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Review

A Review of the G4 "Tin Granites" and Associated Mineral Occurrences in the Kivu Belt (Eastern Democratic Republic of the Congo) and Their Relationships with the Last Kibaran Tectono-Thermal Events

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Abstract: The Mesoproterozoic Kibaran belts host large amounts of mineral resources such as cassiterite, wolframite, gold, and columbite-group minerals ("coltan"), all of them in high demand for new technologies and related industries. Most of these mineral occurrences are linked to the latest Mesoproterozoic to early Neoproterozoic G4 granitoid intrusions, also termed "tin(-bearing) granites". Three main parts constitute the Kibaran belts: the Kibaride Belt (KIB) in the south, the Karagwe-Ankole Belt (KAB) in the east, and the Kivu Belt (KVB) in the west. Geological detail concerning the metallogeny of the KVB, which hosts large parts of these mineral resources, is very sparse. Previously, there was an assumed time gap of about 200 Ma between the formation of the last Kibaran terranes (1250 to 1200 Ma) and the emplacement of the G4 granites (ca. 1050 to 970 Ma), which generated the main mineralizations. Recent studies dated the last Kibaran tectono-thermal events younger than 1120 to 1110 Ma, which gave evidence for a drastic reduction in this time gap. Thus, the two newly recognized tectono-thermal events have likely contributed to the remobilization of older mineralized granites. These new data allow us to link the G4 granitoids and the associated mineralizations with the terminal Kibaran orogeny. However, the G4 emplacement and its relationships with older granites, with their host rocks and associated mineralizations, are not yet understood. Here, the main occurrences of the KVB are reviewed, and comparisons with similar mineralizations in the adjacent KAB are undertaken to improve our understanding on these complex relationships.

Keywords: Mesoproterozoic Kibaran orogen; Kivu Belt; post-granitic G4 intrusions; concentrations of economic ore bodies; Kivu; Eastern Congo; Central Africa

1. Introduction

Many occurrences of economic interest, such as gold, cassiterite, wolframite, and (Nb-Ta) columbite-group minerals ("coltan"), are currently associated with the G4 granitoid intrusions that were emplaced between ca. 1050 and 970 Ma in the Central African Mesoproterozoic Kibaran Belt (Table 1). These G4 granites, also called "tin granites", contain minerals deposits such as beryl, amblygonite, spodumene, apatite, and tourmaline. With respect to the geodynamic evolution of the whole Kibarides (previously named "Burundian Belt"), these granites are considered as post-orogenic [1] or even anorogenic owing to the previously assumed time gap (almost 200 Ma) between the main late Kibaran tectonic event (D2) dated around 1250 Ma [2] or around 1200 Ma [3] and the granitic G4 emplacement. Taking into account the lack of known tectono-metamorphic events during this time gap in Kivu and neighboring regions, [4] attributed the G4 granitic intrusions of Zambia to a "post-collisional relaxation after far field tectonics effect of the 1 Ga main compressional events in the Irumide Belt". However, new age determination of detrital zircon in the KVB [5] gave evidence for two new stratigraphic groups which record two metamorphic events during the previously presumed D2–G4 time gap. This time gap between the latest tectono-metamorphic events that are younger than 1100 Ma and the first intrusions of the G4 granites at ca. 1050 Ma is thus strongly reduced. Therefore, the G4 intrusive event can be now considered as the latest Kibaran. Nevertheless, the origin of these G4 granites is not yet clearly understood. Here, special attention has to be paid to the mineral resources associated with the G4 granitoids, which host significant amounts of the world's tantalum, minor proportions of niobium reserves, and large amounts of other economic and strategic minerals.

2. Regional Framework

The Kibaran belts, which extend over 700 km from the Katanga Province (Southeastern Congo) to Uganda, were formed by the Mesoproterozoic collision of the Western Congo Craton, with the Eastern Tanzanian, Bangweulu, and Zimbabwe cratons (Figure 1a). The latest studies suggest a separation of the Kibaran belts in three main sections [5]. The Kibaride Belt (KIB) to the south, the Kivu Belt (KVB) to the northwest, and the Karagwe-Ankole Belt (KAB) to the northeast (Burundi, Rwanda, and Uganda). The KIB is separated from the KVB and KAB by the NW-SE trending Ubendian Belt, which is a Paleoproterozoic structure that was repeatedly reactivated, particularly during the Neoproterozoic formation of the Katangian Belt. The KIB was studied in [6–9]. The KAB was studied in [10–20], while the KVB section was studied in [21–26] and recently in [5]. A discussion of stratigraphic, tectonic, metamorphic, and geodynamic comparisons between these three sections can be found in [5]. For this review, we focus our study on the KVB (Figure 1), which presents many similarities to the KIB.

According to a recent synthetic paper [5] based on U-Pb age determination of zircon in an area located between the KVB and KAB sections, five main cycles including the final G4 granitic intrusions, four granitic groups, six metamorphic events, and at least nine geodynamic stages have been distinguished (Figure 2). The initial two geodynamic stages are similar within the KIB and the KVB but different from the equivalent KAB stages. All authors working in the KIB and KVB identified a subduction/collision process between ca. 1400 and 1375 Ma. Authors with a focus on the KAB favored an extensive regime during this period. Reference [27] proposed to extend the "subduction/collision" model from the KIB to the KVB belt with a "subducting" stage until ca. 1400 Ma and a collision stage until ca. 1180 Ma. However, the large quantity of K2 sediments (almost 10,000 m) deposited in the KVB between ca. 1350 and 1185 Ma is not consistent with a collisional stage. Owing to the lack of subduction-related remnants and associated volcanic arcs, during this K2/Cy2 stage, an intra-continental geodynamic model is favored for this K2/Cy2 stage.

A new geodynamic model, similar to the triple rift junction model, has been proposed in [5] in order to reconciliate the subduction process in the KIB and KVB with an intra-continental basin in the KAB. However, this hypothesis only considers the Ky1 stage.

The tectono-thermal events generated several intrusive episodes mainly with emplacement of granitic batholiths. The first classification of these granitoids has been delivered by [28], which distinguished four main groups of granitic events (G1 to G4).

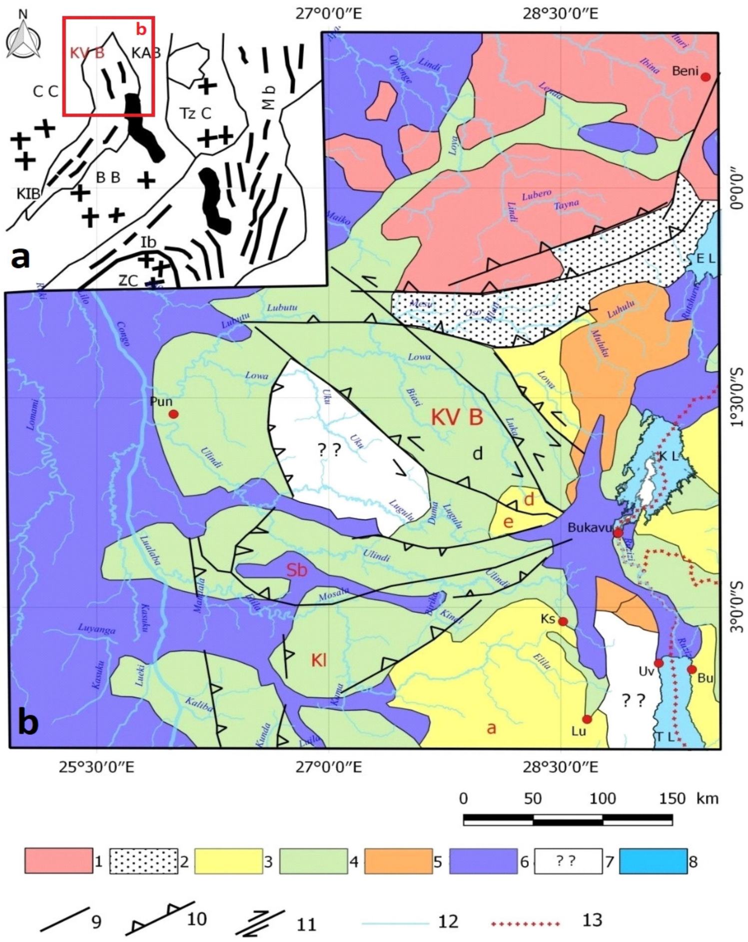

Figure 1. Sketch map of the main formations in the KVB. Legend: (**a**): CC—Congo Craton, BB—Bangweulu Block, TzC—Tanzanian Craton, ZC—Zimbabwe Craton, KIB—Kibaride Belt, KVB—Kivu Belt, KAB—Karagwe-Ankolean Belt, Ib—Irumide Belt, Mb—Mozambique Belt (Neoproterozoic). (**b**): 1—Kibalian basement (Paleoproterozoic), 2—Bilatien, 3—K1 unit, 4—K2 unit, 5—K3 and K4 formations, 6—post-Kibaran formations (Neoproterozoic to Quaternary), 7—non-studied areas, 8—lakes, 9—faults, 10—thrusts, 11—strike slip faults, 12—rivers, 13—frontiers. CC—Congo Craton, KVB—Kivu Belt, KL—Lake Kivu, TL—Lake Tanganyika, not in the map, Kl—Kalima, Sb—Shabunda, Pun—Punia, Ks—Kasika, Lu—Luemba, Uv—Uvira, Bu—Bujumbura (Burundi).

Ages indicated in Figure 2 should be taken with caution. There are some discrepancies due to the method of age determination. For example, the Chitwe granite of Uganda displays an age of 1146 ± 40 Ma when dated by the Rb/Sr method [29], while the U-Pb method on zircon yielded an age of 1568 ± 23 Ma [30]. Furthermore, extensive dating in Rwanda, based on Rb/Sr, was invalidated in [17] using the U-Pb method on zircon. These discrepancies could explain the large scarcity of granitoid intrusion ages and the lack of true age clusters. However, there is a general agreement to distinguish the four main groups of granitic bodies proposed in [28]. G1 provided large batholiths of deformed granites dated in the KAB around 1375 Ma [17], together with granitic gneiss and granites dated around 1350 ± 50 Ma in the KVB [31]. The G2 event provided deformed A-type granitoids that display ages between approximately 1360 and 1260 Ma in the KAB [2,32,33] and porphyroid granodiorites until 1265 ± 15 Ma in the KIB [31]. The G3 event provided deformed sub alkaline granites dated in the KAB, between ca. 1220 and 1111 Ma [11] and monzogranites dated around 1189 ± 69 Ma in the KVB [31]. Finally, the G4 event provided less deformed alkaline leucocratic granites, also called "tin granites", displaying ages between ca. 1000 and 950 Ma [4,7,17,28,34] or up to ca. 1020 Ma [35]. Moreover, intrusions around 1070 and 1050 Ma may be part of this granitic group. Except for the G4 group, there is much local confusion between other groups. For example, G1 of [36] corresponds to the G2 of [21], and so on.

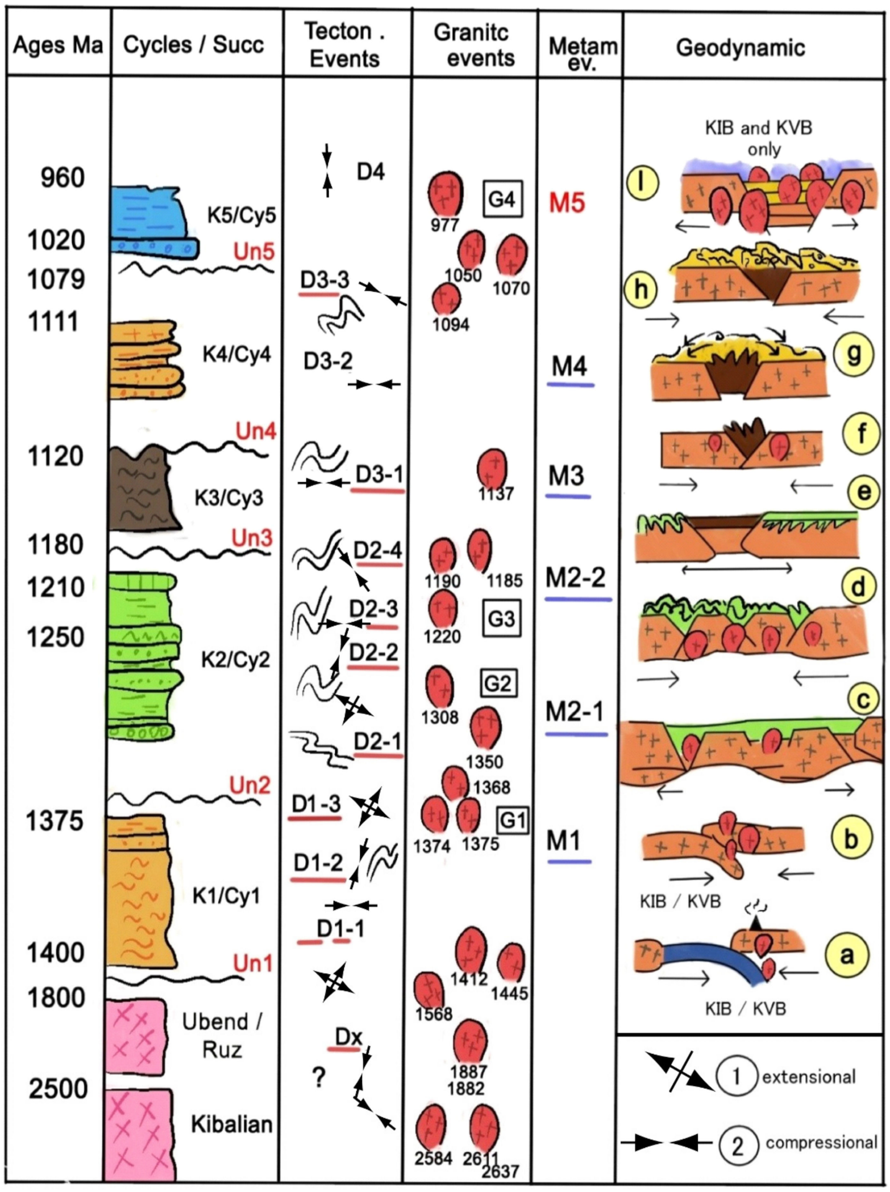

Figure 2. The main geologic events in the Kibaran belts according to [5], modified. Legend: Un = unconformity, Cy = cycles, D = tectonic events, G = granitic events, M = metamorphic events, (a) to (i) = geodynamic stages; KIB = Kibaride Belt, KAB = Karagwe-Ankolean Belt, KVB = Kivu Belt.

Figure 2 shows the main granitic bodies that have already been dated in the KAB, KIB, and KVB. Each group can be correlated to tectonic events, to a cycle, and to a geodynamic stage. Notably, only the G4 granites provide minerals of interest at high economic levels such as cassiterite, columbite-group minerals, wolframite, tourmaline, gold, and associated minerals such as beryl, spodumene, and chalcopyrite [37]. During the initial scientific investigation, the focus was on mineralogical studies [38], whereas there are few metallogenic studies. Mining was essentially performed in alluvial occurrences but not at primary sites. Then, the geological interest of ore bodies increased depending on their economic interest. Gold was the first mineral of interest, followed by cassiterite and wolframite. Finally, minerals of the columbite group came to the fore, due to the rapid development of computers and telecommunication technologies. Administrative reports indicate that by 1994, the Maniema and Kivu provinces had produced 390,000 t of cassiterite, 10,000 t of wolframite, 7700 t of "coltan", 2300 t of monazite, and 6000 t of beryl. Basic research was carried out in [39] and by N. Varlamoff [40–47], who studied gold, cassiterite, and wolframite ore bodies in the Kivu area between 1948 and 1956. N. Varlamoff expanded his fieldwork to Rwanda and Burundi between 1960 and 1969 in order to study similar mineralizations. Since 1960, the investigations on the origin of minerals deposits have mainly focused on the KAB, and numerous papers have been published [4,48–59]. The best studied occurrence is the Gatumba mine in Central Rwanda [4,54,57]. Detailed studies in this district provide much useful information related to the evolution of ore bodies.

According to [4,37], there are two types of mineralization, pegmatite dikes and quartz veins, which are cross-cutting each other. In the pegmatites of the Gatumba area, several parageneses have been evidenced: (1) Nb-Ta paragenesis with K-feldspar (pink color) + quartz + muscovite + biotite + beryl + phosphates + tourmaline + columbite–tantalite + traces of cassiterite; (2) albitization paragenesis; (3) sericitization with tourmaline, quartz, and muscovite; and (4) muscovitization with quartz + muscovite + the main cassiterite amount. It has to be noted that columbite–tantalite mineralization precedes the main cassiterite mineralization. This is confirmed by geochronological data on columbite–tantalite samples (U-Pb method) and on muscovite (Ar/Ar method). The first paragenesis with columbite-group minerals occurred between ca. 975 and 965 Ma. The second paragenesis is dated between ca. 951 and 938 Ma by U-Pb on "coltan". Ages are given in [16], in which U-Pb was applied to columbite in Burundi (965 $\pm$ 5 Ma), and in [60–62], in which several columbite-group mineral occurrences of the Kibaran belts were dated with additional data from the literature. Accordingly, the columbite-group mineralizations are dated between ca. 1030 and 920 Ma with a main peak at ca. 990 to 960 Ma. Younger U-Pb ages of "coltan" (ca. 700–500 Ma) have been recorded in the vicinity of Lake Kivu and interpreted as "pan-African rejuvenation of older mineralized structures" [62]. Gold mineralizations cover a large span of time between ca. 908 and 535 Ma. A plateau age on muscovite from the gold quartz veins in Gatumba displays an age of 592 $\pm$ 0.34 Ma [4] indicating a Neoproterozoic tectono-thermal event. These results could be a guide for mineral studies elsewhere in the Kibaran belts. However, this potential guide should be adapted to each locality depending firstly on the local ages of the G4 intrusions and secondly on the different hydrothermal events with possible resetting of the dated mineral as shown in [4].

3. Geology of the Kivu Belt and Review of Granitic Occurrences within the Kivu Belt

3.1. Location

The Kivu Belt (KVB, Figure 1) stretches out over an area of ca. 110,000 km^2, from the Kaiko River (to the north) to the Luama River (to the south) and from the Lualaba River (to the west) to the Rift valley (to the east). The KVB extends over the three administrative provinces: South Kivu, North Kivu, and Maniema. This belt is limited to the West by the Congo Basin and to the South by the Luama Trough, which is considered as an extension of the Tanzanian Ubendian Belt.

3.2. Lithostratigraphy

The main lithostratigraphic units of the KVB are shown in Figure 3.

The pre-1800 Ma basement is restricted to the northern Kibalian outcrops. The southern outcrops of the Ruzizian and Ubendian belts are outside of Figure 1. The KV1 formation (ca. 1400–1375 Ma) is composed of micaschist, gneiss, phyllite, shale, granulite, and granite that crop out to the south of Kasika (a), in the Kahuzi area (d and e), and in the Walikale area (f). In the Kahuzi area (Lushasha Formation), granulites and gabbros may represent remnants of a suture. The KV2 formation (green color) contains black shale, arkose, phyllite, quartzite, and micaschist as well as granite and is located in the central part of the belt. Previous studies [25,26] interpret this formation as remnants of intra-continental basins that may have been opened between ~1375 and ~1210 Ma. The K3 and K4 formations consist of sandstone, quartzite, shale, phyllite, micaschist, and granite. Their maximum ages of deposition were recently dated at ca. 1120–1079 Ma in the Nya Ngezie area, which is located to the south of Bukavu [5]. Potential correlations across the Kivu area extend the spatial distribution of these formations to the Masisi area, which is located at the northwestern part of Lake Kivu. The violet-colored area corresponds to the post-Kibaran terranes including all sediments from the Neoproterozoic to the modern deposits. White areas with question marks correspond to the areas that have not yet been studied. Detailed maps show intensive deformations and transcurrent faults corresponding to the numerous tectonic events exposed in Figure 3. Figure 3 gives a succession of granitic intrusions with their coeval metamorphic events. At least four metamorphic (M1 to M4) and five tectonic events (D1, D2, D3-1, D3-2, and D4) have been reported in the KVB.

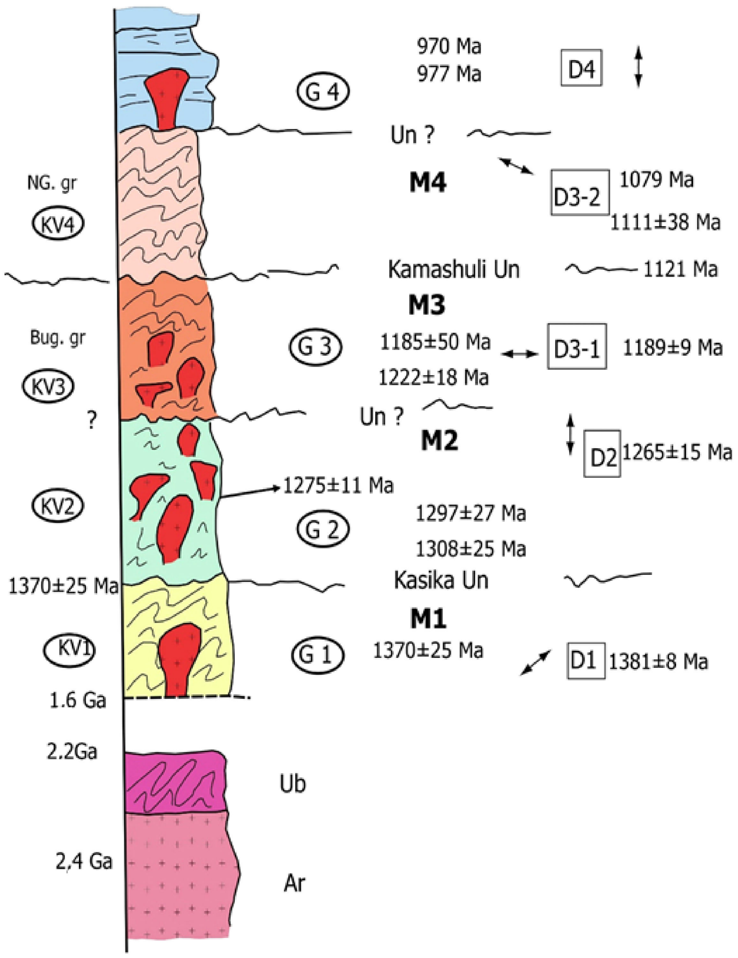

Figure 3. The main tectono-stratigraphic events in the Kivu Belt (KVB). KV1, KV2, KV3, and KV4–main Kibaran formations in the Kivu Belt, M1 to M4-main metamorphic events, D1 to D4-main tectonic events. Ages are given in million years.

3.3. Granitoid Intrusions and Metamorphic Events

The main challenge is to distinguish the G4 granites from the G2 and G3 plutons. There are numerous granitic intrusions in the KVB (Figure 4). Among them, there are the four major massifs called the Kasese Massif (A), Punia Massif (B), Gondo Ya Bushema Massif (C), and Lubero Massif (D). At least 40 small-scaled outcrops of granitic intrusions are mapped in Figure 4. In a first approach, the largest massifs were ascribed to the G2 and G3 batholiths [36], and the smallest are presumably formed by the G4 granites.

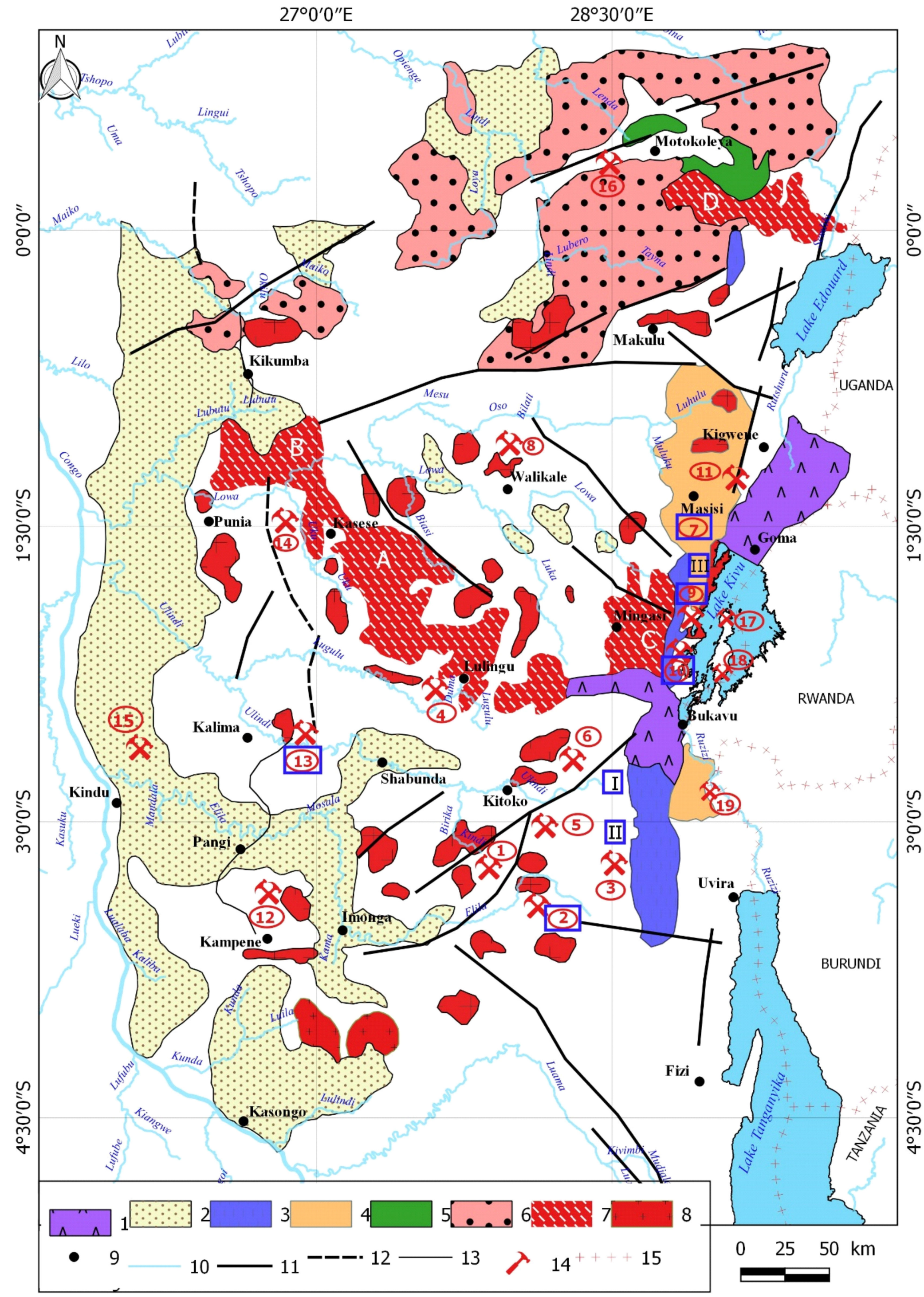

Figure 4. The main granitic outcrops and mineral districts in the Kivu Belt (KVB). Legend: 1—tertiary volcanism, 2—Karoo and post-Karoo formations, 3—Neoproterozoic formations, 4—K4 and K5 units, 5—Motokoleya Formation, 6—Kibalian (Paleoproterozoic basement), 7—granites of Kasese, Punia, Gondo Ya Bushema and Lubero (G1, G2 and G3 types), 8—granites of Kasika, Nzombe, Nyamakubi, Numbi, Kirumba, and Kobokobo (G4 type), 9—cities, 10—rivers, 11—main faults, 12—main faults supposed, 13—main roads, 14—main mining districts, 15—national borders. Circled numbers correspond to mineral districts cited in the text. Number in blue squares = geochronological samples, number in red circles included in blue squares = geochronological samples from mineral sites. Details are given in Table 2.

These G2 or G3 massifs are concordant with the local structures and general metamorphism and do not present any specific metamorphic aureole. The studies of [36] in the "Mount Hango" granite and [63] in the "Kalehe" granite show that the granitic P/T conditions are in concordance with the gneiss and micaschist host rocks. There are very few geochemical studies on these G2 or G3 massifs in the KVB. According to [31], the G1 and G2 granites have potassic calc-alkaline affinities, and according to [63] the "Kalehe" massif (G2) also presents some calco-alkaline affinities. G3 and G4 are mainly alkaline. In [31], G1 (I-type) batholiths are linked to a subduction process, while G2 (S-type) batholiths are linked to the collisional stage. G3 (S-type) are syn-kinematic and G4 (S-type) are late-kinematic.

There are no geochronological data that can differentiate the G2 and G3 groups in Kivu. Furthermore, fewer than 10 massifs (Nzombe [64], Kasika [17,28,65], Nyamakubi [64], Numbi [64], Kirumba [64], Kobokobo [66], etc.) have been dated using different methods. All of them are linked to the G4 intrusions. These age data are listed in Table 1.

Table 1. Main geochronological age determination of the KVB granitic massifs. Locations of samples are in blue squares in Figure 4.

	Location	Methods	Age	Granite Type	Host Rocks	References
I	Kasika	Rb/Sr, whole rock	976 ± 10 Ma	G4	KV1/KV2	[28]
		Rb/Sr on microcline	520 ± 9 Ma	G2/G4	KV1/KV2	[65]
		U-Pb on zircon	986 ± 10 Ma	G4	KV1/KV2	[17]
II	Nzombe	Rb/Sr, whole rock	~976 Ma	G4	KV1/KV2	[64]
III	Kirumba	Rb/Sr, whole rock	578 ± 9	G4	KV3	[64]
2	Kobokobo	U-Pb on beryl	~900 Ma	G4	KV3	[66]
		U-Pb on uranite	~850 Ma	G4	KV3	[66]
7	Masisi	U-Pb on columbite-group minerals	950.2 ± 4.4 Ma	G3/G4	KV3	[61]
9	Numbi	Rb/Sr, whole rock	~648 Ma	G4	KV2/KV3	[64]
10	Nyamakubi	Rb/Sr, whole rock	~976 Ma	G3/G4	KV2/KV3	[64]
13	Kalima-Moga	Rb/Sr, whole rock	989 ± 28 Ma	G4	KV2	[28]
		Ar/Ar on muscovite (max.)	1024.3 ± 5.5 Ma	G4	KV2	[35]
		Ar/Ar on muscovite (min.)	986.6 ± 5.3 Ma	G4	KV2	[35]
		U-Pb on columbite-group minerals	993 ± 1 Ma	G4	KV2	[35]

The Rb/Sr ages on minerals indicate more recent tectono-metamorphic events, while the U-Pb ages on zircon indicate the emplacement ages.

First, geochronological data were obtained by the Rb/Sr method, which was used in [65] on the microcline of the Kasika granite (520 ± 10 Ma) and in [67], displaying a 1020 ± 50 Ma with Rb/Sr on whole rocks. Later, in [28] a similar method was used to date this granitic intrusion at 989 ± 28 Ma. Then, the Kasika granite was dated again in [17] using the U-Pb method on zircon resulting in an age of 986 ± 10 Ma. The discrepancies between the results from the Kasika massif likely reflect the influence of the post-Kibaran tectono-metamorphic events and particularly the subsequent pan-African events. These pan-African events are well described by the results of Ar/Ar geochronology on muscovite and biotite [4] or by U-Pb on monazite [16]. Thus, even if the cycles Cy3 and Cy4 have exclusively affected the KVB (Figure 2), there is no long-lasting gap of the geological activity between ca. 1210 and 980 Ma, as previously supposed. The time gap between the last G3 granite batholiths (ca. 1137–1070 Ma) and the first G4 intrusions (ca. 1020 Ma) can again be reduced if the ca. 1094, 1070, and 1050 Ma granitic batholiths are considered as a part of the G4 group.

Four metamorphic events are distinguished in Figure 3:

- M1 with staurolite + garnet + biotite + muscovite studied in the Kamituga district (1 in Figure 4).
- M2 with staurolite + kyanite + garnet + biotite studied in the Kasika, Luntukulu, and Kalehe districts. (5, 6, and 10 in Figure 4).
- M3 with staurolite + garnet + biotite + muscovite (locally andalusite) studied in the Masisi and Kamanyola districts (7 and 19 in Figure 4).
- M4 with biotite + muscovite + sericite studied in the Nya-Ngezie district.
- However, although we know the local impact of these metamorphic events, we do not know their regional effect. For example, we do not know if the M3 event is local and restricted to the Masisi or Kamanyola areas or if it is covering a large part of the KVB.
- M5 is ascribed to the G4 granitic intrusive event but is not a part of this study.
- However, there are some questions that remain unsolved:
- Some of the smaller massifs could be the outcropping apexes of large concealed batholiths. Thus, several granitic massifs (G1, G3, G3, or G4) could be concealed underneath the sedimentary pile. However, they can be evidenced by their metamorphic aureole, such as in the Luntukulu area.
- In the past, numerous geologists have considered that the G2 and G3 granites are extending along the main structures, while the G4 granites are cross-cutting these structures. In contrast, [36] notes that accordance between the magmatic batholiths and their host structures does not necessarily indicate a syn-kinematic emplacement. Thus, the N-S elongated G4 granites had likely used the older D2-2 structures (Figure 2) to reach the surface.
- Reference [68] indicates that large granitic massifs (G2) are located in the center of large anticlines and are cross-cut by G4 intrusions.
- From [69] it is known that granitic batholiths, such as Gondo Ya Bushema (C in Figure 3), are complex composite structures and may include several intrusions of various ages.
- It is necessary to distinguish the metamorphic aureoles induced by the granitic intrusions in the field. For example, the G4 Kasika granite is not related to the large metamorphic imprint that stretches out for several km-wide concentric zones of staurolite, garnet, and biotite (more than 20 km away from Kasika), but it is related to a local imprint with skarns and breccias. The Barrovian metamorphism is associated with the G2 and G3 intrusions, while the contact metamorphism with andalusite is associated with the G4 intrusions. For example, the Luntukulu metamorphism with kyanite, staurolite, and biotite may be linked to concealed G2 granitic batholiths.
- The lack of geochemical studies does not allow us to draw conclusions on the origin of the G4 granites that are considered by many geologists as "alkaline". This is not in agreement with the occurrences of spodumene, beryl, and amblygonite mainly associated with peraluminous magmatism. These mineralogic associations and the spatial relationships between the G2 and G3 batholiths suggest a G4 thermo-metamorphism giving way to crustal feeding. Recent investigations [59] in the ca. 1 Ga G4 granitoids of Rwanda show the inheritance of zircon from the G1 granites in the G4 occurrences and thus favoring an intra-continental geodynamic context and an anatectic origin of melts. Migmatitic melting of a fractionation of large magma chambers is considered by these authors. This is also in accordance with our field observations.
- The thermo-tectonic environment of these G4 granitic bodies is also not well understood. Some bodies are tectonized (Kasika, Mt. Hango), while others remain undeformed. Finally, the metamorphic conditions are also not well studied. The results of [59] suggest a metamorphic origin in a compression context. However, such environmental studies have not been conducted in the Kivu area.
- G1 and G2 granites in Rwanda are different from the Kivu ones. In Rwanda, such granites are hyper-alkaline with sand A types. They are related only to an intra-continental geodynamic model. Thus, no subduction process is considered in Rwanda and Burundi.

- Cahen and Ledent [28] considered that the low 87Sr/86 Sr ratio (0.7002 ± 0.0021) in the G4 granite of Maniema and the higher ratio in Rwanda (0.7782 ± 0.0151) reflect the host gneisses of local G1 or G2 batholiths.
- The detailed geological contexts of the granitic intrusions in the KIB, KAB, and KVB remain unclear despite recent specialized studies.

4. Review of the Main Occurrences of Ore Bodies in the KVB

Numerous occurrences of mineralizations are well-established in the Kivu area. However, few were studied with respect to their metallogeny. The main metallogenic contributions prior to 1960 came from [40,41,43–46,70–72], in which the first classification of mineral bearing pegmatites was developed [44]. After the independence of the Democratic Republic of the Congo, the metallogenic studies were largely restricted to the company reports except for [66,73,74], and finally [75]. The types of the investigated minerals varied through time depending on the economic conditions and the evolution of technologies. Initially, gold was in the focus of interest, then cassiterite, followed by wolframite, and finally columbite-group minerals, which are currently among the minerals of highest economic interest. Further minerals that have been studied in the KVB are ferberite, monazite, amblygonite, tourmaline, beryl, etc. Mineralizations are mainly located in pegmatites, quartz-veins, and greisens, where they occur in cleavages, diaclases, or in fold apexes. The main mining centers in the KVB are mapped in Figure 4, but only 19 are summarized here (Table 2, [28,35,37,61,66,72,76–84]). Caron et al. [85] listed Sn, W, Nb-Ta, Be, Ce, Th, Au, Pt, Cu, Co, Ni, Mo, Ti, and Fe as the main mineral occurrences linked to the Kibaran belts.

Table 2. The main mineral occurrences in the Kivu Belt. Associated granites, metamorphism, host rocks, and bibliographic references are listed.

N°	Location	Mineralization	Mineral Type	Associated Granites	Associated Met. Event	Host Fm.	Reference
1	Kamituga	Au, Sn, Be	pegmatite	G4	M1/M2	KV1	[77,79]
2	Kobokobo	Sn, Be, Nb, U, As, Li, Bi	pegmatite	G4	M1/M2	KV1	[66]
3	Nzovu	Nb-Ta, Sn	pegmatite	G4?	M2	KV2	[66]
4	Lulingu	Nb-Ta, Sn, Au	pegmatite	G3/G4?	M2	KV2	[61,80]
5	Luntukulu	Sn, W, Au	qtz. veins, shales	G2/G4	M2	KV2	[78]
6	Nzibira	Sn, W, Fe	qtz. veins	?	M2?	KV2	[81]
7	Masisi	Sn, Nb-Ta, W	n.a.	G3/G4	M3	KV3	[61]
8	Walikale	W, Sn, Zn, Pb	n.a.	G4?	?	KV2	[37]
9	Mumba/Numbi	Sn, W, Nb-Ta	pegmatite, qtz. veins	G2/G3/G4	M2/M3	KV2/KV3	[72,82,83]
10	Lemerat/Kalehe	Sn, Au, W	n.a.	G2/G3, G4	M2/M3	KV2	[83]
11	Bishusha	W, Sn, Nb-Ta, Au	qtz. veins	G4?	?	KV2	[84]
12	Kama-Kampene	Nb-Ta, Sn, W	pegmatite in granite	G4?	M2?	KV2	[37]
13	Kalima-Moga	Sn, W, Nb-Ta, Mo	pegmatite, qtz. veins	G4	M2	KV2	[28,35,37]
14	Punia–Aissa	Sn, W, Nb-Ta	qtz. veins, greisen	G2/G4	M2	KV2	[61,76]
15	Kailo-Kamilanga	W, Sn	qtz. veins	G4?	M2	KV2	[76]
16	Etaetu	Sn, W, Nb-Ta, Au	qtz. veins	?	?	?	[61,76]

Table 2. *Cont.*

N°	Location	Mineralization	Mineral Type	Associated Granites	Associated Met. Event	Host Fm.	Reference
17	Kamole-Burhonga	W, Nb-Ta, Be	pegmatite, greisen	G4	M1	KV1?	Kalikone, pers.com; 3 March 2020
18	Bihumba	W	pegmatite	G4	M2	KV3	Kalikone, pers.com; 3 March 2020
19	Mulengezi	W	qtz. veins	?	M3	KV3	Kalikone, pers.com; 3 March 2020

4.1. In the South Kivu Province

The Kamituga district (1) hosts the Mobale mine where gold was extracted from quartz veins. Furthermore, pegmatites were mined for barite, cassiterite, pyrite, and chalcopyrite, but all of them yielded only small quantities of raw materials [79]. Additionally, beryl, graphite, scheelite, and actinolite occur at some places [6]. According to our own observations [77] and interpretations [26], these rocks presumably belong to the K1 unit. Landsat images suggest a km-sized circular granitic intrusion. First age determination performed by the authors of [67] on the G4 granite of Kamituga by Rb/Sr on whole rocks display an age of 1020 ± 50 Ma. Further data on pegmatites display ages of ca. 910 and 850 Ma. To the southeast of Kamituga, there is the Kaboboko mine (2), which is an elliptic intrusion of alkaline granitoids mineralized with cassiterite, beryl, columbite, uranite, amblygonite, etc. The granitic intrusion itself has not yet been dated, but single beryl crystals yielded ages of ca. 900 Ma and are related to a potassic phase, while the uranite was dated at ca. 850 Ma [66] and is related to a further albitic phase. This is consistent with data known from the abovementioned Gatumba site of Rwanda [4]. The relationships between the granitic intrusion and the staurolite, garnet, and biotite metamorphism are unknown. In the Nzovu district (3) there are numerous occurrences of pegmatites containing cassiterite and columbite-group minerals, such as the Katulu and Kasili pegmatites [66]. The Lulingu district (4) is located to the South of the Kasese batholiths. Pegmatites within the G4 muscovite-granites provide large amounts of columbite-group minerals, which are associated with cassiterite, gold, amblygonite, anorthite, spodumene, topaz, scheelite, etc. mineralizations [61,80]. The Luntukulu district (5) was investigated in 1971 by an author of the present study [78]. This district is located between Bukavu and Kamituga. The host rocks belong to the K2 unit and are represented by a succession of black shales intercalated with thin orange arkosic levels. Mineralizations are cassiterite, scorodite, wolframite, tourmaline, and accessory gold. Cassiterite is preferably concentrated in quartz veins inside the arkosic levels, while the wolframite occurs almost exclusively in black shales. The pegmatites are oriented N-S and E-W. No granitic outcrop is visible on the surface, but rocks present a metamorphic gradient with chiastolith, kyanite, staurolite, and biotite. Black shales are not transformed into micashists, and so centimetric crystals of kyanite and staurotide may be collected along the roads owing to the erosion of their host rocks. Another important district of the south Kivu province is Nzibira (6) to the north of Luntukulu. The host rocks of the mineralization belong to the K2 unit, and the mineralized quartz veins contain cassiterite and wolframite and are furthermore associated with arsenic, tourmaline, as well as pyrite. The Mumba-Numbi district (9) is located to the west of Lake Kivu and is framed by the granitic batholiths of Mt. Hango to the East and Mt. Sula to the West. The latter displays a calk-alkaline affinity, while the Mt. Hango granite displays an alkaline affinity. Without chemical analyses, no consistent conclusion can be drawn. This area was studied in [72,82,83]. Mineral-bearing host rocks belong to the K2 units, and the axial trends of most structures are N-S. Mineralizations are mainly cassiterite and wolframite at Mumba [76] and columbite-group minerals (up to 300 kg/m^3), cassiterite, and wolframite at Numbi. The Numbi mineralizations are close to a nepheline-syenitic (foyaite) massif and were well studied in [72], who distinguished three different zones around the granitic batholiths over a distance of ca. 5 km. These three zones are: Z1 (1 km from the granite limit), which provides potassic pegmatite with Sn, W, Au, Ta (columbite-group minerals); Z2 (2 to 3 km from the granite), which contains sodo-lithic pegmatites with Sn only; and Z3 (up to 5 km from the granite), which shows quartz veins with Sn, Au, Fe, As, and S. The Lemerat/Nyamakubi district (10) is more or less linked to the Kalehe granite that crops out at the western shore of Lake Kivu. The ore of the Twagiza gold mine about 40 km SSW of Bukavu is hosted within organic-rich siliciclastics of the Kibaran age [37].

4.2. In the North Kivu Province

The main sites that have previously been studied are: The Masisi district (7), which is located in the northwestern part of Lake Kivu. There, the host rocks belong to the K3 and K4 units, and structures are oriented NW-SE. Similarly, most of the granitic intrusions crop out in the apex of NE-SW anticlines. These granitic intrusions could be linked to the G4 granitic group. Mineralizations are mainly cassiterite, columbite-group minerals, wolframite, and tourmaline. Columbite-group mineral crystals from Mutiko in the Masisi district were dated at 950.2 ± 4.4 Ma [61]. The Walikale district (8) is located to the West of the Masisi district. There are at least four mineral centers scattered in the dense forest, which mainly produce cassiterite and wolframite. Among the mines, the polymetallic type exploited in the Bisie tin mine was discovered in the early 2000s and became the country's largest tin producer since then [37]. The host rocks of these mineralizations belong to the K2 unit. The Bishasha district (11) is located to the North of Masisi. Mineralizations, mainly wolframite, are concentrated in the quartzite beds, which also display Sn, Nb-Ta, molybdenite, cassiterite, gold, tourmaline, pyrite, and minor lithium [84]. The northernmost mining district is the Etaetu district (16) close to Butembo. Mineralizations are very similar to those of Bishasha with quartz veins containing wolframite and associated cassiterite, columbite-group minerals, molybdenite, gold, and sulfur [61,76]. The district of Kabubu is located in the pan-African part of the Itombwe Syncline that was first described in [86] and studied for gold mineralizations by the author of [87] and is not considered here as the mineralizations are not related to the G4 granitic system but to a pan-African thermo-tectonic event.

4.3. In the Maniema Province

More than 11 mining districts have been active in this province since the 20th century. Thanks to Varlamoff, the metallogeny of this province is well investigated, and the mined placers were very profitable. The Kama-Kampene district (12) is located in the southern part of the province. Mineralizations are concentrated in intra-batholith pegmatites with a tripartite zoning: Z1: columbite-group minerals, Z2: columbite-group minerals and cassiterite, and Z3: wolframite. The Kalima-Moga district (13) is located to the north of Kampene and has produced half of the overall cassiterite and wolframite extracted from the Congo basement. Sphalerite, stannite, and molybdenite are also reported from this district [37]. Mineralizations are related to two main batholiths, and host rocks are ascribed to the K2 unit. Two generations of quartz veins have been distinguished: The first ones that are very close to the batholiths contain cassiterite, wolframite, columbite-group minerals, and thoreaulite, while the second generation contains ferberite, anthoinite, tourmaline, and bismuthine. Pegmatites with columbite-group minerals are limited to the granitic batholith dated at 988 ± 28 Ma with the Rb/Sr method [28]. According to [35], the first, non-mineralized pegmatites display an age of 1024 ± 55 Ma ($^{40}Ar/^{39}Ar$ method on muscovite), and the mineralized pegmatites display ages between 986 ± 5.3 and 992 ± 5.4 Ma ($^{40}Ar/^{39}Ar$ method on muscovites, [35]), suggesting that the G4 granitic intrusions were emplaced between ca. 1020 and 990 Ma despite large uncertainties in muscovite dating. Then, these granites underwent three metasomatic phases: muscovitization, sericitization, and tourmalinization. The Punia–Aissa district (14) is located around two granitic massifs close to Punia. The mineralizations which consist of cassiterite and wolframite are concentrated in quartz veins and greisens. Columbite-group minerals and tapiolite are mentioned in [76] for this region. Additionally, rarely occurring Sn^{2+}-bearing phases such as foordite were reported from this area [61]. The Kailo-Kamilanga district (15) contains cassiterite and wolframite in quartz veins [76] included in chloritic shales belonging to the K2 unit.

These main mineralized sites across the Kivu Belt show that granitic intrusions (presumably G4) are not related to any specific stratigraphic units. All of those stratigraphic units are cross-cut by the G4 granites except, of course, the Neoproterozoic part of the Itombwe structure.

4.4. Columbite-Group Minerals in the KVB

In contrast to the mediatic opinions published in newspapers and social networks, the columbite-group mineral occurrences are not concentrated around the Masisi district in the North Kivu province. Instead, many columbite-group mineral-rich deposits have been described all along the KVB since the discovery of the first occurrences in 1931 in the Punia, Lowa, and Lukulu rivers [38]. Nevertheless, there are some mines with cassiterite and wolframite that do not contain columbite-group minerals (Kamituga, Luntukulu, Mumba, Punia–Aissa, Kailo, etc.). This review of the columbite-group mineralizations of the Kivu Belt confirms the results from the Gatumba mine (Rwanda) [4] and particularly the occurrence of columbite-group minerals in the first stage of thermal process (linked to metamorphism) including the remobilization of cassiterite in a second stage. Thus, columbite-group minerals are spatially located in the vicinity of the granitic bodies (for example in the Kama-Kampene district), but the close relationships between them have not yet been investigated. As this mineral is listed to provide "strategic" metal, it is very useful in new technologies, particularly for telecommunication and computer technologies, and there is currently a high demand in the world market. Consequently, the columbite-group minerals are prospected and mined at constantly growing rates. Prior to 1994, 7700 tons of columbite-group minerals have been extracted from the Kivu basement. The Kibaran belts and particularly the KVB contain significant amounts of the world reserves of columbite-group minerals [88] and thus will be a target for exploration in the near future. Further occurrences are in Australia, Brazil, and Canada [88,89].

5. Discussion

Beyond the review of G4 granitoid intrusions and related mineralizations, an important aim of this study is to show that the G4 granitic intrusions are not disconnected from the Kibaran Orogeny. At least two sedimentary units (K3 and K4), two metamorphic events (M3 and M4), and three tectonic events (D3-1, D3-2, and D3-3) occurred in the time interval between the G2 and G4 granitic intrusions. Consequently, the G4 granitoid intrusions should be considered as late tectonic rather than anorogenic. The first one could arise in a compressional tectonic regime, while the latter could have been formed in an extensive regime. Nevertheless, the origin of these granitic bodies is not well constrained. In its present state this study raises the following 10 questions:

(1) The first one deals with the duration of the Kibaran Orogeny. There is a general agreement to consider the beginning of the Kibaran Orogeny at around 1400 Ma, [17,18], but the assumptions about the end of this orogen varies between ca. 1250, 1200, 1000, and even 950 Ma [3,9,90]. By including the K3 and K4 units in the Kibaran Orogeny, a minimum age of ca. 1110 Ma should be accepted for the last tectonic events [11]. However, if the G4 granitic intrusions are interpreted as a late orogenic event, the duration of the Kibaran Orogeny has to be extended to ca. 960–950 Ma. If these granites are interpreted as post-tectonic, and therefore intruded during an extensive event giving way to the pan-African orogeny, the Kibaran Orogeny should have ended prior to ca. 1000 Ma.

(2) The G3 and G4 granites should be differentiated by geochemistry as well as by geochronology. In the field, both groups cannot easily be distinguished from each other. For example, the Kasika granite was dated at 986 ± 10 Ma in [17], but this intrusion cannot be responsible for the regional metamorphic imprint observed in a distance of more than 20 km away from this granite. Therefore, a concealed G2 or G3 batholith suggests a remobilization at around 986 Ma. Such confusing interpretations arise in many places such as around the Kasese and the Mt. Hango batholiths and could be clarified by further studies.

(3) There is also a debate on the age of the G4 intrusions. Although [17] proposes an age of 986 ± 10 Ma and [34] provides a similar age of 969 ± 8 Ma, it can also be considered that the whole intrusive events are not coeval at all. This becomes evident as some of them took place between ca. 1094 and 1020 Ma [35] depending on their location in the Kibaran Belt.

(4) In many places the G4 bodies show a concordance in the axial trend with the main structures (folds and faults) and with the G3 batholiths [36]. Very often, the emplacements of the G4 intrusions follow the pre-existing structures. In many cases, the G3 batholiths and the associated G4 intrusions occur in the center of anticlines [21,72,82] and could be related to a regional compressional event.

(5) Details of the mineralization process are still unclear. If the columbite-group minerals were crystallized during the first metasomatic stages close to the granitoid intrusions and the cassiterite was emplaced in a subsequent event, radiochronological data will be necessary to understand the period of the pegmatitic or quartz vein formation. Ages obtained from columbite–tantalite [91] do not have the same significance as those displayed by Ar/Ar dating on muscovite. More specific dating should be performed to separate the different tectono-thermal events that occurred between the emplacement of the G4 granitoids and the setting of the associated pegmatites and quartz veins.

(6) The relationships between the G2, G3, and G4 granitic occurrences should be clarified. Of course, the pegmatites and quartz veins related to the G4 granitoids do not exceed 5 km from the granitoid body. Accordingly, they cannot have induced a metamorphism with staurolite and garnet more than 20 km away from the G4 granitic intrusions. Thus, a map with the G3 and G4 metamorphic envelopes could shed light on this problem. In the field, G2, G3, and G4 are closely associated, and potential further remobilizations of G2 and G3 during anatexis should be taken into account. Many G4 intrusions could be linked to concealed G2 or G3 batholiths.

(7) The G4 granitic intrusions are scattered over the KVB but are not attached to a specific formation or terrane, implying that the presumed M5 tectono-thermal event (Figure 2) has affected the whole KVB and likely the entire Kibaride system. However, the G4 intrusions are largely dependent on previous structures.

(8) According to several studies, the mineral concentrations are related to the fusion of previous gneisses or granitic rocks enriched by metasomatic fluids during the several metamorphic remobilizations (M1, M2, M3, M4, and M5) but not to the sedimentary deposits which are generally poor in such primary elements. Mineralizations in black shales seem to be related to the trapping of metasomatic fluids rather than containing sediments. The "tin belts", "tungsten belts", and "coltan belts" hypotheses should not be taken in consideration at this stage of knowledge.

(9) Is there one or are there several geodynamic contexts for the different G4 intrusions? In other words, there may be several separated granitic occurrences linked to different geodynamic environments depending on the setting time.

(10) Why have these granitic events generated such large quantities of strategic mineralizations with respect to similar granitoid occurrences around the world? Potentially, this is the consequence of the many (here: four) metamorphic stages that were not recorded in other mineral provinces.

6. Conclusions

The Kivu Belt (KVB) as part of the Kibaran belts contains a large part of the world reserves of industrial minerals such as cassiterite, wolframite, and molybdenite. Furthermore, up to 70% of the world reserves of strategic minerals such as those of the columbite group are likely to be found in this region. Despite its economic interest, this region is little known in relation to its geodynamic evolution and its metallogeny. Owing to the political situation since the middle of the 20th century, the KVB has not been systematically studied. Therefore, the relationships between the geodynamic evolution of this belt and its subsequent mineralizations are little known. However, we consider mineralizations associated with the G4 granitic event as the final stage of four or five metasomatic remobilizations occurring during the different metamorphic events of the Kibaran orogen. We show that the specific tectono-thermal event linked to the G4 granite intrusions and the associated mineralizations had a long duration (between ca. 1020 and 970 or 950 Ma). This thermo-mineral event underwent several epigenetic events such as muscovitizsation, sericitization, tourmalinization, and silicification. Owing to the presence of new formations belonging to the last period of the Kibaran Orogeny, the interpretation of the thermo-tectonic events that triggered the mineralization processes could be expanded. Finally, this review raises many unsolved questions that are highly emphasized for future study within the next steps, taking into account the importance of strategic mineralization such as columbite-group minerals. We are expecting that, taking into account the worldwide interest in these minerals, further research programs will focus on the KVB.

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