

PETROLOGY AND LITHOGEOCHEMISTRY OF THE MINERALIZED TANZANITE-GROSSULAR BEARING ROCKS IN THE MERELANI-LELATEMA AREA, NORTHEASTERN TANZANIA.

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ABSTRACT

The Merelani-Lelatema area, which is occupied by late Proterozoic metasedimentary rocks, lies along the Lelatema fault zone. The rocks are mainly pelitic and semi-pelitic gneisses, psammitic gneisses, hydrothermally altered rocks, crystalline dolostones, pegmatites and quartz veins. The occurrence of gem-quality tanzanite and grossular has been found to occur mainly in boudinaged pegmatitic veins and hydrothermal fracture fillings. These fracture fillings occur in brecciated and hydrothermally altered graphite-bearing gneiss in a mineral association containing glass-clear quartz, diopside, zoisite, graphite and calcite. The psammitic gneisses are more siliceous and enriched in feldspars. They are grouped into graphite-kyanite gneiss with thin interlayers of quartz-feldspar fels. The pelitic and semi-pelitic gneisses are aluminium-rich and thus have been grouped into garnet-biotite-sillimanite and/or kyanite graphite gneisses. The hydrothermally altered rocks are strongly deformed and contain varying amounts of clay minerals, which characteristically show distinct banded layers due to alterations of minerals.

The rocks have been folded and the fold structures have undergone three deformation episodes (D1, D2 and D3). D1 and D2 were accompanied by high-grade metamorphism whereas D3 was associated with retrograde metamorphism and the formation of retrograde shear zones. Evidence from metamorphosed graded bedding confirms the existence of the antiform and also shows that the macroscopic F2 folds are superimposed on a previously inverted stratigraphic succession. This inversion is the consequence of D1 deformation. The polyphase nature of these rocks with which pegmatites and quartz veins occur is shown by rotation of boudins, presence of overturned tight isoclinal folds resembling F1, presence of F2 folds and refolded folds shown by quartz veins. Features like boudins shown by quartz veins and pegmatites at the limbs and along the axial planes of F1 folds with S1 development in the host rocks and disruption of limbs of tight folds resembling F1, shown by these veins also point to significant amount of flattening during F1 folding phase and longitudinal stretching of the late stage of their development. Slippage in the later stages of deformation phase (D1) is also distinct in displaced veins.

Lithogeochemical studies reveal that the gneisses originated from miogeosynclinal sediments composed of sand; organic matter rich in V, U and fine Al-rich materials. These underwent advanced weathering, deposited in a lake and during metamorphism and after the Pan-African tectonothermal event, the silicates were altered, trace elements released and migrated with hydrothermal solutions rich in Ca, Mg, CO₂ and SO₃. Finally these elements together with V, U, Sr, Zn and heavy REE elements were deposited in the hydrothermal zone. Emplacement of gemstones (tanzanite and green grossular) in the area is structurally controlled along the Lelatema fault system.

INTRODUCTION

The general structural map of the studied area and the extent of the Cainozoic cover, the principal volcanic centres, and the distribution of large faults have been outlined by Wilkinson et al. 1965, Fairhead 1980 (Fig.1). Supracrustal gneisses, schists and granulites crop out over a large area of northeastern Tanzania where they form an integral part of the late Proterozoic, metamorphic sequence of the Mozambique Belt (Malisa 1987). Geological descriptions of these rocks have been published by earlier workers like (Downie and Wilkinson 1965, Saria 1973, Macfarlane 1975, Grainger 1978, Cileck 1980) and this paper is intended to provide a detailed synthesis of the petrologic and geochemical characteristics of the rocks in the area.

Petrologic investigations of metamorphic rocks are important in the understanding of the evolution of ancient orogenic belts since they supply information about pressures and temperatures prevailing in each specific orogenic environment. Further, disequilibrium textures in metamorphic rocks such as rims, coronas, or resorption textures, are of particular interest because they reflect discontinuous or continuous reactions under changing physical chemical conditions and thus they can contribute to the recognition of metamorphic and tectonic processes in the deep crust.

The supracrustal gneisses and schists of the Merelani-Lelatema area are of somewhat peculiar nature and invite consideration of their petrology and geochemistry. Pegmatites and quartz veins are quite common in these rocks. The study of their nature, deposition and relationship with the host rocks reveal many interesting facts regarding the deformation events that affected them and the host rocks. They act as important structural markers and give clues of the deformation phases and superposed strain in rocks.

STRUCTURAL SETTING

The metasedimentary formations occurring in the area exhibit a conformable outcrop pattern without any decipherable unconformity between them (Fig. 2). Strike of the lithological boundaries varies from NE to SW and dips are high towards NW. The formations in the investigated area have been subjected to one orogenic episode. This orogeny consists of three phases of folding. The earliest recognizable deformation (D1) affected the primary stratification surface (S0). It produced isoclinal folds and coevally developed axial plane foliation (S1) parallel to S0 surface. The fold axes (F1) and the accompanying lineation (L1) plunge moderately in the NW to W. The regional surface of lithological boundaries within a bedding plane (S0) and foliation (S1) constitutes the form surface of these folds. Striae and boudins occur at the limbs of these folds. The nature of the S2 surface is crenulation foliation, widely as well as closely spaced, and is associated with F2 folds. It is more prominent at the crestal parts of the folds and shows fanning. The third phase of deformation (D3) brought about folds on S1 and S2 with general WNW-ESE strike of axial planes superimposed on the earlier structures. The direction of fold axes is varying and also the amount of plunge.

ANALYTICAL METHODS

Two hundred and thirty samples from the surface and underground mine were taken from the different lithological units for analysis. Special attention was paid to the hydrothermally altered zone where pegmatites and quartz veins occur associated with gemstones. Since most of the rock samples are carbonate-rich and thus soft, they were impregnated and dried at room temperature. Thin sections were prepared with synthetic resin (Petropoxy, Palause Petro-products, U.S.A., r.i.= 1.54) and dried at 30° C. Thin sections were then studied under normal polarizing microscope. Sixty-one samples were chosen for chemical

analysis. The samples were crushed by jaw crusher and the pieces ground in vibrating disc mill with steel pan (Schwingmühle, manufactured by Messrs. Siebtechnik G.m.b.H., Mülheim BRD). Major, minor and trace elements were determined by inductively coupled argon plasma spectrometry (ICAP). In ICAP analysis, HF and B(OH)₃ were used for the dissolution of silicate samples and NHO₃ and HClO₄ for carbonates. Some major and trace elements were also determined by X-ray fluorescence spectrometry at the Geological Survey of Finland (GSF), Espoo, with a Philips PW 1410 instrument. S and C were determined at the laboratories of the GSF, Espoo with Leco analyser (Sulphur Determinator SC32 and Carbon Determinator CR12). FeO and H₂O were determined and Au and Pd with an AAS (Perkin Elmer 2280 with HGA-500 graphite oven (Kontas 1981, Kontas et al. 1987). To confirm the reliability of these analyses part of the samples were analysed by ICP at the ACME analytical laboratories in Vancouver, Canada. To reduce the length of this paper however, discussions on trace elements will be considered in a separate publication (Malisa 2003).

PETROLOGY

The rocks in the studied area are grouped into several categories: the pelitic and semi-pelitic gneisses, psammitic gneisses, hydrothermal and hydrothermally altered rocks, pegmatites and quartz veins. Within the hydrothermally altered zone, thin bands of carbonate, gypsum, iron-rich and calc-

silicate rocks are observed (Fig. 2). The pelitic and semi-pelitic gneisses together with the psammitic gneisses will be discussed in detail in another publication. However, the other rocks are discussed as follows:

Hydrothermal and hydrothermally altered rocks

These rocks have been grouped together since their mineralogical compositions are almost the same except the minerals in the later rock group are more altered (Table 1-D). The hydrothermal and hydrothermally altered rocks are economically important for hosting the gem-quality tanzanite. In association with tanzanite is green grossular possessing high vanadium content. This is the only locality so far in the world known for the production of gem-quality tanzanite. All these rock groups are easily recognized through the red-yellow colour of iron oxyhydroxides, buff white colour of clay, gypsum and carbonates. They are rusty looking due to reaction with hydrothermal solutions or white due to alteration of feldspars to kaolinite and other clay minerals. In these rock associations, pegmatites and quartz veins may occur distinctly or together, in the main hydrothermal zone and are brecciated. Different types of folds including isoclinal, recumbent folding and boudinaged structures, either widely or closely spaced are common.

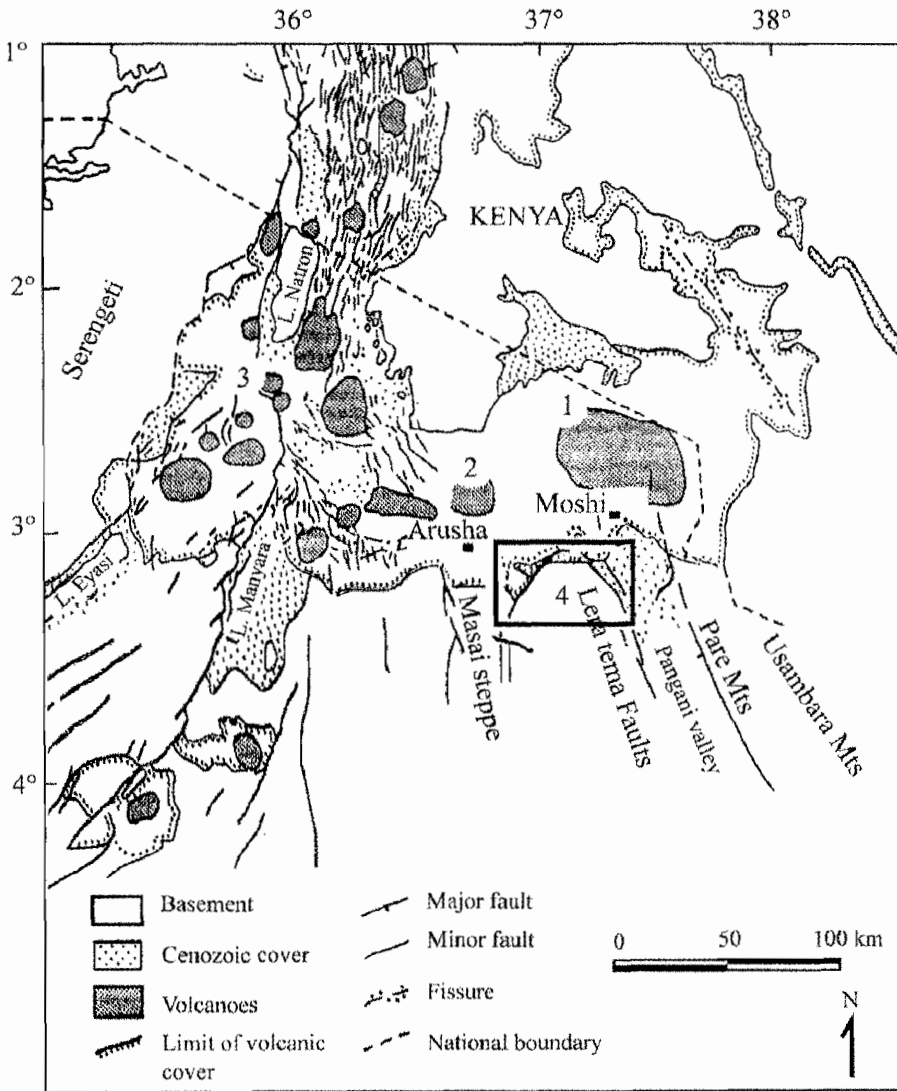


Figure 1 The structural map of the northern Tanzania showing the studied area (square 4), the volcanic province, the extent of the Cenozoic cover (sediments and Volcanoes), the principle volcanic centers, and the distribution of large faults (after Fairhead 1980).

Crystals of tanzanite occur mainly in boudinaged veins, hydrothermal fracture fillings and in a brecciated and hydrothermally altered graphite-bearing diopside gneisses in a mineral association containing, in addition to tanzanite and grossular, quartz, graphite, plagioclase (bytownite), calcite, clay minerals and to a

minor quantity hematite and sphene (Figs.3A, B & C). The formation of these rocks is thought to be before the emplacement of pegmatites and quartz veins and therefore young if volcanogenic rocks are excluded. They have formed through hydrothermal processes and will be grouped on the basis of their mineral composition

and field occurrence (Table 1-D). The order of presentation is based mostly on decreasing silica content. The distinction between hydrothermal and carbonate (or gypsum)-rich hydrothermal rocks is based on the carbonate and sulphate contents (Table 1-E). This grouping has been done in order to investigate the behavior of chemical elements at different stages of the hydrothermal processes as the temperature and pressure of solutions decreases (Malisa 2003). The rocks associated with the hydrothermally altered zone are heterogeneous containing coarse-medium grained minerals such as diopside, zoisite, grossular, micas and plagioclase feldspar and their alteration products. They are highly altered, soft, and contain mixtures of fine-grained and poorly crystallized minerals (silica, gypsum, magnesite, carbonates and clay minerals, iron-oxyhydroxides and jarosite). In general, all the rocks in the studied area are tectonized, altered as indicated by the alteration of silicates and by increase of water, carbonates and sulphates. On the basis of field relationships and the mineralogical composition, the hydrothermal rocks form thin zones and are divided into: hydrothermally altered-carbonate-gypsum-rich and iron-rich rocks (Table 1-F). Due to gypsum and magnesite layers in these rocks, slicken slides are clearly observed. Carbonate veins occur as branching veinlets, few centimetres thick, as fissure and fracture fillings in brecciated rocks. These carbonate fillings are white, soft, and powdery and are mainly composed of calcite; gypsum mixed with amorphous silica. The hydrothermally altered rocks are mainly diopside bearing and in places intruded by quartz veins and thus their mineral composition is mainly: diopside, zoisite, plagioclase feldspar with alteration products, grossular, carbonate, sericite and quartz occurring together in vugs with graphite, opaque phases and minor

constituents of zircon, sphene, rutile, and apatite.

Diopside occurs as dark to pale-green anhedral to subhedral grains (0.1-0.5 mm. in diameter). In many cases the content may approach 80% by volume. Under the microscope it occurs associated with gypsum veinlets, graphite, magnetite, and microcrystalline material as inclusions (Fig. 4A). Diopside is sometimes corroded by carbonates. It carries crystallographically arranged rectangular inclusions of titanite and rutile. Commonly it is twinned and may in places be altered to fibrous green hornblende (uralite), especially on the margins and along cleavage planes.

Zoisite is found mainly in the hydrothermal and hydrothermally altered zone but may also occur as minor constituents in the psammitic gneisses. It is grey-brown or nearly colourless and occurs as anhedral to subhedral crystals up to 3 cm long associated with carbonates (Fig. 4B). Characteristics are the well-developed transverse cracks and one pronounced rather widely spaced cleavage.

Tanzanite, a gem variety zoisite is much rare and is found mainly in the hydrothermally altered zone and detailed studies have been reported by (Hurlbut 1969, Malisa et al. 1986). It crystallizes mostly into vugs or into folded rocks where pure white quartz boudins are present. Tanzanite is violet blue but the colour varies according to the orientation of the optical axis from violet blue to yellowish blue (Fig.4B). Twinning is observed parallel to the tube-like fractures, which are filled with colloform carbonate or recrystallized quartz. Tanzanite occurs in paragenesis with green grossular, glass-clear quartz, bytownite, and diopside and clay minerals (4B).

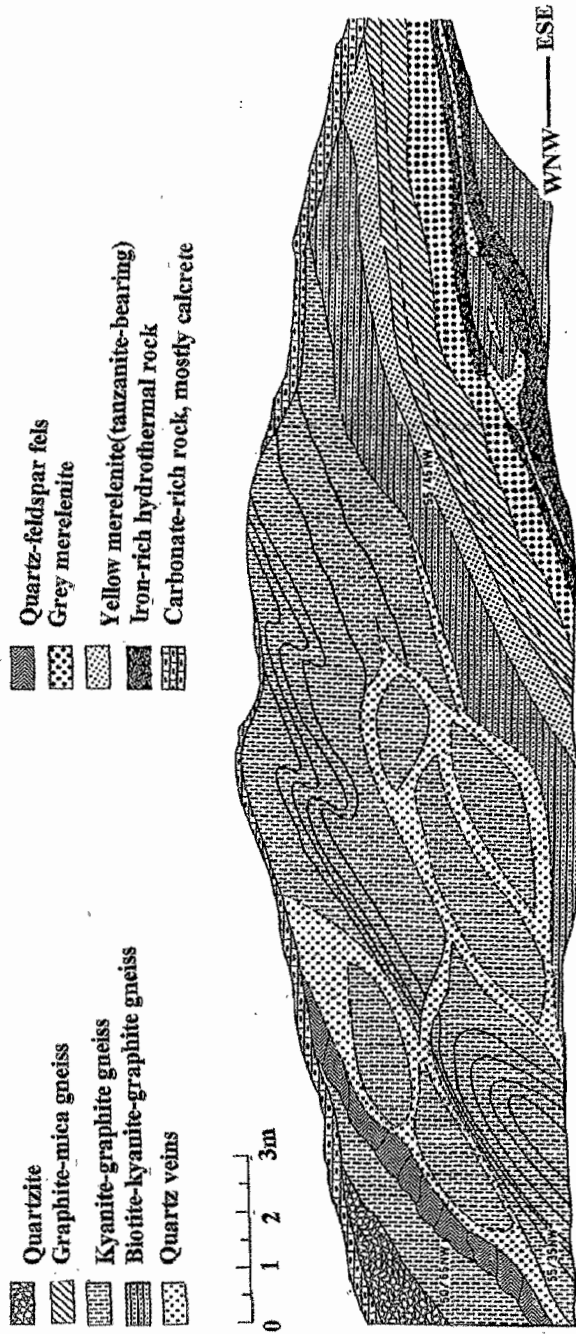


Fig. 2. Detailed geological map of part of the Merelani tanzanite mining area showing different lithological units along the hydrothermally altered zone.

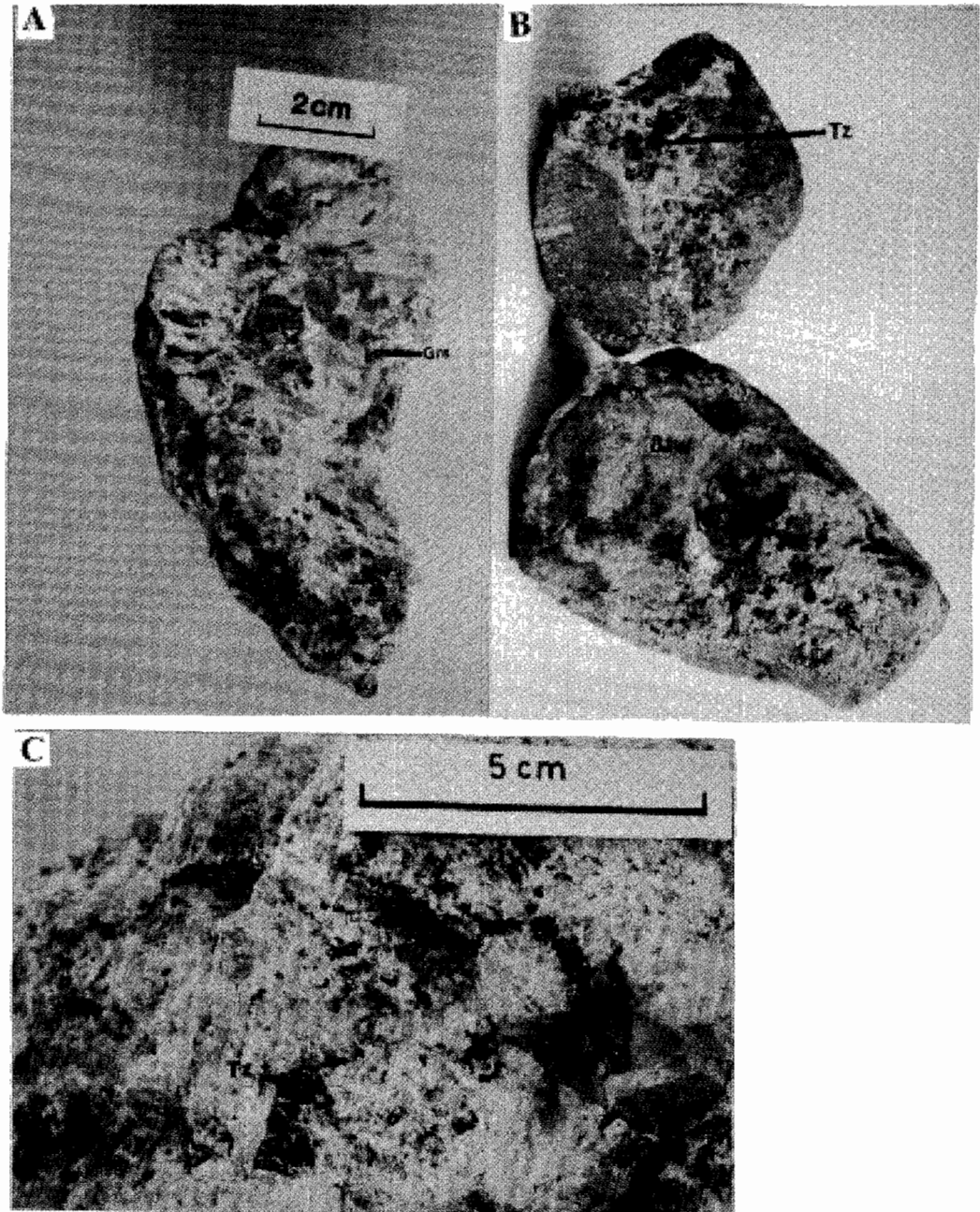


Fig. 3. Photos showing the mode of occurrence and paragenesis of tanzanite and green grossularite A) Blue tanzanite (Tz) and green grossularite (Grs) in boudinaged quartz vein B) Honey yellow tanzanite in fracture fillings rock associated with bytownite and carbonate C) Tanzanite (Tz) in brecciated rock in association with green grossularite and yellow clay (Cly).

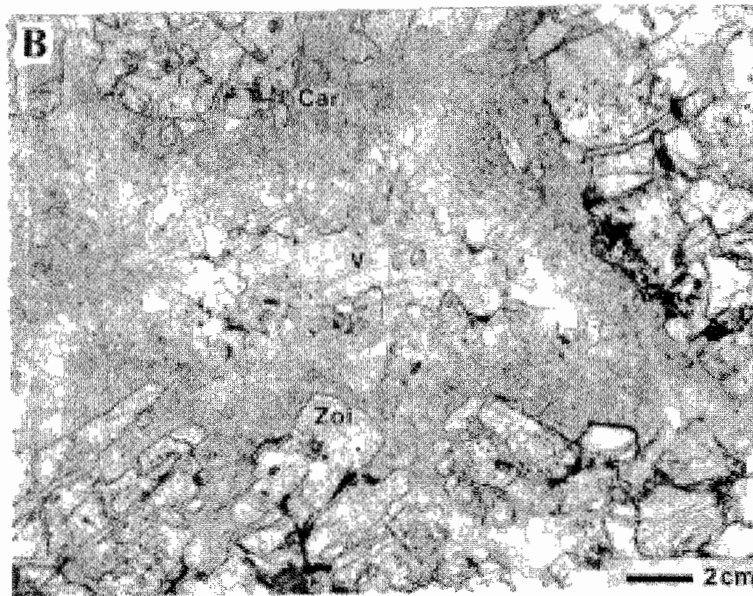
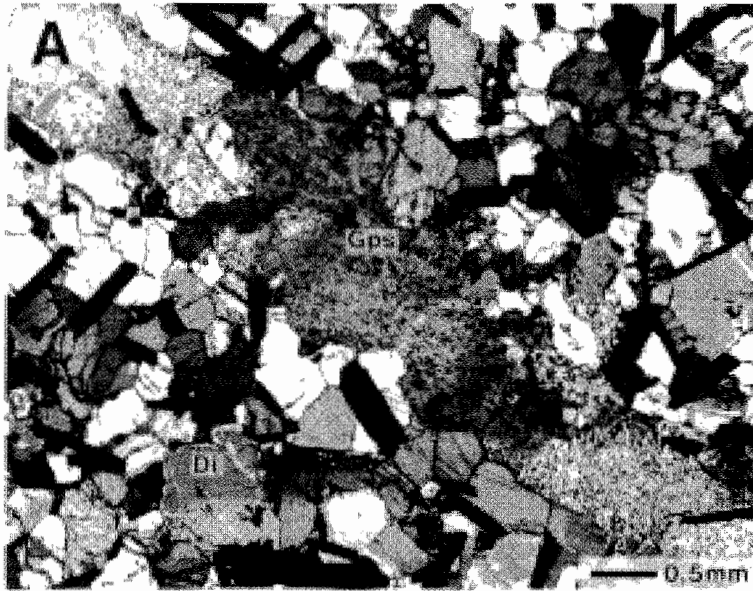


Fig. 4. Photomicrographs of minerals in the hydrothermal and hydrothermally altered rocks

- A) Gypsum veins (Gps) in the diopside rock B) Zoisite (Zoi) in vugs (V) associated with carbonates (Car).

Plagioclase feldspar and its alteration products. Plagioclase (bytownite) occurs associated with tanzanite. It occurs sometimes as distinct with well-developed crystal faces but in most cases it is corroded by carbonate and occurs in the matrix as medium-grained crystals often polysynthetically twinned. It also occurs as large phenocrysts, maximum size 2.8x2.2 mm somewhat altered to very fine-grained alteration products such as sericite and kaolin. The plagioclase feldspar sometimes occurs as strained and fractured and the cracks are filled by flaky sericite or granular to fibrous carbonate, less often by granular quartz or pyrite filaments. It shows simple and albite twinning. Few smaller albite-twinned grains in groundmass and traces of hydrothermal (albitic) feldspar as twinned crystals in thin veinlets with maximum grain size 250x250 μm are observed.

Grossular occurs as transparent green grains ranging in diameter but averaging 0.5 mm. It occurs as granular aggregates or idiomorphic dodecahedral crystals. Grossular is mostly isotropic, but anisotropic, with or without zonal structures is present as well. Seen under the microscope, without crossed nicols, the anisotropic variety appears a little more transparent than the isotropic varieties. Green grossular is often intergrown with clear quartz, tanzanite and diopside or magnesite quartz, diopside, calcite and zircon.

Carbonate occurs as granular carbonate partly as oriented pressure shadows on plagioclase phenocrysts. It is dolomitic in composition with strong twinkling on rotation. It is disseminated in veinlets and as oriented overgrowths on plagioclase phenocrysts. Sericite foliae of very fine grains of white mica constitute much of the rock. Sericite is also abundant as flaky alteration products of plagioclase phenocrysts.

Quartz occurs with a variety of colours as euhedral or anhedral crystals, varying in

sizes. It is abundant as lining in cavities but low in the extensively altered rocks. Many different forms and varieties are found: polycrystalline and polygonal quartz sometimes scattered in carbonate matrix, and as crystals with well-developed faces lining around vugs and cavities. Cryptocrystalline quartz is present in all rocks, as colloidal precipitate from hydrothermal solutions or as a disintegration product. Single crystals of quartz occur scattered in the hydrothermal zone. Most of them are so thoroughly corroded by carbonates that only small grains remain. Well-developed prismatic, rhombohedral, and double terminated crystals are found in cavities and vugs. Transparent clear quartz without fractures or inclusions occur in association with tanzanite and green grossular in boudinaged veins. Smoky and milky quartz are also encountered in a few places along the hydrothermal zone.

Graphite is present as disseminations, massive and sometimes as flakes rendering the rocks to be gray dark in colour. The flakes are deformed and sheared, which is a strong evidence that the altered zone lies in a shear zone. Detailed studies on graphite and its application as a geothermometer has been proposed (Malisa 1998). Opaque phases consisting of mixtures of Fe-Ti oxides, magnetite, ilmenite with pyrite or chalcopyrite are common. Ragged Fe-Ti oxides partly altered to other phase such as sphene occur. Also minor manganese oxides in fractures occur as coatings.

Pegmatites and quartz veins

Pegmatites of varying dimensions both with concordant and discordant relationships occur. They are unzoned, nonfoliated, very coarse grained, white to pale brownish in colour. The pegmatites consist of orthoclase, microcline, quartz, tourmaline, muscovite, and rarely garnet and beryl. The concentration of hornblende and garnet along the margins of pegmatite is common when these occur in association with amphibolites, marble and pelitic gneisses.

Tourmaline is generally concentrated at the margins of the small pegmatites; in some cases it occurs in large crystals oriented normal to the general trend of the tabular pegmatites (Table 1-C).

The study of field relationships, orientation and the nature of pegmatites reveal their development during the various deformation phases. Pegmatites on minor scale are more important in this respect as they distinctly show minor deformation structures. In the majority of cases minor pegmatites have concordant relations with the host rocks and are parallel to the general strike of the formational boundaries. However, in some instances, they transect the formational boundaries and the prominent foliation (S₁). Concordant pegmatites commonly show extensional structures as boudins, pinch and swell structures along prominent foliation S₁, a product of the earliest phase of folding (F₁). These structures are also rotated by later deformations and probably formed during the late stages of the development of the F₁ folds when the limbs of these folds were at a high angle to the maximum principal compression direction. This is confirmed in some of the outcrops where minor pegmatites show tight folds resembling F₁ with S₁ cutting at hinges and have boudinaged limbs.

Their orientation conforms to earliest phase folds (F₁) in the host rocks. The limbs of these folded pegmatites are broadly warped, and their axial direction coincides with that of F₃ set of folds in the host rocks. These features suggest that, some pegmatites formed in the late F₁ phase of folding, experienced extension along the S₁ plane. This is evident from boudinaged limbs of folded pegmatites, which have undergone superposed strain, as indicated by folding. Pegmatites on a minor scale also transect F₁ tight isoclinal folds, traced by quartzite layers in quartzo-feldspathic fels and psammites. Such pegmatites also show broad folds, which corroborate in orientation to F₂ folds, suggesting pegmatite

development later to F₁ phase folding. The majority of the mappable pegmatite bodies are discordant to formational boundaries and the stratification/foliation S₁ planes. The pegmatite bodies trend in the E-W or WNW-ESE direction conforming to the axial trend of F₃ folding and the trend of F₃ linear structures. At the borders of few such pegmatites, slight bending of adjacent rock foliations, abrupt change in S₁ foliation attitude and slight displacement of lithological units are observed. These pegmatites have a straight tabular shape, rarely show branching, and are never lensoid or pod-like in nature. In the majority of cases, rock units in both sides of the pegmatites match well. It could be suggested that pegmatites have been emplaced in some cases forcefully and in other instances permissively along fractures. Regular or irregular shapes of pegmatite may depend on the amount of pegmatitic material emplaced as well as structural control. Pegmatites emplaced parallel to the axial planes of the F₃ structures may possibly have been emplaced towards the close of the F₃ folding movement. It is pertinent to note that F₁ or F₂ folding has affected none of these pegmatites. However, a few strained microcline grains, showing bent twin lamellae, suggest that some pegmatites were emplaced when folding continued.

Quartz veins

Both concordant and discordant quartz veins are present, the former being more prominent. Sets of quartz veins are developed parallel or sub-parallel to the early foliation S₁ in psammitic horizons. These veins, which are deformed during F₂ folding, are useful strain markers and often enable the D₁ and D₂ deformation phases to be easily separated. They show boudinaged, pinch and swell structures conformable to stratification (S₀) and foliation S₁, which developed coevally with the F₁ folds. These structures, suggest extension and superimposed strain, have been rotated by later deformation. Broad rotation of the boudins corroborates with the F₃ phase

folding in axial orientations. Boudins are also in some cases noticed along the limbs of F2 phase folds. They indicate slippage along limbs and also indirectly help in establishing the origin of folding.

LITHOGEOCHEMISTRY

The chemical composition of the rocks from the different lithological units at Merelani-Lelatema area is presented in Tables 1 (A-F). Most of the lithological units are chemically distinct, and this supports their geological subdivision. Generally the rocks seem to have significant differences and possibly have undergone different geological processes, which have induced the chemical modifications of these rocks. The pelitic and psammitic gneisses, which are of slightly higher metamorphic grade, show higher contents of Al₂O₃, SiO₂, and low TiO₂ approaching granitic composition.

There is a distinct separation of the fields occupied by the gneisses and those in the sheared zones while the pegmatites show certain similarities with the gneisses. Since the silica was depleted in shear zones, it is concluded that depletion of alkalis was accompanied by increase in calcium. Generally, magnesium shows a pattern of behaviour very similar to calcium, by being increased in the shear zones. The significant increase in correlation to magnesium with other oxides in the shear zones indicates that magnesium was mobile during metamorphism in these zones. However, pegmatites in these zones show a relatively large increase in magnesium compared to psammo-pelitic rocks. The variations in magnesium and particularly calcium contents along the hydrothermal zone are high because of the general high concentration of these elements in the carbonate rocks in the area. It is possible that a slight calcium loss occurred during the partial melting of the banded gneisses. Correlation of elements Ba, Ni and Sr with CaO or MgO, show that Ba show a binary

spread while Ni and Sr show a scattered relationships indicating that Ni and Sr were enriched in the hydrothermal zone while Ba was probably incorporated as Ba₂SO₄ and was not able to migrate in the hydrothermal zone (Fig. 5).

DISCUSSIONS

Petrological and structural features show that the rocks in the Merelani tanzanite mining area have participated in early polycyclic plastic deformation and late stage rigid block movements, and have been altered at a very late stage by hydrothermal solutions. The mineral associations in it as inclusions suggesting an older stage of growth. In the case of biotite and plagioclase intergrowth, kyanite indicates a simultaneous growth. Pegmatites seem to have formed through anatexis because their major element compositions are very similar to those of the surrounding gneisses.

Textural observations indicate that retrograde metamorphism of granulite and lower facies have occurred and such processes as chloritization of biotite, sericitization of plagioclase, its alteration to clay minerals, and crystallization of muscovite have occurred encompassing such process. In the hydrothermal zone where tanzanite occurs associated with green grossular, the rocks are graphite-rich and are enriched in Al, C, Ca, Mg but poor in SiO₂, Mn and Na. When graphite crystallized (520-880^oC) trace elements incorporated in the organic mater migrated into the lattices of silicates (Malisa 1998). Iron did not migrate in ionic form, at least not as Fe²⁺ because the Fe²⁺ is low in silicates that have crystallized in the hydrothermal zone (Malisa 1987). The hydrothermal rocks carrying the gem-quality minerals are thought to have originated from a spatially restricted rock sequence. The rocks representing a small apex of the Latelama fold.

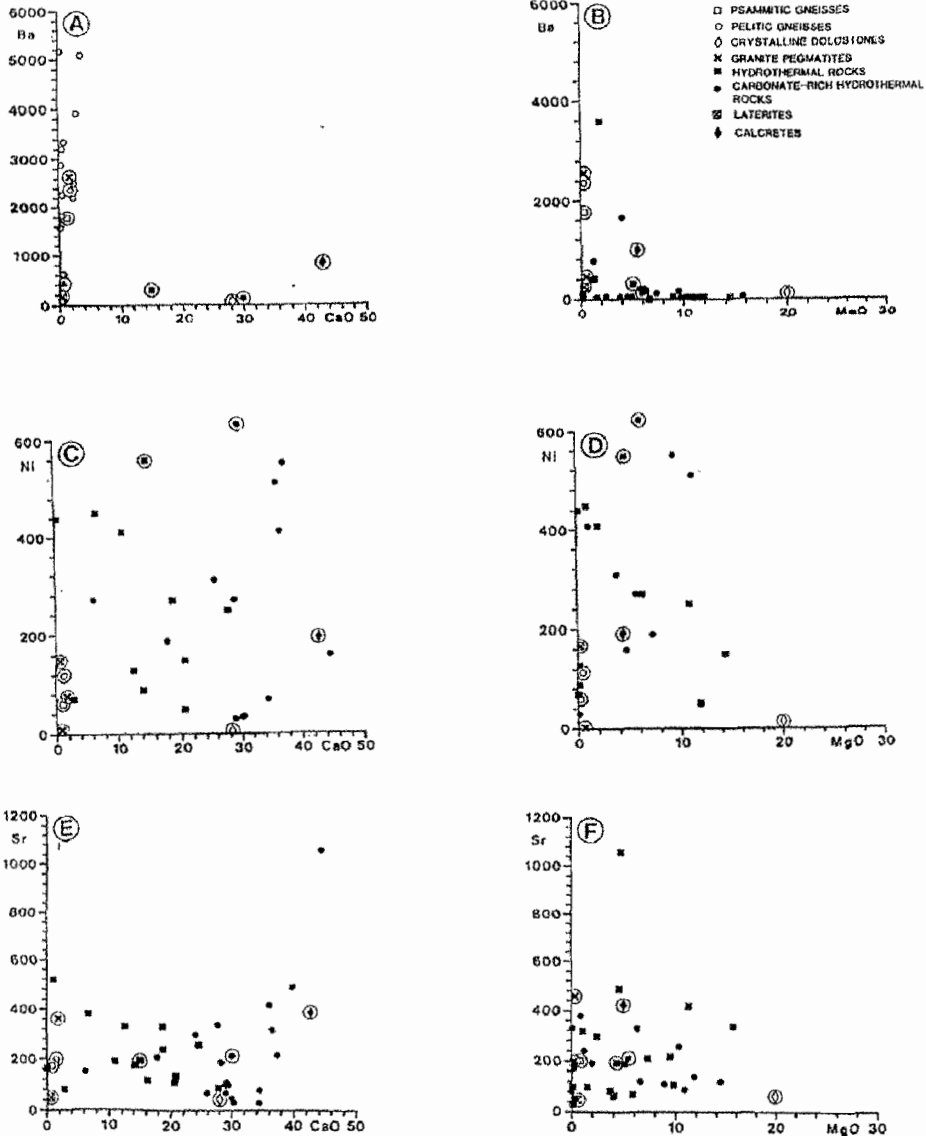


Fig. 5. Correlation diagrams of Ba, Ni, and Sr against CaO and MgO in the Merelani tanzanite mining area.

The rocks in the hydrothermal zone are mostly calc-silicate rocks composed of bytownite, grossular, diopside, zoisite, and quartz with low temperature late precipitates such as cryptocrystalline quartz, dolomite, calcite, magnesite, gypsum, iron oxyhydroxides and clay minerals. The

precipitates appear to have crystallized when the temperature of the mineralizing hydrothermal solutions decreased after the main phase of the Pan-African event. The host rocks where vanadiferous zoisite (tanzanite) occurs have undergone considerable hydrothermal alterations. This

is indicated by field observations and petrological evidence including silicification, kaolinitization, sericitization, albitization, chloritization, and development of green muscovite at the contact zones.

Field studies indicate that high quality deep blue tanzanite is restricted to the boudinaged pegmatitic quartz veins surrounded by transparent clear quartz. However, other varieties of colours of tanzanite in the hydrothermally altered rocks occur paragenetically associated with or without green grossular, pure clear quartz, graphite, bytownite and calcite in hydrothermal fracture fillings and in brecciated and hydrothermally altered graphite-bearing diopside gneiss. The study of the nature and deformation structures imprinted in pegmatites and quartz veins in Merelani-Lelatema area, is important in identifying subsequent deformations. Superposed deformation and modification of earlier structures taking place in progressive deformation is revealed by this study. The majority of pegmatites have been emplaced in late stage of F3 phase folding permissively and, in some cases, forcefully. The presence of folds in minor pegmatites, and quartz veins correlate well with the folding phases F1 and F2 in the rocks. The disruption of pegmatites forming boudins along the axial planes of F1 folds and the foliation S1, presence of pinch and swell structure in quartz veins at the limbs of F1 folds parallel to its axial plane, the attenuation and disruption of limbs of tight folds shown by quartz veins, point to significant amount of flattening of F1 folds and longitudinal stretching in the late stage of their development. The rotation of boudins of quartz veins, overturned tight isoclinal folds F1 shown by quartz veins, refolding of their limbs in pegmatites by F3 and by F2 folds shown by quartz veins, reveals clearly that the rocks in the area have undergone polyphase deformation.

CONCLUSIONS

Within the metamorphosed-hydrothermal rock sequence in the Merelani-Lelatema fold

system, there are various gemstone deposits including green grossular, zoisite (tanzanite), green tourmaline, varieties of quartz, scapolite and rubby. The deposits reflects the existence of unique geological processes in the area, and probably in other parts of the Mozambique Belt as well, processes that differ from those usually encountered in high metamorphic terrains. Intense advanced argillic alteration and silicification are characteristically associated with the gemstone mineralization. Gemstone-bearing rocks are mainly veins, boudins, vugs, but mineralized hydrothermal breccias are commonly present. Structural control is important for this occurrence. Both regional and local scale structures appear as relevant features related to the genesis of tanzanite. The different constraints from major element geochemistry have allowed the following conclusions: the gneisses originated from miogeosynclinal sediments composed of sand, organic matter rich in V and U, and fine Al-rich materials. These sediments evidently underwent advanced weathering and were deposited into a lake. During metamorphism and after the Pan-African tectono-thermal event (600-450 Ma), the silicates were altered and the trace elements were released, migrated with hydrothermal solutions bearing Ca, Mg, CO₂, and SO₃ ions and were deposited, in the hydrothermal zone, where Ca, Mg, V, U, Zn and heavy REE elements were enriched. The rocks along the hydrothermal zone carrying gem-quality minerals are thought to have originated from a spatially restricted rock sequence. The occurrence of vanadium bearing zoisite (tanzanite) in the Merelani area, the only place in the world, reflects the existence of unique geological processes, different from those encountered in other high-grade metamorphic terrains.

Table 1. Representative chemical analyses (wt.%) of different rocks in the Merelani tanzanite mining area.

	A (10)	B (10)	C (7)	D (9)	E (9)	F (7)
SiO ₂	68.34	77.70	70.09	50.68	28.94	36.04
TiO ₂	0.84	0.51	0.41	0.43	0.29	0.35
Al ₂ O ₃	14.59	8.31	15.54	8.34	5.96	4.67
Fe ₂ O ₃	3.41	1.79	1.90	0.16	4.04	38.39
FeO	0.72	0.18	0.30	0.16	0.14	0.03
MnO	0.01	0.02	0.02	0.15	0.20	0.03
MgO	0.69	0.34	0.71	6.04	4.45	0.71
CaO	0.90	0.83	1.62	12.92	27.75	2.96
Na ₂ O	0.72	1.00	2.37	1.64	0.27	0.23
K ₂ O	1.93	1.95	5.12	0.47	0.46	0.27
P ₂ O ₅	0.09	0.07	0.12	0.12	0.16	0.14
S	0.93	0.62	0.28	1.24	0.09	1.21
C	2.18	4.46	0.41	8.13	6.23	4.17
CO ₂	0.22	0.02	0.21	1.12	17.77	1.59
H ₂ O ⁺	0.22	0.73	0.80	2.13	2.53	6.15
H ₂ O ⁻	0.24	0.11	0.28	2.80	1.28	2.92
Na ₂ O/K ₂ O	0.41	0.76	0.76	0.52	0.21	0.39
V*	559	293	310	755.56	553.33	2578.89
Sr*	176	169	462.86	168.89	161.11	167.89

CIPW-Norm	A (10)	B (10)	C (7)	D (9)	E (9)	F (7)
Qz	54.01	61.47	30.90	21.81	12.12	23.97
Or	12.36	12.20	33.53	2.99	2.97	1.41
Ab	5.92	9.12	19.88	1.96	1.03	1.30
An	2.44	3.18	5.67	13.04	8.15	3.06
Di/wo	-	-	0.00	16.72	5.21	0.00
Di/en	-	-	0.00	14.45	4.44	0.00
Di/fs	-	-	0.00	0.00	1.37	0.00
Wo			0.00	4.30	3.36	0.00
Hy/en	1.71	0.85	1.78	0.62	5.60	1.38
C	10.27	3.13	3.58	2.97	2.22	2.22
Mt	0.93	0.06	0.10	0.62	0.93	1.08
Hm	2.92	3.11	1.86	4.21	3.20	29.55
Il	0.71	1.09	0.51	0.36	0.34	0.23
Ru	0.47	0.49	0.06	0.12	0.04	0.20
Ti	-	-	-	0.23	0.02	0.00
Ap	0.20	0.29	0.30	0.30	0.34	0.26
Cm	0.03	0.06	0.02	0.02	0.03	0.01
Cc	0.53	0.09	0.40	2.56	41.56	2.95
Pr	0.21	0.09	0.02	0.07	0.14	0.04
Zr	0.04	0.05	0.01	0.03	0.09	0.02
H ₂ O	2.65	1.94	1.11	4.07	3.55	5.10

A: Pelitic and semi-pelitic gneisses, B: Psammitic gneisses, C: Granitic gneisses, D: Hydrothermal and hydrothermally altered rocks, E: Carbonate or gypsum-rich hydrothermally altered rocks F: Iron-rich hydrothermally altered rocks. Numbers in parenthesis indicate the total samples analysed and averaged. * Values in ppm.

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