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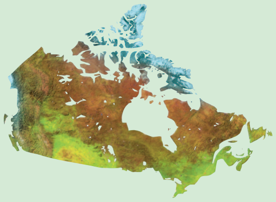

Mass changes and element mobility associated with the Westwood deposit ore zones, Doyon-Bousquet-LaRonde mining camp, Abitibi, Quebec

A. Wright-Holfeld, P. Mercier-Langevin, and B. Dubé

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Critical review
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Abstract: The world-class Westwood gold deposit in the Abitibi greenstone belt of northwestern Quebec consists of three main mineralized corridors stacked in the Bousquet Formation: the zone 2 extension in the north, the north corridor in the central stratigraphy, and the Westwood-Warrenmac corridor in the south. Mass changes of major and trace elements related to the hydrothermal alteration in the upper member of the Bousquet Formation were calculated using Zr as the least mobile element. The precursors used for mass-change calculations were the least altered rocks from the neighbouring LaRonde Penna deposit, which occurs in the same stratigraphic interval as the Westwood deposit. Mass changes in the host rock of the Westwood deposit can be used to make initial inferences about fluid flow in the ore-forming hydrothermal system and define vectors toward mineralization. Extensive mass gains in K and mass losses in Na in an approximately 150 m thick zone encompassing the north corridor and Westwood-Warrenmac footwall indicate widespread effects attributed to the hydrothermal system responsible for the formation of the deposit. This, combined with Mn-rich garnet and Mg-rich chlorite previously reported, indicates that the mineralizing fluid transported substantial amounts of Mn, Mg, and K. High field-strength elements and Y show patterns of maximum mass loss associated with the Westwood-Warrenmac corridor mineralization and maximum mass gains associated with the Bousquet Fault. The hydrothermal fluids at Westwood leached the underlying rock of mobile elements and redeposited them higher in the stratigraphy.

Résumé : Le gisement aurifère de classe mondiale de Westwood, situé dans le ceinture de roches vertes de l'Abitibi, dans le nord-ouest du Québec, se compose de trois corridors minéralisés principaux superposés dans la Formation de Bousquet : la zone 2 extension, au nord, le corridor nord, dans la partie centrale de l'empilement stratigraphique, et le corridor Westwood-Warrenmac, au sud. En utilisant Zr comme élément le moins mobile, on a pu calculer les changements de masse des éléments majeurs et des éléments traces associés à l'altération hydrothermale dans le membre supérieur de la Formation de Bousquet. Les précurseurs utilisés pour calculer ces changements de masse étaient les roches les moins altérées du gisement de LaRonde Penna, qui se situe à proximité du gisement de Westwood, dans le même intervalle stratigraphique que celui-ci. Les changements de masse dans la roche encaissante du gisement de Westwood permettent d'effectuer les premières déductions quant à l'écoulement des fluides dans le système hydrothermal minéralisateur, ainsi que de définir des vecteurs pointant vers la minéralisation. D'importants gains de masse en K et pertes de masse en Na ont été relevés dans une zone d'environ 150 m d'épaisseur qui englobe le corridor nord et le mur du corridor Westwood-Warrenmac, ce qui témoigne d'effets étendus attribuables au système hydrothermal à l'origine du gisement. Ces phénomènes, conjugués à la présence antérieurement signalée de grenat riche en Mn et de chlorite riche en Mg, indiquent que le fluide minéralisateur a transporté des quantités importantes de Mn, Mg et K. Les éléments à fort effet de champ ainsi que Y présentent des configurations de distribution témoignant de pertes de masse maximales associées à la minéralisation du corridor Westwood-Warrenmac, de même que des gains de masse maximaux liés à la faille de Bousquet. Les fluides hydrothermaux du gisement de Westwood ont lessivé les roches sous-jacentes de leurs éléments mobiles pour les déposer plus haut dans la stratigraphie.

INTRODUCTION

The Au-rich quartz-sulphide vein systems and volcanogenic massive sulphide (VMS) lenses of the Westwood deposit are located in the Doyon-Bousquet-LaRonde mining camp, which is hosted in the Bousquet Formation located in the Neoarchean Blake River Group in northwestern Québec (Fig. 1; Mortensen, 1993; Ayer et al., 2002; Lafrance et al., 2005; McNicoll et al., 2009). The Westwood deposit (107.9 metric tonnes, at 7.6 g/t; Mercier-Langevin et al., 2010) contains three mineralized zones that are stacked from north to south: the zone 2 extension, the north corridor, and the Westwood-Warrenmac corridor (Fig. 2; Mercier-Langevin et al., 2009). Because of the stacking of mineralized horizons in complex stratigraphy that represents continued volcanic activity and protracted hydrothermalism, difficulty arises in accurately defining the temporal and spatial relationships between unique hydrothermal-alteration footprints and distinct mineralizing events. Inferred sequential stacking of synvolcanic ore lenses potentially indicates that some polyphase alteration occurred. Alternatively, alteration assemblages observed may be due to a single, long-lived hydrothermal event. A combination of both processes is also highly possible.

The Westwood deposit is hosted by mafic to felsic volcanic rocks, which are locally highly strained. Deformation zones often hinder recognition of the original stratigraphy and primary features such as volcanic textures and facies, adding a level of complexity to the study of this deposit. Upper greenschist- to lower amphibolite-grade metamorphism is extensive in the eastern part of the Blake River Group (Powell et al., 1995), and consequently, inferred hydrothermal alteration assemblages in this area are metamorphosed and do not reflect primary assemblages. For a detailed description of regional and deposit-scale geology and alteration assemblages, the reader is referred to the first part of this study (Wright-Holfeld et al., 2010).

The study of the Westwood deposit was undertaken by the Geological Survey of Canada, Iamgold Corp., and the Ministère des Ressources naturelles et de la Faune du Québec (MRNF) as part of a metallogenic synthesis of the Doyon-Bousquet-LaRonde mining camp that includes a Master's thesis at the Institut national de la recherche scientifique – Centre Eau, Terre et Environnement that is presented in part in this report.

The purpose of this contribution is to complement the results of field and analytical work reported in Wright-Holfeld et al. (2010) and to test whether or not geochemical trends documented therein are related to hydrothermal processes or merely functions of variations in protolith composition. An estimation of the scale of effects of the ore-forming hydrothermal system can be made by mass-change analysis carried out for samples in the upper member of the Bousquet Formation. Additionally, this paper serves to provide an initial characterization of the ore-bearing hydrothermal fluid or fluids related to the formation of the Westwood deposit.

METHODOLOGY

Geochemical-analysis techniques

Samples for this study were taken at regular intervals along drillholes logged, and were processed and analysed at Activation Laboratories in Ancaster, Ontario. Samples containing silica-rich veins and veinlets were omitted in order to provide a more accurate lithogeochemical signature for geological units observed. Geochemical analysis of samples was achieved by a combination of methods including mass spectrometry, coulometry, spectroscopy, gravimetry, neutron activation, and atomic absorption following total digestion by alkaline fusion.

Mass change calculations

Mass changes were calculated using the single precursor method outlined by MacLean and Kranidiotis (1987), and Barrett and MacLean (1994). Zirconium was used as the least mobile element for the enrichment factor (EF):

$$\mathrm{EF} = \mathrm{Zr}_{\mathrm{precursor}}/\mathrm{Zr}_{\mathrm{altered\ sample}}$$

The reconstructed composition (RC) of altered samples was calculated from anhydrous values in weight per cent (wt %) and parts per million (ppm):

$$\mathrm{RC} = (\mathrm{EF}) \times (\mathrm{wt\ \%\ or\ ppm})_{\mathrm{altered\ sample}}$$

The mass change of each element in each sample was then calculated by subtracting the precursor value of that element from the reconstructed composition of the sample:

$$\text{Mass change} = \mathrm{RC} - \text{precursor value}$$

Attempts were made to use the multiple precursor system method outlined in Barrett and MacLean (1994); however, due to the limited number of samples taken for the Westwood study, a definitive fractionation trend, and therefore the required hypothetical protoliths for the Westwood samples, could not satisfactorily be found. As outlined below, mass-change calculations were made using the least altered samples from the LaRonde Penna deposit to the east of the Westwood deposit.

MASS CHANGES IN THE WESTWOOD DEPOSIT HOST SEQUENCE

In order to calculate mass changes within a system, the immobility of at least one element must be demonstrated (e.g. Barrett and MacLean, 1994). Commonly accepted immobile elements that are incompatible during magmatic

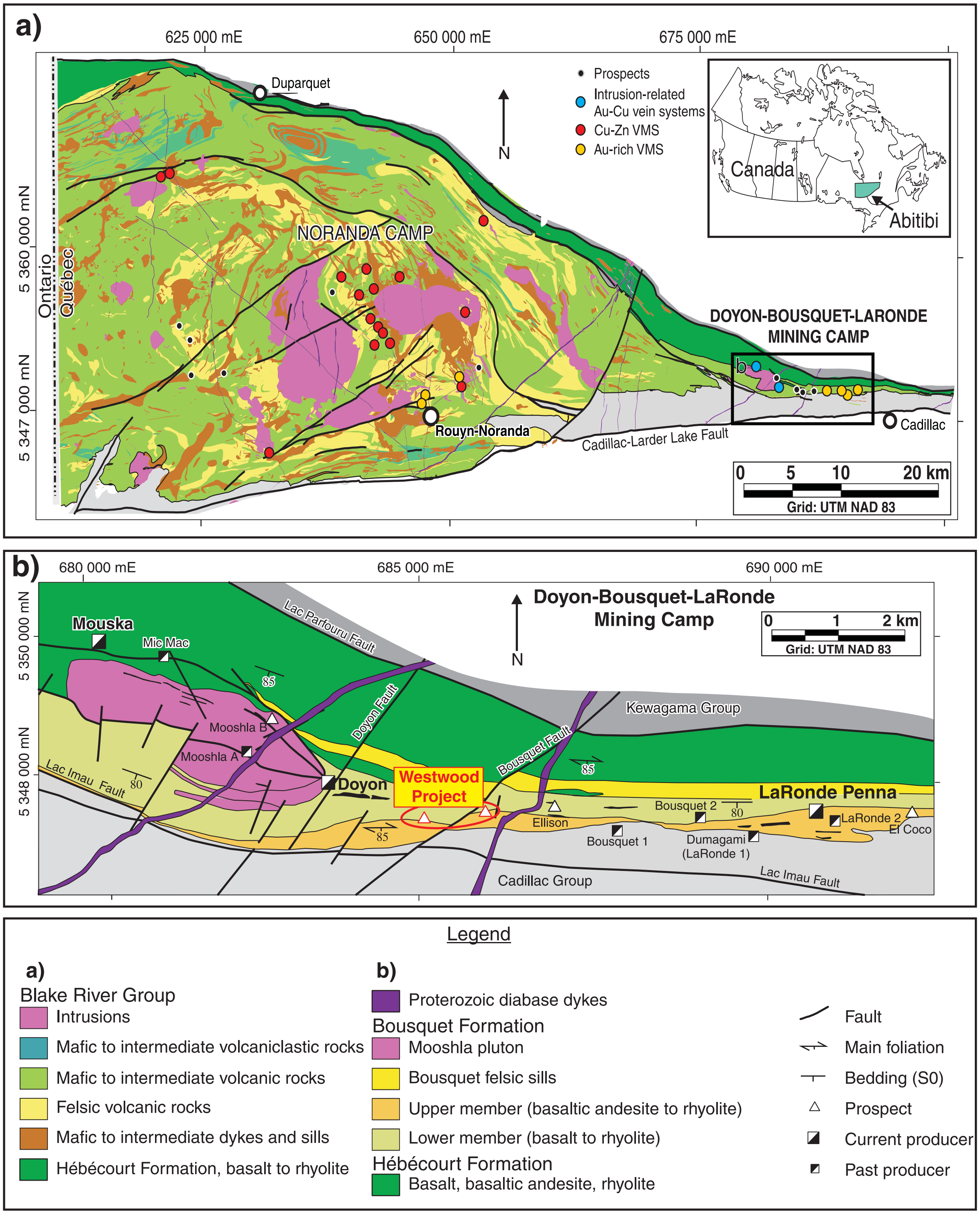

Figure 1. a) Simplified geological map of the Bousquet Formation and location of Doyon-Bousquet-LaRonde mining camp, *modified from* Lafrance et al., 2003. **b)** Inset map of the Doyon-Bousquet-LaRonde mining camp showing the location of the Westwood deposit, and other major deposits in the camp.

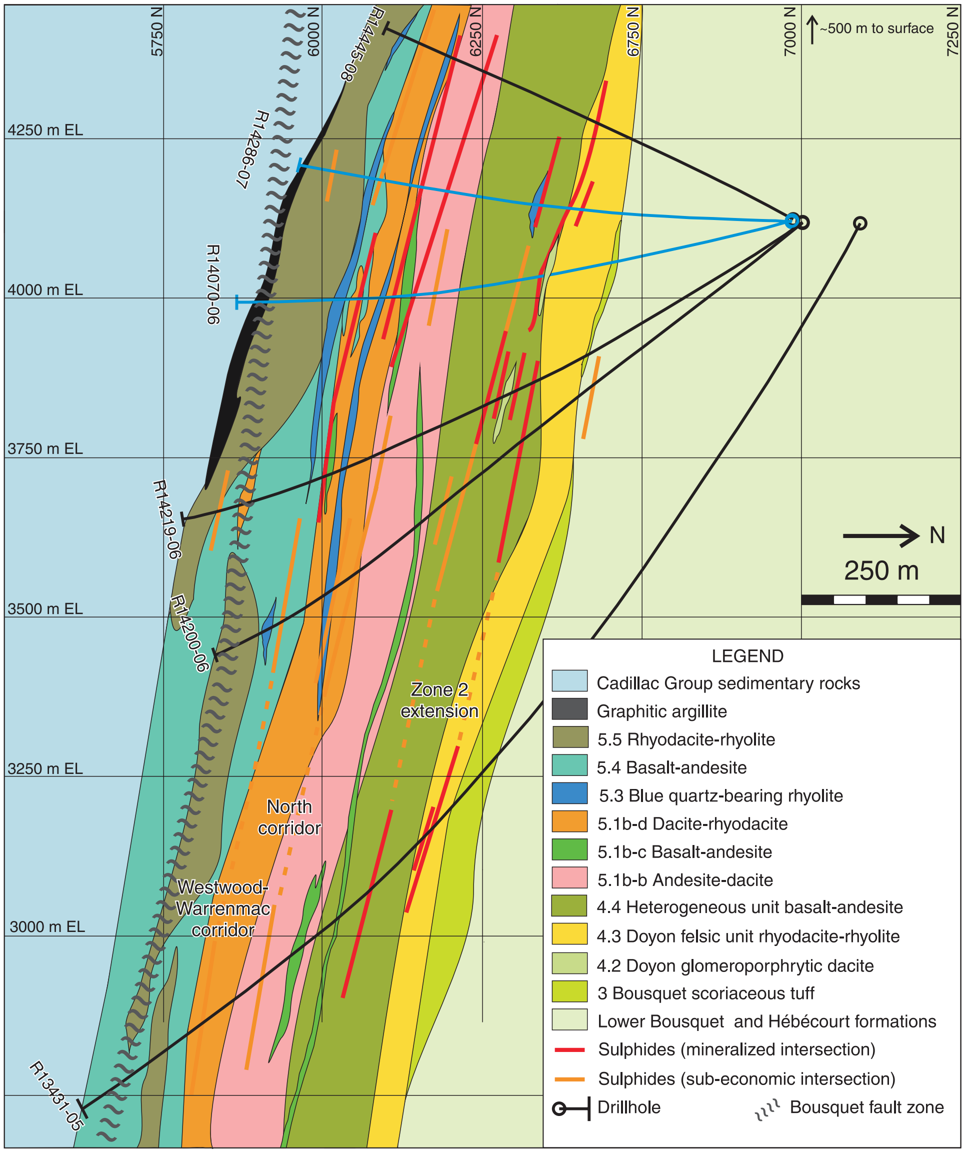

Figure 2. Westwood deposit geology showing mineralized intersections and drillhole traces (Wright-Holfeld et al., 2010).

fractionation, such as the high field-strength elements (HFSE) and Y, were plotted in bivariate graphs (Fig. 3; Fig. 4d *in* Wright-Holfeld et al., 2010) in an attempt to test the incompatibility and immobility of elements in the Westwood deposit, and in order to determine a suitable element for the enrichment factor for mass-change calculations. Based on previous work by many authors, and attempts at defining fractionation trends and alteration trends using Westwood samples, Zr was determined to be the least mobile element in the Westwood suite of samples taken.

The plots of high field-strength element values suggest their higher degree of immobility during alteration. Generally speaking, Hf and Zr behave similarly during magmatic fractionation (e.g. Sun and McDonough, 1989) and also during alteration processes, as demonstrated by their approximately constant ratio (Fig. 3d). The approximately constant ratio of Hf and Zr shows that these elements are both incompatible during fractionation as compatibility in either one of the elements would result in a greater spread of the data points, such as in Figure 3a. The fact that the linear trend between Hf and Zr is still present in heavily altered rocks indicates that they are highly immobile during secondary processes (Barrett and MacLean, 1994).

Despite the generally accepted notion of HFSE and Y immobility in VMS-related hydrothermal alteration (e.g. Pearce and Cann, 1973; Winchester and Floyd, 1977; MacLean and Barrett, 1993), our results show that these elements have experienced some mobility, thus resulting in changes in concentration at Westwood.

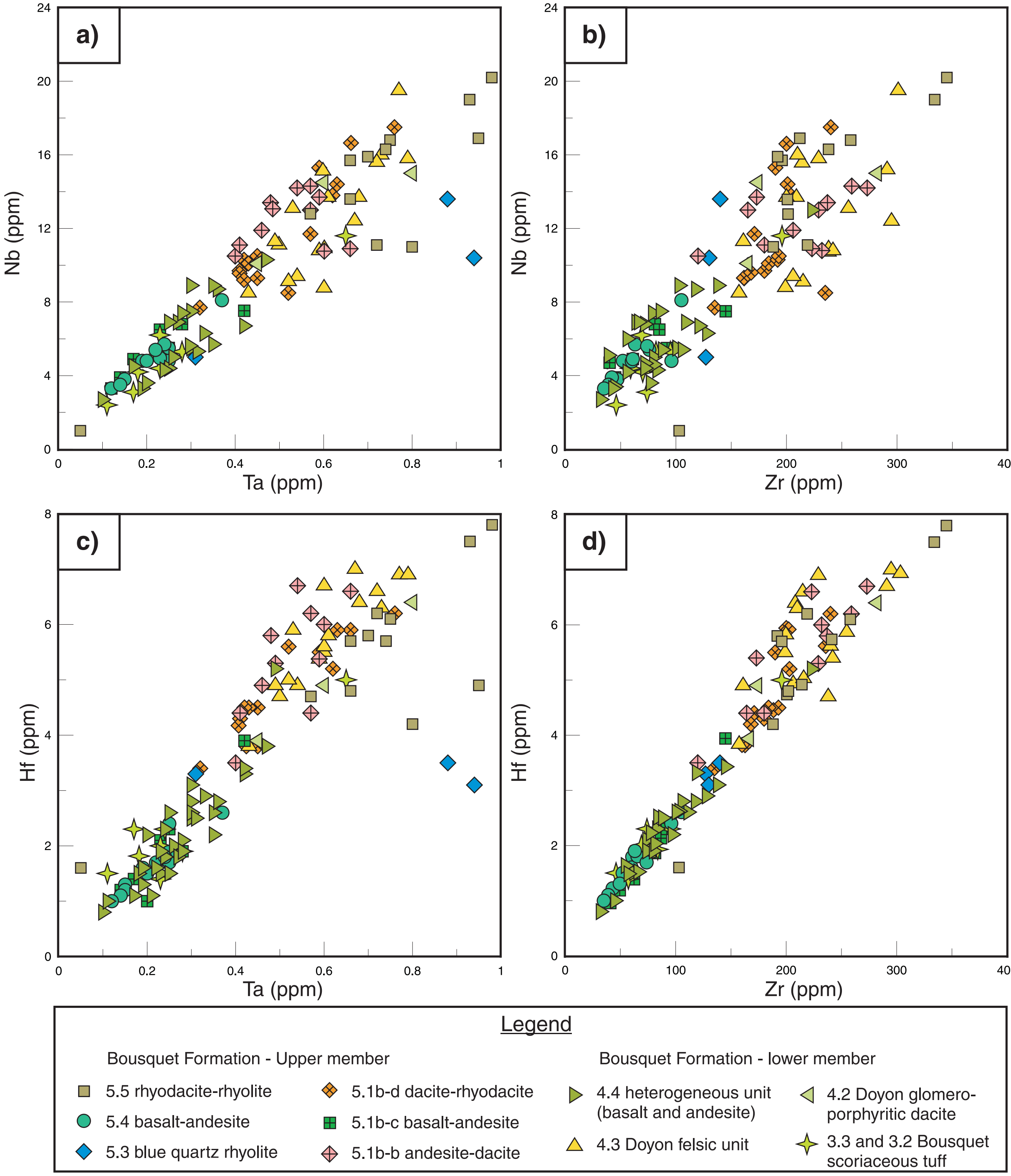

Figure 3. Bivariate plots of high field-strength elements (HFSE) used to verify magmatic incompatibility during fractional crystallization and immobility during alteration, metamorphism, and weathering. Westwood deposit samples in the upper and lower members of the Bousquet Formation. **a)** Nb-Ta bivariate plot, **b)** Nb-Zr bivariate plot, and **c)** Hf-Ta bivariate plot showing some alteration trends or compatibility during magmatic fractionation in the spread of data. **d)** Approximately linear Hf-Zr trend indicating high degree of immobility for Zr. Zirconium was chosen for the enrichment factor for mass-change calculations. Unit numbers refer to stratigraphy from Lafrance et al. (2003) and Mercier-Langevin et al. (2009).

To calculate mass changes for the Westwood samples the following assumptions were made:

1. Zirconium immobility and incompatibility: calculations were made using an enrichment factor based on Zr immobility and incompatibility during fractionation in all rock types (basalt to rhyolite) and all magmatic affinities (tholeiitic to calc-alkaline).
2. Precursor suitability: due to the highly altered nature of the rocks in the Westwood deposit area, the LaRonde Penna deposit least altered rocks (Dubé et al., 2007; Mercier-Langevin et al., 2007b) were used as precursors for Westwood sample comparison and mass-change calculations.

The lack of unaltered rocks in the Westwood samples hindered conclusive results of mass-change calculations based on the least altered Westwood samples. More coherent results were obtained by calculating mass changes in the Westwood deposit host rocks by using the least altered samples from LaRonde as precursors for altered Westwood samples. Despite the distance of approximately 8 km between the LaRonde Penna and Westwood deposits, lithological-unit correlations between the two deposits can be made based on major- and trace-element geochemistry, and textural and mineralogical similarities (Lafrance et al., 2003; Mercier-Langevin et al., 2007a; 2009; Wright-Holfeld et al., 2010), hence allowing for a quantification of mass gains and losses relative to an estimated least-altered protolith of the Westwood host rocks.

Major-element mass changes

Results of mass-change calculations for the north and Westwood-Warrenmac corridors showed that all major elements were mobile to some degree in the Westwood hydrothermal system (Table 1). Examination of mass changes in the stratigraphic column allows for the correlation of element mobility with ore zones and primary volcanic features such as fragmental textures, and associated porosity and permeability. Figure 4 illustrates the major oxide mass changes in samples taken from drillhole R14070-06 in the upper member of the Bousquet Formation at the Westwood deposit, to highlight mass changes with respect to lithological units and ore-zone host rocks. Core from drillhole R14070-06 was chosen to compare mass changes because the close spacing of samples in this drill hole allowed for a clearer idea of mass change trends along volcanic stratigraphy.

Results showed that Si has undergone extensive leaching, with local areas of mass addition in the upper member of the Bousquet Formation (Fig. 4). Mass losses occured in an approximately 100 m wide zone around the north corridor, which coincides with the Westwood-Warrenmac footwall rocks. In areas of fragmental volcanic rocks, Si mass changes were variable, including gains and losses. Despite their generally accepted immobility (Barrett and MacLean, 1991; MacLean and Barrett, 1993), Al and Ti showed some mass changes in Westwood deposit fragmental and coherent host rocks as well (Fig. 4, Table 1). Their mobility was confirmed by their spread of data on bivariate plots (not shown) using other more immobile elements such as Zr, and the HFSE on the x axis. Iron and S were systematically enriched in mineralized zones, as was expected by the presence of pyrite, sphalerite, chalcopyrite, and pyrrhotite.

Manganese and Mg were the most mobile major elements aside from Fe in the Westwood deposit alteration system (Table 1). Manganese and Mg generally displayed behaviour similar to each other in mass gain and loss patterns in the stratigraphy (Fig. 4). Averages of the absolute values of percent mass changes relative to LaRonde precursors served as a proxy for elemental mobility (*cf*. Barrett and MacLean, 2000), and showed that Mn and Mg were added and lost to the system up to 310% and 190% of precursor values, respectively, indicating a high degree of mobility for these elements. Of the major oxides, only Fe had a higher average mass change of 720%, which corresponded to weight-percent gains up to 590%. The large gains in Fe reflected the addition of iron sulphides associated with the mineralization.

The average of mass gains and losses in CaO (Table 1) showed that Ca was of high to intermediate mobility in the upper member of the Bousquet Formation at Westwood. Calcium was generally gained in north corridor and Westwood-Warrenmac corridor footwall rocks, although ore-bearing samples showed Ca losses. Calcium was consistently lost in the Westwood-Warrenmac ore zone and hanging wall in drillhole R14070-06, despite the presence of carbonates and other Ca-bearing minerals (Wright-Holfeld et al., 2010). However, Ca was gained in Westwood-Warrenmac hanging-wall samples from drillholes R14219-06 and R13431-05, suggesting major spatial variations in the effects of the hydrothermal system or local disturbances in the geochemical composition of alteration zones (e.g. fluid flow associated with inferred synvolcanic or late faults).

Extensive Na leaching of up to approximately 6 weight percent lost mass, corresponding with maximum losses of 97% relative to precursor values, occurred in the upper member of the Bousquet Formation. Only 6 of the 59 samples used for calculations showed Na mass gains. Mass gains in Na occurred in the hanging wall of the Westwood-Warrenmac ore zones in core from drillholes R14219-06 and R14070-06, in proximity to the ore zones, as well as in the Bousquet Fault.

Potassium showed widespread gains throughout the upper member of the Bousquet Formation, in association with both the north corridor and Westwood-Warrenmac corridor mineralization. Mass-change calculations yielded mass gains for the majority of samples. The average of the absolute values of mass changes relative to precursors indicated that K had high to intermediate mobility (Table 1).

Table 1. Average of absolute values of mass changes are used as a proxy for element mobility at the Westwood deposit.

	Maximum mass change (% of LaRonde precursor)	Minimum mass change (% of LaRonde precursor)	Average mass change (% of LaRonde precursor)	Increasing mobility
Zr	0.0	0.0	0.0	↓
Hf	37.5	0.2	9.3	
Nb	94.1	0.8	18.9	
Yb	62.6	1.0	20.6	
Ta	52.1	0.5	20.9	
Ho	60.9	0.4	21.6	
Sm	58.4	0.5	21.8	
Dy	78.9	0.6	22.2	
Er	75.6	1.2	22.4	
Nd	60.9	0.7	22.4	
Ce	63.3	0.1	22.5	
Tm	61.7	1.9	22.5	
La	66.8	0.6	23.0	
Al_2O_3	148.1	0.2	23.8	
U	58.8	0.2	24.1	
Pr	64.8	0.3	24.4	
Lu	68.5	2.4	25.9	
Y	121.2	0.4	26.3	
Th	58.8	2.6	26.6	
Eu	89.0	0.3	26.9	
Gd	82.7	0.0	26.9	
Tb	95.7	0.6	27.4	
TiO_2	151.6	0.8	27.8	
Ti (calc)	152.4	0.7	28.0	
SiO_2	383.0	0.3	28.0	
Sc	261.4	1.4	41.5	
Ba	287.2	0.4	49.0	
V	432.3	6.1	50.9	
Sr	93.7	3.7	57.6	
P_2O_5	475.8	0.1	62.7	
Na_2O	97.7	3.5	67.5	
Cs	922.9	0.9	70.3	
Be	638.6	0.0	87.6	
K_2O	423.6	5.1	89.9	
Rb	363.8	0.0	96.6	
CaO	622.5	4.1	97.5	
Co	2018.8	1.7	125.0	
MgO	1020.9	1.1	187.7	
FeO	4420.9	0.2	242.1	
Ni	8787.0	2.0	260.8	
MnO	3072.0	6.0	310.3	
Cr	7585.9	8.5	422.5	
Fe_2O_3(total)	16360.6	0.7	719.8	
Pb	1077827.9	0.4	18540.4	
Cd	1211356.3	0.0	20844.6	

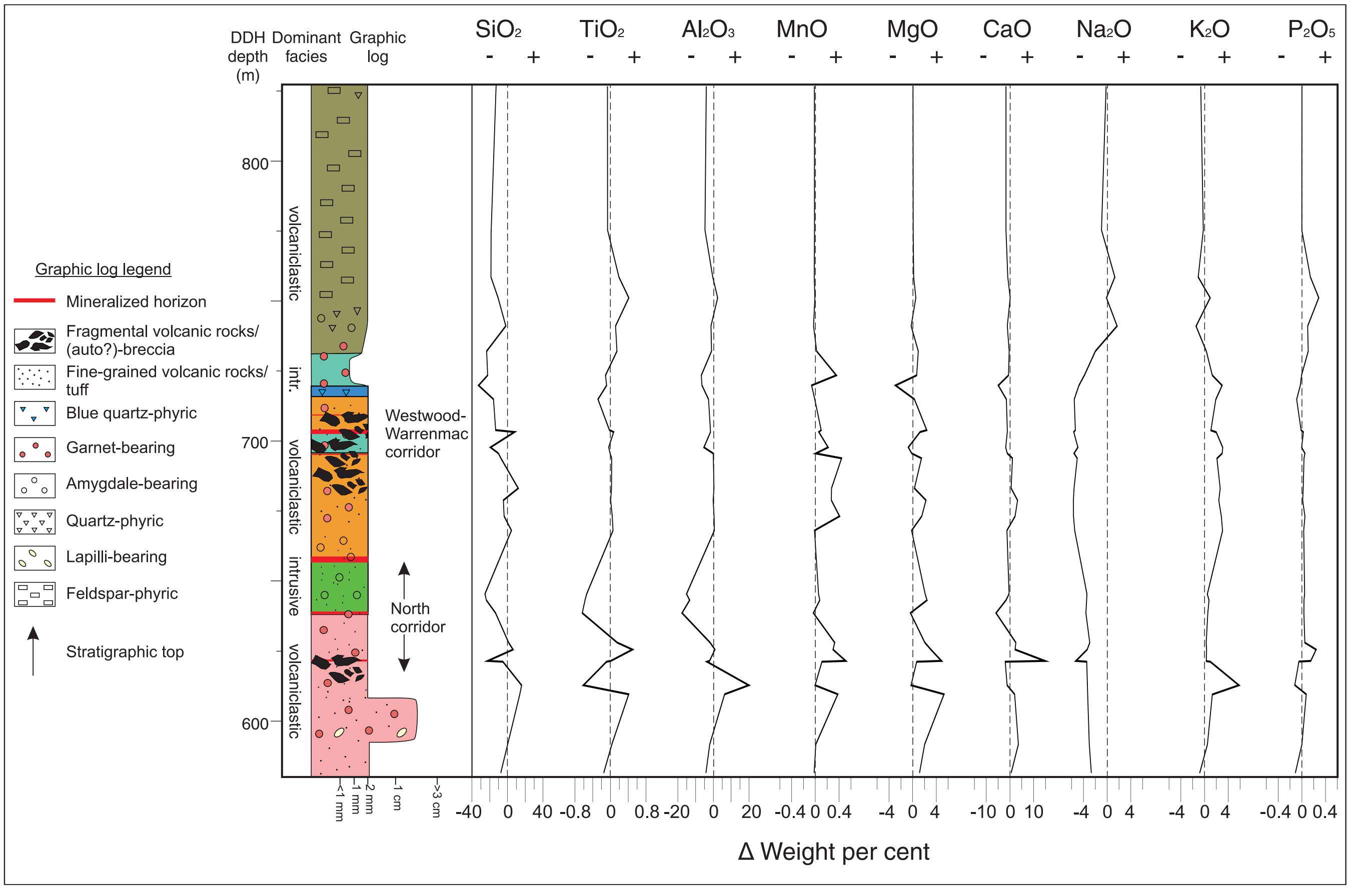

Figure 4. Graphical representation of major-oxide mass changes in the upper member of the Bousquet Formation at the Westwood deposit in core from drillhole R14070-06. Mass gains and losses are shown in weight percentage mass changes on the right and left of the dashed lines, respectively. Largest changes occur in conjunction with north corridor and Westwood-Warrenmac corridor mineralization, as well as with inferred primary fragmental textures (Wright-Holfeld et al., 2010) indicating enhanced mobility associated with permeability and increased fluid flow. Dominant volcanic facies is indicated, however primary textures are often difficult to distinguish. *See* Figure 2 for lithological units legend.

Trace-element mass changes

Mass-change calculations carried out for trace elements demonstrated some degree of mobility of these elements in the Westwood deposit ore-forming hydrothermal system and inferred synvolcanic faults, and possibly mobility associated with late-stage faulting events. Mass changes for these elements are reported as relative variations with respect to precursor values (Fig. 5). Mass-change calculation results for the trace elements in lower concentrations were less accurate than those of the major elements. However, anomalous values of some traces elements were observed in core from drillholes away from the Bousquet fault zone, in the lower member of the Bousquet Formation, but associated with inferred synvolcanic faults and mineralization, and may provide some insight to the syn-ore fluids responsible for the Westwood deposit.

High field-strength elements and yttrium

The high field-strength elements showed patterns in drillhole profile (Fig. 5) indicative of lesser mobility compared to other elements in the deposit area, and had the smallest departures from 0% mass change (Table 1).

Niobium and Ta showed behaviour similar to each other and to Hf in drillhole profile, although Ta showed a larger variation in mobility than Nb. They were both more mobile than Hf, which was the expected result due to Zr and Hf coupling during magmatic fractionation, and Zr being chosen for the enrichment factor. Calculations yielded maximum relative gains of approximately 90% and 50% of precursor values for Nb and Ta, respectively, and maximum relative losses of approximately 40% and 45%. Maximum relative mass losses occured in the footwall rocks of the Westwood-Warrenmac corridor mineralization. Averages of relative values of mass changes for these elements were about 20%, indicating their higher degree of immobility in the Westwood deposit, compared to other trace elements (Table 1).

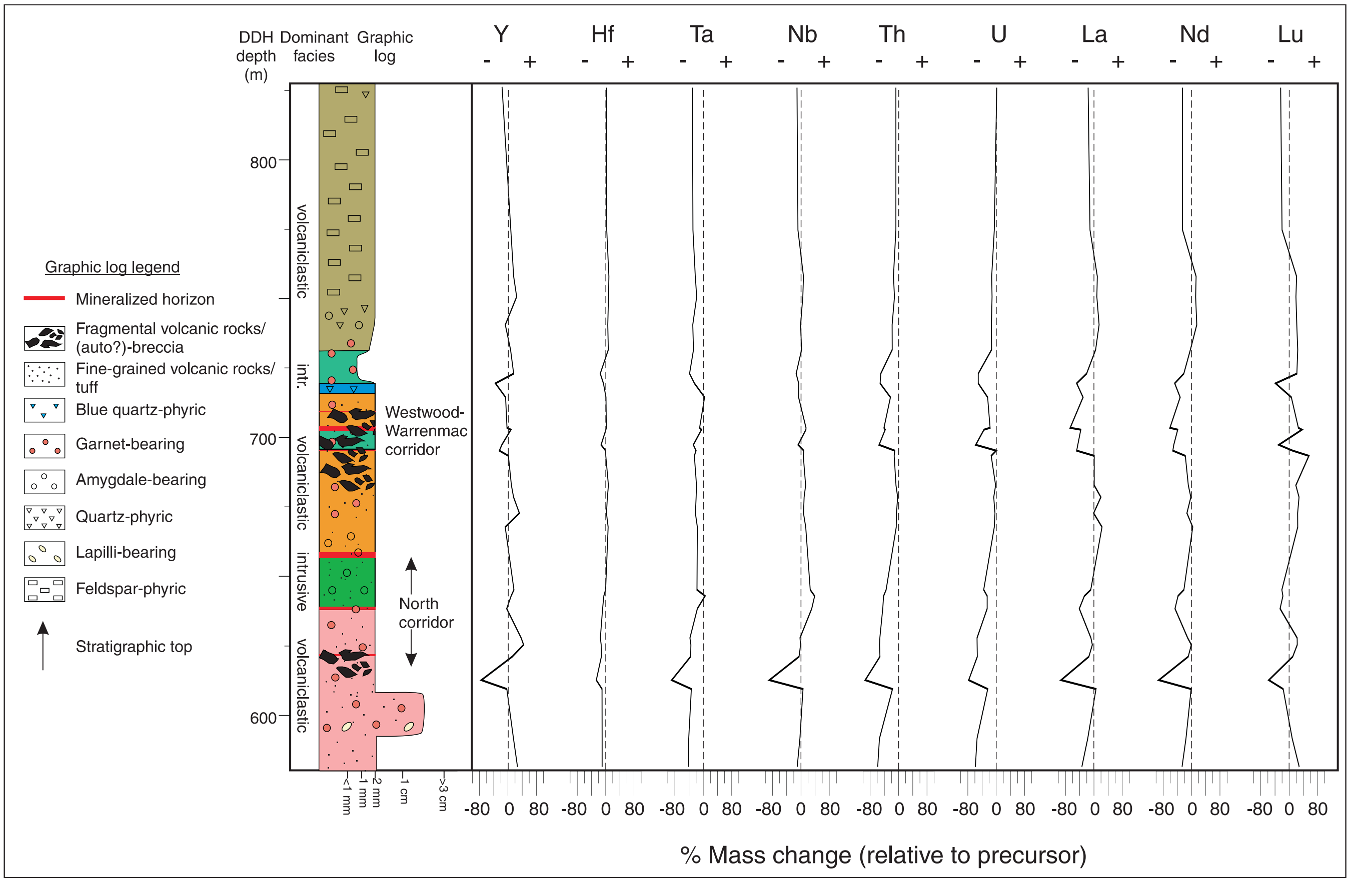

Figure 5. Graphical representation of mass changes of selected trace elements in the upper member of the Bousquet Formation at the Westwood deposit in core from drillhole R14070-06. Mass gains and losses are shown in per cent relative to precursor on the right and left of the dashed lines, respectively. Largest changes occur in conjunction with north corridor and Westwood-Warrenmac corridor mineralization, as well as with inferred primary fragmental textures (Wright-Holfeld et al., 2010) indicating enhanced mobility associated with permeability and increased fluid flow. Dominant volcanic facies is indicated, however primary textures are often difficult to distinguish. *See* Figure 2 for lithological units legend.

Maximum gains of approximately 35% and losses of 15% relative to precursor values indicated that Hf was the least mobile of the HFSE in the Westwood hydrothermal system. These maximum gains and losses occurred in areas that are inferred to have increased fluid flow. Maximum Hf mass loss occurred in the Westwood-Warrenmac ore zone hanging wall in drillhole R14070-06 (Fig. 4), and maximum Hf mass gain occurred within approximately 50 m of the Bousquet Fault in core from drillhole R14219-06, and an inferred synvolcanic fault.

Yttrium is generally considered to be immobile (e.g. MacLean and Barrett, 1993); however, mass-change calculations for the Westwood samples showed that Y was one of the most mobile of the trace elements, and of intermediate mobility for all elements for which mass changes were calculated (Table 1). Like the HFSE, Y experienced maximum mobility associated with areas of inferred increased fluid flow. Maximum gains of up to approximately 120% of precursor occurred within 50 m stratigraphically above the Bousquet Fault, and maximum losses of 40% occurred in the fragmental rocks located in the immediate footwall of the Westwood-Warrenmac ore zones.

Lanthanoids: La-Lu

To illustrate their behaviour within the volcanic sequence of the upper Bousquet Formation, relative mass changes for select rare-earth elements (REE) in core from drillhole R14070-06 are shown in Figure 5, and the maximum gains and losses, as well as average mass changes for all REE, are shown in Figure 6. Largest mass changes were associated with the north corridor and Westwood-Warrenmac ore horizons, as well as with inferred primary volcanic fragmental textures such as lapilli tuffs and volcanic breccia (Wright-Holfeld et al., 2010, and references therein) implying added mobility in conjunction with enhanced permeability in response to increased fluid flow. Mass-change calculations showed that light rare-earth elements (LREEs) were generally more mobile than heavy rare-earth elements (HREEs).

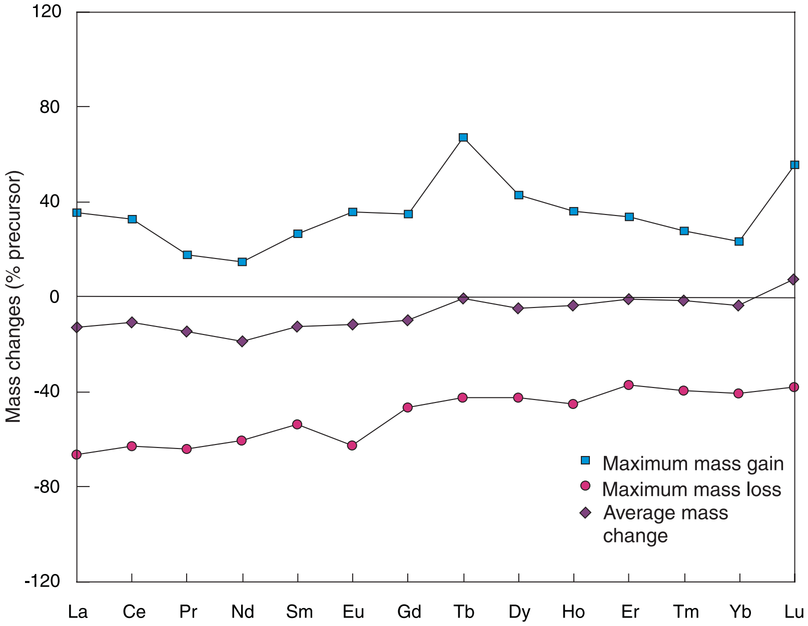

Figure 6. Rare-earth element (REE) maximum mass changes as a per cent relative to precursor for core from drillhole R14070-06 in the upper member of the Bousquet Formation. Variable maximum gains indicate variable mobility in the light rare earth elements (LREE). Linear decrease in gains from Dy to Yb shows lesser mobility of heavy rare-earth elements (HREE). Systematic decrease in maximum losses with increasing atomic number may indicate lesser mobility of HREE compared to LREE. Averages of mass changes approximately equal to zero for HREE supports that they experienced decreased mobility during alteration processes.

In the core from drillhole R14070-06, losses decreased linearly from La to Lu; however, gains in mass were more variable throughout the Lanthanide series (Fig. 6). Gains of up to approximately 95% of precursor values, and losses up to 70%, corresponding with approximately 0.4 ppm Tb, and 29 ppm La respectively (Fig. 6), indicated the mobility of the REEs in the Westwood deposit system.

Actinoids: Th and U

Like the Lanthanoids, Th and U had maximum mobility associated with the north corridor and Westwood-Warrenmac corridor, indicated by major losses of approximately 60% relative to precursor values in the massive sulphide-bearing horizons (Fig. 5). However, in contrast to other elements, Th and U were almost consistently lost in all units of the upper member of the Bousquet Formation: 103 of 118 samples used for calculations showed mass losses in Th and U; and Th displayed the least number of samples with mass gains.

DISCUSSION

Quantifying exactly the mass gains and losses is difficult in any system, and especially so in a strongly altered deposit such as the Westwood, where unaltered samples are difficult to obtain. Keeping in mind the assumptions made in order to carry out these mass-change calculations, some statements of a general nature, and some more speculative, regarding the Westwood deposit hydrothermal ore-forming system, can be made. The observations and results of mass-change calculations in the Westwood deposits show that the biggest gains and losses occur within primary fragmental volcanic rocks, and ore zones, which are also primary. Therefore, a good case can be made for some of the mass changes observed reflecting primary processes associated with hydrothermal or magmatic activity in the volcanic pile, and with ore-forming events. Additionally, the spatial relationship of mass changes with later faulting suggest some component of post-ore remobilization of elements.

Major elements and mineralogical correlations

Mass gains in Mn, Mg, K, and Ca correlate well with increased abundance of metamorphosed hydrothermal-alteration minerals spessartine (Mn-Al garnet), chlorite, biotite, muscovite or sericite, and calcite in the footwall of both the north corridor and Westwood-Warrenmac ore zones (Wright-Holfeld et al., 2010). Manganese and Mg were consistently added to the main host rocks of the north corridor and Westwood-Warrenmac corridor in the upper member of the Bousquet Formation. Mass-change calculations show that Mn was the most mobile and most added element in the system (Table 1), aside from ore-forming elements, such as Fe and Pb. Addition of Mn in the footwall rocks further supports the idea of a Mn-rich ore-forming fluid (Wright-Holfeld et al., 2010). Gains in Mg occurred at a maximum in the north corridor footwall, and systematically decreased upward in the stratigraphy. This pattern or zonation may reflect an initial precipitation of Mg at depth in the system, and exhaustion of Mg supply in the hydrothermal fluid, or alternatively, a waning hydrothermal system possibly caused by, or causing, a decreased fluid-rock ratio. Mass gains in Mn and Mg terminated in the immediate hanging wall of the uppermost Westwood-Warrenmac ore zone and showed little mass gain or loss in the upper felsic unit (Fig. 4). This may suggest that the ore-generating hydrothermal system did not significantly alter the hanging-wall rocks, and therefore may limit the potential for additional ore zones in the immediate upper stratigraphy of the studied section. Gains in Mn and Mg were reflected by the widespread presence of Mn- and Mg-rich garnet and chlorite in the north corridor and Westwood-Warrenmac alteration halos, and the largest gains correlated with lithologies interpreted to have primary volcanic porosity (Fig. 4; Wright-Holfeld et al., 2010). This spatially restricted pattern of mass gains was also noted at the Doyon mine (Guha et al., 1982), and the relationship between porous rocks and mineralization has been noted previously in the camp (Stone, 1988). Mass gains in Fe (sulphides) correlated with Mn-rich garnet and Mg-rich chlorite, implying that Mn-Mg bearing fluids were those associated with Fe-sulphide VMS formation.

In contrast to Mn and Mg which show systematic variations, Ca mass changes appear to vary randomly in the Westwood-Warrenmac corridor mineralization and hanging wall, despite the presence of calcium carbonates and other Ca-bearing minerals (Wright-Holfeld et al., 2010). Variable behaviour of Ca in Westwood-Warrenmac corridor hanging wall in core from drillholes (loss in R14070-06, gains in R14219-06 and R13431-05) may indicate spatial or temporal variations in both the hydrothermal and primary volcanic processes, and additionally may reflect metamorphic fluid overprinting. The irregular behaviour of Ca suggests that it was more sporadically mobilized and precipitated in the system. Sporadic input may imply a magmatic source periodically venting fluids rich in CO_2 resulting in the precipitation of primary calcium-bearing carbonates. The presence of primary carbonates is known in the camp, and previous studies (e.g. LaRonde: Dubé et al., 2007), as well as this study, suggest that metamorphic minerals garnet and chlorite may have replaced Mn- and Mg-altered hydrothermal carbonates. Manganese-rich garnets containing inclusions of REE- and F-rich calcium carbonates were found in thin section and analyzed by microprobe (Wright-Holfeld et al., 2010). This inclusion relationship is thought to be caused by replacement and may imply that an earlier REE-bearing Ca-, and CO_2-rich fluid was overprinted by a later fluid which either supplied Mn or remobilised Mn. Textural evidence in other VMS deposits indicates carbonate infill of porous zones in, and the selective carbonate replacement of, volcanic host rocks (Peter and Scott, 1988; Large et al., 2001; and references therein). In addition to these alteration processes, the variable behaviour of Ca may reflect differing intensities of the hydrothermal system with time, and Ca leaching associated with seawater alteration of clinozoisite, epidote, or Ca-plagioclase (Barrett and MacLean, 1994), all of which are present in the Westwood deposit (Wright-Holfeld et al., 2010). Additionally, Ca may have been supplied to the system by late-stage fluids in areas adjacent to the Bousquet Fault, or may have been added by metamorphic fluids.

To a large degree, muscovite, sericite, and biotite alteration mineralogy reflects hydrothermal K metasomatism associated with the formation of the Westwood VMS system. Like Mn and Mg, K was added to the system in a broad zone of approximately 150 m stratigraphically below the north corridor and Westwood-Warrenmac corridor ore horizons (Fig. 4). Intervals of greatest mass addition occurred in fragmental volcanic rocks, indicating permeability-enhanced fluid flow.

Despite the albitization of some feldspar crystals in the Westwood-Warrenmac corridor, there was a net mass loss in Na in a large envelope around the deposit, and in other deposits in the camp (e.g. LaRonde: Dubé et al., 2007). Extensive Na leaching occurred in conjunction with K metasomatism in a broad sericitization zone below the Westwood-Warrenmac ore zones and encompasses the north corridor mineralized horizons (Fig. 4). This pattern reflects the intensity of the hydrothermal system associated with the Westwood-Warrenmac ore zones, and may indicate that the Westwood-Warrenmac fluids overprinted the north corridor alteration, or that the two ore zones formed concomitantly. Silicon and Na depletion coinciding with Fe, Mg, Mn, and K gains in the Westwood-Warrenmac footwall and north corridor ore zones suggests that the mineralizing fluid or fluids added Fe, Mg, Mn, and K to the system, and removed Si and Na (Fig. 4). Large-scale alteration envelopes of K addition and Na losses, especially in the footwall to VMS lenses, are known in other VMS and epithermal hydrothermal systems (Huston, 2000; Large et al., 2001; Gemmell, 2007; Warren et al., 2007).

Trace elements and mineralogical correlations

The systematic decrease of mass changes with atomic number in the REE indicates that HREE were less mobile than LREE at Westwood (Fig. 6). This pattern provides some support for the validity of assumptions made in order to carry out mass-change calculations. Mass changes of minimal departure from zero variation confirmed an expected behaviour of HREE with respect to a least mobile element, in this case Zr (Barrett and MacLean, 1994). An overall loss of REE (Fig. 6) implies that a small net loss occurred in the Westwood ore-forming system, despite mass gains in some elements and in some volcanic units. Rare-earth element mass gains correlated with increased abundance of allanite and synchysite closely associated with the north corridor and Westwood-Warrenmac corridor mineralization (Wright-Holfeld et al., 2010).

Trace elements were mobile in the Westwood hydrothermal system as evidenced by results of mass-change calculations (Table 1). The most pronounced trace-element mass changes were associated either with ore zones or with volcanic facies that are immediately recognizable as fragmental, albeit deformed and altered. This implies that enhanced fluid flow associated with ore-forming hydrothermal activity, or the presence of permeable fluid pathways, or both, was a causal factor in mobilizing the HFSE and REE. In particular, the presence of halogen-rich fluids may have enhanced HFSE mobility (Hole et al., 1992; de Hoog and van Bergen, 2000). High values of Hf mass gains were associated with fluorite-rich veins in the lower Bousquet Formation in drillhole core studied. Mass changes in HFSE were also associated with quartz-tourmaline veins. The presence of fluorine-rich REE-bearing carbonate inclusions in syntectonic spessartine, combined with the increased trace-element mobility associated with ore zones may provide some further insight to mineralizing fluids. Halogen complexing with HFSE, REE, Th, and U in later stage F- and CO_2-bearing magmatic fluids has been suggested as a mechanism for increasing the mobility of trace elements (de Hoog and van Bergen, 2000). Therefore, in addition to major cations discussed above, the hydrothermal fluids in the Westwood ore-forming system may have transported B, F, CO_2, as well as SO_4^{2-}, based on the close association of anhydrite with ore zones (Wright-Holfeld et al., 2010). Such CO_2-rich fluids have been proposed for the Doyon mine zone 2 mineralization (Guha et al., 1982; Trudel et al., 1992). However, at the Doyon mine, there appears to have been at least one other highly acidic syn-ore fluid responsible for aluminosilicate alteration, in addition to a CO_2-rich fluid.

Yttrium mobility at the Westwood deposit

In drillhole profile comparing measured abundances of trace elements, Y showed some differences compared to other HFSE, especially in ore zones (Fig. 5). The distribution of Y can be attributed at least partially to mobility induced by alteration processes, since the behaviour of HFSE and Y should be approximately similar to one another during magmatic processes (e.g. MacLean and Barrett, 1993). Departures of Y behaviour from other HFSE patterns seen in the drillholes were most likely due to hydrothermal fluid flow and halogen complexing associated with the formation of the Westwood deposit. The fact that Y displayed such mobility in the Westwood stratigraphy confirms that the hydrothermal activity was very intense in that area. It is suggested here that Y mass gains in coherent volcanic rocks of the upper Bousquet Formation combined with Si and Na depletion and Fe, Mg, Mn, and K gains can be used as vector toward ore bodies.

SUMMARY AND CONCLUSIONS

Study of mass changes in major and trace elements in the Westwood deposit has permitted the further recognition and confirmation of processes and characteristics of the hydrothermal fluid responsible for the formation of the ore zones.

The host sequence at Westwood has been shown to be similar to that of the LaRonde Penna deposit, suggesting minor differences in rock types between the two deposits. More importantly, at Westwood, large-scale mass changes occurred across lithological units. This suggests that the geochemical trends defined at Westwood are due to the hydrothermal alteration (Fig. 8 *in* Wright-Holfeld et al., 2010) that can be attributed to hydrothermal fluid upflow associated with VMS formation, rather than solely a function of precursor chemistry. Therefore the geochemical trends at Westwood represent vectors to ore.

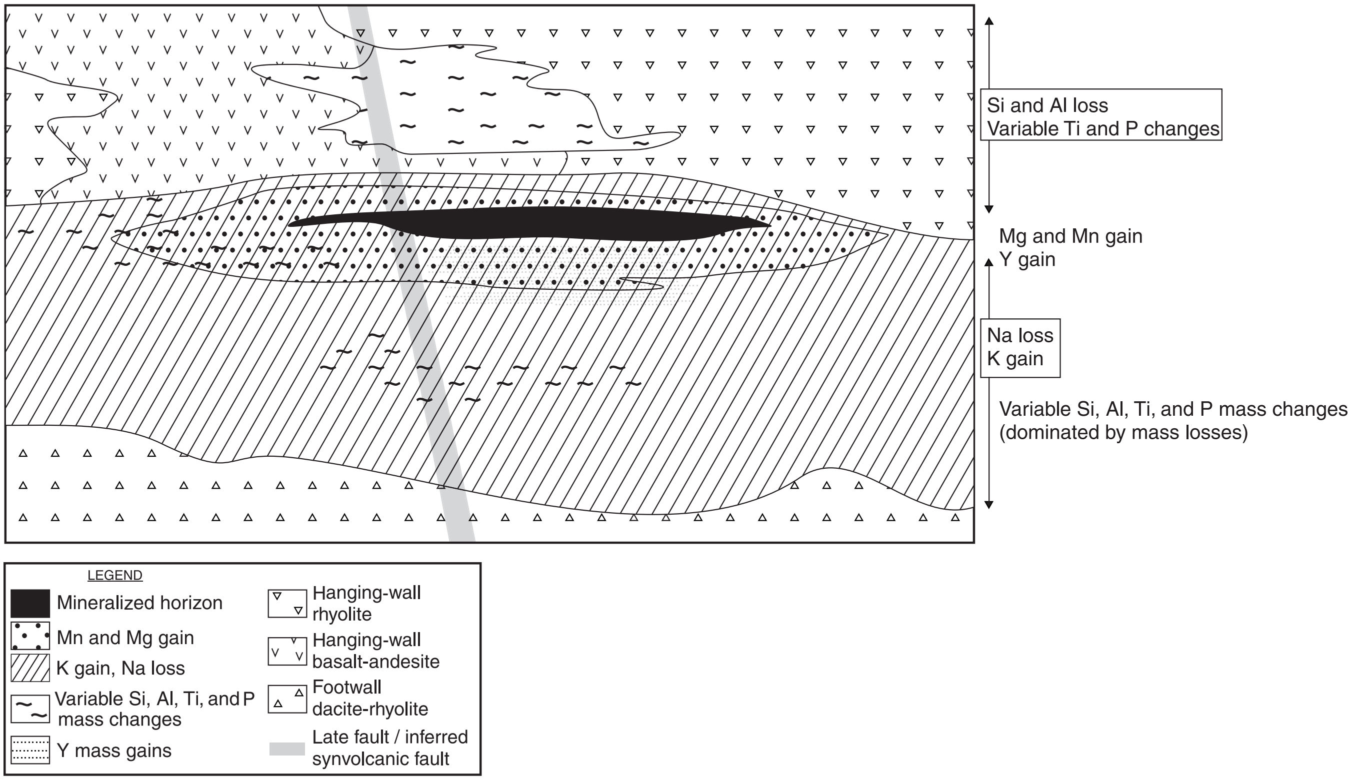

Figure 7. Schematic representation of the main mass gains and losses observed in the Westwood deposit host rocks.

The largest mass changes at Westwood were related to ore formation and enhanced fluid flow in permeable rocks. At Westwood, primary permeability appears to have been a major factor in focusing the mineralizing fluids, as shown by the spatial correlation of some mineralized horizons with fragmental volcanic rocks (e.g. Figure 4 and 5; Wright-Holfeld et al., 2010). High field-strength elements and Y showed a pattern of maximum mass loss associated with the ore zones, and maximum mass gains associated with the Bousquet Fault. The unusual HFSE and REE mobility at Westwood can perhaps be explained by complexing of typically immobile elements with late-stage venting of halogen-bearing magmatic fluids (Hole et al., 1992; de Hoog and van Bergen, 2000). Although it is difficult to establish the nature of the alteration associated with the late-stage Bousquet Fault, its association with intense epidote veining and alteration (Wright-Holfeld et al., 2010) suggests post-ore, syndeformation circulation of Ca-rich fluids along the fault. The variable behaviour of Ca and lack of pattern of Ca mobility with respect to ore zones or areas of increased primary permeability and porosity, and the presence of Ca-bearing carbonates away from the Bousquet Fault may suggest that Ca may have been sporadically added or retained by the system, perhaps in relation to periodic influx of CO_2, or that Ca was selectively mobilised from areas due to permeability and porosity controlled collection or leaching of elements.

Alteration mineralogical observations, inferred subseafloor style of mineralization previously reported (Wright-Holfeld et al., 2010), and the mass-balance calculations made at Westwood support the conclusion that the mineralizing fluids consisted of seawater carrying K, Mg, Mn, and some Ca in solution, with variable input of magmatically derived volatile- and halogen-bearing phases which may have remobilized or added some of the commonly accepted least mobile elements. Large-scale alteration halos and mass changes around VMS deposits are caused by the entrainment of seawater and its subsequent modification by mixing with hydrothermal fluids, and mineral reactions (e.g. Von Damm et al., 1997; Huston, 2000; Large et al., 2001).

Sodium mass losses combined with K mass gains, relative to least altered protoliths, provide the most powerful distal exploration vector to gold-bearing massive-sulphide horizons, while in closer proximity to mineralized sections, Mg and Mn mass changes indicate mineralogical and therefore fluid chemistry changes associated with the ore-forming hydrothermal system (Fig. 7). At the Westwood deposit, Ca mass-change behaviour is difficult to define in terms of patterns related to ore zones, despite the presence of primary carbonates, due in part to some Ca association with the late-stage Bousquet Fault, and therefore its use as a vector toward mineralization is not recommended. Additionally, Y mass gains, in conjunction with above major-element mass changes may be useful vectors toward VMS mineralization.

The results presented and interpretations reported herein are preliminary, and provide the basis for more study of the Westwood deposit. There are some assumptions made in order to make these mass-change calculations. A lack of an unaltered protolith for the altered samples at Westwood makes it somewhat difficult to accurately quantify mass changes, but this discussion hopes to provide some initial insight into the formation the deposit, and into the relative importance of magmatic and hydrothermal fluids in the mineralizing system.

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