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Geologic Setting of Volcanic-Associated Massive Sulfide Deposits in the Kamiskotia Area, Abitibi Subprovince, Canada

B. HATHWAY,[†,*]

Mineral Exploration Research Centre, Laurentian University, Sudbury, Ontario, Canada

G. HUDAK,

Department of Geology, University of Wisconsin, Oshkosh, Oshkosh, Wisconsin

AND M. A. HAMILTON

Department of Geology, University of Toronto, Toronto, Ontario, Canada

Abstract

The Upper Archean volcanic succession in the Kamiskotia area (Abitibi greenstone belt, Timmins region) hosts a series of past-producing copper-zinc volcanic-associated massive sulfide (VMS) deposits. All of these occur within a restricted, east-facing stratigraphic interval in the upper part of the Kamiskotia Volcanic Complex. New U-Pb ages for this interval, ranging from 2701.1 ± 1.4 to 2698.6 ± 1.3 Ma, and an age of 2703.1 ± 1.2 Ma from the lower part of the Kamiskotia Volcanic Complex, indicate that the complex is likely part of the Blake River assemblage (2701–2697 Ma) rather than the older Tisdale assemblage (2710–2703 Ma). The Kamiskotia Volcanic Complex consists largely of felsic and mafic lava flows, and VMS mineralization appears to have generally developed at or near the sea floor close to inferred synvolcanic faults.

New U-Pb ages of 2714.6 ± 1.2 and 2712.3 ± 2.8 Ma from the northeast-facing volcanic succession in the northern part of the study area (Loveland, Macdiarmid, and Thorburn Townships) indicate that it forms part of the Kidd-Munro assemblage (2719–2710 Ma). A west-northwest–trending faulted contact is inferred between this older succession and the Kamiskotia Volcanic Complex rocks to the south. The Kidd-Munro assemblage rocks are coeval with the Kidd Volcanic Complex, which hosts the giant Kidd Creek VMS deposit 30 km to the east of the study area. The lower part of the succession, in south-central Loveland Township, consists of high silica FIIIb rhyolites. These rocks are geochemically similar to ore-associated FIIIb rocks from Kidd Creek and seem likely to represent the most prospective part of this succession.

Future exploration in the Kamiskotia Volcanic Complex is probably best focused on the along-strike extension of the VMS-hosting interval and, in particular, on areas close to the intersections of synvolcanic faults. Mafic and felsic volcaniclastic strata which can be replaced by VMS mineralization, and felsic coherent facies flows and/or domes, appear to be important potential targets.

Introduction

THIS STUDY examines the stratigraphy, volcanic facies, and structural style of the Archean volcanic succession that hosts past-producing copper-zinc volcanic-associated massive sulfide (VMS) deposits in the Kamiskotia area of the Abitibi greenstone belt in the Timmins region (Fig. 1, Table 1). The study involved regional bedrock mapping (1:10,000 and 1:20,000 scale) and deposit-scale research on the Kam Kotia and Canadian Jamieson VMS deposits (Fig. 1). Outcrop studies were supplemented by diamond drill core data and existing core was relogged wherever possible. In addition, 156 whole-rock lithogeochemical samples were analyzed for major oxides and selected trace elements in order to characterize the volcanic units (representative analyses in Table 2), and new U-Pb ages were obtained on zircons from seven samples (Table 3). A detailed study of the Genex VMS deposit is described in a separate paper by Finamore-Hocker et al. (2008).

Previous work in the area includes mapping by Hogg (1955) and Middleton (1973, 1974, 1975, 1976). More recently, Barrie (1990, 1992, 2000) mapped and described the southern part of the study area, including the past-producing VMS deposits. Recent maps by Vaillancourt et al. (2001) and Hall and Smith (2002a) cover the southernmost part of the Kamiskotia area.

The Kamiskotia area is one of a number of VMS districts in the Abitibi subprovince of the Superior province (Franklin et al., 2005). The Archean rocks in the southern part of the study area are assigned to the Kamiskotia Gabbroic Complex, which includes both mafic and felsic intrusive rocks, and the Kamiskotia Volcanic Complex, both defined by Barrie (1992). Four past-producing VMS deposits and numerous VMS occurrences (including the Steep Lake and Halfmoon Lake prospects) occur in the Kamiskotia Volcanic Complex (Fig. 1, Table 1). Combined, the four mines (Kam Kotia, Canadian Jamieson, Genex, and Jameland) produced nearly 8.5 million metric tons (Mt) of copper-zinc ± gold ± silver ore (Franklin et al., 2005). Age data presented in this paper indicate that Archean mafic and felsic volcanic rocks in the northern part of the area form part of the older Kidd-Munro assemblage. All the Archean volcanic rocks in the area have undergone greenschist-facies metamorphism. North-northwest–trending diabase dikes of the ~2450 Ma (Paleoproterozoic) Matachewan swarm are common throughout the area and are

[†] Corresponding author: e-mail, ben.hathway@ercb.ca

[*] Present address: Alberta Geological Survey, Twin Atria Building, 4th Floor, 4999 – 98th Avenue, Edmonton, Alberta, Canada T6B 2X3.

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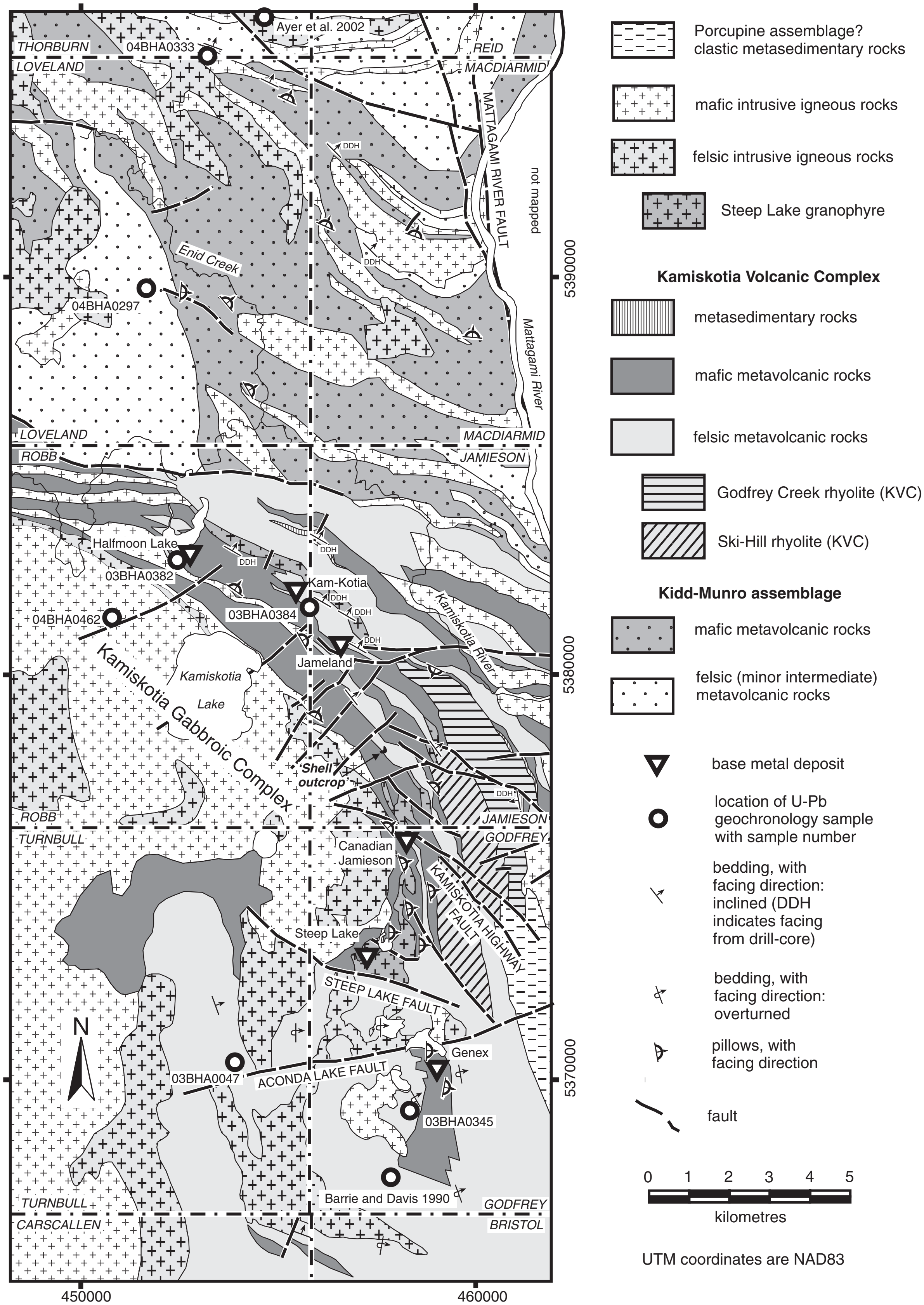

Fig. 1. Geologic sketch map of the Kamiskotia area, based on mapping by Hathway (this study), Hogg (1955), Middleton (1973, 1974, 1976), and Hall and Smith (2002a).

TABLE 1. Grade and Tonnage Data for the VMS Orebodies in the Kamiskotia Area (after Franklin et al., 2005)

Volcanogenic massive sulfide deposits in the Kamiskotia area

Deposit	Lithostratigraphic Classification[1]	Million metric Tons (Mt) ore	Cu (%)	Zn (%)	Au (g/t)	Ag (g/t)
Kam Kotia	Bimodal mafic	5.84[2]	1.1[2]	1.2[2]	0.26[2]	2.57[2]
Jameland	Bimodal mafic	0.49[2]	1.6[2]	2.0[2]	0.03[3]	3.12[3]
Canadian Jamieson	Bimodal mafic	0.76[2]	2.3[2]	3.5[2]	0.31[3]	30.17[3]
Genex	Bimodal mafic	0.042[4]	2.9[4]	1.6[3]	—	—

— = not available
[1] Classification based on Franklin et al. (2005)
[2] Data from Barrie and Pattison (1999)
[3] Data from Franklin et al. (2005)
[4] Data from Hocker et al. (2005)

TABLE 2. Representative Analyses of Volcanic Rocks from the Kamiskotia Area

Sample no.	04-BHA-0297	04-BHA-0318	04-BHA-0333A	03-BHA-0293	04-BHA-0194	03-BHA-0332	04-BHA-0296	04-BHA-0086B
Township	Loveland	Macdiarmid	Thorburn	Carscallen	Jamieson	Bristol	Godfrey	Jamieson
UTM East NAD83	451789	458058	453889	454161	460889	456491	457939	459050
UTM North NAD83	5389811	5389287	5395611	5365591	5377704	5365457	5373600	5380222
Unit/rock type	KMA Rhyolite	KMA Pillow lava	KMA Felsic clast	KVC Rhyolite	KVC Rhyolite	KVC NEB Pillow lava	KVC pillow lava (below VMS)	KVC pillow lava (above VMS)
SiO_2 (wt %)	76.66	56.04	68.08	72.19	78.65	51.09	47.58	50.18
TiO_2 (wt %)	0.12	0.84	0.74	0.2	0.18	2.02	1.21	2.7
Al_2O_3 (wt %)	10.87	15.96	14.7	11.68	11.23	16.22	13.72	14.97
Fe_2O_3 (wt %)	2.68	8.63	3.12	3.78	1.48	9.35	11.55	13.98
MgO (wt %)	0.18	4.97	1.82	0.65	0.16	3	7.37	3.49
CaO (wt %)	2.27	6.6	2.99	2.19	0.22	6.02	6.62	5.38
Na_2O (wt %)	3.27	4.12	5.14	3.58	2.39	6.2	2.54	3.82
K_2O (wt %)	2.21	0.45	1.01	3.24	5.46	0.49	0.54	0.46
MnO (wt %)	0.078	0.121	0.046	0.08	0.017	0.12	0.192	0.358
P_2O_5 (wt %)	0.02	0.16	0.21	0.03	0.03	0.52	0.12	0.45
Cr_2O_3 (wt %)	0	0.01	0		0		0.02	0.02
LOI (wt %)	1.66	2.23	2	2.28	0.5	4.96	8.63	4.14
TOTAL	100	100.14	99.85	99.89	100.31	99.99	100.09	99.94
Th (ppm)	5.61	1.56	2.36	6.61	11.74	3.28	0.59	1.49
Nb (ppm)	22.4	6.1	8.4	29.3	35.5	36.6	3.7	9.3
La (ppm)	46.38	12.9	17.61	51.16	59.69	44.78	5.72	12.61
Ce (ppm)	106.19	29.37	38.3	120.6	136.69	110.35	14.44	33.11
Pr (ppm)	13.499	3.808	4.806	15.423	19.269	14.123	2.095	4.895
Nd (ppm)	53.38	15.75	20.11	63.3	82.75	54.83	9.76	24.37
Zr (ppm)	315.3	143.7	206.1	392.6	374.4	182.5	91	285.9
Hf (ppm)	9.5	3.6	5.1	11.1	13.4	4.2	2.5	6.7
Sm (ppm)	11.99	3.57	4.58	13.92	21.51	9.12	2.99	6.92
Eu (ppm)	1.389	0.959	0.884	2.642	2.884	2.472	1.019	2.226
Ti (ppm)	591	4234	3804	863	879	10526	6347	15667
Gd (ppm)	12.033	3.705	4.704	14.13	24.67	7.212	3.945	8.839
Tb (ppm)	2.043	0.605	0.776	2.185	4.241	0.987	0.699	1.539
Dy (ppm)	12.573	3.637	4.835	13.131	26.344*	5.548	4.403	9.895
Y (ppm)	78.29	20.21	28.06	69.02	132.234	27.13	24.9	58.52
Ho (ppm)	2.721	0.772	1.035	2.651	5.474	1.086	0.959	2.157
Er (ppm)	8.193	2.251	3.145	7.662	16.348	2.944	2.822	6.446
Tm (ppm)	1.242	0.33	0.473	1.109	2.494	0.409	0.42	0.946
Yb (ppm)	8.12	2.16	3.1	7.14	16.65	2.61	2.76	6.33
Lu (ppm)	1.236	0.33	0.491	1.079	2.43	0.394	0.424	0.963
V (ppm)	N.D.	134.2	46.3	2.3	0.9	181.5	294.3	285
Sc (ppm)	3.2	18.1	11.3	3.1	2	17.6	37.6	40.3
La/YbCN	4.10	4.28	4.07	5.14	2.57	12.31	1.49	1.43
Zr/Y	4.03	7.11	7.34	5.69	2.83	6.73	3.65	4.89
Eu/Eu*[1]	0.35	0.81	0.58	0.58	0.38	0.93	0.91	0.87

Abbreviations: KMA = Kidd-Munro assemblage, KVC = Kamiskotia Volcanic Complex, NEB = Nb-enriched basalt
[1] Eu/Eu* calculated using method of Taylor and McLennan (1985)
Notes: Major oxides analyzed using XRF at Ontario Geoscience Laboratories (04-BHA-0293, 03-BHA-0332) and ActLabs (remaining samples); trace elements for all samples analyzed using ICP-MS at Ontario Geoscience Laboratories; for the results of all analyses and details of analytical procedures see Hathway et al. (2005)

TABLE 3. U-Pb Isotope Data for Zircon from Sample Localities in the Kamiskotia Area

Sample Fraction	Analysis no.	Weight (mg)	U (ppm)	Th/U[1]	Pb* (pg)	Pb_C (pg)[2]	Isotopic ratios[3] $^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	± 2σ	$^{207}Pb/^{235}U$	± 2σ	$^{207}Pb/^{206}Pb$	± 2σ	$^{207}Pb/^{206}Pb$ Age (Ma)	± 2σ	Disc. (%)[4]	Corr. Coeff.[5]
04BHA-0297 Quartz-feldspar-phyric rhyolite, central Loveland Twp. (NAD83, Zone 17, UTM 451785E, 5389819N)																	
Z1[6]	DWD4689	0.0040	55	0.51	130.0	1.5	4963	0.52093	0.00171	13.4103	0.0455	0.18671	0.00030	2713.4	2.6	0.5	0.8846
Z2[7]	DWD4690a	0.0020	59	0.51	69.6	3.3	1221	0.52036	0.00199	13.3884	0.0641	0.18660	0.00051	2712.5	4.5	0.5	0.8211
Z3[8]	DWD4691	0.0015	89	0.50	57.6	0.6	5678	0.37736	0.00134	9.6567	0.0367	0.18560	0.00020	2703.5	1.7	27.6	0.9609
Z4[9]	MAH4097a	0.0016	105	0.63	102.2	0.8	6778	0.52078	0.00135	13.4203	0.0392	0.18690	0.00018	2715.1	1.6	0.6	0.9433
04BHA-0333 Felsic debris flow, south Thorburn Twp. (NAD83, Zone 17, UTM 453583E, 5395777N)																	
A1[10]	MAH4098	0.0002	82	0.59	9.0	0.5	1018	0.52258	0.00399	13.4540	0.1165	0.18672	0.00063	2713.5	5.5	0.2	0.9223
A2[10]	MAH4099	0.0001	81	0.55	4.9	0.6	488	0.52458	0.00713	13.5002	0.2075	0.18665	0.00109	2712.9	9.7	-0.3	0.9256
B1[11]	MAH4080	0.0008	39	0.42	17.9	0.8	1244	0.52076	0.00250	13.3909	0.0752	0.18650	0.00046	2711.5	4.1	0.4	0.8996
B2[12]	MAH4081	0.0004	133	0.57	33.7	1.5	1296	0.55605	0.00167	15.6682	0.0631	0.20436	0.00043	2861.4	3.4	0.5	0.8603
B3[13]	MAH4082	0.0004	88	0.87	22.9	0.6	2208	0.50485	0.00201	12.7341	0.0567	0.18294	0.00034	2679.7	3.1	2.0	0.9088
03BHA-0047 Felsic lapilli tuff, eastern Turnbull Twp. (NAD83, Zone 17, UTM 453921E, 5370435N)																	
Z1[14]	DWD4686	0.0020	75	0.49	87.7	0.8	6342	0.51661	0.00199	13.2165	0.0541	0.18555	0.00021	2703.1	1.9	0.8	0.9597
Z2[15]	DWD4687c	0.0021	85	0.52	105.0	0.8	7173	0.51838	0.00162	13.2669	0.0437	0.18562	0.00024	2703.7	2.2	0.5	0.9187
Z3[16]	DWD4688b	0.0019	33	0.47	36.3	0.7	2985	0.51844	0.00266	13.2509	0.0682	0.18537	0.00039	2701.5	3.5	0.4	0.9163
03BHA-0345 Felsic lapilli tuff, Godfrey Twp. (NAD83, Zone 17, UTM 458483E, 5369414N)																	
A1a[17]	MAH4043	0.0014	36	0.53	29.8	5.8	305	0.52159	0.00236	13.3108	0.1669	0.18509	0.00174	2699.0	15.6	-0.3	0.7847
A1b[17]	MAH4044	0.0011	28	0.56	18.2	0.3	3097	0.52148	0.00222	13.3197	0.0615	0.18525	0.00027	2700.4	2.4	-0.2	0.9508
A1c[17]	MAH4045	0.0014	26	0.51	22.3	0.3	4524	0.52247	0.00199	13.3218	0.0542	0.18493	0.00021	2697.5	1.9	-0.5	0.9597
03BHA-0384 Felsic lapilli tuff, Robb Twp. (NAD83, Zone 17, UTM 455853E, 5381788N)																	
A1[18]	MAH4018	0.0016	23	0.56	22.5	2.6	491	0.51943	0.00246	13.2770	0.1128	0.18539	0.00106	2701.6	9.4	0.2	0.7709
A2[19]	MAH4019	0.0019	333	0.79	392.6	1.8	11499	0.51914	0.00238	13.2671	0.0621	0.18535	0.00027	2701.3	2.4	0.3	0.9515
A3[20]	MAH4020	0.0014	77	0.59	66.8	1.4	2631	0.52009	0.00155	13.2897	0.0453	0.18533	0.00029	2701.1	2.5	0.1	0.8920
A4[21]	MAH4021	0.0016	64	0.59	61.3	2.8	1215	0.51969	0.00195	13.2719	0.0641	0.18522	0.00046	2700.2	4.1	0.1	0.8634
03BHA-0382 Quartz-phyric rhyolite, Robb Twp. (NAD83, Zone 17, UTM 452485E, 5383020N)																	
A1[22]	MAH4046	0.0005	103	0.46	30.2	0.5	3486	0.52182	0.00153	13.3257	0.0433	0.18521	0.00026	2700.1	2.3	-0.3	0.9020
A2[22]	MAH4047	0.0003	237	0.41	37.3	0.7	3273	0.52189	0.00158	13.3195	0.0459	0.18510	0.00022	2699.1	2.0	-0.4	0.9407
A3[22]	MAH4048	0.0003	178	0.40	30.0	0.4	4760	0.52154	0.00162	13.3268	0.0446	0.18533	0.00025	2701.1	2.2	-0.2	0.9152
04BHA-0462 Granophyre, Kamiskotia Gabbroic Complex, Robb Twp. (NAD83, Zone 17, UTM 451049E, 5381502N)																	
A1a[23]	MAH4102	0.0007	100	0.37	39.4	0.6	3883	0.51833	0.00151	13.2758	0.0435	0.18576	0.00026	2705.0	2.3	0.6	0.9073
A1b[24]	MAH4107	0.0012	169	0.78	123.6	0.8	8591	0.51983	0.00182	13.3038	0.0464	0.18561	0.00031	2703.7	2.7	0.2	0.8870
A1c[23]	MAH4108	0.0006	73	0.48	27.3	1.2	1337	0.51847	0.00184	13.2892	0.0608	0.18590	0.00041	2706.2	3.7	0.6	0.8817

Notes: All fractions represent least magnetic, air-abraded single zircon grains, free of inclusions, cores or cracks, unless otherwise noted;

Pb* = total radiogenic Pb (pg), uranium decay constants are from Jaffey et al. (1971); samples were processed and analyzed using conventional isotope dilution thermal ionization mass spectrometry (ID-TIMS) techniques at the Jack Satterly Geochronology Laboratory, University of Toronto; further details of analytical methodology and results are provided by Ayer et al. (2005)

[1] Th/U is model value calculated from radiogenic $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age assuming concordance

[2] Pb_C is total measured common Pb (pg) assuming the isotopic composition of laboratory blank: 206/204 = 18.221; 207/204 = 15.612; 208/204 = 39.360 (errors of 2%)

[3] Pb/U isotope ratios are corrected for spike, fractionation, blank, and, where necessary, initial common Pb; $^{206}Pb/^{204}Pb$ is corrected for spike and fractionation

[4] Disc. (%) - per cent discordance for the given $^{207}Pb/^{206}Pb$ age

[5] Correlation coefficient

Zircon grain descriptions: [6] clear, colorless, stubby, with rod melt inclusions; [7] clear, colorless, equant, with rod inclusions; [8] clear, colorless, equant; [9] clear, colorless, stubby; [10] clear, colorless to pale pink, sharp, elongate; [11] clear, colorless to pale yellow, stubby, sharp; [12] clear, pale brown, stubby, sharp; [13] clear, colorless to pale pink, stubby, sharp; [14] clear, colorless, equant, flat; [15] clear, colorless, short prism, with rod inclusions; [16] clear, colorless, irregular; [17] clear, colorless to pale yellow, stubby to equant prism; [18] clear, colorless, elongate (3:1), prismatic, minor inclusions: [19] clear, pale brown, slightly elongate (2:1), prismatic, minor inclusions: [20] clear, colorless, equant, prismatic, minor inclusions: [21] clear, colorless to pale brown, slightly elongate (2:1), prismatic: [22] clear, pale brown to brown, short, sharp, prismatic: [23] clear, colorless, elongate: [24] clear, colorless to pale brown, irregular fragment easily recognized as narrow, moderately magnetic linear features in geophysical surveys (Barrie, 2000).

Kidd-Munro Assemblage

Ayer et al. (2002) reported a U-Pb zircon age of 2719.5 ± 1.7 Ma for a felsic volcanic unit from southern Thorburn Township (Fig. 1), which indicated that the rocks to the north of the Kamiskotia Volcanic Complex might form part of the older Kidd-Munro assemblage (2719–2710 Ma). This is confirmed by new ages for felsic volcanic rocks reported here from Loveland and Thorburn Townships. Owing to lack of outcrop, the nature and location of the northern (and eastern) boundaries of the Kamiskotia Volcanic Complex have been poorly constrained. Barrie (1992) suggested a bounding line parallel to stratigraphy and extending from a point 2 km north of the Kam Kotia mine to a point 2 km east of the Genex mine, representing a demarcation between metavolcanic rocks with few geophysical conductors to the west and metavolcanic-metasedimentary rocks with numerous conductors to the east. The boundary between the Kidd-Munro assemblage and Kamiskotia Volcanic Complex appears to trend broadly east-west in the area along the Kamiskotia River in northern Robb Township (Fig. 1), where there is a marked discordance in the airborne geomagnetic signature. Rocks appear to face to the northeast on each side of this boundary, implying a faulted contact with substantial displacement. It is difficult to trace the contact farther east as there is little or no outcrop, and magnetic signatures are subparallel to each other. Therefore, the boundary shown in that area in Figure 1 is provisional.

Felsic to intermediate metavolcanic rocks

The lowermost part of the Kidd-Munro assemblage in the study area consists of felsic volcanic rocks locally exposed in northernmost Robb Township and south-central Loveland Township (Fig. 1). The extent of these rocks is further delineated by numerous overburden holes drilled to bedrock by Gulf Minerals Canada Ltd. (1979, Reid Overburden Drilling Project: unpub. assessment file) and more recent diamond drilling (e.g., Mullen, 1998). This area has a relatively flat magnetic signature and coincides with a marked gravity low (Ontario Geological Survey, 2003a, b). All outcrops appear to consist of massive, commonly flow-banded, quartz- and feldspar-phyric coherent rhyolite. Aphyric rhyolite and minor felsic volcaniclastic intervals within the succession have been intersected by drilling (Mullen, 1998). A hole drilled through the eastern contact with overlying mafic pillow lavas encountered 2 m of thin-bedded graphitic argillite and siltstone at the top of the felsic succession.

Felsic intervals stratigraphically higher in the Kidd-Munro assemblage appear to be wholly volcaniclastic. There is no exposure of the felsic rocks lying immediately beneath and within the thick series of mafic-ultramafic intrusions just west of the Mattagami River (Fig. 1). Drilling indicates that they consist of thick, commonly amalgamated units of redeposited, monomict felsic lapilli tuff (larger lapilli are vesicular and quartz-phyric), with intercalated thin-bedded tuff, tuffaceous sandstone, and graphitic argillite. Units with sharp bases, grading, flame structures, and load casts in finer grained facies indicate facing to the northeast. Felsic to intermediate volcaniclastic rocks exposed in northwest Macdiarmid Township, northeasternmost Loveland Township, and southeast Thorburn Township are intercalated with and overlie a thick pillow lava succession to the south. Here, exposed rocks are largely massive, poorly sorted breccias and tuff breccias. Clasts (up to 1 m across) are typically angular, commonly sparsely vesicular, and either coarsely feldspar-phyric or finely quartz and feldspar-phyric. Bedding is rarely seen, but an outcrop on the Thorburn-Loveland Township boundary exposes breccia units up to 3.5 m thick with sharp bases and finer grained, commonly stratified, upper divisions up to 20 cm thick (facing to the north). In drill core, the coarser volcaniclastic facies are seen to be associated with substantial intervals of graphitic argillite with thin, intercalated tuffaceous sandstone units.

Lithogeochemistry: Rhyolites from the lower, southwestern part of the Kidd-Munro assemblage in northern Robb and central Loveland Townships have high silica contents (SiO_2 = 76–80 wt %) and low TiO_2 contents (0.11–0.15 wt %). All analyzed rhyolites of the Kidd-Munro assemblage show consistent, relatively flat, normalized REE patterns (Fig. 2A) with a strong negative Eu anomaly (Eu/Eu^* = 0.31–0.47), and fall in the FIIIb tholeiitic rhyolite field on the Hart et al. (2004) plot of chondrite-normalized La/Yb versus Yb (Fig. 3A). On a plot of Zr/Y versus Y (Fig. 3B) most samples fall in the field for ore-associated FIIIb rhyolites from Kidd Creek and Kamiskotia defined by Lesher et al. (1986). Two clasts from the largely volcaniclastic felsic-intermediate succession in the northermost part of the study area were analyzed. They fall in the calc-alkaline dacite and andesite fields on the Jensen cation plot (Jensen, 1976). REE patterns (Fig. 2B) are similar to those shown by the underlying pillow lavas, suggesting that they form part of the same suite. These rocks plot in the FII calc-alkaline field in the $[La/Yb]_{CN}$ versus $[Yb]_{CN}$ diagram (Fig. 3A).

Mafic metavolcanic rocks

Between the rhyolites in south-central Loveland Township and the felsic volcaniclastic rocks at the northern edge of the study area, the Kidd-Munro assemblage consists largely of variably silicified, massive to pillowed, commonly amygdaloidal mafic volcanic rocks. These are generally sparsely plagioclase-phyric (to 1 mm) with a groundmass of fine-grained chlorite, amphibole, and quartz. Clots of actinolite up to 1 cm across are common and patches and veins of epidote are locally abundant. Pillows are commonly large (up to 2 m), and thick intervals of hyaloclastite breccia are found at several locations. Pillow-facing directions are to the east-northeast or northeast.

Lithogeochemistry: Pillowed and massive mafic lavas from Loveland and Macdiarmid Townships typically have from 51 to 61 wt percent SiO_2 and plot in the field of calc-alkaline basalts and andesites on the Jensen plot (Jensen, 1976). Primitive mantle-normalized REE patterns for most samples (Fig. 4A) are similar, with a rather flat pattern in the middle and heavy REE and a moderately steep negative slope in the light REE (La/Yb_{PM} = 2.60–5.17). Zr-Hf anomalies may be absent, slightly negative or slightly positive, and Ti depletion is moderate to strong. There is generally a slight negative Eu anomaly (Eu/Eu^* = 0.76–0.99). One sample has an anomalous flat REE pattern (04BHA0330: La/Yb_{PM} = 0.99).

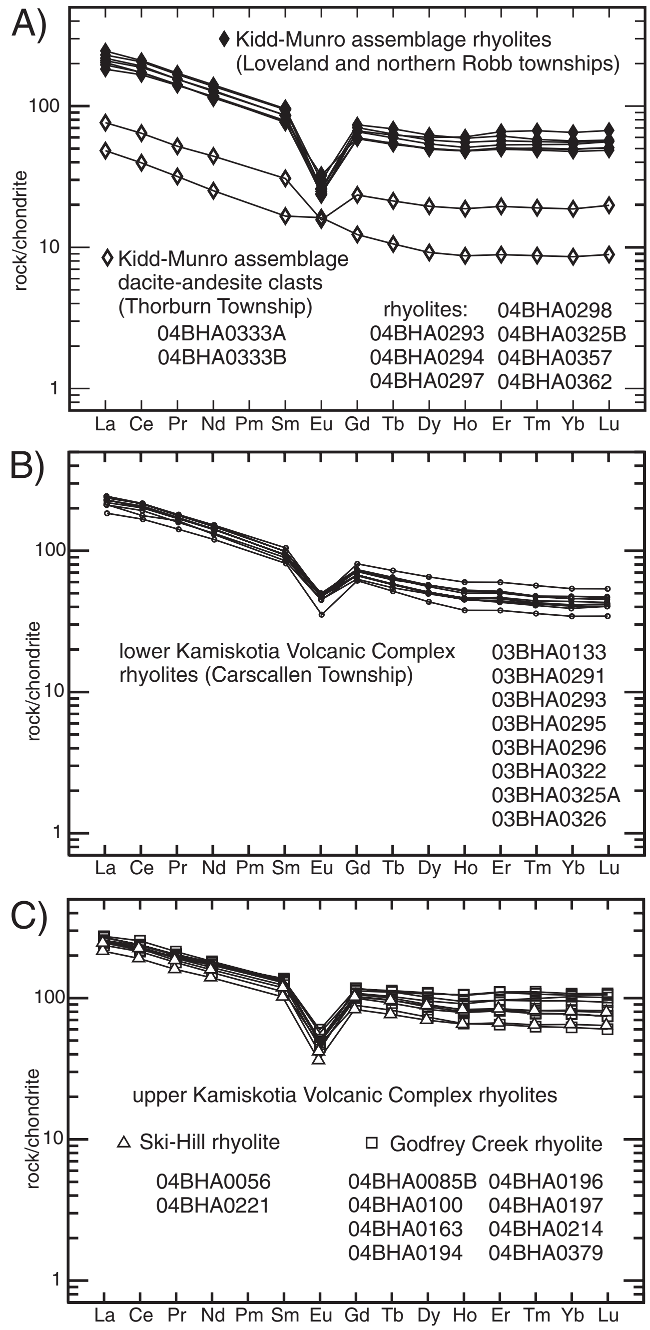

FIG. 2. Chondrite-normalized rare earth element (REE) patterns for Kamiskotia area felsic-intermediate metavolcanic rocks. Normalizing values are from Sun and McDonough (1989).

Igneous rocks intruding the Kidd-Munro assemblage

Medium- to coarse-grained granitoid rocks, described as granodiorite and quartz monzonite by Middleton (1974), crop out sparsely in Loveland Township but have been shown to be more laterally extensive by overburden drilling in southern Thorburn Township. These rocks are likely to be related to granitoid intrusions farther south described by Barrie (1992: Cote Township and Groundhog River tonalites, with U-Pb zircon ages of 2694 ± 4 and 2696 ± 1.5 Ma, respectively), which are younger than and not related to the Kamiskotia Gabbroic Complex or Kamiskotia Volcanic Complex. The Kidd-Munro assemblage volcanic succession is also intruded by numerous, broadly concordant, sill-like mafic intrusions. Most of the larger bodies are gabbroic, but drilling data shows that the large intrusion in central-western Macdiarmid Township (Fig. 1) is a layered ultramafic to mafic body (serpentinized dunite to gabbro-gabbronorite). Minor, finer grained mafic intrusions are also common. Although there is no geochronological data for these rocks in the study area, similar intrusions cutting rocks of the Kidd-Munro assemblage elsewhere in the region are known to be of Tisdale age (J. Ayer, pers. commun., 2005).

Geochronology

New ages of 2714.6 ± 1.2 Ma for a flow-banded, quartz- and K-feldspar-phyric rhyolite (sample 04BHA0297) in Loveland Township and 2712.3 ± 2.8 Ma for a felsic debris flow (sample 04BHA0333) in southernmost Thorburn Township (Figs. 1, 5; Table 3) confirm that these rocks belong to the Kidd-Munro assemblage. These ages indicate younging to the north, consistent with the northeast-facing indicators seen throughout this succession. The older U-Pb age of 2719.5 ± 1.7 Ma reported by Ayer et al. (2002) was determined on a felsic volcanic sample collected approximately 1.5 km northeast of sample 04BHA0333 (Fig. 1) and suggests that there may be an intervening structural discontinuity between these dated units.

Kamiskotia Volcanic Complex

The Kamiskotia Volcanic Complex includes all the known VMS deposits in the study area (Fig. 1). It lies stratigraphically above and along strike from the Kamiskotia Gabbroic Complex, and the two complexes were thought by Barrie (1992) to be broadly coeval. Geochemically, the Kamiskotia Volcanic Complex is markedly bimodal, with a compositional gap between 56 and 72 wt percent SiO_2, comparable to the gap between 64 and 71 wt percent SiO_2 identified in the Blake River Group in the Rouyn-Noranda district (Gélinas et al., 1977). Facing directions determined from pillow packing and sharp-based, graded volcaniclastic units in the Kamiskotia Volcanic Complex south of the Steep Lake fault (Fig. 1) are to the east or northeast. These rocks generally dip steeply to the west (typically ≥75°). The east-facing succession continues north into northern Godfrey and southern Jamieson Townships and swings to a northwest-southeast strike in northern Robb Township. In these areas the volcanic succession is underlain by intrusive rocks of the Kamiskotia Gabbroic Complex to the west and south, and observed facing directions are uniformly to the east or northeast, except in Jamieson Township about 2 km east of the Jameland mine, where pillow packing indicates facing to the southwest (Fig. 1). The reversal in facing direction suggests the presence of a synclinal axis in that area.

Felsic metavolcanic rocks

The lower part of the Kamiskotia Volcanic Complex, to the south of the Steep Lake fault (Fig. 1), consists mainly of felsic metavolcanic rocks. The stratigraphy of the lowermost part of the succession is most clear in eastern Turnbull Township. Here a lower, western unit consists of coarsely

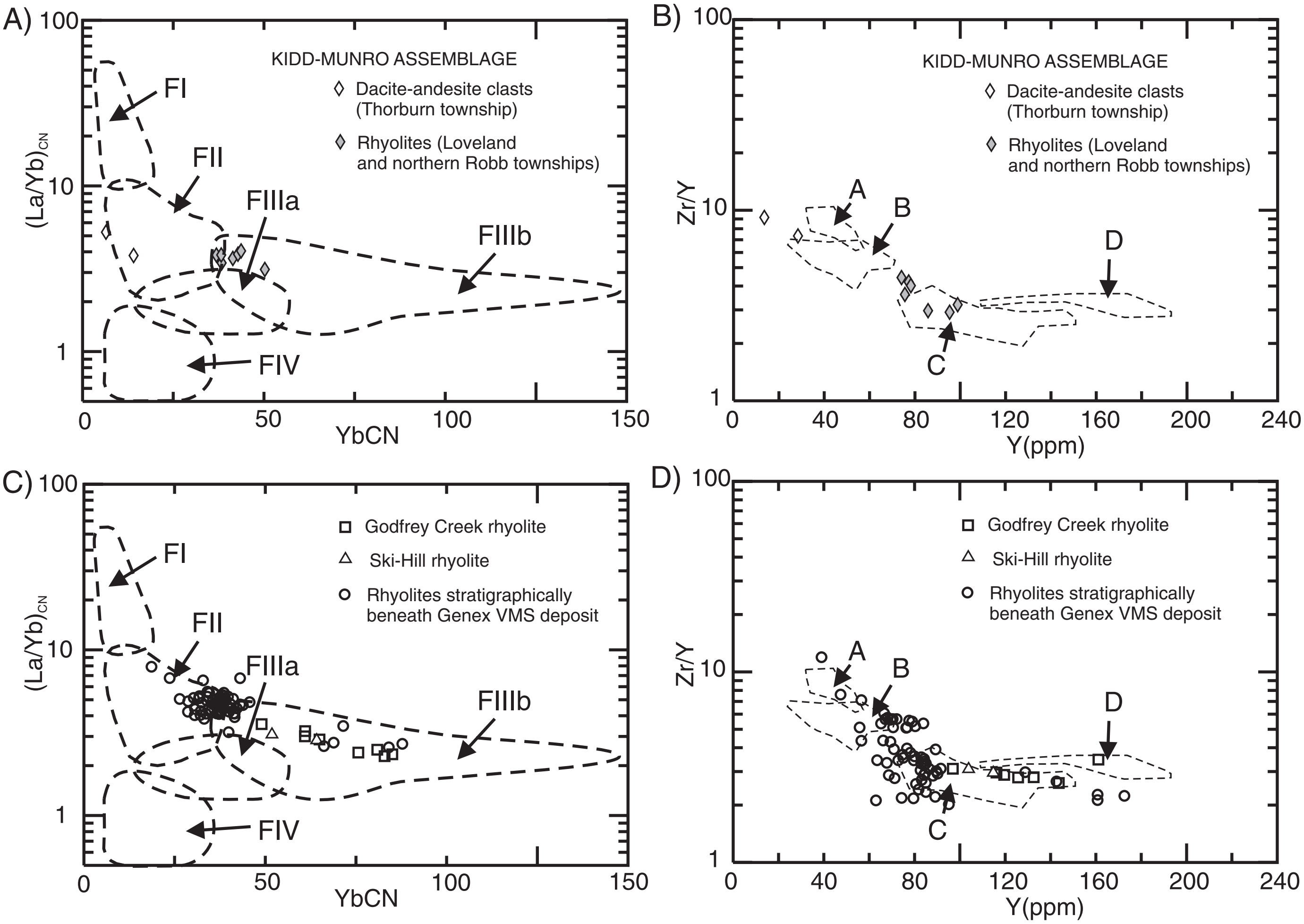

FIG. 3. Plots of $[La/Yb]_{CN}$ vs. $[Yb]_{CN}$ and Zr/Y vs. Y for Kidd-Munro assemblage felsic and intermediate rocks from Loveland, Robb, and Thorburn Townships (A) and (B) and Kamiskotia Volcanic Complex rhyolites stratigraphically below and above the main VMS-hosting interval (C) and (D). Fields for FI to FIV rhyolites in (A) and (C) are from Hart et al. (2004). Fields in (B) and (D) are from Lesher et al. (1986): A = nine ore-associated FII samples from Sturgeon Lake area, B = 23 reassociated FIIIa rhyolites from the Noranda district, C = 21 ore-associated FIIIb rhyolites from Kamiskotia and Kidd Creek, D = five ore-associated FIIIb rhyolites from the Matagami district. Normalizing values in (A) and (C) are from Nakamura (1974).

porphyritic coherent rhyolite with associated tuff-breccia and lapilli tuff in which clasts and matrix are characteristically hard to distinguish. This is overlain by a unit of finely porphyritic to aphyric, finely flow-banded rhyolite and associated lapilli tuff. The latter consists of pale, unvesiculated lithic lapilli and more ductile, dark, originally glassy fragments in a dark, sericite-rich matrix. The middle part of the felsic succession is best exposed to the north of the Aconda Lake fault (Fig. 1), where it consists of intervals of massive quartz- and feldspar-phyric coherent rhyolite from 100 to 700 m thick, alternating with similar thicknesses of compositionally similar, commonly bedded, sericitized lapilli tuff. Farther south, the mafic pillow lavas in the Genex mine area (Hocker, 2005) are underlain by at least 600 m of felsic lapilli tuff with minor tuff breccia but relatively little coherent rhyolite.

Higher in the succession, north of the Steep Lake fault and southeast of Steep Lake (Fig. 1), there is a large area of strongly foliated porphyritic coherent rhyolite and lapilli tuff, with minor intercalated mafic pillow lava. These felsic rocks appear to be continuous with an interval of felsic lapilli tuff that extends north within a mainly mafic volcanic succession to the felsic volcanic intervals at the level of the Canadian Jamieson mine. Intervals of rhyolite, rhyolite breccia, and lapilli tuff to the northeast of the mine seem to be a further northward continuation of this stratigraphic interval, offset to the east across the Kamiskotia Highway fault (Fig. 1). The felsic rocks continue along strike to the northwest, through the thick-bedded rhyolite breccia and lapilli tuff exposed in the large "Shell outcrop" (Fig. 1; described in detail by Comba et al., 1986) to a cluster of outcrops exposing northeast-facing felsic lapilli tuffs 1.5 km south-southeast of the Jameland mine. Although there is no exposure of felsic rocks in the intervening area, drill core intersections suggest that this felsic interval is continuous, across a series of further eastward fault offsets, with the rhyolites and felsic volcaniclastic rocks at the Kam Kotia mine. Although the Kamiskotia Volcanic Complex is not exposed in the area from Kam Kotia west to Halfmoon Lake, drilling indicates that the succession at this level is

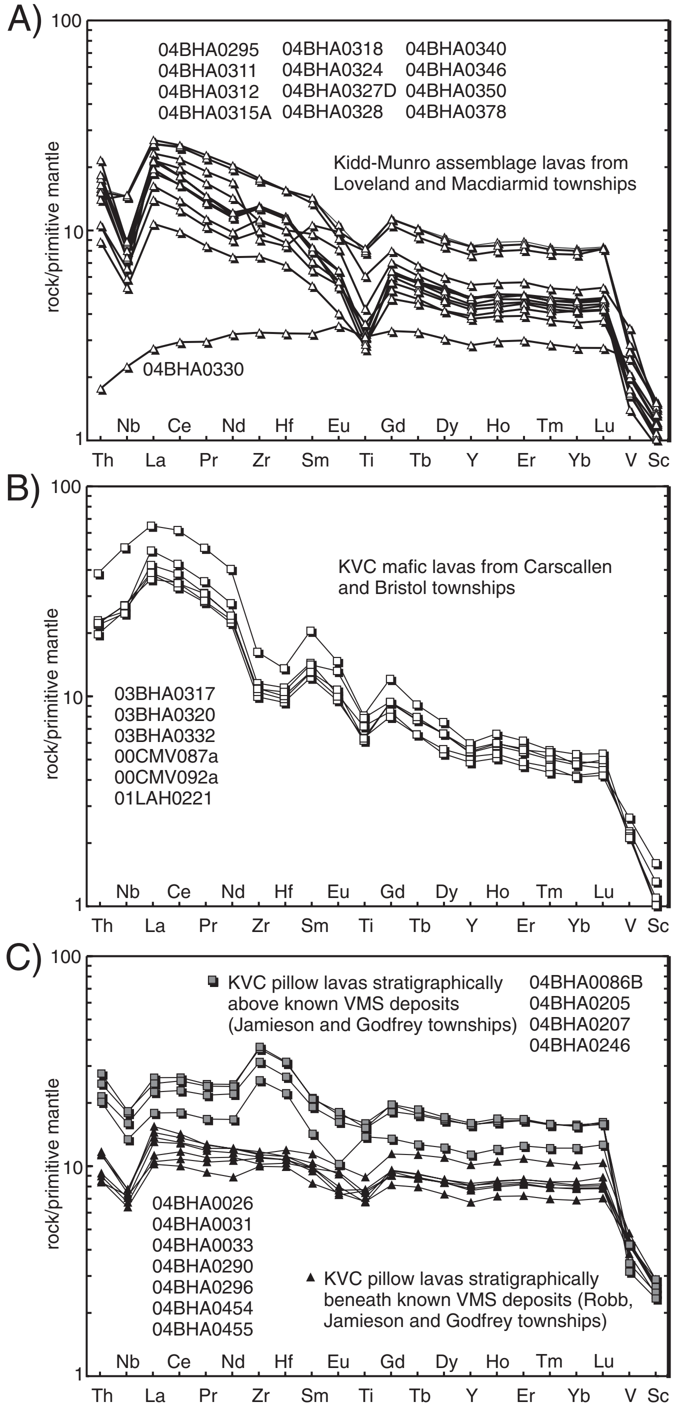

FIG. 4. Primitive mantle-normalized trace element plots for mafic-intermediate lavas from the Kamiskotia area. All data are from this study, except samples 00CMV and 01LAH in (B), which are from Vaillancourt and Hall (2003). Normalizing values are from Sun and McDonough (1989) and Kerrich and Wyman (1996: Sc and V).

almost wholly mafic. Closely spaced drilling shows that the area around and beneath the southern part of Halfmoon Lake (Fig. 1) is underlain by a series of stacked lenses of coherent rhyolite (commonly strongly foliated) with subordinate lapilli tuff. Farther west, felsic rocks form a series of relatively thin lenses, commonly enclosed by gabbro.

The felsic volcanic interval extending south from the Canadian Jamieson mine is overlain by east-facing mafic volcanic rocks. Stratigraphically above these are the extensively exposed Ski- Hill and Godfrey Creek rhyolite units (Fig. 1; informally named here). The main part of the Ski- Hill unit (~900 m thick) consists of aphyric coherent rhyolite with locally abundant chlorite-rich inclusions (usually <1 cm). The easternmost part of the unit (to 180 m thick) is a porphyritic rhyolite which gradationally overlies the aphyric facies. An interval of coarse-grained quartz-feldspar intrusive rock up to 90 m thick (see Kamiskotia Gabbroic Complex below), which apparently grades upsection into aphyric rhyolite, is typically present at the base of the Ski-Hill unit. The Godfrey Creek rhyolite, which lies immediately east of the Ski-Hill unit, consists of finely phyric to aphyric, commonly flow-banded, coherent rhyolite, with subordinate rhyolite breccia and minor lapilli tuff. The dark inclusions seen in the Ski-Hill rhyolite are absent. An outcrop just north of the Kamiskotia Highway fault exposes a sharp, unfaulted contact between the porphyritic eastern zone of the Ski-Hill unit and rhyolite breccia of the Godfrey Creek unit. The southwest-facing pillows in Jamieson Township lie immediately northeast of the Godfrey Creek rhyolite; rhyolitic breccias close to the unexposed contact are intensely sheared. The mafic volcanic rocks, accompanied by sedimentary rocks farther south, appear to form a discontinuous interval on the eastern flank of the rhyolite. Rhyolite and felsic lapilli tuff similar to the Godfrey Creek unit are exposed beyond this to the northeast, in the area toward the Kamiskotia River.

Sparse diamond drilling and rare outcrops in the area to the northeast of and stratigraphically above the Kam Kotia VMS deposit indicate the presence of a thick succession of aphyric coherent rhyolite flows and associated rhyolite breccia. This includes subordinate mafic volcanic rocks and, about 1.5 km north of Kam Kotia mine, a northeast-facing sedimentary interval. Although these rocks lie broadly along strike from the Ski-Hill and Godfrey Creek rhyolites, it is difficult to correlate between the two areas with the available data.

Lithogeochemistry: Rhyolites from the lower part of the Kamiskotia Volcanic Complex, stratigraphically beneath the Genex VMS deposit, have high silica contents (74–82 wt % SiO_2) and low TiO_2 contents (0.09–0.4 wt %). REE patterns typically show gentle negative slopes and strong negative Eu anomalies (Hathway et al., 2005); however, rocks from the lowermost part of the succession (Fig. 2B) have weaker Eu anomalies. In the $[La/Yb]_{CN}$ versus $[Yb]_{CN}$ diagram (Fig. 3C), these rhyolites cluster in the FII field and the low Yb part of the FIIIb field, with most having slightly higher $[La/Yb]_{CN}$ and lower $[Yb]_{CN}$ than the rhyolites of the Kidd-Munro assemblage. In the stratigraphically higher, eastern part of the area, but still beneath the Genex deposit, rhyolites are distinctly enriched in HREE, plotting well into the FIIIb field in the $[La/Yb]_{CN}$ versus $[Yb]_{CN}$ diagram. Rhyolites in drill core along strike to the southeast of the Kam Kotia deposit fall in the FIIIb field, and a rhyolite from the felsic lens hosting the Halfmoon Lake deposit falls in the FII field. In a detailed study of the Halfmoon Lake prospect, T. J. Barrett and W. MacLean (unpub. data) found FIIIa and FIIIb rhyolites, and FII-type high Ti dacites in this lens, although many of their analyses appear to be of volcaniclastic rocks.

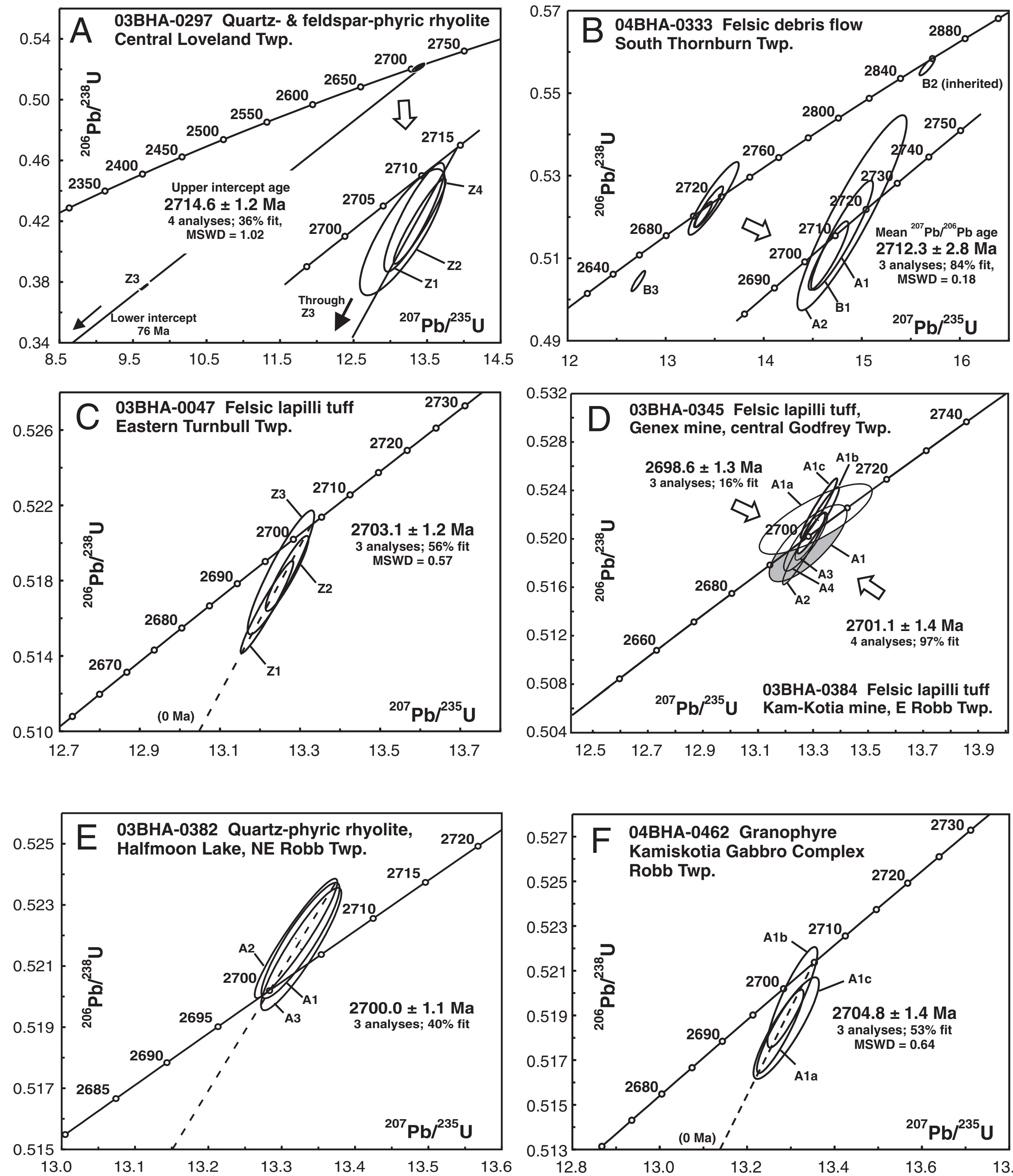

FIG. 5. Concordia diagrams showing U-Pb zircon data from the Kamiskotia area.

Rhyolites from the Ski-Hill and Godfrey Creek units in the upper part of the Kamiskotia Volcanic Complex, above the VMS deposits, contain 75 to 82 wt percent SiO_2, with TiO_2 ranging from 0.15 to 0.4 wt percent. These rocks show flat REE patterns with strong negative Eu anomalies (Fig. 2C) and plot well into the FIIIb field in the $[La/Yb]_{CN}$ versus $[Yb]_{CN}$ diagram (Fig. 3C).

Thus, rhyolites in the lower part of the Kamiskotia Volcanic Complex and at the level of the VMS deposits include FII and low Yb FIIIb types, with minor high Yb FIIIb rocks, whereas rhyolites in the upper part of the Kamiskotia Volcanic Complex are uniformly of the high Yb FIIIb type (Fig. 3C, D).

Mafic metavolcanic rocks

In the southernmost part of the study area, mafic volcanic rocks form a west-northwest–trending lens in northeast Carscallen and northwest Bristol Townships (Fig. 1). They consist of aphyric to sparsely plagioclase phyric, massive and pillowed flows, with minor amoeboid pillow breccia. Pillows are typically large (to 3 m) and weather to a distinctive pinkish gray (Hall and Smith, 2002b). Facing directions are inconclusive but suggest tops broadly to the east.

East-facing, typically aphyric, pillowed and massive basaltic lavas in the Genex mine area and syndepositional mafic sills in the underlying felsic volcaniclastic succession are described in detail by Finamore et al. (2008). Basaltic units in the Steep Lake area, and extending north to Canadian Jamieson mine, appear to be broadly stratigraphically equivalent to the Genex basalts. To the southeast of the Canadian Jamieson mine and across the Kamiskotia Highway fault to the northeast, pillow lavas at the top of this succession immediately underlie the Ski-Hill rhyolite. These basalts appear to extend north, offset by a series of faults, to form the thick succession of pillowed and massive basalt that underlies the Kam Kotia and Jameland VMS deposits. A thick succession of generally aphyric, variably vesicular pillow lavas with associated hyaloclastite and pillow breccia, stratigraphically above the Kam Kotia VMS deposit has been intersected by a number of drill holes (e.g., Falconbridge J51-01, J51-07). The southwest-facing pillow lava section in Jamieson Township consists of a number of ~5-m-thick flows, with massive bases and pillowed upper parts.

Lithogeochemistry: Mafic lavas from Carscallen and Bristol Townships are geochemically distinct basalts to basaltic andesites characterized by fractionated REE (La/Yb_{PM} = 7.4–12.3), high absolute Nb abundances, and negative Zr-Hf anomalies on primitive mantle-normalized plots (Fig. 4B). Most samples contain between 17.7 and 19.4 ppm Nb and are therefore classed as Nb-enriched basalts (Nb = 6–20 ppm; Wyman et al., 2002), although one sample is a high Nb basalt (>20 ppm). Normalized Nb abundances are greater than Th (Th/Nb_{PM} = 0.7–0.9) and lower than La (Nb/La_{PM} = 0.5–0.8).

Kamiskotia Volcanic Complex mafic lavas in Godfrey, Jamieson, and Robb Townships are basalts to basaltic andesites with Nb between 3.7 and 10.6 ppm. Hart (1984) divided these rocks into primitive and overlying, more evolved types, with the former having lower Ti, Zr/Y, Zr/TiO_2, Zr/Hf, and total REE, and higher Mg than the latter. New geochemical data reported here support this division, which is clear on plots of TiO_2 against Zr and P_2O_5. The division between the two lava types appears to coincide with the VMS-hosting interval at the Canadian Jamieson and Kam Kotia mines. On the Jensen cation plot, both types fall in the tholeiitic basalt field, but basalts lying stratigraphically above the VMS deposits are more Fe rich than those below. Both types have relatively flat normalized REE patterns (La/Yb_{PM} = 1.33–1.98), generally with slight to moderate negative Eu anomalies (Eu/Eu^* = 0.74–1.00), but there is a consistent increase in total REE stratigraphically upward from the primitive into the more evolved lavas (Fig. 4C). The latter also show marked positive Zr-Hf anomalies on primitive mantle-normalized plots (Fig. 4C). These evolved lavas are geochemically similar to Fe, Ti, and incompatible element-enriched tholeiitic basalts (Fe-Ti basalts) reported by Barrie and Pattison (1999) in their detailed study of the Kam Kotia deposit. They describe a footwall consisting largely of primitive tholeiites, with minor Fe-Ti basalt intrusions, whereas the hanging wall includes thick, evolved Fe-Ti basalt sill-flow units (interpreted here as sills).

Clastic sedimentary rocks

A sedimentary succession up to 200 m thick and extending for at least 2.3 km along strike was intersected by a series of drill holes (e.g., Falconbridge DDH R56-02, J51-02) northeast of the Kam Kotia mine (Fig. 1). This interval is underlain and overlain by coherent rhyolite and felsic lapilli tuff. It consists largely of thin- to medium-bedded tuffaceous sandstone and thick (up to at least 1.3 m), poorly sorted granule- to pebble-grade beds consisting mainly of angular to subrounded felsic volcanic lithic clasts. Sandstone beds commonly have upper divisions of graphitic mudstone. The thicker beds contain abundant mudstone and/or sandstone intraclasts and variable amounts of pyrrhotite fragments. Facing is to the northeast. A sedimentary interval intersected by drilling (e.g., Falconbridge DDH J14-01, J14-02) in southern Jamieson Township to the east of the Godfrey Creek rhyolite is described as graphitic argillite with intercalated felsic tuff and lapilli tuff. It lies broadly along strike from the sedimentary rocks northeast of Kam Kotia and could represent a southeastward extension of that interval. These strata occur within and form part of the Kamiskotia Volcanic Complex.

Geochronology

A U-Pb zircon age of 2705 ± 2 Ma for a Kamiskotia Volcanic Complex rhyolite outcrop in Godfrey Township (Barrie and Davis, 1990) led Ayer et al. (2002) to place that succession in the Tisdale assemblage (2710–2703 Ma). Figure 5 and Table 3 present new U-Pb zircon ages of 2703.1 ± 1.2 Ma for a felsic lapilli tuff from eastern Turnbull Township (sample 03BHA0047), 2698.6 ± 1.3 Ma for a felsic lapilli-tuff from the Genex deposit (sample 03BHA0345), 2701.1 ± 1.4 Ma for a felsic lapilli-tuff from Kam Kotia (sample 03BHA0384), and 2700.0 ± 1.1 Ma for a quartz-phyric rhyolite from Halfmoon Lake (sample 03BHA0382). The four new ages together are interpreted to span the age range for the greater part of the Kamiskotia Volcanic Complex (Fig. 1). The three latter ages, all from felsic rocks underlying the main VMS-hosting intervals, are within error of each other, indicating a similar timing for VMS mineralization in the three areas. Although the new age from Turnbull Township is within error of the older Barrie and Davis (1990) age, the new ages from the upper part of the Kamiskotia Volcanic Complex are significantly younger. They indicate that this part of the succession is slightly younger than the youngest previously known Tisdale rocks and thus coeval with the Blake River assemblage (2701–2697 Ma: Ayer et al., 2002).

Kamiskotia Gabbroic Complex

Barrie (1992) divided the Kamiskotia Gabbroic Complex into four zones, of which only the uppermost two are found in the present study area. Gabbro-norite and hornblende gabbro of the Upper zone are exposed to the northeast and southwest of Kamiskotia Lake and to the northeast of Steep Lake. Northeast-facing directions were determined by Barrie (1992) in Upper zone cumulates to the south and west of Kamiskotia Lake. Intrusive rocks generally of felsic to intermediate composition lying above and along strike from the Upper zone were included in the granophyre zone (Barrie, 1992). To the south of the Steep Lake fault, these rocks form numerous broadly concordant sill-like bodies which are typically fine to medium grained and equigranular but may be plagioclase-phyric. Areas of microgabbro also occur, and in Robb and Jamieson Townships gabbroic sills are common in the Kamiskotia Volcanic Complex up to and above the level of the Kam Kotia and Jameland VMS deposits.

The felsic intrusive rocks exposed to the south and east of Steep Lake have been described as spherulitic granophyre (Hogg, 1955) and spherulitic microdiorite (Middleton, 1976). These rocks are feldspar-phyric to aphyric with a groundmass dominated by spheroidal structures up to 2 mm across. Darker, generally fine-grained, chlorite- ±carbonate-rich inclusions are common, locally making up the greater part of the rock. Intermittent outcrops and drill core data indicate that the Steep lake granophyre extends north to the footwall of the Canadian Jamieson mine and beyond, offset across the Kamiskotia Highway fault (Fig. 1). Farther to the northeast, similar inclusion-rich felsic intrusive rocks are found in drill holes beginning 600 m east of the Jameland mine and extending northeast along strike, through and beyond the Kam Kotia hanging wall, for over 4 km. The inclusion-rich facies is exposed in a number of small outcrops immediately north of the Kam Kotia open pit. Barrie and Pattison (1999, fig. 6) interpreted these rocks as mixed-magma intermediate lapilli ash tuffs; however, they are lithologically similar to phases of the granophyre east of Steep Lake and may represent part of the same intrusive body.

Geochronology

A new U-Pb zircon age of 2704.8 ± 1.4 Ma for a granophyric phase of the Upper zone of the Kamiskotia Gabbroic Complex (sample 04BHA0462: Fig. 5F, Table 3) is slightly younger than a previous age of 2707 ± 2 Ma from the stratigraphically lower, Middle zone gabbro in Turnbull Township, west of the present study area (Barrie and Davis, 1990). The new age is slightly older than (but within error of) the age of 2703.1 ± 1.2 Ma for the lower part of the Kamiskotia Volcanic Complex, which the gabbro appears to intrude, and significantly older than the 2700.0 ± 1.1 Ma Kamiskotia Volcanic Complex rhyolite age from Halfmoon Lake, only 2 km to the northeast (Fig. 1). This problematic age relationship is discussed further below.

VMS deposits

The four past-producing VMS deposits in the Kamiskotia Volcanic Complex have a number of characteristics in common: (1) they comprise numerous small lenses of massive sulfide; (2) they occur in a restricted (<150 m) stratigraphic interval that is broadly correlative between the deposits (Barrie, 2000; Hathway et al., 2005); (3) their host rocks are predominantly mafic volcanic rocks with subordinate felsic lithologic units; (4) they are characterized by alteration zones comprising proximal chloritic alteration and silicification with more widespread semiconformable sericitic ± chloritic alteration; and (5) the ore consisted largely of pyrite, pyrrhotite, chalcopyrite, and sphalerite, with minor magnetite and/or galena (Barrie, 2000).

Kam Kotia mine

Development and production at the Kam Kotia mine took place mainly between 1961 and 1972 (Barrie and Pattison, 1999; Barrie, 2000). Ore was recovered from seven steeply dipping, shallowly (30°) northwest-plunging massive sulfide lenses (six Cu-rich, one Zn-rich). VMS mineralization was hosted by a steeply northeast dipping, northeast younging succession of mafic and felsic lavas and volcaniclastic strata, chemical metasedimentary rocks (chert exhalites, massive sulfide horizons), and mafic intrusions (Fig. 6). Lenses lower in the stratigraphy consisted of massive sulfide, whereas stringer-type mineralization characterized the uppermost lenses.

New mapping identified three northeast-trending faults south and west of the Kam Kotia open pit (Fig. 6). The two fault zones located immediately south-southwest of the open pit are believed to be synvolcanic structures based on offsets in stratigraphic units and VMS horizons, the presence of disconcordant diabase intrusions (described below), and an increase in alteration intensity. The location of these two faults broadly coincides with a synvolcanic fault zone described by Barrie and Pattison (1999).

The lower part of the succession consists of at least 155 m of variably amygdaloidal basaltic pillow lava and associated interpillow hyaloclastite. A 60- to 80-m-thick succession of thin- to very thick bedded rhyolitic tuff breccia, lapilli tuff, and tuff overlies the pillow basalts and can be traced for at least 500 m along strike. A locally sulfide-bearing chert horizon up to 2 m thick occurs at the base of this interval. These felsic volcaniclastic strata occur approximately 100 m into the footwall of the Kam Kotia orebodies. A second interval of amygdaloidal basaltic pillow lava and hyaloclastite crops out approximately 100 m west-southwest of the Kam Kotia open pit. This unit is up to 95 m thick and can be traced along surface for at least 400 m west of the open pit. Outcrops of matrix-supported pillow breccia with a chlorite-rich recrystallized hyaloclastite matrix approximately 50 m west of the open pit are typically stained brownish red owing to the presence of oxidized sulfide minerals. These rocks hosted the western, subsurface lenses of the Kam Kotia orebody (Barrie and Pattison, 1999).

Coherent high silica rhyolite (Barrie and Pattison, 1999) and associated breccia and tuff form the immediate footwall and host rocks to the main Kam Kotia massive sulfide lens. A lower interval consisting of 4 to 25 m of spherulitic rhyolite and associated breccia and tuff breccia is commonly strongly sericite altered and locally replaced by pyrite-rich massive sulfide. This is overlain by 8 to 16 m of locally flow-banded, sparsely quartz-phyric, sparsely to moderately amygdaloidal coherent spherulitic rhyolite which can be traced from 50 m northwest to 350 m southeast of the open pit. Overlying this is a second, 8- to 25-m-thick interval of coherent spherulitic rhyolite with localized chlorite- and quartz-altered autoclastic and hyaloclastite breccias and tuff breccias. This unit is locally

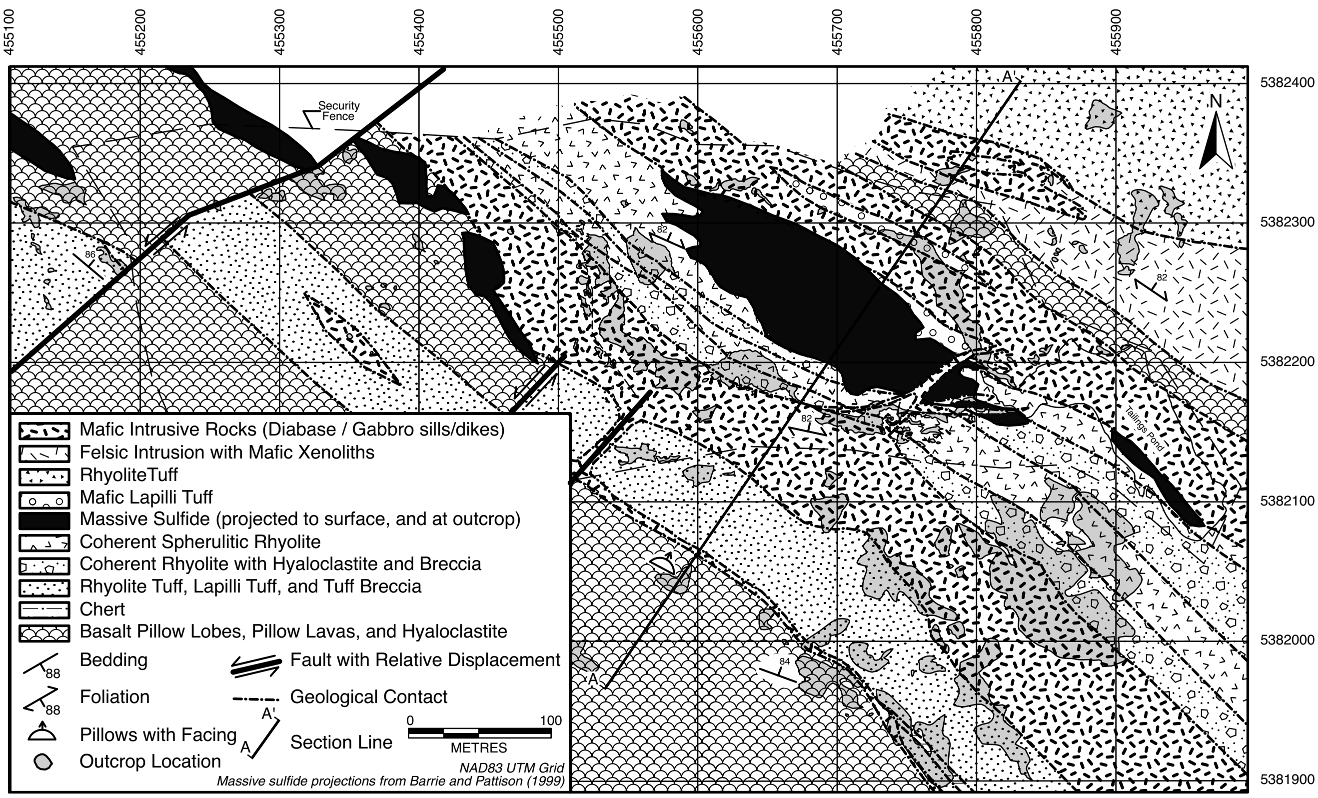

FIG. 6. Surface geologic map of the Kam Kotia mine area (after Hathway et al., 2005). Section A-A' is shown in Figure 9.

cut by several generations of quartz sulfide veins and significantly to totally replaced in the southeastern wall of the open pit by up to several meters of semimassive to massive pyrite, with minor sphalerite and chalcopyrite. An uppermost interval consists of 8 to 33 m of sparsely quartz-phyric, locally flow-banded, spherulitic rhyolite that locally shows well-preserved perlitic fractures (see Barrie and Pattison, 1999, fig. 5A).

The immediate hanging wall of the main Kam Kotia orebody consists of two lenses of massive mafic lapilli tuff, with maximum thicknesses of 11 and 16 m, separated by a basaltic sill (see below). The lapilli tuffs consist of 15 to 20 vol percent locally amoeboid, scoriaceous lapilli in a chlorite-rich matrix containing abundant subhedral feldspar crystals. An amygdaloidal pillow basalt unit up to 25 m thick crops out approximately 65 m into the hanging wall. This is overlain by feldspar- and quartz- phyric felsic tuff and lapilli tuff, which form the uppermost stratigraphic unit mapped in the mine area, and have been geochemically classified by Barrie and Pattison (1999) as high K, high silica rhyolite.

Three distinct types of intrusion occur in the Kam Kotia mine area. Fine- to medium-grained diabasic to gabbroic sills occur in the immediate footwall and hanging wall to the largest orebody. The footwall sill consists of tholeiitic basalt (Barrie and Pattison, 1999), is up to 90 m thick, and can be traced along strike for at least 450 m. The easternmost of the inferred synsedimentary faults has been identified by the presence of a disconcordant diabase intrusion that may have been a feeder to this sill. A hanging-wall sill up to 65 m thick is lithologically similar to the footwall sill. Fine-grained dikes (described as pyroxenite dikes by Barrie and Pattison, 1999) up to several meters across are locally present in outcrops rimming the Kam Kotia open pit, where they appear to have cut the massive sulfide mineralization. Rocks thought to represent part of the Steep Lake granophyre are exposed at two locations to the north and northeast of the open pit.

Hydrothermal alteration in the area of the Kam Kotia mine is variable and affects all rock types present. Chlorite, sericite, and, locally, quartz are the major alteration minerals, and epidote, zoisite and/or clinozoisite, iron carbonate, and fine-grained biotite or stilpnomelane occur in minor amounts. Chlorite alteration with local silicification is most prominent in the mafic and felsic footwall volcanic strata within approximately 150 m of the northeast-trending faults to the southwest of the open pit (Fig. 6) and in the mafic volcanic and volcaniclastic rocks that make up the north wall of the open pit. Intense sericite alteration affects both coherent and volcaniclastic felsic rocks east of the zone of chlorite alteration in the immediate footwall to the main orebody, suggesting the presence of a chlorite-sericite alteration pipe with a chlorite-rich core and sericite-rich margin centered on the northeast-trending faults. Less intense sericite alteration occurs in the felsic strata upsection from the deposit.

Jameland mine

The Jameland mine is situated 1.2 km southeast of, and along strike from, the Kam Kotia mine (Fig. 1). Minor production from this deposit (Table 1) occurred between 1966 and 1972 (Barrie and Pattison, 1999). Due to a lack of surface exposure and representative diamond drill core, the Jameland mine was not evaluated in detail during this study, and the description here is based on work by Pyke and Middleton (1971) and Middleton (1973). Host rocks for the mineralization included chloritized and brecciated mafic volcanic rocks and felsic tuffs. The central and eastern part of the deposit consisted of up to ten southeast-plunging (30°–35°) irregularly shaped lenses, whereas the western part comprised a single 15-m-thick lens. Metal distribution in the deposit was similar to that at the Kam Kotia mine, with the lower lenses being composed of massive, zinc-rich sulfides, and the upper lenses consisting largely of stringer-type, copper-rich ore.

Canadian Jamieson mine

Development of and production from the Canadian Jamieson mine (Fig. 7; Table 1) took place between 1966 and 1971. Ore was recovered underground from three stratabound sulfide lenses (the south, central, and north ore zones; Barrie, 2000). Economic mineralization occurred over a stratigraphic interval of approximately 100 m, primarily within mafic lapilli tuffs and tuff breccias, as well as interbedded rhyolite tuffs and chert, and rhyolitic lava flows and associated flow breccias.

At the base of the east-northeast–younging succession, a basaltic lava unit up to 140 m thick consists of pillows up to 3 m across surrounded by strongly chloritic interpillow hyaloclastite zones. This is overlain by an interval of laminated to thinly bedded felsic tuffs up to 6.5 m thick. A massive basalt lava flow or sill up to 22 m thick overlies the felsic tuffs with a sharp contact. A second interval of basaltic pillow basalt and associated hyaloclastite up to 60 m thick occurs immediately upsection from the massive basalt. Overlying the pillowed flows is a succession of interbedded felsic tuff and sulfide-bearing, laminated cherty exhalite up to 25 m thick. This is locally overlain by massive mafic lapilli tuff containing angular chert lapilli (1 vol %) and amygdaloidal basalt lapilli. Coherent spherulitic rhyolite and associated autoclastic and hyaloclastite breccia overlie the interbedded exhalites and felsic tuffs, as well as the mafic lapilli tuff. These rocks appear to have formed the immediate footwall and host rocks to VMS mineralization at the mine. The lower 13 m of this felsic succession consists of autoclastic rhyolite breccia. This is overlain by up to 65 m of weakly flow-banded, locally spherulitic, sparsely quartz-phyric coherent rhyolite, which grades upsection into a second horizon of autoclastic and hyaloclastite rhyolite breccia up to 25 m thick. This sequence is similar to those found in lobe-hyaloclastite flows in both ancient (Gibson, 1990) and modern (Yamagishi, 1991) settings. There is a sharp contact between the upper rhyolite breccias and an overlying succession of bedded felsic tuffs up to 20 m thick. A strongly chlorite- and/or carbonate-altered, matrix-supported, massive mafic lapilli tuff and/or tuff breccia containing up to 15 vol percent sparsely to moderately amygdaloidal basalt clasts immediately overlies the felsic tuffs. This unit, which is up to 40 m thick, also contains up to 12 vol percent lens-shaped clasts up to 15 cm across consisting of dark gray quartz and semimassive pyrite. Barrie (2000) noted that this unit forms the along-strike extension of the Canadian Jamieson north ore zone. A third horizon of sparsely amygdaloidal pillow basalt and associated hyaloclastite overlies the mafic tuffs and tuff breccias and is up to 70 m thick. The basalts are overlain by at least 80 m of massive felsic tuff, which forms the uppermost unit mapped in the area.

Fine- to medium-grained, north-northwest–trending Archean diabase dikes occur in the central and eastern parts of the Canadian Jamieson area. These dikes commonly show polygonal tortoise-shell jointing, as well as columnar jointing, suggesting that they were synvolcanic and quenched by seawater (McPhie et al., 1993). The north-northwest trend of the dikes, an apparent increase in alteration intensity, and proximity to VMS mineralization suggest that their emplacement was controlled by a synvolcanic fault zone. Coarser grained olivine diabase dikes of the Paleoproterozoic Matachewan swarm cut the Archean dikes in the south-central part of the mine area.

Hydrothermal alteration in the Canadian Jamieson area varies with both stratigraphic position and lithology. Rocks close to the mineralization are generally chlorite and/or sericite altered, although carbonate alteration, silicification, and epidotization also occur locally. Mafic coherent and volcaniclastic rocks, as well as the synvolcanic diabase dikes, generally show patchy to pervasive chlorite alteration and are locally patchily silicified. Chlorite is iron rich (showing anomalous "Berlin-blue" birefringence) and is associated with iron carbonate (footwall only) and dolomite or calcite (hanging-wall rocks). Patchy to dendritic veins of epidote up to 1 cm across are locally present in the mafic volcanic rocks. Felsic rocks show moderate to intense alteration to sericite (up to

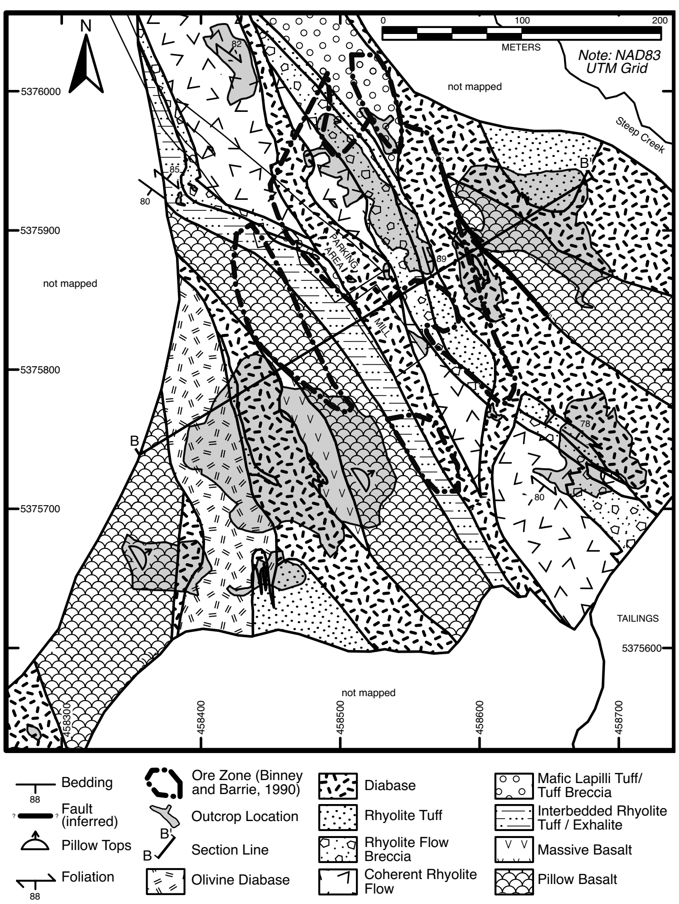

FIG. 7. Surface geologic map of the Canadian Jamieson mine area (after Hathway et al., 2005). Section B-B' is shown in Figure 9.

40 vol %) and iron-rich chlorite (up to 20 vol %). Trace quantities of andalusite are found locally within the footwall felsic tuffs.

Sericite- and chlorite-rich alteration mineral assemblages in the Canadian Jamieson area are typical of those produced by subaqueous hydrothermal systems proximal to VMS mineralization (Franklin, 1986; Morton and Franklin, 1987; Gibson et al., 1999; Franklin et al., 2005). The minor andalusite in the footwall felsic tuffs may record localized alteration by high-temperature acidic hydrothermal fluids moving up toward the paleosea floor near synvolcanic fault zones. The close association of ore zones with volcaniclastic strata suggests that primary permeability focused the hydrothermal fluid and subsequent alteration and mineralization. Sulfide replacement textures evident in surface exposures of the mafic lapilli tuff and/or tuff breccia suggest at least a partial synvolcanic replacement origin for the Canadian Jamieson orebodies.

Genex mine

The Genex mine (Fig. 8; Table 1) comprised two main orebodies (the C and H zones) from which 242 t of copper concentrate were produced between 1964 and 1966 (Middleton, 1975; Binney and Barrie, 1991). The stratigraphy and lithogeochemistry of the east-facing, steeply east dipping succession in the mine area are described in detail by Hocker (2005) Hocker et al. (2005), and Finamore-Hocker et al. (2008). The lower part of the succession consists of up to 590 m of felsic tuff breccia, lapilli tuff, and tuff with minor felsic lava and and associated flow breccia. The H zone mineralization occurs near the top of this unit adjacent to synvolcanic intermediate dikes. The felsic volcaniclastic rocks are overlain by a 130-m-thick massive basalt unit, and overlying this is a 200-m-thick interval of pillow basalt and associated pillow breccia and hyaloclastite. The C zone mineralization is hosted by an 8-m-thick pillow breccia immediately overlying the pillow basalts. The hanging wall to the C zone comprises a 52-m-thick massive basalt flow that is overlain by a 35-m-thick interval of felsic lapilli tuff and tuff. The felsic volcaniclastic strata are overlain by a second basaltic flow unit, with a massive, 70-m-thick basal portion and an upper, 360-m-thick pillowed division. These lavas are overlain by 370 m of volcaniclastic deposits (tuff breccia, lapilli-tuff, and tuff), epiclastic strata (mudstone, graphitic argillite), and minor mafic and felsic lavas. The Genex succession has been intruded by numerous synvolcanic intermediate and mafic sills and dikes. The contacts between these intrusions and adjacent volcanic strata are commonly irregular and locally peperitic. There is a close spatial association between synvolcanic intermediate dikes and VMS mineralization, suggesting that east-trending synvolcanic structures played a role in localizing both the mineralization and subsequent magmatism.

There is no well-defined zonation of alteration mineral assemblages in the Genex area (Hocker, 2005). Felsic rocks are

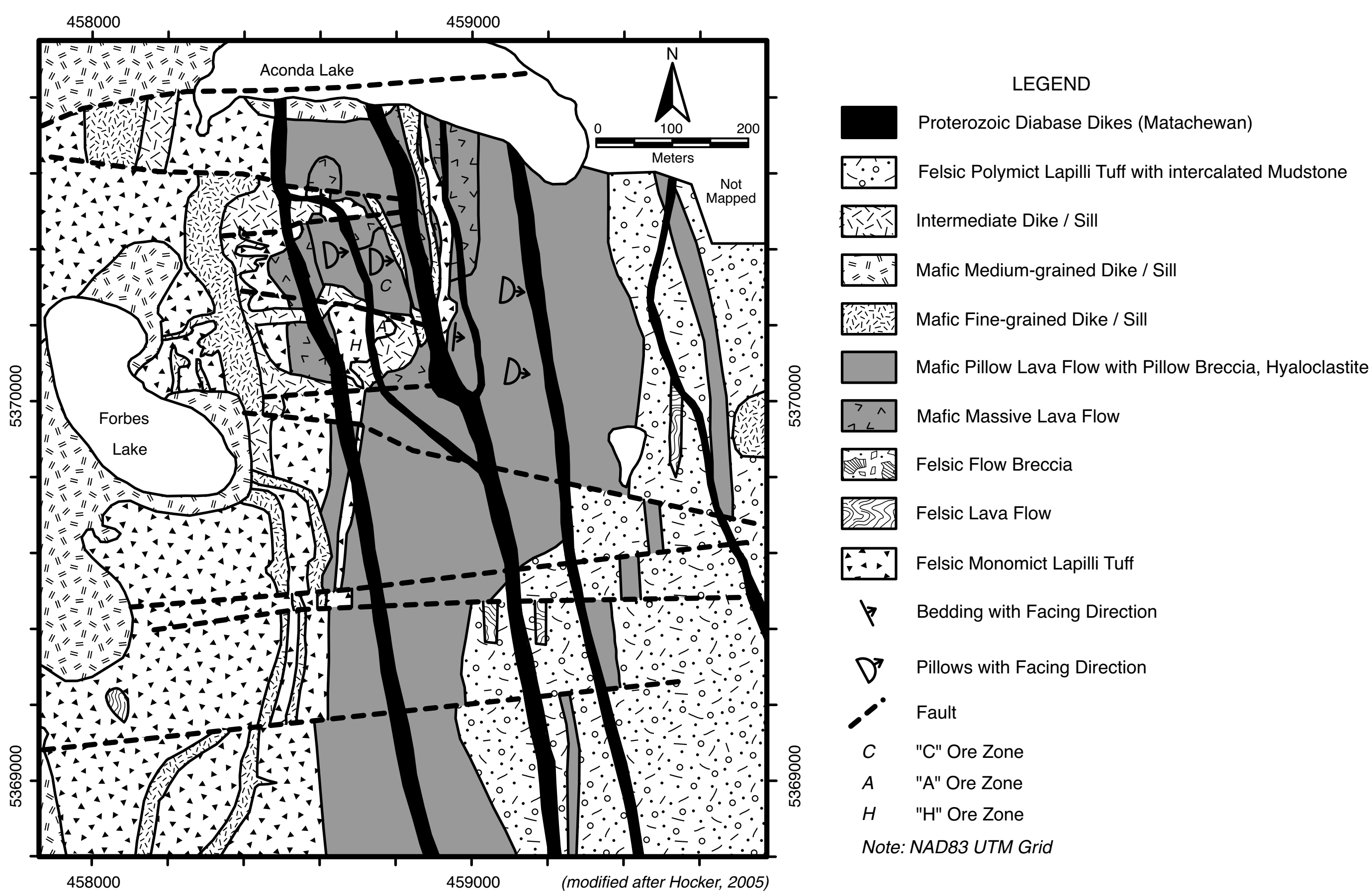

FIG. 8. Surface geologic map of the Genex mine area (modified after Hocker et al., 2005).

principally sericitized, with alteration more intense in footwall than hanging-wall rocks, perhaps reflecting waning hydrothermal activity after the mineralizing event (Hocker, 2005). Mafic extrusive rocks, as well as the intermediate and mafic synvolcanic intrusions, are largely chloritized, with volcaniclastic facies generally more intensely altered than coherent units, suggesting localization of alteration-associated hydrothermal fluids in more permeable facies. The Genex deposits are interpreted by Finamore et al. (2008) as subseafloor replacement deposits.

Synvolcanic Faults in the Kamiskotia Volcanic Complex

There is a well-defined break in the Kamiskotia Volcanic Complex stratigraphy across the east-northeast–trending Aconda Lake fault in Godfrey and Turnbull Townships (Fig. 1). Although the nature of any displacement within the Kamiskotia Volcanic Complex is uncertain owing to lack of marker horizons, this fault appears to have localized the emplacement of Kamiskotia Gabbroic Complex intrusive rocks, suggesting an early synintrusion and/or synvolcanic history. A series of northwest-trending faults (including the Steep Lake and Kamiskotia Highway faults) occurs in northern Godfrey and southern Jamieson Townships (Fig. 1). Offset of marker intervals (e.g., Steep Lake granophyre, Ski-Hill rhyolite) across these faults is consistently dextral in plan view. Although there is little firm evidence for synvolcanic movement, outcropping of the Ski-Hill rhyolite terminates abruptly to the north across one of these faults. A system of northeast-trending faults is well developed in Robb Township, southwest Jamieson Township, and northern Godfrey Township (Fig. 1). These are marked by offset of exposed felsic volcanic intervals in southern Jamieson Township. Farther west (Kamiskotia Lake area), offset of magnetic phases of the Kamiskotia Gabbroic Complex and gabbroic sills in the complex are clear from aeromagnetic data, but there appears to be no consistent sense of movement. Although the relationship of these faults to the northwest-trending faults is uncertain, there is evidence for synvolcanic displacement on northeast-trending faults in the Kam Kotia mine area. Numerous synvolcanic fault zones have been recognized at the Kam Kotia, Canadian Jamieson, and Genex mines, and their location proximal to mineralization and hydrothermally altered strata suggests they played a major role in focusing hydrothermal fluids during ore genesis.

Depositional Processes and Setting

Felsic volcaniclastic intervals in the lower part of the Kidd-Munro assemblage and much of the Kamiskotia Volcanic Complex are typically poorly sorted and massive to crudely stratified. They consist mainly of monomict tuff breccia and lapilli tuff composed largely of angular, nonvesicular, commonly flow-banded clasts. Vesiculated pumice fragments may be present but are rarely abundant. Clasts are generally lithologically similar to adjacent coherent rhyolite, and these volcaniclastic rocks are interpreted as primary autobreccia and hyaloclastite (cf. Fisher and Schmincke, 1984). Together with associated rhyolites they are interpreted as representing the lobe-hyaloclastite flows of Gibson et al. (1999). Well-bedded, graded, typically monomict felsic volcaniclastic units intercalated with fine tuff and/or more rarely mudstone are interpreted as syneruptive autoclastic or hydroclastic deposits that have undergone downslope redeposition by sediment gravity flows (cf. Gibson et al., 1999). The polymict-oligomict volcaniclastic rocks found in the upper part of the Kidd-Munro succession are interpreted as epiclastic mass-flow deposits. Reposited volcaniclastic intervals in the Kidd-Munro assemblage and Kamiskotia Volcanic Complex show no evidence for deposition above storm wave base.

The common relationship between semimassive and massive sulfide mineralization and volcaniclastic strata (autoclastic breccia, hyaloclastite, pillow breccia) suggests that the Kamiskotia Volcanic Complex VMS deposits may have formed primarily as synvolcanic replacement-type (Doyle and Allen, 2003; Stix et al., 2003) massive sulfides within permeable strata immediately beneath the sea floor rather than as mounds on the sea floor. Preservation of VMS deposits is greatly enhanced in such environments. Although Barrie and Pattison (1999) suggested that the presence of amygdaloidal pillow lavas at Kam Kotia might indicate a shallow submarine environment, the depth of water in which the deposit formed remains poorly constrained. The lack of wave-generated bedforms in the volcaniclastic strata suggests deposition at a depth of at least 150 to 200 m (Draper, 1967; Butman et al., 1979). Water depths of at least 500 to 1,000 m would have been required to prevent extensive boiling of the hydrothermal fluids (Herzig and Hannington, 1995).

Regional Significance

Kidd-Munro assemblage

The new U-Pb ages of 2714.6 ± 1.2 and 2712.3 ± 2.8 Ma indicate that the Kidd-Munro assemblage rocks in Loveland, Macdiarmid, and Thorburn Townships are coeval with the Kidd Volcanic Complex (2717.0 ± 2.6 to 2711.5 ± 1.5 Ma: Bleeker et al., 1999), which hosts the giant Kidd Creek VMS deposit 30 km east of the study area. There, ore-forming hydrothermal activity is thought to have been long-lived, lasting for up to 3 m.y. (Bleeker et al., 1999). The rhyolites in Loveland Township are geochemically similar to FIIIb rhyolites in the footwall and immediate hanging wall of the Kidd Creek deposit, and overlying mafic lavas show some similarities to light REE-enriched evolved arc basalts in the Kidd Creek hanging wall (Wyman et al., 1999). However, the komatiites and low Ti tholeiites that form much of the Kidd Creek footwall (e.g., Wyman et al., 1999) do not appear to be present in the Kamiskotia area.

Kamiskotia Volcanic Complex

Nb-enriched basalts, similar to those found in Carscallen and Bristol Townships, have not been previously identified in the Blake River Group or elsewhere in the Timmins area. However, they do occur elsewhere in the Superior province (e.g., Wawa and Wabigoon subprovinces), where they are associated with tholeitic to calc-alkaline arc basalts and are interpreted as the products of intra-arc extension and/or transtension (Wyman et al., 2002). Nb-enriched basalt forms part of a magmatic association with adakite and high Mg no. andesites (Wyman et al., 2002). Most of the upper Kamiskotia Volcanic Complex pillow lavas analyzed in this study can be classed as high Mg no. andesites (andesitic lavas with Mg nos. >0.3 and <10 wt % MgO: Kelemen, 1995), as can a high proportion of Blake River Group lavas elsewhere (Wyman et al., 2002). Although adakites are not found in the Kamiskotia Volcanic Complex they have been identified nearby in the Timmins area, forming the broadly coeval (2698 ± 4 Ma) Krist fragmentals (Jackson and Fyon, 1991; Wyman et al., 2002).

Rhyolites in the lower part of the Kamiskotia Volcanic Complex and at the level of the VMS deposits include FII and low Yb FIIIb types, with minor high Yb FIIIb rocks, whereas rhyolites in the upper part of the Kamiskotia Volcanic Complex are uniformly of the high Yb FIIIb type. Lesher et al. (1986) found no evidence for systematic vertical trace element geochemical variations in relationship to mineralization in Superior province felsic metavolcanic rocks. However, the variation seen in the Kamiskotia Volcanic Complex does appear to resemble the trend from barren FII to mineralized FIIIb rhyolites upstratigraphic section noted in the Confederation Lake area by Thurston and Fryer (1983).

U-Pb ages from the Genex, Kam Kotia, and Halfmoon Lake successions indicate a similar timing for VMS mineralization in the three areas. These ages from the upper part of the Kamiskotia Volcanic Complex indicate that it is slightly younger than the youngest previously known Tisdale assemblage rocks and may be more correctly considered as part of the Blake River assemblage (2701–2697 Ma: Ayer et al., 2002). The volcanic successions in the Kam Kotia and Canadian Jamieson areas are similar, with a similar stratigraphic position for the VMS deposits in the two areas (Fig. 9). The Kamiskotia VMS deposits show many similarities to the intracauldron VMS deposits in the time-equivalent Noranda succession in the Blake River Group of northwestern Quebec (Gibson and Watkinson, 1990). As at Noranda, the Kamiskotia Volcanic Complex deposits are largely confined to a single time-stratigraphic interval within a bimodal mafic lithostratigraphic assemblage (Barrie and Hannington, 1999; Franklin et al., 2005). In terms of the two-fold classification of VMS-hosting footwall successions proposed by Gibson et al. (1999), the Kamiskotia Volcanic Complex and Noranda successions represent lava flow- rather than volcaniclastic-dominated environments. The two footwall types are thought to correspond broadly to deep- and shallow-water settings, respectively (Gibson et al., 1999), although it is clear that further work is necessary to more accurately determine water depths in ancient VMS systems (Franklin et al., 2005). In flow-dominant successions, owing to the relative impermeability of host rocks, ascending hydrothermal fluids and resulting proximal discordant alteration are typically restricted to areas immediately adjacent to permeable synvolcanic structures, as seen at the Kam Kotia mine. Host-rock impermeability in coherent (flow) facies also tends to localize sulfide precipitation at the sea floor, typically resulting in lens-shaped massive sulfide deposits with underlying stringer and/or stockwork zones, as seen in the Kamiskotia Volcanic Complex deposits. However, the localization of economic massive sulfide mineralization in volcaniclastic facies at each of the Kamiskotia Volcanic Complex ore deposits reflects the important role that the primary permeability of volcaniclastic strata plays in localizing hydrothermal fluid flow, as well as sulfide-replacement mechanisms.

Although synvolcanic faulting has been inferred in the Kamiskotia Volcanic Complex, it is uncertain whether extension

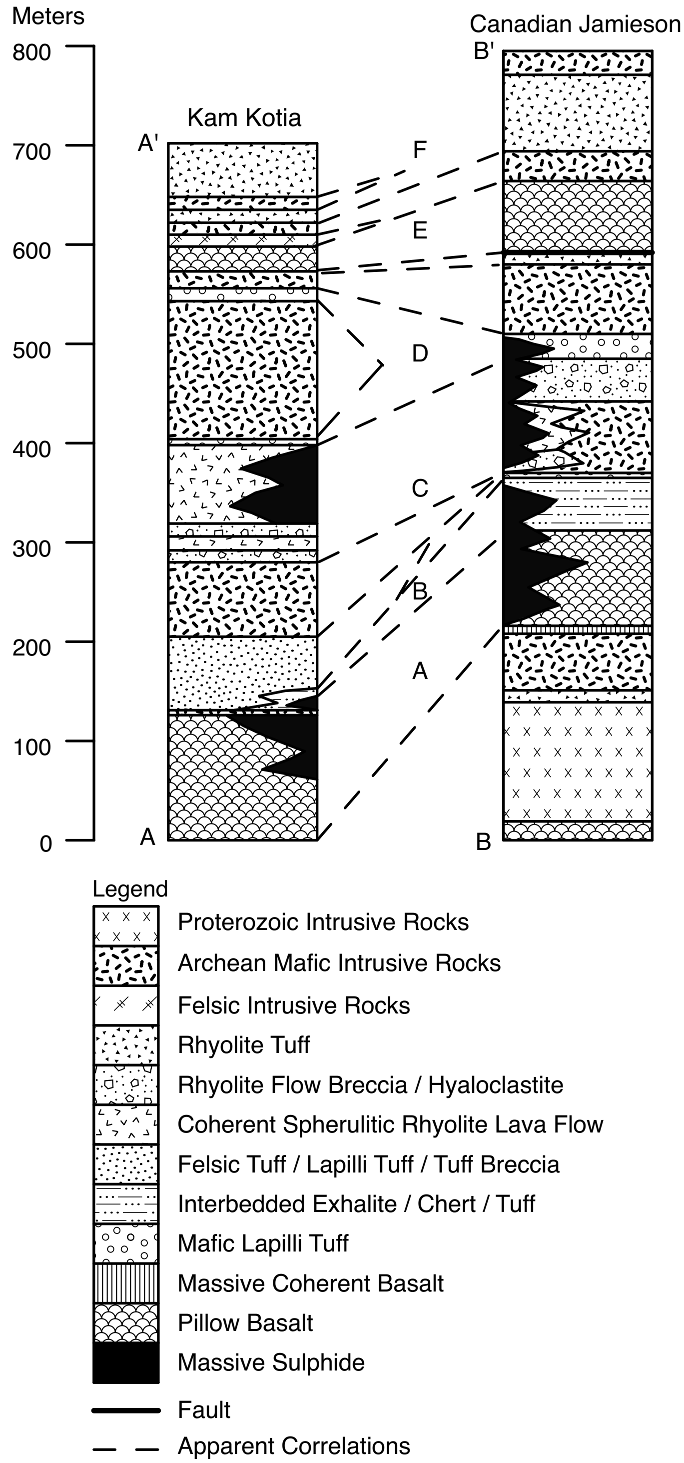

FIG. 9. Apparent stratigraphic correlations between the Kam Kotia and Canadian Jamieson VMS deposits, based on composite stratigraphic sections. Note that the detailed lithostratigraphic sequences and stratigraphic positioning of VMS mineralization at the two deposits are similar. From the base of the stratigraphic sections, these correlations include: (1) pillowed basalt with VMS mineralization; (2) exhalites, cherts, and tuffs and associated VMS mineralization; (3) rhyolite lavas flows and associated volcaniclastic facies with VMS mineralization; (5) mafic lapilli tuffs and tuff breccias with VMS mineralization; (6) pillow basalts; and (7) felsic tuffs. Stratigraphic positions of VMS mineralization at Kam Kotia and Canadian Jamieson are based on Barrie and Pattison (1999) and Binney and Barrie (1991), respectively.

took place within a cauldron, as in the Noranda succession (Gibson, 1990; Gibson and Watkinson, 1990), or within a wider, less focused extensional basin. Subsidence in the Noranda cauldron is thought to have occurred above a magma chamber now represented by the Flavrian pluton (Gibson, 1990). The spatial association of the VMS deposits with the underlying Kamiskotia Gabbroic Complex suggests the possibility of a similar relationship in the Kamiskotia area (cf. Finamore et al., 2008). If such a volcanic subsidence structure is identified in the Kamiskotia area, it is likely to have resulted from voluminous effusive rather than explosive volcanism, a feature characteristic of Abitibi calderas (Mueller et al., 2004). Field relationships and geochemical similarities indicate that felsic rocks in the upper part (granophyre zone) of the Kamiskotia Gabbroic Complex represent the intrusive equivalent of felsic volcanic rocks in the upper part of the Kamiskotia Volcanic Complex (Hathway et al., 2005). However, the new U-Pb age of 2704.8 ± 1.4 Ma from the Upper zone (Barrie, 1992) of the Kamiskotia Gabbroic Complex west of Kamiskotia Lake is significantly older than the 2700.0 ± 1.1 Ma age from the overlying Kamiskotia Volcanic Complex at Halfmoon Lake, suggesting that the gabbroic complex may be a multiphase intrusion. If these two ages are accepted, the Halfmoon Lake succession must have been deposited on a slightly older basement complex already intruded by the gabbro. As Halfmoon Lake is only 2 km to the northeast of the dated Upper zone outcrop, any such older succession must be relatively thin. During emplacement of the gabbro, a thickness of cover rocks at least equal to that of the intrusion would have been required in order to prevent lithostatic failure and eruption of magma to surface (Galley, 2003). This suggests that a considerable thickness of rocks overlying the gabbro may have been removed prior to emplacement of the younger Halfmoon Lake succession. Given the suggested deep-marine setting, significant erosion of volcanic rocks seems unlikely, but it is possible that a thick section could have been removed by another mechanism, such as sector collapse of a volcanic edifice (e.g., McGuire, 2003; H. Gibson, pers. commun.).

Suggestions for VMS Exploration in the Kamiskotia Region

High silica FIIIb rhyolites in south-central Loveland Township are coeval with and geochemically similar to FIIIb rhyolites associated with massive sulfide ore at the Kidd Creek VMS deposit and appear to represent the most prospective part of the Kidd-Munro assemblage in the Kamiskotia region.

Within the Kamiskotia Volcanic Complex, it appears that the Kam Kotia, Canadian Jamieson, and probably the Jameland VMS orebodies are situated in the same time-stratigraphic interval. As many VMS deposits in a district may occur along a single stratigraphic level (Franklin et al., 1981; Gibson et al., 1999), this interval is an important target for future VMS exploration. Identification of VMS targets within the interval may be accomplished by detailed analysis of lithologic facies, identification of a change in mafic volcanic geochemistry from primitive to evolved, recognition of increased intensity of chlorite or sericite alteration, as well as associated lithogeochemical enrichment in magnesium and iron, and depletion in alkali and alkali earth elements (Barrie and Pattison, 1999), and the recognition of synvolcanic intrusive rocks that may have been emplaced within synvolcanic fault zones which could have acted as conduits for potential ore-forming fluids.

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