Filling the Gap in the Classification of Phlogopite-Bearing Ultramafic Rocks

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ABSTRACT

In recent years, the many new occurrences reported in the literature of ultramafic rocks that have phlogopite as a major constituent and do not fall into the categories of kimberlites, lamproites, and lamprophyres have highlighted the need for a classification that includes this abundant mineral phase. Currently, a broadly accepted classification with phlogopite does not exist, and the only term used by scientists is "phlogopite-bearing" when this phase is above 5 vol% and up to 90 vol%. For this reason, we propose a new classification that integrates phlogopite into the current classification of ultramafic rocks without modifying the already accepted terminology or the classificative criteria [i.e., the mineral modal abundances]. Phlogopite is added as an end member in the ultramafic-rocks classification diagrams, changing their shapes from triangular to tetrahedral. An Excel spreadsheet containing the new diagrams and a macro that automatically classifies the rocks is provided.

Online enhancement: supplemental table.

Introduction

In many areas of the continental crust, the number of discoveries of ultramafic rocks rich in phlogopite that are different from kimberlites, lamproites, and lamprophyres has increased (Judd 1885; Johanssen 1938; Cotelo Neiva 1947; Dawson and Smith 1977; Kramers et al. 1983; Meyer and Villar 1984; Moreva-Perekalina 1985; Szabó 1985; Erlank et al. 1987; Sen 1988; Neal and Taylor 1989; Giannetti and Luhr 1990; Lloyd et al. 1991; Ionov and Hofmann 1995; Mues-Schumacher et al. 1996; Dessai and Vaselli 1999; Zanetti et al. 1999, 2013, 2014, 2016; Righter and Rosas-Elguera 2001; van Achterberg et al. 2001; Grégoire et al. 2002; Morishita et al. 2003, 2008; Downes et al. 2004a, 2004b; Bell et al. 2005; Devaraju et al. 2006; Ho et al. 2006; Liu et al. 2011; Selverstone and Sharp 2011; fernando et al. 2013; Giovanardi et al. 2013, 2014; Vrijmoed et al. 2013; Bucholz et al. 2014; Trubač et al. 2015; Kaczmarek et al. 2016]. In these rocks, the term “phlogopite” is used not only to point out the trioctahedral mica’s Mg end member but also to denote Mg-rich intermediate micas between the phlogopite and annite end members (down to Mg# = 0.64; Ionov and Hofmann 1995]. In this article, we use the term “phlogopite” according to the biotite classification of Deer et al. [1966], which comprehends all the trioctahedral micas with Mg# > 0.67 [i.e., phlogopite and Fe-rich phlogopite]. Some of the best examples of phlogopite-bearing peridotites and pyroxenites outcrop in the Finero massif [Ivrea-Verbano Zone, western Southern Alps, Italy; Zanetti et al. 1999, 2013, 2014, 2016; Morishita et al. 2003, 2008; Selverstone and Sharp 2011; Giovanardi et al. 2013, 2014]. Other examples are given by mantle xenoliths entrapped in alkaline and high-alkaline melts, like the so-called MARID [mica-amphibole-rutile-ilmenite-diopside; Dawson and Smith 1977], PP and PKP [phlogopite-bearing and phlogopite-K richterite-bearing peridotites, respectively, Erlank et al. 1987], and PIC [phlogopite-ilmenite-clinopyroxene-minor rutile; Grégoire et al. 2002] suites of xenoliths in kimberlites. In these cases, authors have commonly used acronyms to name the rocks. More frequently, the term...
“phlogopite-bearing” is used in association with the current classification of ultramafics, thus not considering the percentage by volume of phlogopite, which can vary from 5 vol% to 90 vol%. Moreover, the nomenclature reported in the literature to describe this type of rock is rather obsolete and unused. For example, the term “abessedite” indicates a variety of peridotite composed of olivine, hornblende, and phlogopite [Abessedo Mine, Bragança district, Portugal; Cotela Neiva 1947], the name “pikeite” denotes a phlogopite peridotite [Pike County, Arkansas; Johannsen 1938], and “sceylite” describes an olivine-hornblendite with phlogopite [Loch Scye, Scotland; Judd 1885]. In few cases, phlogopite-rich rocks are known by local names, as for the Finero area, where “tomboghisinite” is a peridotite formed by phlogopite and olivine, “foerdabilite” is a peridotite formed by olivine and hornblende, and “celhodurite” is a phlogopite- and hornblende-rich websterite [Zanetti et al. 1999; A. Zanetti, personal communication].

Currently, the only attempt to classify phlogopite-rich rocks has been put forward by Szabó [1985], who has provided a specific classification system for ultramafic xenoliths with high phlogopite modal content found in Hungarian lamprophyric dikes. However, this classification does not include the presence of both phlogopite and orthopyroxene (Szabó 1985), which could coexist normally in ultramafic rocks [e.g., the phlogopite-bearing harzburgite in Finero, Zanetti et al. 1999, among others], thus leaving a major classification gap. Yet there is no broadly accepted classification that considers phlogopite as a main mineral phase along with those most commonly contained in ultramafic rocks, that is, olivine, orthopyroxene, clinopyroxene, and hornblende.

The classification we propose uses a terminology that is not in conflict with the current classification of ultramafics accepted in the scientific community but constitutes an extension. In addition, an Excel spreadsheet [also compatible with Libreoffice and Openoffice], available online, has been created to allow the practical use of the newly proposed diagrams. To demonstrate the functionality of the new classification, some ultramafic rock samples rich in phlogopite reported in the literature have been reclassified according to the new nomenclature.

The Current International Union of Geological Sciences (IUGS) Ultramafic-Rock Classification

The IUGS Recommendation. The classification of ultramafic igneous rocks is carried out with the modal composition expressed as percentage by weight of the constituent minerals. The IUGS subcommission on the systematics of the igneous rocks suggests the use of two triangular diagrams designed by Streckeisen [1973]. The first one is based on the modal proportions of olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx; hereafter the Ol-Opx-Cpx diagram; figs. 1, 2). The second one is based on Ol, pyroxenes (Px), and hornblende (Hbl), where “hornblende” comprehends all the amphibole-group minerals; in this article, we use this term in the same meaning; hereafter the Ol-Px-Hbl diagram; figs. 3, 4), with M > 90%, where “M” means mafic and related minerals, for example, mica, Hbl, Px, Ol, opaque minerals, accessory minerals (e.g., zircon, apatite [Ap], titanite), epidote, allanite, garnet, melilite, monticellite, and primary carbonate. With this method it is possible to distinguish three main groups of ultramafic rocks: (1) peridotites, containing more than 40% Ol, with the rest consisting of Px or Hbl [dunites have more than 90% Ol], (2) pyroxenites, and (3) hornblendites, containing less than 40% Ol and mainly composed of either Px or Hbl.

Problems in the Classification of Rocks Rich in Phl. There are several examples in literature of ultramafic rocks that, along with the most common phases, such as Ol, Px, and Hbl, consist of nonnegligible amounts of Phl, sometimes even more than 20%. An example is sample PC128 [Giannetti and Luhr 1990] from the Roccamonfina volcano [Italy], whose modal composition includes Ol [8.6%], Cpx [63.1%], Phl [27.9%], and Sp [trace], or sample RGM319101 from Siebengebirge in Germany [Moreva-Perekalina 1985], formed by Ol [10%], Cpx [60%], and Phl [30%].

The lack of a classification suitable for ultramafic rocks with Phl triggers systematic anomalies in the nomenclature documented by cases in which the same name is given to rocks that have significantly different compositions. For example, sample FL19 of Lloyd et al. [1991], consisting of Cpx [44.5%], Phl [51.2%], and Sp [trace], where the dominant mineral is Phl, is named “phlogopite pyroxenite,” but so is sample AY-506 from Rigter and Rosas-Elguera [2001], with Ol [1.7%], Cpx [57.6%], Phl [31.6%], and Ap [9.1%], where Cpx is the most abundant mineral phase.

Conversely, we have encountered cases in the literature where the composition of two samples is very similar but their nomenclature is different. For example, the A sample of Lloyd et al. [1985], con-
sisting of Ol (trace), Cpx (52.5%) and Ap (1.0%), is named “phlogopite clinopyroxenite,” whereas the LSC188 sample of Downes et al. (2004a) made of Opx (6.0%), Cpx (54.4%), Phl (36.0%), is defined as “mica websterite.”

Another type of incongruity concerns rocks that are classified as peridotites when the percent recalculations are performed after Phl is removed from the modal composition. This is the case of sample LSC240 of Downes et al. (2004a), from the Bearpaw Mountains in Montana, consisting of Ol (32.2%), Opx (10.1%), Cpx (18.8%), and Phl (39%). If this sample is classified with the Ol-Opx-Cpx diagram of Streckeisen (1973), the recalculated modal composition results in Ol (52.8%), Opx (16.7%), and Cpx (30.7%), corresponding to a lherzolite (Downes et al. 2004a classified the rock as a “mica lherzolite”), even though the original Ol content is less than 40%.

The Classification of Phl-Bearing Ultramafic Rocks

The basic idea for the new classification was to keep unchanged the nomenclature and classes proposed by Streckeisen (1973) for ultramafic rocks and only to integrate the missing Phl component. Moreover, we wanted to create a fairly intuitive classification with a nomenclature based upon the existing one.

Figure 1. “Exploded” faces of the POCO (phlogopite [Phl]-olivine [Ol]-clinopyroxene [Cpx]-orthopyroxene [Opx]) diagram and nomenclature.
Since the goal is to create a classification applicable to Phl-rich ultramafic rocks, we decided to implement the modal Ol-OpX-Cpx and Ol-Px-Hbl triangular diagrams, adding the Phl. The two obtained systems have four phases each (Phl-Ol-Cpx-Opx and Phl-Ol-Px-Hbl), resulting in two tetrahedral diagrams named “POCO” and “POPH,” respectively.

Both the inner volume and the outer faces of the tetrahedrons have been divided into fields. The bases of the tetrahedrons POCO and POPH correspond to the Streckeisen [1973] ternary diagrams Ol-OpX-Cpx and Ol-Px-Hbl, respectively; therefore, the existing subdivisions have been applied.

The other faces represent new ternary diagrams for which we propose the following subdivisions. For the POCO tetrahedron, Ol-Phl-Cpx and Ol-Phl-Opx faces have been constructed with the fields of dunite (Ol > 90%), clinopyroxenite (Cpx > 90%), orthopyroxenite (Opx > 90%), and phlogopitite (Phl > 90%) at the vertices. In literature there is no consensus on the name for rocks composed mainly of Phl: some authors prefer the old german term “glimmerite,” while others prefer to decline the mineral name with the -ite ending (i.e., phlogopitite), similar to pyroxene-rich rocks (i.e., pyroxenite, orthopyroxenite and clinopyroxenite). We have decided to use the term “phlogopitite” to follow the IUGS recommendations. According to the Streckeisen diagrams, a line corresponding to 40% Ol modal content and other lines corresponding to 5% of Cpx, Opx, Phl, and Ol are plotted. Another segment connects the 50% on the Cpx-Phl and the Opx-Phl sides of the two diagrams with the dunite field. The latter segment is also projected on the face Phl-Cpx-OpX to form the segment passing through 50% of the Phl modal content. Likewise, on this face, the fields of orthopyroxenite, clinopyroxenite, and phlogopitite have been outlined, along with the segments for 5% modal content of each mineral. The fields obtained in the four faces of the POCO tetrahedron mark different inner volumes in the solid diagram.

In order to easily determine the new nomenclature for the created fields, a set of all the faces of the diagram can be obtained by “exploding” the tetrahedron into a flat shape (fig. 1). Terms already established by the IUGS subcommission for the fields within the Streckeisen triangle have been maintained. The name “phlogopite-dunite” indicates those rocks consisting mainly of these two minerals, with Ol > 40% and Phl < 60%.

Specifically, the POCO tetrahedron is subdivided internally into various volumes (fig. 2). For mineral abundances equal to 0%, the rock name is the one reported on the specific tetrahedron face. Planes representing sums of two phases equal to 5% cut the tetrahedron edges and are truncated at the vertices by single-phase fields. The names of these internal solid volumes have been conceived by generalizing those already used for the faces. The POCO internal volumes are (1) olivine and phlogopite websterite (<40% Ol and >50% Pxl), (2) pyroxene and olivine phlogopitite (<40% Ol and >50% Pxl), (3) phlogopite

Figure 2. POCO (phlogopite [Phl]-olivine [Ol]-clinopyroxene [Cpx]-orthopyroxene [Opx]) diagram (A) and its internal volumes of phlogopite and pyroxene dunite (B), phlogopite lherzolite (C), pyroxene and olivine phlogopitite (D), and olivine and phlogopite websterites (E). The order of the minor abundant phases is fixed for convenience. Authors must change the term order on the basis of the relative abundances of the phases (e.g., phlogopite and olivine websterite if the Phl is more abundant than the Ol). A color version of this figure is available online.
lherzolite (>40% Ol and more Px than Phl), and (4) phlogopite and pyroxene dunite (>40% Ol and more Phl than Px).

The POPH tetrahedron (figs. 3, 4) has been constructed similarly to the POCO. However, it has been necessary to add an extra plane, which separates the pyroxenite and hornblende fields, and extend it to the peridotite volume. In this diagram, the name "hornblende-dunite" indicates those rocks consisting mainly of these two minerals, with Ol > 40% and Hbl < 60%.

Internal volumes in POPH are (1) pyroxene and hornblende phlogopite (>50% Phl, <40% Ol, and more Px than Hbl), (2) hornblende and pyroxene phlogopite (>50% Phl, <40% Ol, and more Hbl than Px), (3) phlogopite, pyroxene, and olivine hornblende dunite (>50% Hbl and <40% Ol), (4) phlogopite, hornblende, and olivine websterite (>50% Px and <40% Ol), (5) phlogopite, pyroxene, and hornblende dunite (>40% Ol, more Phl than the sum of Hbl and Px, and more Px than Hbl), (6) phlogopite, hornblende, and pyroxene dunite (>40% Ol, more Phl than the sum of Hbl and Px, and more Hbl than Px), (7) hornblende, phlogopite, and pyroxene dunite (>40% Ol, more Hbl than the sum of Phl and Px), and (8) phlogopite and hornblende peridotite (>40% Ol and more Px than the sum of Hbl and Phl).

The classificatory mineral phases present in minor modal proportions must be expressed according to their relative abundances. For example, "pyrox-
ene and olivine phlogopitite” is used if the Px are more abundant than Ol and “olivine and pyroxene phlogopitite” if the Ol is more abundant.

The Extension of the Ultramafic-Rocks Classification

The new tetrahedral classification has also been implemented to include both Opx and Cpx at the vertices of the diagram, combining the Ol-Opx-Cpx and Ol-Px-Hbl diagrams. This allows a more specific and accurate classification of samples. The diagram has been named “COHO” [Cpx-Opx-Hbl-Ol] and has the same subdivisions as the POCO tetrahedron [figs. 5, 6].

Internal volumes (>5% of the sum of two phases and >0% of each phase) are [1] hornblende and olivine websterite (<40% Ol, >50% the sum of Cpx and Opx), [2] pyroxene and olivine hornblendite (<40% Ol, more Hbl than the sum of Cpx and Opx), [3] hornblende lherzolite (40% Ol, less Hbl than the sum of Cpx and Opx), and [4] hornblende and pyroxene dunite (>40% Ol, more Hbl than the sum of Cpx and Opx).

In summary, for each point of the various tetrahedrons, either on the faces or within their volumes, the sum of the four components is equal to 100. At each vertex, the presence of a specific mineral is 100%, and hence the remaining value is 0%. If the sum of the modal percentages of the sample falls on a face, the rock will assume the name of the field; if it falls within the tetrahedron, the rock will be classified according to the name of the volumetric field in which it is located.

For Hbl > 5% and Phl < 5%, the Phl is considered negligible and the classification can be made with the COHO tetrahedron. When the amount of Phl exceeds 5% and the presence of Hbl is less than 5%, the POCO tetrahedron comes into play. If both Hbl and Phl exceed 5%, the POPH tetrahedron is used.

CLASS-ULTRAMAFIC: A New Spreadsheet for the Classification of Ultramafic Rocks

The best way to view the data within a tetrahedron is to use suitable software. We modified the Excel spreadsheet “Tetra-Plot” (Cucciniello 2016) on the basis of a spreadsheet developed by Shimura and Kemp [2015] and applied several improvements.

Figure 4. POPH [phlogopite [Phl]-olivine [Ol]-pyroxenes [Px]-hornblende [Hbl]] diagram [A] and its internal volumes of phlogopite, hornblende, and pyroxene dunite (B); phlogopite, pyroxene, and hornblende dunite (C); hornblende, phlogopite, and pyroxene dunite (D); phlogopite and hornblende peridotite (E); hornblende, pyroxene, and olivine phlogopitite (F); pyroxene, hornblende, and olivine phlogopitite (G); phlogopite, pyroxene, and olivine hornblendite (H); and phlogopite, hornblende, and olivine websterite (I). The order of the minor abundant phases is fixed for convenience. Authors must change the term order on the basis of the relative abundances of the phases [e.g., phlogopite and hornblende peridotite if the Phl is more abundant than the Hbl]. A color version of this figure is available online.
The CLASS-ULTRAMAFIC Excel file contains a calculation sheet and a diagram sheet for each tetrahedron: POCO, POPH, and COHO. The “Instructions” sheet contains all the information for the use of the spreadsheet. The “Input data” sheet contains a table of 18 columns and more than 1000 rows. In this sheet, the modal abundance, in percent, must be entered for each mineral found in the rock sample (symbols and text must be avoided). The data are automatically reported in each calculation sheet and evaluated by a function that determines the right classification. Internal functions in the “Calculated data” sheets halt the classification in the sheets that are not relevant, writing “***” in column H and modifying the mineral abundances to 0%. The data in the proper classification sheet are then recalculated to 100% to apply the classification and are transformed into \((X, Y)\) coordinates with the following trigonometric equations:

\[
Y' = X \times \cos \left( \frac{\gamma}{180} \right) \times \sin \left( \frac{\beta}{180} \right) \\
\times -\sin \left( \frac{\alpha}{180} \right) + \sin \left( \frac{\gamma}{180} \right) \times \cos \left( \frac{\alpha}{180} \right) \\
+ Y \times \sin \left( \frac{\gamma}{180} \right) \times -\sin \left( \frac{\beta}{180} \right) \\
\times -\sin \left( \frac{\alpha}{180} \right) \times \cos \left( \frac{\alpha}{180} \right) \\
+ Z \times \cos \left( \frac{\beta}{180} \right) \times \sin \left( \frac{\alpha}{180} \right) ,
\]

Figure 5. “Exploded” faces of the COHO (clinopyroxene [Cpx]-orthopyroxene [Opx]-hornblende [Hbl]-olivine [Ol]) diagram and nomenclature.
\[ X' = X \times \cos\left(\frac{\beta \pi}{180}\right) \times \cos\left(\frac{\gamma \pi}{180}\right) + Y \times -\sin\left(\frac{\gamma \pi}{180}\right) \times \cos\left(\frac{\alpha \pi}{180}\right) + Z \times \sin\left(\beta \frac{\pi}{180}\right), \]

where \( \gamma, \alpha, \) and \( \beta \) are the rotation angles of the tetrahedron visible in the “Tetrahedron” sheet in column B, rows 3–5. The results of these calculations are shown in the “Calculated data” sheet.

Each “Tetrahedron” tab displays the tetrahedral diagram with the selected minerals at the vertices. Within the tetrahedron, the planes are identified by different colors. Depending on the volume where the data falls, the sample name can be easily defined.

The tetrahedron is able to rotate on the three axes \( \{X, Y, Z\} \) orthogonal to each other, so that the position of the samples within the diagram can be observed. Angle values can be changed by moving the sliders of the three scroll bars in the upper-left corner of the sheet. During the rotation, the positions of the data and the planes remain solid within the tetrahedron.

The spreadsheet is also equipped with a classification macro, which automatically provides the rock name according to the new classification. The macro works only if column B (sample name) in the “Input data” is filled. If the cell is filled, the macro automatically tries to read the proper classification values in the “Calculated data” sheet and inserts the rock name in column U (Classification) of the “Input data” sheet. To start the macro, the “Classify” button must be clicked.

The CLASS-ULTRAMAFIC spreadsheet is an xlsx file and requires the software Excel 2007 or a newer version. The file also runs in Libreoffice and Openoffice, permitting a completely free use of the spreadsheet, similar to a few software packages in the literature (e.g., the Hf-INATOR; Giovanardi and Lugli 2017). Within the spreadsheet, an exhaustive compilation of Phl-rich ultramafic rocks from literature is reported and classified.

**Examples Based on the New Classification**

The new proposed classification for ultramafic rocks that includes Phl as a major end member will be helpful to homogenize the currently extremely heterogeneous terminology for this kind of rocks. Rocks with a nonnegligible content of Phl will now have more appropriate names. Some examples are sample RGM 319407 [Ol 85%, Phl 15%], named “duname” by Moreva-Perekalina (1985) and now classified as phlogopite dunite; sample WC253 [Ol 75.5%, Cpx 7%, Phl 16.7%] named “mica wehrlite” by Downes et al. (2004a) and now classified as phlogopite and clinopyroxene dunite; and sample LSC241 [Ol 36%, Cpx 15.4%, Phl 48.5%], named “mica wehrlite” by Downes et al. (2004a) and now classified as olivine and clinopyroxene phlogopitite.
Rocks with different compositions will now have different names, as in the case of samples WC253 and LSC241 reported above; the case of samples LSC238 (Ol 35.4%, Cpx 15.9%, Phl 48.6%; Downes et al. 2004a) and FL251 (Ol 44.3%, Cpx 41.5%, Phl 10.7%; Lloyd et al. 1991), both previously named “mica wehrlite” and now classified as olivine and clinopyroxene phlogopitite and phlogopite wehrlite, respectively; or the case of samples FL251 and FL4 (Ol 78.4%, Cpx 8.3%, Phl 11.6%; Lloyd et al. 1991), both previously named “mica wehrlite” and now classified as phlogopite wehrlite and phlogopite clinopyroxene dunite, respectively. Conversely, rocks with similar mineralogical composition will have the same name. For example, samples JSL177-2 (Cpx 29%, Phl 67%; van Achterberg et al. 2001) and LSC225 (Cpx 19.2%, Phl 80.8%; Downes et al. 2004), previously named “garnet phlogopite peridotite” and “mica clinopyroxenite,” respectively, are now classified as clinopyroxene phlogopitite.

The new classification also comes with a useful Excel spreadsheet, already formatted and including a macro for automatic classification.

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