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Current state of knowledge of the gold mineralization at Imonga-Saramabila, Maniema (DR Congo): a petrographic and mineralogical study of the mineralized vein system

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ABSTRACT

The Great Lakes area in Central Africa forms a large metallogenic province that hosts important deposits of gold mineralization. We present a petrographic, mineralogical and geochemical study of unique borehole samples from the Imonga-Saramabila gold deposit, a historical mine site located in the Maniema Province (DR Congo) in the Karagwe-Ankole belt (KAB) in the Great Lakes area and one of the only places in the Maniema province with accessible boreholes allowing to study the mineralization. The samples are metasedimentary rocks belonging to the Mesoproterozoic Kivu Supergroup, with bedding-parallel meta-igneous rocks. These rocks have undergone upper greenschist to lower amphibolite facies metamorphism, based on the presence of andalusite and chiastolite porphyroblasts, and are affected by hydrothermal alteration. The porphyroblasts formed during peak metamorphism and posterior to a first vein generation. Three additional vein generations were identified at Imonga based on crosscutting relationships, with the second and third events overprinting the porphyroblasts by intense chloritization, and associated with sulfide mineralization. The fourth vein generation is again barren. The first veining event formed pre-folding and the three subsequent generations postdate folding, as concluded based on the relationship of the veins with the cleavage. Only one important folding event is proposed based on the development of only one cleavage. Gold occurs as free gold or is included in pyrite in the second (and maybe third) vein generation. Based on the paragenesis, structural characteristics, and the link between veining and metamorphic minerals, the gold mineralization at Imonga is interpreted to be linked to the early Neoproterozoic (~980 Ma) compressional deformation event, associated with the amalgamation of the Rodinia supercontinent.

KEYWORDS

orogenic gold mineralization, Karagwe-Ankole belt, early Neoproterozoic, Rodinia amalgamation, multistage deformation

Article history

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1. Introduction

The Great Lakes area in Central Africa spans the Kivu and Maniema provinces of the Democratic Republic of Congo (DR Congo), Tanzania, Rwanda and Burundi. The Imonga-Saramabila area is located in the Central African Karagwe-Ankole belt (KAB) which forms, together with the Kibara belt (KIB), a Mesoproterozoic geological structural domain (Fig. 1; Tack et al., 2010). The KAB extends from SW Uganda, Rwanda, Burundi, northwestern Tanzania to the Kivu – Maniema provinces in the DR Congo, while the KIB occurs in the southwestern part of the DR Congo (Tack et al., 2010; Fernandez-Alonso et al., 2012). The two belts are separated by a Rusizian basement rise that represents the NW extension across Lake Tanganyika of the Paleoproterozoic Ubende belt (SW Tanzania) (Fig. 1). The study area forms part of the proto-Congo craton (Fernandez-Alonso et al., 2012). Most cratons have thick, buoyant, cold and rigid lithosphere. However, different processes can reactivate the craton which leads to 'metacratonization' (Liégeois et al., 2013). Metacratonization will lead to the loss of the craton's lithospheric rigidity, ultimately transforming the cratonic margins into orogenic belts in which old lithologies are mixed with younger ones, favoring the circulation of fluids to form mineralization (Black & Liégeois, 1993).

The KAB, and the Kivu and Maniema provinces of the DR Congo especially, is famous for its metal ore deposits, often of world class. Many of these metals (e.g. Nb-Ta-W-REE) have been defined as critical metals that are of vital importance for the high-tech and green industry. Notwithstanding the presence of important mineral resources, geological studies on deposits in the eastern part of the DR Congo are rather rare and date mainly from Belgian colonial periods (for e.g. Varlamoff, 1950; Kazmitcheff, 1961; Steenstra, 1967). Consequently, knowledge about the geology and mineralization in the Kivu and Maniema provinces is limited.

Although there have been many recent studies on Sn-Nb-Ta granite-related mineralization in the Great Lakes area (e.g. Dewaele et al., 2011, 2016; Melcher et al., 2015; Hulsbosch et al., 2016), Au mineralization in this area is still under-investigated (Wouters et al., 2020), even though it is an important source of income for the local population in this region and the presence of numerous world-class deposits in the area. Currently, the geological setting and the formation history of the gold mineralization, especially in the eastern part of the DR Congo is largely unknown. Different origins have been proposed for the gold mineralization in the Great Lakes area, varying from the formation as volcanogenic massive sulfide deposits (Franceschi, 1990) to the more widely accepted orogenic gold deposits, related to fold-and-thrust belt formation (Pohl & Günther, 1991; Brinckmann et al., 2001; Pohl et al., 2013). There is now more or less a consensus that the gold in the studied region is of orogenic style, whereby the gold is mainly found in quartz veins, but can also be present in the surrounding host rock (Wouters et al., 2020).

Even though there is some consensus on the type of gold mineralization in the Karagwe-Ankole belt (KAB), the exact relationship between gold mineralization and the different magmatic, metamorphic and deformation events in the KAB is still a matter of debate due to the badly known geology of the area. The KAB has been deformed by at least two compressional deformation events during the Meso- and Neoproterozoic, but has also been reactivated multiple times during the Phanerozoic, as indicated by the present-day development of the Western Rift. However, compared to the Proterozoic geodynamic processes in the Great Lakes area, this Phanerozoic tectonic activity is poorly studied, notwithstanding the effect on the current geomorphology, volcanic activity, occurrence of earthquakes and remobilized mineralization. Gold mineralization has been linked to one or more of the several deformation events. The mineralization has been given an Early Mesoproterozoic age (Koegelenberg et al., 2016), an early Neoproterozoic age (Brinckmann et al., 2001; Pohl et al., 2013) related to the main Kibaran deformation event, and a Pan-African age of ~530 Ma (Brinckmann et al., 2001; Walemba et al., 2004; Fernandez-Alonso et al., 2012).

In this study, we focus on the geology and paragenesis of the Au mineralization in the Imonga-Saramabila area (Figs 1 to 3), which was a historical center of mineral exploitation in the Maniema province (DR Congo) between c. 1930 and 1958 by Cobelmin—Compagnie BELge d'entreprises MINières—(Kazmitcheff, 1961, 1967). The deposit is well documented in the mining archives and rock collections of the Royal Museum for Central Africa (RMCA, Tervuren, Belgium), forming an ideal case to study the geology of this area, the formation history of the gold mineralization present, and to increase our knowledge about the tectono-metamorphic history of the KAB in the Great Lakes area.

2. Geologic Setting

2.1. Regional geology

Imonga-Saramabila is located in the Great Lakes area in the eastern part of the DR Congo (Fig. 1). It is situated in the southern part of the Maniema province of DR Congo, in a geologically complex area located at the intersection of three major belts: the Ubende-Rusizi belt, the Kibara belt (KIB) and the Karagwe-Ankole belt (KAB) (Fig. 1). Based on the geological map of Lepersonne (1974), it seems that Imonga is situated in the KAB, which was long thought to be one continuous belt together with the KIB, separated by the Paleoproterozoic Ubende-Rusizi belt due to crustal-scale structural reactivation (Tack et al., 2010; Fernandez-Alonso et al., 2012). The KAB, located to the NE of the Ubende-Rusizi belt, is generally composed of greenschist- to amphibolite-facies metasedimentary and metavolcanic rocks intruded by different generations of S-type granitoids and to a lesser extent (ultra-)mafic rocks (Tack et al., 2010). The KIB is situated SW of the Ubende-Rusizi belt and consists of similar rocks as the KAB (Tack et al., 2010; Ilombe et al., 2017;). Different geodynamic models have been proposed for the Great Lakes area during the Mesoproterozoic. The two major ideas are: (1) an intracratonic protracted extensional setting with anorogenic bimodal magmatism at ~1375 Ma and two far-field compressional events, at ~1.0 Ga and 550 Ma (e.g., Tack et al., 2010; Fernandez-Alonso et al., 2012), and (2) a subduction-collision setting with convergence and compression at ~1375 Ma coupled with asthenospheric upwelling and delamination, eventually evolving into a continent-continent collision at ~1.0 Ga (e.g., Kokonyangi et al., 2004; Debruyne et al., 2015; Nambaje et al., 2021). Around 1 Ga, the main period of compressional deformation and folding occurred in both the KAB and KIB belts (Tack et al., 2010; Fernandez-Alonso et al., 2012).

The KAB has been affected by several major magmatic events. A large bimodal magmatic event, the 'Kibaran' event, occurred in the early Mesoproterozoic, 1400–1370 Ma (Tack et al., 2010), which comprises peraluminous S-type granite intrusions, as well as subordinate (ultra-)mafic intrusive rocks. This main granite generation (G1-3 granites) was dated at 1381 ± 8 Ma by U-Pb SHRIMP zircon age dating (Tack et al., 2010; De Clercq et al., 2021; Nambaje et al., 2021). The mafic intrusive rocks constitute the Kabanga-Musongati (KM) alignment (Tack et al., 2010). Along the KM, minor intrusions

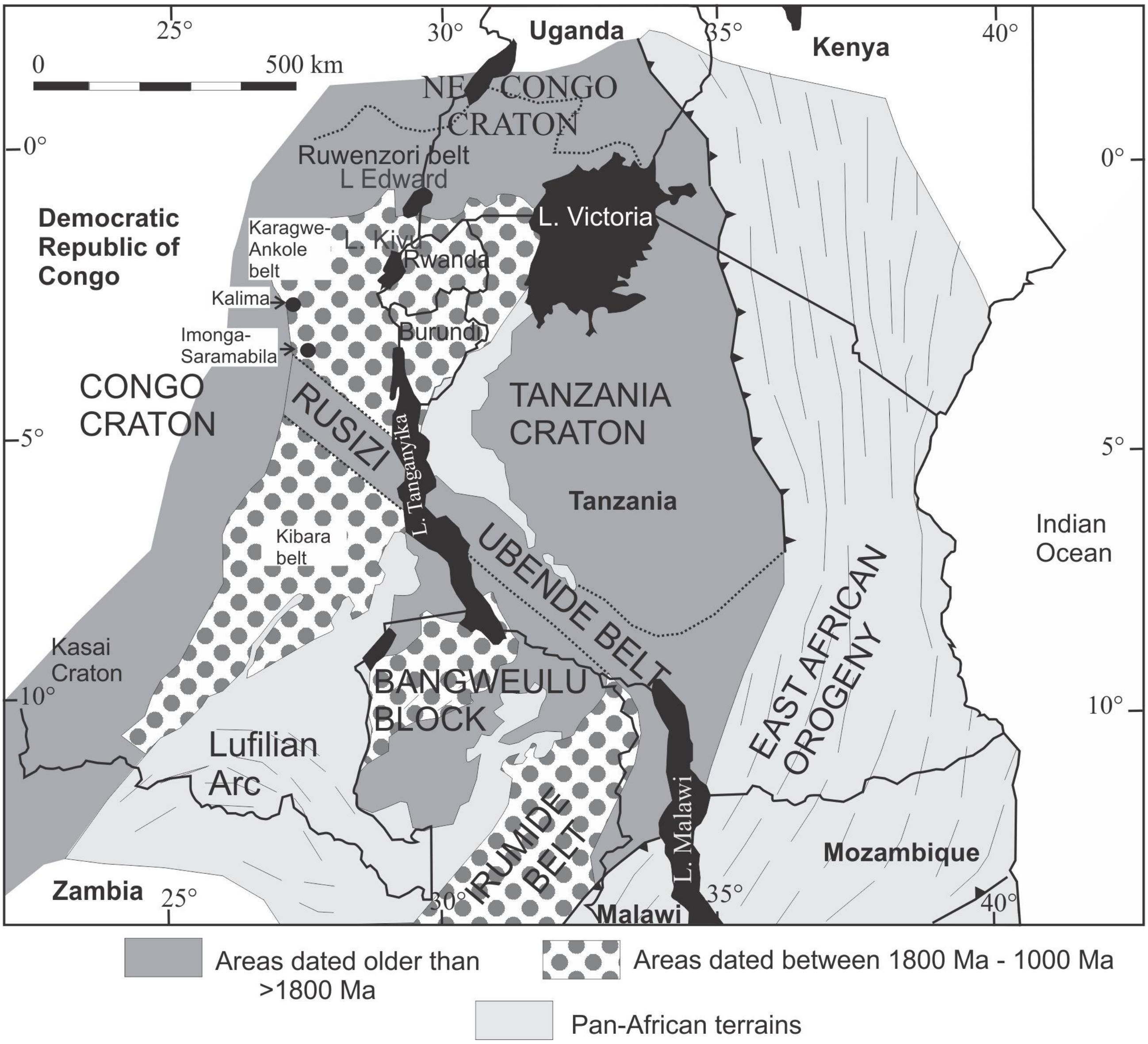

Figure 1. Regional tectonic setting of the Kibara belt (KIB) and the Karagwe-Ankole belt (KAB) in Central Africa (modified after Brinckmann et al., 2001; Dewaele et al., 2011), with indication of the locations of Imonga-Saramabila (3°35'41" S, 27°03'16" E) and Kalima in the Maniema province in the DR Congo.

of A-type granites dated at 1205 ± 19 Ma were emplaced (Tack et al., 2010). The youngest generation of leucogranite intrusions (G4-granites, also known as "tin granites") in the KAB, which are associated with mineralized pegmatites and quartz veins (Dewaele et al., 2016), was dated at ~1 Ga by U-Pb SHRIMP zircon age dating (De Clercq et al., 2021). This granite generation is considered to be post-tectonic to the late Mesoproterozoic–early Neoproterozoic (~1.0 deformation) event based on structural observations (Pohl, 1994; Tack et al., 2010; Muchez et al., 2014). They are considered as the parental granites of the Sn-Nb-Ta-W pegmatite and quartz vein hosted mineralization.

The tectono-metamorphic evolution of the Mesoproterozoic Karagwe-Ankole Belt (KAB) has recently been reinterpreted by Van Daele et al. (2021). These authors describe two-fold generations which are interpreted as the consequence of two separate compressional regional deformation events. The first fold generation (F1) consists of regional-scale symmetrical folds, with a N30W to NS axial plane strike and variable fold-cylindricity. This fold generation is associated with the regional main penetrative tectonic foliation S_{F1}. Based on geochronological data from literature, the first major compressional event has been connected to the late Mesoproterozoic Rodinia assembly during the Stenian–Tonian. By studying the petrography and mineral composition of rocks of the Pindura and Cyohoha Group of the Akanyaru Supergroup, Van Daele et al. (2021) concluded that regional Barrovian-type metamorphism reached its amphibolite facies climax during this deformation event, prior to the emplacement of the ~1.0 Ga leucogranite and pegmatite intrusions as these did not undergo amphibolite facies metamorphism nor were they deformed. The second generation (F2) is expressed by local small-scale folds with a generally steep axial plane, superposed on the regional fold structure. The strike of the F2 axial planes may vary, based on the possibly buttressing effect of batholiths, locally occurring in the subsurface. A second foliation generation, S_{F2}, formed associated with this second fold generation. This deformation event has been explained by the influence of the late Neoproterozoic Gondwana assembly in the KAB, presumably during the Ediacaran (Van Daele et al., 2021). Different quartz vein generations, mineralized and non-mineralized, were formed in the KAB during this tectonic evolution. Early quartz veins have been strongly shortened or emplaced during F1. In addition, bedding-parallel boudinaged quartz veins have been deformed pre- to syn-F2, while also undeformed syn- to post-F2 quartz veins can be identified. At circa 750 Ma Rodinia started to break up again and some alkaline plutonic complexes have been identified in the area, some even with carbonatites (Fernandez-Alonso et al., 2017). Subsequently, Gondwana was formed around 550 Ma, resulting from the Pan-African orogeny. According to Fernandez-Alonso et al. (2012), this deformation phase left a N-S oriented overprint in the area. Finally, the formation of the Pangea supercontinent took place at ~300 Ma, with the break-up of Pangea starting 50 My later. The latter can be linked with the opening of the Atlantic Ocean and the continental rift in the African Plate (Fernandez-Alonso et al., 2012). The area has, however, remained tectonically active until the development of the present-day Western Rift.

2.2. Geology of southern Maniema, DR Congo

The area around Imonga-Saramabila mainly comprises rocks of two major supergroups (Figs 2, 3): the Rusizi and the Kivu Supergroups (Fernandez-Alonso et al., 2017). The Paleoproterozoic Rusizi Supergroup (formerly called Uvira Group; Van Eykeren, 1951; Cahen, 1954;) consists of schists, metapelites, conglomerates, gneisses, amphibolites, pyroxenites and feldspar-rich quartzites. Some porphyritic-textured granitic massifs and gabbroic dykes can be found in the Rusizi Supergroup (Cahen, 1954). The Rusizi rocks have mainly been deformed during the Paleoproterozoic Ubendian or Rusizian deformation event and form a NE to ENE directed orogenic belt (Cahen, 1954), extending towards the Ubendian shear belt in Tanzania (Lenoir et al., 1994). The Mesoproterozoic Kivu Supergroup occurs to the north-east of the Ubende-Rusizi chain. The Kivu Supergroup consists of sandstones, arkoses, schists and metapelites, with many concordant intercalations of mafic to felsic igneous rocks (Van Eykeren, 1951). The Kivu Supergroup’s rocks have been intruded by granites of various generations (Van Eykeren, 1951). Pegmatites at Kalima in the western part of the Maniema province (Fig. 1), that are associated with the youngest granite generation, have been dated at 1024 ± 5.5 Ma (Dewaele et al., 2015), corresponding to the age of the G4 granites in the eastern part of the KAB (Tack et al. 2010; De Clercq et al., 2021; Nambaje et al., 2021). The Phanerozoic Karroo System (indicated as Lukuga Group on Figure 2) formed a transgressive and discordant system on top of the Kivu System. The current river systems follow approximately the original depressions that have been filled with Karroo sediments (Van Eykeren, 1951). On top of all previous layers, there is a younger formation belonging to the Kalahari System.

2.3. Geology of the Imonga-Saramabila mine area

The current study is based on two boreholes (S1 and S3) from the Imonga-Saramabila gold mine (Kazmitcheff, 1961) (Fig. 3). This ancient gold mine is located at 140 km east-south-east from Kindu and about 40 km to the east of Kampene (Kazmitcheff, 1961). Imonga forms part of a continuous belt of small gold deposits (Kazmitcheff, 1961). The most important gold occurrences in Maniema are located in the area between the Lualaba River and the Great Lakes (Fernandez-Alonso et al., 2017). Imonga is one of the minor mineralization belonging to the Namoya branch (Fernandez-Alonso et al., 2017).

The studied boreholes were drilled in the flanks of a hill, forming part of a relatively continuous series of hills extending along a 15 km long N-S axis containing many gold occurrences (Kazmitcheff, 1961). The Imonga hill has different river valleys, where alluvial gold mineralization has been exploited (Fig. 3). The boreholes are located at the source of the Mwatshiamingi River (Kazmitcheff, 1961). Based on the historical borehole description of Kazmitcheff (1961), it can be concluded that the geological structure of the rocks is complex, as evidenced by the many variations in the measured angle of the stratification of the rocks compared to the core axis. The bedding is generally steeply inclined towards the NE. Values of dip angles indicated in the descriptions by Kazmitcheff (1961), varying between 5°–60° with respect to the core axis, can belong to any azimuth and are, therefore, only an assumption based on observations at the surface. Based on the position of Imonga on the geological map of Lepersonne (1974), it would seem that the host rocks of the Imonga mineralization belong to the Rusizi Supergroup (Fig. 2), but this has not been confirmed by field observation.

The gold mineralization at Imonga occurs as mineralized quartz veins (Van Eykeren, 1951). The gold grains in the veins are on average 0.5 to 1.5 mm large and rarely reach more than a few millimeters. According to Van Eykeren (1951), the gold veins at Imonga-Saramabila are usually spatially associated with mafic rock units. There are no granites clearly associated with the presence of gold mineralized structures reported in the immediate vicinity of Imonga-Saramabila. In addition to gold, historical chemical analyses mention low concentrations of Cu, Ag and Bi (Cobelmin, unpublished archives available at RMCA, Tervuren, Belgium). No additional historical information is available on the mineralogy of the mineralization.

3. Methodology

This study is based on a compilation of historical unpublished archives about the Imonga-Saramabila area and the ancient gold mine itself, as well as a petrographic and mineralogical study of the borehole samples of the Kazmitcheff (1961) collection. No fieldwork has been carried out in the area due to logistics and safety issues. Unpublished archives of the Royal Museum for Central Africa (RMCA) and old mining maps of Cobelmin were consulted, in addition to limited existing publications, such as de Bethune & Borgniez (1949–1950), De Dycker (1948, 1949) and Van Eykeren (1951). Most importantly, the work by Kazmitcheff (1961) was thoroughly reviewed and used for this study.

The collection of Kazmitcheff (1961) consists of a selection of cores from three well-located boreholes (S1, S2 and S3), which are diamond-core drillings that were collected in 1953 (Figure 3). The drillholes penetrated a thick layer of altered and weathered rocks (51 m for S1, 34 m for S3) before reaching harder rocks. Borehole S1 was drilled with an initial inclination of 43°W with respect to the vertical axis. For borehole S3, the initial inclination was 37°70’E. The resulting drill cores had a diameter of 41 mm for the altered and weathered fraction, and 32 mm for the harder rocks. Because of its initial inclination of 63°W with respect to the vertical axis, the trajectory of borehole S2 resulted in a drill core composed of mainly altered and weathered rocks, which was evaluated not to be useful for further analysis, which explains the limited amount of material available in the collection of the RMCA (Kazmitcheff, 1961).

Macroscopic core description was carried out, before and after staining. The use of a potassium hexacyanoferrate and Alizarin Red S solution on polished slabs (Dickson, 1966) allowed the identification of carbonate minerals in the alteration and crosscutting veins. Based on the macroscopic observations, samples have been selected for a further detailed microscopic study. Different vein generations and alteration zones with various thicknesses and at various angles to the bedding or foliation can be identified. Based on the composition of the veins, the angle at which they cross the core, their relation to the developed foliation, the crosscutting relation between the different vein generations, the veins are grouped and classified in different generations of fracturing and cementation.

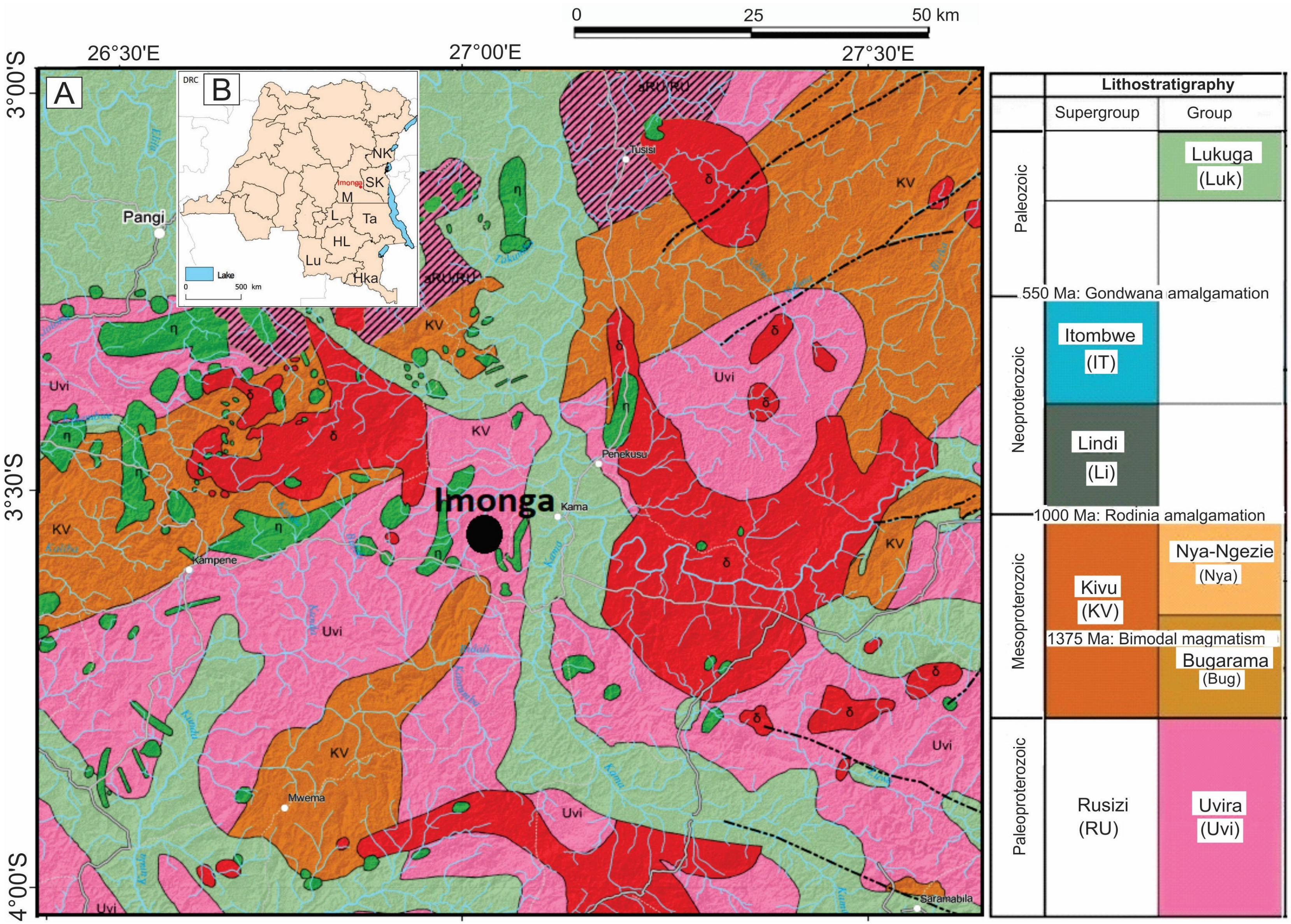

Figure 2. A. Extract from the geological map of Kivu-Maniema, DR Congo, showing the location of Imonga (modified after Fernandez-Alonso et al., 2017). The Uvira Group corresponds to the Rusizi Supergroup. The Lukuga Group belongs to the Karroo System. The younger rocks belonging to the Kalahari System have not been indicated on the map. **B.** Location of the different provinces in the Eastern part of the DR Congo with Imonga indicated by the red dot. M: Maniema, SK: South Kivu, NK: North Kivu, Lu: Lualaba, L: Lomami, HL: Haut-Lomami, Ta: Tanganika, Hka: Haut-Katanga.

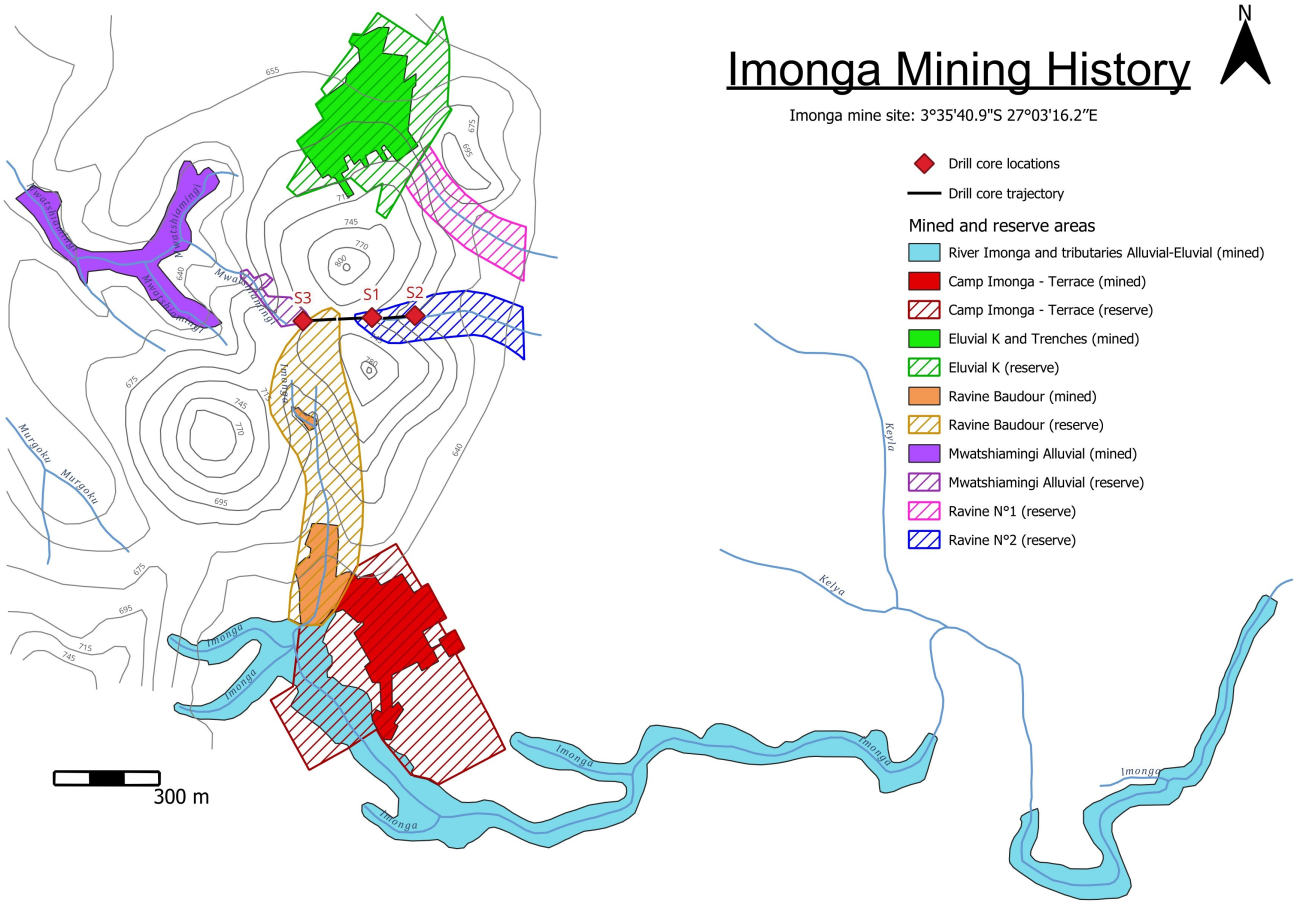

Figure 3. Synthetic overview map of mined and reserve areas at Imonga in the Maniema province in the DR Congo (3°35'41" S, 27°03'16" E), for the period 1931–1955 and the locations of the boreholes S1 – S3 (Unpublished archives of Cobelmin, available at RMCA, Tervuren; Kazmitcheff, 1961).

Transmitted and reflected light microscopy was carried out on thin (n ~ 55) and polished sections (n ~ 25).

4. Results

4.1. Petrography of the host rocks

The host rocks of the Imonga gold mineralization can be identified as fine-grained meta-igneous rocks and minor meta-sedimentary rocks. All host rocks have been affected by intense metamorphism and alteration. Especially, the protolith of the meta-igneous rocks is difficult to identify due to this intense metamorphic recrystallization and alteration. However, the primary magmatic rocks can still be identified based on their preserved porphyritic texture, while the meta-sedimentary rocks are characterized by development of bedding. In addition, portable X-Ray Fluorescence (pXRF) was used to identify their origin. The elemental composition of the drill cores was investigated with an Olympus DELTA Professional XRF Analyzer. A clear relationship exists between the lithology and the concentrations of SiO_2, CaO, FeO and to a lesser extent MgO, and a rather systematic variation with depth throughout the boreholes can be observed. The meta-igneous rock in the boreholes has a relatively low SiO_2 content, a relatively high CaO and FeO content and in some parts a relatively high MgO content (Fig. 4). For the meta-sedimentary rock sections, the opposite is the case. Occasionally, trace elements such as As, Cu, Pb and Zn were also detected in the samples, but for most elements (e.g. Au), the concentrations were below the detection limit of the used pXRF. Higher concentrations of As, Cu, Pb and Zn can be found associated with veins (Fig. 4) and can be related to the occurrence of sulfides.

In core S1, six intervals of meta-igneous rocks are recognized, with a thickness varying between 2 and 26 m (Fig. 4A). In drill core S3, two large intervals of meta-igneous rocks are recognized: the first 96 m of the core (from 34 m to 120 m, Fig. 4B), as well as at greater depth an interval of ~5 m thickness between the meta-sedimentary rocks. In both cores, no systematic alternation of meta-igneous and meta-sedimentary rocks is observed, which would allow correlation between the cores. The contact between the meta-igneous and meta-sedimentary rocks is strongly recrystallized and altered, which makes it difficult to conclude if these meta-igneous rocks were intruded as sills or if the rocks are of meta-volcanic origin, forming part of a volcano-sedimentary sequence.

The meta-igneous host rocks are characterized by coarser grain size, with predominantly darker and greener color and porphyritic texture without foliation (Fig. 5A). The grain size and texture are in between a plutonic and volcanic rock according to the IUGS classification system. In the literature, the mafic rocks in the KAB are described as dolerite (Gérards, 1965), which is a field term, but correspond to meta-basalt in the IUGS classification system. Although the magmatic rocks are strongly recrystallized and altered, the primary mineralogy of the protolith can still partly be identified. Plagioclase, quartz and some Fe-Ti oxides are present (Fig. 5B & C). Trace amounts of mafic minerals, such as pyroxene and amphibole can be found, in addition to small amounts of epidote. Based on the high plagioclase content, the presence of amphibole and the rock texture and structure, the rocks may be interpreted as

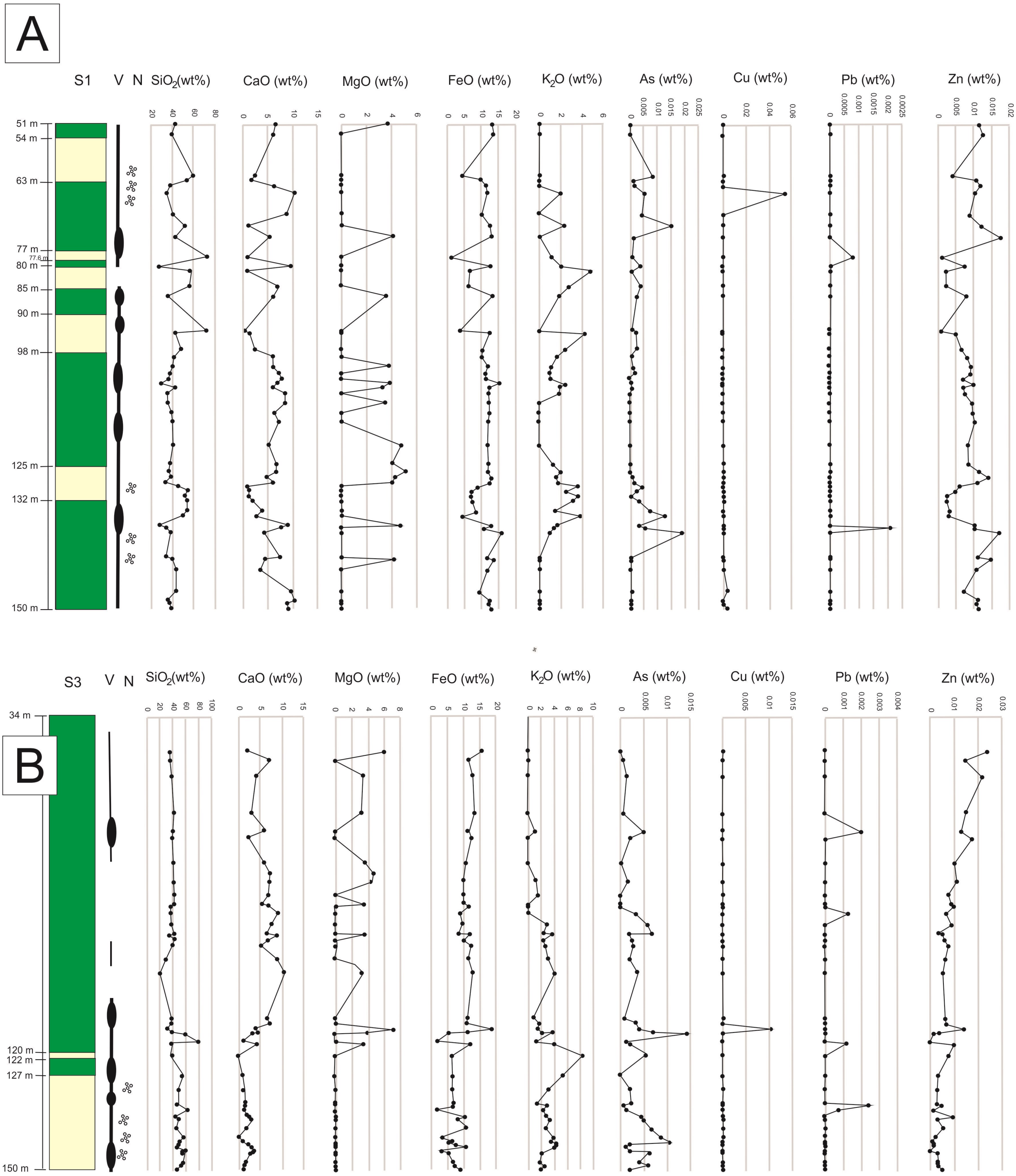

Figure 4. Schematic reconstruction of the different rocks identified in borehole S1 (A) and borehole S3 (B). Zones with higher occurrences of veins (V) and porphyroblasts (N) are indicated with depth along the boreholes. The green color on the borehole indicates meta-igneous rocks, whereas the light yellow color indicates meta-sedimentary rocks. For both boreholes, the results of the pXRF analysis for the main elements (CaO, MgO, SiO_2, K_2O in wt%), as well as for some trace elements is indicated (As, Cu, Zn, Pb in wt%). A relationship between the trace elements and the occurrence of veins can be identified.

originally andesites. The host rock mineralogy is fairly consistent across all studied samples.

A first type of meta-sedimentary host rocks has a fine-grained texture, contains equigranular grains and has a light greyish color. These meta-sedimentary rocks show the development of a foliation (Fig. 5 D & E), allowing the classification as schists. Some samples display a macroscopic lamination, with a lamina thickness of a few millimeters. The schists display an intense alteration due to the formation of mainly phyllosilicates, especially chlorite and sericite, causing some rocks to be classified as sericite-schists and chlorite-schists. A second type of meta-sedimentary rocks can be classified as meta-pelites. They have a very fine grained texture, with a light, greyish color. The original host rock constituents have been altered to phyllosilicates, silica and carbonate. However, unlike the schist, meta-pelites display no foliation.

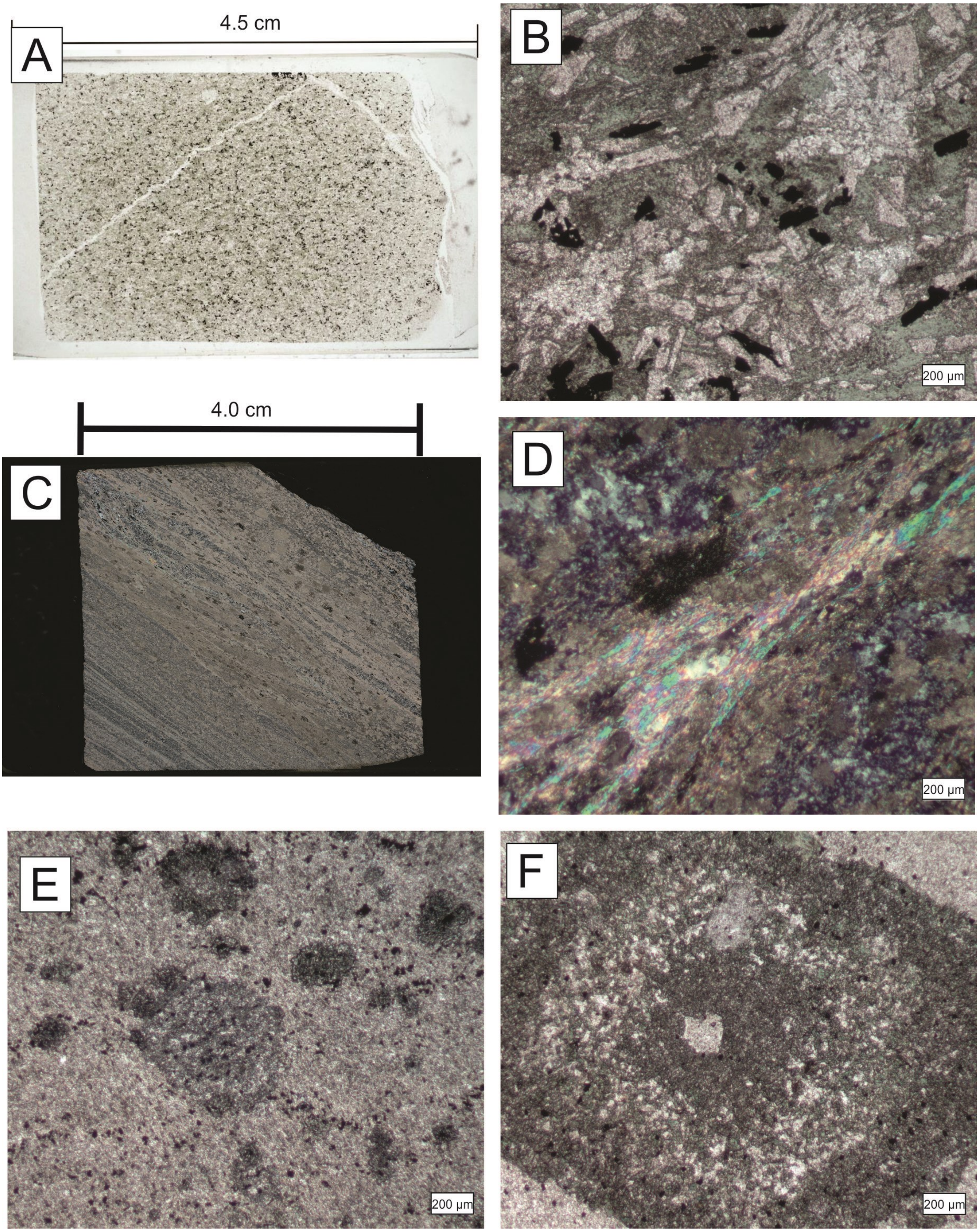

Figure 5. A. Sample IC21IM01 (S1 at a depth of 53 m): meta-igneous host rock (thin section). **B.** Sample IC21IM01 (S1 at a depth of 53 m): meta-igneous host rock under PPL. **C & D.** Sample IC21IM54 (S3 at a depth of 120.2 m): meta-sedimentary schist that has been strongly foliated. Alteration to sericite and muscovite following the foliation as alteration product and muscovite occurring along the foliation. **E.** Sample IC21IM09 (S1 at a depth of 81 m): recrystallized andalusite porphyroblasts, altered to carbonate. **F.** Sample IC21IM62 (S3 at a depth of 144.10 m), after staining: altered andalusite or chiastolite porphyroblasts with rhombic ferroan dolomite grains.

Both types of meta-sedimentary rocks are strongly altered by a variety of alteration processes: sericitization, chloritization, muscovitization, carbonatization (mainly Fe-rich dolomite) and silicification. Large porphyroblasts of andalusite and chiastolite have been observed, as well as porphyroblasts of chlorite. The first type of porphyroblasts is andalusite porphyroblasts (Fig. 5F & G), ranging in size from 200 µm to 2 mm. These porphyroblasts are partially or completely altered to Fe-rich dolomite or to Fe-rich dolomite and chlorite. In some cases, additional silica alteration is observed. The chiastolite porphyroblasts, with an average size of 1–2 mm, have also been strongly altered and are characterized by displaying a zoned pattern of alternating alterations. The center is often siliceous with few Fe-dolomite grains, and is surrounded by rims of chlorite, silica and Fe-dolomite. These original porphyroblasts have been formed post-foliation since they have not developed foliation and have not been affected by deformation. They are interpreted as formed during upper greenschist to lower amphibolite facies metamorphism, probably peak metamorphic conditions. However, the porphyroblasts have been crosscut by different vein generations, containing quartz, carbonate and chlorite. Another type of porphyroblasts that has been observed in the meta-sedimentary rocks consists of chlorite. They have a lighter green color compared to the chlorite occurring as alteration of the host rock and as vein cements. These porphyroblasts have been partially corroded and are overgrown by carbonate minerals and quartz.

The rocks have been affected by metamorphism and intense hydrothermal alteration, especially caused by the formation of different phyllosilicates (chlorite, sericite and muscovite). Chloritization occurred very intensely and is abundant in both meta-sedimentary and meta-igneous rocks. Chlorite varies in grain size but occurs mainly as small grains with a distinct green color and a bluish interference color. It is possible that in the meta-igneous rocks all chlorite resulted from the alteration of pyroxene. In the meta-sedimentary rocks, alteration to chlorite is often concentrated along the foliation, forming a chlorite-schist texture. Besides chloritization of the matrix, porphyroblasts of originally andalusite and chiastolite have also been altered to chlorite. Alteration to sericite or sericitization also occurs very intensely throughout both cores and both host rock types, although more pronounced in the meta-sedimentary rocks. Similar to the chloritization, alteration to sericite can occur aligned, representing the foliation, and resulting in the formation of sericite schist. Muscovitization also occurs but is observed in a limited number of samples of both cores and is more restricted in the paragenetic sequence. Sericitization and muscovitization are typical for phyllic alteration and are often interpreted as the result of the hydrolysis of K-feldspar to muscovite/sericite, with formation of minor quartz, chlorite and pyrite. Carbonatization can be observed as alteration of the matrix, of the porphyroblasts and as a later growth of ferroan dolomite. The matrix of the rocks has partially been altered to carbonates. This alteration results mainly in the formation of Fe-rich dolomite found throughout the cores. In addition, the andalusite and chiastolite porphyroblasts have been completely or partially altered by this carbonatization. Alteration to Fe-rich dolomite is associated with the first and second vein generations, containing ferroan dolomite. During a third vein generation, characterized by ferroan calcite, alteration of the matrix to Fe-rich calcite occurs. Some minor silicification, is observed in some rocks, but is much less intense and abundant than the other alteration types. The observed alteration occurs in proximity of quartz veins. Silicification is observed as overgrowth and in pressure shadows around deformed grains.

Sulfides such as pyrite and chalcopyrite occur disseminated in the matrix of the rock. Pyrite crystals occur in the matrix and show pressure shadows and dissolution cavities. Gold (Au), when observed in the matrix, is included in pyrite crystals, indicating a close relationship between the two and suggesting that gold may have formed just before or contemporaneous with pyrite. However, most mineralization is found in quartz and carbonate veins, or at the interface between veins and their host rock. The mineralization includes Fe-oxides/hydroxides, pyrite, chalcopyrite, arsenopyrite, chalcocite, covellite and rare bornite.

4.2. Petrography of different vein generations

The altered rocks are crosscut by thin (mm- to cm-thick) veins, containing quartz, carbonate (Fe-dolomite and Fe-calcite) and chlorite. Different vein generations and alteration zones with various thicknesses and at various angles to the bedding or foliation can be identified (Fig. 6 A–C). The first type or generation of veins consists of medium to coarse-grained quartz veins with Fe-rich dolomite and chlorite and a limited amount of pyrite and arsenopyrite. The orientation of this generation seems to be subparallel to the bedding. These veins have been fractured, deformed and foliated. The veins of this generation display an alteration zone consisting mainly of Fe-dolomite and chlorite. The second generation is composed of veins containing mostly quartz, combined with chlorite and Fe-dolomite with an average thickness of 0.5 to 1.5 cm, but often more than 4 cm. This generation underwent some deformation such as minor re-fracturing. The veins crosscut the foliation at an angle varying between 40° and 80° and often have smaller bifurcations in various directions. Microscopic observations of veins of this generation result in a further subdivision of this cementation generation, i.e. ferroan dolomite cemented prior to as well as simultaneously with quartz. This vein generation is affected by a later phase of fracturing, causing cracks that were subsequently cemented by mainly chlorite and Fe-rich dolomite. In a few veins of this generation a limited re-opening or additional fracturing of some of the larger veins occurred. This additional deformation phase is supposed to have taken place during or at the end of the second vein generation and resulted in recrystallization of coarse-grained quartz to fine-grained quartz, observed at the edge and in the middle part of the vein. The second vein generation is associated with the main phase of mineralization and enrichment in pyrite, chalcopyrite and some arsenopyrite, as well as gold (Fig. 7 A to F). The third generation of veins has been formed in new fractures, as well as in re-opened fractures of the previous vein generation. Vein cementation is characterized by some quartz and chlorite (distinctive green color, high iron content), but mainly by Fe-rich calcite. Newly formed fractures that have been cemented by ferroan calcite are oriented almost vertically to the foliation. This vein generation is associated with an enrichment in pyrite, chalcopyrite, some arsenopyrite. In general, sulfide mineralization is mostly linked to the second and third vein generations. Some chlorite may be observed in the largest veins of this third generation as filling microfractures in between the calcite and quartz grains. A fourth and final generation of veins is represented by more fine-grained, fibrous veins of quartz. This generation of barren veins shows various orientations, mostly oblique crossing the core and occurs spread throughout both cores. Some of these veins form as a re-opening of previous vein generations causing minor ferroan dolomite to border a few of these veins. Alteration linked to this vein generation is limited to a weak silicification near the veins. Finally, weathering of the copper- and iron-containing sulfide minerals caused the formation of covellite and iron-oxides/hydroxides. The successive phases described above are summarized in a paragenetic sequence (Fig. 8).

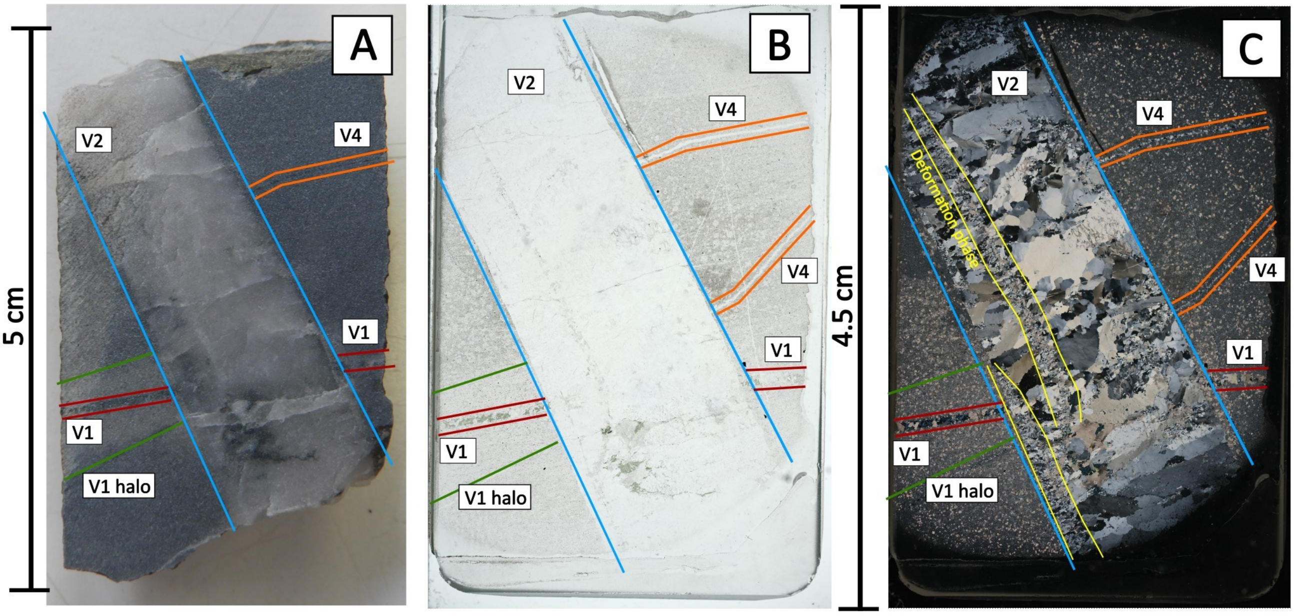

Figure 6. Sample IC21IM02 (S1 at a depth of 61.5 m), rock sample and thin section under PPL and XPL, illustrating the occurrence of three vein generations and alteration halos.

5. Discussion

5.1. Genetic model for the Imonga mineralization

The Imonga deposit consists predominantly of meta-igneous rocks with minor meta-sedimentary successions. Based on macroscopic and microscopic observations, the meta-igneous rocks are identified as andesites. Both rock types underwent upper greenschist to lower amphibolite facies metamorphism, as indicated by the presence of andalusite and chiastolite porphyroblasts, in addition to chlorite, muscovite, quartz, Fe-Ti oxides and epidote. As only one foliation has been observed and since the rocks only underwent lower-grade metamorphism, they are re-interpreted to belong to the Kivu Supergroup succession (Tack et al., 2010; Fernandez-Alonso et al., 2017) and not to the Rusizi Supergroup (or Uvira Group), as was previously indicated on the map of Lepersonne (1974). Rocks of the Kivu Supergroup in the Maniema province are described as sandstones, arkoses, schists and metapelites that contain many concordant intercalations of mafic and to a lesser extent felsic magmatic rocks (Fernandez-Alonso et al., 2017), which also corresponds to the historical description by Van Eykeren (1951) of rocks in the larger Imonga-Saramabila area. The sills are often repeated in the stratigraphy with a thickness varying between 200 and 300 meters (Van Eykeren, 1951). These intrusions in the Kivu Supergroup succession could be linked to the bimodal magmatic event of ~1370 Ma (Tack et al., 2010).

Macroscopic and microscopic observations, including staining, observations of thin and polished sections, have been used to construct the paragenetic sequence. Different phases of veining were identified in this study, often associated with intense alteration. At least three phases of veining have been associated with prominent silicification, chloritization, sericitization, carbonatization and some muscovitization. A first phase of fracturing was followed by alteration which most likely involved chloritization and carbonatization. Fracturing occurred parallel to the bedding and the fractures were cemented with quartz, dolomite and minor chlorite. Around these veins, more intense alteration halos are observed. Minor mineralization associated to this vein generation was observed as pyrite and subordinate arsenopyrite. This first vein generation has been folded and deformed during a subsequent tectono-metamorphic phase. Foliation was developed and can be clearly observed in the meta-sedimentary samples. Porphyroblasts of andalusite, chiastolite and chlorite, as well as metamorphic muscovite, have been formed and are observed to have overgrown minerals in veins of the first generation, and after the development of the foliation. As mentioned above, the porphyroblasts are interpreted to have formed during peak metamorphism under upper greenschist to lower amphibolite metamorphic facies. The original sediments were metamorphosed and deformed to meta-sedimentary rocks, in which often a foliation can be observed.

A second phase of fracturing crosscuts the foliation at an angle varying between 40° to 80°. This vein generation is accompanied by silicification, chloritization, sericitization, carbonatization and possibly muscovitization. This alteration also caused alteration of various porphyroblasts. Cementation of the fractures occurred subsequently by a first ferroan dolomite, quartz, a second ferroan dolomite and by chlorite. This vein generation is observed to cross through altered porphyroblasts. Smaller fractures observed in this vein generation are cemented mainly with chlorite and ferroan dolomite. Additionally, a minor deformation occurred during or at the end of the cementation of the second veining phase. This additional deformation caused local recrystallization of the coarse-grained quartz to fine-grained quartz at the edges or central in the thickest veins of this generation. This phase is related to abundant mineralization and enrichment in sulfides, namely pyrite, chalcopyrite and some arsenopyrite. Bornite and chalcosite were also observed. Gold mineralization has been observed in this vein generation.

A third main fracturing event occurred followed by alteration of the host rocks by silicification, chloritization, sericitization and carbonatization. The carbonatization during this phase is, however, characterized by ferroan calcite. Fractures are cemented with ferroan calcite and some minor quartz and chlorite. Subsequently, minor deformation has taken place and hydrofracturing occurred. No further relation with other vein generations is observed. This cementation is strongly associated with mineralization of pyrite, chalcopyrite and minor arsenopyrite mineralization.

A fourth generation of veins, also accompanied by alteration, only consists of quartz, forming barren, fibrous

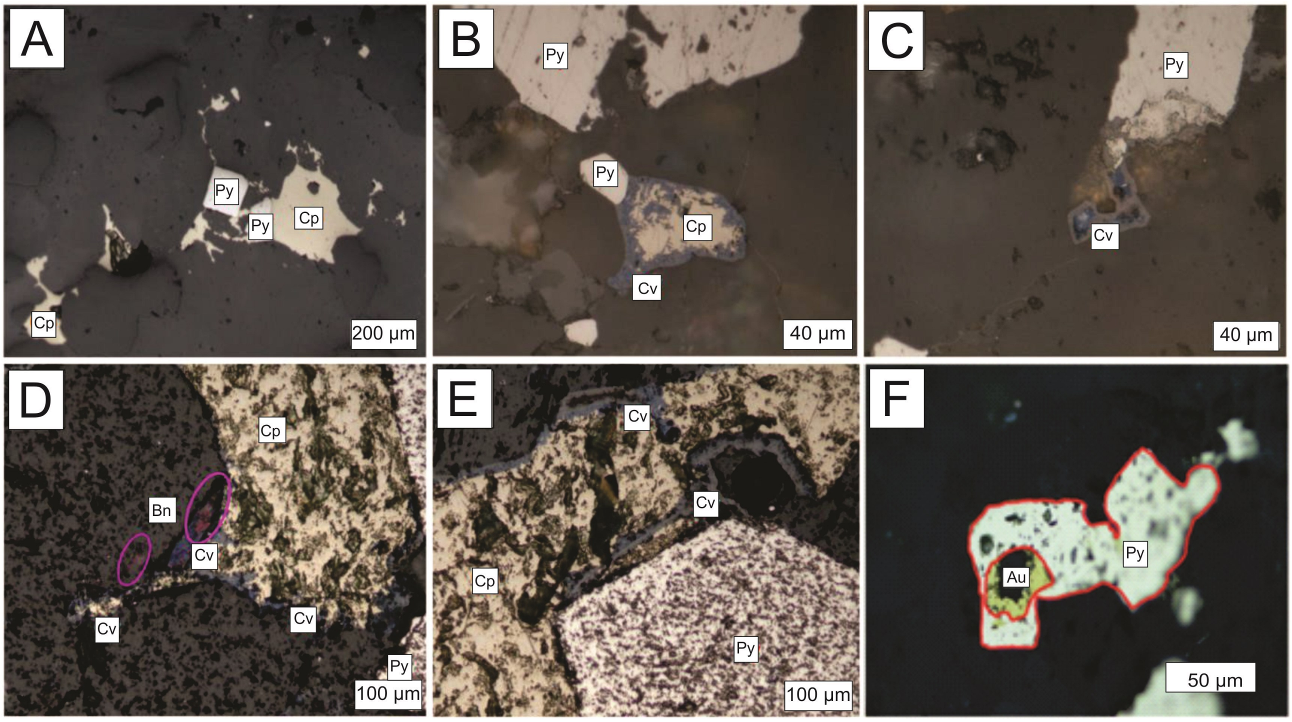

Figure 7. Microphotographs of mineralization associated with vein generation 2. **A.** Sample IC21IM68 (S3 at a depth of 58.5 m): euhedral pyrite (Py) grain associated with chalcopyrite (Cp). **B & C.** Sample IC21IM32 (S1 at a depth of 71.70 m): examples of covellite (Cv) altering chalcopyrite (Cp) and pyrite (Py) grains. **D & E.** Sample IC21IM06 (S1 at a depth of 71.70 m): two large euhedral pyrite (Py) grains surrounded by anhedral chalcopyrite (Cp) grains. Bornite (Bn) and covellite (Cv) alter chalcopyrite (Cp) and pyrite (Py) grains. **F.** Sample IC21IM73 (S3 at a depth of 125.1 m): gold grain (Au) in pyrite (Py).

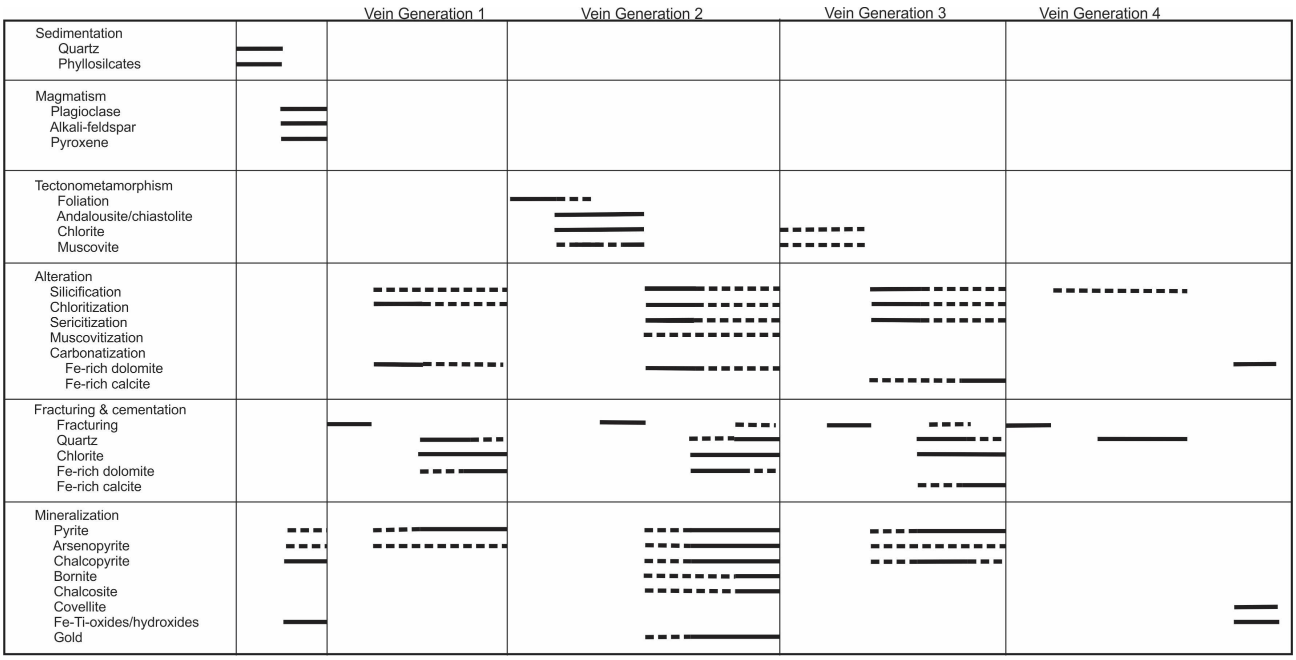

Figure 8. Paragenesis of the Imonga-Saramabila gold mineralization.

quartz veins. Cemented fractures cross the core samples at various angles resulting in thin quartz veinlets.

Carbonatization of the host rock of gold mineralization is a common process (Mennicke et al., 2019). Intense carbonate alteration is likely to be formed by fluids with high partial pressure of CO_2 of hydrothermal magmatic or metamorphic origin. In greenstone belts, this form of alteration is often accompanied by silicification (Mennicke et al., 2019). The original minerals in the metamorphosed magmatic rocks were probably quartz, plagioclase, epidote and amphibole. The latter two minerals would then have reacted with the fluid to form chlorite and carbonate (amphibole + epidote + H_2O + CO_2 = chlorite + dolomite) (Skelton et al., 1997).

Gold has been identified dominantly associated with pyrite. In greenstone belts, this particular type of gold mineralization is explained by metamorphic processes and associated dehydration causing the generation of fluids which are expelled along fault zones (Groves et al., 1998). These fluids interacted with the host rocks causing the precipitation of gangue and ore minerals. In this model, the source of the gold are metamorphic rocks that are situated in the deeper subsurface (Powell et al., 1991). Water-dominated fluids that contain phases, such as $Au(HS)_2^-$ and $Au(HS)^0$, transport the gold upwards towards the precipitation site. By far the most common case in greenstone belts is a chemical reaction consuming the S from the thio-complex, by reaction with Fe from the host rock, and as a result native gold might precipitate (Phillips et al., 1984).

Exact timing of the gold mineralization is not yet possible due to lack of absolute dating of rocks, but since the mineralization postdates the main foliation and since the development of this foliation, at least in Rwanda, occurred during the ~1000 Ma orogeny (Van Daele et al., 2021), the mineralization occurred during or postdates this orogeny. Van Daele et al. (2021) described two-fold generations which are interpreted as the consequence of two separate compressional regional deformation events. However, only the first fold generation (F1) is associated with the regional main penetrative tectonic foliation S_{F1}, which formed during regional-scale symmetrical folding. Based on geochronological data from literature, the first major compressional event has been connected to the late Mesoproterozoic Rodinia assembly during the Stenian–Tonian. Based on observations from rocks of the Pindura and Cyohoha groups of the Akanyaru Supergroup in Rwanda, Van Daele et al. (2021) concluded that regional Barrovian-type metamorphism reached its amphibolite facies climax during this deformation event, prior to the intrusion of the granitoids associated with the Sn-W-Nb-Ta mineralization. Also at Imonga-Saramabila, the peak of metamorphism postdates the main deformation, as the porprhyroblasts are not crosscut by the foliation. A first vein generation at Imonga-Saramabila has been folded with an associated foliation that can clearly be observed in these veins. Porphyroblasts of andalusite and chlorite, as well as metamorphic muscovite have been formed and are observed to have overgrown minerals in veins of the first generation. The alteration associated with the second and third vein generations have caused an alteration of these poprhyroblasts, indicating the relation between the different veining stages and metamorphism. Although no granitoid intrusions have been described near the Imonga-Saramabila mining area, it cannot be excluded that the gold mineralization occurred largely contemporaneous with the emplacement of the parental granites of the Sn-W-Nb-Ta mineralization in the KAB, without necessarily a genetic link between both types of mineralization. No second cleavage generation, S_{F2} (Van Daele et al., 2021) has been identified at Imonga-Saramabila. This fold generation has been defined in Rwanda to occur on local, small-scale folds with a generally steep axial plane, superimposed on the regional fold structure, but clearly postdating regional metamorphism. This deformation event has been explained by the influence of the late Neoproterozoic Gondwana assembly in KAB (Van Daele et al., 2021).

Different quartz vein generations, mineralized and non-mineralized, formed in the KAB during this tectono-metamorphic evolution (Van Daele et al., 2021). Early quartz veins occur, which have been strongly shortened or were emplaced during F1. In addition, bedding-parallel boudinaged quartz veins have been deformed pre- to syn-F2, while also undeformed syn- to post-F2 quartz veins can be identified. The mineralized second and third vein generation at Imonga-Saramabila crosscut the foliation at an angle varying between 40° to 80°, indicating a syn- to post-F1 orogenic formation of the gold mineralization. These vein generations are accompanied by intense alteration. The paragenesis of the rocks at Imonga-Saramabila showed different phases of veining, largely corresponding to those described by Wouters et al. (2020), with pre-folding, folding-related and post-folding veining phases.

5.2. Gold metallogenesis in the KAB

Different origins have been proposed for the gold mineralization in the Great Lakes area, varying from formation as volcanogenic massive sulfide deposits (Franceschi, 1990) to the more widely accepted orogenic gold deposits related to fold-and-thrust belt formation (Brinckmann et al., 2001; Pohl et al., 2013). Although there is some consensus on the type of gold mineralization in the KAB, the exact relationship between gold mineralization and the different magmatic, metamorphic and deformation events in the KAB is still a matter of debate. Gold mineralization has been linked to several deformation events, i.e. during the early Mesoproterozoic (Koegelenberg et al., 2016), the early Neoproterozoic (Brinckmann et al., 2001; Pohl et al., 2013), the late Pan-African at ~530 Ma (Brinckmann et al., 2001; Walemba et al., 2004; Fernandez-Alonso et al., 2012), and even a link was made with the recent development of the Western rift. The findings of this study on the Imonga-Saramabila samples are in agreement with the findings of Dewaele et al. (2015) and of Wouters et al. (2020), providing additional evidence for the model proposed with orogenic gold formation related to the early-Neoproterozoic deformation.

The study of Wouters et al. (2020) was carried out on the Byumba prospect in Rwanda, where auriferous quartz veins were recognized. The alteration and mineralization of the rocks in this area are comparable to those at Imonga-Saramabila. Common metamorphic and alteration minerals identified by Wouters et al. (2020) include muscovite, sericite, authigenic quartz, Fe-rich carbonate and chlorite. In addition, Wouters et al. (2020) established that the chlorite which is present in the host rock and in pressure shadows is more Fe-rich compared to the more Mg-rich chlorite in the quartz veins. Several pyrite generations could be recognized in their samples. A first generation of anhedral pyrite is linked to early authigenic mineralization in the sedimentary protolith and often contains small inclusions of chalcopyrite. This pyrite shows quartz-filled pressure shadows. Later generations of pyrite which are coarse, euhedral and show evidence of resorption and sieve textures overprint the metamorphic fabric of the host rock and also occur inside quartz veins (Wouters et al., 2020). These euhedral pyrites are linked to a post-folding (cleavage development) carbonatization of the rocks. Finally, the presence of gold at Byumba was correlated with an enrichment in As in the form of arsenopyrite and As-rich pyrite (Wouters et al., 2020). Gold has, however, not been observed in any pyrite generation and is thought to be related to sulfide recrystallization.

In our study, four main phases of veining have been identified. The first generation of quartz veins is comparable with the first cm-thick layer-parallel quartz vein generation identified by Wouters et al. (2020). The second vein generation, consisting of quartz, Fe-dolomite and chlorite, with pyrite and chalcopyrite, and associated with carbonate alteration, might correspond to the second veining phase identified by Wouters et al. (2020), since these authors also identified an association of chlorite and pyrite with their second vein generation. The second vein generation at Byumba comprises chlorite- and pyrite-rich veinlets, which are concentrated in fold hinges and related to the primary folding of the layers. It has to be mentioned that the second vein generation at Byumba is syn-folding, while at Imonga this generation is syn- to post-folding. The third vein generation could correspond to the third and last vein generation identified by Wouters et al. (2020). This third vein generation consists of massive or sigmoidal quartz veins, up to more than a decimeter thick, and frequently encloses host rock fragments. As in Imonga-Saramibila, the latter two vein generations at Byumba are associated with intense alteration, showing pervasive chloritization, silicification, sericitization and carbonatization. The fourth and last vein generation identified in Imonga-Saramabila has not been described at Byumba.

6. Conclusion

The unique boreholes crosscutting the mineralized vein system at Imonga-Saramabila in the Maniema province of the DR Congo, form a unique possibility to study the geodynamic history of the area. In addition, the study of the mineralization could significantly contribute to a better understanding of the formation history of gold mineralization in the Karagwe-Ankole belt (KAB) in the Great Lakes area in general. The rocks studied are predominantly meta-igneous rocks with meta-sedimentary successions, which both have undergone upper greenschist to lower amphibolite metamorphism. In addition, these rocks underwent intense alteration during veining and mineralization. Pre-folding, folding-related and post-folding veining phases have developed in the KAB, some of which are associated with gold mineralization.

Due to the relationship between metamorphism, veining and alteration, and foliation development, it is possible to determine the relative timing between gold mineralization and the different magmatic, metamorphic, and deformational events in the KAB. Different vein generations have been identified. The first generation was emplaced parallel to the bedding prior to foliation development and prior to the peak of regional metamorphism, expressed by the presence of porphyroblasts of andalusite and chiastolite, but definitely after the Mesoproterozoic bimodal magmatism of ~1380 Ma. The second and third generation of veins, that are associated with an intense alteration, were emplaced after development of the regional foliation and after peak metamorphism, indicating a late orogenic timing, largely contemporaneous with the emplacement of the parental granitoids of the Sn-W-Nb-Ta mineralization. Due to the absence of a second foliation generation and the link with peak metamorphic conditions, sulfide and gold mineralization is most likely related to the early Neoproterozoic (~980 Ma) compressional deformation event.

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Author contribution

Stijn Dewaele and Philippe Muchez conceptualised the research strategy. The petrographic and geochemical analyses have been carried out by Julie De Groote during her Honors program (3Ba-1Ma) at UGent, under supervision of Stijn Dewaele. Additional petrographic work was carried out by Inge Cools in the framework of her MSc thesis (2Ma) at the KULeuven, under supervision of Philippe Muchez and Stijn Dewaele. The five authors discussed the results and reviewed the manuscript.

Data availability

The unpublished geological and mining archives of the Imonga-Saramabila area, and the borehole samples of the Kazmitcheff collection are stored at the Royal Museum for Central Africa. Thin and polished sections are stored in the collection of the Geology department of KU Leuven.

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