PETROGRAPHY AND MINERAL CHEMISTRY OF THE PELITIC AND SEMI-PELITIC GNEISSES OF THE MERELANI TANZANITE MINING AREA, NORTHEASTERN TANZANIA

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ABSTRACT

Sillimanite/kyanite + K-feldspar + quartz ± garnet + *biotite ± Fe-Ti oxide-bearing rocks occur associated with calc-silicate rocks in the Merelani tanzanite mining area north-eastern Tanzania. The whole rock chemistry shows varying rock oxidation ratios, which are reflected in the mineralogical assemblages. Almandine garnet is oxidized to mixtures of hematite, quartz, and hydrous aluminosilicates in oxidized rocks and is absent in highly oxidized rocks. In the latter, ilmenite is oxidized into mixtures of rutile and hematite. Such relatively high temperature alteration/oxidation effects could have occurred with the influx of water. Absence of staurolite in these aluminium-rich rocks is indicative of high fugacity of oxygen during metamorphism. These rocks were regionally metamorphosed to the high-grade granulite facies with estimated formation temperatures and pressures of 596 – 726^o C and 7.7 – 9.1 kbars and later, underwent retrograde metamorphism to the amphibolite facies.*

INTRODUCTION

Merelani area in the Simanjiro District in the northeastern part of Tanzania is well known as the only locality in the world for tanzanite deposits, a gem variety of zoisite. This area has been studied by many authors including Downie *et al*. 1965, Saria 1973, Macfarlane 1975, Grainger 1978, Cileck 1980 and Malisa, 1987. There are many areas in Tanzania where gemstones are exploited and this area is thought to be one of the most spectacular for its tanzanite occurrence. (Fig.1). Pelitic and calcareous metasediments are associated with tanzanite forming rocks in this area as conformable beds forming part of the late Proterozoic metasedimentary gneisses commonly constituting the hill ranges of the Lelatema mountains. At Merelani these rocks forms patches of outcrops and at some places they occur as low lying hills or tors covered by lateritic soils. They consist of sillimanite/kyanite–K-feldspar-garnet-biotite gneisses and calc-silicate rocks. This study forms part of an investigation of Fe-Ti oxide minerals, their mutual-physical chemical relationships, and their relation to the silicate minerals. The paper deals with metamorphosed magnetite-ilmenite assemblages indicative of low to medium oxygen fugacity (Lindh 1972). The oxide ore minerals of the gneisses are considered to be of primary origin but we cannot exclude the possibility of secondary ilmenite formation.

The aim of the present investigation was to investigate petrography and how the different mineral groups-silicates and oxides react to metamorphic processes and to elucidate this question chemical analyses of coexisting silicates and oxides were made. The distribution of elements among the different phases was studied. In addition the variation in temperature and pressure by using quantitative geothermometry and geobarometry was carried out. Furthermore an attempt has between made to compare and contrast the tectothermal evolution of the major tectonic units of this area.

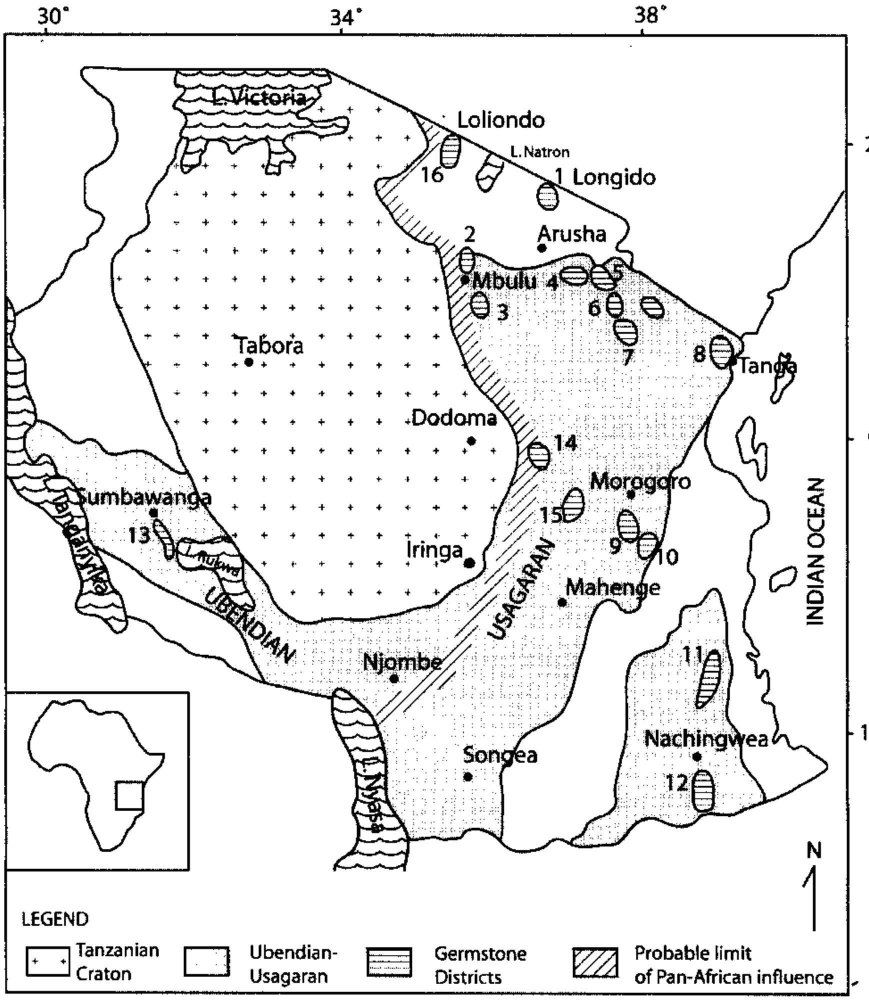

Figure 1: Sketch map showing gemstone mineralization in the Mozambique Belt of Tanzania (Geological Survey of Tanzania 1982): (1) Longido, (2) Manyara (3) Babati (4) Merelani (5) Lelatema (6) Tiriri (7) Landanai (8) Umba (9) Mvuha (10) Magogoni (11) Namaputa (12) Nabunju (13) Sumbawanga (14) Mpwapwa (15) Kilosa (16) Loliondo.

ANALYTICAL METHODS

Ten samples from the surface were analyzed and thin sections were prepared with synthetic resin (Petropoxy, Palause Petro-products, U.S.A., r.i =1.54) and dried at 30^{o} C. Thin sections were then studied under Leitz Ortholux polarizing light microscope. Six 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 NHO_3 and $HClO_4$ 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. FeO and H_2O were determined and Au and Pd with an AAS (Perkin Elmer 2280 with HGA-500 graphite oven (Kontas 1981, Kontas et al. 1987). Thin sections were studied under the microscope and subsequently with microprobe methods. The microprobe analyses were done at the University of Oulu and Geologiccal Survey of Finland with JEOL electron microprobe. The analyzing conditions for the quantitative analyses were 15kV-accelerating voltage, approximately 30nA probe current and beam diameter of about 1μm. An energy-dispersive spectrometer system (EDS) was used to locate the different micas of the pseudomorphs. Usually some mica crystals from three different parts between the core and rim of the pseudomorph or from different zones were analyzed. Natural minerals were used as standards.

PETROGRAPHY AND PETROCHEMISTRY

The pelitic and semi-pelitic gneisses mainly consist of an equigranular assemblage of quartz + sillimanite/kyanite + K-feldspar + Fe-Ti oxides + garnet and biotite. Mineral assemblages and representative modal analyses are given in Table 1. Quartz and potash feldspars are the dominant minerals. Feldspars have grain sizes larger than others and do not show any twinning. Sillimanite occurs as subhedral elongated prisms with one set of cleavages, fibrous or needles. Rarely fine-grained muscovite aggregates are present and appear to be secondary alteration or retrograde products Secondary kaolinite is also common. A notable feature is the oxidation on almandine garnets. Garnets are irregular in shape, traversed and rimmed by dark-red to opaque patches. Chemical analyses show these patches to be mixtures consisting of Fe_2O_3, Al_2O_3 and SiO_2 in varying proportions. In highly oxidized rocks, these oxidation products have completely replaced garnets and formed pseudomorphs after them. Dark-red to opaque Fe-Ti oxides, ilmenite or rutile-hematite intergrowths also appear to have resulted by oxidation from original ilmenite.

Table 1: Mineralogical assemblages and representative modal analyses of pelitic and semi-pelitic gneisses.

Rock No.	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**49**	**51**	**45**	**40**
Quartz	x	x	x	x	x	x	x	x	x	X	23.7	20.9
K-feldspar	x	x	x	x	x	x	x	x	x	X	50.1	51.8
Garnet	n	x	x	n	x	x	x	x	n	X	7.6	0
Biotite	x	x	x	x	x	n	x	x	x	X	0	13.5
Sillimanite	x	x	x	x	x	x	x	x	x	X	9.9	4.5
Kyanite	n	n	x	x	x	x	x	x	x	X	7.6	0
Ilmenite	x	x	x	n	x	x	x	x	x	X	8.5	7.7
Rutile	x	x	n	n	n	x	n	x	x	X	1.2	10.2
Fe-oxides	x	x	x	x	x	x	x	n	x	X	0	0.8
Kaolinite	x	x	n	x	n	n	n	x	x	X	0	2.8
Muscovite	x	n	x	x	n	n	x	x	1.3	X	0	1.3

x -Present n-not present

Whole rock analyses of the gneisses are given in Table 2. When compared with the average composition of pelitic gneisses, CaO, MgO. Na_2O are low. Al_2O_3, TiO_2, K_2O and H_2O are comparable, although water is high, contributed by the presence of secondary kaolinite. The significant feature in the chemistry of these rocks is the variable oxidation ratio. In the highly oxidized rocks (rocks no. 40 and 43), garnet is absent and is totally replaced by mixtures of hematite and anhydrous aluminosilicates. Unlike the variation in oxidation ratios related to inherited pre-metamorphic oxygen content (Chinner 1960, Mueller 1960), the variation recorded in these rocks appears to be a post-metamorphic feature.

WHOLE ROCK CHEMISTRY

Whole rock analyses (determined by XRF and wet chemical method) of the pelitic and semi-pelitic rocks are given in Table 2. The outstanding geochemical feature of these rocks is the chemical changes during metamorphism in their relative silica and graphite enrichment, elements (Fe_2O_3 + MgO + TiO_2 < 20 per cent) but conversely rich in Al_2O_3 as average (16.85 ± 0.5 per cent). They are characteristically depleted in alkali contents, and the dominance of potassium over sodium. The latter occur mainly in the plagioclase, which is seldom more basic than andesine whilst potassium occurs mainly in the potassium feldspar and epidote. FeO is progressively oxidized to Fe_2O_3.

Table 2: Chemical analyses of pelitic and semi-pelitic gneisses.

Rock No.	40	41	42	43	45	55
SiO_2	59.82	69.15	68.28	61.14	74.21	57.61
TiO_2	0.47	1.24	1.04	1.31	0.46	1.11
Al_2O_3	18.7	15.7	19.4	19.16	13.11	25.02
Fe_2O_3	16.68	4.54	2.74	10.45	0.57	3.4
FeO	0.27	3.15	4.31	0.63	1.81	3.37
MnO	0.03	0.01	0.08	0.08	0.01	0.13
MgO	0.47	1.17	0.93	0.14	0.6	1.96
CaO	0.12	0.18	0.2	0.03	1.81	0.17
Na_2O	0.07	0.15	0.2	0.07	1.73	0.76
K_2O	0.12	1.62	1.42	0.12	4.75	2.98
P_2O_5	0.01	0.04	0.02	0.03	0.12	0.01
H_2O	3.16	2.69	1.65	7.01	1.2	3.46
Total	99.91	99.6	100.27	100.21	100.38	99.98
Oxidation Ratio	98.21	56.46	36.44	93.7	22.22	47.6

MINERAL CHEMISTRY

Mineral analyses were done by electron microprobe and are discusses as follows:

Sillimanite. Analyses and formulae are given in Table 3. Fe expressed, as Fe^{3+} is quite significant; V and Cr less commonly substitute for Al. The range of variation in Fe^{3+} in these analyses is inadequate to reflect changes in oxygen fugacity (fo_2), if any, at the time of formation.

Table 3: Chemical analyses of sillimanite

Rock No.	40	41	42	44	49
SiO_2	37.48	37.35	37.1	37.22	37.43
Al_2O_3	62.22	62.08	61.79	62.18	62.29
Cr_2O_3	0.02	0.05	0.03	0.03	0.03
Fe_2O_3*	0.12	0.11	0.13	0.13	0.11
V_2O_3	0.04	0.06	0.06	0.03	0.04
Total	99.88	99.65	99.11	99.59	99.9
	Number of ions on the basis of 20 (O)				
Si	4.048	4.044	4.04	4.034	4.042
Al	7.921	7.922	7.929	7.941	7.927
Cr	0.002	0.004	0.005	0.002	0.003
Fe^{3+}	0.011	0.01	0.012	0.012	0.01
V	0.004	0.006	0.005	0.002	0.004

K- feldspars. The analyses and formulae are given in Table 4. Celcian molecule is consistently present in these feldspars but lower than in the feldspars of adjacent calc-silicate rocks (Koljonen pers. com.). Complete absence of anorthite molecule is noteworthy

Table 4. Analyses of K-feldspars

	41	42	43	45	55
SiO_2	64.77	64.7	65.22	64.72	65.03
Al_2O_3	19.04	18.32	19.42	19.18	18.96
BaO	0.29	0.41	0.36	0.32	0.41
CaO	0.01	0.12	0.01	0.01	0.01
Na_2O	1.18	1.02	0.94	1.33	1.15
K_2O	14.68	15.44	14.76	14.38	14.66
FeO	0.27	0.01	0.27	0.01	0.06
Total	100.24	100.02	100.98	99.95	100.28
	Number of ions on the basis of 32 (O				
Si	11.924	11.982	11.909	11.906	11.946
Al	4.132	3.999	4.181	4.106	4.105
Ba	0.021	0.03	0.025	0.023	0.029
Ca	0	0	0	0	0
Na	0.42	0.367	0.332	0.475	0.409
K	3.447	3.649	3.437	3.375	3.436
Fe	0.057	0	0.42	0	0.002
Si	11.924	11.982	11.909	11.906	11.946
Al	4.132	3.999	4.181	4.106	4.105
Ba	0.021	0.03	0.025	0.023	0.029
Ca	0	0	0	0	0
Na	0.42	0.367	0.332	0.475	0.409
K	3.447	3.649	3.437	3.375	3.436
Fe	0.057	0	0.42	0	0.002

Table 4: Cont.

Sum Z	16.056	15.981	16.09	16.066	16.051
X	3.888	4.05	3.794	3.873	3.874
Mole% Or	88.66	90.11	90.59	87.14	88.69
Ab	10.8	9.06	8.75	12.26	10.56
An	0	0	0	0	0
Cn	0.54	0.74	0.66	0.59	0.75
Sum Z	16.056	15.981	16.09	16.066	16.051
X	3.888	4.05	3.794	3.873	3.874
Mole% Or	88.66	90.11	90.59	87.14	88.69
Ab	10.8	9.06	8.75	12.26	10.56
An	0	0	0	0	0
Cn	0.54	0.74	0.66	0.59	0.75

Garnets. The analyses and formulae are given in Table 5A. These are of the unoxidized remnants and consist mainly of almandine and pyrope molecules with minor grossular and spessartine. Ti, which is so common in andradite of calc-silicate rocks, (Koljonen pers. commun.) is absent here. Octahedral Al is slightly in excess of stoichiometric value and indicates that there is no Fe^{3+} in the mineral. Compositional traverses showed no zoning. Because of the oxidation of almandine component some enrichment of Mg at the interface with oxidation product is expected but no such variation in Mg within the grain could be detected. A notable feature in these rocks is the effect of oxidation on almandine garnets. Garnets are irregular in shape, traversed and rimmed by dark red to opaque patches. Some of these rims are 3-4 microns thick and in some coalesce into patches on garnet to form skeletal networks. Chemical analyses show these patches to be mixtures consisting of Fe_2O_3, Al_2O_3, and SiO_2 in varying proportions (Table 5B). In highly oxidized rocks, these oxidation products have completely replaced the garnets and formed pseudomorphs after them. Dark red to opaque Fe-Ti oxides, ilmenite or rutile-hematite intergrowths also appear to have resulted by oxidation from original ilmenite.

Table 5A: Analyses of almandine garnets

Rock No.	**40**	**41**	**43**	**44**
SiO_2	39.5	39.37	39.57	38.74
Al_2O_3	22.01	21.73	21.63	22.13
FeO*	28.15	29.48	29.13	30.16
MnO	0.23	0.26	0.16	0.25
MgO	9.11	7.99	8.23	7.34
CaO	1.25	1.43	1.21	1.41
Total	100.25	100.26	99.93	100.03
	Number of ions on the basis of 24(O)			
Si	6.013	6.003	6.004	5.989
Al^{3+}	0.01	0.016	0.001	0.032
Al^{4+}	4.03	4.036	4.059	4.032
Fe^{3+}	0	0	0	0
Fe^{2+}	3.584	3.857	3.952	3.952
Mn	0.03	0.033	0.033	0.033
Mg	2.067	1.802	1.737	1.737

Table 5B: Analyses of oxidation Products of garnets

Sample No.	**45**	**46**	**47**
SiO_2	26.95	9.58	13.89
Al_2O_3	23.48	7.16	3.7
Fe_2O_3	39.75	66.94	72.15
CaO	0.23	0.18	0.41
K_2O	0	0	0.08
Total	90.41	83.86	90.23

Table 5: Cont.

Ca	0.237	0.232	0.234	0.234
Total	15.971	15.979	16.02	16.009
%Mg/Mg+Fe	36.58	31.84	33.7	30.53
Mole%				
And	0.56	0.65	0.48	0.52
Gr	3.99	3.91	3.31	3.92
Sp	0.01	0.01		0.01
Al	60.53	65.04	63.85	66.33
Py	34.91	30.39	32.46	29.16

Fe-Ti Oxides. Two types of Fe-Ti oxides are found. The formulae of the analyses are given in Table 6A when calculated on the basis of 6 (O) show good stoichiometry corresponding to ilmenites. There is only slight excess of Ti relative to stoichiometric value. Stoichiomeric excess of Ti over Fe as $FeTi_2O_5$ has been reported in high-grade granulitic ilmenite (Schmidt and Wood, 1976) but this can also be due to low temperature –pressure alteration of ilmenite (Bailey et al., 1956). The second type of Fe-Ti oxides is given in Table 6B. These are from highly oxidized rocks. Their formulae when calculated on 6(O) showed large departures from ilmenite formula. Hence they are expressed as rutile and hematite mixtures. Although they apparently appear to be single phases, they may consist of submicroscopic intergrowths of rutile, hematite and ilmenohematite. They could have resulted from oxidation of original ilmenite:

$$2FeTiO_3 + 1/2O_2 = Fe_2O_3 + 2TiO_2 \qquad (1)$$

In rock no. 40, which has the highest oxidation ratio, no stoichiometric ilmenite is found, and the oxide phase is an aggregate of rutile + hematite.

Fe-Oxides. Some analyses of oxidation products of garnets are given in Table 5B. They appear to be mixtures of varying proportions of hematite, quartz, and hydrous aluminosilicates. The oxidation of almandine in the presence or absence of water can occur through reactions:

$$\underset{\text{Almandine}}{2Fe_3Al_2Si_3O_{12}} + 4H_2O + 3/2O_2 + = 3Fe_2O_3 + \underset{\text{Kaolinite}}{Al_4Si_4O_{10}(OH)_8} + 2SiO_2 \qquad (2)$$

$$\underset{\text{Almandine}}{2Fe_3Al_2Si_3O_{12}} + 3/2O_2 = 3Fe_2O_3 + \underset{\text{Aluminosilicate}}{Al_2SiO_2} + 4SiO_2 \qquad (3)$$

$$2Fe_3A_{12}Si_3O_{12} + H_2O + 3/2\ O_2 = 3Fe_2O_3 + A_{12}SiO_5 + \underset{\text{Pyrophyllite}}{Al_2Si_4O_{10}(OH)_2} + SiO_2 \qquad (4)$$

Table 6: Analyses of ilmenite

A: ILMENITE

Rock No.	41	43	55
SiO_2	0.38	0.54	0.48
TiO_2	53.67	55.1	53.94
V_2O_3	0.2	0.24	0.22
FeO**	43.91	42.16	43.25
MnO	0.19	0.18	0.26
MgO	1	0.72	0.86
Total	99.35	98.94	99.01

B: OXIDIZED ILMENITE

Rock No.	40	43
SiO_2	1.05	0.56
TiO_2	57.08	59.91
V_2O_3	0.35	0.39
Fe_2O_3*	37.76	36.13
MnO	0.16	0.23
MgO	0.43	0
Total	96.83	97.22

Table 6: Cont.

Number of ions on the basis of 6 (O)			
Si	0.019	0.027	0.024
Ti	2.016	2.059	2.028
V	0.008	0.009	0.009
Fe^{2+}	1.835	1.752	1.808
Mn	0.008	0.008	0.011
Mg	0.074	0.054	0.064
Total	3.96	3.909	3.944

Mol.% Rutile	75.13	78.82
% Hematite	24.18	23.1
Total Fe as	Fe_2O_3	

** Total Fe as FeO

Since the analytical totals of the oxidized products are much less than 100, they have considerable quantities of water, so that they could correspond to the mixture of the product phases of reaction (2) or (4). Experiments by Hsu (1968) demonstrate the oxidation effects of garnet. Hsu found that the assemblage hematite-mullite (or sillimanite)-pyrophyllite such as reaction (4) could be produced at temperatures less than 500^{0}C and at log PO_2 above –20, above the magnetite-hematite buffer. Such high temperature alteration might have occurred in these rocks with probable influx of water.

CONDITIONS OF METAMORPHISM

The almandine-biotite geothermometer is based on the distribution of Fe and Mg between these two minerals. At least three calibrations for this geothermometry exists: the experimental one of Ferry and Spear (1978), which is based solely on binary Fe-Mg distribution and the two semi-empirical ones whose calibration takes into account the substitution of minor constituents for Ca and Mg in garnet (Thompson 1976, Goldman and Albee 1977). The garnets analysed were almandine-pyrope with very low contents of Mn and Ca. Because the calibration of Goldman and Albee 1977 may overcorrect for the Mn- and Ca-substitution (Ferry 1980), the calibration of Ferry and Spear 1978 was chosen, and for comparison the modified calibration of Hodges and Spear 1982. Temperatures calculated from the Ferry and Spear 1978 equation range from 596^{o}C-727^{o}C and those obtained from the modified Hodges and Spear 1982 method from 612^{o}C to 743^{o}C (Table 7). The almandine-plagioclase geobarometer were used to estimate the pressure of metamorphism. Compositions of coexisting almandine and plagioclase in an assemblage with quartz and sillimanite and/or kyanite provide an estimate of the pressure attained during metamorphism (Kretz 1964, Ghent 1976). Here, pressure attained by the rocks during metamorphism was estimated by the method of Newton and Hasselton 1981. The calculated pressures, ranging from 7.7 to 9.1 kbars, are presented in Table 8 and together with the temperatures in Fig. 2.

Table 7: Mineral data and temperature estimates.

	Garnet			Biotite				
Sample No	X_{Fe}^{Ga}	X_{Mg}^{Ga}	X_{Ca}^{Ga}	X_{Fe}^{Bi}	X_{Mg}^{Bi}	KD	T (F&S)	T (H&S)
40	0.639	0.325	0.033	0.217	0.485	0.222	679	693
41	0.639	0.325	0.033	0.228	0.502	0.168	687	700
42	0.639	0.325	0.033	0.213	0.507	0.191	654	667
43	0.618	0.332	0.043	0.242	0.514	0.164	727	645
44	0.606	0.349	0.040	0.236	0.539	0.139	726	743
46	0.651	0.304	0.039	0.233	0.547	0.138	623	638
48	0.609	0.349	0.039	0.233	0.537	0.149	719	735
49	0.664	0.292	0.039	0.231	0.549	0.141	596	612
53	0.605	0.351	0.039	0.235	0.542	0.136	725	741
61	0.612	0.342	0.042	0.216	0.565	0.147	654	671

X_i^{Ga} = i/(Fe + Mg + Ca + Mn) in garnet, where i = Fe, Mg, Ca

X_i^{Bi} = i/(Fe + Mg in biotite, where i = Fe or Mg

T (F&S) temperatures °C calculated using the Ferry and Spear (1978) calibration. (T (H&S) temperatures °C calculated using the Hodges and Spear (1982) calibration.

Table 8: Mineral data and pressure estimates

	Plagioclase		Garnet			
Sample No`	X_{An}	X^{Ga}_{Fe}	X_{Mg}^{Ga}	X_{Ca}^{Ga}	P (N&H)	Aluminosilicate (inclusions)
40	0.210	0.574	0.381	0.040	8.2	Kyanite
41	0.209	0.587	0.367	0.042	8.4	Kyanite
42	0.206	0.588	0.367	0.039	9.1	Kyanite
43	0.195	0.595	0.361	0.040	8.1	Sillimanite
44	0.199	0.591	0.364	0.040	8.1	Sillimanite
46	0.201	0.599	0.355	0.041	7.7	Sillimanite
48	0.198	0.580	0.376	0.040	8.3	Kyanite
49	0.200	0.562	0.392	0.039	8.2	Sillimanite
53	0.195	0.606	0.350	0.039	7.7	Sillimanite
61	0.209	0.584	0.372	0.039	8.0	Kyanite

X_{An} = Ca/(Na + Ca + K) in plagioclase

P (N&H) pressure in kbar calculated using the Newton and Hasselton (1981) calibration.

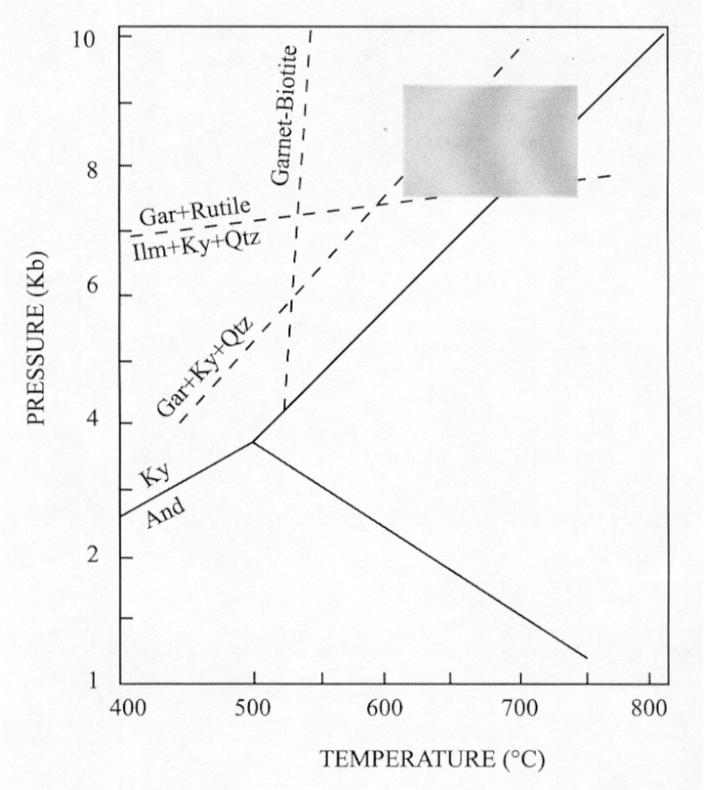

Figure 2: Pressure and temperature estimates (shaded area) for the pelitic and semi-pelitic rocks in the Merelani tanzanite mining area. Diagonal lines indicate gross P-T limits based on the presence of kyanite. Al_2SiO_5 diagram is from Holdaway (1971).

DISCUSSIONS AND CONCLUSIONS

These rocks do show migmatization and, therefore, conditions were above granite solidus. At 6 kbars pressure, to avoid partial melting, temperatures have to be above 700^{o}C and XH_2O has to be at or above 0.6 agreeing well with metamorphic conditions estimated at the Merelani tanzanite mining area. Compared with the average composition of pelitic and semi-pelitic gneisses, CaO, MgO Na_2O are low. Al_2O_3, TiO_2, K_2O and H_2O are comparable, although H_2O is high, contributed by the presence of secondary kaolinite. The significant feature in the chemistry of these rocks is the variable oxidation ratio. In the highly oxidized rocks (No. 40 and 43) garnet is absent and is totally replaced by mixtures of hematite and anhydrous aluminosilicates. Unlike the variation in oxidation ratios related to inherited pre-metamorphic oxygen content (Chinner 1960, Mueller 1960), the variation recorded in these rocks appears to be a post-metamorphic.

The temperatures calculated using Ferry and Spear method ranged from 596^{0} – 727^{0} C and those obtained using Hodges and Spear method ranged from 612^{0}- 743^{0} C.

Pressures attained by the rocks during metamorphism using Newton and Hasselton method was obtained by using almandine-biotite pairs. The calculated pressures range from 7.7 to 9.1 k bars. The temperature estimates obtained by using the Hodges and Spear method are slightly higher than those obtained by the Ferry and Spear, but the difference ranges are small. The biotite-garnet pairs provide slightly scattered temperatures since the composition of biotite varies. However, the results obtained are reasonable and in accordance with those reported in granulite facies rocks elsewhere.

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