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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 with phlogopite as a major constituent and not falling into the category of Kimberlites, Lamproites and Lamprophyres, have highlighted the need of 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 'bearing phlogopite' 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.

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 with phlogopite as a major constituent and not falling into the category of Kimberlites, Lamproites and Lamprophyres, have highlighted the need of 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 'bearing phlogopite' 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.

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; Johannsen, 1938; Cotelo Neiva, 1947; Dawson and Smith, 1977; Kramers et al., 1983; Meyer and Villa, 1984; Moreva, 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; Schumacher et al., 1996; Dessai and Vaselli, 1999; Zanetti et al., 1999, 2013, 2014, 2016; Righter and Elguera, 2001; Van Achterberg et al., 2001; Grégoire et al., 2002; Morishita et al., 2003, 2008; Downes et al., 2004a, b; 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; Bulchoz et al., 2014; Trubac 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-endmember, but also to denote Mg-rich intermediate micas between the phlogopite and annite endmembers (down to Mg# = 0.64, Ionov and Hofmann, 1995). In this article we will 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 (Phlogopite-bearing Peridotites) and PKP (Phlogopite-K-richterite-bearing Peridotites; Erlank et al. 1987) and PIC rocks (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 'phlogopite-bearing' term is used in association with the current classification of ultramafics, thus not considering the % of phlogopite volume, which can vary from 5 % by Vol. up to 90 %. Moreover, the nomenclature reported in the literature to describe this type of rocks is rather obsolete and unused. For example, the term "Abessedite" indicates a variety of peridotite composed of olivine, hornblende and phlogopite (Cotelo Neiva, 1947, Abessédo Mine, Bragança district, Portugal), the name "Pikeite" denotes a phlogopite peridotite (Johannsen, 1938; Pike County, Arkansas, USA), or "Scyelite" that describes an olivine-hornblendite with phlogopite (Judd, 1885, Loch Scye, Scotland, UK). 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, "Föeradibalite" is a peridotite formed by olivine and hornblende and "Celhodurite" is a phlogopite and hornblende rich websterite (Zanetti et al., 1999; Zanetti, personal communication).

Currently, the only attempt to classify Phl-rich rocks has been put forward by Szabó (1985), which 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 and 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) 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 IUGS ULTRAMAFIC ROCK CLASSIFICATION

The IUGS Recommendation

The classification of ultramafic igneous rocks is carried out using the modal composition expressed as percentage by weight of the constituent minerals. The IUGS subcommission on the systematic of the igneous rocks suggests the use of two triangular diagrams designed by Streckeisen (1973). The first one is based on the modal proportion of olivine, orthopyroxene and clinopyroxene (Fig.s 1 and 2). The second one is based on olivine, pyroxenes and hornblende (Fig.s 3 and 4), with M = mafic and related minerals, e.g. mica, amphibole, pyroxene, olivine, opaque minerals, accessory minerals (e.g. zircon, apatite, titanite), epidote, allanite, garnet, melilite, monticellite, primary carbonate > 90%. With this method it is possible to distinguish three main groups of ultramafic rocks: 1) peridotites, formed by more than 40% of olivine and the rest of pyroxenes or amphibole (dunites with more than 90% of olivine); 2) pyroxenites and 3) hornblendites, containing less than 40% olivine, mainly composed of either pyroxenes or amphiboles.

If the rocks contain less than or equal to 5% spinel, garnet, magnetite, chromite or phlogopite, this might be indicated by the addition of the word "with" after the name of the rock followed by that of the specific mineral (e.g. peridotite with garnet). However, more recently, it has become of common use to delete the "with" word and precede the rock name by the mineral name (e.g. garnet peridotite).

Problems in the Classification of Rocks Rich in Phlogopite

There are several examples in literature of findings of ultramafic rocks that, along with the most common phases such as olivine, pyroxene and amphibole, consist of non-negligible amounts of phlogopite, 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) [1] or sample RGM319101 from Siebengebirbe in Germany (Moreva, 1985) formed by Ol (10%), Cpx (60%) and Phl (30%).

The lack of an appropriate classification, suitable for ultramafic rocks with phlogopite, triggers systematic anomalies in the nomenclature documented by cases in which the same name is given to rocks that have a significantly different composition. 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 phlogopite, is named phlogopite pyroxenite, but such is named also sample AY-506 from Righter and Elguera (2001) with Ol (1.7%), Cpx (57.6%), Phl (31.6%) and Ap (9.1%), where clinopyroxene 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, (1985) consisting of Ol (Trace), Cpx (52.5%), Phl (37.0%) and Ap (1.0%), is named phlogopite clinopyroxenite, whereas the LSC188 sample of Downes et al. (2004) 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 recalculation is performed after removing phlogopite from the modal composition. This is the case of sample LSC240 of Downes et al. (2004) from Bearpaw Mountains in Montana (USA) consisting of Ol (32.2%), Opx (10.1%), Cpx (18.8%) and Phl (39%). If this sample is classified using the Ol-Opx-Cpx diagram of Streckeisen (1973), the recalculated modal composition results in Ol (52.8%), Opx (16.7%), Cpx (30.7%), corresponding to a lherzolite (Downes et al., 2004, classified the rock as a 'mica lherzolite'), even though the original Ol content is less than 40%.

THE CLASSIFICATION OF PHLOGOPITE 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 phlogopite component. Moreover, we wanted to create a fairly intuitive classification with a nomenclature that takes upon the existing one.

Since the goal is to create a classification applicable to phlogopite-rich ultramafic rocks, we decided to implement the modal Ol-Opx-Cpx and Ol-Px-Hbl triangular diagrams adding the phlogopite. 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 consensum on the name for rocks composed mainly by phlogopite: some authors prefer the old german term 'glimmerite' while others prefer to decline the mineral name using the -ite ending (i.e. phlogopitite) similar to pyroxene-rich rocks (i.e. pyroxen-ite, orthopyroxen-ite and clinopyroxen-ite). We have decided to use the phlogopitite term to follow the IUGS recommendations. According to the Streckeisen diagrams, a line corresponding to 40% olivine modal content and other lines corresponding to 5% of clinopyroxene, orthopyroxene, phlogopite, and olivine 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 phlogopite 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 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 olivine over 40% and phlogopite less than 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: a) olivine and phlogopite websterite (less than 40% of Ol and more than 50% of Px), b) pyroxene and olivine phlogopitite (less than 40% of Ol and more than 50% of Phl), c) phlogopite lherzolite (more than 40% of Ol and more Px than Phl) and d) phlogopite and pyroxene dunite (more than 40% of Ol and more Phl than Px).

The POPH tetrahedron (Fig.s 3 and 4) has been constructed similarly to the POCO. However, it has been necessary to add an extra plane, which separates the “pyroxenite” and “hornblendite” 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 olivine over 40% and hornblende less than 60%.

Internal volumes in POPH are: a) pyroxene and hornblende phlogopitite (more than 50% of Phl, less than 40% of Ol and more Px than Hbl), b) hornblende and pyroxene phlogopitite (more than 50% of Phl, less than 40% of Ol and more Hbl than Px), c) phlogopite, pyroxene and olivine hornblendite (more than 50% of Hbl and less than 40% of Ol), d) phlogopite, hornblende and olivine websterite (more than 50% of Px and less than 40% of Ol), e) phlogopite, pyroxene and hornblende dunite (more than 40% of Ol, more Phl than the sum of Hbl and Px, and with more Px than Hbl), f) phlogopite, hornblende and pyroxene dunite (more than 40% of Ol, more Phl than the sum of Hbl and Px, and with more Hbl than Px), g) hornblende, phlogopite and pyroxene dunite (more than 40% of Ol, more Hbl than the sum of Phl and Px) and h) phlogopite and hornblende peridotite (more than 40% of Ol, more Px than the sum of Hbl and Phl).

The classificatory mineral phases present in minor modal proportion must be expressed according to their relative abundances: e.g. 'pyroxene and olivine phlogopitite' if the pyroxenes are more abundant than olivine or 'olivine and pyroxene phlogopitite' if the olivine is more abundant.

THE EXTENSION OF THE ULTRAMAFIC ROCKS CLASSIFICATION

The new tetrahedral classification has also been implemented to include both ortho- and clinopyroxene 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 that have been described for the POCO tetrahedron (Fig.s 5 and 6).

Internal volumes (more than 5% of the sum of two phases and more than 0% of each phases) are: a) hornblende and olivine websterite (less than 40% of Ol, more than 50% of the sum of Cpx and Opx), b) pyroxene and olivine hornblendite (less than 40% of Ol, more Hbl than the sum of Cpx and Opx), c) hornblende lherzolite (more than 40% of Ol, sum of Cpx and Opx more than Hbl) and d) hornblende and pyroxene dunite (more than 40% of Ol, Hbl more 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 amphibole higher than 5% and phlogopite less than 5%, the phlogopite is considered negligible and the classification can be made the COHO tetrahedron.

When the amount of phlogopite exceeds 5% and the presence of amphibole is less than 5%, the POCO tetrahedron comes into play. If both amphibole and phlogopite 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) based on a spreadsheet developed by Shimura and Kemp (2015) and applied several improvements.

The CLASS-ULTRAMAFIC Excel contains a calculation sheet and a diagram sheet of each tetrahedron: POCO, POPH and COHO. An "Instructions" sheet contains all the information to 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 to be used. Internal functions in the "Calculated data" sheets halt the classification in the not relevant sheets 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 transformed into x, y coordinates using trigonometric equations [1] and [2].

$$[1]\ Y' = X * \cos(\gamma * \pi / 180) * -\sin(\beta * \pi / 180) * -\sin(\alpha * \pi / 180) + \sin(\gamma * \pi / 180) * \cos(\alpha * \pi / 180) + Y * \sin(\gamma * \pi / 180) * -\sin(\beta * \pi / 180) * -\sin(\alpha * \pi / 180) * \cos(\alpha * \pi / 180) + Z * \cos(\beta * \pi / 180) * -\sin(\alpha * \pi / 180)$$

$$[2]\ X' = X * \cos(\beta * \pi / 180) * \cos(\gamma * \pi / 180) + Y * -\sin(\gamma * \pi / 180) * \cos(\alpha * \pi / 180) + Z * \sin(\beta * \pi / 180)$$

where γ, α and β are the rotation angles of the tetrahedron visible in the "Tetrahedron" sheet in column B, rows 3,4 and 5.

The results of these calculations are shown in the table "Calculated Coordinates".

The "tetrahedron" sheet 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 and z orthogonal to each other, in order to observe the position of the samples within the diagram. 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 position of the data and the planes remain solid with 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 is a .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 few literature software (e.g., the Hf-INATOR; Giovanardi and Lugli, 2017). Within the spreadsheet, an exhaustive compilation of phlogopite-rich ultramafic rocks from literature is reported and classified.

EXAMPLES BASED ON THE NEW CLASSIFICATION

The new proposed classification for ultramafic rocks that includes phlogopite as a major end-member will be helpful to homogenize the currently extremely heterogeneous terminology for this kind of rocks.
Rocks with a non-negligible content of phlogopite will now have more appropriate names. Some examples are: sample RGM 319407 (Ol 85%, Phl 15%;) named dunite by Moreva (1985) and now

classified as phlogopite dunite, or sample WC253 (Ol 75.5%, Cpx 7%, Phl 16.7%;) named by Downes et al. (2004a) mica wehrlite and now re-named phlogopite and clinopyroxene dunite, or sample LSC241 (Ol 36%, Cpx 15.4%, Phl 48.5%;), named by Downes et al. (2004a) mica wehrlite 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, or in the case of samples LSC238 (Ol 35.4% Cpx 15.9%, Phl 48.6; Downes et al., 2004a) and sample FL251 (Ol 44.3%, Cpx 41.5%, Phl 10.7%; Llyod et al., 1991), named both as mica wehrlite and now classified as olivine and clinopyroxene phlogopitite and phlogopite wehrlite respectively, or in the case of sample FL251 and FL4 (Ol 78.4%, Cpx 8.3%, Phl 11.6%; Llyod et al., 1991), both named as mica wehrlite and now classified as phlogopite wehrlite and phlogopite and clinopyroxene dunite, respectively.

Conversely, rocks with similar mineralogical composition will have the same name: for example, samples JSL177-2 (Cpx 29%, Phl 67%; Lloyd, 1985) and LSC225 (Cpx 19.2%, Phl 80.8%; Downes et al., 2004a), 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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FIGURE CAPTIONS

Fig. 1: 'exploded' faces of the POCO (Phl-Ol-Cpx-Opx) diagram and nomenclature.

Fig. 2: the POCO (Phl-Ol-Cpx-Opx) diagram (A) and its internal volumes: B) phlogopite and pyroxene / dunite; C) phlogopite lherzolite; D) pyroxene and olivine / phlogopitite and E) olivine and phlogopite / websterites. The order of the minor abundant phases is fixed for convenience. Authors must change the terms order based on the relatively abundances of the phases (e.g. phlogopite and olivine websterite if the phlogopite is more abundant than olivine).

Fig. 3: 'exploded' faces of the POPH (Phl-Ol-Px-Hbl) diagram and nomenclature.

Fig. 4: the POPH (Phl-Ol-Px-Hbl) diagram (A) and its internal volumes of: B) phlogopite, hornblende and pyroxene dunite; C) phlogopite, pyroxene and hornblende dunite; D) hornblende, phlogopite and pyroxene dunite; E) phlogopite and hornblende / peridotite; F) hornblende, pyroxene and olivine / phlogopitite; G) pyroxene, hornblende and olivine / phlogopitite; H) phlogopite, pyroxene and olivine / hornblendite and I) phlogopite, hornblende and olivine / websterite. The order of the minor abundant phases is fixed for convenience. Authors must change the terms order based on the relatively abundances of the phases (e.g. phlogopite and hornblende peridotite if the phlogopite is more abundant than hornblende).

Fig. 5: 'exploded' faces of the COHO (Cpx-Opx-Hbl-Ol) diagram and nomenclature.

Fig. 6: the COHO (Cpx-Opx-Hbl-Ol) diagram (A) and its internal volumes: B) hornblende and pyroxene / dunite; C) hornblende lherzolite; D) pyroxene and olivine / hornblendite and E) olivine and hornblende / websterites;. The order of the minor abundant phases is fixed for convenience.

Authors must change the terms order based on the relatively abundances of the phases (e.g. pyroxene and olivine hornblendite if the pyroxene is more abundant than olivine).

Footnotes

[1]: in this article mineral acronyms are used to report mineral modal compositions of rocks. The used acronyms are: Apatite, Ap; Clinopyroxene, Cpx; Hornblende, Hbl; Olivine, Ol; Orthopyroxene, Opx; Phlogopite, Phl; Pyroxenes, Px; Spinel, Sp.

Figure 1 Click here to download Figure Fig 1.tif

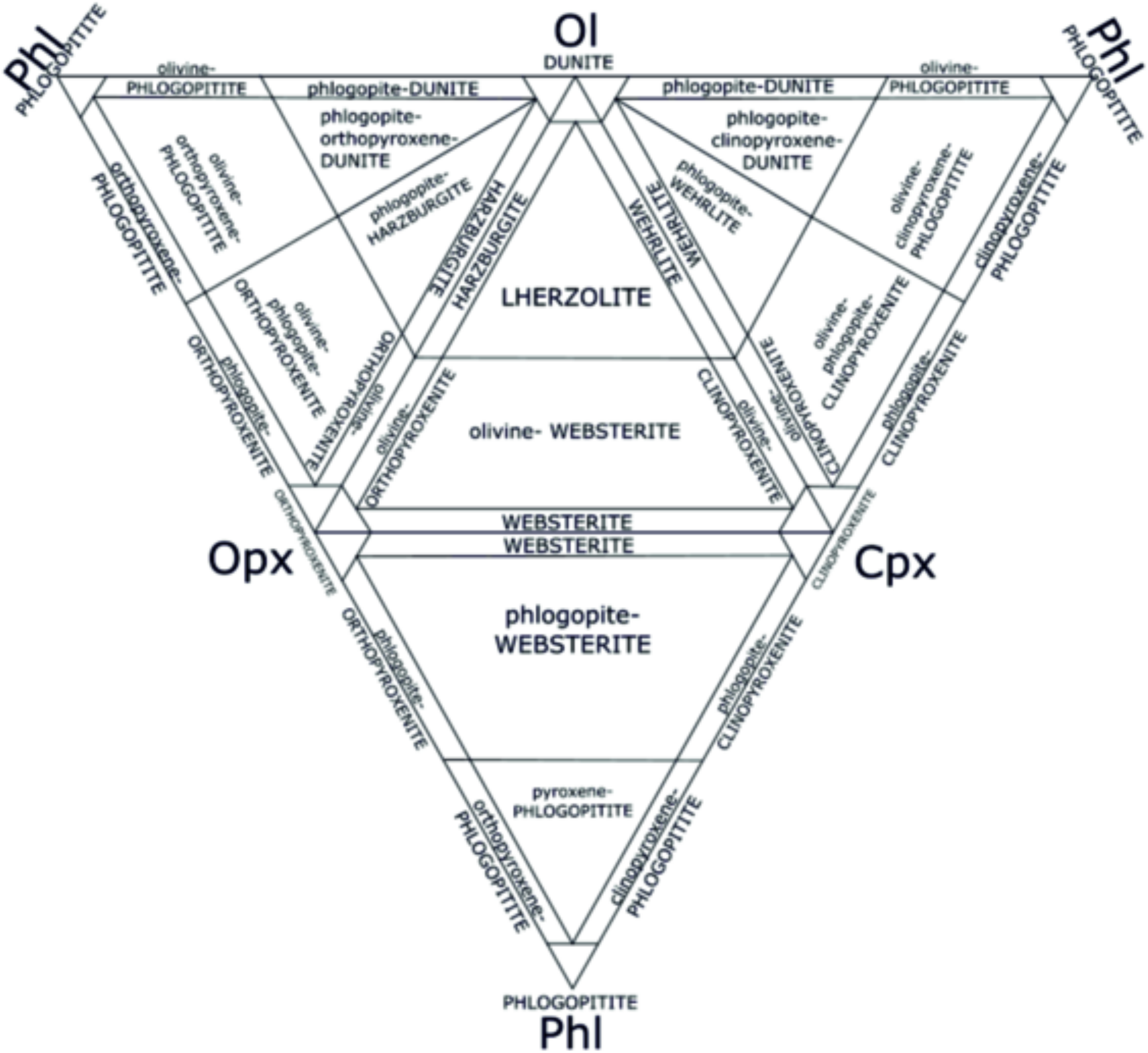

Figure 2

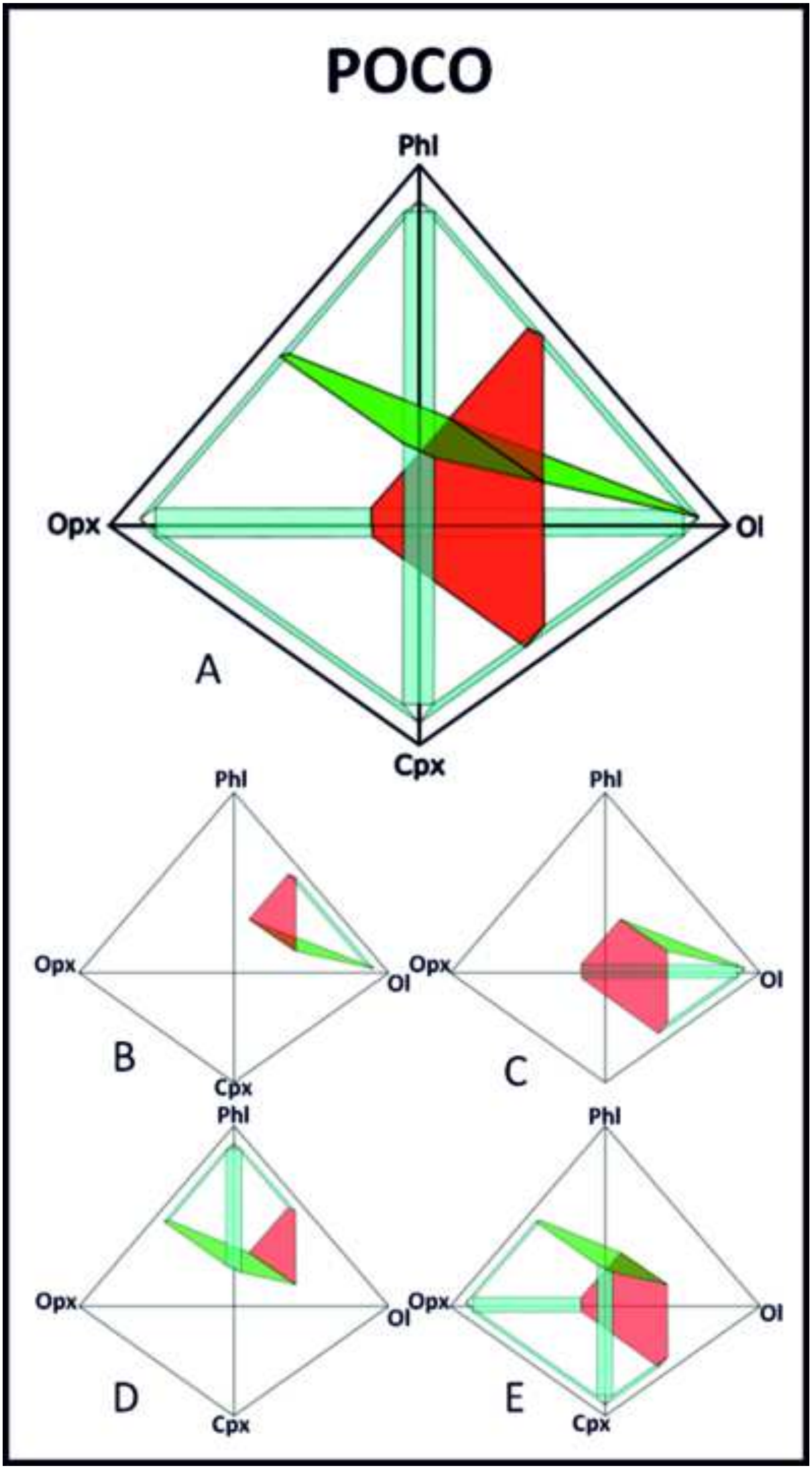
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Figure 3

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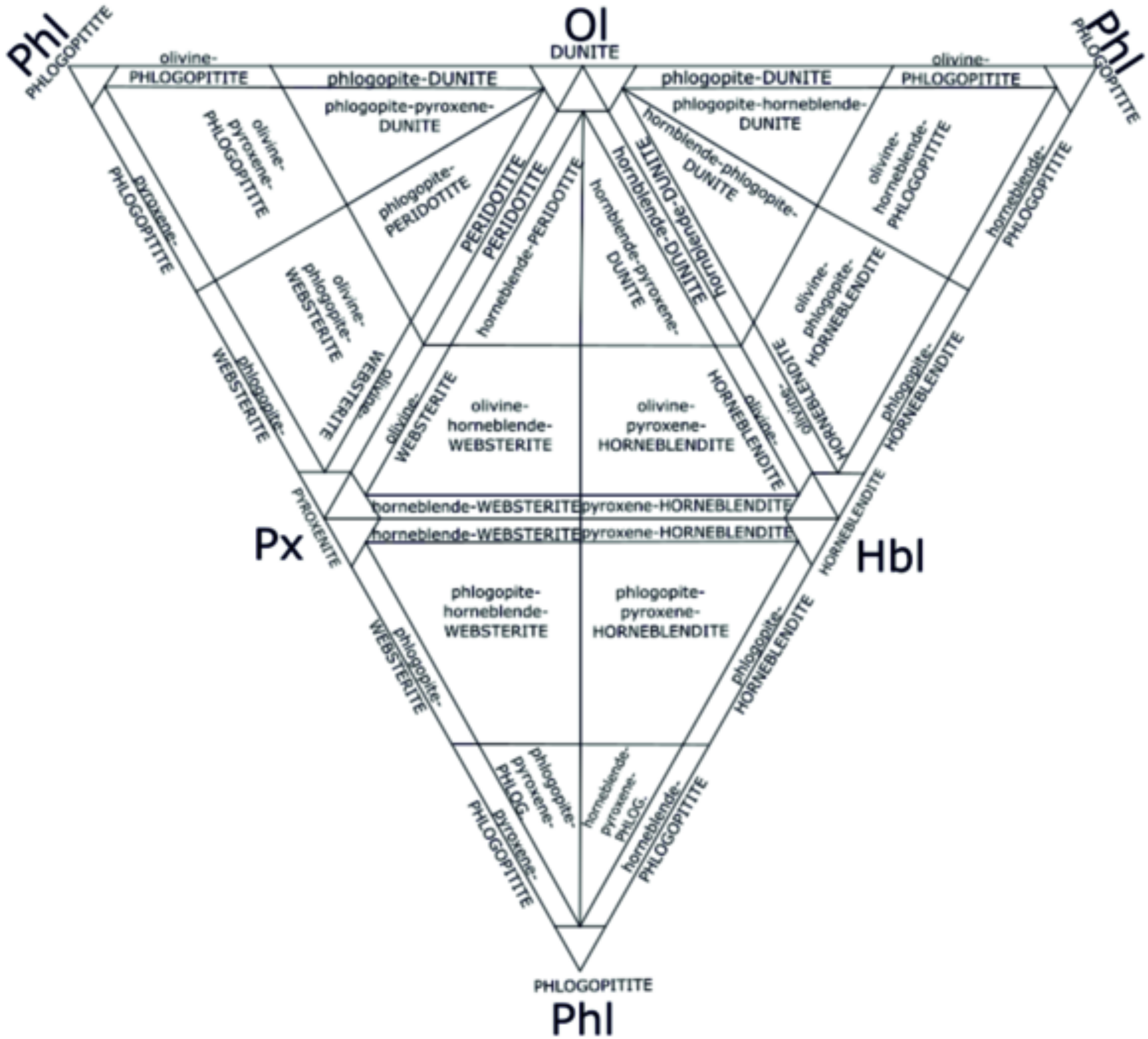

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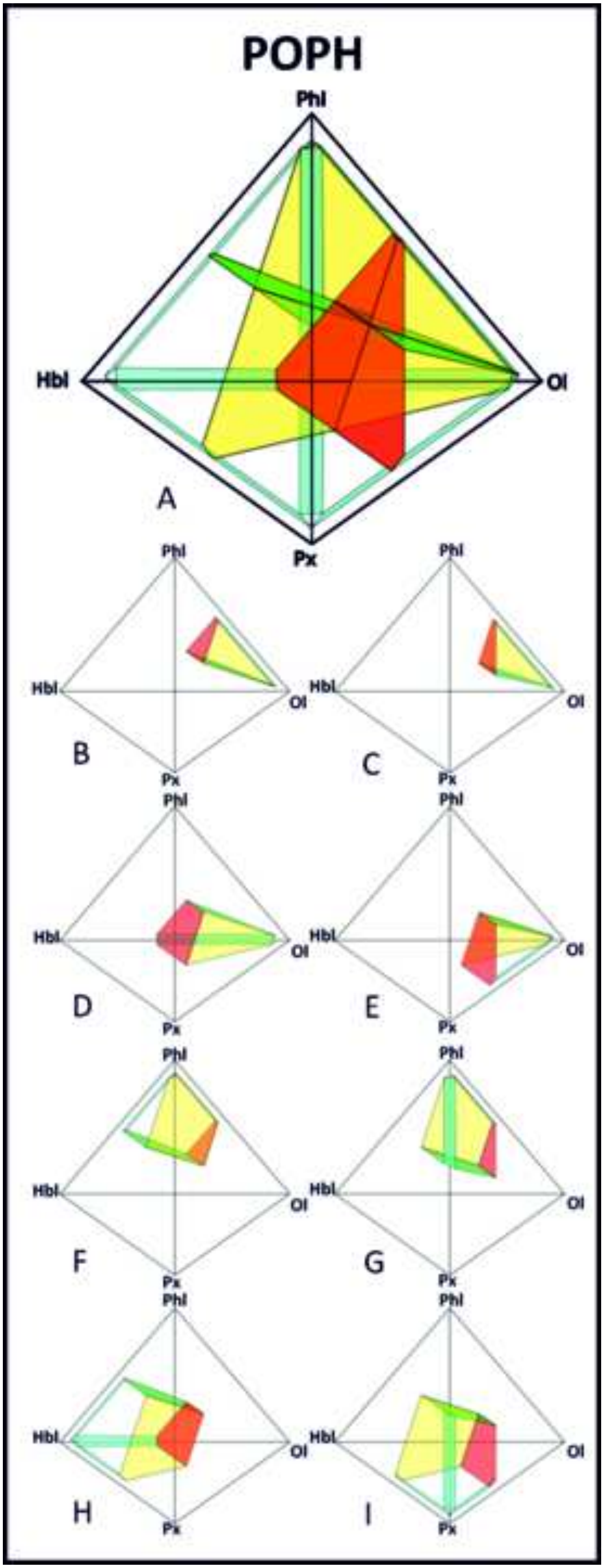

Figure 5

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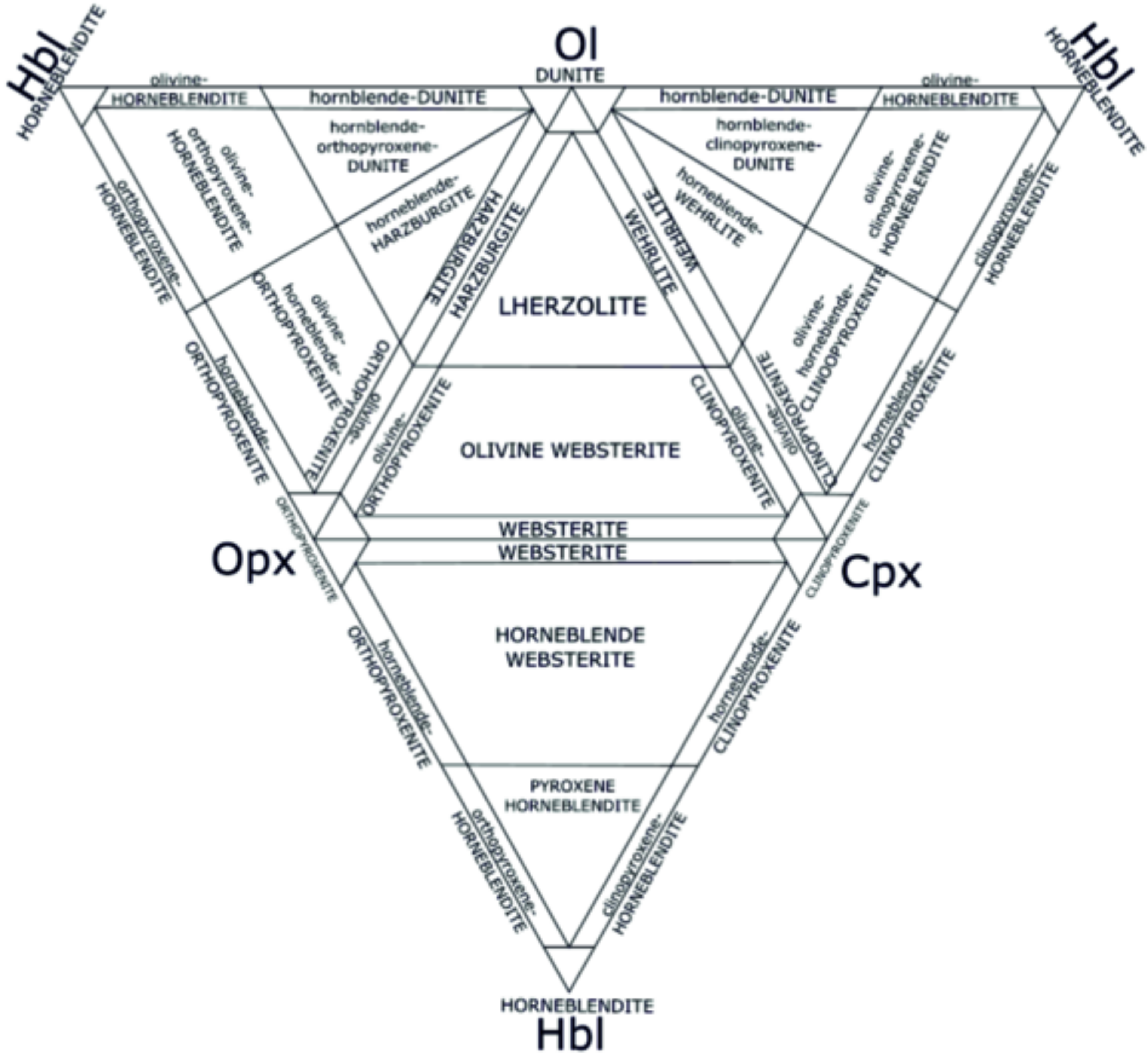

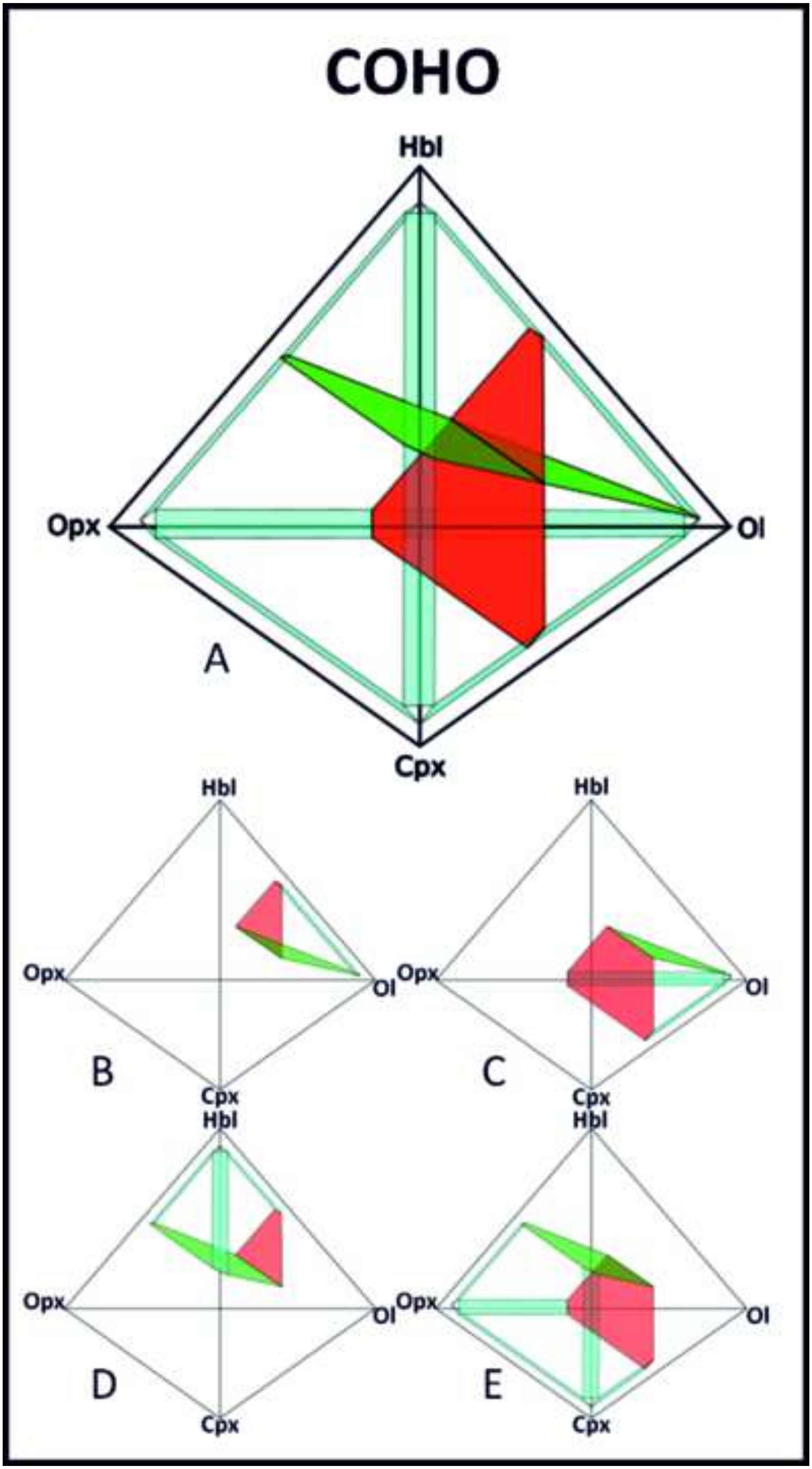
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