CHAPTER VII

DISCUSSION AND CONCLUSION

7.1 Introduction

In this chapter, an attempt will be made to compare the chemical data, luminescence behavior and types of mineral inclusions of Songea corundum with those of some well known basaltic and metamorphic deposits.

7.2 Trace element composition

The chemical data from the EDXRF analysis of the red and purple varieties of Songea corundum are compared with those of some basaltic and metamorphic rubies and pink sapphires kindly provided by the GIT in Table 7.1 and a similar kind of comparison for the blue variety is shown in Table 7.2. As shown in Tables 7.1 and 7.2, the red, purple and blue varieties of Songea corundum have extremely high Fe_2O_3 content comparable to those of basaltic rubies and sapphires from Thailand, Australia and Cambodia while metamorphic corundums from Sri Lanka, Madagascar and Vietnam show much lower Fe_2O_3 contents.

Plots of Fe_2O_3/Cr_2O_3 versus TiO_2/Ga_2O_3 (see Sutherland and Schwarz, 2001; Sutherland et al., 2003) of all varieties of Songea corundum together with basaltic and metamorphic rubies (Figure 7.1) show clearly that the red variety of Songea corundum is plotted closer to Chanthaburi rubies of basaltic origin (Figure 7.1). Although Luc Yen pink sapphires of metamorphic origin have a similar Fe_2O_3/Cr_2O_3 range to the red variety of Songea, TiO_2/ Ga_2O_3 ratios of Luc Yen are somewhat lower. The other varieties of Songea corundums also contain TiO_2/Ga_2O_3 within the same range of basaltic and metamorphic rubies. However, their Fe_2O_3/Cr_2O_3 ratios are much high due to the fact that smaller amount of Cr_2O_3 are actually present in other color varieties. The plot of Fe2O3 versus Ga2O3 contents (Figure 7.2) also shows similarly that all varieties of Songea corundum fall closer to Chanthaburi rubies of basaltic origin (some Songea corundums even have higher Fe_2O_3 content than the Chanthaburi rubies).

Plots of TiO_2+Fe_2O_3 versus Ga_2O_3 and Fe_2O_3 versus Ga_2O_3 of all Songea samples with blue sapphires from some basaltic and metamorphic sources are displayed in Figures 7.3 and 7.4, respectively. These plots can clearly discriminate the Songea blue sapphire as well as the other varieties of Songea corundum from those basaltic and metamorphic blue sapphires. The blue variety contains high TiO_2+Fe_2O_3 or Fe_2O_3 contents similar to those of basaltic blue sapphires and clearly higher than those of metamorphic blue sapphires (Figure 7.3). However their Ga_2O_3 contents fall somewhat closer to those of the metamorphic blue sapphires. Some Songea corundums even have higher Fe_2O_3 content than the basaltic blue sapphires (Figure 7.4).

Table 7.1 Comparison of trace element oxides in the red and purple varieties of Songea corundum with those of basaltic and metamorphic rubies and pink sapphires.

Localities	Varieties	Trace Elements (Wt.%)				
(no. of sample)		Ga_2O_3	TiO_2	V_2O_5	Cr_2O_3	Fe_2O_3
*basaltic						
Chanthaburi (10)	ruby	<0.01	0.04-0.18	<0.01	0.09-0.49	0.57-1.57
*metamorphic						
Mong Hsu (27)	ruby	<0.04	0.01-0.35	0.02-0.19	0.42-5.99	0.03-0.26
W.Africa (11)	ruby	<0.01	0.02-1.25	<0.03	0.03-0.39	0.42-0.62
Tamatave (9)	ruby	<0.01	0.04-0.64	<0.03	0.19-0.57	0.03-0.64
Ilakaka (22)	pink	<0.02	<0.04	<0.02	0.06-0.13	0.04-0.61
Luc Yen (51)	pink	<0.06	0.02-0.65	<0.13	0.04-1.82	0.03-1.06
Songea (12, 8)	red	<0.01	0.03-1.37	<0.04	0.05-0.54	1.04-1.69
	purple	<0.02	0.01-0.23	<0.02	<0.14	1.01-1.91

*with the courtesy of GIT

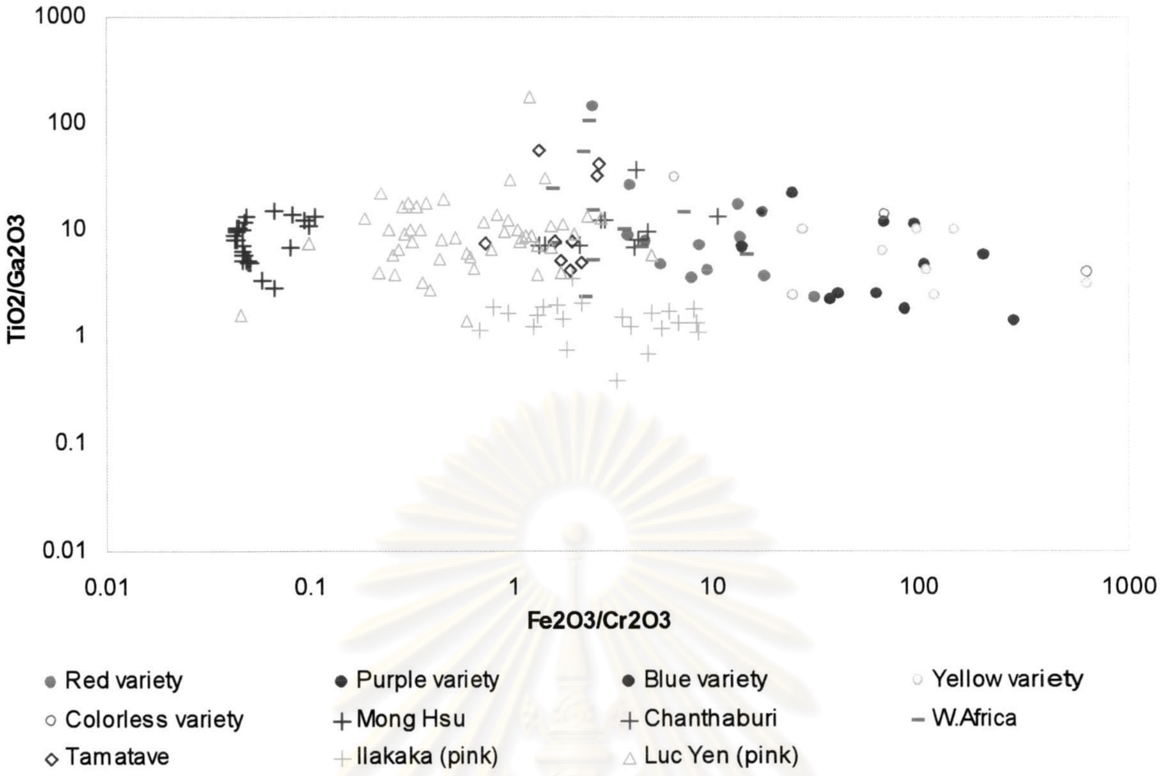

Figure 7.1 Trace compositions plotting between Fe_2O_3/Cr_2O_3 and TiO_2/Ga_2O_3 of all Songea corundum samples and some with basaltic and metamorphic rubies.

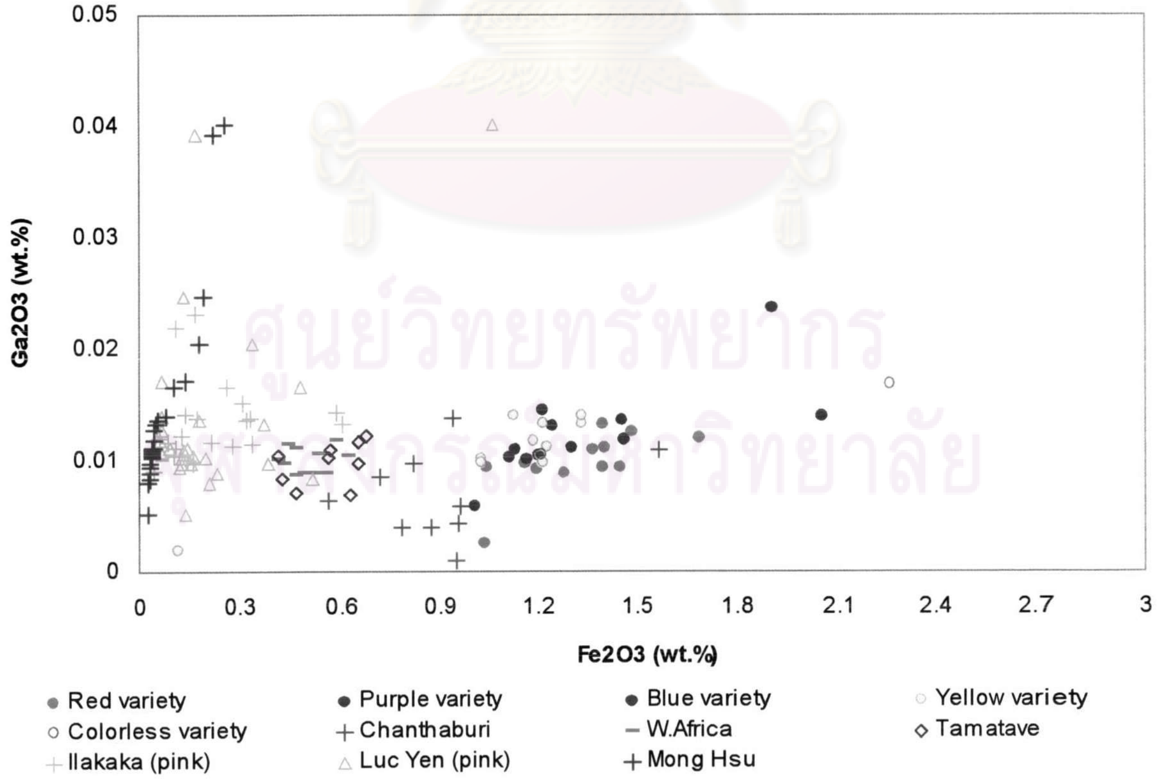

Figure 7.2 Fe_2O_3 versus Ga_2O_3 plots of all Songea corundum samples and some basaltic and metamorphic rubies.

Table 7.2 Comparison of trace element oxides in the blue variety of Songea corundum with those of some basaltic and metamorphic blue sapphires.

Localities	Varieties	Trace Elements (Wt.%)				
(no. of sample)		Ga_2O_3	TiO_2	V_2O_5	Cr_2O_3	Fe_2O_3
basaltic						
Kanchanaburi (13)	blue	<0.05	0.02-0.20	<0.02	<0.03	0.48-1.76
Inverell (27)	blue	0.02-0.04	0.02-0.15	<0.01	<0.01	0.66-1.32
Cambodia (18)	blue	0.03-0.22	0.03-0.86	<0.01	<0.02	0.38-2.08
metamorphic						
Sri Lanka (11)	blue	<0.02	0.01-0.05	<0.01	<0.03	0.09-0.41
Skaraha (19)	blue	<0.03	0.01-0.24	<0.01	<0.07	0.09-0.66
Ilakaka (10)	blue	<0.02	0.02-0.13	<0.02	<0.06	0.05-0.32
Songea (4)	blue	<0.02	0.02-0.16	<0.01	<0.03	1.13-2.06

*with the courtesy of GIT

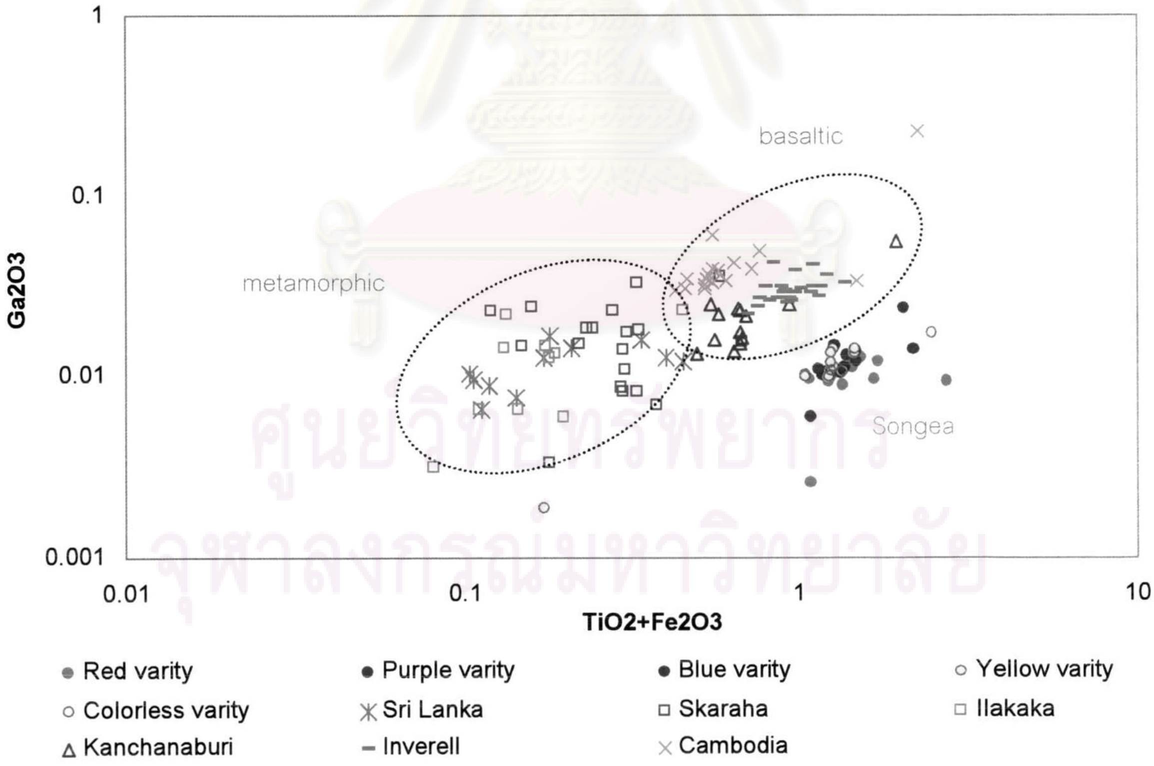

Figure 7.3 Plots of TiO_2+Fe_2O_3 vs Ga_2O_3 of all Songea corundum samples and blue sapphires from some basaltic and metamorphic origins.

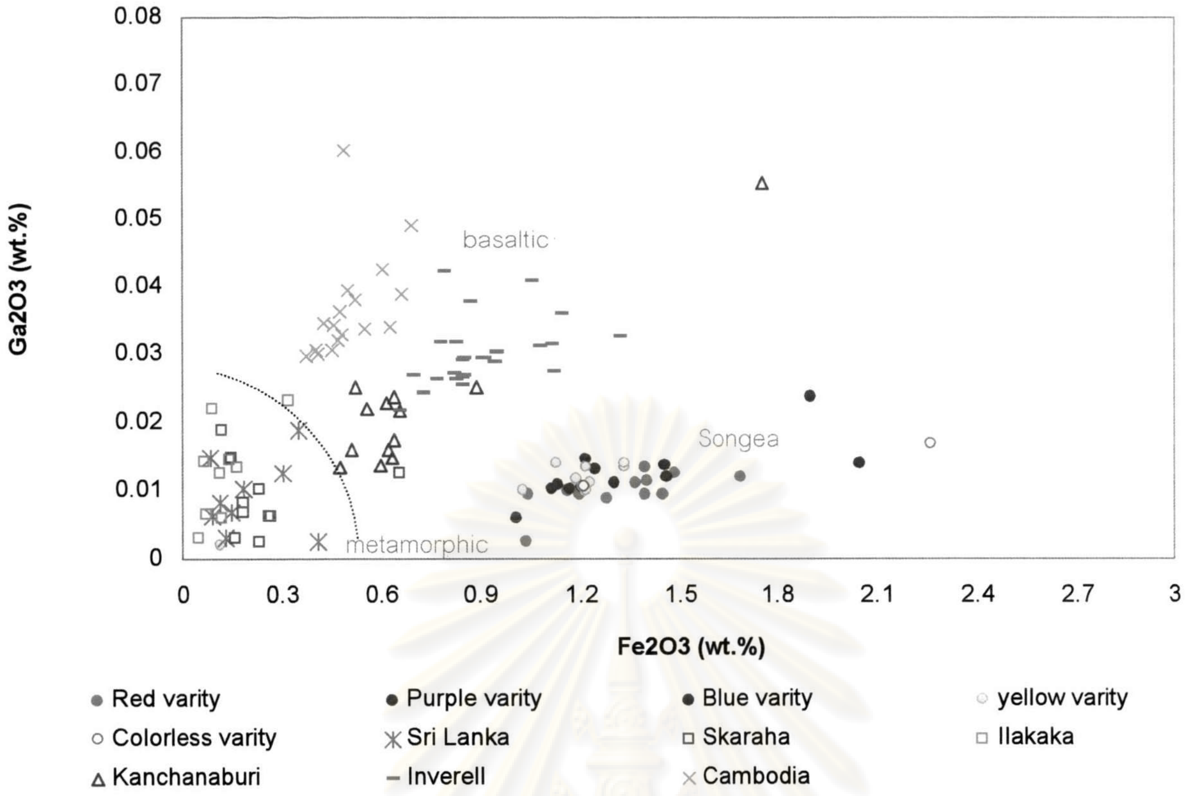

Figure 7.4 Plots of Fe_2O_3 versus Ga_2O_3 in wt.% of all Songea corundum and blue sapphires from some basaltic and metamorphic sources.

7.3 Luminescence

Luminescence under ultraviolet lamps (both long wave and short wave) of all Songea corundums are compared with some colored corundums from major deposits of metamorphic and basaltic origins (Table 7.3). In general, luminescence in basaltic corundum is relatively lower than that of metamorphic corundum having the same color shades. However, for Songea corundums, luminescence is inert to moderate under longwave and mostly inert under shortwave. This characteristic is quite different from other metamorphic corundums. Instead, they seem like basaltic origin. Moreover, samples in red variety of Songea corundums examined by cathodoluminoscope yield unexpectedly very weak luminescence (Figure 7.5). This is obviously different from strong cathodo-luminescence of Umba metamorphic ruby (Figure 7.5) which also comes from the same Mozambique Orogenic belt of Tanzania.

Songea Umba

Figure 7.5 Cathodo-luminescence of red Songea corundum appears rather weak red in contrast to strong red of an Umba metamorphic ruby.

Table 7.3 Luminescence under ultraviolet of corundum from other localities compared with Songea corundums (modified from Hughes, 1997).

Variety	Long wave	Short wave
Red variety: Songea	Weak to moderate red	Inert
Ruby: Myanmar, Sri Lanka (metamorphic)	Moderate to very strong red or red-orange	Moderate to strong red or red-orange, slightly weaker than long wave
Ruby: Thailand, Cambodia (basaltic)	Weak to moderate red or red-orange	Inert to moderate red or red-orange, slightly weaker than long wave
Ruby: Kenya (metamorphic)	Strong to very strong red or red-orange	Moderate to very strong red or red-orange, slightly weaker than long wave
Purple variety: Songea	Weak red	Inert
Purple and violet sapphire: Sri Lanka (metamorphic)	Weak to strong red to orange-red	Inert to strong red to orange-red
Blue variety: Songea	Inert	Inert
Blue sapphire: Sri Lanka (metamorphic)	Inert to strong red or orange	Inert to moderate red or red-orange, slightly weaker than long wave
Blue sapphire: Myanmar (metamorphic)	Inert to moderate red or orange	Inert to moderate red or orange
Blue sapphire: Cambodia, Australia, Thailand (basaltic)	Generally inert	Generally inert, rarely week chalky blue to green
Blue sapphire: Kashmir (metamorphic)	Inert to moderate red or orange	Inert to moderate red or orange
Yellow and orange sapphire: Songea	Moderate orange-moderate red	Inert
Yellow and orange sapphire: Sri Lanka (metamorphic)	Inert to strong orange to orange-red	Inert to strong orange to orange-red
Yellow and orange sapphire: Australia, Thailand (basaltic)	Inert to moderate red	Very weak to weak red
Colorless variety: Songea	Inert	Inert
Colorless sapphire: Sri Lanka (metamorphic)	Inert to strong orange to orange-red	Inert to moderate orange to orange-red, rarely weak to moderate chalky blue to green

7.4 Mineral inclusions

Mineral inclusions in Songea corundums observed under microscope and identified using Raman Spectroscopy are apatite, epidote, plagioclase, garnet, hematite, mica, paragonite and rutile. They are summarized and compared with mineral inclusions reported from other metamorphic corundums including Umba corundums (Hughes, 1997; Wathanakul et al., 2002) in Table 7.4. The comparison is aimed to distinguish Songea corundums from other deposits in Mozambique belt and elsewhere. Unfortunately, data sets of mineral inclusions in corundum from other localities along the Mozambique belt have not been widely published; hence only data sets of Umba corundums are used for this comparison.

As shown in Table 7.4, some mineral inclusions have been found in both Umba and Songea; they are apatite, hematite, mica and rutile. Several minerals, such as boehmite, calcite, dolomite, graphite, monazite, pyrrhotite, spinel and zircon, have been reported from Umba corundum but still have not been found in Songea corundum in this study. However a few significant mineral inclusions, i.e. epidote, andesine plagioclase, almandine garnet and paragonite, are discovered in this study (Table 7.4). These new mineral inclusions, especially almandine and probably epidote and paragonite, indicate a metamorphic origin of Songea corundums in the Mozambique belt. The rock type and metamorphic environment in the Songea area may be somewhat different from that in the Umba Valley area. The relatively high iron content (which could depress the luminescence behavior) in Songea corundum may be related to the fact that there are several BIF found in this metamorphic belt.

As for the Mangari ruby from Kenya located within Mozambique belt and the Mogok ruby, they show different assemblages of mineral inclusions, such as diaspore, graphite, monazite and zircon, which are uncommon in Songea corundums.

The comparison between Songea corundums and basaltic corundums from Kanchanaburi (Thailand), Huai Sai (Laos) and NSW & Anakie (Australia) is shown in Table 7.5. Apatite, epidote and almandine garnet are still unique for Songea metamorphic corundums (Table 7.5). Feldspar, mica and rutile have been reported from both basaltic localities and the Songea but they may contain difference types of feldspar, for example orthoclase feldspar has been reported in Kanchanaburi sapphires while plagioclase feldspar is found in Songea corundums. Besides, other basaltic mineral inclusions such as biotite, bismuth, diopside, ferro-columbite, gahnite, herceynite, ilmenite, monazite, nepheline, pleonaste, pyrrhotite, pyrite, spinel, thorite and zircon are absent from Songea metamorphic corundum.

Table 7.4 Mineral inclusions found in corundums from Songea and other metamorphic corundum deposits.

Minerals	[1]**Mogok ruby**	[1]**Mangari ruby**	[1+2]**Umba corundum**	**Songea corundum**
Apatite	x		x	x
Boehmite			x	
Calcite			x	
Diaspore	x			
Dolomite			x	
Epidote				x
Feldspar				andesine
Garnet				almandine
Graphite	x	x	x	
Hematite			x	x
Mica		x	x (biotite)	x, paragonite
Monazite		x	x	
Paragonite				x
Pyrrhotite			x	
Rutile	x		x (needles)	x (needles & crystals)
Spinel			x	
Zircon	x		x	

[1] Hughes (1997); [2] Wathanakul et al. (2002)

Table 7.5 Mineral comparison between Songea corundum and basaltic corundums from South East Asia and Australia.

Minerals	[1]**Kanchanaburi sapphire**	[2]**Huai Sai sapphire**	[3]**NSW & Anakie corundum**	**Songea corundum**
Apatite				x
Biotite	x			
Bismuth	x			
Diopside	x			
Epidote				x
Feldspar	orthoclase		x	andesine
Ferro-colombite	x	x	x	
Gahnite	x			
Garnet				almandine
Hematite				x
Herceynite	x			
Ilmenite	x		x	
Mica		x		x, paragonite
Monazite	x			
Nepheline	x			
Pleonaste	x			
Pyrrhotite			x	
Pyrite		x		
Rutile	x		x	x
Spinel	x		x	
Thorite	x	x	x	
Zircon	x		x	

[1] Intasopa et al. (1998); [2] Wathanakul et al. (2003); [3] Hughes (1997)

7.5 Petrogenesis

Because of the fact that Songea corundums have been mined from secondary alluvial deposits. Hence their geological origin was largely obliterated. It is however an additional purpose of this research to gain some information on the petrogenesis of corundum-bearing rocks before the weathering, erosion, transportation and re-deposition have taken place. The study on the mineral chemistry of inclusions was consequently carried out to get more evidences for this aspect. Chemical compositions of some mineral inclusions were reported in section 3.5 and Table 3.3.

Garnet is chemically characterized by almandine-rich composition that could be comparable to composition of almandine in chlorite-phengite-biotite-garnet-albite-quartz schist from Dora-Maira massif, Western Italian Alps (Deer et al., 1992). Almandine garnets can be crystallized in wide range of metamorphism such as thermal hornfels, granulite and eclogite facies. However, they seem to be related to iron-rich composition.

Feldspar inclusions in Songea corundum have composition of plagioclase range (Ca-Na feldspar), which their atomic ratios of Ca:Na are about 4:6 falling in andesine (Figure 3.23). The andesine composition may resemble an andesine antiperthite in two-pyroxene granulite, charnockite series, Madras, India (Deer et al., 1992).

The EPMA analysis of epidote and rutile inclusions unfortunately yield somewhat low total oxide content that may be effected by a rather small grained size and low quality of polished surface. However, the analytical results still give qualitative information indicating the compositions of epidote and rutile (Deer et al., 1992). Epidote could be formed in a wide range of metamorphic condition, green schist to amphibolite facies, and even in hydrothermal alteration. Rutile usually originates in high pressure, high temperature conditions of probably amphibolite to eclogite facies (Deer et al., 1992). It however can also be found in igneous rocks.

Unfortunately, the composition of paragonite and several unknown mineral inclusions could not be confirmed by EPMA, due to the difficulty of sample preparation. Otherwise they should give some good evidences to unravel the origin of Songea corundums. However, an experiment running from 520°C at 1 kbar to 630°C at 7 kbar that are in amphibolite facies mentioned by Deer et al. (1992) is an interesting reaction as follows:

Paragonite → albite + corundum + water

Concerning petrology of Mozambique rocks in Tanzania, they are composed of Archaean basement and several younger metasedimentary sequences (Moeller et al., 2000; Appel et al., 1998). They reported that this metamorphic belt appeared to have been metamorphosed several times. Granulite facies were likely to be the peak of the metamorphism. Usagaran rock sequences mainly occupy the Songea deposits as a part of the Mozambique Belt, particularly on the eastern craton. Rocks of these sequences are characterized by medium- to high-grade metamorphic gneisses, schists, granulites, quartzites, marbles and amphibolites (www.africaonline.co.tz). P-T estimations of Mozambique granulites have been reported about 12-13 kbar and 750°C -800°C (Sommer et al., 2003).

Besides mineral inclusions may be crystallized before or equilibrated at the time of corundum crystallization. Hence, corundums in Songea deposits could originate in a granulite facies rocks and subsequently retrograded to amphibolite facies rocks. This is because epidote is usually formed in (lower metamorphic grade) amphibolite facies while almandine garnet is normally equilibrated in (higher metamorphic grade) granulite facies. The other inclusions, e.g. andesine plagioclase and paragonite mica, could be equilibrated in both amphibolite and granulite facies. However, these processes could also be started from epidote-corundum amphibolite rock transition to higher grade of garnet-corundum granulite rock have taken place.

7.6 Conclusions

Physical Characteristics

The dominant characteristics of corundum samples from Songea for this study are unique in range of color, generally are red, orange, blue, violet, purple, yellow, green, colorless, etc, and every combination in between.

Change of color can be observed in purple and blue samples. The varying reaction to ultraviolet light are common in red and purple varieties which display weak to moderate red in long wave and inert in short wave. Cathodo-luminescence of Songea corundums, particularly red variety is very weak red (similar to basaltic corundum), and are obviously different from other metamorphic corundums.

Trace element composition

Fe_2O_3 contents in Songea corundums are obviously higher than most metamorphic corundums (e.g. Mong Hsu, Sri Lanka, Ilakaka, Sakaraha and Luc Yen). They are close to range of basaltic origins, such as Thailand and Cambodia. In addition, Fe_2O_3 contents of some Songea corundums are even higher than those of basaltic corundums.

Petrogenesis

Mineral inclusions in Songea corundum, namely apatite, epidote, feldspar, garnet, hematite, mica, paragonite and rutile, are partly similar to those reported from Umba corundums in Mozambique Belt. However, several types of inclusions found in Umba have not been found in Songea corundums available in this study. It should be notified that epidote, andesine plagioclase and almandine garnet are recognized in Songea corundums. The presences of epidote inclusion may suggest that the corundum might have formed at high pressure and high temperature in granulite facies and subsequently retrograded to low pressure and low temperature in amphibolite facies.

Most mineral inclusions and their mineral chemistry are probably related to metamorphic events in Mozambique Belt (Usagaran in this area). Corundums appear to have been equilibrated during prograde and retrograde metamorphic conditions between amphibolite facies and granulite facies. More corundum samples and their inclusions should be investigated further. They may indicate more clearly in all aspects.

Heat treatment

Songea corundums have low potential for heat treatments either in oxidizing condition or reducing condition. This is effected by Mg:Ti ratio of 1:1 and high Fe content, which trend to turn colorless at high temperature. However, blue shade in purple stone can be decreased and then improve color quality to red stone.