Corundum-Spinel-Taafeite-Scheelite bearing Metasomatites in Bakamuna, Sri Lanka: Modeling of its Formation

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INTRODUCTION

Sri Lanka has long been renowned for its wide variety of gemstones dominated by varieties of corundum, chrysoberyl, garnet, spinel, tourmaline, zircon etc. Most of the gem deposits occur in stream valleys as placer deposits. A peculiar kind of corundum-spinel-scheelite-taafeite occurrence has been found associated with marble at Bakamuna within the central granulite belt of Sri Lanka (Fig 1). Although scheelite and taaffeite are found in Sri Lankan alluvial plains, this is the first reported in-situ occurreces of scheelite and taaffeite *(Fernando & Hofmeister, 2000).*

Corundum deposits localized in marbles are widely known in history as a source of precious stones in many countries including Burma, Kashmir, Afghanistan, Tanzania and as well as the Urals and the Pamirs deposits. The formation of these deposits is explained by; (1) metamorphism of lime-stones primarily contaminated by aluminous products of weathering *(Okrusch et al., 1976; Rossovskiy et al., 1982);* (2) metasomatic transformations of terregenous layers in marbles by metamorphic solutions *(Dmitriev, 1982; Kisin, 1991);* and (3) influx of Al into marbles by endogenic solutions related to the alkalic magmatism *(Terekhov et al., 1999).* Corundum-spinel-scheelite-taafeite-bearing rocks in Sri Lanka cannot be explained by any of the above methods due to the fact that corundums are localized neither within the marble nor in
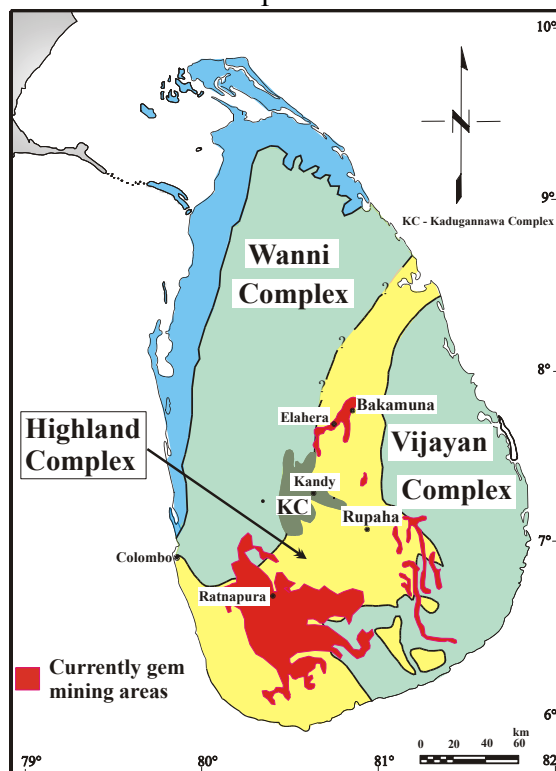

Fig.1: Generalized geological map of Sri Lanka and the location of study (after Cooray, 1994)

neighbouring pelitic gneisses. Instead corundum and other gem minerals bearing mineralogical zoning were observed sandwiched in between these two rocks.

This paper attempts to model the formation of corundum and other gem minerals-bearing lenses or pockets at Bakamuna on the basis of field relations, phase petrology and condition of formation, rock and mineral chemistry under the influence of hydrothermal fluids.

FIELD RELATONSHIPS, CHEMISTRY AND PETROLOGY

Lenticular or irregularly shaped, corundum and other gem mineral-bearing layers are present along the tectonic contacts between pelitic gneisses and marble. These discontinuous layers and lenses are from 20 centimetres to a few metres in thickness and may be traced for tens of metres along the strike. These layers are commonly less deformed, with coarse-grained embedded crystals, which may be seen as endo- and exometamorphic reaction zones. Minerals reaction zones represent the transformation of the host marble to Al-rich pelitic gneisses. The texture of reaction zones vary from fine-grained, equigranular to coarse-grained (approaching pegmatitic), locally displaying pseudo-orbicular texture. The rocks immediately adjacent to the mineralogically zoned body are marble and high-grade pelitic gneiss. The body comprises three mineralogically different zones as summerized below.

Marble | *Spl + Phl* | *Crn +Phl* | *Crn +An* | **High Grade Pelitic Gneiss**

The inner zone in contact with marble is spinel and phlogophite rich, in which the X_{Phl} content is 0.98 on average (Table 1). The purple coloured middle zone is confined to the minerals spinel and corundum. The zone adjacent to pelitic rock is a coarse-grained pegmatitic-looking rock with corundum and andesine feldspar (Ab = 70%; An = 30% on average) as main constituents. Both middle zone and pegmatite-looking zone collectively form an area of extensive vein development. Corundum crystals may be idiomorphic, xenomorphic or skeletal and may vary from near gem quality to those with abundant solid inclusions.

Two types of late mineralization have been recognized. One is thought to have formed just after the thermal peak, reflected by minerals such as scheelite, nepheline, albite and scapolite (Me = 50% on average), while the other is obviously very late consisting mainly of calcite, muscovite, chlorite and other carbonate minerals. Seconday overprints of taaffeite are confined to inclusions in spinel in the form of needles/blades whereas nepheline and scapolite are seen towards the contact of the pelitic zone (Fig.2). The textural evidence also suggests that scheelite and taafeite, which are not produced during
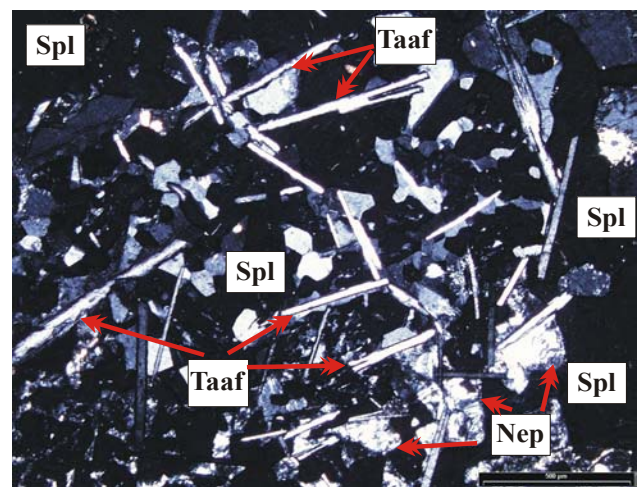

Fig.2. Photomicrograph showing the Taafeite and nepheline overprints on spinel at the reaction zones

metasomatism, may have been nucleated at later stages. Scheelite was identified by the UV shortwaves. Wide variations of mineral compositions across the zones are also evident. Biotite composition varies from phlogopite to eastonite where as plagioclase is anorthite in one cases, and albite, in others as overprints towards the pelitic gneisses. Corundum crystals commonly alter to muscovite along fractures and twin planes. These stages of mineralization as evidenced by thin section studies can be illustrated as follows.

Country Rock		Reaction Bands			Country Rock
Stage (1) **Marble**	| *Spl + Phl*	| *Crn +Phl*	| *Crn +An*		**Pelitic Gneisses**
Stage (2)	| *Taaf*	| *Neph +Alb*	| *Scap*	|	
Stage (3)	|	*Scheelite*		|	
Stage (4)	|	*Chl + Mus +Cal*		|	

Mineral abbreviations: Phl-phlogipite, Crn-corundum; Spl-spinel; Scap-scapolite; Neph-nepheline; Taaf-taaffeite; Alb-Albite, Mus–muscovite, Chl- chlorite, Scap -Scapolite , Cal-Calcite, An-Anorthite

Table 1.1 Chemistry of Minerals in the Reaction Zones *(Primary Minerals)*

Mineral	Spl	Spl	Phl	Phl	Phl	Plag	Plag	Plag	Plag	Mineral	Crn	Crn	Crn
Sample	96	103	107	108	109	48	49	50	51	Sample	10	3	5
SiO2	0	0.042	37	37.27	36.79	58.76	59.22	60.04	60.45	Al2O3	99.88	99.89	99.81
TiO2	0.037	0	4.91	4.28	5.7	0.067	0.022	0	0.052	SiO2	0.027	0.033	0.028
Al2O3	70.21	70.35	18.2	18.2	18.73	25.34	24.75	25.03	24.09	MgO	0.016	0.014	0.015
FeO	3.15	3.15	1.052	1.09	1.108	0	0.032	0	0	Sc2O3	0	0	0
Cr2O3	0.019	0.053	0	0	0	0.019	0.029	0	0	CaO	0	0.013	0
MnO	0.122	0.097	0	0	0.035	0.022	0.026	0.015	0.02	GeO2	0.022	0.01	0
MgO	26.23	26.25	22.32	22.83	21.8	0.01	0	0	0	Cr2O3	0.007	0	0.011
CaO	0	0.016	0.032	0.08	0	7.27	6.73	6.6	5.59	V2O3	0	0.012	0
Na2O	0.038	0	1.206	1.93	1.44	7.68	8.18	8.36	8.92	Ga2O3	0.016	0.01	0.03
K2O	0	0	7.89	8.44	7.78	0.028	0.051	0.015	0.045	FeO	0.072	0.097	0.09
BaO	0.019	0.053	1.48	0.832	1.66	0.153	0.073	0.065	0.221	MnO	0.015	0	0.008
BeO										TiO2	0.032	0.031	0.034
F	0	0	0.436	0.34	0.342	0	0	0.008	0.213				
Cl	0	0	0.051	0.117	0.012	0	0.005	0.008	0.019				
Total	99.825	100.01	94.577	95.409	95.397	99.348	99.118	100.14	99.62	Total	100.09	100.11	100.03
Si	0.000	0.001	5.243	5.243	5.179	10.577	10.676	10.699	10.826	Si	0.0005	0.0006	0.0005
Ti	0.001	0.000	0.523	0.453	0.604	0.009	0.003	0.000	0.007	Al	1.9952	1.995	1.9951
Al	1.993	1.993	3.039	3.017	3.107	5.375	5.258	5.257	5.084	Ti	0.0004	0.0004	0.0004
Fe	0.063	0.063	0.125	0.128	0.130	0.000	0.005	0.000	0.000	Fe2	0.001	0.0014	0.0013
Cr	0.000	0.001	0.000	0.000	0.000	0.003	0.004	0.000	0.000	Cr	0.0001	0	0.0001
Mn	0.002	0.002	0.000	0.000	0.004	0.003	0.004	0.002	0.003	Mn	0.0002	0	0.0001
Mg	0.942	0.941	4.715	4.788	4.575	0.003	0.000	0.000	0.000	Mg	0.0004	0.0004	0.0004
Ca	0.000	0.000	0.005	0.012	0.000	1.402	1.300	1.260	1.073	Ca	0	0.0002	0
Na	0.002	0.000	0.331	0.526	0.393	2.680	2.859	2.888	3.097	Ga	0.0002	0.0001	0.0003
K	0.000	0.000	1.426	1.514	1.397	0.006	0.012	0.003	0.010	V	0	0.0002	0
Ba	0.000	0.000	0.082	0.046	0.092	0.011	0.005	0.005	0.016	Sc	0	0	0
Be										Ge	0.0002	0.0001	0
F	0.000	0.000	0.195	0.151	0.152	0.000	0.000	0.005	0.121				
Cl	0.000	0.000	0.012	0.028	0.003	0.000	0.002	0.002	0.006				
Cations	3.004	3.002	15.697	15.906	15.636	20.069	20.126	20.122	20.242	Cations	1.9982	1.9984	1.9982
Anions	4	4	22	22	22	32	32	32	32	Anions	3	3	3

Comparison of the bulk compositions of all the sequences demonstrates that significant quantities of components have been added to the mineralized zones, especially for tungsten and Berrylium. Bakamuna rocks give values for tungsten ranging from 0.37% to 1.63% in the spinel-nepheline-taaffeite-bearing zone (Table 2).

Table 1.2 Chemistry of Minerals in the Reaction Zones (*Overprints/Altered Minerals)*

Mineral	Albite	Albite	Albite	Taaf	Taaf	Taaf	Taaf	Mus	Mus	Chl	Chl
Sample	23	46	47	90	91	92	111	117	120	104	105
SiO2	43.11	41.94	42.48	0.01	0.109	0.019	0.034	52.4	46.37	27.34	28
TiO2	0.01	0.015	0	0.01	0.01	0	0	1.492	2.22	0.259	0.44
Al2O3	34.29	34.7	34.31	74.03	74.18	73.12	74.07	20.11	18.31	28.84	28.03
FeO	0	0.021	0	1.37	1.49	1.38	1.35	0.409	0.67	11.07	11.69
Cr2O3	0.011	0.027	0	0	0.05	0	0.045	0	0.016	0.027	0.026
MnO	0	0	0.035	0.017	0.048	0.069	0.028	0	0	0.02	0.011
MgO	0	0.02	0	18.74	18.65	18.38	19.33	11.76	17.42	17.06	17.44
CaO	2.17	1.74	1.83	0.009	0	0	0.022	1.82	0.959	0.055	0.03
Na2O	17.76	18.46	18.23	0.023	0.037	0.023	0	5.73	3.75	0.073	0.107
K2O	2.37	2.89	2.86	0	0	0	0.016	4.8	6.72	0.185	0.307
BaO	0	0	0	0	0	0	0	0.036	0	0.02	0.051
BeO *				5.791	5.426	6.982	5.105				
F	0	0	0	0	0	0	0	0.228	0.36	0	0
Cl	0	0	0	0	0	0	0	0.006	0.02	0.086	0.072
Total	99.85	99.822	99.745	94.209	94.574	93.018	94.895	98.79	96.815	85.035	86.205
Si	8.216	8.040	8.135	0.001	0.010	0.002	0.003	6.725	6.200	6.975	7.077
Ti	0.001	0.002	0.000	0.001	0.001	0.000	0.000	0.144	0.223	0.050	0.084
Al	7.701	7.840	7.743	8.025	8.058	7.892	8.058	3.042	2.885	8.670	8.349
Fe	0.000	0.003	0.000	0.105	0.115	0.106	0.104	0.044	0.075	2.361	2.471
Cr	0.002	0.004	0.000	0.000	0.004	0.000	0.003	0.000	0.002	0.005	0.005
Mn	0.000	0.000	0.006	0.001	0.004	0.005	0.002	0.000	0.000	0.004	0.002
Mg	0.000	0.006	0.000	2.570	2.563	2.509	2.660	2.250	3.473	6.488	6.571
Ca	0.443	0.357	0.375	0.001	0.000	0.000	0.002	0.250	0.137	0.015	0.008
Na	6.562	6.861	6.768	0.004	0.007	0.004	0.000	1.426	0.972	0.036	0.052
K	0.576	0.707	0.699	0.000	0.000	0.000	0.002	0.786	1.146	0.060	0.099
Ba	0.000	0.000	0.000	1.280	1.201	1.536	1.132	0.002	0.000	0.002	0.005
Be *				1.2795	1.201	1.5355	1.132				
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.093	0.152	0.000	0.000
Cl	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.037	0.031
Cat	23.500	23.820	23.727	11.988	11.962	12.054	11.967	14.763	15.270	24.705	24.754
Anions	32	32	32	16	16	16	16	22	22	36	36

Be Calculated by difference (mocroprobe analysis was done at the University of Mainz Germany)

Petrological studies and comparisons of bulk compositions of all sequences demonstrate that significant quantities of non-volatile components have been added (W) to or subtracted (eg. Ca etc.) from the mineralized zone. Especially whole rock geochemistry of corundum-scheelite bearing lenses reveals remarkable high values for W, averaging 1.002 ± 0.694 % (1σ). According to our observations and studies by Silva & Siriwardena, (1986), the formation of reaction bands at Bakamuna can be considered as skarn-type metasomatism. Mineralization at the reaction zone is divided into contact metamorphism at the peak metamorphic conditions, retrograde skarn and late stage alteration on the basis of mineral

chemistry and petrographic analysis. Sequence of skarn-related mineralization include: (1) formation of phlogopite, spinel, corundum, anorthite –rich reaction bands; (2) Enrichments of Be and Na components
by overprinting of taafeite in the spinel zone and nepheline, albite and scapolite in the corundum-anorthite zone; (3) Tungsten enrichment is marked by the presence of scheelite; and (4) late and retrograde chlorite, muscovite and calcite mineralization.

GENETIC MODELING

On the basis of geochemical, textural, and field criteria, the significant mineralogical zoning is developed as a result of diffusive exchange of Si, Al, Mg, which served to decrease the differences in chemical potential between chemically dissimilar rocks. Presence of high-temperature assemblages of spinel-corundum at the reaction bands suggests the high-temperature skarn metasomatism (~850°C/9kbar) could have occurred at lower crustal levels.

The composition of the initial rock was formed by mixing of calcite or dolomite with pelitic gneiss in different proportions. If the initial fluid is not saturated in Al and Si with respect to any silicates, then silicate minerals gradually disappear being replaced by carbonates from outer zones to inner zones. In calcic marbles, Mg is extracted from silicates and enters into carbonates, that result in zones of dolomitization and an enrichment of calcite in Mg. In contrast, in dolomitic marbles, Mg is extracted from dolomite and enters into silicate, mostly in phlogopite. That explains a constant attachment of the corundum-bearing deposits to marbles consisting of Mg-calcite with dolomite or without it, which is observed in all deposits. The Na/K ratio is 1 at the corundum-plagioclase zone before alteration takes place. An increase of Na/K ratio up to 5 at the second stage (see Table 2 in the spinel-nepheline zone) results in appearance of nepheline and albite instead of corundum or without it, and subsequently to the formation of nepheline + scapolite + albite assemblage. At Na/K = 5, nepheline and scapolite are stable. At XCO_2 at lower levels and T up to 400°C, chlorite and muscovite form instead of phlogophite. In all the above variants, Al and Si saturate the fluid during its interaction with silicate-carbonate rocks. Concentration of Si in the initial fluid is critical for the formation of mineral zoning.

Granitoid-ultramafics related scheelite and taaffeite deposits hosted in metasomatic zones were deposited by fluids with temperatures from 200-400°C in the mid crustal levels. The paragenetic data from the scheelite bearing rocks demonstrate unambiguously a separate cycle of hydrothermal activity, resulting in metasomatism and mineralization. The infiltration of saline fluids along with H_2O-CO_2 may have transported metals like sodium, beryllium and especially tungsten to mid crustal levels to produce scheelite and taaffeite . The fluids responsible for

Table 2: Whole rock chemistry of reaction zone Total Fe as FeO -chemical analysis was done at the geochemistry lab of University of Erlangen,

	Spl-Neph	Crn-Plag
%	Zone	Zone
SiO2	18.8	6.3
TiO2	0.17	0.13
Al2O3	47.66	86.59
FeO	1.45	0.85
MnO	0.04	0.03
MgO	4.26	0.04
CaO	2.93	1.66
Na2O	4.35	0.11
K2O	1.1	0.11
P2O5	0.05	0.03
LOI	3.52	2.3
Total	84.33	98.15
(ppm)		
Ba	300	30
Nb	590	34
Rb	76	4
Sr	18	248
U	111	25
W	16339	3697
Zn	331	63
Zr	327	242

mineralization of taafeite and scheelite are not the same. Fluid with a magmatic signature can be inferred from taafeite, whereas scheelite appears to contain some component of meteoric water.

propose that fluid discharging from a crystallizing deep-seated magma, mixing with deep circulating Ca-bearing palaeo-groundwater gave rise to the deposition of scheelite. The scheelite mineralization occurred after the Pan-African regional metamorphism.

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