Geological mapping and implications for Nb-Ta, Sn and W prospection in Rwanda

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Key-words. - geological mapping, ore deposits, ore prospection, Rwanda, sustainable development

Summary. - Rwanda contains many mineral commodities that are of major economic interest for the current high-tech industry worldwide. Especially the mining of tantalum-niobium, tungsten and tin were and are still important. Geological maps of the country are available, however, these are at a regional scale (1:100.000 scale) and as such not straightforward to use for focused exploration and mine planning. Therefore, a more detailed geological mapping focusing on exploration and exploitation has been carried out. Regional zonation patterns of the mineral occurrences have been established which could be used as exploration vectors. A lithological and structural control on the mineralization has been recognized and several minerals have been identified that could be used as pathfinders for ore exploration. In our opinion, the occurrence and scale of the Rwandan deposits favour small-scale industrial exploitation by junior mining companies.

Geologische kartering en implicatiesvoor Nb-Ta, Sn en W prospectie in Rwanda

Sleutelwoorden. - geologische kartering, ertsafzettingen, ertsprospectie, Rwanda, duurzame ontwikkeling

Samenvatting. - Rwanda bevat veel minerale grondstoffen die van groot economisch belang zijn voor de huidige hoogtechnologische industrie. Vooral de ontginning van tantalum-niobium, wolfraam en tin waren en zijn nog steeds zeer belangrijk. Geologische kaarten van het land zijn beschikbaar. Zij zijn echter op een regionale schaal (1:100.000 schaal) en niet echt geschikt voor doelgerichte exploratie en mijnplanning. Daarom werd een meer gedetailleerde geologische kartering uitgevoerd, die zich richt op de exploratie en exploitatie van de ertsen. Een regionaal zoneringspatroon van de ertsvoorkomens, dat kan gebruikt worden als exploratievector, werd uitgewerkt. Een structurele en lithologische controle op de ertsgenese werd herkend en verschillende gidsmineralen, die als ‘pathfinders’ voor de ertsexploratie kunnen gebruikt worden, werden geïdentificeerd. Gezien het karakteristieke voorkomen en de ruimtelijke verspreiding van de Rwandese ertsafzettingen, is naar onze mening een relatief kleinschalige industriële uitbating door junior mijnbouwbedrijven het meest aangewezen.

Cartographie géologique et implications pour la prospection de Nb-Ta, Sn and W en Rwanda

Mots clés. - cartographie géologique, gisements de minerai, développement durable, prospection de minerai, Rwanda

Résumé. - Le Rwanda contient de nombreuses ressources minérales qui sont d'un intérêt économique majeur pour l'industrie de haute technologie dans le monde entier. Surtout l'extraction de tantale-niobium, de tungstène et d'étain, ont été et sont encore importantes. Des cartes géologiques du pays sont disponibles, mais ils sont à l'échelle régionale (1:100.000 échelle) et pas vraiment utiles pour l'exploration et la planification minière. Par conséquent, une cartographie géologique plus détaillée, se concentrant sur l'exploration et l'exploitation, a été réalisée. Des zonations régionales des occurrences métalliques ont été établies, pouvant être utilisées comme vecteurs de l'exploration. Un contrôle lithologique et structural sur la minéralisation a été reconnu et plusieurs minéraux ont été identifiés qui pourraient être utilisés comme éclaireurs ('pathfinders') pour l'exploration du minerai. À notre avis, la présence et l'échelle des gisements rwandais est favorable à une exploitation industrielle à petite échelle par des petites sociétés minières.

1. Introduction

Rwanda contains many of the mineral commodities that are of major significance for the current high-tech industry worldwide. The main metals exploited in Rwanda historically and nowadays are tantalum-niobium, tin and tungsten. Tantalum, niobium and tungsten have been classified based on their economic importance and the supply risk as critical raw materials for the high-tech industry in the European Union (European Commission, 2014). In 2012, the production of tantalum-niobium in Rwanda was 600 t, which represents about 12% of the total world tantalum output (Yager, 2014). The tantalum import in the United States of America from Rwanda represented in 2012 about 24% of their total import. In 2011, the production of tin was 5,197 t and of tungsten 1,235 t, corresponding to 2% and 1% of the world production respectively (Yager, 2014).

The main driving emerging technologies for tantalum are micro-capacitors and medical technology (surgical and orthopaedic products). Tantalum is also essential for the production of high-performance alloys for aeronautical, nuclear and military applications. Other uses of tantalum are based on its high melting point, high density, oxidation resistance and optical properties, e.g. furnaces, thermowells, shaped charges and camera lenses . The criticality of tantalum is based on its supply risk due to an important part of its production in the

Democratic Republic of Congo (DRC), on the limited recycling potential and the difficulty to substitute with often a loss of performance when substituted. Niobium has its main economic applications in micro-capacitors and ferroniobium high-performance alloys, but also in the production of stainless steel, super conductors and super conducting magnets, and electroceramics. The lack of niobium production in the EU, the production monopoly of Brazil (92%) and Canada (7%), the lower percentage of recycled material (~20%) and higher costs with loss in performance when substituted, causes niobium's criticality for the EU (European Commission, 2014). Industrial application of tungsten is based on its highest melting point of all metals and its high density. It has been widely applied in the production of tungsten carbide abrasives and cutting tools, high-performance alloys, armaments, high-temperature filaments and nozzles, and in chemical application as lubricant and catalyst. Tungsten raw material supply is dominated by China, which also has the largest reserves of tungsten ore worldwide. Its criticality for the EU is mainly based on the important production in China, but also on the minor substitution possibilities (European Commission, 2014). A major part (~50%) of the tin is used in solder. The remaining part is largely used in tin plating (coatings), chemicals (organotin compounds), brass and bronze alloys, float glass and other applications such as in Li-ion batteries. The high demand of these metals for a high-tech economy requires a profound insight in the formation processes of the ores, state-of-the art exploration models and efficient exploitation and recovery strategies.

The aim of this study is to provide detailed geological mapping to obtain the required insight in the controlling factors on the occurrence of the ore deposits which can be applied in exploration and exploitation. In addition, exploration vectors and pathfinder minerals for exploration are determined from literature and own observations. Finally, these data are explained in a new metallogenic model proposed for the area studied. The latter is the Gatumba-Gitarama area in western Rwanda (Fig. 1).

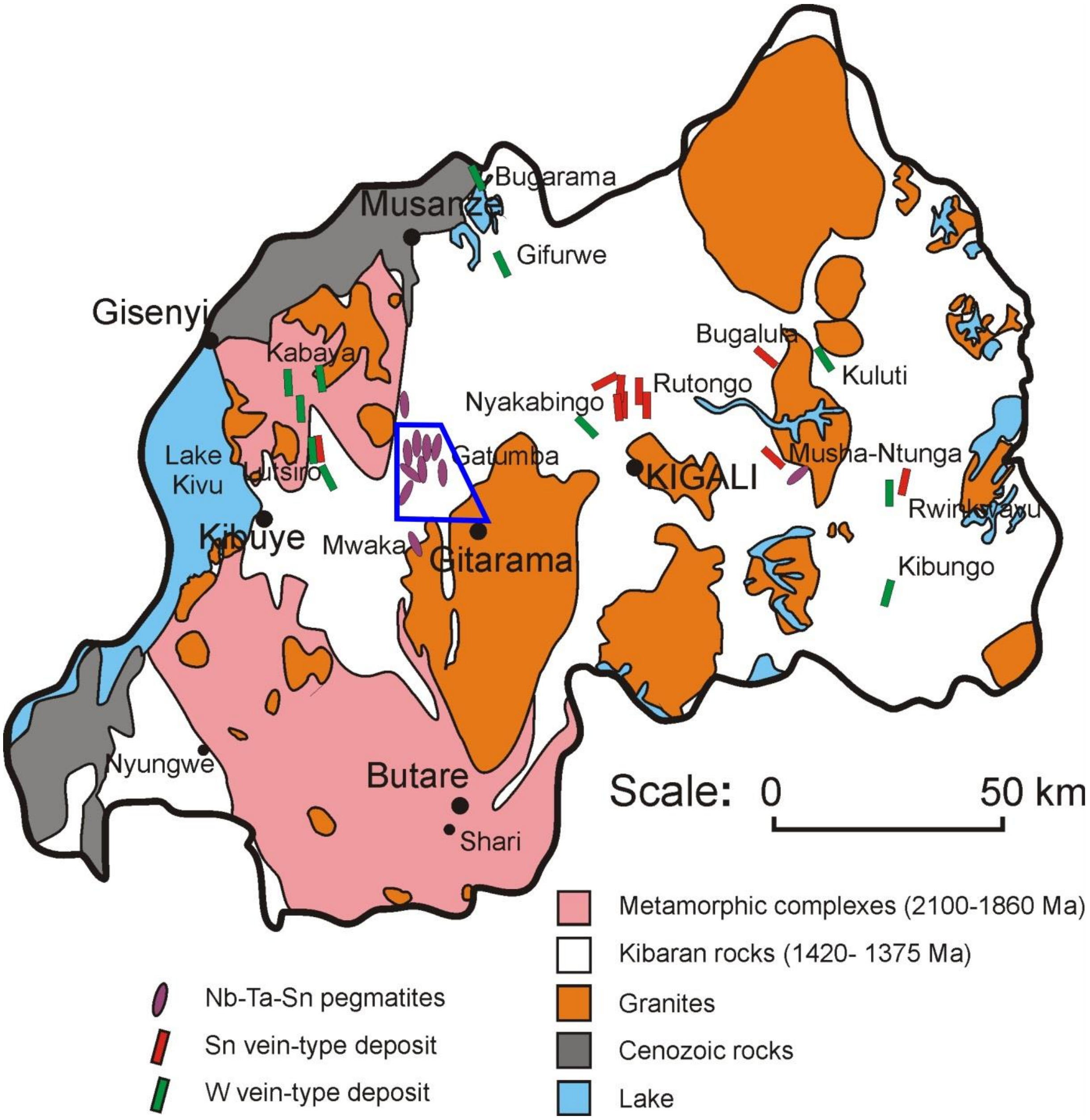

Fig. 1. – Simplified geological map with the main ore deposits in Rwanda (after Baudin et al., 1982; Fernandez-Alonso et al., 2007). The area studied is indicated in blue.

2. Mining history and current state

Starting with the first discoveries of ore deposits at the end of the 1920ies, mining of tin, niobium, tantalum, tungsten and gold took place in Rwanda. However, mining activities have decreased enormously since the mid-1980ies. This has resulted in the abandonment of many historic mining sites which have not been remediated (Figure 2).

Fig. 2. –Abandoned mining site at Biyoyo.

Currently, the main production comes from artisanal miners (Figure 3), which are often working for subcontractors that operate as intermediaries between the mine workers and mining companies (Perks, 2014). Only very recently in Rwanda, artisanal mining evolved at certain locations to a more semi-industrial, small-scale mining (ASM; Perks, 2014). The artisanal mining is mostly non-systematic due to a lack of detailed geological information. Moreover, metal recoveries have been estimated to be as low as 10 to 30%. This leads to a significant loss of mineral resources. More than 450 mine sites have recently been reported to be exploited. For early 2014, the Rwandan mining sector estimated their number of direct employees at approximately 34,000 (Cook & Mitchel, 2014). In total 170,000 Rwandans directly depend upon the mining sector or ~1.5% of the total population. The mining sector's contribution to the national gross domestic product is, however, only 1.3% (Yager, 2014). The government wants to increase this number to 5.3% in 2017/2018 (World Bank, 2014 in Cook & Mitchell, 2014).

Fig. 3. –Artisanal mining at Gatumba South.

The Gatumba area in Rwanda was and still is one of the main production areas of columbite-tantalite and cassiterite. Between 1929 and 1985, the Gatumba area has produced about 17,600 tonnes of mixed cassiterite and columbite-tantalite concentrate. This production mainly came from the exploitation of eluvial and alluvial deposits and from deeply weathered pegmatites. The reserves have been estimated at ~950 tonnes, with further resources between 2400 and 3400 tons of cassiterite (unpublished data Société Minière du Rwanda, Somirwa). The economic potential of the hard-rock pegmatites has not been evaluated (Dewaele et al., 2011).

3. Geological setting of the ores

The Karagwe-Ankole Belt (KAB) of Central Africa is composed of Meso- and Palaeoproterozoic metasedimentary and metavolcanic rocks (±1450 – 1000 Ma). The KAB forms a metallogenetic province with principally Nb-Ta, Sn and W commodities. The ores occur associated with peraluminous S-type granites that intruded the KAB around 986 ± 10 Ma (Tack et al., 2010). Niobium-tantalum and part of the tin are present in pegmatites that have a spatial relation with these S-type granites (Varlamoff, 1954; 1972). Tin is especially

concentrated in greisenized cupolas of the granites and greisenized zones of the pegmatites (Varlamoff, 1963). In the pegmatites or altered zones of the pegmatites, tungsten can only be found as an accessory ore mineral (Daltry & von Knorring, 1998). Tungsten, but also tin, occur in quartz veins in the metapelitic rocks intruded by the granitic rocks. Tungsten mineralized quartz veins are dominantly present in dark-coloured (often organic-rich) metapelites that alternate with more coarse-grained siliciclastic rocks, such as sandstones and quartzites. Tin-bearing quartz veins, however, dominate in massive sandstones and quartzites. This demonstrates the lithological control on the tungsten and tin mineralization in the rocks. Based on field work in the Democratic Republic of Congo and Rwanda, Varlamoff (1972) proposed a performant mineralogical zonation model of different pegmatite types around the granites. He was able to distinguish seven pegmatite types from the granites outward: biotite, biotite–tourmaline, biotite–tourmaline–muscovite, muscovite–tourmaline, muscovite, beryl and albitized pegmatites. The work of Varlamoff (1954; 1963; 1972) forms an excellent basis for further geological and ore-forming studies. For example, the Gitarama granite has been proposed as the parental granite for the pegmatites in the Gatumba area, but this, however, remains a matter of debate (Lehmann, et al., 2014). A recent geochemical study of biotite, muscovite, tourmaline and feldspar minerals (orthoclase, microcline, albite) allowed to simplify the 7-zone, mineralogical Varlamoff' (1954) zonation into one involving only four mineralogical zones (Hulsbosch et al., 2013). This zonation is further used in this work, both from a theoretical and practical point of view. Varlamoff (1954) classified tourmaline-containing pegmatites as separate regional zones. However, the observed compositional variation of tourmaline (Hulsbosch et al., 2013) and the spatial occurrence of tourmaline-containing pegmatites, being more erratic than postulated in the zonation of model Varlamoff (1954), demonstrate that tourmaline cannot be used as an indicator mineral for defining the regional pegmatite zonation (cf. Varlamoff, 1972). The four pegmatite zones used are biotite, biotite-muscovite (or two-mica), muscovite and mineralized pegmatites (Hulsbosch et al., 2013). Also the minerals present in the latter, which could be used as a pathfinder for the ores, are discussed below.
In order to determine the regional distribution of the pegmatites in the Gatumba-Gitarama area and other large- and small-scale geological characteristics, a detailed geological map of the area has been made based on existing maps (Gérards, 1965; Theunissen et al., 1991) and documents present in the archives of the Royal Museum for Central Africa (RMCA), and based on several field campaigns by the authors between 2007 and 2014. A first detailed map of the Gatumba area was published by Dewaele et al. (2011).The area mapped occurs between 1475 m and 2460 m asl and is characterized by an intense vegetation. Geological outcrops are abundant along road cuts of less than a meter to more than 10 m high (Figure 4) and in abandoned and active mines and quarries where stones are exploited. Seven sections have been mapped in an area of approximately 400 km^2.

Fig. 4. –Geological mapping along large and well exposed road sections (Gatikabisi-Gitarama transect).

4. Results

The existing geological data and the results of the field campaigns are integrated in an updated geological map (Figure 5). The Gitarama batholith consists of two main pluton types. The first is a fine-grained quartz, feldspar and biotite granite that shows a well-developed foliation (Figure 6A). Near Mushubati (~5 km west of Gitarama), this granite even shows a very fine mylonitic foliation. The second type is a leucogranite with centimetre- to decimetre-size quartz, feldspar crystals (Figure 6A). This leucogranite contains pods (up to metre-scale) of quartz-feldspar graphic intergrowths (Figure 6B). The leucogranite and pods clearly crosscut and thus post-date the foliated granite. In the Gitarama-Gatumba area, pegmatites can be observed inside granite batholiths as well as in the enclosing metasedimentary country rocks and are as such termed endo- and exo-pegmatites, respectively. Biotite pegmatites occur exclusively as endo-pegmatites, found in the cupola at the roof of the Gitarama batholith (Figure 6C). Biotite-muscovite and muscovite pegmatites can occur as endo-pegmatites, but are also very abundant in the metasedimentary rocks in the area studied.

From Gitarama town to the northwest (Figure 5), the zonation follows the typical pattern from biotite, two mica, muscovite and mineralized pegmatites (Figure 6D). A similar zonation has also been recognized along a northwest oriented transect south of Rutobwe and in eastern direction starting from the leucogranite near Gatikabisi. In all three cases, endo-pegmatites are associated with quartz-feldspar graphic textured granites.

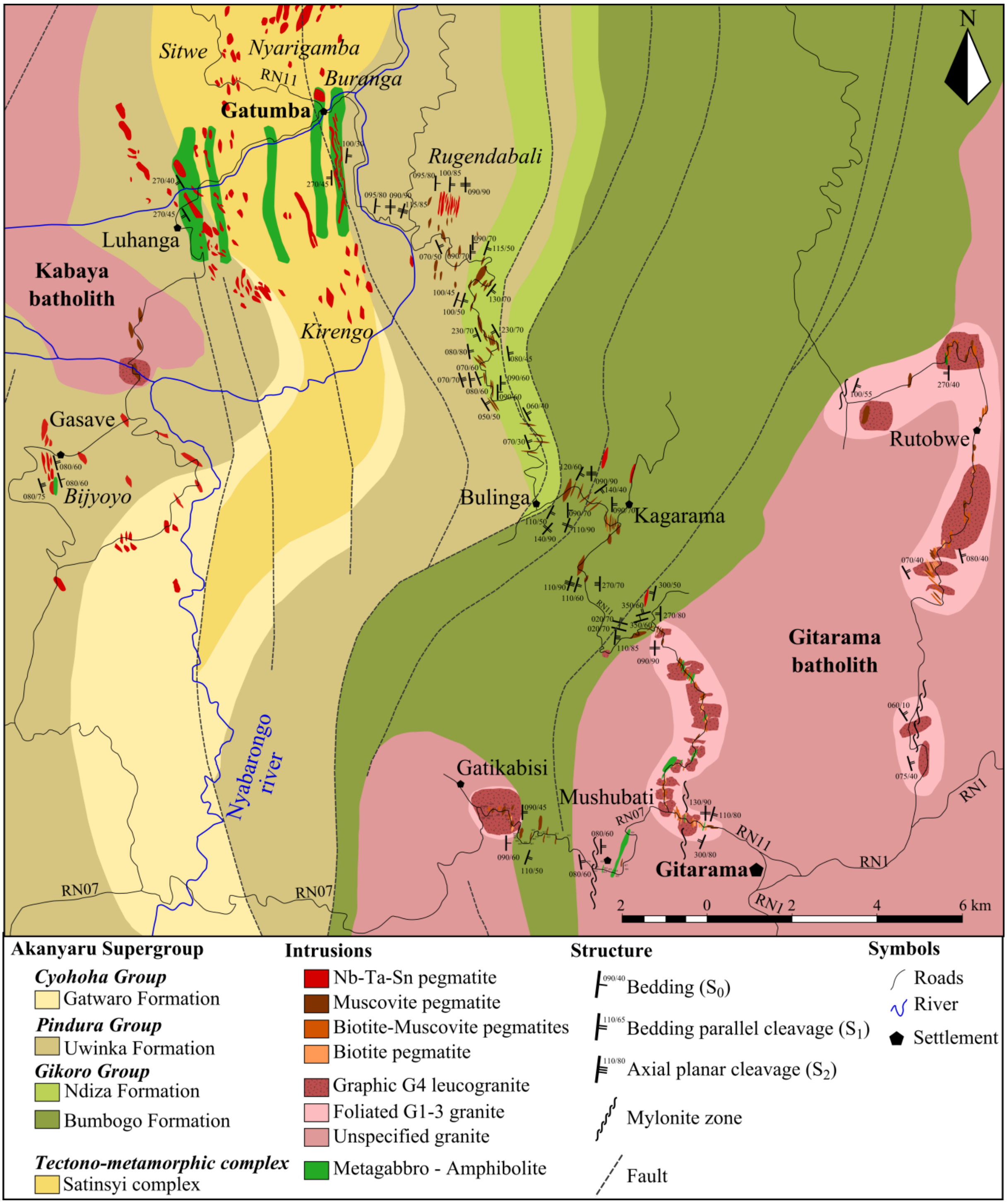

Fig. 5. –Geological map of the Gatumba-Gitarama area (geological map after Theunissen et al., 1991; Nb-Ta-Sn pegmatite outcrops based on Varlamoff, 1954 and Dewaele et al., 2011).

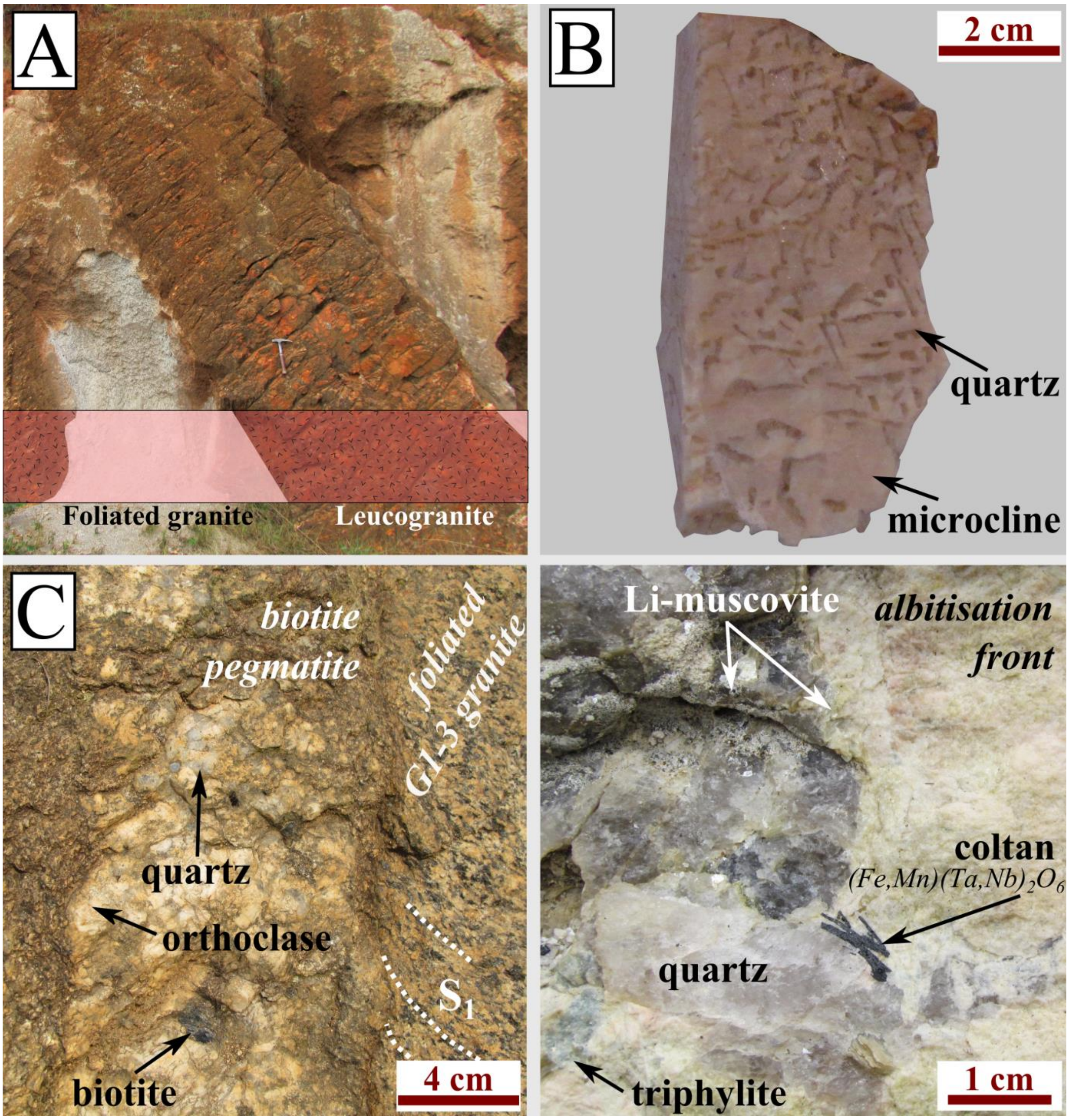

Fig. 6. - A. Fine-grained, foliatedG1-3 granite mainly consisting of quartz, feldspar and biotite being crosscut by a coarse-grained G4 leucogranite with quartz and feldspars. B. Sample of a quartz-feldspar granitic pod with a graphic texture.C. Endo-granitic biotite pegmatite intruded in foliated G1-3 granite. D. Detail of coltan ($[Fe,Mn][Ta,Nb]_2O_6$) mineralized pegmatite composed of a typical assemblage of Li-muscovite (muscovitization), quartz, secondary albite and phosphates (blue triphylite), which can be used as mineral pathfinders for Nb-Ta exploration.

Pegmatite intrusions have been mapped in the metasediments of the Bumbogo, Ndiza (Shyorongi) and Uwinka formations (Baudet et al., 1988; Fernandez-Alonso et al., 2012). The Bumbogo Formation is composed of an alternation of sandstones or quartzites and shales, with a dominance of thin layers of sandstones at the top. The Ndiza Formation is more coarse-grained and consists of thick layers of massive quartzites and metasiltstones and of regular alternations of sandstones/quartzites and shales. Finally, the Uwinka Formation is fine-grained and consists dominantly of metapelitic rocks. On a regional scale, the metasedimentary rocks studied form part of the normal dipping western flank of the regional Ndiza-Nduba anticline, and its secondary, superimposed synformal structure. The metasediments are consequently characterized by the development of tight, superimposed parasitic NS folds (Figure 7A). The eastern flank of the Ndiza syncline, only composed of Bumbogo metasediments, is overturned. Where the folds hinges are visible, a distinction can be made between a first bedding-parallel cleavage (S_1) sub-parallel to bedding (S_0), and a second axial-planar cleavage (S_2). Individual pegmatite dykes vary in thickness from a few millimetres up to a hectometre. They often intrude parallel to the S_1 foliation (Figure 8). Pegmatites are most abundant in formations that consist of an alternation of shales, metasiltstones and fine-grained quartzites (Bumbogo and Ndiza formations; Fig. 7B and C).

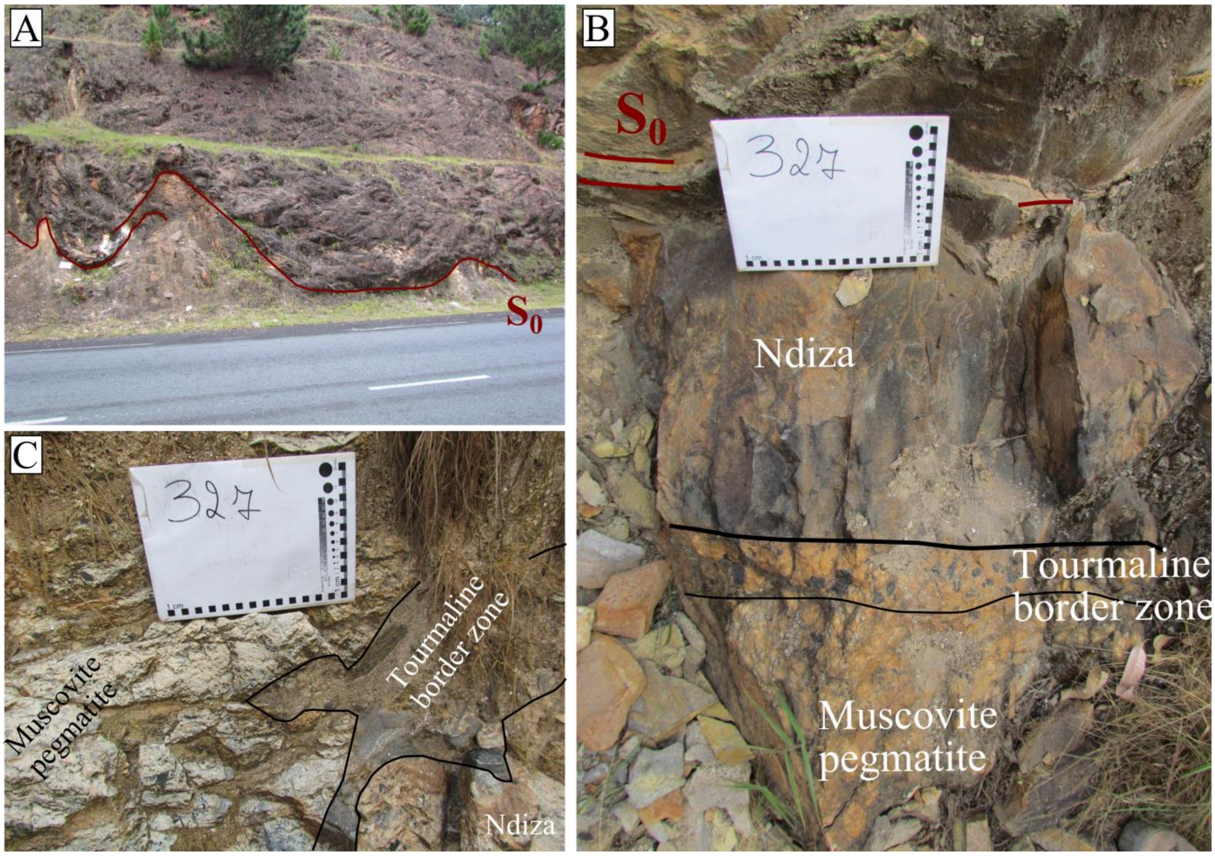

Fig. 7. - A. Metasedimentary rocks showing tight NS folds in metapelites of the Bumbogo Formation. B. Pegmatite parallel to the bedding planes in coarse-grained quartzite of the Ndiza Formation. C. Several metre-thick, massive pegmatite crosscutting the quartzites of the Ndiza Formation.

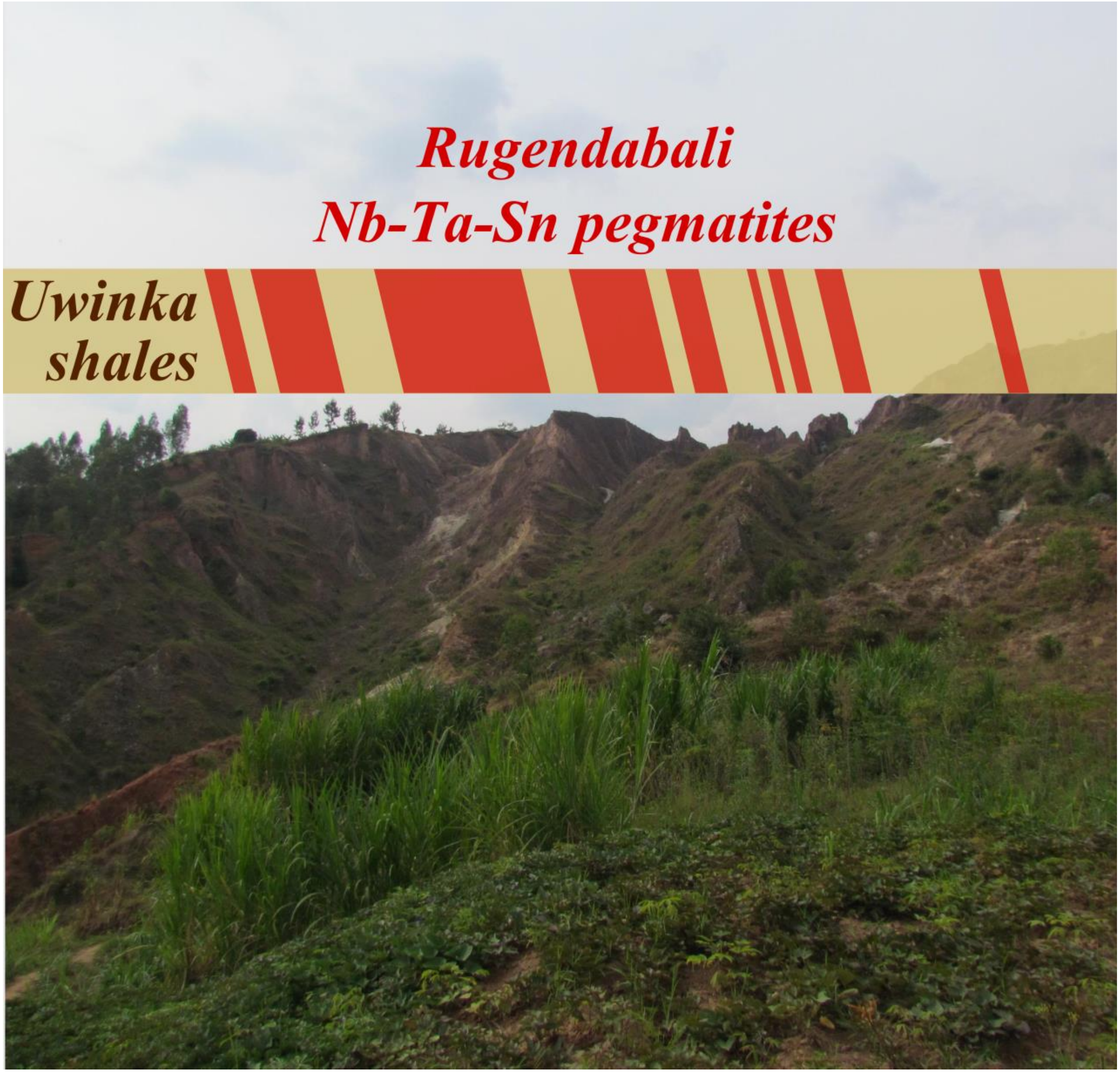

Fig. 8. –Intensely exploited mineralized pegmatites (in red) parallel to the foliation of the Uwinka shales (in brown) at Rugendabali.

The Uwinka Formation contains intensely foliated shales and fewer pegmatites. In more coarse-grained quartzites, such as the Ndiza Formation, pegmatites only intruded partly parallel to the anisotropy in the rocks, which is represented by bedding planes and existing fractures. Pegmatites that crosscut the quartzites are often several meters thick.

The mineralized pegmatites may show an internal mineralogical zonation, which can properly be observed at the Gatumba mine site and in the open pit of the Buranga pegmatite. This internal mineralogical build-up is a primary, magmatic feature expressed through the inward spatial evolution of grain size, mineral assemblage and rock fabric. It defines, from the rim inward to the centre of the pegmatite body, a border-, wall-, intermediate- and core zone. The border zone is a thin layer (mm to dm thick) that completely surrounds the pegmatite body in contact with its host rocks. The grain size is very fine-grained, the texture is granitic granular and the zone can contain tourmaline. The wall zone also totally surrounds the pegmatite body and the mineralogy is essentially the same as the border zone. Compared to the border zone, the wall zone of most pegmatites is thicker (cm to several m), coarser grained and marked by the anisotropic orientation of inwardly elongate and flaring crystals of feldspars and micas, but also tourmaline (i.e. unidirectional solidification texture; UST). Cassiterite has been observed in this wall zone. The intermediate zone is marked by an increase in crystal size. It is mineralogically dominated by one or two minerals, typically perthitic microcline, plagioclase, muscovite, spodumene or phosphates (triphylite, amblygonite, burangite etc.), all in association with massive quartz. Disseminated columbite-tantalite mineralization is present in this zone. The innermost core zone of the pegmatite body is predominantly monominerallic quartz. However, elbaite-quartz cores are observed in the Nyaligamba pegmatite and also quartz-poor cores, composed of albite and/or lepidolite have been observed in the area (Varlamoff, 1954). Secondary albite and subsequent muscovite replacement are superimposed on the primary assemblages. A volumetric important phase of cassiterite is associated with the muscovite replacement, or so-called greisen. The mineralized pegmatites are well-known for the presence of numerous characteristic minerals, several of which have even been described (historically) for the first time in the area studied. Characteristic minerals are spodumene, elbaiet, beryl, dm-sized Li-muscovite, lepidolite and phosphates (triphylite, gatumbaite, burangite, amblygonite, etc.). Other typical features are intense albitization and muscovitization (greisenization) of the pegmatites.

5. Interpretation

The main pegmatite zones recognized by Varlamoff (1954) have also been identified in this study. The delineation and thickness of the zones mapped differ, however, largely from the study of Varlamoff (1954). In addition, the general zonation pattern from the Gitarama batholith outwards to the Gatumba mine area is a simplification of the actual situation. In the field, multiple leucogranite feeder zones can be recognized, evolving outward to a zonation with biotite, two-mica and muscovite pegmatites. The regional zonation sequence is in fact a complex, superimposed distribution of individual pegmatite zonations each starting from a single leucogranite extrusion source. Based on the new map, a potentially large area with mineralized pegmatites has been recognized in the Bulinga-Kagarama area, ~8 km southwest of Rutobwe (Fig. 5).

The intensely foliated granite observed near Mushubati has been interpreted as a mylonitized granite by Klerkx et al. (1984) and Theunissen et al. (1996). The observation that the leucogranite and quartz-feldspar graphic granite crosscut this mylonitic foliation confirms the late-orogenic origin of these granites, which formerly were described as G4 granites (Tack et al., 2010). Both crosscutting granites can clearly be distinguished from the older fine-grained foliated biotite granites which were described as G1-3 granites (Tack et al., 2010). However, both types are present in what is called the Gitarama batholith. This contributes to the confusion which granite actually is the source for the pegmatites. Only detailed mapping combined with drilling will allow to distinguish the multitude of G4 granites present in the area.

The pegmatites are unfoliated and unfolded and thus post-date the deformation of the rocks, as already could be deduced from their association with the late-orogenic G4 granites. The typical occurrence of the pegmatites along preferential places of structural weakness, such as the bedding and cleavage planes and fractures, demonstrate the control that these discontinuities had on pegmatite emplacement. A likely hypothesis is that the latter discontinuities dilated during the intrusion of the G4 granites and the related uplift of the area. Very fined-grained rocks such as shales with intense cleavage development, are less suitable for the intrusion of pegmatites, but large granites and pegmatites may be present (e.g. at Biyoyo) due to fracturing during the intrusion of the host rock.

Typical alteration patterns, such as muscovitization and albitization, and mineral occurrences, such as Li-rich muscovites, spodumene and numerous rare phosphate minerals, occur with the mineralized pegmatites. Therefore, these alteration patterns and minerals can be used as pathfinders for the ores.

6. Discussion

Varlamoff (1954; 1972) was the first to define the typical pegmatite zonation around the granites. It is generally accepted that the rare-element pegmatites result from extremely differentiated magma (Webster et al., 1997; Alfonso & Melgarejo, 2008; Kontak & Kyser, 2009; London, 2005; Thomas et al., 2012). The change in mineralogical and chemical composition of the pegmatites is interpreted to originate from differentiation of a common source pluton. Successive periods of melt extraction produce the regional zonation towards more fractionated, distal pegmatites (Cerný, 1991). The origin and chemical evolution causing the zonation in the pegmatites of Rwanda has been investigated by Hulsbosch et al. (2013; 2014). Based on a geochemical study of the major, trace and rare earth element (REE) geochemistry of separate mineral phases (biotite, K-feldspar, plagioclase, muscovite and tourmaline), these authors interpreted the pegmatite zonation around the G4 granites as the result of a single fractionation path. The importance of the crystallization of minor minerals, such as monazite and apatite, on the trace element content is demonstrated by geochemical modelling of the REE patterns in combination with the Rayleigh fractionation model of the alkali metals (Hulsbosch et al., 2014). So, the geochemical analysis of separated mineral phases combined with the geochemical modelling form the scientific backbone for the exploration model.

The lithological and structural control (foliation) on the mineralization resulted in relatively small ore deposits. These small deposits require a selective mining. Due to the nature of the mineralization, specific enrichment procedures are required and thus an up-to-date industrial treatment of the ore. A recovery of 10 to 30% by artisanal mining results in a loss of the resources available, which should be avoided. In our opinion, small-scale industrial mining, likely by junior companies is ideal for the Nb-Ta-Sn-W exploitation in Rwanda. However, it is possible that such companies do not have the necessary scientific background in the regional geology. An appropriate and efficient vision on mining the ores should be based on a good geological knowledge. In addition, little attention has been paid to the remediation of the mining sites. For all countries, but especially for a mountainous country such as Rwanda where agricultural is of outmost importance, closure of the mining site and remediation has to be an essential part of the mining strategy.

7. Conclusion

The current study demonstrates the importance of detailed geological field studies, including mapping, to delineate prospective areas for Nb-Ta-Sn ore deposits, to specify exploitation strategies related to the geological structure and the occurrence of the ore. In addition, pathfinders for mineralized pegmatites are defined. This knowledge will also enable mining companies to define the exploitation and ore treatment procedures to be applied. Finally, it forms the basic knowledge for the necessary mine remediation after closure.

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