C. R. Geoscience 342 (2010) 778–785

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Petrology, geochemistry (Ore deposits)

Lithostratigraphic and structural controls of 'tsavorite' deposits at Lemshuku, Merelani area, Tanzania

Contrôles lithostratigraphique et structural des gisements de « tsavorite » de Lemshuku, région de Merelani, Tanzanie

Julien Feneyrol [a,*], Gaston Giuliani [a,b], Daniel Ohnenstetter [a], Elisabeth Le Goff [c], Elias P.J. Malisa [d], Mark Saul [e], Eric Saul [e], John Saul [f], Vincent Pardieu [g]

[a] *CRPG-CNRS, Nancy université, 15, rue Notre-Dame-des-Pauvres, 54501 Vandœuvre-lès-Nancy, France*
[b] *IRD-LMTG, 24, avenue Édouard-Belin, 31200 Toulouse, France*
[c] *BRGM, 3, avenue Claude-Guillemin, 45060 Orléans, France*
[d] *Department of Geology, University of Dar-es-Salaam, P.O. Box 35052, Dar-es-Salaam, Tanzania*
[e] *Swala Gem Traders, Sokoine Road, Arusha, Tanzania*
[f] *ORYX, 3, rue Bourdaloue, 75009 Paris, France*
[g] *GIA, 10th Floor, U-Chu-Liang Building, 968, Rama IV Road, Silom Bangrak, Bangkok, Thailand*

ARTICLE INFO

Article history:
Received 2 February 2010
Accepted after revision 10 July 2010
Available online 15 September 2010

Presented by Zdenek Johan

Keywords:
Tanzania
Lemshuku Mine
'Tsavorite'
Quartz vein
Lithostratigraphic and structural controls

Mots clés :
Tanzanie
Mine de Lemshuku
« Tsavorite »
Veine de quartz
Contrôles lithostratigraphique et structural

ABSTRACT

The first study of the Lemshuku 'tsavorite' mining district is presented. From bottom to top, the lithostratigraphic column corresponds to a metasedimentary sequence composed of quartzite, fine-grained graphitic gneiss, kyanite-graphite gneiss, biotite-almandine gneiss, metasomatized graphitic gneiss and dolomitic marble. 'Tsavorite' occurs in quartz veins and rarely as nodular concretions. Two factors control mineralization: (1) lithostratigraphy, with 'tsavorite' in association with pyrite and graphite confined to quartz veins within the metasomatized graphitic gneiss; and (2) structure, with the mineralized veins characteristically controlled by tight isoclinal folds associated with shearing.

RÉSUMÉ

Le district minier de Lemshuku, exploité pour ses gisements de « tsavorite », est décrit pour la première fois. La colonne lithostratigraphique de la séquence métasédimentaire est composée, de bas en haut, de quartzites, de gneiss graphiteux fins, de gneiss graphiteux à kyanite, de gneiss à biotite et almandin, de gneiss graphiteux métasomatisés et de marbres dolomitiques. La « tsavorite » est associée principalement à des veines de quartz, mais parfois à des nodules. La minéralisation à « tsavorite » est contrôlée par deux métallotectes : (1) lithostratigraphique car la « tsavorite » cristallise uniquement dans des veines de quartz, à pyrite et graphite contenues dans les gneiss graphiteux métasomatisés ; (2) structural, marqué par la formation de plis serrés et isoclinaux associés à du cisaillement, responsables de la formation et de la géométrie des veines minéralisées.

* Corresponding author.
E-mail address: feneyrol@crpg.cnrs-nancy.fr (J. Feneyrol).

1631-0713/$ – see front matter © 2010 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.crte.2010.06.003

1. Introduction

'Tsavorite'[1], the green vanadian variety of grossular $Ca_3(Al,V)_2(SiO_4)_3$, is a high value gemstone which combines the important gemmological properties of hardness, high dispersion, brilliance and transparency (Pardieu, 2005; Pardieu and Hughes, 2008). 'Tsavorite' is rare and economic deposits are known only in Kenya (Bridges, 1974; Pohl and Niedermayr, 1978; Suwa et al., 1996), Tanzania (Bridges, 1974; Malisa, 1987; McClure, 1999) and Madagascar (Mercier et al., 1997). It was first discovered in the late 1960s by C. Bridges (Bridges, 1974) in the Lemshuku area of northeastern Tanzania, with subsequent discoveries made in the region south of the Taita Hills of southeastern Kenya. Other 'tsavorite' occurrences have been described more recently in the Swat Valley, Pakistan (Hussain, 2005; Jackson, 1992), and in the Sør Rondane mountains of Antarctica (Osanai et al., 1990). All these worldwide vanadian grossular deposits formed during the Panafrican orogenesis, 730–530 Ma (Meert, 2003), and are hosted in vanadian graphitic gneisses belonging to metasedimentary formations of the Neoproterozoic Mozambique Belt (Walton and Marshall, 2007) (Fig. 1). The gemmological features of 'tsavorite' from Kenya and Tanzania have been characterized extensively (Kane et al., 1990; Muije et al., 1979; Schmetzer and Bank, 1982; Switzer, 1974) but the genetic model of the deposits has not been proposed.

The present contribution gives detailed mapping, field relationships, lithostratigraphy and structural data for the Lemshuku 'tsavorite' deposit, as well as setting out the main features of the mineralization. The importance of the lithostratigraphic and tectonic control is based on field evidence obtained during recent mining operations at Lemshuku. Guides for regional exploration are proposed.

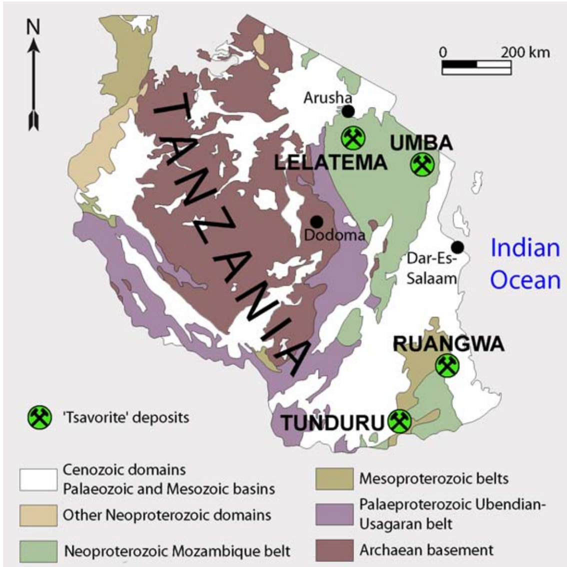

Fig. 1. Geological map of Tanzania (modified after Pinna et al. (2004)) and the 'tsavorite' deposits. The Merelani, Lemshuku and Namalulu mines are located in the Lelatema area.

Fig. 1. Carte géologique de la Tanzanie (modifiée d'après Pinna et al. (2004)) et des gisements de « tsavorite ». Les mines de Merelani, Lemshuku et Namalulu sont situées dans la région de Lelatema.

2. Geological setting

The Mozambique Belt (Holmes, 1951), a part of Gondwana, was formed by crustal segments deformed and metamorphosed during Neoproterozoic to Cambrian times (Meert et al., 1995). This north-south trending orogenic belt stretches from the Arabian-Nubian Shield to Madagascar (Muhongo, 1999; Stern, 1994), and occurs also in India (Kriegsman, 1995), Sri Lanka (Kriegsman, 1995), and eastern Antarctica (Jacobs et al., 1998). The Mozambique Belt resulted from a Late Neoproterozoic continental collision of 'Himalayan type' between eastern and western Gondwanaland following the closure of the 'Mozambique Ocean' (Shackleton, 1996). Most of the gems occur in deposits located in the north-south high-grade metamorphic Mozambique Belt (Le Goff, 2008), also called the 'Gemstone belt of East Africa' (Malisa and Muhongo, 1990). These include garnets ('tsavorite', rhodolite, pyrope-spessartine, i.e. 'color change garnet'), ruby, sapphire, vanadian zoisite 'tanzanite', tourmalines, kyanite, diopside, scapolite (Le Goff, 2008; Malisa, 1987) and several others as kornerupine and kyanite.

In Tanzania, the Neoproterozoic structures of the Mozambique Belt are characterized by thrusts and faults (Le Goff, 2008; Le Goff et al., 2010). Three main deformation events are recognized in the northeastern part of the country:

(a) the D_1 phase is characterized by the formation of recumbent and sheath folds. From studies of metasedimentary units in South-East Kenya (Taita Hills) which are correlated with those of Tanzania's Masai Steppe, this phase of deformation is estimated to have occurred at ca. 640 Ma (Hauzenberger et al., 2007) under granulitic conditions, $P = 10–12$ kbar, $T = 760–840$ °C (Hauzenberger et al., 2004). In the Eastern Granulites in north-east Tanzania orthogneisses and metapelites gave $P = 9.5–11$ kbar and $T = 810$ °C (Appel et al., 1998);

(b) the D_2 event consists of heterogeneous deformations most readily observed at tectonic contacts between the basement and overlying metasedimentary units (Le Goff, 2008; Le Goff et al., 2010); it took place under amphibolite facies conditions ($P = 5.4–6.7$ kbar, $T = 620–670$ °C) as estimated in metasedimentary units in South-East Kenya (Mercier et al., 1999).

(c) the D_3 event forms in the amphibolite facies and is characterized by large north-south trending folds such as the Lelatema Fold Belt (Le Goff, 2008; Le Goff et al., 2010) in the Merelani-Arusha region. This deformation is coeval with the formation at ca. 560 Ma (Hauzenberger et al., 2007) of NW-SE vertical and sinistral shear zones forming mylonites in amphibolite-greenschist

[1] The trade terms 'tsavorite' (vanadian grossular) and 'tanzanite' (vanadian zoisite) are not approved by the International Mineralogical Association.

facies and formation of the Merelani 'tanzanite' deposit and the Lossogonoi ruby deposit (Le Goff, 2008; Le Goff et al., 2010).

The 'tsavorite' and 'tanzanite' mineralizations in the Merelani, Lemshuku and Namalulu mining districts all occur in the Lelatema Fold Belt of the Eastern Granulites (Fritz et al., 2009) (Fig. 1). In the Merelani-Lemshuku areas, the metamorphic formations have been isoclinally and tightly folded, and the foliation is oriented NE-SW with dips commonly ranging from 30 to 60° towards the northwest (Muhongo et al., 1999). Several metamorphic facies have been distinguished in the two mining areas including garnet-kyanite/sillimanite-biotite gneiss, kyanite/sillimanite-graphite gneiss, biotite-graphite gneiss, calc-silicate rocks, quartz-feldspar gneiss, dolomitic marble, and pegmatites (Malisa, 1987; Muhongo et al., 1999). The rocks have been retrograded from granulite to greenschist facies (Muhongo et al., 1999) at 600 Ma (Malisa, 1987). P-T conditions for the Merelani gneisses have been estimated at 600–740 °C and 7.7–9.1 kbar (Malisa, 1987), and at 610–670 °C and 6–6.5 kbar (Muhongo et al., 1999).

The most prominent producing district is in the Merelani area, with the 'Tanzanite One' mine (Wilson et al., 2009) located in a metasedimentary unit on the western slope of the Lelatema Fold Belt in the upper part

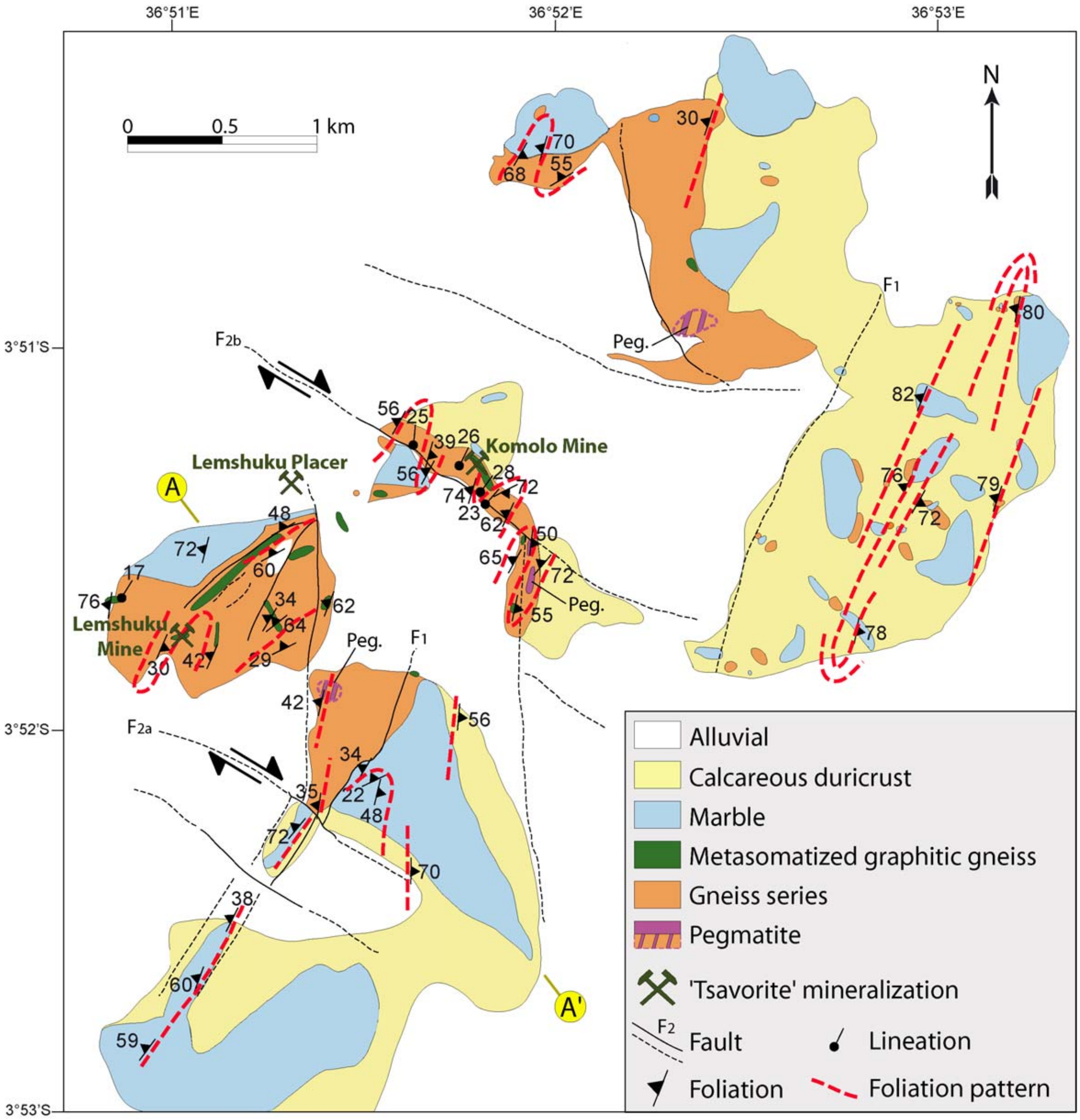

Fig. 2. Geological map of the Lemshuku area (see Fig. 1 for the location). Pegmatite thickness has been exaggerated to show their occurrences and orientation.

Fig. 2. Carte géologique de la zone de Lemshuku (voir Fig. 1 pour la localisation). L'épaisseur des pegmatites a été exagérée, afin de pouvoir les localiser sur la carte et d'indiquer leur orientation.

of the Neoproterozoic nappes. The mineralization is hosted by graphitic gneiss, and 'tanzanite' is commonly associated with 'tsavorite' in faulted and hydrothermally altered zones with boudinaged pegmatites and quartz veins concordant to the regional foliation (Malisa, 1987). The gems commonly occur in extensional veins in fold hinges (Malisa, 1987; Malisa and Muhongo, 1990). The second most important zone of economic mineralization is likewise hosted in graphitic schists on the western slope of the Lalatema Fold Belt and its extension, and includes the 'tsavorite' occurrences at Lemshuku and Namalulu.

3. The Lemshuku mining district

Two types of 'tsavorite' deposit are known in this area (Fig. 2):

(a) primary deposits formed by a polyphased metamorphic-hydrothermal system at the Komolo (3°51'36.25"S – 36°51'48.51"E) and Lemshuku mines (3°52'2.80"S – 36°50'59.70"E). At these localities, two subtypes of mineralization have been recognized:
   a1) 'Tsavorite'-bearing quartz veinlets and gashes which cross metasomatized vanadian graphitic gneiss. This is the main type of mineralization at Komolo and Lemshuku. According to miners, the Komolo mine was the most productive 'tsavorite' mine in the area during its heyday, 1992 to 1998.
   a2) 'Tsavorite'-bearing potato-like nodules, averaging 8 cm in diameter. To date, such nodules are very rare and have only been found in the wastes of the Komolo mine. They correspond to porphyroblasts with kelyphitic rims;

(b) placer deposit at Lemshuku (3°51'37.01"S – 36°51'15.94"E) formed down-slope of the primary occurrences as the hillside eroded away forming proximal accumulations in a detritic basin. The placer is composed of fragments and blocks of graphitic gneiss characterised by kyanite and green mica, with lengths ranging from a few centimetres to more than a metre and commonly consolidated by fine-grained particles. Lower parts of the placer contain larger and more angular fragments with smaller sizes and better-rounded materials found near the top. 'Tsavorite' occurs in angular and weakly rounded fragments up to 3 cm in size, as are other gemstones, including green tourmaline, kyanite and ruby.

4. Lithostratigraphic column

From bottom to top, the 100-metre Lemshuku lithostratigraphic column (Fig. 3) is composed of the following units:

(1) a reddish quartzite unit with concordant amphibolite layers, 2–5 m thick;
(2) white to grey fine-grained graphitic gneiss, about 7 m in total thickness, composed of medium-grained quartz, feldspars and disseminated graphite in 60 cm thick layers;

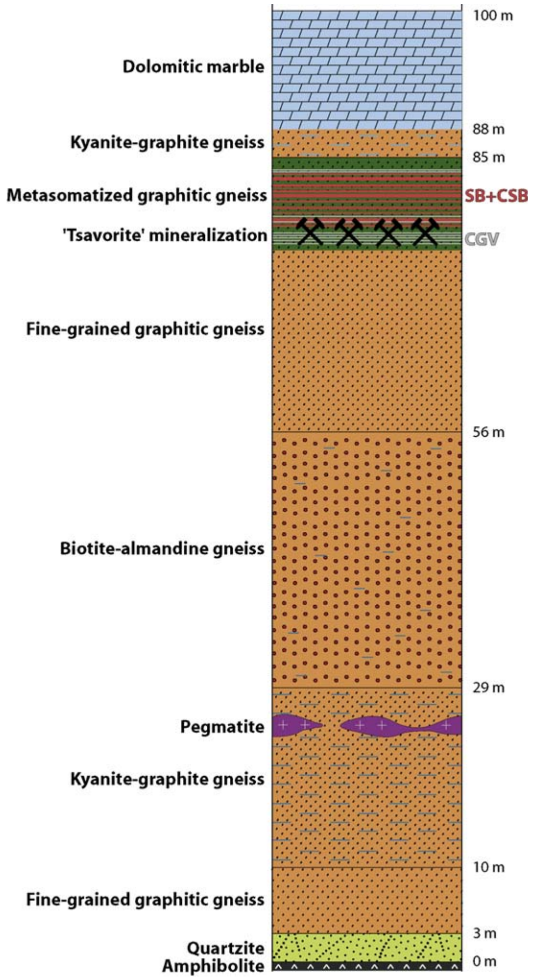

Fig. 3. Lithostratigraphic column of the Lemshuku area. CSB: calc-silicate bands; CGV: carbonate-gypsum veinlets; SB: siliceous bands.

Fig. 3. Colonne lithostratigraphique de la zone de Lemshuku. CSB : bandes calco-silicatées ; CGV : veinules à carbonates et gypse ; SB : bancs siliceux.

(3) kyanite-graphite gneiss, 20 m thick with kyanite crystals up to 3 cm in length, some of which are gem quality. Green mica is locally associated with the kyanite and both are found underlining the lineation at ca. N025° which follows the regional foliation (Fig. 4). Granitic pegmatites, up to 2 m wide, concordant with the regional foliation, were injected into the kyanite-graphite gneiss. The pegmatites are boudinaged and may host green Cr-bearing tourmaline;
(4) biotite-almandine gneiss, 27 m thick, with a composition of quartz + feldspars + biotite + disseminated almandine. Kyanite and graphite are rare;
(5) fine-grained graphitic gneiss hosting 'tsavorite' mineralization. The bottom and middle sections of this unit are formed by an assemblage ofquartz + feldspars + graphite + green micas + kyanite + hematite. The upper part of the unit, composed of fine-grained vanadian graphitic gneiss intercalated with siliceous and calc-silicate bands, is affected by major fluid–rock interactions concurrent with the formation of the

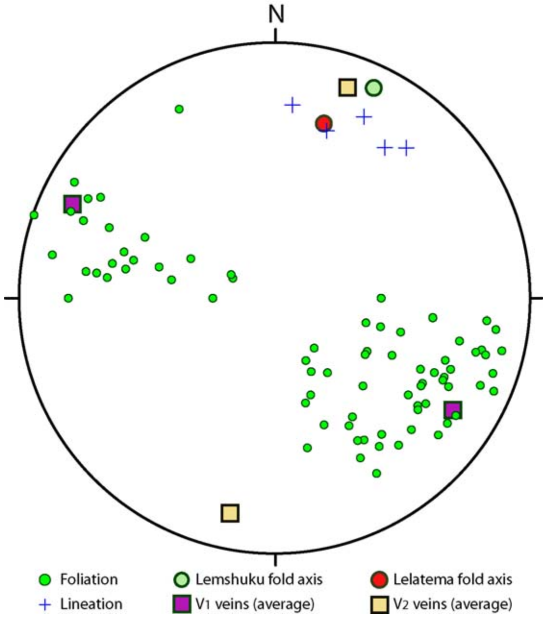

Fig. 4. Stereonet diagram (Schmidt diagram, lower hemisphere) showing the Lemshuku foliation variations which give the fold axis of the study area. Quartz vein families V_1 and V_2 are represented by their average poles.

Fig. 4. Diagramme stéréographique représentant les variations de mesure de foliation de la zone de Lemshuku, qui permettent de déterminer l'axe du pli. Les deux familles de veines de quartz V_1 et V_2 sont représentées par leurs pôles moyens (diagramme de Schmidt, hémisphère inférieur).

'tsavorite'-bearing quartz veinlets. This metasomatism is characterized by an intense silicification, graphitization and sulphuration with pyrite, chalcopyrite and sphalerite. 'Tsavorite' mineralization occurs in quartz veins, veinlets and gashes, where the grossular is associated with quartz, carbonate, pyrite, and graphite. These associated minerals are also disseminated in the graphitic gneiss in the proximity of the quartz veinlets. The 'tsavorite' crystals have a deep green colour, are 1–10 cm long and are larger than those found in the placer. Blue zoisite, i.e. 'tanzanite', may develop as rims around the grossular crystals. Carbonate-gypsum veinlets (CGV), a few millimeters to 2 cm in thickness, have been injected into the metasomatized gneiss, siliceous bands (SB), and calc-silicate bands (CSB);

(6) kyanite-graphite gneiss, 2 m thick, overlies the fine-grained metasomatized graphitic gneiss;

(7) the top of the lithostratigraphic column is made up of whitish coarse-grained dolomitic marble that formed the tops of many of the hills in the mining area.

The lithostratigraphic columns of the Merelani and Namalulu areas are similar to that at Lemshuku, though at Namalulu the dolomitic marble unit presents different variations in facies: with (from bottom to top) whitish anhydrite-bearing marble, whitish baryte-bearing marble, yellowish to orange marble. These marbles are overlaid by a greyish marble layer which contains concordant decametric lenses of gypsum-anhydrite-pyrite as well as 3 m long lenses of calcitic marble with green and gemmy diopside, scapolite (60% marialite), pyrite and graphite.

5. Structure

In the Lemshuku area, the stratification and the foliation planes are parallel as observed in the Merelani and Namalulu areas. This S_{0-1} plane strikes N031° with a dip ranging from 40 to 70° to the north-west or in places toward the south-east (Fig. 2 and Fig. 4). The NE-SW direction of S_{0-1} is concordant with the regional strike of the foliation reported for the Merelani area (Grainger, 1964; Macfarlane, 1965; Muhongo et al., 1999; Tanzanian Geological Survey, 2002). The stereonet in Fig. 4 shows that the Lemshuku area has been affected by a fold with an axial plane oriented N010° and dipping 30° to the east (fold axis is N025°–10°NNE). The axial plane of the regional Lelatema fold has a strike of N010° with a dip of 75° to the east (fold axis is N016°–30°NNE) (Grainger, 1964; Macfarlane, 1965). It is similar to the calculated strike for the Lemshuku fold. The foliation pattern shows that these folds are isoclinal and very tight (Fig. 2). Such features are typically observed in the mines where tight decimetre to multicentimetre isoclinal folds affect the fine-grained graphitic gneiss.

The regional faults have two sets of directions which are also found in the smaller Lemshuku area (Fig. 2): F_1 exhibits NNE-SSW (ca. N030°) orientations, and F_2 ENE-WSW (ca. N120°). F_1 are parallel to the foliation and are consistent with the Lelatema fault system which circumscribes the Lelatema Fold Belt on the western slope and downthrows to the west (Macfarlane, 1965). They are ductile faults and materialized contacts between metasedimentary and volcanoplutonic formations (Le Goff, 2008; Le Goff et al., 2010). F_2 have been observed on a more local scale in the northern part of the Lemshuku area and crosscut the Lemshuku fold. F_2 are interpreted as brittle down-throwing faults (Macfarlane, 1965). In the Lemshuku area, a number of field criteria indicates that F_2 faults have a shear component with a predominant dextral movement direction (Fig. 2): (1) F_{2a} shows a clear displacement of the marble unit in a dextral sense; (2) F_{2b} is characterized by the presence of drag-folded marble and gneiss indicating a dextral shearing; (3) sigmoidal quartz is present.

The 'tsavorite' deposit consists of veins and veinlets which present two main directions (Fig. 4): the first set V_1, parallel to the foliation S_{0-1}, is oriented N010 to N040° (average azimuth N029°) with a steep dip of 65 to 85° mainly to the northwest but also to the southeast; the second set V_2 strikes N090 to N130° (average azimuth N104°), similarly dipping 60 to 80°, mainly to the northeast but also to the southwest. V_1 and V_2 are fault-filled veins varying in thickness from a few millimetres to 20 cm, with an average of ca. 5 cm. These veins form parallel elongated and boudinaged lenses disposed *en echelon* within their host structures. 'Tsavorite' occurs in the lenses where V_1 and V_2 present their maximum thicknesses (ca. 20 cm), and in places where V_1 and V_2 cross and form a pocket vein. In the shear zones at the Komolo mine, it is observed that near their lateral terminations V_1 veins grade into isolated veinlets separated by barren wall rock. V_1 veins are also associated with major fluid circulation and interaction with the wall rocks. Individual quartz bands may be separated by slip surfaces coated by graphite and pyrite. Crack-seal textures are also recorded in V_1, indicating that repeated episodes of oblique extension of the shear fracture have alternated with episodes of slip along the fractures. Hydraulic breccias are observed and consist of angular metasomatized wall-rock fragments cemented by an hydrothermal matrix (graphite-pyrite-quartz), showing no evidence of rotation during the implosion.

6. Discussion and conclusion

'Tsavorite' mineralization in the Lelatema Fold Belt is hosted in a tightly and isoclinally folded Neoproterozoic metasedimentary sequence located on the Eastern Granulites cover of the Mozambique Belt (Fritz et al., 2009). The economic occurrences of Merelani, Lemshuku and Namalulu are restricted to the western flank of the high amplitude Lelatema anticlinal fold. Lithostratigraphic and structural controls are both important factors for the occurrence of 'tsavorite' deposits.

6.1. Lithostratigraphic control

The metamorphosed and deformed platformal sediments hosting these 'tsavorite' deposits are 100 m thick at most. In the Lemshuku and Namalulu mining districts, the 'tsavorite' mineralization is located at the contact between the fine-grained vanadian graphitic gneiss and the marble unit. Graphitic gneiss and marble contrast with one another in their competency and chemistry and at Lemshuku, the 'tsavorite' mineralization is located in the transition zone between the two. The ore zone is composed of metasomatized graphitic gneiss and quartz veins-bearing 'tsavorite'-carbonate-anhydrite and (gypsum)-graphite-sulphides veins. The metasomatic rocks are the result of fluid-flow alteration and are marked by epigenetic growth of pyrite, V-pyrrhotite, sphalerite, V-micas, quartz and carbonates. Originally, the host-rocks were black shales (Giuliani et al., 2008) and the V-Cr precursor minerals were consumed during the prograde metamorphism, with resultant vanadium and chromium contents of the graphitic gneiss of 797 and 213 ppm, respectively. During the metasomatic event, these elements were mobilized by pervasive fluids related to the formation of quartz veins and concentrated in the hydrothermal phases. The graphitic gneisses provided vanadium, chromium, alumina and silica, and the intercalations of marble and sulphates gave calcium necessary for the formation of the vanadian grossular. All these elements were proximal and the formation of the 'tsavorite' is therefore controlled by the lithology and fluid–rock interaction.

6.2. Mineralization versus structure

At the Lemshuku mine, 'tsavorite' is contained in fault-filled veins related to the main shear-zone. Such veins are observed in brittle-ductile to ductile shear zones (Robert and Poulsen, 2001). The conformity of strike of the lineation, foliation, and V_1 fault-filled veins means that folding, shearing and vein-growth were coeval. Crack-seal bands of cleaved wall-rock, pyritization on the foliation planes of the tight decimetric isoclinal folds, and the extensional veins which formed in the hinge of the folds (saddle reef structure (Cox et al., 1995; Sibson and Scott, 1998)) are indicative of vein formation and hydrothermal-metasomatic fluid circulation during regional metamorphism. Such structures are also described in the Merelani mines. In the ore zones, the quartz veins are relatively narrow or/and disappear on fold limbs but are thicker on the crests of anticlines (Malisa and Muhongo, 1990). They are found for over a kilometre along strike and up to 300 m down dip from the surface in the 'Tanzanite One' mine (Wilson et al., 2009).

At the Lemshuku mine, fluid pressure and stress constraints caused by differences in competency of lithologies, tensile strength, and internal friction (Sibson and Scott, 1998) have opened extensional fractures generating fault-fracture meshes which produced the V_2 veins. Fluid overpressure characterized by the presence of hydraulic breccias (Sibson et al., 1988) testifies to repeated episodes of hydraulic fracturation, fluid circulation and metasomatic alteration.

In the Lemshuku area, the style of deformation of the metasediments is characterized by tight faulted folds parallel to the bedding. This has led to shearing which has increased the stratigraphic thickness of the units (Fig. 5).

6.3. Comparisons with other worldwide 'tsavorite' deposits

The association of graphitic gneiss and marble for the host rocks of 'tsavorite' was first mentioned by Bridges in North-East Tanzania and in South-East Kenya (Bridges, 1974). This association may characterize 'tsavorite' deposits throughout the Mozambique Belt (Walton and Marshall, 2007). In general, the marble unit is located adjacent to the graphitic gneiss or metapelites as in the case in

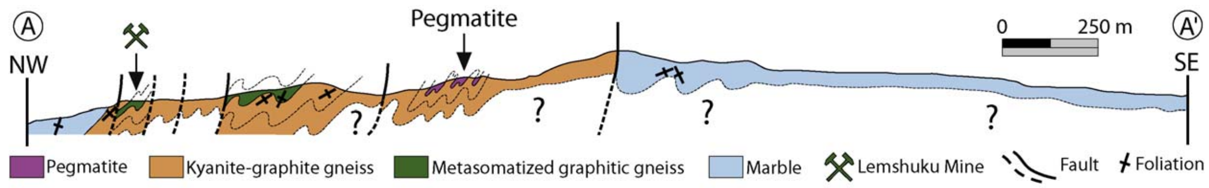

Fig. 5. Cross-section of the Lemshuku area (see Fig. 2 for the location). The vertical scale has been exaggerated for better visualisation.

Fig. 5. Coupe géologique de la zone de Lemshuku (voir Fig. 2 pour la localisation). L'échelle verticale a été exagérée, afin d'obtenir une meilleure représentation des structures.

northern Tanzania, in Madagascar (within the Precambrian granulitic Vohibory Group (Mercier et al., 1997)), and in Pakistan (within the Pacha Formation of the Early Proterozoic Manglaur Group which consists of pelite-psammite, quartzite and minor marble, calc-silicate rock, graphitic schist and amphibolite (Hussain, 2005)). In the Voi region of Kenya, the 'tsavorite' is restricted to the upper part of the Lualenyi Member of the Mgama-Mindi Formation (Pohl and Niedermayr, 1978). This formation is composed of orthogneiss, paragneiss, mica schist, kyanite schist, graphite schist, quartzite, calc-silicate rock and marble (Walton and Marshall, 2007). The 'tsavorite' is found in graphitic gneiss interbedded within calcareous nodules or immediately adjacent to marble (Pohl and Niedermayr, 1978; Walton and Marshall, 2007). In the Baragoi region, north of Nairobi, the marbles occur in calcareous seams disseminated in graphitic schist (Key and Hill, 1989). In the Menipa mountain in Antarctica, the 'tsavorite' is hosted by graphite-bearing calcareous meta-pelites (Osanai et al., 1990).

Two types of mineralization are recognized in the Lemshuku area:

(1) nodular concretions only known from the tailings of the Komolo mine though commonly observed *in situ* in Kenya (Suwa et al., 1996) and Antarctica (Osanai et al., 1990). In Kenya, the nodules form a mineralized horizon within calc-silicate graphite gneiss (Suwa et al., 1996) or they are found in a zone within graphitic gneiss adjacent to a pegmatite wall (Pohl and Niedermayr, 1978). The nodules are commonly rimmed by a narrow green kelyphitic assemblage of scapolite (meionite), vanadian zoisite ('tanzanite'), quartz and spinel.
(2) 'tsavorite'-bearing quartz veins, as observed at the Lemshuku and Namalulu mines are also described in Pakistan (Hussain, 2005) and Merelani as pockets filled by quartz, 'tanzanite', 'tsavorite', pyrite and graphite (Malisa, 1987).

6.4. Genesis of the Lemshuku and Namalulu deposits

Several stages leading up to the formation of the 'tsavorite' deposits in the Lemshuku-Namalulu mining districts can now be identified:

(1) sedimentation of the protoliths in a continental platformal series with evaporitic deposition such as proposed (Suwa et al., 1996) for the origin of scapolite in the Lualenyi deposit in Kenya;
(2) during the Pan-African orogenesis the sediments were metamorphosed to the amphibolite facies, transforming detrital arenites into quartzites, shales rich in organic matter into vanadian graphitic schist, and carbonates into marble (see lithostratigraphic column in Fig. 3). The association of anhydrite (and gypsum) with 'tsavorite' in quartz veins in Lemshuku, the presence of lenses of gypsum and anhydrite, graphite, and scapolite in carbonate lenses within the Namalulu marbles indicate the deposition of evaporites (salts and sulphates) in an euxenic carbonate platform environment, probably isolated from the open sea (Garnier et al., 2008);
(3) deformation of the metasedimentary platform units during the formation of the high amplitude Lelatema fold belt with shearing, formation of fault-filled veins, and metasomatism in the upper part of the graphite-rich gneissic unit.

6.5. Prospecting implications

The new information on the lithostratigraphy and structure of the Lemshuku and Namalulu 'tsavorite' deposits provides guidelines for prospecting on the western flank of the Lelatema Fold Belt. These include the need to locate: (1) fine-grained graphitic gneiss overlain by marbles containing lenses of meta-evaporites; and (2) structural details within the regional Lelatema anticline corresponding to second and third-order anticlines and synclines in a saddle reef model (Windh, 1995), along with shear zones associated with the deformation. Preliminary remote sensing studies of the Lelatema Fold Belt should provide a sufficiently detailed structural map; the focus can then change to standard geological mapping and prospecting in the field. Useful index minerals and rocks include: (1) gypsum-anhydrite in fractures within graphitic gneiss or as lenses in marble; (2) scapolite in marble or graphitic gneiss; (3) soils with the sulphate mineral jarosite which is formed by the oxidation of pyrite in arid areas, and is known from Merelani (Malisa, 1987).

Acknowledgements

The authors (JF, GG, DO) thank Swala Gem Traders of Arusha, Tanzania, for logistical support on the field. D. Gasquet, an anonymous reviewer, and F. Chabaux from the Editorial Board are thanked for the corrections and suggestions of the manuscript. This research was supported by grants from the IRD, CRPG/CNRS, MRT no. 410 and the project AO2009 INSU- Sciences de la Terre. This study is part of JF's PhD realized at the INPL-RP2E Doctoral School, Nancy, France.

References

Appel, P., Möller, A., Schenk, V., 1998. High-pressure granulite facies metamorphism in the Pan-African belt of eastern Tanzania: P-T-t evidence against granulite formation by continent collision. J. Metamorph. Geol. 16 (4), 491–509.
Bridges, C.R., 1974. Green grossularite garnets ('tsavorites') in East Africa. Gems Gemology 14, 290–295.
Cox, S.F., Sun, S.S., Etheridge, M.A., Wall, V.J., Potter, T.F., 1995. Structural and geochemical controls on the development of turbidite-hosted gold quartz vein deposits, Wattle Gully mine, central Victoria. Aust Econ. Geol. 90 (6), 1722–1746.
Fritz, H., Tenczer, V., Hauzenberger, C., Wallbrecher, E., Muhongo, S., 2009. Hot granulite nappes – Tectonic styles and thermal evolution of the Proterozoic granulite belts in East Africa. Tectonophysics 477 (3–4), 160–173.
Garnier, V., Giuliani, G., Ohnenstetter, D., Fallick, A.E., Dubessy, J., Banks, D., Vinh, H.Q., Lhomme, T., Maluski, H., Pêcher, A., Bakhsh, K.A., Long, P.V., Trinh, P.T., Schwarz, D., 2008. Marble-hosted ruby deposits from Central and Southeast Asia: towards a new genetic model. Ore Geol. Rev. 34 (1–2), 169–191.
Giuliani, G., Ohnenstetter, D., Palhol, F., Feneyrol, J., Boutroy, E., De Boissezon, H., Lhomme, T., 2008. Karelianite and vanadian phlogopite

from the Merelani Hills gem zoisite deposits, Tanzania. Can. Mineral. 46 (5), 1183–1194.

Grainger, D.J., 1964, Geological map at 1:125,000, Shambarai, no. 71, Tanzanian Geological Survey.

Hauzenberger, C.A., Bauernhofer, A.H., Hoinkes, G., Wallbrecher, E., Mathu, E.M., 2004. Pan-African high pressure granulites from SE-Kenya: petrological and geothermobarometric evidence for a polycyclic evolution in the Mozambique Belt. J. Afr. Earth Sci. 40 (5), 245–268.

Hauzenberger, C.A., Sommer, H., Fritz, H., Bauerhofer, A., Kröner, A., Hoinkes, G., Wallbrecher, E., Thöni, M., 2007. SHRIMP U-Pb zircon and Sm-Nd garnet ages from the granulite-facies basement of SE Kenya: Evidence for Neoproterozoic polycyclic assembly of the Mozambique Belt. J. Geol. Soc. Lond. 164 (1), 189–201.

Holmes, A., 1951. The sequence of Precambrian orogenic belts in South and central Africa. In: Sandford, K.S., Bondel, F. (Eds.), 18th International Geological Congress. 14, pp. 254–269.

Hussain, S., Geology of the Indus Suture Zone and high Himalayan crystalline block west of Besham syntaxis and study of some associated minerals, unpublished PhD, University of the Punjab, Lahore (2005) 510 p.

Jackson, B., 1992. Vanadian grossular garnet (tsavorite) from Pakistan. J. Gemmol. 23 (2), 67–70.

Jacobs, J., Fanning, C.M., Henjes-Kunst, F., Olesch, M., Paech, H.J., 1998. Continuation of the Mozambique Belt into East Antarctica: Grenville-age metamorphism and polyphase Pan-African high-grade events in central Dronning Maud Land. J. Geol. 106 (4), 385–406.

Kane, R.E., Kampf, A.R., Krupp, H., 1990. Well-formed tsavorite gem crystals from Tanzania. Gems Gemology 26 (2), 142–148.

Key, R.M., Hill, P.G., 1989. Further evidence for the controls on the growth of vanadium grossular garnets in Kenya. J. Gemmol. 21, 412–422.

Kriegsman, L.M., 1995. The Pan-African event in East Antarctica: a view from Sri Lanka and the Mozambique Belt. Precambrian Res. 75 (3–4), 263–277.

Le Goff, E., Deschamps, Y., Guerrot,C., Cocherie, A., Ketto, D. Contexte géologique des minéralisations de la Ruby Belt tanzanienne, In: Conférence RST, Nancy, France, 21–24 April, Abstracts volume (2008) p. 133.

Le Goff, E., Deschamps, Y., Guerrot, C., 2010. Tectonic implications of new single zircon Pb-Pb evaporation data in the Lossogonoi and Longido ruby-districts, Mozambican metamorphic Belt of north-eastern Tanzania. C. R. Geoscience 342, 36–45.

Macfarlane, A., 1965. Geological map at 1:125,000, Arusha Chini, no. 72, Tanzanian Geological Survey.

Malisa, E., 1987. Geology of the tanzanite gemstone deposits in the Lelatema area, NE Tanzania, Annales - Academiae Scientiarum Fennicae, Series A III: Geologica- Geographica. 146 p.

Malisa, E., Muhongo, S., 1990. Tectonic setting of gemstone mineralization in the Proterozoic metamorphic terrane of the Mozambique Belt in Tanzania. Precambrian Res. 46 (1–2), 167–176.

McClure, S., 1999. A new source for tsavorite. Gems Gemology 35 (2), 151–152.

Meert, J.G., 2003. A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics 362 (1–4), 1–40.

Meert, J.G., Van Der Voo, R., Ayub, S., 1995. Paleomagnetic investigation of the Neoproterozoic Gagwe lavas and Mbozi complex, Tanzania and the assembly of Gondwana. Precambrian Res. 74 (4), 225–244.

Mercier, A., Moine, B., Delorme, J., Rakotondrazafy, M.A.F., 1997. A note on a new occurrence of vanadian grossular garnet from Madagascar. J. Gemmol. 25 (6), 391–393.

Mercier, A., Debat, P., Saul, J.M., 1999. Exotic origin of the ruby deposits of the Mangari area in SE Kenya. Ore Geol. Rev. 14 (2), 83–104.

Muhongo, S., 1999. Anatomy of the Mozambique Belt of eastern and southern Africa: Evidence from Tanzania. Gondwana Res. 2 (3), 369–375.

Muhongo, S., Tuisku, P., Mtoni, Y., 1999. Pan-African pressure-temperature evolution of the Merelani area in the Mozambique Belt in northeast Tanzania. J. Afr. Earth Sci. 29 (2), 353–365.

Muije, P., Muije, C.S., Muije, L.E., 1979. Colorless and Green Grossularite From Tanzania. Gems Gemology 16, 162–173.

Osanai, Y., Ueno, T., Tsuchiya, N., Takahashi, Y., Tainosho, Y., Shiraishi, K., 1990. Finding of vanadium-bearing garnet from the Sør Rondane Mountains, East Antarctica. Antarctic Rec. (Japan) 34, 279–291.

Pardieu, V., 2005. Tsavorite : une pierre africaine. Rev. Gemmol. 154, 8–11.

Pardieu, V., Hughes, R.W., 2008. Tsavorite - the untamed beauty. InColor Fall-Winter 12–20.

Pinna, P., Muhongo, S., Le Goff, E., Mcharo, B.A., Deschamps, Y., Milesi, J.P., Vinauger, P., Ralay, F., 2004. Geology and mineral map of Tanzania, scale 1:2,000,000, Geol. Surv. France.

Pohl, W., Niedermayr, G., 1978. Geology of the Mwatate Quadrangle and the vanadium grossularite deposits of the area. Geol. Surv. Kenya 101, 55.

Robert, F., Poulsen, K.H., 2001. Vein formation and deformation in greenstone gold deposits. Rev. Econ. Geol. 14, 111–155.

Schmetzer, K., Bank, H., 1982. Gelbgrüner Grossular aus Ostafrika. Z. Dt. Gemmol. Ges. 31, 80–84.

Shackleton, R.M., 1996. The final collision zone between East and West Gondwana: where is it? J. Afr. Earth Sci. 23 (3), 271–287.

Sibson, R.H., Robert, F., Poulsen, K.H., 1988. High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits. Geology 16, 653–659.

Sibson, R.H, Scott, J., 1998. Stress/fault controls on the containment and release of overpressured fluids: examples from gold-quartz vein systems in Juneau, Alaska; Victoria, Australia and Otago, New Zealand. Ore Geol. Rev. 13 (1–5), 293–306.

Stern, R.J., 1994. Arc assembly and continental collision in the Neoproterozoic East African Orogen: implications for the consolidation of Gondwanaland. Annu. Rev. Earth Pl. Sci. 22, 319–351.

Suwa, K., Suzuki, K., Agata, T., 1996. Vanadium grossular from the Mozambique metamorphic rocks, south Kenya. J. South Asian Earth Sci. 14 (3–4), 299–308.

Switzer, G.S., 1974. Composition of Green Garnet from Tanzania and Kenya. Gems Gemology 14, 296–297.

Tanzanian Geological Survey, Geological map at 1:125,000, Naberera, no. 87.

Walton, L., Marshall, D., 2007. Tanzanite and tsavorite. Mineral. Assoc. Can., Short Course 37, 153–160.

Wilson, W.E., Saul, J.M., Pardieu, V., Hughes, R.W., 2009. The Merelani tanzanite mines. Mineral. Rec. 40 (5), 347–408.

Windh, J., 1995. Saddle reef and related gold mineralization, Hill End gold field, Australia: evolution of an auriferous vein system during progressive deformation. Econ. Geol. 90 (6), 1764–1775.