Journal of Geology and Mining Research Vol. 1(1) pp. 001-007 March, 2009
Available online http://www.academicjournals.org/jgmr

Full Length Research Paper

Fluid inclusions and mineral chemistry of some detrital heavy minerals of alluvium sediments from Meluli-Namuhuca area, Mozambique

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Accepted 4 March, 2009

Geochemistry and fluid inclusions studies were carried out on garnet and beryl from Quaternary alluvium deposits of Meluli-Namuhuca area, Mozambique. Garnet occurs as euhedral large crystals and is commonly brownish red, with a moderate brown hue in transmitted light. Apatite and ilmenite are the common inclusions. Geochemically, garnet is characterized by nearly homogenous chemical composition with Pyr $_{(46.72\text{-}48.35)}$, Alm $_{(39.77\text{-}48.35)}$, Gr $_{(10.03\text{-}10.56)}$ and Sps $_{(1.14\text{-}1.31)}$ mol %. This garnet is referred to as iron-rich pyrope or pyrope – almandine. Chemical compositions reflect their crystallization from magma (Mg-Fe isomorphism).The high-Mg, and low Na of the studied garnet are consistent with high temperature eclogitic garnet associated with diamond. Fluid inclusions study indicates that garnet was deposited from high saline and high temperature fluids. Beryl is present as euhedral hexagonal crystals with different color (green emerald, blue aquamarine, and yellow heliodors). It enclosed cassiterite, wolframite and barite micro-inclusions, which support that the studied beryl is connected to hydrothermal ore-bearing fluids. Fluid inclusions study reveal that beryl was deposited due to boiling process of medium salinity (9-12 wt.% NaCl eq.), and medium temperature (180-240 °C) fluids. Pressure of trapping was estimated between 400 and 700 bars.

Key words: Fluid inclusions, geochemistry, heavy minerals, Mozambique.

INTRODUCTION

The geochemical relationship between detrital sedimenttary minerals and its source rocks is a complex function of chemical changes that accompany weathering, transport and depositional processes. The provenance models of sedimentary rock fragments have, generally taken into account the mineralogical and/ or chemical compositions of the detrital fragments (Van de Kamp and Leake, 1995; Acquafredda et al., 1997). The composition of the detrital minerals as well as the mineral assemblages of the coarse grained rock fragments are sensitive indicators of source rocks (Morton et al., 1989; Nechaev and Isphording, 1993; Fornelli and Piccarreta, 1997). This paper deals with the types and chemical compositions of the detrital alluvium minerals occurring in the Quaternary sediments of Meluli-Namuhuca area, Mozambique (Figure 1) as well as the fluid inclusions in these minerals to infer the genesis and the nature of the studied minerals.

Geology

The Mozambique belt is a part of the Pan-African East African orogen that formed by the collision of East and West Fontana. This collisional event was caused by a long-lived subduction system in which island arcs were accelerated between 750 – 500 Ma (Tenczer et al., 2005). The thrust propagation formed a Pan – African metamorphic overprint with a gradient from greenschist facies in the west to high pressure granulite facies in the east.

The geological map of the studied area and the location of the samples are shown in Figure 2. The area represents a plateau at about 400-600 m above sea level, and

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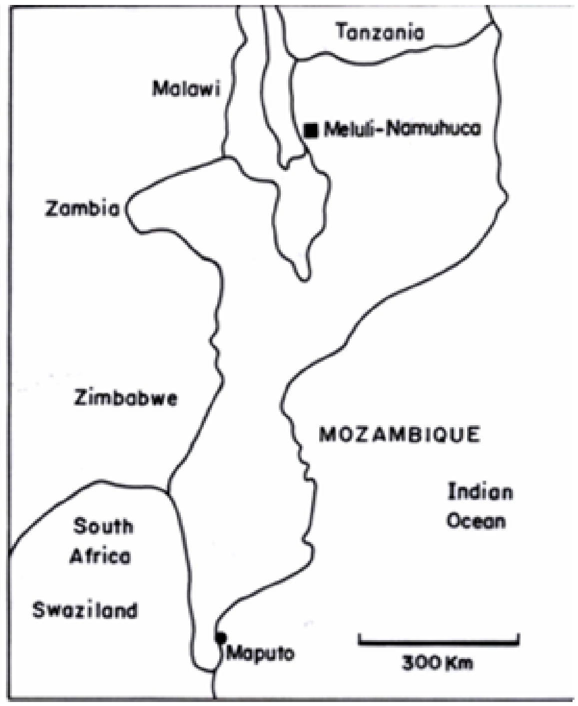

Figure 1. Location map showing the studied area.

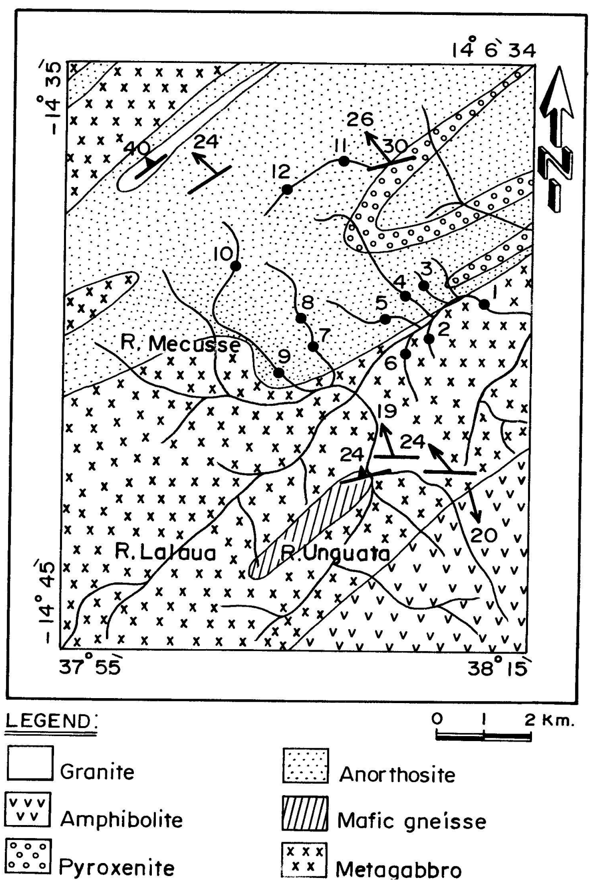

Figure 2. Geological map of the studied area after Amadeu, 1997. The solid circles indicate the location of the samples.

dissected by numerous rivers and streams. Several steep mountains are located on this plateau. These mountains are composed of Precambrian metamorphic and magmatic rocks including metagabbro, pyroxenite, anorthosite, amphibolite, granite and mafic gneisses. Regions with mafic – poor arc volcanic rocks, blueshist and ecologite are considered favourable for subduction-diamond exploration (Barron et al., 1996). The drainage is well developed. The entire area slopes generally northeastwards and the main river, Rio Lalaua flows in this direction and drains most of the investigated area. The streams and rivers are rich in water during the rainy season, but some completely dry off during the dry season. There are also several springs in the area. The studied samples are collected from the alluvial detrital sediments which disintergrated from the Precambrian metamorphic and magmatic rocks present in the area. The depth of the collected samples is about 20 cm below the surface. The minerals range in size from 5 mm up to 6 cm and composed mainly of garnet, tourmaline and beryl.

Mineral chemistry

Sample set and analytical technique

Electron microprobe analyses of thirty nine spots of garnet crystals collected from the alluvial samples of the studied area have been performed. Polished Carbon – Coated thin sections were analyzed with a Camera SX – 100 electron microprobe (University of Vienna, Department of lithospheric Sciences). Mineral analyses were made against natural standards using four wavelength – dispersive spectrometers; acceleration voltage and beam current were 15 KV and 20 n A respectively and standard correction procedures were applied. Smallest mineral inclusions were characterized using energy – dispersive spectrometer (EDS). Mineral formulae were calculated using a PASFORM program (Bjereg et al., 1995). Fe^{2+} - Fe^{3+} redistribution from electron microprobe analyses is made using the general equation of Droop (1987) for estimation of Fe^{3+}. The average composition of representative garnet analyses for core and rim and the calculated structural formulae are presented in Table 1.

Quantitative electron microprobe analyses for cores and rims of the studied detrital garnet crystals do not reveal significant internal compositional variations. This indicates that the studied garnets are homogeneous and unzoned. The main composition is pyrope and almandine which is characterized by Pyr_{49}, Alm_{39-42}, $Sp_{1.14-1.31.6}$ (Figure 3). This indicate that the analyzed garnet may be derived from high grade and/or slowly cooled source terrains in which diffusion may have eliminated original compositional variations (Morton et al., 1989). On the Mg-Fe-Ca diagram (Figure 4) the studied garnets cluster near the Mg-Fe axis with Ca contents unchanged. Garnet compositions likely reflect the magmatic origin (Mg-Fe isomorphism) rather than metasomatic origin (Kostrovitsky et al., 2008). The studied garnet has inclusions of py-

Table 1. Average compositions of electron microprobe analyses of garnet.

Sample No.	3		5		8		10		11	
	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core
SiO_2	40.09	40.01	40.23	39.82	39.93	40.16	40.19	40.41	39.87	40.18
TiO_2	0.02	0.01	0.03	0.05	0.01	0.05	0.06	0.01	0.05	0.01
Al_2O_3	22.77	22.97	22.88	22.70	22.82	22.78	22.87	22.63	22.82	22.77
Fe_2O_3	0.99	1.60	1.36	1.70	1.78	1.14	1.12	1.08	1.80	1.20
FeO	18.52	18.60	18.83	18.69	18.99	19.38	19.09	19.43	18.73	19.22
MnO	0.56	0.58	0.56	0.58	0.55	0.57	0.57	0.56	0.60	0.63
MgO	13.27	13.23	13.26	13.02	12.93	12.88	13.04	13.02	13.07	12.94
CaO	4.05	3.89	3.95	4.02	3.99	4.00	3.99	3.98	3.94	4.00
Na_2O	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
K_2O	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sum	100.30	100.92	101.11	100.60	101.02	100.97	100.96	101.14	100.89	100.97
Oxygen	24	24	24	24	24	24	24	24	24	24
Si	5.95	5.91	5.93	5.91	5.91	5.95	5.94	5.97	5.90	5.95
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Al	3.98	4.00	3.98	3.97	3.98	3.97	3.99	3.94	3.98	3.97
Fe^{3+}	0.11	0.18	0.15	0.19	0.20	0.13	0.13	0.12	0.20	0.13
Fe^{2+}	2.30	2.30	2.32	2.32	2.35	2.40	2.36	2.40	2.32	2.38
Mn	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08
Mg	2.94	2.91	2.92	2.88	2.85	2.84	2.87	2.87	2.86	2.86
Ca	0.65	0.62	0.62	0.64	0.63	0.63	0.63	0.63	0.63	0.63
Na	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
K	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
X alm	39.77	40.62	40.62	41.15	41.80	41.15	40.92	41.45	41.38	41.28
X sps	1.15	1.15	1.15	1.14	1.14	1.15	1.15	1.15	1.15	1.31
X pyr	48.35	47.86	47.86	47.21	46.72	46.78	47.36	47.04	47.12	46.87
X grs	10.56	10.03	10.20	10.49	10.33	10.38	10.39	10.36	10.18	10.36

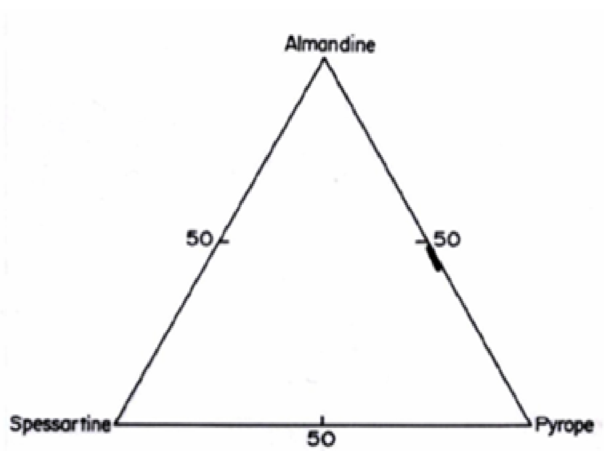

Figure 3. Composition of garnet from the studied area plotted in terms of end member components Almandine-Spessartine-Pyrope.

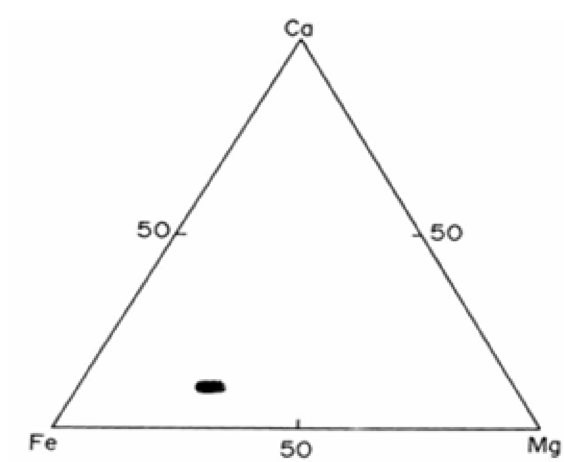

Figure 4. Ternary diagram showing chemical compositions of garnet from the studied area.

rite, iron-titanium oxides (ilmenite) and pure apatite.

Fluid inclusions study

Samples of beryl of different colors (green emerald, blue aquamarine and yellow heliodors), and garnet were collected from alluvium in the studied area for fluid inclusions study.

In beryl, fluid inclusions in all studied samples are represented mainly by two-phase (L+V) aqueous inclusion.

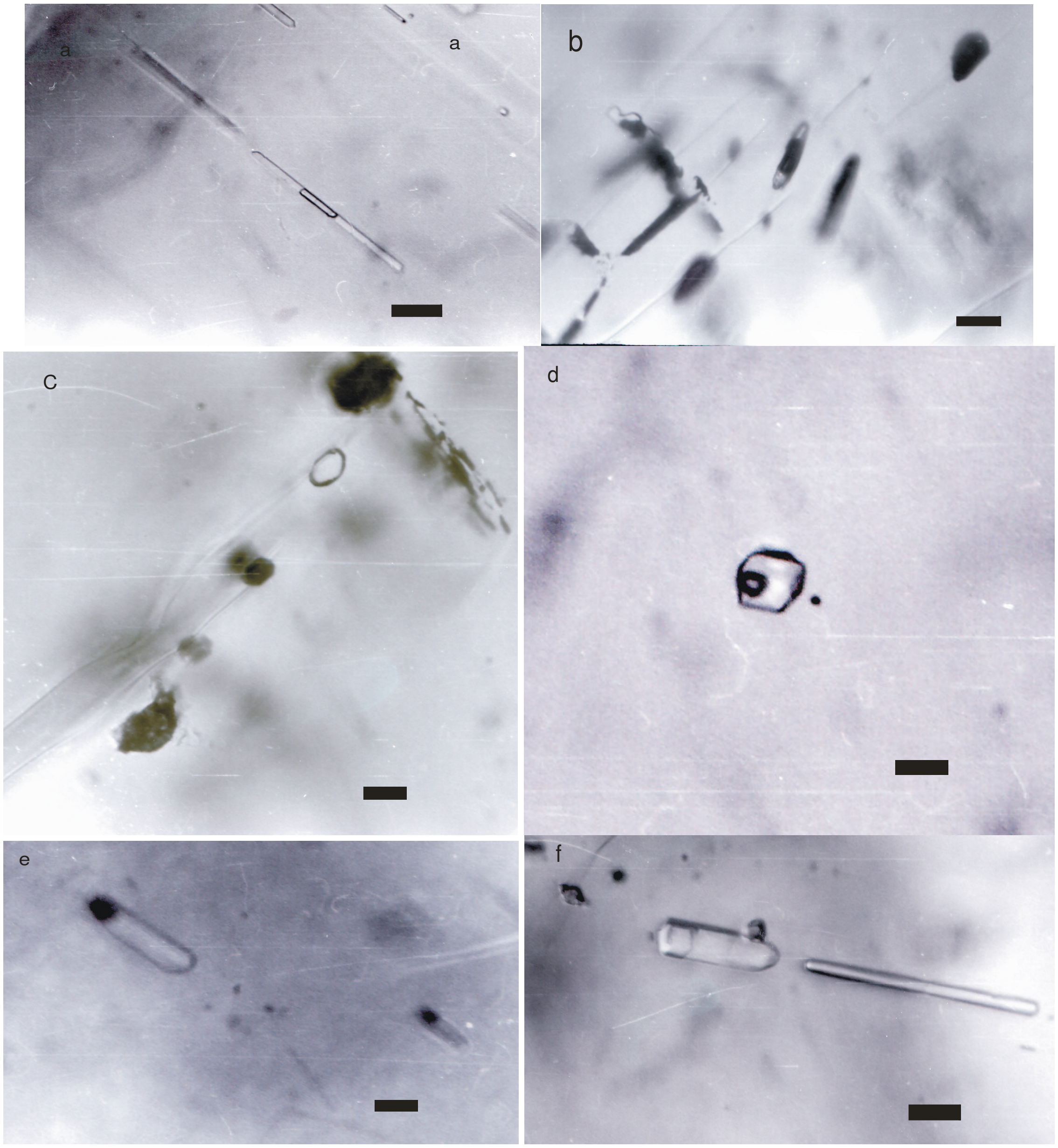

Figure 5. Micrographs show types and distribution of fluid inclusions from beryl and Garnet (a and b) Primary distribution of two-phase aqueous inclusions in beryl. (c) Coexisting mono-phase liquid and vapour with two phase aqueous inclusions in beryl. (d, and e) Primary distribution of two-phase aqueous inclusions in garnet (f) Liquid inclusions with six-side solid crystal in garnet. (Scale bar = 30 µm).

Inclusions are elongated and oriented parallel to c-axis of beryl as primary inclusions (Figure 5a and b), and are hosted in inter-grain trails parallel to crystal boundaries as pseudosecondary inclusions (Roedder, 1984). Isolated solitary inclusion is also recorded. The shape of inclusions varied but most are prismatic and elliptical. The sizes of inclusions varied from 10 to 200 µm (Figure 5a and b) with most of them 30 to 50 µm. These inclusions have irregular degree of filling, and vapour mono-phase and liquid mono-phase inclusions are coexisting with the two-phase inclusions (Figure 5c). In garnet, two –phase (L+V), aqueous inclusions are re-corded. The shapes are prismatic, sub-rounded and negative crystals, and the size range from 5 to 100 µm with most 20-to 40 µm with nearly regular degree of filling (Figure 5 d and e). The inclusions are distributed parallel to the growth planes as primary inclusions (Roedder, 1984). Liquid inclusion with cubic solid crystal is also observed (Figure 5 f).

Microthermometry

Method of study

Microthermometric measurements were performed by studying

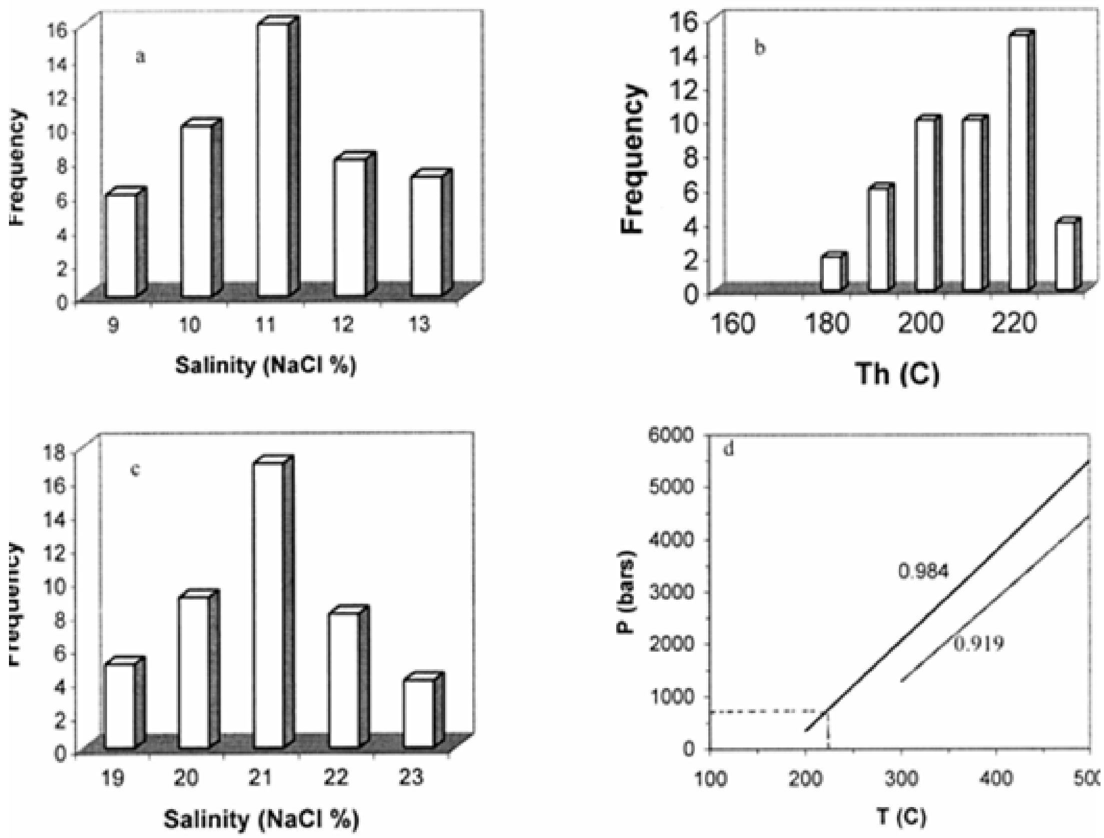

Figure 6. Histograms showing the distribution of salinity (a) and (b) total homogenization temperatures for fluid inclusions in beryl. (c): Histogram showing the distribution of salinity for fluid inclusions in garnet. (d) Estimated trapping conditions for beryl from isochores calculated using FLINCOR Computer Program (Brown, 1989).

phase transition in fluid inclusions between -184 and +600°C. It has been carried out on double polished wafers 0.2-0.3 mm thick using a Chaixmeca heating freezing stage (Poty et al., 1976) at the Geology Department, Assiut University. The stage was calibrated for temperature between -100 and 400°C using Merck chemical standards as well as according to the melting point of distilled water (0°C) and phase transition in natural pure CO_2 inclusions with triple point at -56.6°C.

Microthermometric results

In beryl, the first melting of ice, corresponding to eutectic temperatures (Te) was achieved between -15 to -25°C, indicating the presence of NaCl and KCl in the fluids (Brown, 1998). The final ice melting (Tm_{ice}) observed at temperatures was between -6 and -9°C. These temperatures confirm medium salinity between 9.21 to 12.85 wt. % NaCl eq., (Bodnar 1993) and the data are skewed at 11 wt.% NaCl eq. (Figure 6a). Bulk homogenization (Th_{tot}) measured range was between 180 and 240°C, with majority at 220°C (Figure 6b).

In garnet, The eutectic temperatures measured in some inclusions between -50 to -60°C, confirm the presence of CaCl and MgCl in addition to NaCl in the fluids (Brown, 1998).The final ice melting (Tm_{ice}) was measured at temperatures between -16 and -20°C, corresponding to high salinity between 19.45 to 22.38 wt.% NaCl eq. with majority at 21 wt.% NaCl eq. (Figure 6c).Total homogenization temperature was never achieved until 600°C (the higher temperature limit of the stage), and this confirmed that the temperatures of total homogenization are generally > 600°C. Dissolution of the solid phase was never achieved.

DISCUSSION

Generally, garnets exhibit broad chemical variability between the known end-member, the commonest of which are pyrope, almandine, spessartine, grossular and andradite. The studied garnet is brownish – red in color, and intermediates in composition between pyrope and almandine. Such garnet is referred to as Fe-rich pyrope or pyrope-almandine (Stockton and Mason, 1985). Seifert and Varna (2003) stated that this type of garnet is formed during the metamorphism of the rocks. Kryvoshlyk (2003) classified the garnet inclusions in diamonds (GID) into three subfields (three sources of diamonds?): one peridotitic (GID-3)) and two ecologitic. The number of ecologitic sub-field might reflect the existence of two genetically different types of eclogites: metamorphic (GID-2) and magmatic (GID-1). The pyrope-almandine garnet (Pyr_{49}, Alm_{39-42}, Gr_{10-11}) of the studied area may well be of eclogitic affinity (Barron et al., 1996; Ross, 1986; Dawson, 1980), and is consistent in composition with the ecologite garnet (Figure 7) associated with dia-

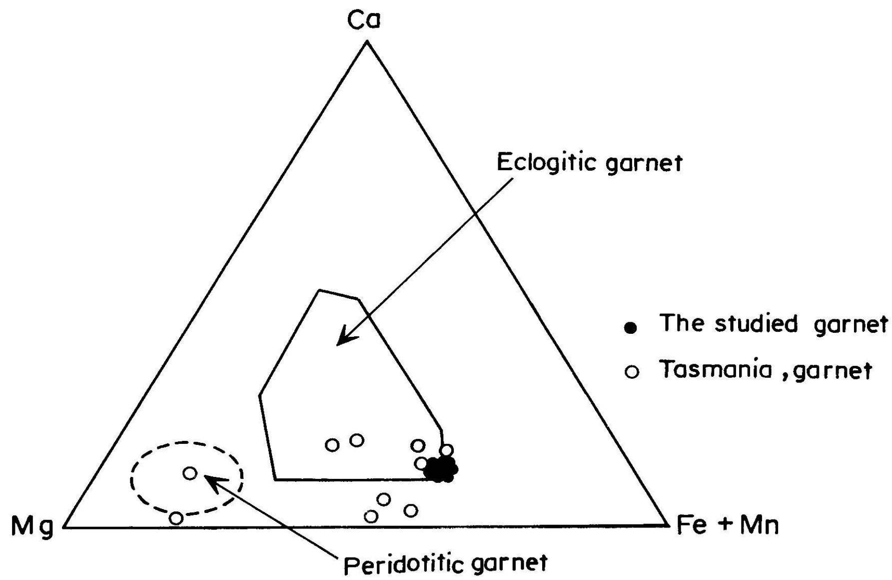

Figure 7. Compositions of the investigated garnets of the present study compared to the Tasmanian garnets of possibly high-pressure origin (from Brown 1984; Sutherland, 1984; and Charchalis, 1988a,b), with fields for diamond-associated garnets from Barron, et al. (1996).

mond at Tasmania (Bottrill, 1998).

Pressure estimation and interpretation of fluid inclusions data

In beryl, microthermometric measurements of fluid inclusions reveal medium salinity (9-12 wt. % NaCl.eq.) and medium temperatures (180 -240°C) aqueous fluids trapped in the beryl crystals. Coexisting vapour monophase, liquid monophase, and two-phase (L+V) indicate that these inclusions were trapped during boiling process. The latter is one of two processes that commonly provide the necessary conditions for effective ore mineral precipitation (Wilkinson, 2001).

Lodzinski and Michalik (2004) distinguished three types of beryl crystals on the basis of mineral inclusions assemblages. Type 1, is related to crystallization from highly evolved magma, type 2 is connected to hydrothermal ore-bearing fluids, and type 3 devoid of mineral inclusions and has not been genetically classified. The studied beryl includes cassiterite, wolframite and barite as mineral inclusions, and belongs to type 2 of Lodzinski and Michalik (op.cit).

To estimate the conditions of precipitation of beryl, isochores were calculated from fluid inclusions data using FLINCOR computer program (Brown, 1989). The precipitation conditions consistent with trapping conditions estimated from isochors (Figure 6d) are at pressure between 400 and 700 bars, at temperature between 180 and 240°C

In garnet, Fluid inclusions study in garnet indicates the presence of high salinity (20-23 wt.% NaCl eq.) and high temperature > 600°C. This is consistent with the mineral chemistry of garnet (pyr – rich). The studied garnet is genetically related to basic-ultabasic country rocks of the area.

Conclusions

Geochemical study of garnet from alluvium deposits of Meluli- Namuhuca area, Mozambique revealed that the garnet is pyrope – almandine in composition. This garnet is similar to ecologitic garnet that formed at high temperature and pressure. Fluid inclusions study of garnet is supporting the geochemical results. The studied garnet is chemically similar to the ecologitic garnets associated with diamond deposits at many places of the world. Therefore, intensive diamond exploration in the studied area using mineralogical and geochemical methods is recommended.

Fluid inclusions study in beryl from alluvium deposits indicate that the studied beryl may be derived from ore-bearing hydrothermal fluids due to boiling process. The deposition has taken place at temperature between 180 ans 240°C, and pressure between 400 and 700 bars.

ACKNOWLEDGMENTS

The authors are greatly indebted to Prof. Ntaflos, who kindly made available facilities to carry out the microprobe analyses at the Faculty of Earth Sciences, Vienna University, Austria. Also, deep thanks to Sh. A. Shehata (Ph. D. student) for his help during his stay in Vienna.

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