Economic Geology

CONSONORM_LG: new normative minerals and alteration indexes for low-grade metamorphic rocks

--Manuscript Draft--

Manuscript Number:	SEG-D-15-00018
Full Title:	CONSONORM_LG: new normative minerals and alteration indexes for low-grade metamorphic rocks
Article Type:	Regular Paper
Abstract:	The CONSONORM_LG method provides a standardized solution for approximating metamorphic parageneses as well as indexes for estimating chemical and mineralogical changes caused by hydrothermal alteration. CONSONORM_LG is designed for rocks dominated by silicates, Fe-Ti oxides and/or carbonates, and it approximates the main parageneses of greenschist and lower amphibolite-grade metamorphic rocks for three sets of temperature and pressure conditions (2SV350, 2SV450 and 2AMP575 facies of the norm). For each of the facies modelled, the norm calculates the main paragenesis using an ACFMNK tetrahedron, a convenient way of representing a large number of silicate assemblages. In addition to silicate minerals, CONSONORM_LG calculates Fe-Ti oxides and other accessory minerals from minor elements, as well as sulfides from analyzed S or from analyzed metals, and carbonates from analyzed CO2 or from normative CO2 estimated from LOI. CONSONORM_LG also calculates several alteration indexes to estimate Fe-Mg (e.g. chloritization), Ca (e.g. propylitic alteration), Na and K acid alterations (e.g. sericitization, phyllic alterations) and Al gain (e.g. argillization). Carbonatation indexes are also calculated using the amount of normative minerals formed by this type of alteration, i.e. carbonates, chlorite and muscovite. The normative calculation is validated using published whole rock analyses and petrographic descriptions. Alteration indexes are validated using several natural samples of alteration halos around base metal and gold deposits.

CONSONORM_LG: new normative minerals and alteration indexes for low-grade metamorphic rocks

Trépanier, S[a]., Mathieu, L.[b*], Daigneault, R[c].

[a]Mines Virginia (mining exploration company) – 300 Saint-Paul, suite 200, Québec, Canada, G1K 7R1

[b]CONSOREM (Consortium de Recherche en Exploration Minérale - mineral exploration research consortium), Université du Québec à Chicoutimi (UQAC) – département des Sciences appliquées, 555 Boul. de l'Université, Chicoutimi, Canada, G7H 2B1.

[c]Centre d'études sur les Ressources minérales (CERM) - Université du Québec à Chicoutimi (UQAC) – département des Sciences appliquées, 555 Boul. de l'Université, Chicoutimi, Canada, G7H 2B1.

* Corresponding author: mathiel@tcd.ie, 1-418-545-5011 ext. 2538

ABSTRACT

The CONSONORM_LG method provides a standardized solution for approximating metamorphic parageneses as well as indexes for estimating chemical and mineralogical changes caused by hydrothermal alteration. CONSONORM_LG is designed for rocks dominated by silicates, Fe-Ti oxides and/or carbonates, and it approximates the main parageneses of greenschist and lower amphibolite-grade metamorphic rocks for three sets of temperature and pressure conditions (2SV350, 2SV450 and 2AMP575 facies of the norm). For each of the facies modelled, the norm calculates the main paragenesis using an ACFMNK tetrahedron, a convenient way of representing a large number of silicate assemblages. In addition to silicate minerals, CONSONORM_LG calculates Fe-Ti oxides and other accessory minerals from minor elements, as well as sulfides from analyzed S or from analyzed metals, and carbonates from analyzed CO_2 or from normative CO_2 estimated from LOI. CONSONORM_LG also calculates several alteration indexes to estimate Fe-Mg (e.g. chloritization), Ca (e.g. propylitic alteration), Na and K acid alterations (e.g. sericitization, phyllic alterations) and Al gain (e.g. argillization). Carbonatation indexes are also calculated using the amount of normative minerals formed by this type of alteration, i.e. carbonates, chlorite and muscovite. The normative calculation is validated using published whole rock analyses and petrographic descriptions. Alteration indexes are validated using several natural samples of alteration halos around base metal and gold deposits.

1. INTRODUCTION

The challenge of exploration geology is to discover and define small-volume concentrations of metals or other economic substances. This search uses vectors as many "footprints" of the mineralizing process. As most deposits are formed by hydrothermal processes, the "footprints" most often sought by exploration geologists are rocks modified by the circulation of hydrothermal fluids. These modifications are either chemical or mineralogical, or both; they are related to metasomatic and alteration processes, respectively (Stanley and Madeisky, 1994) and form what will be designated as altered rocks in this contribution.

If the recognition of altered rocks is crucial to exploration geology, qualifying and quantifying the alteration is as important in directing the investigations and in identifying the substance most likely to have been concentrated in a given context. The recognition, qualification and quantification of alteration can be approached using various methods briefly summarized here.

The first is mass balance calculations that use chemical analyses of major elements. In addition, for some methods volatile or trace element analyses might be required. Mass balance methods are based on a mass transfer equation (Gresens, 1967; Stanley and Madeisky, 1994; Leitch and Lentz, 1994) used to compare altered rocks to their un-altered equivalents using ratios of immobile elements to estimate the amount of mass gained and lost by mobile elements (Grant, 1986; Barrett and MacLean, 1994; Stanley and Madeisky, 1994; Trépanier, 2009). The main limit of mass balance methods is the need for a protolith representative of the chemical composition of the fresh precursor of the altered samples. This can be a field sample (Grant, 1986; Barrett and MacLean, 1994) or a modelled igneous rock (Trépanier, 2009; Faure et al., 2011; Faure et al., 2014). Another approach is the Pearce Element Ratios – PER method and diagrams (Pearce, 1968), which is a method that can be applied to alteration-related mass transfers and that avoids the fresh precursor difficulty (Beswick and Soucie, 1978; Stanley and Madeisky, 1994; Nicholls and Gordon, 1994). But the PER technique is difficult to manipulate, especially in an exploration context.

Alteration can also be approached using alteration indexes often calculated from major element analyses. Most alteration index methods use excesses and deficiencies in major elements to identify the minerals formed or destroyed by an alteration process. For example, the sericite-albite index (Kishida and Kerrich, 1987), the Hashimoto index (Ishikawa et al., 1976) and the alkali index (Saeki and Date, 1980) use Al_2O_3 and alkalis to estimate feldspar destruction and mica formation. Others, such as the chlorite index (Saeki and Date, 1980) and the CCPI-Chlorite-Carbonate-Pyrite index (Large et al., 2001) use FeO and MgO to identify the formation of chlorite or other mafic minerals. The main advantage of alteration indexes is their simplicity; their main disadvantages are their great sensitivity to lithological variations and their poor mineralogical constraints.

To address this last problem, some indexes are derived from a full normative calculation. For example, the strategy proposed by NORMAT (Piché and Jébrak, 2004) allows for a more precise estimate of the amount of chlorite and white micas for example, likely to be actually present in a rock. The NORMAT method enables the calculation of indexes less sensitive to lithological variations and which do not require the recognition of fresh protoliths.

Furthermore, and contrary to mass balance calculations, NORMAT requires only major element analyses and can identify alteration processes involving CO_2 or H_2O volatiles based on the analysis of the LOI (Loss On Ignition) (Piché and Jébrak, 2004). NORMAT is designed for lower greenschist facies rocks and is thus suitable in many shallow hydrothermal contexts. Also, NORMAT uses a ternary diagram to store its four main silicate parageneses and uses petrologic rules to calculate hydrothermal and precursor minerals sequentially. This calculation strategy models hydrothermally altered rocks but prevents the generalization of the method to other rock types and metamorphic facies; however, a technique entirely based on thermodynamic equilibrium might be easier to generalize and may model natural parageneses more accurately.

Recognizing the advantages of the normative approach, the authors have built on the NORMAT method, replacing the ternary diagram by a tetrahedron, adopting a different calculation sequence and proposing an extension of the norm to mid-grade (this contribution) and to high-grade metamorphic rocks (Mathieu, 2014). This contribution extends the method to three low- to mid-grade facies not covered by NORMAT: two greenschist facies (350^{o} C and 450^{o} C, 2.5 kbars) and a lower amphibolite facies (575^{o} C, 2 kbars). Among other advantages, the new norm better describes the mineralogical changes induced by carbonatation. The new method is called the CONSONORM_LG norm, with LG standing for "low grade". It proposes a calculation of normative minerals and alteration indexes that will be tested on natural examples in the last section of this contribution.

2. NORMATIVE CALCULATIONS

CONSONORM_LG calculates equilibrium assemblages, i.e. minerals co-existing under given conditions of pressure and temperature, for three sets of conditions: 1) 350° C and 2.5 kbars (2SV350 facies); 2) 450° C and 2.5 kbars (2SV450 facies) and 3) to 575° C and 2 kbars (2AMP575 facies).

CONSONORM_LG norm uses a sequential calculation inspired by the CIPW norm (Cross et al., 1902; 1912), the simultaneous calculation of several minerals proposed by MATNORM (Pruseth, 2009) and the virtual estimation of CO2 from the LOI, which is an innovation of NORMAT (Piché and Jébrak, 2004). Also, available norms use ternary diagrams (NORMAT; Piché and Jébrak, 2004) or tetrahedrons (MESONORM; Barth, 1959) to solve for the main silicate assemblage. Similarly, CONSONORM_LG uses one tetrahedron per facies. Tetrahedrons are preferred to ternary diagrams because they display a greater number of mineral assemblages which limits the sequential adjustments required to approximate natural parageneses better.

3. METAMORPHIC TETRAHEDRONS

Tetrahedrons are the cornerstone of the CONSONORM_LG calculation and are designed to represent theoretical silicate assemblages for each of the pressure-temperature conditions modelled. The three tetrahedrons used by CONSONORM_LG consider H_2O and SiO_2 to be in excess. Their poles correspond to the molar proportions of Al_2O_3, CaO, FeO+MgO+MnO and Na_2O+K_2O, and are designated as the A, C, FM and NK poles, respectively, of the ACFMNK main tetrahedrons (Fig. 1, 2, 3).

Each tetrahedron is an assemblage of four ternary diagrams published by Spear (1993) or modelled by the intermediary of the Theriak-Domino software using the JUN92.BS database of thermodynamic data (de Capitani and Petrakakis, 2010). The tetrahedrons were designed by cross-referencing the information provided by the following ternary diagrams:

- Tetrahedron of the 2SV350 facies (Fig. 1): ANK, AKF, AKM, AFM (projected from muscovite) and ACM ternary diagrams from Spear (1993); and a modelled ACK diagram.
- Tetrahedron of the 2SV450 facies (Fig. 2): ACM, ACF, AFM (projected from epidote), ANK, ACM, AKF, AFM, AKM (projected from muscovite) ternary diagrams form Spear (1993); and modelled ACK, ACF and AFM diagrams.
- Tetrahedron of the 2AMP575 facies (Fig. 3): AKM, AKF, AFM (projected from muscovite) and ANK ternary diagrams from Spear (1993); and modelled ACM, ACF, AFM (projected from anorthite) and AKC ternary diagrams.
- The silica deficiency is solved using information provided by ternary diagrams with a pole represented by SiO_2 (diagrams from Spear, 1993).

The ACFMNK tetrahedrons are designated as the main tetrahedrons, which are made of an assemblage of small tetrahedrons each defined by four minerals (Fig. 1, 2, 3). Also, the paragenesis of FeO- versus MgO-rich rocks and Na_2O- versus K_2O-rich rocks can be very different and the full variability of these parageneses cannot be represented on a single tetrahedron. For this reason, the ACFMNK tetrahedrons are designed for MgO-rich and K_2O-rich rocks and adjustments are made during the norm calculation for rocks rich in FeO and/or Na_2O (see section 4).

4. CALCULATION SEQUENCE

CONSONORM_LG is a Visual Basic code provided as supplementary material. This code prompts the user to choose one of three facies to calculate the norm, i.e. the 2SV350, the 2SV450 or the 2AMP575 facies, and to choose between using analyzed or modelled values of CO_2. The code also uses measured values of FeO and Fe_2O_3 only, and the user is encouraged to either analyze these values or to estimate them from Fe_2O_3T prior to initiating a CONSONORM_LG calculation. Discussions on strategies for estimating FeO and Fe_2O_3 can be found in LeMaître (1976).

Once the calculation is started, CONSONORM_LG initiates a succession of operations summarized by Fig. 4. The first set of operations aims to extract and prepare the chemical elements for the norm calculation (see step 1 of Fig. 4) and are conducted as follows:

1) The calculation starts by extracting the main oxides (SiO_2, Al_2O_3, CaO, MgO, FeO, Fe_2O_3, MnO, Na_2O, K_2O, TiO_2, P_2O_5), volatiles (H_2O^+, H_2O^-, S, CO_2, LOI), some trace elements (Cr, Pb, Zn, Ni, Mo, Cu, As) and the TOTAL from the input file.

2) The elements are then re-calculated to 100% and converted to moles. Note that if a value for TOTAL is not provided by the user, the norm sums the main oxides, volatiles and trace elements in order to re-calculate each analysis to 100%.

3) If the user chooses to estimate CO_2 normatively, following the method developed by Piché and Jébrak (2004), the GOI (Gain on Ignition) is calculated (equation 1). The GOI, i.e. the oxidation of the iron contained in sulfides and carbonates during the heating of a sample, is calculated from the amount of iron contained in the normative carbonates and sulfides. Its value is null at this stage and will be adjusted as these minerals are calculated (equation 1).

$$GOI\% = (sulfide\% * Fe\_molar\_in\_sulfide * 1.5 + carbonate\% * Fe\_molar\_in\_carbonate * 0.5) * 15.998 \quad \text{(equation 1)}$$

The normative calculation starts with the sequential calculation of accessory minerals, i.e. sulfides, carbonates and Fe-Ti oxides (see step 2 of Fig. 4):

1) First, galena, sphalerite, millerite, molybdenite, chalcopyrite, arsenopyrite, pyrite and anhydrite are calculated until exhaustion of sulfur or the metals, including iron. If sulfur was not analyzed, then pyrite will not be calculated and Pb, Zn, Ni, Mo, Cu and As will be combined with a calculated amount of sulfur until exhaustion of these metals. It is strongly recommended to analyze or estimate the amount of sulfur for rocks containing over 1 wt% iron sulfides, otherwise an incorrect amount of iron will be allocated to silicates and carbonates later in the calculation.

2) The carbonates are then calculated if $CO_2 > 0$. For the 2SV350 and 2SV450 facies, carbonates are calculated using a sequence based on that used in NORMAT (Piché and Jébrak, 2004): 1) calculation of calcite; 2) calculation of magnesite and siderite simultaneously; 3) reaction of these minerals to form dolomite and ankerite. For the 2AMP575 facies, carbonates are not calculated at this stage because they are not always stable in the presence of quartz (Spear, 1993).

3) The Fe-Ti oxides are then calculated sequentially using observations made by Spear (1993) on natural rocks. If $MgO/(MgO+FeO+Fe_2O_3)$ molar < 0.45 (Spear, 1993), ilmenite, then magnetite, titanite, rutile and hematite are calculated successively. Otherwise the calculation sequence is titanite, rutile and hematite, which are calculated until exhaustion of Fe_2O_3 or/and TiO_2.

4) The GOI is adjusted according to the normative amount of Fe-bearing oxides and carbonates.

The next series of operations aim at calculating the silicates (see step 3 of Fig. 4). The calculation sequence is the following:

1) The sample is located in one of the small tetrahedrons of the main ACFMNK tetrahedron using the sample's composition in Al-Ca-K-Na-Fe-Mg. This small tetrahedron is identified using the following steps: a) calculation of the barycentric coordinates of the sample using the main tetrahedron as a reference, followed by a conversion to Cartesian coordinates; b) calculation of the barycentric coordinates of the sample using each small tetrahedron as a reference. The small tetrahedron for which the samples' coordinates are all strictly > 0 is the one that contains the sample.

2) At this stage, the norm calculates the Mg# (i.e. MgO/(MgO+FeO) molar) and the K# (i.e. $K_2O/(K_2O+Na_2O)$ molar) using the amount of FeO, MgO, Na_2O and K_2O remaining after the calculation of accessory minerals.

3) The four minerals represented by the previously selected small tetrahedron are calculated simultaneously by matrix inversion using a method developed by Pruseth (2009). Then, and for the minerals that represent solid solutions between MgO-FeO and Na_2O-K_2O, the molar masses are distributed between each mineral species using the Mg# and K# values.

4) As the ACFMNK tetrahedrons are designed for MgO-rich rocks, adjustments are here made for FeO-rich rocks. These adjustments enable the formation of chloritoid (facies 2SV450) and garnet, staurolite and cordierite (facies 2AMP575) (Table 1).

5) The ACFMNK tetrahedrons are designed for K_2O-rich rocks, and adjustments for Na_2O-rich rocks are necessary. If white micas and alkali feldspars co-exist, K_2O is attributed to micas preferentially and Na_2O is increased in feldspars. Also, paragonite and orthoclase are reacted to form albite and muscovite as these minerals do not co-exist according to ANK ternary diagram (Spear, 1993).

6) Finally, the amount of silicon used by the normative silicates is calculated. If the silicates' silicon content is less than the amount of SiO_2 available, then quartz is formed; otherwise the silicon deficit is addressed by turning SiO_2-rich minerals into less SiO_2-rich phases (Table 2), following the CIPW norm (Cross et al., 1902; 1912).

At this stage, the WITHOUTCO2 alteration indexes are calculated using the proportions of silicates (wt%) calculated in a carbonate-free paragenesis (see section 5) (Fig. 4). These indexes are thus calculated if $CO_2 = 0$, which is always the case during the first loop of normative mineral calculations. If the user choses to use the amount of analyzed CO_2, then the normative minerals are destroyed and the calculation of the norm resumes one time to include the amount of analyzed CO_2 and to enable carbonate formation. Otherwise iteration will be initiated (see next paragraph). The WITHOUTCO2 indexes will no longer be calculated during successive loops (Fig. 4).

If the user chooses to estimate CO_2 normatively, following the Piché and Jébrak method (2004), then the iteration is initiated as follows (step 4 of Fig. 4): firstly, the amount of H_2O consumed by the hydrous normative minerals (H_2O_mineral%) is calculated. Then, the following conditions are checked:

1) If LOI% > (H_2O_mineral% + CO_2_normative% + S_analyzed% + H_2O^-_analyzed% - GOI%), then the amount of CO_2_normative% is increased by 0.1%, the normative minerals are destroyed and the calculation resumes from the first step, i.e. the extraction of chemical data. The norm calculation will then be resumed as many times as necessary for the values of CO_2_normative%, H_2O_mineral% and GOI% to be properly adjusted to the LOI%. Note that a more accurate estimate of CO_2_normative% will be obtained if the LOI is carefully measured.

2) If LOI% <= (H_2O_mineral% + CO_2_normative% + S_analyzed% + H_2O^-_analyzed% - GOI%), the iteration ceases.

At this stage the calculation of normative minerals is achieved (see step 5 of Fig. 4). The proportions of minerals (wt%) are estimated and re-calculated to 100%. The density of each sample is also estimated using mineral densities from Piché and Jébrak (2004) and from internet compilations (e.g. http://webmineral.com by D. Barthelmy, 2014). Finally, the WITHCO2 alteration indexes are calculated (see section 5).

CONSONORM_LG provides the following outputs to its users:

1) The proportions (wt%) of all the normative minerals calculated during the first loop (i.e. the WITHOUTCO2 minerals) and calculated by the last calculation loop – all other types of minerals.

2) The values of the WITHCO2 and WITHOUTCO2 alteration indexes.

3) The estimated density of the sample.

4) The TOTALoxide (i.e. the sum of original chemical data prior to re-calculating the analysis to 100%) and the TOTALmineral (i.e. sum of normative minerals prior to re-calculation to 100%) parameters are provided to be used as quality control of the norm – confidence should be accorded to the normative calculation only if these parameters are close to 100%.

5) The ACFK parameter provides the four minerals of the small tetrahedron selected to represent the main paragenesis.

6) The EXCESSDEFICIT parameter gives specific information on the calculation performed.

7) The CO_2_normative%, GOI% (equation 1) and H_2O^+_normativeMolar (equation 2) values are also given to the user.

$$H_2O^+\_normativeMolar = (LOI\% + GOI\% - S\_analyzed\% - H_2O^-\_analyzed\% - CO_2\_normative\%) / 9.01 \quad \text{(equation 2)}$$

5. ALTERATION INDEXES

The alteration indexes compare the proportions of alteration-related minerals and fresh rock-related minerals using ratios (equation 3).

alteration index = (alteration-related minerals) / (alteration-related minerals + fresh rocks-related minerals) (equation 3)

Because carbonatation may induce mineralogical changes in a rock without necessarily modifying the absolute concentrations of the main oxides (Kishida and Kerrich, 1987), two main types of indexes are proposed: WITHCO2 and WITHOUTCO2. Indeed, chlorite and muscovite, which are usual markers of FeO, MgO and K_2O gains, may form in FeO-, MgO- or K_2O-bearing rocks as a result of carbonatation alone (equations 4 and 5; after Kishida and Kerrich, 1987).

epidote + actinolite + CO_2 --> chlorite + calcite + quartz (equation 4)

albite + chlorite + calcite --> muscovite + ankerite (equation 5)

The WITHOUTCO2 indexes are calculated from carbonate-free parageneses, in which the normative muscovite and chlorite can be related to chloritization and sericitization alteration processes with more confidence (Table 3). The WITHOUTCO2 indexes thus document the Fe-, Mg-, K-, Na- and Ca-types of alterations. On the other hand, the WITHCO2 indexes use carbonates as well as the normative amounts of carbonatization related chlorite and muscovite (Table 4) and are thus dedicated to CO_2-type of alteration. Note that the 2AMP575 facies, for which carbonates are not calculated, provides only WITHOUTCO2 indexes.

6. CASE STUDY

In this section, CONSONORM_LG is used to recalculate the chemical composition of a number of samples. The calculation is performed on altered rocks from the Touquoy and Beaufor gold deposits and from the Hellyer and Montauban VMS deposits, using published analytical data (Prabhu and Webber, 1984; Gemmell and Large, 1992; Bernier and MacLean, 1993; Bierlein and Smith, 2003; Roussy, 2003) (see section 6.3 for a brief description of each deposit). A modern database of fresh magmatic rocks is also used to constrain threshold values for the indexes (section 6.2).

6.1. Validating the normative calculation

We used published analysis from the Touquoy and Beaufor gold deposits to validate the CONSONORM_LG calculations, as both the chemistry and petrology of these rocks are published. The petrology data were obtained from quantitative XRD analyses (Touquoy deposit; Bierlein and Smith, 2003) and from observations made in thin sections (Beaufor deposit; Roussy, 2003).

We performed the CONSONORM_LG calculations for the 2SV350 facies on bulk samples, using an Fe_2O_3/Fe_2O_3T (wt%) ratio of 0.3 to estimate FeO and Fe_2O_3 from Fe_2O_3T, and a normative estimation of CO_2. The normative parageneses were then compared to the observed phases (Fig. 5), showing a good correlation between modelled and natural minerals.

6.2. Lithological dependence of indexes and threshold values

The alteration indexes have been calculated for fresh magmatic rocks to establish threshold values. We used the GEOROC database (http://georoc.mpch-mainz.gwdg.de/) downloaded in 2014. Rocks that were possibly altered were removed from the database by deleting the analysis with LOI > 3 wt% and/or CO_2 > 1 wt%. The samples were then classified using their original name in the dataset. These names were validated using the De La Roche et al. (1980) classification – the R1-R2 diagram – and the samples were eventually classified as felsic, intermediate, mafic and ultramafic magmatic rocks (n= 1125 samples). Alteration indexes were then calculated for each class, and threshold values corresponding to the maximum value of 80% of each dataset (i.e. 80th percentile) were established (Table 5).

Threshold values are less than 20 for index values that range from 0 to 100, indicating a limited dependency of indexes on the variable composition of unaltered magmatic rocks (Table 5). The ALT_PHYLLO and ALT_AND indexes, which are sensitive to the amount of normative aluminosilicates, are particularly low for fresh magmatic rocks. Also, note that threshold values for these indexes, as well as for the indexes that use phyllosilicates, are expected to be higher for fresh sedimentary rocks.

6.3. Calculating the indexes for hydrothermally altered rocks

Touquoy gold deposit, Nova Scotia, Canada – The Touquoy deposit is hosted in metasiltstones (see Hudgins, 1989 for details on the lithology). The alteration halos surrounding the mineralized veins are characterized by feldspar and chlorite destruction, as well as carbonates, muscovite and disseminated sulfide formation that reflect gains of CO_2, K_2O, Au, As, S and loss of Na_2O (Bierlein and Smith, 2003). The veins formed at $250\text{-}350^{o}$ C and 1-2 kbars, and were then metamorphosed under mid-greenschist facies conditions (Reynolds et al., 1987).

The samples used here were collected along a drill hole and correspond to unaltered to intensely altered meta-sedimentary rocks (Bierlein and Smith, 2003). We calculated the 2SV350 facies and indexes using the CONSONORM_LG method with normative CO_2 and a Fe_2O_3/Fe_2O_3T (wt%) ratio of 0.3, or using the analyzed values of CO_2, FeO and Fe_2O_3 whenever possible.

The alteration indexes for the 2SV350 facies (Fig. 6A) point to phyllosilicate alteration (muscovite and ± chlorite) and to carbonatation (carbonates and related chlorite). These alterations correspond to the K_2O and CO_2 gains reported by Bierlein and Smith (2003), indicating concordance between previously interpreted alterations and CONSONORM_LG indexes.

Hellyer VMS, Tasmania, Australia – The Hellyer VMS deposit is hosted by an assemblage of felsic to mafic magmatic and sedimentary rocks (see detailed geology in Jack, 1989; McArthur and Dronseika, 1990; Sharpe, 1991; Gemmelle and Large, 1992; Waters and Wallace, 1992; McArthur, 1996; Solomon and Zaw, 1997). The footwall pipe alteration is zoned with a siliceous core surrounded by chloritic and sericitic zones (Gemmell and Large, 1992; Schardt et al., 2001). The deposit formed at an average temperature of 200-350^{o} C and was then weakly deformed and metamorphosed (Gemmell and Large, 1992; Large, 1992).

The samples used correspond to median values representative of the chemistry of the main alteration zones (Gemmell and Large, 1992), for which the 2SV350 facies and indexes of the CONSONORM_LG method were calculated using normative CO_2 and a Fe_2O_3/Fe_2O_3T (wt%) ratio of 0.2.

The ALT_CHLO alteration index for the 2SV350 facies (Fig. 6B) is high only for the sample from the chloritic zone. The ALT_MUSCV points to sericitization in the silicified core and in the muscovite-bearing zones. The ALT_PHYLLO index confirms that all the zones are rich in phyllosilicates, and the other indexes (i.e. ALT_CHLO and ALT_ MUSCV) show that the phyllosilicate phase varies from one zone to the next. Also, there is no evidence of carbonatization based on the ALT_MUSCV_CARBS, ALT_CHLO_CC_TLC and ALT_CARBS indexes.

Beaufor gold deposit, Abitibi, Québec – The Beaufor and nearby Perron orebodies are hosted by the dioritic Bourlamaque batholith (see detailed geology by Tremblay, 2001; Tessier, 1990; Belkabir et al., 1993). The mineralized veins are surrounded by zoned alteration halos that grade from carbonate-sericite rocks, albite-rich rocks and mesocratic rocks to unaltered rocks (Roussy, 2003). Most of the Abitibi rocks are at greenschist facies (Goulet, 1978; Jolly, 1978), including the rocks of the Bourlamaque pluton (Campiglio and Darling, 1976).

The samples used here were published by Roussy (2003). The 2SV350 facies and indexes of CONSONORM_LG were calculated using normative CO_2 and a Fe_2O_3/Fe_2O_3T (wt%) ratio of 0.3. The samples were grouped using observations made by Roussy (2003) (Fig. 6C). The alteration indexes point toward alterations dominated by carbonatation, which formed carbonates, chlorite and muscovite in the altered rocks. All the rocks, including the rocks of the so called unaltered group, had been carbonatized. The rocks of the albite zone are particularly enriched in carbonates and are poorer in phyllosilicates compared to the other groups of rocks (Fig. 6C).

Montauban VMS, Québec, Canada – Montauban is a deformed and metamorphosed Zn-Pb-Cu-Ag-Au deposit of VMS origin (Sangster, 1972; MacLean et al., 1982; Bernier et al., 1987; Morin, 1987) located in the allochthonous monocyclic belt of the Proterozoic Grenville Province (see Rivers (1989) for the main divisions of the Grenville orogeny). The deposit is hosted by biotite gneiss and biotite-muscovite-quartz-feldspar gneiss which likely correspond to meta-felsic magmatic rocks (Prahbu and Webber, 1984). The VMS deposit likely formed in greenschist facies conditions and was then metamorphosed to a maximum of 650° C and 4.5 kbars (Bernier, 1992).

The samples used here were published by Bernier and MacLean (1993) and Prabhu and Webber (1984). The 2AMP575 facies and indexes of CONSONORM_LG were calculated using normative CO_2 and a Fe_2O_3/Fe_2O_3T (wt%) ratio of 0.2.

The rocks of the unaltered group contain some muscovite, cordierite, anthophyllite and biotite based on the alteration indexes (Fig. 6D). The altered rocks have the same paragenesis, but contain excess biotite (in all alteration zones, see ALT_BIOT index), excess cordierite-anthophyllite (for the cordierite- and sillimanite-bearing groups especially, see ALT_CRD_ANT index), excess aluminosilicates (for the nodular sillimanite-bearing rocks only, see ALT_AND index) and a slight excess in muscovite (for the quartzite unit, see ALT_MUSC index) (Fig. 6D).

The hydrothermal alteration associated with the Montauban deposit is mostly marked by cordierite, biotite and anthophyllite. These mafic minerals point toward an Fe-Mg alteration (i.e. chloritization). Note that the potassium in the biotite likely originated from the felsic magmatic precursor and is unlikely to be related to a hydrothermally induced K_2O gain.

7. CONCLUSIONS

CONSONORM_LG is a new method for the recognition of rocks altered by the circulation of hydrothermal fluids. This normative solution standardizes parageneses, links minerals observed in hand sample to modelled phases and calculates alteration indexes.

Compared to other methods dedicated to the recognition and quantification of alteration processes, CONSONORM_LG has the following advantages:

1) It requires only major element analyses and solutions are available even if only the LOI and Fe_2O_3T are analyzed (i.e. samples for which FeO, Fe_2O_3, H_2O^+, H_2O^- and CO_2 are not available). This is an advantage compared to the mass balance methods that require trace element analyses (Stanley and Madeisky, 1994; Trépanier, 2009; Faure et al., 2011; Faure et al., 2014) and volatile analyses (carbonatation estimates described by Grant (1986)).

2) CONSONORM_LG can be applied to any rock type, an advantage compared to the mass balance method of Trépanier (2009) that is designed for magmatic rocks only.

3) CONSONORM_LG does not require the identification of a fresh precursor, an advantage compared to most mass balance methods (Grant, 1986; Trépanier, 2009).

4) CONSONORM_LG method is particularly high-performing in quantifying carbonatation and discriminating between muscovite and chlorite formed as a result of carbonatation from those formed as a result of K or Fe-Mg alterations (i.e. sericitization and chloritization). Also, its performance for recognizing and quantifying K, Na, Fe-Mg and Ca types of alteration is satisfactory. In addition, the mineralogical concepts used to calculate the CONSONORM_LG indexes are sounder than those used to calculate major element ratio based indexes.

5) CONSONORM_LG has the same advantages as NORMAT (Piché and Jébrak, 2004). The tetrahedrons of the CONSONORM_LG method improve the normative calculation, enabling a more precise characterization of the parageneses and opening the

door to carrying out normative calculations for high-grade metamorphic rocks (CONSONORM_HG; Mathieu 2014).

CONSONORM_LG and its alteration indexes represent a new set of tools available to the mining exploration industry or to anyone interested in characterizing hydrothermally induced chemical and mineralogical changes, especially those related to carbonatation processes.

ACKNOWLEDGEMENT

The authors warmly thank their colleagues Stéphane Faure, Benoit Lafrance and Silvain Rafini for constructive discussions on this project. They also thank Denys Vermette for contributing his data to the initial project, Michel Jébrak for constructive comments, Geneviève Boudrias for editing the original Consorem report on this work (report written in French, available online at http://www.consorem.ca/, Trépanier, 2012) and Judit Ozoray for correcting this manuscript's spelling. The members of the Consorem group for the years 2011-2012 are also thanked as a group for defining this project and for constructive comments throughout its realization. The CONSONORM_LG calculation has been available to Consorem members as part of the non-public LithoModeleur software since April 2012, and its users are thanked for constructive comments on the method throughout the years.

REFERENCES

Barrett, T.J., and MacLean, W.H., 1994, Chemostratigraphy and hydrothermal alteration in exploration for VHMS deposits in greenstones and younger volcanic rocks: Alteration and alteration processes associated with ore-forming systems, Geological Association of Canada, Short Course Notes, v. 11, p. 433-467.

Barth, T.F.W., 1959, Principles of classification and norm calculations of metamorphic rocks: Journal of geology, v. 67, p. 135-152.

Barthelmy, D., 2014, Mineralogy Database website (http://webmineral.com).

Belkabir, A., Robert, F., Vu, L., and Hubert, C., 1993, The influence of dikes on auriferous shear zone development within granitoid intrusions: the Bourlamaque pluton, Val-d'Or district, Abitibi greenstone belt: Canadian Journal of Earth Sciences , v. 30(9), p. 1924-1933.

Bernier, L., 1992, Caractéristiques géologiques, lithogéochimiques et pétrologiques des gîtes polymétalliques de Montauban et de Dussault./Geological, lithogeochemical and petrological caracteristics of the Mntauban and Dussault polymetallique deposits: Ministère de l'Énergie et des Ressources du Québec (Geological Survey of Québec), report DV-92-03, p. 31-34.

Bernier, L., and MacLean, W.H., 1993, Lithogeochemistry of a metamorphosed VMS alteration zone at Montauban Grenville Province, Quebec: Exploration and Mining Geology, v. 2, p. 367-386.

Bernier, L., Pouliot, G., and McLean, W.H., 1987, Geology and metamorphism of the Montauban gold zone: a metamorphosed polymetallic exhalative deposit, Grenville Province, Québec: Economic Geology, v. 82, p. 2076-2090.

Beswick, A.E., and Soucie, G., 1978, A correction procedure for metasomatism in an Archean greenstone belt: Precambrian Research, v. 6(2), p. 235-248.

Bierlein, F.P., and Smith, P.K., 2003, The Touquoy Zone deposit: an exemple of "unusual" orogenic gold mineralization in the Meguma terrane, Nova Scotia, Canada: Canadian Journal of Earth Sciences, v. 40, p. 447-466.

Campiglio, C., and Darling, R., 1976, The geochemistry of the Archean Bourlamaque batholith, Abitibi, Québec: Canadian Journal of Earth Sciences, v. 13(7), p. 972-986.

Cross, W., Iddings, J.P., Pirrson, L.V., and Washington, H.S., 1902, A quantitative chemicomineralogical classification and nomenclature of igneous rocks: Journal of geology, v. 10, p. 555-590.

Cross, W., Iddings, J.P., Pirsson, L.V., and Washington, H.S., 1912, Modifications of the "Quantitative System of Classification of Igneous Rocks": The Journal of Geology, v. 20(6), p. 550-561.

De Capitani, C., and Petrakakis, K., 2010, The computation of equilibrium assemblage diagrams with Theriak/Domino software: American Mineralogist, v. 95, p. 1006-1016.

De La Roche, H., Leterrier, J., Grandclaude, P., and Marchal, M., 1980, A classification of volcanic and plutonic rocks using R1-R2-diagram and major-element analyses—Its relationships with current nomenclature: Chemical geology, v. 29(1), p. 183-210.

Faure, S., Daigneault, R., Lafrance, B., Rafini, S., and Trépanier, S., 2011, Mineral exploration problems and real solutions: CONSOREM’s contributions to applied research [ext. abs.]: Québec Exploration meeting, Ministère de l'Énergie et des Ressources du Québec (Geological Survey of Québec), report DV 2011-04, Faure, S., Trépanier, S., and Daigneault, R., 2014, Exploration methods for volcanogenic massive sulphides in the Abitibi: Contribution of geochemical data processing [ext. abs.]: Québec Exploration meeting, Ministère de l'Énergie et des Ressources du Québec (Geological Survey of Québec), report DV 2014-04,

Gemmell, J.B, and Large, R.R., 1992, Stringer system and alteration zones underlying the Hellyer volcanogenic massive sulfide deposit, Tasmania, Australia: Economic Geology, v. 83(3), p. 620-649.

GEOROC database, 2014, GEOROC database website (http://georoc.mpch-mainz.gwdg.de/georoc/).

Goulet, N., 1978, Stratigraphy and structural relationships across the Cadillac-Larder Lake Fault, Rouyn-Beauchastel area, Québec: Ministère de l'Énergie et des Ressources du Québec (Geological Survey of Québec), report DPV-602, 155 p.

Grant, J.A., 1986, The isocon diagram-a simple solution to Gresen's equation for metasomatic alteration: Economic Geology, v. 81, p. 1976-1982.

Gresens, R.L., 1967, Composition-volume relationships in metasomatism: Chemical Geology, v. 2, p. 291-306.

Hudgins, A.B., 1989, Report on geological resource estimates and bulk sample results, Touquoy Project, Moose River, Halifax County, Nova Scotia: Nova Scotia Department of Natural Resources, Assessment report,

Ishikawa, Y., Sawaguchi, T., Iwaya, S., and Horiuchi, M., 1976, Delineation of prospecting targets for Kuroko deposits based on modes of volcanism of underlying dacite and alteration halos: Mining Geology, v. 26, p. 105-117.

Jack, D.J., 1989, Hellyer host rock alteration: Unpublished M.Sc. thesis, Hobart, Tasmanio, University of Tasmania, 182 p.

Jolly, W.T., 1978, Metamorphic history of the Archean Abitibi belt: Metamorphism in the Canadian Shield, Geological Survey of Canada, p. 78-100.

Kishida, A., and Kerrich, R.D., 1987, Hydrothermal alteration zoning and gold concentration at the Kerr-Addison lode gold deposit, Kirkland Lake, Ontario: Economic Geology, v. 82(3), p. 649-690.

Large, R.R., 1992, Australian volcanic-hosted massive sulfide deposits; features, styles, and genetic models: Economic Geology, v. 87(3), p. 471-510.

Large, R.R., Gemmell, J.B., Paulick, H., and Huston, D.L., 2001, The alteration box plot: A simple approach to understanding the relationship between alteration mineralogy and lithogeochemistry associated with volcanic-hosted massive sulfide deposits: Economic Geology, v. 96(5), p. 957-971.

Le Maître, R.W., 1976, The chemical variability of some common igneous rock: Journal of Petrology, v. 7, p. 589-639.

Leitch, C.H.B., and Lentz, D.R., 1994, The Gresens approach to mass balance constraints of alteration systems: methods, pitfalls, examples: Alteration and alteration processes associated with ore-forming systems: Geological Association of Canada, Short Course Notes, v. 11, p. 161-192.

MacLean, W. H., St. Seymour, K., and Prabhu, M. K., 1982, Sr, Y, Zr, Nb, Ti, and REE in Grenville amphibolites at Montauban-les-Mines, Québec: Journal of Petrology, v. 19(4), p. 633-644.

Mathieu, L., 2014, Caractéristiques minéralogiques et chimiques des altérations dans les roches de haut grade métamorphique - phase I./ Mineralogical and chemical caracteristics of alterations in high grade metamorphic rocks: Consorem report 2013-04 (report in french, available at: http://www.consorem.ca/rapports_publics.html).

McArthur, G.J., 1996, Textural evolution of the Hellyer massive sulphide deposit: Unpublished Ph.D. thesis, Hobart, Tasmania, University of Tasmania, 272 p.

McArthur, G.J., and Dronseika, E.V., 1990, Que River and Hellyer zinc-lead-silver deposits: Geology of the mineral deposits of Australia and Papua New Guinea, Melbourne, Australian Institute of Mining and Metallurgy, v. 2, p. 1257-1266.

Morin, G., 1987, Gîtologie de la région de Montauban./ Gitology of the Montauban region: Unpublished M.Sc. thesis, Montréal, Québec, Université du Québec à Montréal, 59 p.

Nicholls, J., and Gordon, T.M., 1994, Procedures for the calculation of axial ratios on Pearce element-ratio diagrams: The Canadian Mineralogist, v. 32(4), p. 969-977.

Pearce, T.H., 1968, A contribution to the theory of variation diagrams: Contributions to Mineralogy and Petrology, v. 19(2), p. 142-157.

Piché, M., and Jébrak, M., 2004, Normative minerals and alteration indices developed for mineral exploration: Journal of Geochemical Exploration, v. 82, p. 59-77.

Prabhu, M.K., and Webber, G.R., 1984, Origin of quartzofeldspathic gneisses at Montauban-les-Mines, Québec: Canadian Journal of Earth Sciences, v. 21(3), p. 336-345.

Pruseth, K., 2009, Calculation of the CIPW norm: new formulas: Journal of Earth Science Systems, v. 118(1), p. 101-113.

Reynolds, P.H., Elias, P., Muecke, G.K., and Grist, A.M., 1987, Thermal history of the southwestern Meguma zone, Nova Scotia, from an 40Ar/39Ar and fission track dating study of intrusive rocks: Canadian Journal of Earth Sciences , v. 24(10), p. 1952-1965.

Rivers, T., Martignole, J., Gower, C.F., and Davidson, A., 1989, New tectonic divisions of the Grenville Province, southeast Canadian Shield: Tectonics, v. 8(1), p. 63-84.

Roussy, J., 2003, Relations entre la distribution de l'or, la structure, la composition des veines et de l'altération hydrothermale à la mine Beaufor, Val d'Or, Québec./ Relationships between gold distribution, structure, veines composition and hydrothermal alteration at the Beaufor mine, Val d'Or, Québec: Unpublished M.Sc. thesis, Montréal, Québec, Laval university, 311 p.

Saeki, Y., and Date, J., 1980, Computer application to the alteration data of the footwall dacite lava at the Ezuri Kuroko deposits: Akito Prefecture: Mining Geology, v. 30, p. 241-250.

Sangster, D.F., 1972, Precambrian volcanogenic massive sulfide deposits in Canada: a review: Geological Survey of Canada paper 72-22, 44 p.

Schardt, C., Cooke, D.R., Gemmell, J.B., and Large, R.R., 2001, Geochemical modelling of the zoned footwall alteration pipe, Hellyer volcanic-hosted massive sulfide deposit, western Tasmania, Australia: Economic Geology, v. 96, p. 1037-1054.

Sharpe, R., 1991, The Hellyer baritic and siliceous caps: Unpublished B.Sc. dissertation, Honors thesis, Hobart, University of Tasmania, 114 p.

Solomon, M., and Zaw, K., 1997, Formation on the sea floor of the Hellyer volcanogenic massive sulfide deposit: Economic Geology, v. 92(6), p. 686-695.

Spear, F., 1993, Metamorphic phase equilibria and pressure-temperature-time paths: Mineralogical Society of America, Washington, D. C., 799 p.

Stanley, C.R., and Madeisky, H.E., 1994, Lithogeochemical exploration for hydrothermal ore deposits using Pearce element ratio analysis: Alteration and alteration processes associated with ore forming systems, Geological Association of Canada Short Course Notes, v. 11, p. 193-211.

Tessier, A.C., 1990, Structural evolution and host dilatation during emplacement of gold-bearing quartz veins at Perron deposit, Val-d'Or, Québec: Unpublished M.Sc. thesis, Kingston, Ontario, Queen's University, 242 p.

Tremblay, A., 2001, Postmineralisation fault in the Beaufor gold deposit, Abitibi Greenstone belt, Canada: geometry, origin and tectonic implications for the Val-D'Or mining district: Economic Geology, v. 96, p. 509-524.

Trépanier, S., 2009, Guide pratique d’utilisation de différentes méthodes de traitement de l’altération et du métasomatisme./ Review of method for the recognition and quantification of alteration and metasomatism: Consorem report 2008-07 (report in French, available at: http://www.consorem.ca/rapports_publics.html).

Trépanier, S., 2012, Norme Lithomodeleur./ Lithomodeleur norm: Consorem report 2011-04 (report in French, available at: http://www.consorem.ca/rapports_publics.html).

Waters, J.C., and Wallace, D.B., 1992, Volcanology and sedimentology of the host succession to the Hellyer and Que River volcanic-hosted massive sulfide deposits, northwestern Tasmania: Economic Geology, v. 87(3), p. 650-666.

Figure captions

Fig. 1 – Exploded view of the main ACFMNK tetrahedron of facies 2SV350.

Fig. 2 – Exploded view of the main ACFMNK tetrahedron of facies 2SV450.

Fig. 3 – Exploded view of the main ACFMNK tetrahedron of facies 2AMP575.

Fig. 4 – Calculation sequence of CONSONORM_LG (see text for details).

Fig. 5 – Binary diagrams comparing the normative and observed minerals of the Touquoy (A) and Beaufor (B) deposits. The normative minerals are calculated for the 2SV350 facies.

Fig. 6 – Box plots and binary diagram displaying the alteration indexes calculated for the Touquoy (A), Heyller (B), Beaufor (C) and Montauban (D) deposits.

Table caption

Table 1: Mineral reactions used to adjust the parageneses for FeO-rich rocks

Table 2: Mineral reactions used to solve silica deficits

Table 3: WITHOUTCO2 indexes for Na, K, Ca, Fe-Mg and Al alterations

Table 4: WITHCO2 indexes for carbonatation-type alteration

Table 5: Threshold values of alteration indexes for magmatic rocks

SUPPORTING INFORMATION

- **File 1:** copy of the CONSONORM_LG code, and instructions for importing it into Microsoft Visual Studio software.

ANNEX A: CONSONORM_LG CODE

CONSONORM_LG is provided as three Visual Basic .NET classes, compatible with .NET version 3.5 and later. The first class – CONSONORM_LG.vb – contains the calculation sequence for a single rock sample. The second class – FormMain.vb – serves as an interface with the user; it is used to input options and data to the code from a .txt file, to calculate the norm and indexes for several samples and to output the data as a .txt file. The third class – TypeDataMx.vb – defines geochemical data types.

The code contained in these three .NET classes is copied to a .pdf file (see supplementary material). This file contains instructions for integrating the code into the Microsoft Visual Studio software, as well as instructions about input data format.

The MathNet.Numerics.LinearAlgebra module was also used to define matrices (see http://numerics.mathdotnet.com). This .NET compatible module is required to compile the VB code properly.

ANNEX B: CONSONORM_LG MINERALS

Mineral	σ	Formula	Mineral	σ	Formula
Albite	2.63	NaAlSi3O8	Pyrope	3.56	Mg3Al2Si3O12
Almandine	4.32	Fe3Al2Si3O12	Pyrophyllite	2.81	Al2Si4O10(OH)2
Andalusite	3.15	Al2SiO5	Quartz	2.65	SiO2
Anorthite	2.75	CaAl2Si2O8	Serpentine	2.54	Mg6Si4O10(OH)8
Anthophyllite_FE	3.8	Fe7Si8O22(OH)2	Staurolite_FE	3.64	Fe2Al9Si4O20(OH)4
Anthophyllite_MG	3.67	Mg7Si8O22(OH)2	Staurolite_ MG	3.54	Mg2Al9Si4O20(OH)4
Biotite_FE	3.34	KFe3AlSi3O10(OH)2	Talc	2.75	Mg3Si4O10(OH)2
Biotite_MG	2.83	KMg3AlSi3O10(OH)2	Tremolite	3.05	Ca2Mg5Si8O22(OH)2
Brucite	2.39	MgOOH	Ankerite	3.05	CaFe(CO3)2
Chlorite_FE	3.3	Fe10Al4.5Si5.5O20(OH)16	Calcite	2.71	CaCO3
Chlorite_ MG	2.75	Mg10Al4.5Si5.5O20(OH)16	Dolomite	2.84	CaMg(CO3)2
Chloritoid_FE	3.7	FeAl2SiO5(OH)2	Magnesite	3	MgCO3
Chloritoid_ MG	3.57	MgAl2SiO5(OH)2	Rhodochrosite	3.69	MnCO3
Cordierite_FE	2.67	Fe2Al4Si5O18	Siderite	3.96	FeCO3
Cordierite_ MG	2.48	Mg2Al4Si5O18	Hematite	5.28	Fe2O3
Diaspore	3.4	AlOOH	Ilmenite	4.79	FeTiO3
Diopside	3.26	CaMgSi2O6	Magnetite	5.15	Fe3O4
Epidote	3.3	Ca2Al3Si3O12(OH)	Rutile	4.8	TiO2
Fayalite	4.66	Fe2SiO4	Titanite	3.48	CaTiSiO4(OH)
Ferroactinolite	3.51	Ca2Fe5Si8O22(OH)2	Arsenopyrite	6.19	FeAsS
Forsterite	3.22	Mg2SiO4	Chalcopyrite	4.19	CuFeS2
Grossular	3.59	Ca3Al2Si3O12	Galena	7.4	PbS
Grunerite	3.66	Fe7Si8O22(OH)2	Millerite	5.5	NiS
Hedenbergite	3.68	CaFeSi2O6	Molybdenite	5	MoS
Hornblende_FE	3.38	Ca2Fe5AlSi7O22(OH)2	Pyrite	5.01	FeS2
Hornblende_MG	2.96	Ca2Mg5AlSi7O22(OH)2	Sphalerite	4.08	ZnS
Leucite	2.48	KAlSi2O6	Anhydrite	2.35	CaSO4
Muscovite	2.83	KAl3Si3O10(OH)2	Apatite	3.19	Ca5P3O12(OH)
Nepheline	2.61	NaAlSiO4	Chromite	5.09	FeCr2O4
Orthoclase	2.56	KAlSi3O8	Halite	2.17	NaCl
Paragonite	2.78	NaAl3Si3O10(OH)2	Sylvite	2	KCl

Figure 1

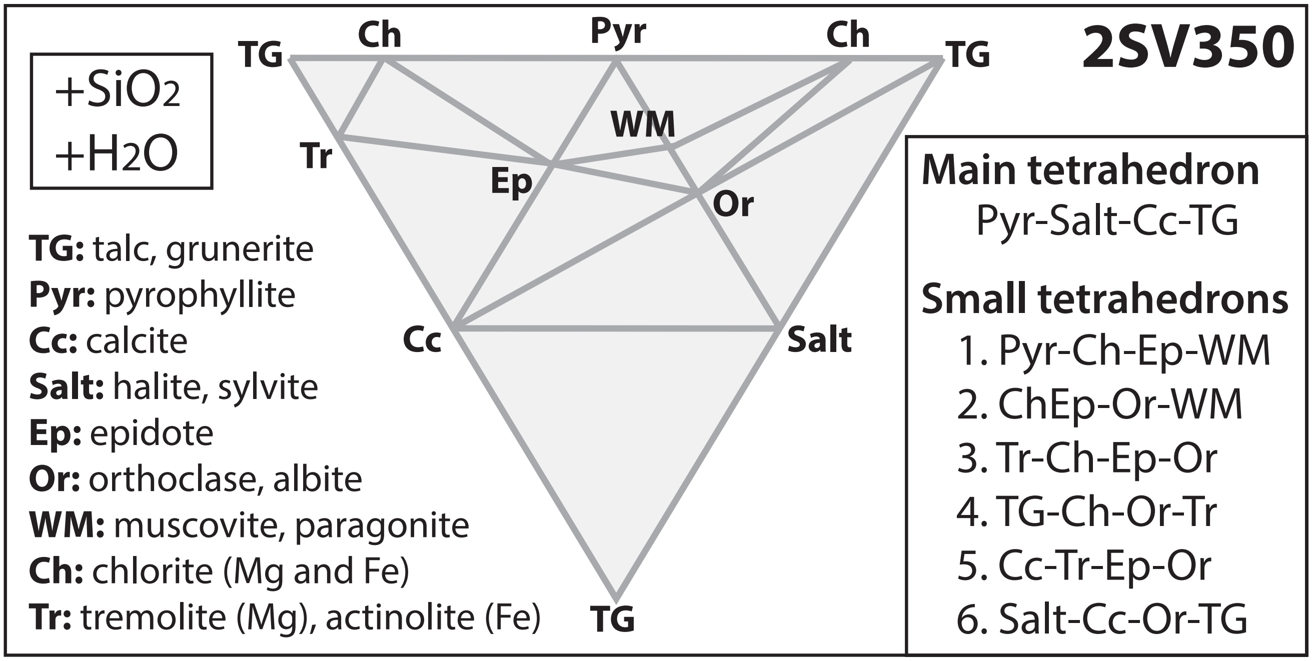


Fig. 1

Figure 2

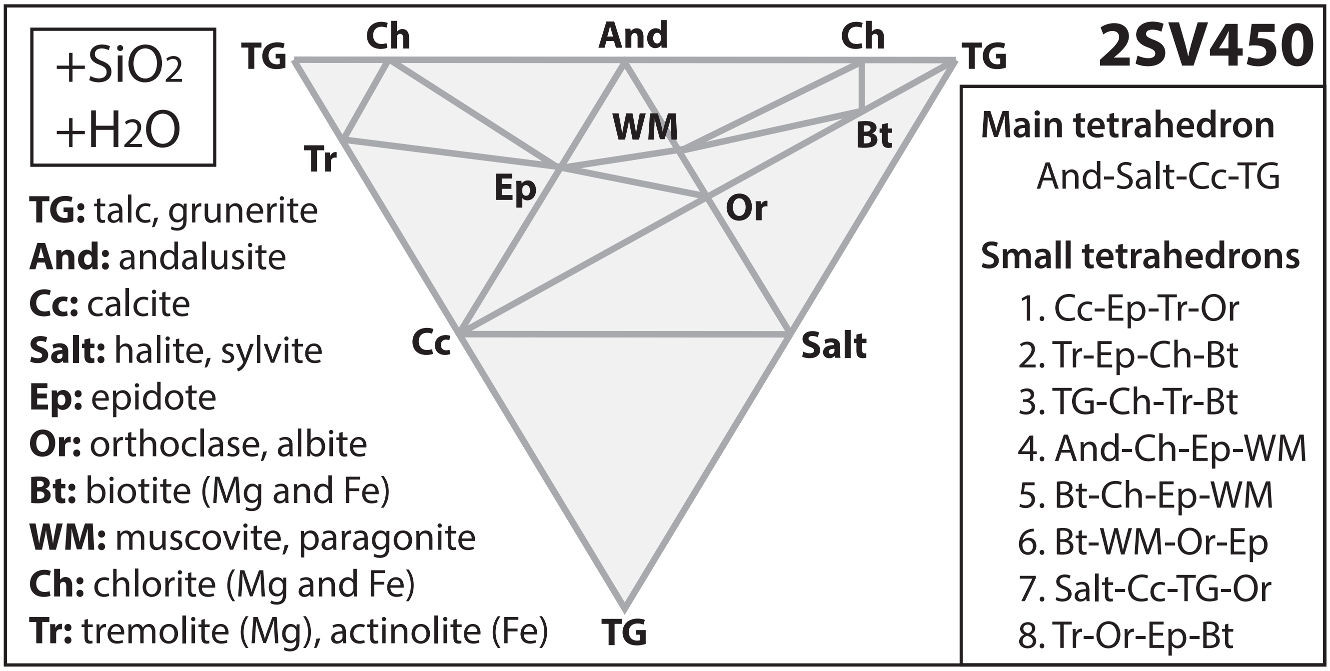
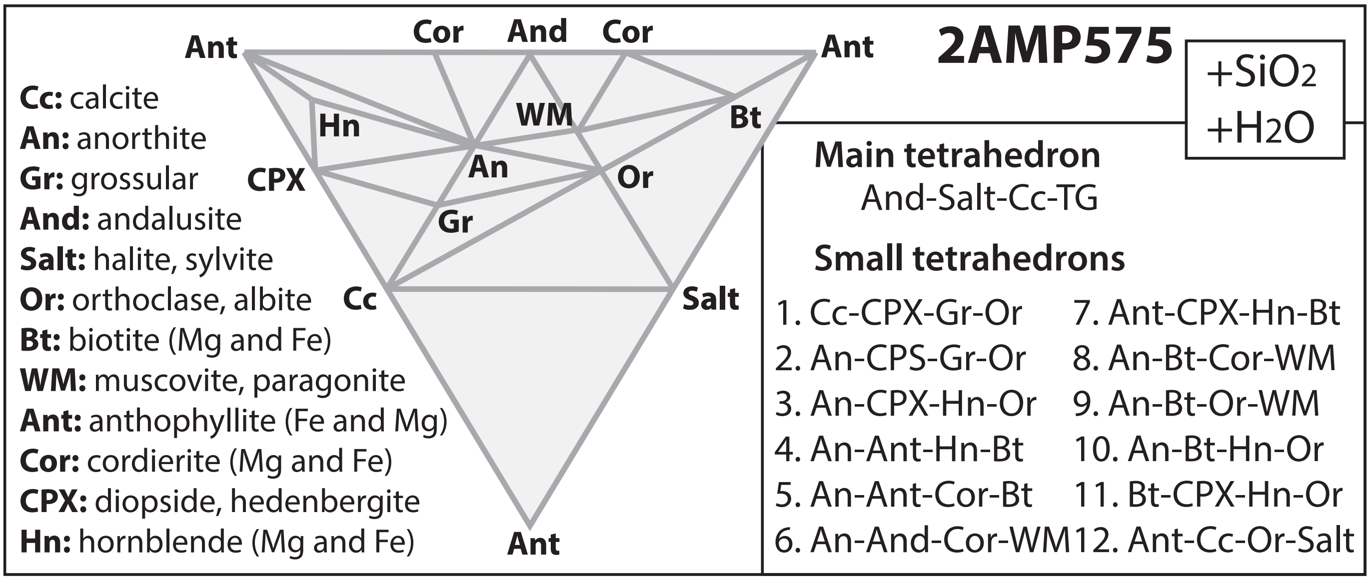


Fig. 2

Figure 3



Cc: calcite
An: anorthite
Gr: grossular
And: andalusite
Salt: halite, sylvite
Or: orthoclase, albite
Bt: biotite (Mg and Fe)
WM: muscovite, paragonite
Ant: anthophyllite (Fe and Mg)
Cor: cordierite (Mg and Fe)
CPX: diopside, hedenbergite
Hn: hornblende (Mg and Fe)

Main tetrahedron
And-Salt-Cc-TG

Small tetrahedrons
1. Cc-CPX-Gr-Or
2. An-CPS-Gr-Or
3. An-CPX-Hn-Or
4. An-Ant-Hn-Bt
5. An-Ant-Cor-Bt
6. An-And-Cor-WM
7. Ant-CPX-Hn-Bt
8. An-Bt-Cor-WM
9. An-Bt-Or-WM
10. An-Bt-Hn-Or
11. Bt-CPX-Hn-Or
12. Ant-Cc-Or-Salt

Fig. 3

Figure 4

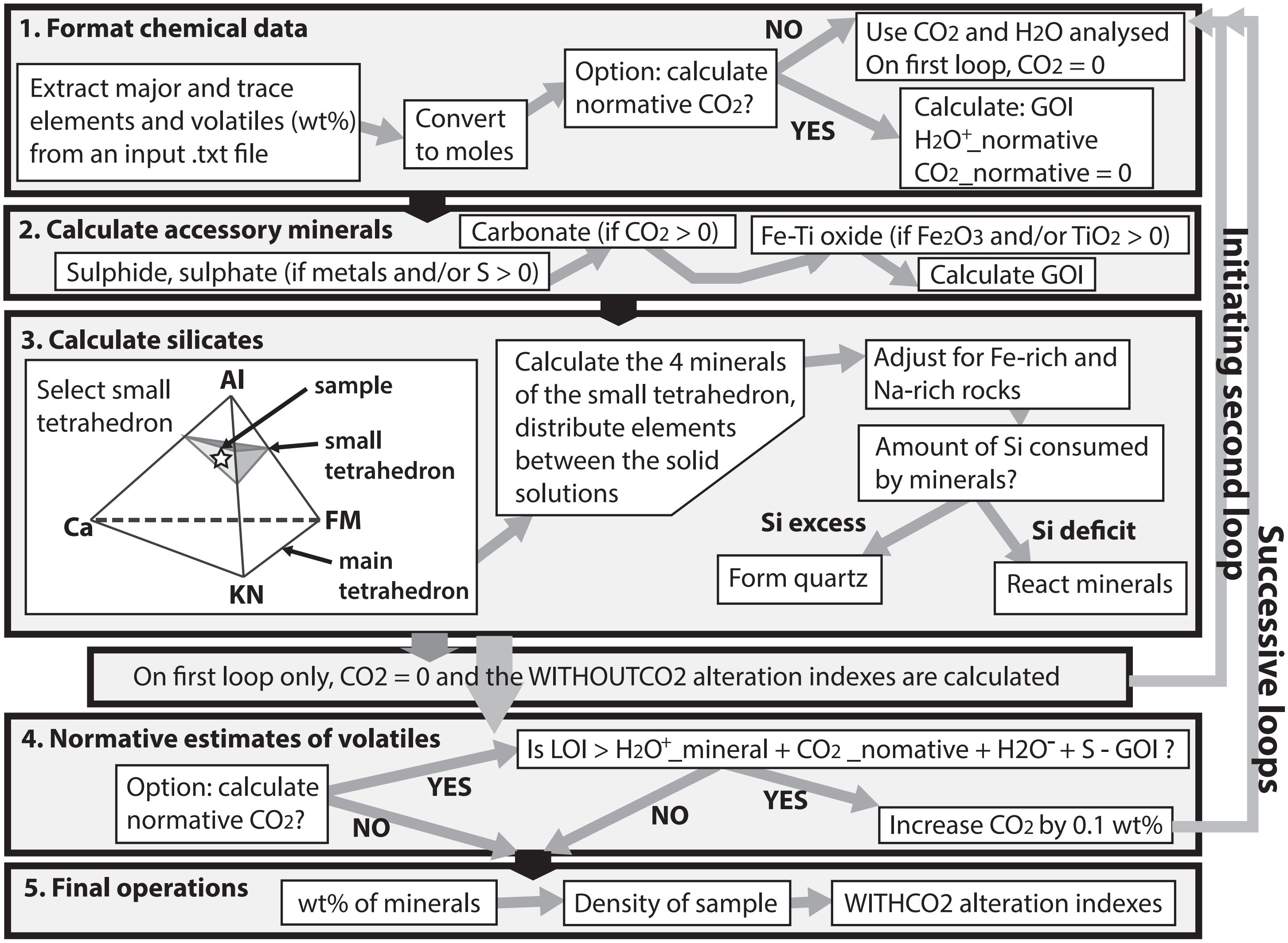


Fig. 4

Figure 5

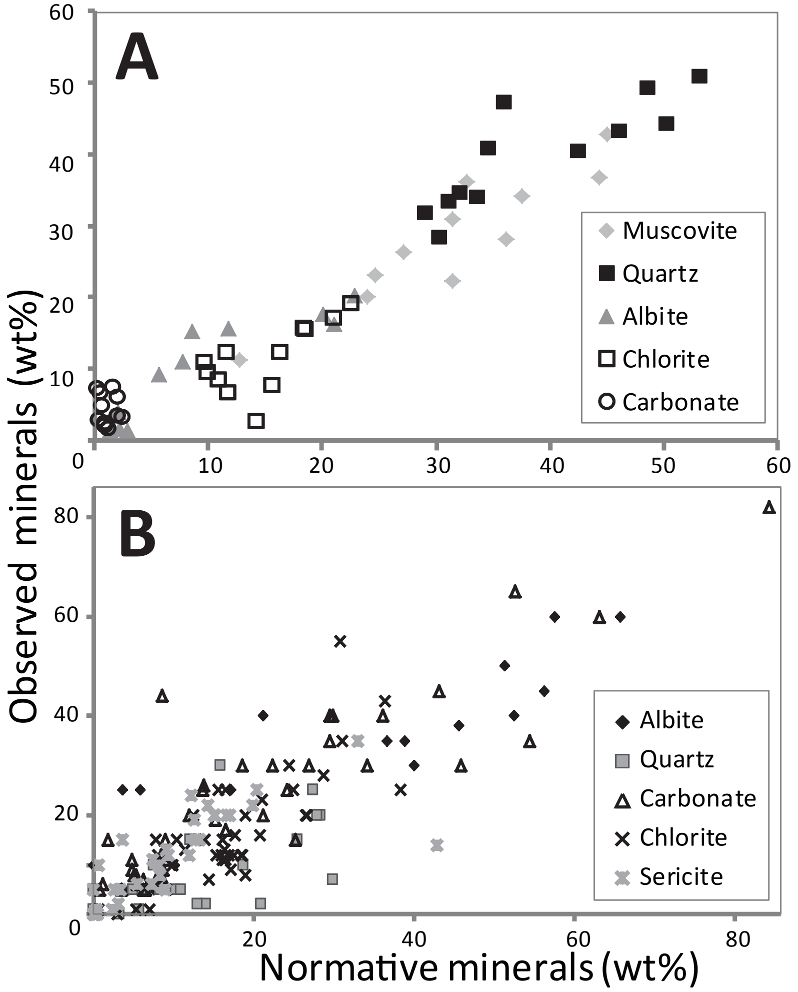


Fig. 5

Figure 6

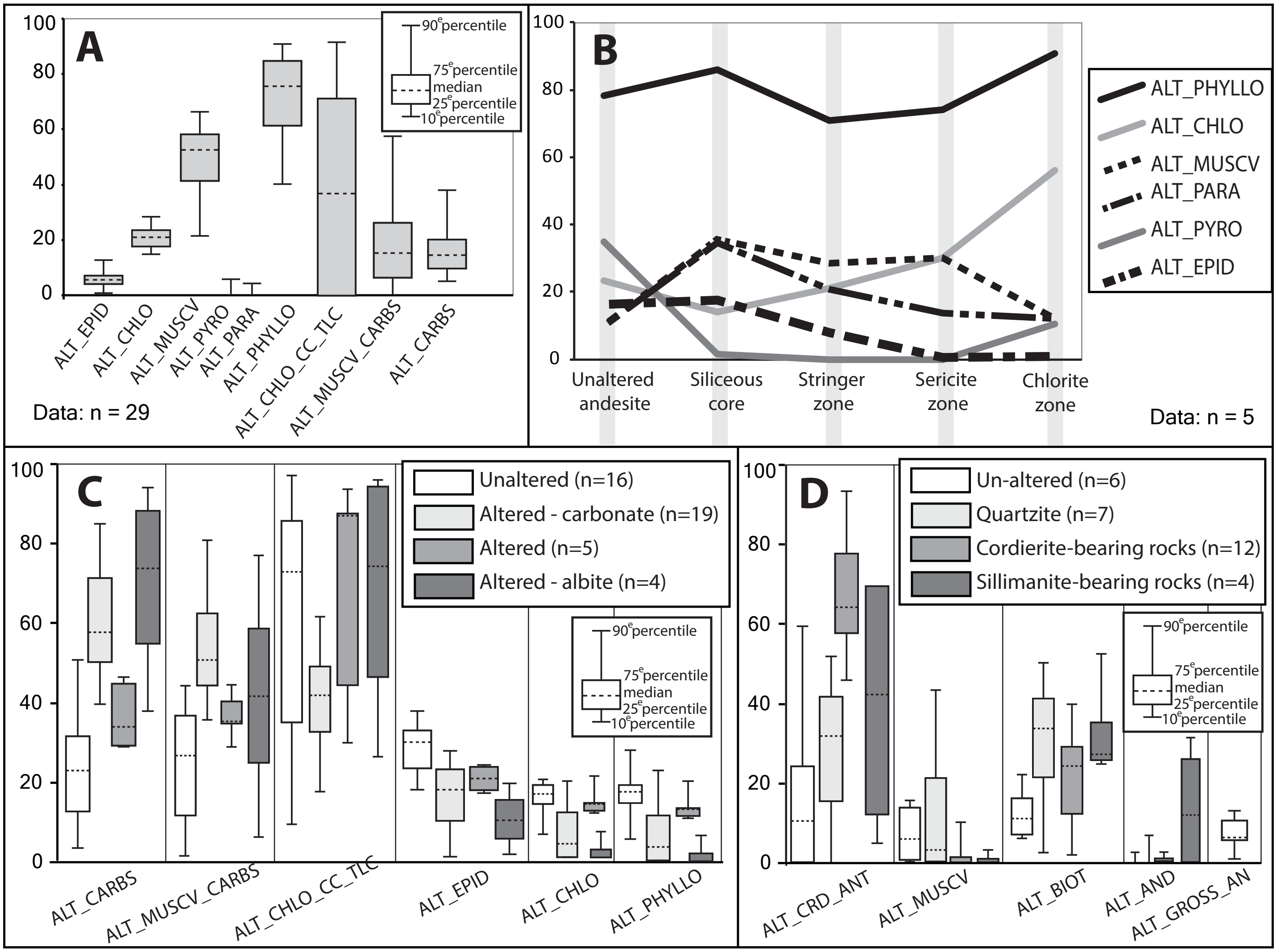


Fig. 6

Table 1: Mineral reactions used to adjust the parageneses for FeO-rich rocks

Facies	**Reactions performed**	**Condition**
2SV450	chlorite + 7.75 andalusite + 2.5 H_2O --> 10 chloritoid + 3.25 quartz 0.516 chlorite + 0.516 muscovite --> 2.161 chloritoid + 2.161 biotite + 0.677 quartz + 1.709 H_2O	Mg#* <0.3 and muscovite there
2SV450	chlorite + 7.75 andalusite + 2.5 H_2O --> 10 chloritoid + 3.25 quartz	Mg# <0.65 and epidote there
2AMP575	7.5 cordierite + 5 muscovite --> 5 biotite + 20 andalusite + 17.5 quartz 3.5 cordierite + H_2O --> anthophyllite + 7 andalusite + 1.25 H_2O	Mg# <0.55 and muscovite there
2AMP575	9 andalusite + 0.286 anthophyllite + 1.714 H_2O --> staurolite + 2.785 quartz 15.5 andalusite + 2 biotite + 6 H_2O --> 3 staurolite + 2 muscovite + 3.5 quartz staurolite + 1.64 anthophyllite --> 4.5 almandine + 3.643 quartz + 3.643 H_2O 70 staurolite + 3.833 biotite + 9.5 quartz --> 4.5 almandine + 3.833 muscovite + 3.833 H_2O	Mg# <0.3 and muscovite there
2AMP575	2 cordierite+ 5/7 anthophyllite --> 3 almandine + 63/7 quartz + 5/7 H_2O	Mg# <0.4 and anorthite there

*Mg# = MgO/(MgO+FeO) molar, calculated with the bulk of FeO and MgO.

Table 2: Mineral reactions used to solve silica deficits

Facies	**Reaction**
2SV350, 2SV450	2 talc + 2 H_2O --> serpentine + 4 quartz
2SV350	serpentine --> 6 brucite + 4 quartz + 2 H_2O
2SV450	serpentine --> 3 forsterite + 1 quartz + 4 H_2O
2AMP575	anthophyllite--> 3.5 forsterite + 4.5 quartz + H_2O
2SV450, 2AMP575	forsterite + H_2O --> 2 brucite + 1 quartz
2SV350, 2SV450	pyrophyllite --> diaspore + 2 quartz
All the facies, only if (Na+K) > Al (molar)	albite --> nepheline + 3 quartz orthoclase --> leucite + 2 quartz

Table 3: WITHOUTCO2 indexes for Na, K, Ca, Fe-Mg and Al alterations

Facies	**Indexes**	**Formula**
2SV350, 2SV450	ALT_CHLO*	100 * (chlorite_Mg * 0.75 + chlorite_Fe) / SUM**
	ALT_MUSCV	100 * muscovite / SUM
	ALT_EPID	100 * epidote / SUM
2SV350	ALT_PYRO	100 * pyrophyllite / SUM
	ALT_PHYLLO***	100 * (chlorite_Mg*0.75 + chlorite_Fe + muscovite + paragonite + pyrophyllite) / SUM
2SV450	ALT_CTD	100 * (chloritoid_Mg + chloritoid_Fe) / SUM
	ALT_PHYLLO	100 * (chlorite_Mg*0.75 + chlorite_Fe + muscovite + andalusite + biotite + Chloritoid) / SUM
2SV450, 2AMP575	ALT_BIOT	100 * biotite / SUM
	ALT_AND	100 * andalusite / SUM
2AMP575	ALT_MUSCV	100 * muscovite / SUM
	ALT_GROSS_ AN	100 * (grossular + anorthite * 0.5) / SUM
	ALT_STD_GRT	100 * (staurolite + almandine + pyrope) / SUM
	ALT_CRD_ANTH	100 * (cordierite + anthophyllite) / SUM

*ALT_CHLO: the 0.75 factor is used to decrease the effect of mafic, naturally chlorite rich protoliths, on the values of this alteration index.

**SUM = sum of all minerals (with chlorite_Mg multiplied by 0.75) except quartz and sulfides.

***ALT_PHYLLO: index similar to the IFRAIS index of NORMAT (Piché and Jébrak 2004).

Table 4: WITHCO2 indexes for carbonatation-type alteration

Facies	**Indexes**	**Formula**
2SV350	ALT_CHLO_CC_TLC	100 * (chlorite - chlorite_WITHOUTCO2 + calcite + talc) / SUM*
	ALT_MUSCV_CARBS	100 * (ankerite + dolomite + magnesite + siderite + muscovite – muscovite_WITHOUTCO2) / (SUM + orthoclase + muscovite)
2SV350, 2SV450	ALT_CARB**	100 * (calcite + dolomite + ankerite + magnesite + siderite) / SUM

***S**UM: sum of all FeO-, MgO- or/and CaO-bearing minerals, except sulfides.

**ALT_CARBS: similar to the IPAF index of NORMAT (Piché and Jébrak 2004).

Table 5: Threshold values of alteration indexes for magmatic rocks

Facies	**Indices**	**Felsic rocks**
2SV350, 2SV450	ALT_CARBS, ALT_CHLO_CC_TLC	> 20 (F); > 0 (I, M, UM*)
	ALT_EPID	> 15 (F); > 30 (I); > 20 (M); > 0 (UM)
	ALT_CHLO, ALT_PHYLLO	> 5-10 (F); > 15 (I, M, UM)
All	ALT_MUSCV, ALT_MUSCV_CARBS	> 5-10 (F); > 0 (I, M, UM)
	ALT_PARA, ALT_PYRO, ALT_CTD, ALT_AND	> 0 (F, I, M, UM)
2AMP575	ALT_GROSS_AN	> 10 (F); > 15 (I); > 10 (M); > 5 (UM)
	ALT_BIOT	> 10 (F, I, M, UM)
	ALT_CRD_ANTH	> 0 (F); > 10 (I, M); > 25 (UM)

*F, I, M and UM stand for felsic (F), intermediate (I), mafic (M) and ultramafic (UM) magmatic rocks.