procedure involves the baking of samples for at least 14 hours at 300°C in concentrated aqua regia, with subsequent chemical separation steps for rhenium and osmium. Samples were measured for Os using NTIMS and Nu-Plasma ICP-MS for Re. Initial Re/Os and γOs were calculated using the known age of the Complex, 1.1 billion years.

Oxygen isotope extraction was carried out at Indiana University, using standard procedures. Approximately 8 mg aliquots of each of the oxide concentrates were weighed and dried overnight in a vacuum oven. They were then placed in a standard BrF_5 isotope extraction vacuum line where they were allowed to bake overnight at ~ 600°C. The O_2 gas produced in the reaction chamber was then collected as CO_2. The gas was measured on a Finnigan MAT mass spectrometer to find the $\delta^{18}O$ of each sample, and then standardized to VSMOW.

RESULTS

Table 2 contains all data referred to in this section. Cells containing asterisks in the table denote samples that were not large enough for Re-Os analysis, cells containing #s denote samples that have not been returned from Maryland for $\delta^{18}O$ analysis. Figure 11 shows the abundance of Re and Os in each sample. Figure 12 shows data in relation to the 1.1 GA chondritic isochron, calculated using the method in Walker, et al. (1994). Figure 13 shows the random distribution of γOs for the samples, based on drill core location.

	Rock Type	Wt. (gm)	Re (ppb)	Os (ppb)	Re/Os	$^{187}Os/^{188}Os$	$^{187}Re/^{188}Os$	Initial (1.1Ga) $^{187}Os/^{188}Os$	gamma Os	$\delta^{18}O$
B1-131, 2060.3	Cr sill									#
B1-211, 2060.3-2063	Cr sill	***								6.5900
B1-301,1723-1725	Cr sill	1.7139	0.2276	3.0858	0.0737	0.1370	0.3638	0.1303	8.9794	7.1520
BL 90-1,2372.5	U3-Mass. Oxide	1.8140	1.3345	19.3402	0.0690	0.4387	0.3460	0.4323	261.526	2.3470
BL 90-1,2383.0	U3-Mass. Oxide	1.7732	0.9264	5.7192	0.1620	0.4430	0.8126	0.4280	257.936	3.0260
BL 90-1, 2393.2	U3-MT-ORT	1.6499	1.5023	18.7338	0.0802	0.4331	0.4018	0.4256	255.986	
BL 95-1, 1432.7	U3-ORT w/ Oxide	1.8366	0.8855	7.2574	0.1220	0.3701	0.6065	0.3589	200.170	8.2730
BL 95-1w, 1339.8	PEG-Mass. Oxide	1.7994	2.9650	24.2000	0.1225	0.3627	0.6086	0.3515	193.958	
Du 15, 2354-2359	U3-Mass. Oxide	1.7346	1.9271	7.3768	0.2612	0.3941	1.3026	0.3700	209.419	6.9610
Du 15, 2411,2412	U3-SM-Mass. Oxide	1.7249	1.0159	48.2675	0.0210	0.3189	0.1040	0.3169	165.066	5.7880
Du 15, 2413-2414	U3-Mass. Oxide	1.8440	1.1272	42.2201	0.0267	0.3269	0.1320	0.3245	171.385	#
Du 15, 2419-2420	U3-Oxide MT	1.7277	1.3743	4.8221	0.2850	0.3832	1.4191	0.3569	198.522	10.2490
Du 15, 2434-2438	U3-MT + SM Oxide	1.7597	3.6161	27.4790	0.1316	0.3454	0.6531	0.3334	178.812	8.5170
Du 9, 2591.3-2592.1	PEG-PEG AT	1.7785	1.2619	26.7681	0.0471	0.3372	0.2343	0.3328	178.366	#
Du 9, 2593.7-2596.7	PEG-Oxide T/AT	***								9.8240
Du 9, 2634.1	U3-SM Oxide	1.7304	0.6549	0.0916	7.1534	1.4057	40.0635	0.6647	455.953	5.0960
Du 9W,2631b	U3-SM Oxide/Ox. MT	1.7386	1.0052	0.7254	1.3857	0.7694	7.2348	0.6356	431.604	5.2850
FHL-2, 319.4-324.3	Semi-Mass. Oxide	1.6519	0.9931	17.5259	0.0567	0.1353	0.2748	0.1302	8.8808	7.4540
FHL-2, 324.3-325.4	Semi-Mass. Oxide	1.7963	1.1586	31.9408	0.0363	0.1366	0.1757	0.1333	11.5250	7.2100
FHL-2, 325.4-327	Altered Chlorite Zone	***								8.1140
SL19A, 446-446.7	Plag.-Ox.-Ol. Rock	1.8470	3.6817	15.3266	0.2402	0.2065	1.1694	0.1849	54.6215	6.4480
W12, 561.3	Unit II-MT	1.8869	4.1157	2.6768	1.5375	0.2831	7.5603	0.1433	19.8102	#
W-14, 585.5-586.0	Unit III - TA?									#

Table 2. List of samples analyzed for Re-Os and $\delta^{18}O$ with results. Samples that have not been returned from University of Maryland for $\delta^{18}O$ are denoted by #. Samples that were too small for Re-Os are denoted by *** See Appendix 2 for Excel file (on CD).

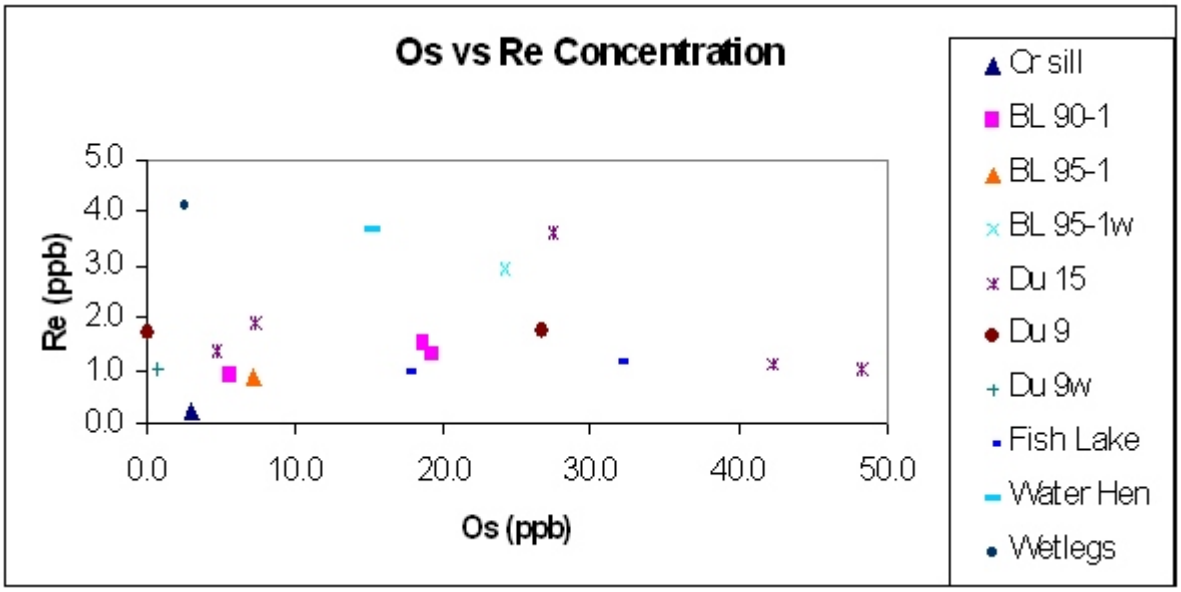

Figure 11.. Os concentration vs. Re concentration for contact margin samples. Specific values for each data point can be found in Table 2.

Re-Os

All Re-Os values were normalized to chondrite prior to data analysis. Re-Os ratios ranged from 0.02 to 7.2 for the samples analyzed. Initial $^{187}Os/^{188}Os$ values were between 0.13 and 0.66. Overall, γOs ranged from 8.9 to 456. The samples from Fish Lake, Waterhen, Wetlegs, and Cr sills all had much lower γOs values (8.9 – 54.6) than the samples from the area close to Birch Lake (165 – 456).

$\delta^{18}O$

Oxygen values have been standardized to VSMOW. The $\delta^{18}O$ for these values range from 2.3 per mil to 10.2 per mil with no break in values between sample locations as was exhibited in the Re-Os values (Table 2).

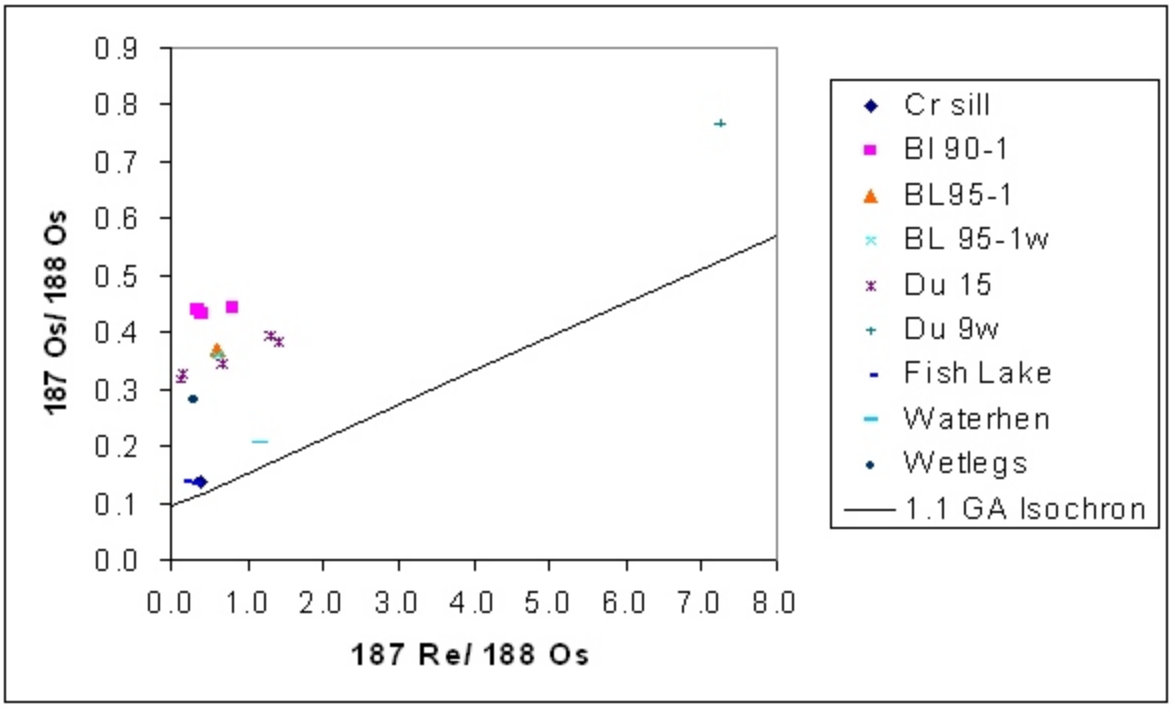

Figure 12. $^{187}Re/^{188}Os$ vs. $^{187}Os/^{188}Os$ diagram including the 1.1 Ga isochron. One outlying point has been removed for scaling purposes. All data are above the chondritic isochron, indicating crustal contamination. Note the grouping of the Birch Lake samples from the South Kawishiwi intrusion versus the other samples from the Partridge River intrusion.

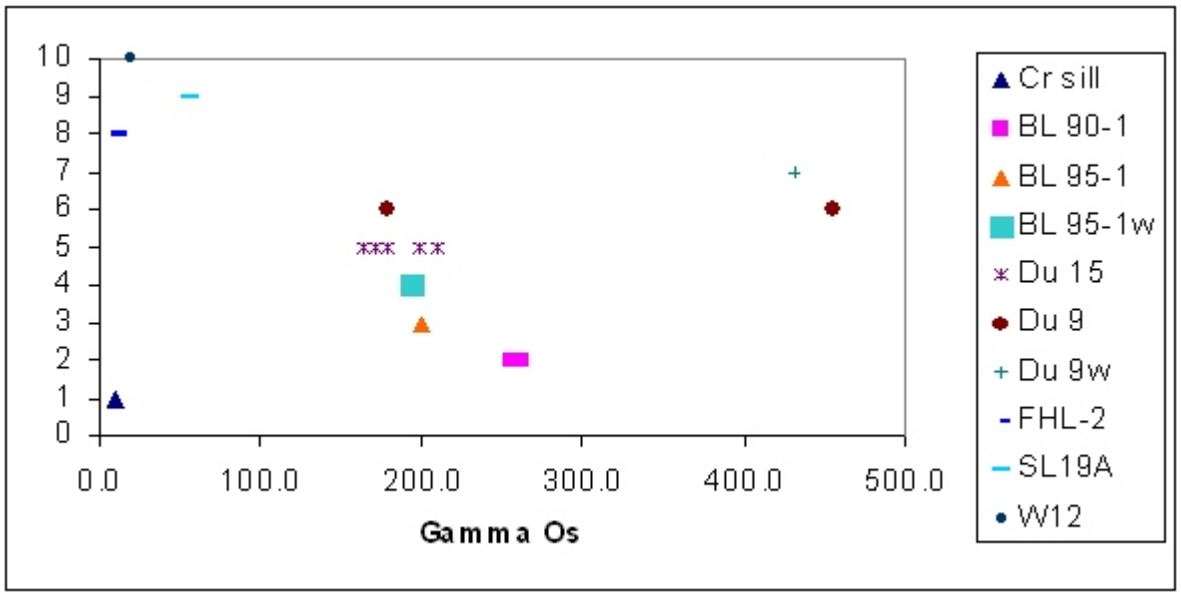

Figure 13. γOs by location, chondritic γOs equals 0. All γOs from the Birch Lake area indicated high levels of mixing. Non-Birch Lake samples indicate much lower mixing levels. The Y-axis graphically represents the various samples in the legend, e.g., 1-Cr sill, 2-BL 90-1, etc. Partridge River intrusion samples are numbers 1, 9, 10, the Layered Series at Duluth is number 8, and the remaining samples are from the Birch Lake area in the South Kawishiwi intrusion.

DISCUSSION

The Re-Os values found for all of these samples indicate crustal contamination. High γOs values (165-456) indicate a high degree of contamination from a crustal source. The assumption that all of the oxides in the Birch Lake area result from a high level of assimilation of the Biwabik Iron Formation by the South Kawishiwi intrusion is supported by the highly contaminated γOs values found in this area. Fish Lake, Wetlegs, Waterhen, and the Cr-sills experienced less intense contamination, therefore having lower, though still contaminated, γOs values. Figure 13 shows the wide range of γOs values, particularly the grouping of the non-Birch Lake sample values at γOs < 50. This major difference in γOs between the two groups may indicate one of two things. One hypothesis is that the South Kawishiwi intrusion at Birch Lake experienced much more mixing with country rock during emplacement than the other samples; thus, samples from that area have much higher γOs. Another hypothesis is that the same level of mixing occurred throughout the South Kawishiwi, but a greater abundance of radiogenic Os was taken up at Birch Lake during emplacement than in the other locations. This would be a by-product of the abundance of Re and Os in the country rock that was assimilated at Birch Lake, specifically the Biwabik Iron Formation. Additional Re-Os data for the Biwabik Iron Formation is needed to clearly delineate which of the previously stated hypotheses is correct, and to establish the exact level of mixing in this area. Preliminary mixing estimates, based on this limited number of samples, indicate 3-5% mixing of Duluth Complex magma with country rocks. This estimate will be refined in an upcoming Ph. D. dissertation by Paula Shafer, with additional samples of unmetamorphosed Biwabik Iron Fm. samples. Previous work (Ripley et al., 1999) in areas south of Birch Lake also concluded that 3-5% was a viable level of mixing.

The $\delta^{18}O$ values for the oxides show a more complex scenario. The data show three possible divisions of $\delta^{18}O$ values: 1) crustal values of ~7 per mil up to ~10 per mil; 2) mantle-like values of ~4 per mil to ~6.5 per mil; and 3) oddly lower values of ~2 per mil to ~3 per mil. This might be explained by the initial $\delta^{18}O$ values of the incorporated Biwabik oxides (group 1 above) being over-printed by a later, lower $\delta^{18}O$, alteration fluid, thereby lowering the $\delta^{18}O$ values to mantle-like values (group 2). Continued exposure to this type of fluid may be responsible for the anomalously low values in group 3. This theory is supported by petrographic evidence of high levels of alteration in some of the drill core locations.

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APPENDIX 1

Drill Hole Locations
(On CD in back – *Appendix1.xls*)

Column Headings For Drill Hole Location File
(From Patelke, 2003)

HEADER Table-Short description
This table contains the drill hole location information, length, dip angle, azimuth, deposit name, and other information that can be applied to the drill hole in its entirety.

Column Order in Data Tables
Note that the column order may not be the same in all similar tables, nor be in the order given in these descriptions. Also note that when the GCDBDC.MDB file is loaded as a blank project into Gemcom, the column display order will be sorted alphabetically, left to right.

Table 3. Format of Header Table (see Appendix 1 in Patelke (2003) for expanded explanation.)

DDH: drill hole number
EASTSP27: easting NAD27 state plane feet
NORTHSP27: northing NAD27 state plane feet
COLLAR-EL: collar elevation in feet above sea level
TOTALDEPTH: total depth in feet
DIP: collar dip, measured from horizontal, 0˚ = horizontal, -90˚ = vertical
AZIMUTH: collar azimuth relative to true north
EASTSP83: easting NAD83 state plane feet
NORTHSP83: northing NAD83 state plane feet
EASTUTM27 easting NAD27 UTM meters
NORTHUTM27: northing NAD27 UTM meters
EASTUTM83 easting NAD83 UTM meters
NORTHUTM83: northing NAD83 UTM meters
COL-EL-MET: collar elevation in meters above sea level
TOTDEPMETR: total depth in meters
DEPOSIT: deposit area
INTRUSION: which intrusion drill hole is located in
QUAD: USGS 7.5 minute quadrangle
TOWNSHIP: Public Land Survey Township
RANGE: Public Land Survey Range
SECTION: Public Land Survey Section

FORTY: partial list of forty acre subdivision
COUNTY: St. Louis, Lake, or Cook County
GEOLOGIST: geologist responsible for the logging or company that supplied data
DATE-DRILL: Date drilling finished
GRIDEAST: Grid east on original company grid
GRIDNORTH: Grid north on original company grid
GRIDCOMP: Company responsible for original grid
OVBTHICK: overburden thickness
FWDEPTH: depth to footwall (i.e., basal contact)
LESSEE: best available information for which company drilled this hole
VERT-ANG: vertical or angled at collar
INITIAL?: initial hole or wedge
SUR-UNDG: hole drilled from surface or underground drift
NRRI-XSECT: NRRI cross-section which shows this drill hole
COMP-XSECT: Company cross-section on which this drill hole should plot-listed only for Dunka Road (NorthMet) and Babbitt/Serpentine (Mesaba). These cross-sections are not necessarily available.
BEST-REF: best first reference for report about area containing drill hole, not intended to be a definitive listing
HEAD-COMM: Comments related to data in the header file for this drill hole
SURV-COMM: Comments related to data in the survey file for this drill hole
LITH-COMM: Comments related to data in the lithology file for this drill hole
ASSAY-COMM: Comments related to data in the assay file for this drill hole
SOURCEFILE: NRRI record keeping entry
XLSFILE: The lithology and assay tables needed to be split to stay within the 64,000 line limit of Microsoft Excel, this shows which file set this drill hole is in, either “EAST” or “WEST”, *.XLS and *.CSV. This data is carried in all interval tables, even though not all files are split

APPENDIX 2

Re-Os and Oxygen Isotope Data
(on CD in Back – *Appendix 2.xls)*