GEOLOGY AND MINERALIZATION OF A CYCLIC LAYERED SERIES, WATER HEN INTRUSION, ST. LOUIS COUNTY, MINNESOTA

by

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March, 1990

Technical Report
NRRI\GMIN-TR-89-17

Funded by the Greater Minnesota Corporation

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ABSTRACT

The Water Hen intrusion is an oxide-bearing (ilmenite + magnetite) ultramafic intrusion (OUI) that is emplaced along a pre-basement fault into the troctolitic series rocks of the Duluth Complex. The intrusion consists of medium-grained dunite and peridotite and local pegmatitic pyroxenite approximately 1,600 ft. x 500 ft. x 700 ft. in size. Oxide (>90% ilmenite) composes from 5-50% of the various lithologies. Sulfides are minor, about 2-5%, and are predominantly pyrrhotite with minor cubanite, chalcopyrite and pentlandite. Concentrations of 5-80% graphite also occur within the intrusion.

Surrounding the Water Hen intrusion is a zone of mixed lithologies (Mixed Zone) consisting of the host rock troctolites, apophyses of OUI and local inclusions of footwall rocks. The Mixed Zone (M) is dominated by >60% troctolitic rocks with OUI composing the remainder. The OUI apophyses vary from 1-50 ft. thick and have sharp contacts with the country rock.

The troctolitic host rocks for the Water Hen intrusion consist of medium- to coarse-grained troctolite to anorthositic troctolite (TA unit) and a troctolitic cyclically layered series (TL unit). The cyclically layered series is similar to troctolitic layered rocks at Bardon Peak. The individual cyclic layers are 6 in. to 10 ft. in thickness and the entire unit is over 300 ft. thick. The An content decreases from An_{80} at the bottom of the unit to An_{60} near the top of the unit. The individual cyclic layers are composed of ilmenite-dunite at the base and grade upward to anorthositic troctolite. The bottom contacts are sharp and each successive layer within the individual unit is identified by the occurrence of biotite or clinopyroxene. In the bottom olivine-rich layer, the oxides ($\leq$5%) are ilmenite >> magnetite. The sulfides in this same layer (3-5%) are coarse-grained with cubanite > chalcopyrite > pentlandite >> pyrrhotite. In the more feldspathic layers, the sulfides (1-3%) are fine-grained with chalcopyrite >> pentlandite = cubanite + pyrrhotite. The oxides (1-

5%) are also fine-grained with ilmenite >> magnetite.

The footwall rocks in the Water Hen area consist of very fine-grained metamorphosed Virginia Formation and fine-grained hornfelsed basalt and/or troctolite. There are >100 ft. of basalt or chilled margin rocks within the footwall. This mafic hornfels commonly occurs between the Virginia Formation and the TA unit. Orthopyroxenite dikes and dikelets also occur in the mafic hornfels. These dikes contain anomalous PGEs and secondary sulfide mineralization.

The copper-nickel sulfides are primary igneous sulfides associated with the troctolitic rocks. Violarite, pyrite and secondary magnetite in cross-cutting veinlets and other secondary sulfides indicate that the primary sulfides were altered and remobilized by a later event. Cu:Ni ratios have a bimodal distribution that is not followed by the PGEs. However, Cu, Ni, Ag, Au, Pt, Pd are all highly correlated with each other. This high inter-element correlation suggests that the late-stage (secondary) remobilization locally redistributed and reconcentrated these elements.

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INTRODUCTION

The Water Hen intrusion is an oxide-bearing ultramafic intrusion (OUI) that is emplaced into basal troctolitic series rocks of the Duluth Complex. The intrusion is located along the western contact of the Duluth Complex approximately 15 km south of Hoyt Lakes, Minnesota in Section 28, T. 57 N., R. 14 W., in St. Louis County (Fig. 1).

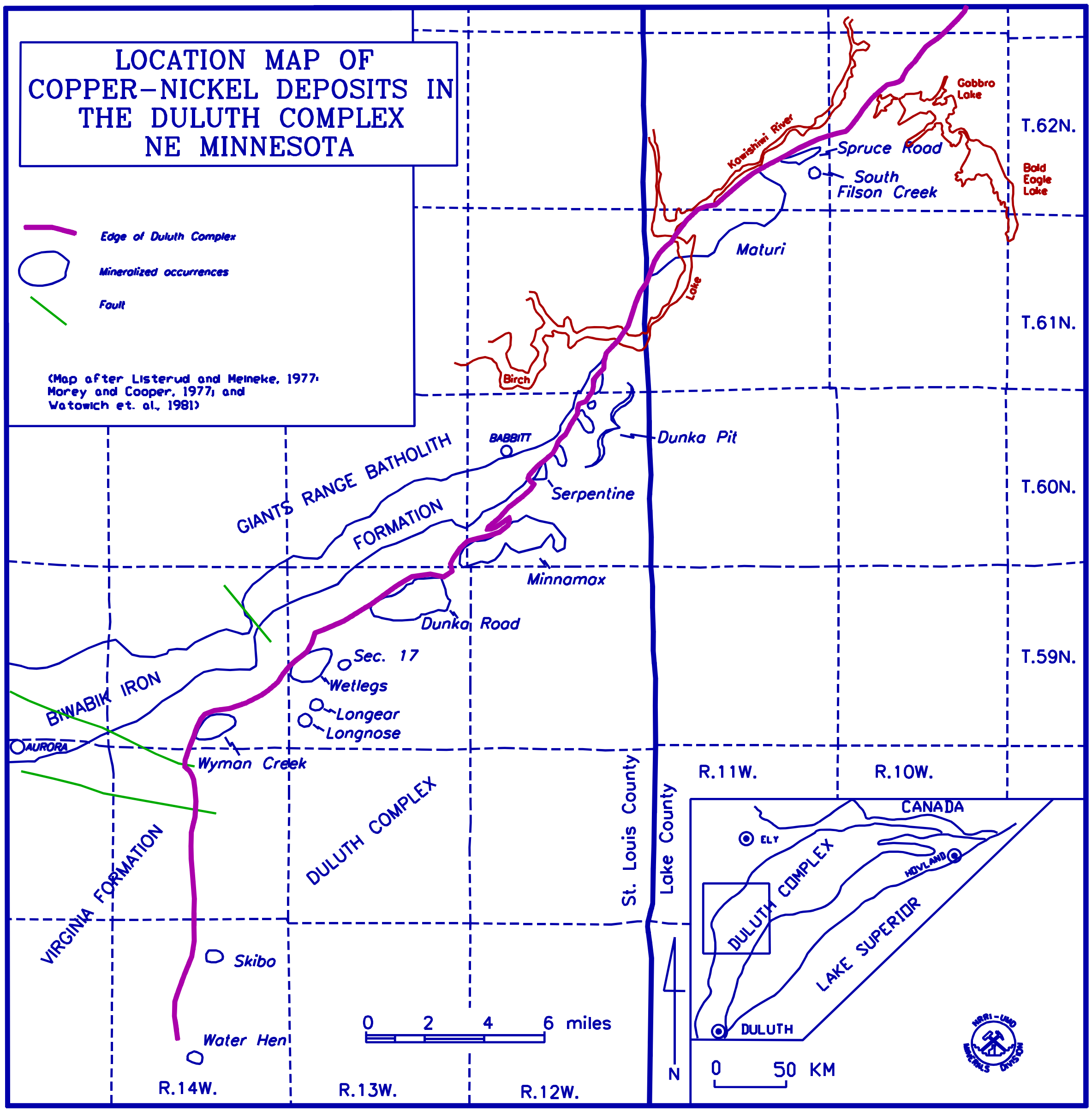


Figure 1. Location map of copper-nickel deposits in the Duluth Complex.

The Water Hen intrusion was first explored by American Shield Company in the late 1950s. Drilling (Plate 1), electromagnetic and induced polarity surveys were conducted, and at that time, the intrusion was considered to be a potential titanium deposit. Later, samples were collected to define copper-nickel potential. Assay data on these programs are presented in Appendix A.

Mainwaring (1975) studied several drill holes in the intrusion and concluded that the Water Hen intrusion was large (about 2 square miles), lens-shaped and consisted of two members: 1) a thick basal dunite (which contains most of the ilmenite); and 2) sulfide-bearing cyclically layered rocks. He noted the relationship between the percent sulfide and the number of hornfels inclusions, mostly Virginia Formation. He documented through sulfur isotopic studies that much of the sulfur was derived from the country rocks (Virginia Fm.) and suggested that the large amounts of graphite present, both in the dunite and in the cyclically layered rocks, were also the result of contamination by country rocks (Mainwaring and Naldrett, 1977).

Ross (1985) compared the modal layering of troctolitic series rocks at Bardon Peak near Duluth to the layering observed at Water Hen. He concluded that the layering was similar in both areas and suggested that the cyclic rocks mapped by Mainwaring (1975), as being part of the Water Hen intrusion, were actually part of the host troctolitic rocks of the Duluth Complex. He compared the Bardon Peak Peridotite, a very small cross-cutting OUI, to some saprolitic parts of the Water Hen and suggested that both intrusions may have been formed through late stage metasomatism of troctolites by magmatic fluids. This is not the accepted genesis by either Mainwaring and Naldrett (1977) or the authors of this report.

Recently, attention has been focussed on the Water Hen intrusion by Morton and Hauck (1987, 1989), Morton (1989) and Dahlberg (1987). These authors documented areas of the Water Hen that were anomalous with respect to platinum group element (PGE) content. The anomalous samples (> 500 ppb combined Pt + Pd) were concentrated not in the ultramafic intrusion (or the basal dunite of Mainwaring, 1975), but rather in late-stage pyroxenite dikes, in gabbroic pegmatites in the troctolites and also in cyclically layered rocks (TL of this report) that may or may not be part of the Water Hen intrusion. These data are compiled in Appendix A.

The purpose of this study was to: 1) relog all the core in the Water Hen; 2) select core for both petrographic and chemical analysis; and 3) to document whether or not the cyclically layered rocks (TL) are part of the Water Hen intrusion or simply part of the basal troctolitic series rocks. The results of the relogging and reinterpretation of the geology and shape of the Water Hen Intrusion and surrounding troctolitic and hornfelsic rocks are shown in Plates 2 through 12.

ACKNOWLEDGEMENTS

This study was funded by a grant from the Greater Minnesota Corporation, whose support is gratefully acknowledged. We would also like to thank the following individuals and organizations for their assistance and cooperation with this study: Mr. William Ulland of the American Shield Company, Duluth, Minnesota and Mr. Gary Parkison of Westmont Mining Inc., Englewood, Colorado, for providing drill core access, geophysical data, and assay data, and the Minerals Division of the Department of Natural Resources for providing access to drill core for examination.

REGIONAL GEOLOGY

The Duluth Complex (Complex) consists of a series of multiple intrusions of dominantly mafic composition associated with the Keweenawan (1.1 Ga) mid-continent rift (Severson, 1988; Severson and Hauck, 1990; Weiblen & Morey, 1980). It is exposed in an arcuate belt from Duluth in the south, north to Ely and east to Hovland (Fig. 1). The Duluth Complex is divided into an older anorthositic series (Davidson, 1972) and a younger troctolitic series (Bonnichsen, 1972) that has intruded below the anorthositic series. Together, these series have intruded along an unconformity between Early to Middle Precambrian rocks (Rove, Virginia and Thomson Formations) and Upper Precambrian Keweenawan basalts (North Shore Volcanic Group; Phinney, 1972). In places, the Duluth Complex is both overlain and underlain by basalts of the North Shore Volcanic Group.

Because of the presence of a thick cover of glacial overburden both north of and in the Water Hen area, most of the information concerning the Duluth Complex comes from drill core that were drilled to the base of the Complex. Consequently, host troctolitic rocks in the area have simply been called undifferentiated troctolite on surface maps of the Duluth Complex (Bonnichsen, 1972). To the north, from the Wyman Creek to Dunka Road area (Fig. 1), the troctolitic series rocks are a part of the Partridge River intrusion (Bonnichsen, 1972; Severson, 1988; Severson and Hauck, 1990), but it is not known if rocks in the Water Hen area are a part of this intrusion.

In the Water Hen area, metamorphosed basalt forms part of the footwall of the Duluth Complex, however, most of the footwall rocks in the southwest portion of the Duluth Complex consist of either the Virginia or Thomson Formations. The Virginia Formation is composed of intercalated graywacke, siltstone and shale with local quartzite, graphitic black slate, and sulfide facies iron-formation (Keighin, *et al*, 1972). Near the basal contact of the Duluth Complex, the Virginia Formation has been metamorphosed in many areas to plagioclase-quartz-biotite-orthopyroxenite-cordierite hornfels (Ripley and Taib, 1988). Mainwaring (1975) documents this same assemblage in hornfels inclusions and some footwall rocks in the Water Hen area.

LOCAL GEOLOGY

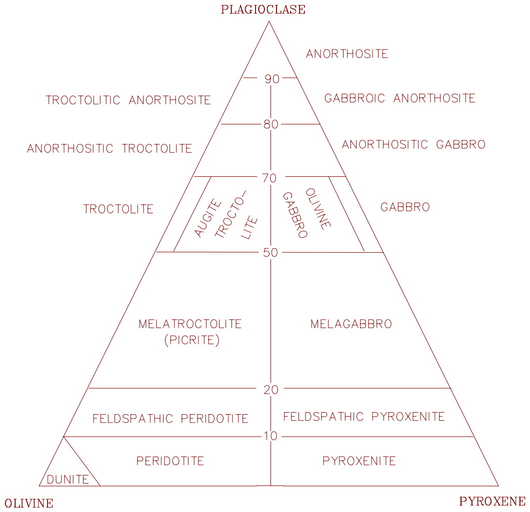


Figure 2. Rock classification chart for mafic and ultramafic rocks in the Duluth Complex. (after Phinney, 1972)

Mainwaring (1975) and Mainwaring and Naldrett (1977) first defined the Water Hen intrusion as a lens-shaped body about 2 miles in diameter that consisted of a basal dunite and an upper zone of cyclically layered units. These units were defined on the basis of core logging and geophysical data. After these studies, more drill core became available and much more work has been done on the troctolitic rocks all over the Complex (Severson, 1988, for a good review) and it became obvious that many more oxide-rich ultramafic intrusions have been found. Examples (Fig. 1) are Longnose (Linscheid, in prep.), Longear (Ulland, pers. comm.), Sec. 17 (Severson and Hauck, 1990) and Skibo (Seitz and Pasteris, 1988). We have reinterpreted the geology of the Water Hen intrusion and redefined the intrusion to be Mainwaring and Naldrett's (1977) basal dunite only, not the dunite plus cyclically layered rocks. We have simplified the geology to include five rock types: oxide-bearing ultramafic intrusion (OUI), troctolitic series rocks (TA), layered troctolitic rocks (TL), Mixed Zone (M) which are composed of troctolites with many cross-cutting apophyses of OUI, and Hornfels (H), usually metamorphosed Virginia Formation but may also include metamorphosed basalt and troctolite. The distribution of these rock units are shown in cross-sections, longitudinal sections and plan maps (Plates 2-12). There is a fair amount of consolidation of units in these diagrams, but we feel that they do show the real nature of the intrusion and surrounding rocks. The rock units are described individually using the rock classification of

Phinney (1972) (Fig. 2). Modal analyses of some samples are presented in Appendix B.

OXIDE-BEARING ULTRAMAFIC INTRUSION (OUI)

The OUI at Water Hen is characterized by oxide-bearing (ilmenite+magnetite) dunite and peridotite with local pyroxenite (pinkish-brown) layers. The overall size of the body is approximately 1600 ft. long x 500 ft. wide x 700 ft. deep (Plates 9-12). The OUI is best observed in drill holes SL-1, 3, 7, 10, 11, 21, 26 and holes CN-1, 7 and 9 (Plate 1). Contacts with the host troctolite and layered troctolite are sharp. No chill margins are recognized. Grain size varies from medium-grained (3-5 mm) to pegmatitic (20-30 mm). Commonly the pyroxenite is pegmatitic whereas dunite and peridotite are medium-grained.

Within any one drill hole or two drill holes close together, zones of peridotite, dunite and pyroxenite are easily distinguished and can be correlated over a short distance (about 200 feet). However, on the scale of the sections in Plates 2-8, it is not possible to correlate specific horizons. Generally, dunite is composed of olivine (70-85%) with varying amounts of either oxide (mostly ilmenite), sulfide, and graphite. In some areas, sulfide-bearing dunite contains up to 30% pyrrhotite in net-textured ore. Feldspathic dunite contains up to 15% plagioclase. Peridotite is composed of 20-45% clinopyroxene, 0-15% plagioclase, 45-70% olivine and various amounts of graphite, ilmenite and magnetite. Pyroxenite contains about 60% clinopyroxene, 5-20% olivine, 5-30% ilmenite and 0-5 % graphite. Biotite is common in all three rock types.

Olivine is generally euhedral and is commonly fresh, except in the top of the body where the subcrop has been weathered to saprolite. Olivine is altered to serpentine in some areas. Clinopyroxene (Cpx) is anhedral in dunite and peridotite but is subhedral to anhedral in the pyroxenite. Cpx has a pinkish color due to the presence of titanium in the lattice. Plagioclase, where present, is usually highly irregular and interstitial. The plagioclase may be sub-poikilitic and enclose clinopyroxene or olivine. Graphite occurs in the OUI rocks (average 5%) and may be due to contamination of the OUI magma by assimilation of carbon from the footwall rocks (Mainwaring, 1975). Local concentrations of graphite up to 80% are scattered throughout this unit.

Oxide composes 5-30% of the lithologies in this unit with local concentrations up to 50%. The oxides are interstitial to the silicate minerals. Ilmenite makes up >90% of the oxides with the remainder being magnetite.

Sulfide occurs as fine- to coarse-grained, interstitial blebs and composes 2-5% of the rock. Pyrrhotite is the dominant sulfide mineral making up 65% of the sulfides. Equal amounts of cubanite, chalcopyrite, and pentlandite make up the remainder. Trace amounts of mackinawite are found within pentlandite crystals. Sphalerite occurs as trace amounts as inclusions in iron and copper sulfide minerals. Locally, pyrite replaces pyrrhotite in microfractures. Thin veins of magnetite (?) are found in a few sulfide grains.

Previous assay data indicate there is an increase in copper concentration near the base of the OUI unit. Typical Cu values range from 0.1-0.3% within the unit. Near the base of the unit, however, the Cu values increase to 0.3-0.5%. This is reflected by an overall increase in sulfide content toward the base of the intrusion.

Locally at the bottom of the OUI, there is a massive sulfide zone (from 50-80% sulfide) with net-textured (with olivine) to massive pyrrhotite (in some cases this extends into both Mixed Zone (M) and cyclically layered rocks (TL)). This sulfide zone shows up in drill cores SL-3 (base of OUI), SL-10 (base of OUI), SL-11 (in TL and M rocks), SL-13 (in TL and M rocks), SL-15 (in M), and SL-26 (base of lowest OUI unit; Plates 2-8). Sulfide grains in this zone are as large as 5 mm, and compose 60-90% of the rock. Pyrrhotite composes 80% of the sulfides and has a feathery texture in polished section. This texture may be due to an intergrowth of hexagonal and monoclinic phases of pyrrhotite, however, most of the pyrrhotite in this zone is not magnetic. Cubanite composes 10% of the sulfides in this zone and equal amounts of chalcopyrite and pentlandite compose the remaining

10%. Little or no alteration of the sulfide grains has been observed. However, thin veins of magnetite cross-cut several sulfide grains suggesting a later remobilization, perhaps during serpentinization of olivine(?).

MIXED ZONE (M)

Areas of mixed rock types occur above and below the main OUI unit and extend beyond the intrusion to the north (Plates 9-12). The Mixed Zone unit is a mixture of:

1) the host troctolitic rocks;
2) apophyses of OUI (similar to rocks of the intrusion);
3) local inclusions of footwall rocks (confined to the Mixed Zone beneath the intrusion).

Within this Mixed Zone, troctolite is generally the dominant rock type; OUI-type material makes up less than 40% of the overall unit. The rest is troctolite, anorthositic troctolite, picrite and inclusions of hornfelsed basalt and Virginia Fm. The OUI apophyses vary from 1 to <50 feet in thickness and cross-cut the troctolites (TA, described below). Observed contacts are sharp on both sides and do not show any gradations to troctolite. The contacts commonly parallel foliation where present in core. The OUI apophyses are coarser-grained than the troctolite and contain pinkish pyroxene similar to pyroxene in the main OUI. On the other hand, the troctolitic rocks are medium-grained and pyroxene is grayish-black. This zone overall probably can be correlated with "contaminated rocks" as described by Mainwaring (1975).

TROCTOLITIC UNIT (TA)

The rocks that host the OUI are medium- to coarse-grained, pale greenish-gray troctolite grading to anorthositic troctolite (Fig. 2). These rocks contain: 1) 60-70%, euhedral to subhedral, white plagioclase laths; 2) 25-40%, euhedral, green olivine, locally altered to serpentine; and 3) trace-1% (locally up to 5%), subhedral, gray clinopyroxene that locally occurs as oikocrysts up to 3 cm in diameter.

Sulfide in this unit is very fine-grained (<0.1 mm) and composes <1% of the rock. The dominant sulfide minerals are pyrrhotite and chalcopyrite, each composing 45% of the sulfide minerals. Pentlandite composes the remaining 10%. Trace amounts of cubanite are present. Oxide minerals compose <1% of the rock; dominantly ilmenite with trace amounts of magnetite.

TROCTOLITIC LAYERED SERIES (TL)

This unit consists of a series of cyclic layers (6 in.-10 ft. thick; total thickness 200-300 ft.) of rock that can be correlated in several of the drill cores, both north and south, as well as above and below the OUI unit (Plates 7 & 8). Individual layers are composed of an olivine-rich base that grade upward to anorthositic troctolite. Contacts with the next layer are usually marked by the occurrence of biotite and clinopyroxene. Relogging of drill holes for this study indicates that these layers are related to the host troctolite and not the OUI unit. Evidence for the association with the TA unit is: 1) the absence of abundant oxides (ilmenite and magnetite do occur, however, in the thin olivine-rich layers); 2) when present, pyroxene is similar in size and color to pyroxene in TA; and 3) thin dikelets of OUI are found throughout the TL unit and these are recognized by their sharp contacts on each side and their overall lack of regularity. In drill cores SL-2, SL-5, SL-6, and SL-17 south of the Main OUI unit (Plates 5, 8 and 9), the TL unit is 200 to 300 feet thick and dips 40 to 50 degrees to the east-southeast. Further south in drill cores SL-4, CN-5, CN-6 and CN-9 (Plates 6, 8 and 9), the TL unit thins to less than 100 feet thick and has a dip of <10 degrees to the east. Within the areas of cross-sections B and C (Plates 3, 4, 7 and 8), the TL unit is not recognized. However, there is a large thickness of M rock here and perhaps so much OUI has intruded into the TA and TL that the cyclic layers cannot be recognized.

In the lower olivine-rich portions of each layer, sulfide grains occur as coarse-grained interstitial blebs and compose 3-5% of the layer. Cubanite is the dominant sulfide mineral composing 45% of the sulfides as laths within chalcopyrite. Chalcopyrite composes 30% of the sulfides, pentlandite 20%, and pyrrhotite makes up the remaining 5%. Local concentrations of pyrrhotite can be as much as 20%.

Oxide within the olivine-rich zones is medium- to coarse-grained (2-4 mm), interstitial to the silicate minerals, and compose up to 5% of the rock, locally up to 20%. Eight-five percent of the oxide is ilmenite; the remaining 15% is magnetite.

In the upper (feldspathic) portions of the layers, fine-grained sulfide blebs compose 1-3% of the rock. Fifty percent of the sulfide is chalcopyrite. Pentlandite (25%) plus equal amounts of cubanite and pyrrhotite form the remaining 50%. Violarite replaces pentlandite, bornite replaces chalcopyrite, and pyrite locally replaces pyrrhotite in microfractures. Fine-grained oxides (<1 mm) constitute 1 - 5% of the rock. Ilmenite makes up >90% of the oxides and occurs interstitial to silicate minerals. The remainder is magnetite, which is both interstitial to silicate minerals and associated with later serpentine veins. Secondary magnetite occurs in cross-cutting veinlets.

HORNFELS UNIT (H)

Footwall rocks of the Duluth Complex in the Water Hen area consist of two types: very fine-grained, gray to blue-gray, metamorphosed Virginia Formation and fine-grained, pinkish, granoblastic hornfelsed basalt and/or troctolite. The former locally contains cordierite, which imparts a blue gray color to the rock, and it may also contain large randomly oriented biotite porphyroblasts (up to 5 mm) that give the rock a pseudo-igneous texture. The latter hornfelses are usually composed of pink orthopyroxene, plagioclase and olivine. Both types occur as inclusions in all types of rock (OUI, TA, TL and M).

Although not depicted on the accompanying plates, the mafic hornfels is generally found between the TA and the hornfelsed Virginia Fm. The mafic hornfels may get as thick as 100 feet. Drill hole SL-16 was drilled easterly into the hornfels and only intersects gabbroic or mafic hornfels (Plates 1 and 2). In some holes, wispy plagioclase rich zones have been interpreted to be vesicles. These rocks may be recrystallized basalt from the North Shore Volcanic Group or part of the chilled (and recrystallized) contact of the Duluth Complex.

Orthopyroxenite dikes and dikelets identified in the mafic hornfels (SL-11, 13 and 1) have anomalously high PGE values (Morton and Hauck, 1987). The dikelets in core almost look like magmatic segregations or "sweat-outs" from the hornfels. The true relationship of the dikes and their unusual silicate and sulfide composition to the Water Hen intrusion and associated country rocks is not known or understood at this time. Secondary sulfide mineralization in the dikes (identified by Morton and Hauck, 1987) includes bornite, maucherite, native bismuth, nickeline, parkerite, native silver, and tetradymite. This mineralization is quite different from the primary sulfide mineralization (pyrrhotite, cubanite, chalcopyrite and pentlandite) observed in other parts of the Water Hen area.

STRUCTURE

On longitudinal sections F and G (Plates 7 and 8) at the position where cross-section line C (Plate 4) crosses, there is a rise in the basement topography. On additional plan maps (Plates 9-12), there is considerable offset in the hornfels/troctolite contact at approximately 3000 N. This offset may be a pre-basement fault that acted as a feeder for the OUI itself. Certainly in Plate 8, section G, the Mixed Zone increases in this area too. This Mixed Zone is made up of TA, OUI and hornfels inclusions. The fault appears to strike approximately east-west and from the surface to minus 600 feet, the fault seems to be vertical. However, the exact orientation of the fault is difficult to determine from the spacing of the drill holes.

GEOCHEMISTRY

Sampling of rocks for geochemical analysis was primarily confined to the cyclic layered unit (TL). In total, 110 samples were sent in for assay (Cu, Ni, Pt, Pd, Au, and Ag) to Bondar-Clegg in Vancouver, B.C.; these samples include 14 samples from TA, 7 from M, 7 from OUI and 82 from TL (Appendix C). Of the 82 from TL, nine samples were selected for whole and trace element analysis and these were also analyzed by Bondar Clegg (Tables 1a and 1b, Appendix C). Four additional samples with elevated values of Pt and Pd were analyzed by neutron activation to determine the amounts and distribution for all PGE in the deposit (Table 5).

Table 1a. Whole rock analyses of rocks from DDH SL-2, cyclically layered series (TL)

Sample ID	220-221	221-222	222-222.5	379-379.5	379.5-380	380-380.5	605-607.5	607.5-608	608-609
Rock Unit	TL	TL	OUI (?)	TL	TL	TL	TL	TL	TL
SiO^2	45.40	43.00	20.10	40.90	28.70	23.20	40.30	36.80	26.20
TiO_2	0.82	0.47	21.00	1.78	13.50	15.10	2.46	4.50	15.00
Al_2O_3	21.80	21.70	1.14	19.00	5.62	4.64	19.00	13.70	2.91
Cr2O3	0.06	0.02	0.13	0.03	0.14	0.14	0.02	0.05	0.09
CaO	10.00	10.10	1.24	9.50	6.42	3.14	9.47	6.90	1.84
Fe_2O_3	1.65	2.53	11.83	4.18	5.60	3.72	1.75	3.70	6.95
FeO	7.60	9.15	27.15	11.00	21.60	24.55	13.90	18.90	29.65
MnO	0.11	0.14	0.36	0.16	0.29	0.28	0.17	0.21	0.33
MgO	7.12	8.91	13.20	9.46	11.30	10.80	9.66	11.20	15.20
Na_2O	2.48	1.79	0.10	1.52	0.50	0.41	1.05	0.72	0.12
K_2O	0.23	0.19	0.07	0.15	0.13	0.31	0.12	0.12	0.10
P_2O_5	0.10	0.05	0.22	0.10	0.13	0.11	0.03	0.33	0.13
S	0.08	0.06	1.11	0.50	1.12	1.63	0.21	0.43	0.49
CO_2	0.24	0.20	0.44	0.22	0.43	0.45	0.20	0.19	0.28
H2O+	0.87	0.47	0.13	0.78	2.44	10.76	0.02	0.05	1.48
H2O-	0.34	0.39	0.45	0.45	0.25	0.23	0.20	0.21	0.22
Cl	<0.01	0.01	0.03	<0.01	0.02	0.02	<0.01	<0.01	0.01
Total	98.91	99.18	98.69	99.73	98.19	99.48	98.56	98.00	101.00
LOI	1.75	1.35	1.25	1.55	3.30	11.60	0.30	<0.05	<0.05
wt. % Cu	0.02	0.03	0.40	0.23	0.61	0.72	0.04	0.21	0.08
Au	5	4	20	17	130	119	9	34	8
Pt	<15	20	20	<15	120	150	20	50	15
Pd	5	4	10	38	350	370	6	85	30

Table 1b. Trace element analyses from DDH SL-2, cyclically layered series (TL)

Sample ID	220-221	221-222	222-222.5	379-379.5	379.5-380	380-380.5	605-607.5	607.5-608	608-609
Rock Unit	TL	TL	OUI (?)	TL	TL	TL	TL	TL	TL
Ag	<0.2	<0.2	2	0.8	1.8	2.6	0.2	0.6	<0.2
As	88	115	133	145	94	106	142	72	108
Ba	128	106	93	106	78	93	87	114	82
Bi	23	23	<2	21	<2	<2	20	11	<2
Co	63	64	173	108	180	195	75	148	191
Cu	194	280	3957	2334	6056	7181	436	2084	837
Ga	29	34	<2	33	10	<2	31	13	<2
Li	11	10	8	11	14	8	14	19	16
Mo	2	3	8	3	<1	3	2	5	9
Nb	10	11	<1	10	<1	<1	6	7	<1
Ni	313	253	1095	624	1564	1907	323	623	696
Rb	129	80	<20	<20	<20	191	23	<20	115
Sb	11	12	<5	29	10	<5	21	<5	<5
Sc	4	4	35	7	53	35	8	22	37
Sn	<20	<20	<20	<20	<20	<20	<20	29	<20
Sr	329	296	21	247	88	68	246	231	43
Ta	10	10	<10	20	<10	<10	<10	<10	38
Te	21	30	<10	37	<10	<10	28	45	<10
V	104	57	1352	171	1208	1165	190	467	1112
Y	2	2	4	2	9	6	2	9	4
Zn	76	87	201	107	159	160	114	185	230
Zr	93	90	143	88	111	121	93	120	136

WHOLE ROCK ANALYSIS

Whole rock analysis was done on samples from three layers from unit TL in drill hole SL-2 (Table 1a). A layer was picked from the top, middle, and bottom of the unit, then each layer was split into three separate samples giving a total of nine samples. Results are tabulated in Tables 1a and 1b and normative mineralogy in Table 2. The purpose of this table is to document the geochemical trends within cyclic layers and among layers throughout the unit.

Within any particular layer, SiO_2, Al_2O_3, CaO, Na_2O, K_2O and Sr contents increase upwards whereas FeO, MgO, TiO_2, Fe_2O_3, MnO, Cu, Ni, Co, V, Zn and Zr contents decrease. This is consistent with a mineral graded layer due to one pulse of magma. Differences among layers however are not marked. Scattergrams of TiO_2, CaO, MgO, Co, Sr, and V versus SiO_2 and CaO versus Al_2O_3 are presented in Figures 3a to 3g. There does not appear to be a change in composition among the three different layers selected from the cyclically layered series. Mineral norms however do show a difference in calculated anorthite content. Weighted average anorthite content for the bottommost layer (605-609 ft.) is An 83.6, An 74.5 in the middle (379-380.5 ft.), and An 71 in the top (220-222.5 ft.). These An contents correlate well with microprobe data from Mainwaring (1975) who found An content to vary from An 81 around 600 ft. to An 75 at 400 ft. to An 47-62 at 200 ft. (this sample is actually in the TA unit). Mainwaring (1975) did not note where in any cyclic layer a sample was collected, so the numbers cannot be directly compared. Calculated forsterite content (Table 2), however, varies from Fo 61-68 in the bottom, to Fo 70-77 in the middle to Fo 67-91.7 (this latter number is highly suspect because the sample contains more than 10 wt.% Fe_2O_3). These calculated forsterite contents are at least 10 percent higher than those analyzed by Mainwaring (1975). This may indicate that the ferrous/ferric ratios analyzed by Bondar-Clegg are circumspect.

Table 2. C.I.P.W. normative mineralogy (wt. %) of rocks from DDH SL-2, cyclically layered series (TL)

Footage	220-221	221-222	222-222.5	379-379.5	379.5-380	380-380.5	605-607.5	607.5-608	608-609
Corundum	0.042	0.732	0.182	--	--	--	0.429	1.037	0.197
Zircon	0.019	0.018	0.029	0.018	0.022	0.024	0.019	0.024	0.024
Orthoclase	1.359	1.123	0.414	0.886	0.768	1.832	0.709	0.709	0.650
Albite	20.984	15.146	0.846	12.861	4.231	3.469	8.885	6.092	1.015
Anorthite	47.568	48.629	1.960	44.587	12.709	9.907	45.614	30.971	6.539
Diopside	--	--	--	0.485	12.569	1.743	--	--	--
Hypersthene	6.128	3.663	26.277	7.200	13.494	11.978	8.544	18.757	20.399
Olivine	16.677	23.781	7.461	21.298	14.288	20.777	26.006	24.182	29.912
Magnetite	2.392	3.668	17.138	6.046	8.105	5.394	2.537	5.365	10.077
Chromite	0.108	0.027	0.185	0.048	0.213	0.199	0.031	0.071	0.134
Ilmenite	1.557	0.893	39.884	3.381	25.640	28.679	4.672	8.547	28.489
Apatite	0.232	0.116	0.510	0.232	0.301	0.255	0.070	0.765	0.301
Pyrite	0.150	0.112	2.077	0.935	2.095	3.049	0.393	0.804	0.917
Calcite	0.546	0.455	1.001	0.500	0.978	1.023	0.455	0.432	0.637
Plag. An	68.12	75.16	68.58	76.57	73.90	72.91	82.87	82.73	85.86
Ab	31.88	24.84	31.42	23.43	26.10	27.09	17.13	17.27	14.14
Ol. Fo	67.37	67.38	91.65	70.11	76.73	70.83	61.30	60.61	67.80
Fa	32.63	32.62	8.35	29.89	23.27	29.71	38.70	39.39	32.20

Note: Fe^{+2}, Ni and Mn together; Ba, Sr and Ca included together and water ignored in calculation.

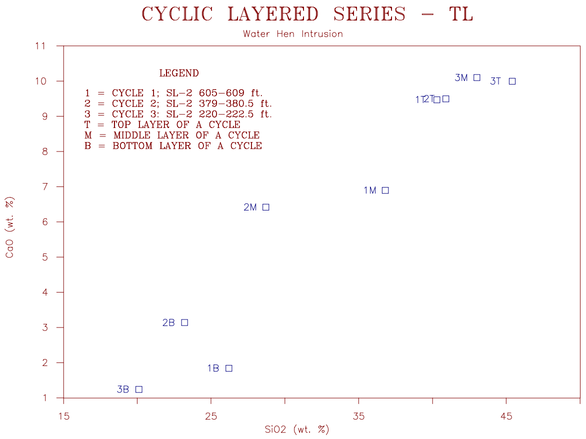


Figure 3a. CaO vs. SiO_2

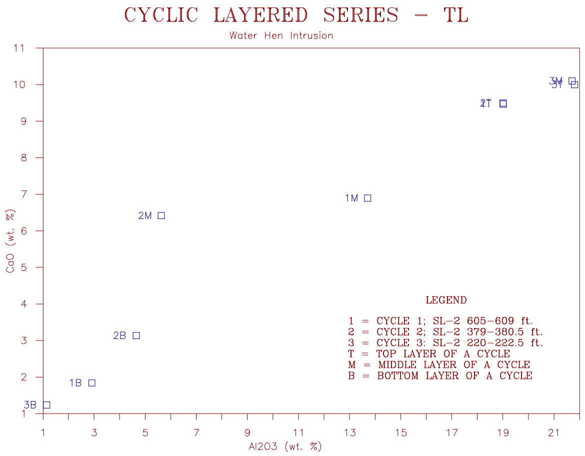


Figure 3b. CaO vs. Al_2O_3

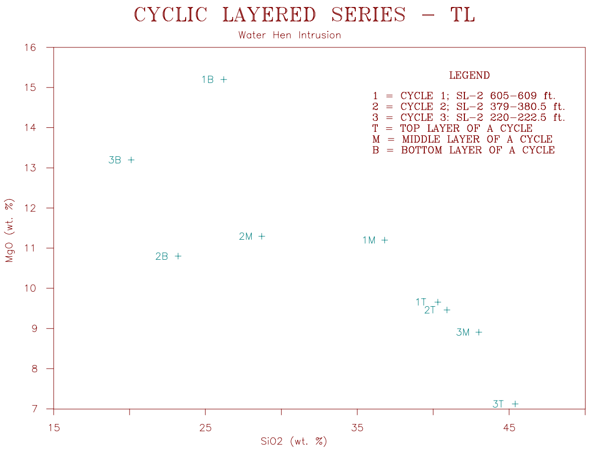


Figure 3c. MgO vs. SiO_2

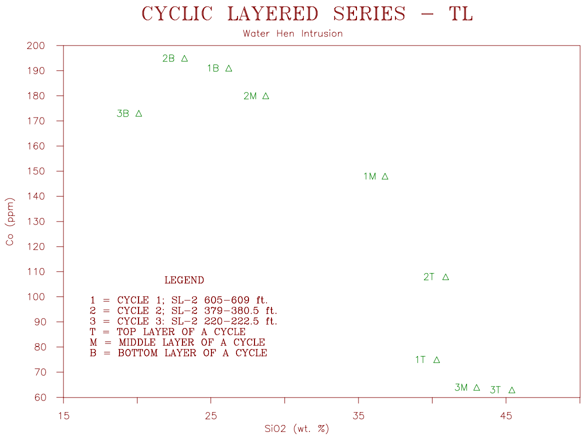


Figure 3d. Co vs. SiO_2

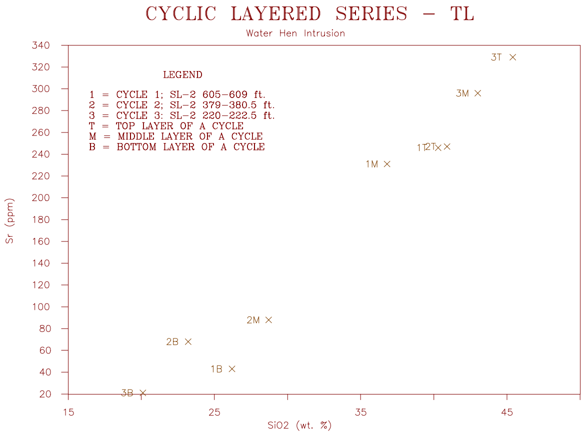


Figure 3e. Sr vs. SiO_2

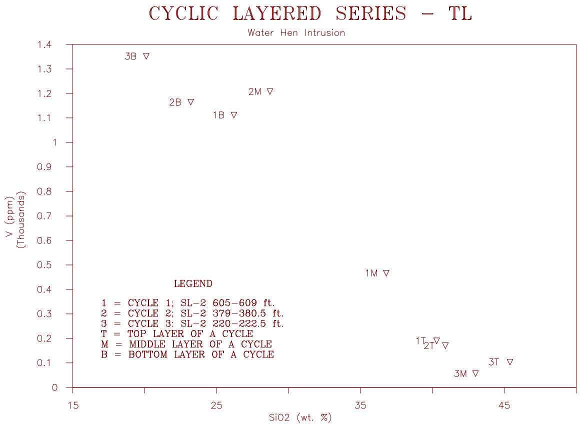


Figure 3f. V vs. SiO_2

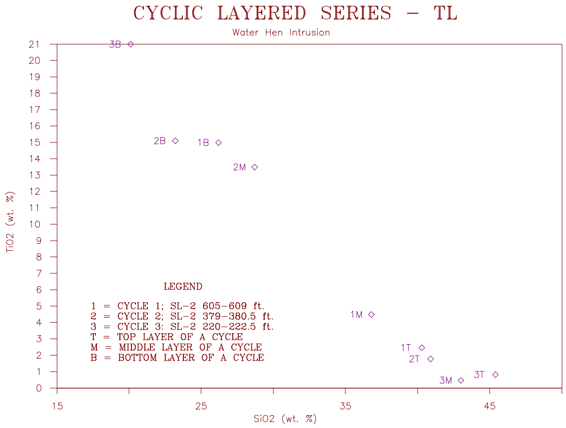


Figure 3g. TiO_2 vs. SiO_2

MINERALIZATION

Previous to this study, the rocks from 395-425 feet in SL-2 were found to have combined Pt+Pd+Au values in excess of 600 ppb (Morton and Hauck, 1989; Morton, 1989). This section was part of a strongly layered series of 11 cyclic layers from 376 to 455 ft. The samples from 379-380.5 ft. also contain PGE contents of about the same level (Table 2), but samples from the very top of the cyclic unit (220-222.5 ft.) and the very bottom (605-609 ft.) are very low in PGE content even though there were visible sulfides in all three layers.

To check whether the TL unit was unusually high in PGE content, samples were collected from various parts of the unit (82 including the samples above) both along strike and at various depths. Average contents of base and precious metal content from all rock units are presented in Tables 3a and 3b. For comparison, a few samples were collected from the M, OUI, and TA units and their averages are also presented in Table 3c. There is one anomalous sample of OUI and because of the small number of samples, averages for the OUI are presented with and without the anomalous sample. A lognormal distribution fits all 6 elements (Au, Pt, Pd, Ag, Cu, Ni) analyzed during this study.

Table 3a. Average contents of Au, Pt, Pd, Ag, Cu and Ni in all rock units analyzed in this study

Waterhen	Au	Pt	Pd	Ag	Cu	Ni
N Used	110	110	110	110	110	110
Mean	24.4	46.4	65.9	0.58	1410	639
Variance	920.6	2546.8	6188.8	0.27	2296759	108816
Std. Dev.	30.3	50.5	78.7	0.52	1516	330
Coef. Var.	124.6	108.7	119.4	90.62	107.5	51.6
Skewness	2.8	3.0	2.1	1.56	2.0	1.1
Kurtosis	11.3	14.3	7.5	5.59	6.4	4.9
Minimum	1	15	2	0.1	82	199
25th %tile	8	15	15	0.2	464	361
Median	14	30	35	0.4	842	582
75th %tile	27	50	87	0.8	1591	815
Maximum	168	310	370	2.6	6890	1996

Note: Au, Pt and Pd in ppb; Ag, Cu and Ni in ppm.

Table 3b. Average lognormal contents of Au, Pt, Pd, Ag, Cu and Ni in all rock units analyzed in this study

Waterhen	Ln[Au]	Ln[Pt]	Ln[Pd]	Ln[Ag]	Ln[Cu]	Ln[Ni]
N Used	110	110	110	110	110	110
Mean	2.692	3.491	3.509	-0.960	6.805	6.333
Variance	0.976	0.583	1.619	0.883	0.886	0.262
Std. Dev.	0.988	0.764	1.272	0.940	0.941	0.512
Coef. Var.	36.696	21.880	36.256	97.884	13.834	8.081
Skewness	0.129	0.879	-0.263	-0.020	0.174	-0.019
Kurtosis	3.104	2.981	2.373	1.877	2.660	2.162
Minimum	0.000	2.708	0.693	-2.303	4.407	5.293
25th %tile	2.079	2.708	2.708	-1.609	6.140	5.890
Median	2.674	3.401	3.555	-0.916	6.736	6.367
75th %tile	3.313	3.912	4.471	-0.223	7.372	6.703
Maximum	5.124	5.737	5.914	0.956	8.838	7.599

Table 3c: Average contents of Au, Pd, Ag, Cu and Ni in the different rock units from the Water Hen area

Rock Unit	#	Au (ppb)	Pt (ppb)	Pd (ppb)	Ag (ppm)	Cu (ppm)	Ni (ppm)	Cu/Cu+Ni	Pt/Pt+Pd
M average	7	18.9	29.3	53.4	0.6	2033	659	.76	.35
M std		15.9	20.4	57.2	0.6	1920	315		
OUI average*	7	39.7	74.3	85.7	0.9	2639	732	.78	.46
OUI average	6	18.3	36.7	46.7	0.6	1931	619		
OUI std-7*		54.1	93.3	100.6	0.7	2165	323	.76	.44
OUI std-6		14.6	15.7	33.7	0.4	1399	182		
TL average	82	26.2	47.6	72.3	0.6	1415	662	.68	.40
TL std		29.7	50.0	81.4	0.5	1418	336		
TA average	14	8.7	22.1	24.7	0.2	450	447	.50	.47
TA std		5.3	19.6	21.1	0.1	210	193		

*includes anomalous sample.

Because these samples all contain varying amounts of sulfide (usually less than 1%), the precious and base metal levels cannot be considered to be background. Averages range from 56 ppb combined Pt+Pd+Au in TA to 146 ppb in TL (deleting the very anomalous sample from OUI). Combined Cu+Ni content ranges from 898 ppm in TA to a high of 2693 in M. It is interesting to note that both TL and TA have approximately two times the total amount of Au+Pt+Pd for the equivalent amount of Cu+Ni as compared to OUI and M. This may mean that TL and TA may be good source rocks of PGE, but not necessarily a place to find ore grade material.

The Pt/Pt+Pd ratio is plotted against the Cu/Cu+Ni ratio for samples from TL and TA (Fig. 4a) and from M and OUI (Fig. 4b). For the troctolitic rocks, there is a complete scatter of points; there appears to be no relation between the two. However in Figure 4b, the Pt/Pt+Pd ratio is negatively correlated (r=.904) with the Cu/Cu+Ni ratio. This may mean that the source of sulfide in the two may be different from that in the troctolitic and layered rocks.

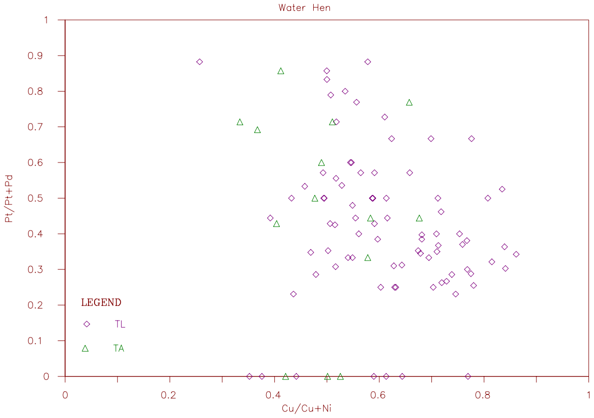


Figure 4a. Pt/Pt+Pd vs. Cu/Cu+Ni for TL and TA.

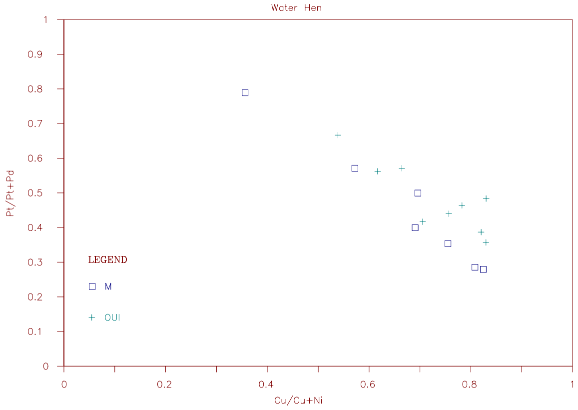


Figure 4b. Pt/Pt+Pd vs. Cu/Cu+Ni for M and OUI.

Total Pt+Pd+Au is plotted against total Cu+Ni content (Fig. 5A) and against Cu/Ni ratio (Fig. 5C) and total Cu+Ni is also plotted against Cu/Ni ratio (Fig. 5B). There are two populations of samples with different Cu/Ni ratios: one with a median of 1.25 and another with a median of 5 (Figs. 5B and 6). The group with the higher Cu/Ni ratio also has a much higher total Cu + Ni content. However, when total PGE is plotted against Cu/Ni ratio (Fig. 5C), there is more of a continuum (except for the five samples with total PGE greater than 550 ppb). Even though samples with high Cu/Ni ratios generally have high Cu+Ni contents, the same cannot be said for precious metal content.

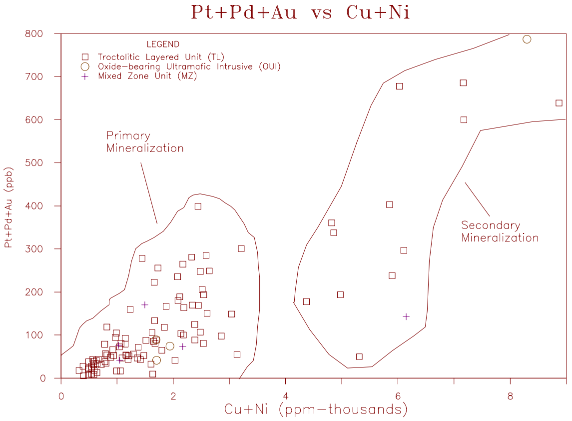


Figure 5a. Pt+Pd+Au vs. Cu+Ni - all samples.

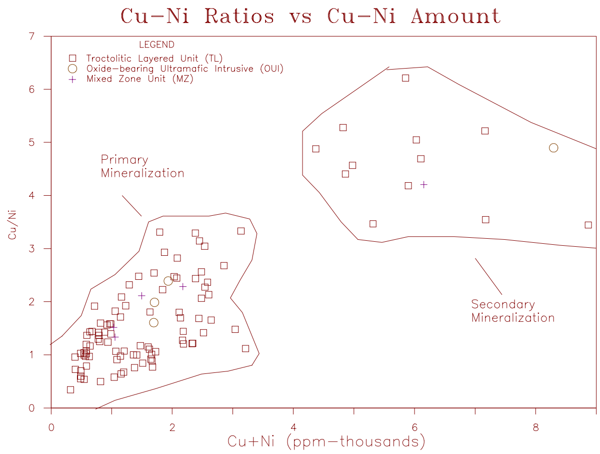


Figure 5b. Cu/Ni vs. Cu+Ni - all samples.

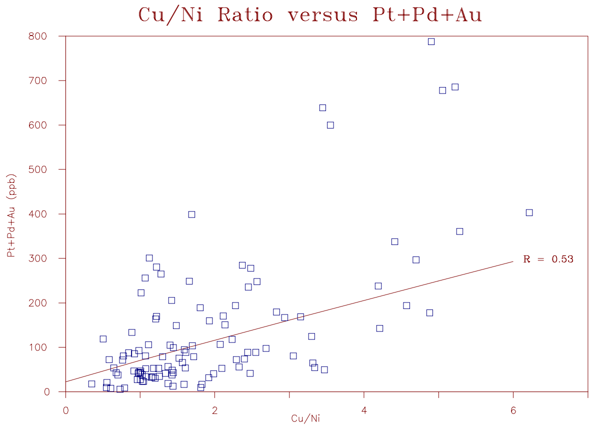


Figure 5c. Pt+Pd+Au vs. Cu/Ni - all samples.

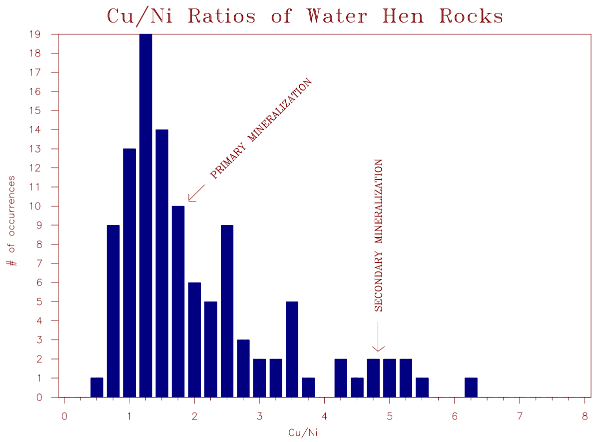


Figure 6. Histogram of Cu/Ni ratios - all samples.

Correlation coefficients for all element pairs from all rock units are listed in Tables 4a and 4b. Tables 4c and 4d list the correlation coefficients for 82 samples from the TL unit. With a sample population of 82, all of the correlations are statistically significant whether using a normal or a lognormal distribution. In particular, Cu is very highly correlated (r > 0.8) with Ag, Pd, and Ni content. Pd is correlation with both Pt and Au (r > 0.8). These high correlations are not seen in previous work (Morton and Hauck, 1987) and suggest that primary mineralization in the cyclically layered series originated in a similar manner as the primary mineralization at Dunka Road and South Filson Creek (Fig. 1; Geerts, *et al*, 1990; Kuhns, *et al*, 1990). The secondary sulfide and oxide (?) minerals present indicates that redistribution/remobilization of primary sulfides was local in extent. This secondary redistribution/remobilization and concentration process is again similar to secondary processes observed at Dunka Road and South Filson Creek.

Table 4a. Correlation coefficients for Au, Pt, Pd, Ag, Cu and Ni in all rock units

[Au]	1.000					
[Pt]	0.721	1.000				
[Pd]	0.852	0.822	1.000			
[Ag]	0.733	0.675	0.790	1.000		
[Cu]	0.750	0.698	0.823	0.901	1.000	
[Ni]	0.650	0.625	0.718	0.774	0.751	1.000
	Au	Pt	Pd	Ag	Cu	Ni

Table 4b. Lognormal correlation coefficients for Au, Pt, Pd, Ag, Cu and Ni in all rock units

log[Au]	1.000					
log[Pt]	0.729	1.000				
log[Pd]	0.889	0.773	1.000			
log[Ag]	0.817	0.659	0.772	1.000		
log[Cu]	0.854	0.663	0.797	0.893	1.000	
log[Ni]	0.766	0.655	0.748	0.774	0.815	1.000
	log[Au]	log[Pt]	log[Pd]	log[Ag]	log[Cu]	log[Ni]

Table 4c. Correlation coefficients* for 82 samples from the cyclically layered series (TL)

Au	1.000					
Pt	0.629	1.000				
Pd	0.826	0.813	1.000			
Ag	0.670	0.640	0.729	1.000		
Cu	0.714	0.696	0.832	0.874	1.000	
Ni	0.616	0.616	0.687	0.754	0.722	1.000
	Au	Pt	Pd	Ag	Cu	Ni

Table 4d. Lognormal correlation* coefficients for 82 samples from the cyclically layered series (TL)

log[Au]	1.000					
log[Pd]	0.709	1.000				
log[Pd]	0.870	0.809	1.000			
log[Ag]	0.800	0.649	0.751	1.000		
log[Cu]	0.838	0.667	0.781	0.896	1.000	
log[Ni]	0.727	0.646	0.711	0.778	0.804	1.000
	log[Au]	log[Pt]	log[Pd]	log[Ag]	log[Cu]	log[Ni]

***Note:** For samples with values less than the detection limit, one-half the detection limit was used.

PGE CHONDRITE PLOT

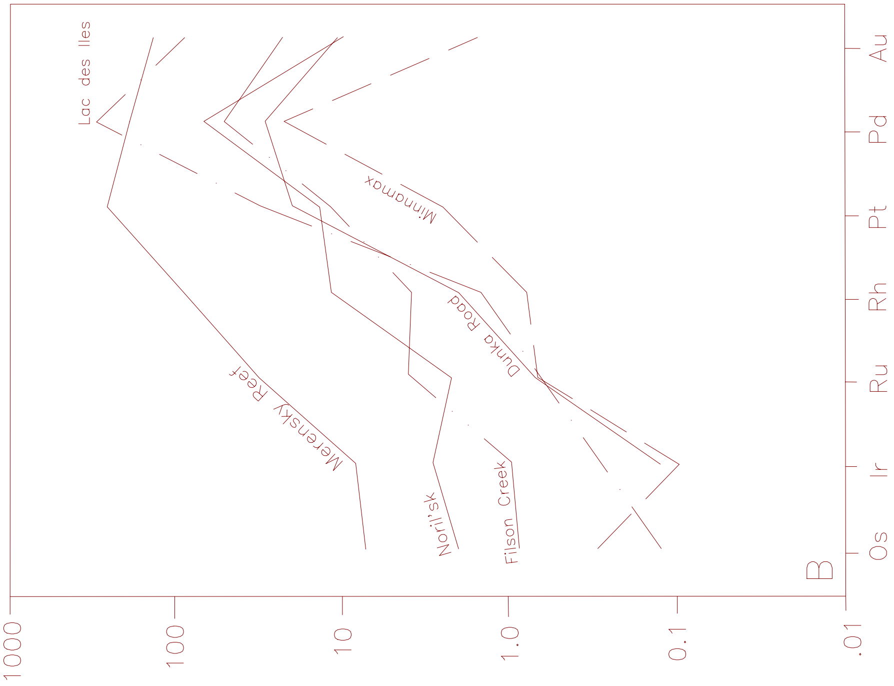
Total PGE content of four samples are reported in Table 5. Two of the samples are plotted on a chondrite normalized plot (Fig. 7a); SL-1 could not be plotted because when it was recalculated to 100% sulfide, it was obvious that much of the Ni was tied up in arsenides, not sulfides. There was not enough sample left to analyze for As. In SL-4, S and Co were not analyzed due to insufficient sample. Of the two other samples, one is from the TL unit, the other from TA. These samples give reasonably similar enrichment patterns, but the SL-2 sample is higher overall, except Pt, than the SL-4 sample.

Compared to other samples from elsewhere in the Duluth Complex, the enrichment pattern is similar to that at Minnamax (Fig. 7b) but much less enriched in Pt+Pd compared to Dunka Road. The trend at Water Hen is similar to South Filson Creek, but it is much lower overall in total PGE content. Compared to samples from Lac des Iles, Water Hen is very depleted in Pt and Pd (Figure 7b).

Table 5. Complete spectrum of PGE, Au, Ag, Cu and Ni content in four samples from the Water Hen area

Sample	Description	Pt	Pd	Au	Ir	Os	Rh	Ru	Ag	Cu	Ni
SL-1 583	Dike	1170	1840	150	8.0	<10	22	<20	27.6	>2%	6878
SL-2 395-400	TL	168	170	33	5.0	<2	14	14	2.5	6755	1173
SL-4 600-605	TA	<50	430	96	2.0	<10	9	<20	2.5	2600	1500
SL-9 250-257	TA	710	87	18	3.0	<2	7	<10	0.8	3613	1163

Note: Pt, Pd, Au, Ir, Os, Rh, Ru in ppb; Ag, Cu, Ni in ppm.



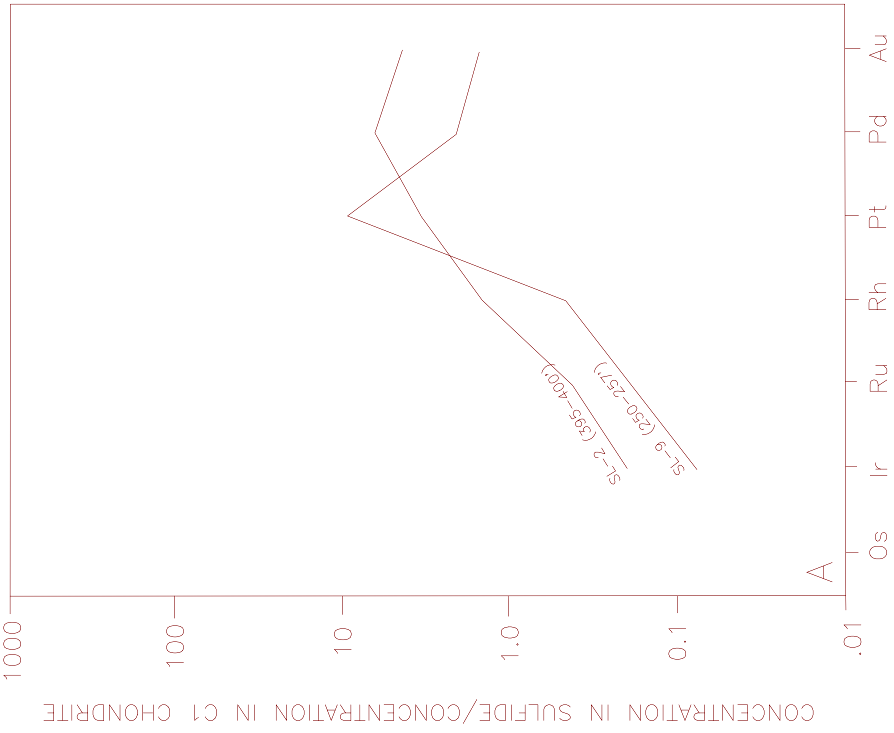


Figure 7a. PGE chondrite plot for 2 Water Hen samples.

Figure 7b. PGE chondrite plot for all Duluth Complex samples, Lac des Iles, Merensky Reef and Noril'sk.

CONCLUSIONS

1. The Water Hen intrusion is an intrusive OUI into troctolitic series rocks at the base of the Duluth Complex. The intrusion has been redefined only to include the dunitic and pyroxenitic portions, not the mineral graded cyclic units as defined by Mainwaring (1975).

2. The cyclically layered series (TL) appears to be related to the layered series rocks at Bardon Peak (Ross, 1985) but is still part of the troctolitic series.

3. The location of the Water Hen intrusion is the result of emplaced along a pre-basement fault.

4. The footwall rocks are not always Virginia Formation. There are at least 100+ ft. of North Shore Volcanic Group or chilled margin rocks in the footwall. Dikelets rich in PGEs occur in these mafic hornfelsed rocks.

5. Each cyclically layered unit varies from ilmenite-dunite at the bottom to anorthositic troctolite at the top. The individual units vary in size from 3 ft. to 10-12 ft. The whole cyclic layered series is about 300 ft. thick and cross-cut by OUIs. The An content decrease from about An_{81} at the bottom of the layered series to An_{60} at the top of the layered series.

6. The size of the dunite (OUI) body is 1,600 ft. x 500 ft. x 700 ft., which is considerably smaller than described by Mainwaring (1975).

7. The copper-nickel sulfides are primary igneous sulfides associated with the troctolitic series and are locally remobilized/redistributed by later secondary processes. This conclusion is supported by the high correlation coefficients between the 6 elements. Similar relationships are observed at the Dunka Road and South Filson Creek deposits.

8. Twice the quantity of PGEs occur in the TL and TA units versus the Mixed Zone and OUI. Within the TL unit Cu is highly correlated with Ag-Pd-Ni and Pd is highly correlated with Pt-Au.

9. The samples with high Cu:Ni ratios have a bimodal distribution, but the PGEs do not follow this trend.

10. Secondary mineralogy (veinlets and replacements) is characterized by bornite, mackinawite, violarite, pyrite and magnetite in the TL unit and bornite, maucherite, native bismuth, nickeline, parkerite, native silver and tetradymite in orthopyroxenite dikes.

11. The cyclically layered series (TL) does not have Cu-Ni-PGE-Au-Ag potential. However, further investigation of the secondary mineralization associated with the orthopyroxenitic dikes may lead to additional PGE-Au targets.

REFERENCES

Bonnichsen, B., 1972, Southern part of Duluth Complex: *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A Centennial Volume; Minn. Geol. Surv., pp. 361-387.

Dahlberg, E.H.,1987, Drill core evaluation for platinum group mineral potential of the basal zone of the Duluth Complex: Minnesota Department of Natural Resources, Div. Minerals, Rept. 255, 60 pp.

Davidson, D.M., Jr., 1972, Eastern part of the Duluth Complex: *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A Centennial Volume; Minn. Geol. Surv., pp. 354-360.

Geerts, S., Barnes, R.J., and Hauck, S.A., 1990, Geology and mineralization in the Dunka Road copper-nickel deposit, St. Louis County, Minnesota: Natural Resources Research Institute, Technical Report, NRRI/GMIN-TR-89-16.

Keighin, C.W., Morey, G.B., and Goldich, S.S., 1972, East-central Minnesota: *in* Sims, P.K. and Morey, G.B. (eds.); Geology of Minnesota: A Centennial Volume: Minnesota Geological Survey, pp. 240-255.

Kuhns, M.J.P., Hauck, S.A., and Barnes, R.J., 1990, Origin and occurrence of platinum group elements, gold and silver in the South Filson Creek copper-nickel mineral deposit, Lake County, Minnesota: Natural Resources Research Institute, Technical Report, NRRI/GMIN-TR-89-15, 59 pp.

Linscheid, E.K., (in prep.), The petrography of the Longnose peridotite deposit and its relationship to the Duluth Complex: Unpubl. M.S. thesis, Univ. Minn., Duluth.

Listerud, W.H., and Meineke, D.G., 1977, Mineral resources of a portion of the Duluth Complex and adjacent rocks in St. Louis and Lake Counties, northeastern Minnesota: Minn. Dept. Nat. Resources, Div. of Minerals, Report 93, 49 pp.

Mainwaring, P.R., 1975, The petrology of a sulfide-bearing layered intrusion at the base of the Duluth Complex, St. Louis County, Minnesota: Unpubl. Ph.D. thesis, University of Toronto, Toronto, Canada, 251 pp.

Mainwaring, P.R., and Naldrett, A.J., 1977, Country-rock assimilation and genesis of Cu-Ni sulfides in the Water Hen intrusion, Duluth Complex, Minnesota: Econ. Geol., v. 72, pp. 1269-1284.

Morey, G.B., and Cooper, P.W., 1977, Bedrock geology of the Hoyt Lakes - Kawishiwi area, St. Louis and Lake Counties, northeastern Minnesota: Minn. Geol. Surv., open-file map, 1:48,000.

Morton, P., 1989, Precious metal contents of rocks associated with the Water Hen Cu-Ni-Ti intrusion, Duluth Complex, NE Minnesota (abs.): Geol. Assoc. Can., Prog. with Abs., v. 14, pp. A79.

Morton, P., and Hauck, S.A., 1987, PGE, Au, and Ag content of Cu-Ni sulfides found at the base of the Duluth Complex, northeastern Minnesota: Tech. Report, NRRI/GMIN-TR-87-04, 68 pp.

Morton, P., and Hauck, S.A., 1989, Precious metals in the copper-nickel deposits of the Duluth Complex (abs.): Minn. Geol. Surv., Inf. Circ. 30, pp. 47-48.

Naldrett, A.J., and Duke, J.M., 1980, Platinum metals in magmatic sulfide ores: Science, v. 208, no. 4451, pp. 1417-1424.

Phinney, W.C., 1972, Duluth Complex, history and nomenclature: *in* Sims, P. K., and Morey, G.B. (eds.); Geology of Minnesota: A Centennial Volume: Minnesota Geological Survey, pp. 333-334.

Ripley E.M., and Taib, N.I., 1988, Carbon isotopic studies of meta- sedimentary and igneous rocks at the Babbitt Cu-Ni deposit, Duluth Complex, Minnesota, U.S.A.: Chem. Geol., v. 73, pp. 319-342.

Ross, B.A., 1985, A petrologic study of the Bardon Peak Peridotite, Duluth Complex: Unpubl. M.S. thesis, University of Minnesota, Duluth, Minnesota, 140 pp.

Seitz, J.C., and Pasteris, J., 1988, Oxide and sulfide mineralization at the base of the Duluth Complex -- Skibo Tower, Minnesota (abs.): Fifth Annual Current Minerals Forum, Chisholm, Minnesota.

Severson, M.J., 1988, Geology and structure of a portion of the Partridge River intrusion: A progress report: Natural Resources Research Institute, Technical Report, NRRI/GMIN-TR-88-08, 78 pp.

Severson, M.J., and Hauck, S.A., 1990, Geology, geochemistry, and stratigraphy of a portion of the Partridge River intrusion: Natural Resources Research Institute, Technical Report, NRRI/GMIN-TR-89-11, 236 pp.

Sutcliffe, R.H., Sweeny, J.M., and Edgar, A.D., 1989, The Lac des Iles Complex, Ontario: petrology and platinum-group-elements mineralization in an Archean mafic intrusion: Can. J. Earth Sci., v. 26, pp. 1408-1427.

Watowich, S.N., Malcolm, J.B., and Parker, P.D., 1981, A review of the Duluth Gabbro Complex of Minnesota as a domestic source of critical and strategic metals: SME-AIME Fall Meeting, Denver, Colorado, 9 pp.

Weiblen, P.W., and Morey, G.B., 1980, A summary of the stratigraphy, petrology and structure of the Duluth Complex: American Jour. Sci., v. 280, pp. 88-133.