Gem-quality taaffeites and musgravites from Africa

Dr Karl Schmetzer[1], Dr Michael S. Krzemnicki[2], Prof. Dr Henry A. Hänni[2], Dr Heinz-Jürgen Bernhardt[3] and Prof. Dr Thomas Pettke[4]

1. *Taubenweg 16, D-85238 Petershausen, Germany*
2. *SSEF Swiss Gemmological Institute, Falknerstr. 9, CH 4001 Basel, Switzerland*
3. *ZEM, Institut für Geologie, Mineralogie und Geophysik, Ruhr-University, D-44780 Bochum, Germany*
4. *Institute of Geological Sciences, University of Bern, CH-3012 Bern, Switzerland*

Abstract: *Gemmological, microscopic, chemical and spectroscopic properties of a parcel of 30 taaffeites and ten musgravites of African origin, most probably all from Tunduru, Tanzania, are presented. The faceted gemstones were identified by a combination of laser Raman microspectroscopy, quantitative electron microprobe analyses and LA-ICP mass spectroscopy. The variation of gemmological properties such as specific gravity and refractive indices is correlated with transition metal contents of the samples. Absorption bands in the UV-Vis range are assigned to iron in different valence states. Typical inclusions are primary apatite and magnesite crystals and healed feathers consisting of cavities that contain fluids and tiny secondary magnesite crystals. Gemmological and microscopic properties of these African stones are compared with characteristic features of taaffeites and musgravites from Sri Lanka. Most gem-quality taaffeites and musgravites from Sri Lanka and Africa originate from magnesian skarns or from calc-silicate rocks of metasomatic origin.*

Introduction

The taaffeite group consists of three independent mineral species, taaffeite, musgravite and pehrmanite (Armbruster, 2002). That the formulae and crystal structures of taaffeite and musgravite are distinct was established in the 1980s (Schmetzer, 1983 a,b; Nuber and Schmetzer, 1983). Only taaffeite and musgravite are known in gem quality, especially from Sri Lanka. Taaffeite, $BeMg_3Al_8O_{16}$, is a rare collector's stone, and musgravite, $BeMg_2Al_6O_{12}$, is considered as one of the rarest gem species known to date (McClure, 2001).

Since the 1980s, faceted taaffeites have continued to appear in parcels of cut and rough stones from Sri Lanka. Additionally, a gem-quality taaffeite from Myanmar has been reported by Spengler (1983) and recently, several samples from the Tunduru area in Tanzania have been described (anonymous, 1996; Burford, 1998). The first faceted musgravites, probably from Sri Lanka, were identified by Demartin *et al.* (1993).

Although the chemical formulae for the two Be-Mg-Al-oxides, taaffeite and musgravite, are no longer in dispute, the special physical and

ISSN: 1355-4565

chemical properties of chromium-, iron- and zinc-bearing, gem-quality taaffeites from Sri Lanka have come to light only within the last decade revealing more detailed knowledge of these gem materials (Schmetzer *et al.*, 2000, 2005 a,b). The first quantitative chemical analyses of gem-quality musgravites from Sri Lanka were also reported recently (Schmetzer *et al.*, 2005 c,d).

Taaffeites from Sri Lanka, in general, contain minor amounts of transition metals, especially iron and zinc, and in red to purplish red or intense purple specimens traces of chromium are also present. Some samples with extraordinarily high values of refractive indices (RI) and specific gravity (SG) contain extremely high zinc and/or iron values up to 8.87 wt.% ZnO and up to 5.62 wt.% FeO. Quantitative chemical analyses of gem-quality musgravites from Sri Lanka mostly revealed minor percentages of iron and zinc, but one sample contained a high amount of iron (4.91 wt.% FeO). Gemmological properties of taaffeites and musgravites such as SG and RI were found to be correlated with trace element contents of individual samples (Schmetzer, 2005; Schmetzer *et al.*, 2006). In both minerals, taaffeite and musgravite, zinc and iron predominantly replace magnesium in the crystal structure.

In contrast to the detailed knowledge of the gemmological, physical and chemical properties of gem-quality taaffeites and musgravites from Sri Lanka established so far (see references cited above), only one chemical analysis of a gem taaffeite from Myanmar is known to the authors (Schmetzer *et al.*, 2000), and quantitative chemical data of material from Tanzania are unknown.

Due to the similar chemical composition and crystal structure of taaffeite and musgravite, the gemmological properties of these independent species overlap. Consequently, for an unequivocal determination of faceted gems of this group a combination of special physical techniques such as X-ray diffraction and/or quantitative chemical analysis and/or micro-Raman spectroscopy is needed (Kiefert and Schmetzer, 1998). Because all specimens from Tunduru have so far been determined only by traditional gemmological methods, it is not known whether the samples described from Tanzania as taaffeites (anonymous, 1996; Burford, 1998) also contained some musgravites.

Consequently, the authors accepted the generous offer of W. Spaltenstein of Multi Colour Gems, Chantaburi, Thailand, to lend us 40 faceted specimens of taaffeite or musgravite of African origin for detailed gemmological, chemical and spectroscopic examination.

Materials and methods

The present study is based on 40 faceted stones ranging in weight from 0.35 to 3.97 ct (*Figures 1* and *2*). The rough gem material used for cutting these stones originated from the Tunduru mining area in Tanzania and consisted of mixed parcels containing the various gem species recovered in that particular area (see, for example, Johnson and Koivula, 1996, 1997; Henn and Milisenda, 1997, Burford, 1998). After cutting large lots of heavily water-worn rough pebbles in Thailand, the different gem materials found within the mixed parcels were sorted and taaffeites or musgravites were selected by gemmological methods, especially by the determination of optical properties.

In the cutting and sorting processes in Thailand, material from Tunduru is commonly mixed with imported rough from Ilakaka, Madagascar. However, at the time of writing (March 2007) gems of the taaffeite group have neither been reported from Ilakaka (see, for example, Schmetzer, 2000; Milisenda *et al.*, 2001) nor identified in the laboratory of the Institut de Gemmologie de Madagascar in Antananarivo (T. Ramerison, pers. comm., 2006). Therefore, we assume that at least the majority of specimens examined in this study originate from Tanzania although we cannot completely exclude the possibility that a few stones could come from Madagascar. We are sure that none of the stones comes from Sri Lanka or Myanmar.

Standard gemmological methods were

used to determine the RI, optical character, SG and fluorescence under long- and short-wave ultraviolet radiation for all samples. Standard microscopic techniques were used to examine internal features of the stones under different lighting conditions, both with and without immersion liquids.

Subsequently we examined all 40 samples by laser Raman microspectroscopy using a Renishaw 1000 system equipped with a 514 nm argon laser. For each Raman spectum, 20 scans (10 seconds/scan) were accumulated. As a result, the lot could be subdivided into 30 taaffeites and 10 musgravites (for the distinction of taaffeites and musgravites using Raman spectra see Kiefert and Schmetzer, 1998). In addition, we analysed the solid inclusions of the samples using the laser Raman system mentioned.

To further characterize the samples we selected 15 taaffeites and all 10 musgravites for chemical analysis. To determine the quantitative chemical composition a Cameca Camebax SX 50 electron microprobe was used to obtain 10 point analyses from traverses across the table facets of all 25 gemstones. For the examination of beryllium contents (which cannot be determined by electron microprobe) and further trace element analysis we selected two taaffeites and three musgravites for laser ablation-inductively coupled plasma-mass spectroscopy (LA-ICP-MS) using a pulsed Excimer ArF laser with a characteristic wavelength of 193 nm, combined with special optics to homogenize the energy distribution across the laser beam combined with the Perkin Elmer ELAN 6100 ICPMS quadrupole instrument. Non-polarized UV-Vis (300-800 nm) absorption spectra were recorded using a Cary 500 Scan spectrophotometer.

Results

Identification of mineral species

The physical properties and chemical compositions of ten taaffeite and ten musgravite samples from Africa are summarized in *Tables I* and *II*. The data for the remaining 20 taaffeites more or less duplicated the properties of the taaffeites given in the table and would not supply any additional information of significance. The identification of our samples by laser Raman microspectroscopy as described by Kiefert and Schmetzer (1998) and recently by Okano *et al.* (2006) was conclusive for most but not all of the faceted taaffeites and musgravites. All specimens showed a high to extremely high background fluorescence in their Raman spectra, and in some this was sufficient to swamp the critical lines for the minerals and prevent unequivocal identification. With a combination of quantitative chemical analysis by electron microprobe and Raman microspectroscopy, however, all 30 taaffeites and ten musgravites were identified.

Figure 1: *These three violet, bluish grey and light purple taaffeites show the variation of colour seen in samples from Africa. The violet sample of 2.68 ct measures 9.0 mm in width.*

Figure 2: *The 10 studied musgravites from Africa show a wide range of colour from intense purple and light purple to violetish grey, bluish grey and bluish greenish grey. The largest sample of 3.97 ct measures 8.2 × 11.6 mm.*

Visual appearance and gemmological properties

The colours of the taaffeites vary between light purple, purplish violet, violet, greyish violet, bluish violet, greyish blue and bluish grey *(Figure 1)*. The musgravites show a similar colour variation, except that one is an intense purple and two have a bluish greenish grey colour *(Figure 2)*. Pleochroism in all stones is very weak or absent. All taaffeites and musgravites are inert to long- and short-wave ultraviolet radiation.

RIs and SGs of the taaffeites vary between 1.719 and 1.729 for ω and 1.715 and 1.723 for ε, and between 3.60 and 3.69 for SG. The musgravites have almost identical values in the same range, but with a smaller variation: their RIs vary between 1.719 and 1.725 for ω and between 1.715 and 1.720 for ε, and their SGs between 3.61 and 3.64. Thus, both groups of samples show overlapping ranges for these diagnostic gemmological properties. Consequently, for an unequivocal determination of a faceted gem of this mineral group a combination of sophisticated techniques such as X-ray diffraction (powder or single crystal techniques) and/or quantitative chemical analysis (for example, by electron microprobe) and/or micro-Raman spectroscopy is needed.

Microscopic observations

In some of the *taaffeites* we were able to identify rounded apatite grains or magnesite crystals. These closely resemble the internal features seen in taaffeites from Sri Lanka (see, for example, Schmetzer *et al.*, 2000, 2005a,b, 2006).

In the *musgravites* we identified several small, somewhat rounded apatite crystals *(Figures 3* and *4)*, and a few larger magnesite inclusions, some of which are located in the centre of a rosette of tiny fluid (?) particles *(Figure 5)*. Healed fractures usually consisting of numerous small negative crystals with multiphase fillings are also present *(Figures 6* and *7)*. With Raman analysis, it was confirmed that the birefringent crystals within these cavities are also small magnesites. In one sample we observed a cluster of brownish tabular crystals *(Figure 8)*, and the Raman spectrum indicated that it was probably mica. In another musgravite we observed a tiny black crystal surrounded by a tension crack, but the Raman spectrum could not be matched with that of a known mineral.

None of the examined taaffeites or musgravites revealed significant growth patterns or colour zoning. Also many were either completely free of or had inclusions that were too small for laser Raman microspectroscopy.

In summary, there was neither any characteristic inclusion that could be used for a distinction of taaffeites from musgravites, nor was any characteristic internal feature observed that would enable separation of African taaffeites and musgravites from stones originating from Sri Lanka.

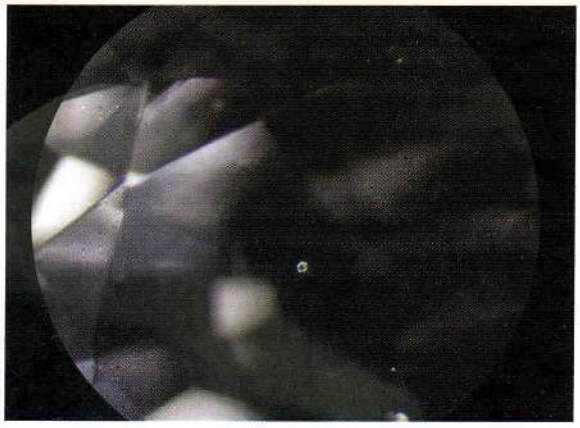

Figure 3: *Small somewhat rounded crystals of apatite are typical inclusions in musgravites from Africa. Magnified 20×.*

Figure 4: *Rounded apatite inclusion in musgravite from Africa, magnified 80×.*

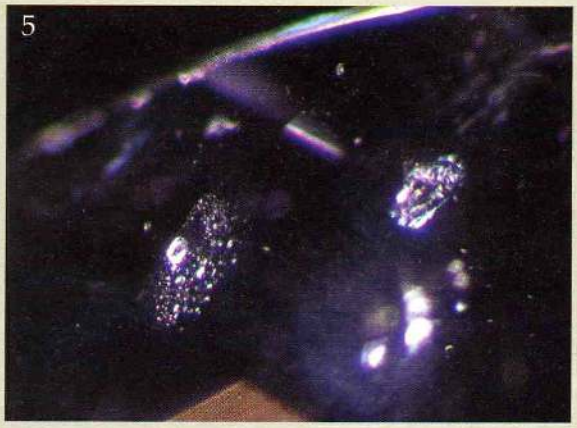

Figure 5: Primary magnesite crystals occasionally with fluid (?) rosettes are also characteristic for musgravites from Africa. Magnified 70×.

Figure 6: Healed feathers consisting of small cavities with multiphase filling (fluid with tiny magnesite crystals) are common in musgravites from Africa. (a) overview, the stone measures 5.5 × 7.5 mm; (b) in immersion, only tiny particles are common; (c) with crossed polarizers, the birefringent crystals are clearly visible. (b) and (c) magnified 70×.

Figure 7: Musgravite with a healed fracture with two-phase filling (fluid and solid). The fluid channels are clearly visible in plane polarized light in immersion (a) and the birefingent crystals become visible using crossed polarizers (b). Magnified 70×.

Figure 8: A cluster of brownish yellow platelets, probably mica, is an inclusion in a musgravite from Africa. Magnified 80×.

Table I: Physical properties and chemical compositions of taaffeites from Africa.

Physical properties

Specimen	A	B	C	D	E	F	G	H	I	J
Weight (ct)	1.10	0.90	2.30	0.63	1.42	1.47	0.35	0.53	0.48	3.51
SG	3.60	3.61	3.60	3.62	3.61	3.63	3.64	3.64	3.66	3.69
RI ω	1.719	1.719	1.719	1.721	1.722	1.723	1.725	1.725	1.726	1.729
ε	1.715	1.715	1.715	1.717	1.718	1.719	1.720	1.720	1.721	1.723
Birefringence	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.005	0.005	0.006

Chemical composition (microprobe analysis, average of 10 analysis points each, wt.%)

Al_2O_3	73.56	73.41	73.63	73.39	73.28	72.98	73.01	72.52	72.52	71.89
V_2O_3	bdl	0.01	bdl	0.01	bdl	0.01	bdl	bdl	0.01	bdl
Cr_2O_3	0.01	0.01	0.01	bdl	0.01	0.02	0.01	0.01	0.01	0.01
TiO_2	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
MgO	21.16	20.98	20.91	20.67	20.41	20.01	19.99	19.68	19.09	18.19
FeO[a]	0.31	0.53	0.67	1.08	1.70	2.33	2.45	2.79	0.86	1.03
ZnO	0.17	0.17	0.12	0.11	0.15	0.08	0.08	0.04	3.34	4.78
MnO	0.01	0.02	0.02	0.02	0.03	0.04	0.05	0.05	0.05	0.02
BeO[b]	4.50	4.49	4.50	4.48	4.48	4.47	4.47	4.44	4.44	4.40
Sum	99.73	99.63	99.87	99.77	100.07	99.95	100.07	99.54	100.33	100.33
sum of transition metal contents (wt.%)[c]	0.51	0.75	0.83	1.23	1.90	2.49	2.60	2.90	4.26	5.85

Cation proportions based on 16 oxygens

Al	8.027	8.027	8.033	8.030	8.019	8.017	8.014	8.013	8.016	8.011
V	-	0.001	-	0.001	-	0.001	-	-	0.001	-
Cr	0.001	0.001	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001
Ti	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Sum trivalent cations	8.029	8.030	8.035	8.032	8.021	8.020	8.016	8.015	8.019	8.013
Mg	2.920	2.902	2.886	2.860	2.825	2.781	2.775	2.751	2.670	2.565
Fe	0.025	0.041	0.052	0.084	0.132	0.182	0.191	0.219	0.068	0.081
Zn	0.011	0.012	0.008	0.008	0.010	0.005	0.005	0.003	0.231	0.334
Mn	0.001	0.001	0.001	0.001	0.002	0.003	0.004	0.004	0.004	0.001
Sum divalent cations	2.957	2.956	2.947	2.953	2.969	2.971	2.975	2.977	2.973	2.981
Be[d]	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

bdl = below detection limit.

[a]Total iron as FeO. [b]Since beryllium is not detectable by microprobe analysis, the BeO content has been calculated for 1 Be per formula unit; for the theoretical composition of taaffeite ($BeMg_3Al_8O_{16}$) an amount of 4.52 wt.% BeO is required. [c]Calculated as (V_2O_3 + Cr_2O_3 + TiO_2 + FeO + ZnO + MnO). [d]Calculated on the basis of 16 oxygens assuming Be = 1.000.

Table II: *Physical properties and chemical compositions of musgravites from Africa.*

Physical properties

Specimen	A	B	C	D	E	F	G	H	I	J
Weight (ct)	1.18	0.44	3.97	0.36	0.46	0.61	0.35	0.86	0.65	0.60
SG	3.61	3.61	3.62	3.61	3.62	3.62	3.62	3.62	3.63	3.64
RI ω	1.719	1.720	1.721	1.721	1.722	1.722	1.722	1.723	1.724	1.725
ε	1.715	1.716	1.717	1.717	1.718	1.718	1.718	1.719	1.719	1.720
Birefringence	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.005

Chemical composition (microprobe analysis, average of 10 analysis points each, wt.%)

Al_2O_3	73.98	74.30	74.32	73.96	74.00	73.75	73.78	74.05	73.63	73.19
V_2O_3	bdl	0.01	bdl	bdl	bdl	bdl	0.01	bdl	0.01	bdl
Cr_2O_3	0.01	0.08	0.01	bdl	0.01	0.01	0.01	0.01	0.01	0.01
TiO_2	bdl	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
MgO	18.99	18.90	18.58	18.45	18.57	18.36	18.32	18.69	18.19	17.99
FeO[a]	0.61	1.09	1.20	1.23	1.45	1.59	1.56	1.51	1.84	2.00
ZnO	0.12	0.06	0.11	0.14	0.15	0.04	0.18	0.36	0.18	0.10
MnO	0.02	0.02	0.06	0.05	0.02	0.03	0.04	0.06	0.12	0.09
BeO[b]	6.04	6.08	6.06	6.03	6.05	6.02	6.03	6.07	6.02	5.98
Sum	99.77	100.56	100.35	99.87	100.26	99.81	99.94	100.76	100.01	99.37
sum of transition metal contents (wt.%)[c]	0.76	1.26	1.39	1.43	1.64	1.68	1.81	1.95	2.17	2.21

Cation proportions based on 12 oxygens

Al	6.004	5.997	6.013	6.013	6.001	6.007	6.007	5.986	6.002	6.003
V	-	0.001	-	-	-	-	-	-	0.001	-
Cr	0.001	0.004	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001
Ti	-	0.001	0.001	0.001	0.001	0.001	0.001	0.001	-	0.001
Sum trivalent cations	6.005	6.003	6.015	6.014	6.003	6.009	6.009	5.988	6.004	6.005
Mg	1.950	1.930	1.901	1.898	1.905	1.891	1.886	1.911	1.875	1.866
Fe	0.035	0.063	0.069	0.071	0.083	0.092	0.090	0.087	0.106	0.117
Zn	0.006	0.003	0.006	0.007	0.008	0.002	0.009	0.018	0.009	0.005
Mn	0.001	0.001	0.003	0.003	0.001	0.002	0.002	0.003	0.007	0.005
Sum divalent cations	1.992	1.997	1.979	1.979	1.997	1.987	1.987	2.019	1.997	1.993
Be[d]	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

bdl = below detection limit.
[a]Total iron as FeO. [b]Since beryllium is not detectable by microprobe analysis, the BeO content has been calculated for 1 Be per formula unit; for the theoretical composition of musgravite ($BeMg_2Al_6O_{12}$) an amount of 6.08 wt.% BeO is required. [c]Calculated as (V_2O_3 + Cr_2O_3 + TiO_2 + FeO + ZnO + MnO).
[d]Calculated on the basis of 12 oxygens assuming Be = 1.000.

Table III: Trace element contents in taaffeites and musgravites from Africa.

Specimen	Taaffeite A	Taaffeite G	Musgravite A	Musgravite H	Musgravite I
Weight (ct)	1.10	0.35	1.18	0.86	0.65
Li	22	3	8	7	127
B	50	24	346	688	220
Ga	610	172	296	259	107
Sn	9	1	11	2	23

N.B. LA-ICP mass spectrometry was used. Results are in ppm and are means of three analysis points for each stone.

Chemical composition

The results of electron microprobe analysis are presented in *Tables I* and *II*. No distinct chemical zoning was observed in the traverses across the table facets of the samples. In addition to the principal components of taaffeite and musgravite, Al_2O_3, MgO and BeO (which is not detectable directly by electron microprobe), the samples contain distinct amounts of iron and zinc. The ranges of iron contents in both minerals (from 0.31 to 2.79 wt.% FeO in taaffeites and from 0.61 to 2.00 wt.% FeO in musgravites) are broadly similar.

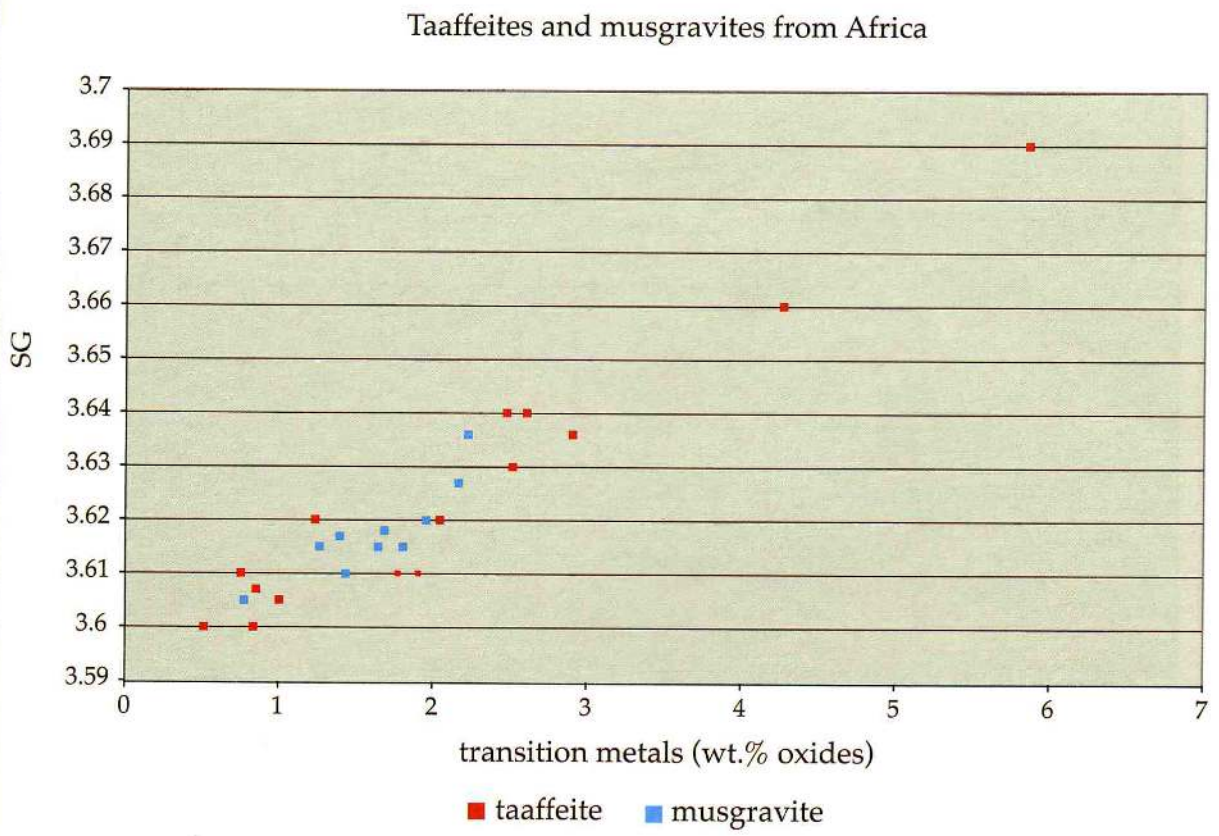

Figure 9a: *A correlation of the sum of transition metal contents with SG indicates the influence of chemical composition on gemmological properties of taaffeite and musgravite samples from Africa (for data see* Tables I *and* II*). 'Normal' samples have transition metal contents of up to 2.90 wt.%; two zinc-rich taaffeites with trace element contents of 4.26 and 5.85 wt.% are shown on the right of the diagram; the overlap of physical properties for samples of both minerals with similar transition metal contents is evident.*

There is, however, a distinct difference in the variation of zinc contents: the range observed for taaffeites is from 0.04 to 4.78 wt.% ZnO and for musgravites only from 0.04 to 0.36 wt.% ZnO. In one sample only (musgravite B) was there a significant chromium content of 0.08 wt.% Cr_2O_3. In addition, there are smaller traces of other transition metals present such as titanium and manganese.

Further trace element analyses for two taaffeites and three musgravites are given in *Table III*. Apart from the main constituents Be, Mg and Al, distinct contents of lithium, boron, gallium and tin were found. Na, Si, P, Ti, V, Cr, Mn, Fe, Co, Ni and Zn were also found as minor to trace elements in these samples, but at or below the detection limit were K, Ca, Sc, Ge, Rb, Sr, Y, Zr, Nb, Cs, La, Ce, Dy, Lu, Hf, Ta, W, Pb, Bi, Th and U. The taaffeites A and G show distinctly lower concentrations of boron than the three musgravites (samples A, H and I), but the other trace elements show overlapping concentration ranges.

The main difference in chemical composition between taeffeite and musgravite is their different beryllium contents, and since these cannot be measured by electron microprobe, the difference was proven directly by mass spectroscopy. Using the analytical results obtained for taaffeite A measured with this technique as an internal standard for the theoretical beryllium content of taaffeite (4.52 wt.% BeO), the value for taaffeite G was calculated to 4.51 wt.% BeO, and the analytical data for the three musgravites A, H and I gave BeO values of 6.03, 5.98 and 5.97 wt.%. These data confirm the generally accepted formulae for both mineral species, which requires an amount of 4.52 wt.% BeO for pure taaffeite (without iron and zinc contents) and an amount

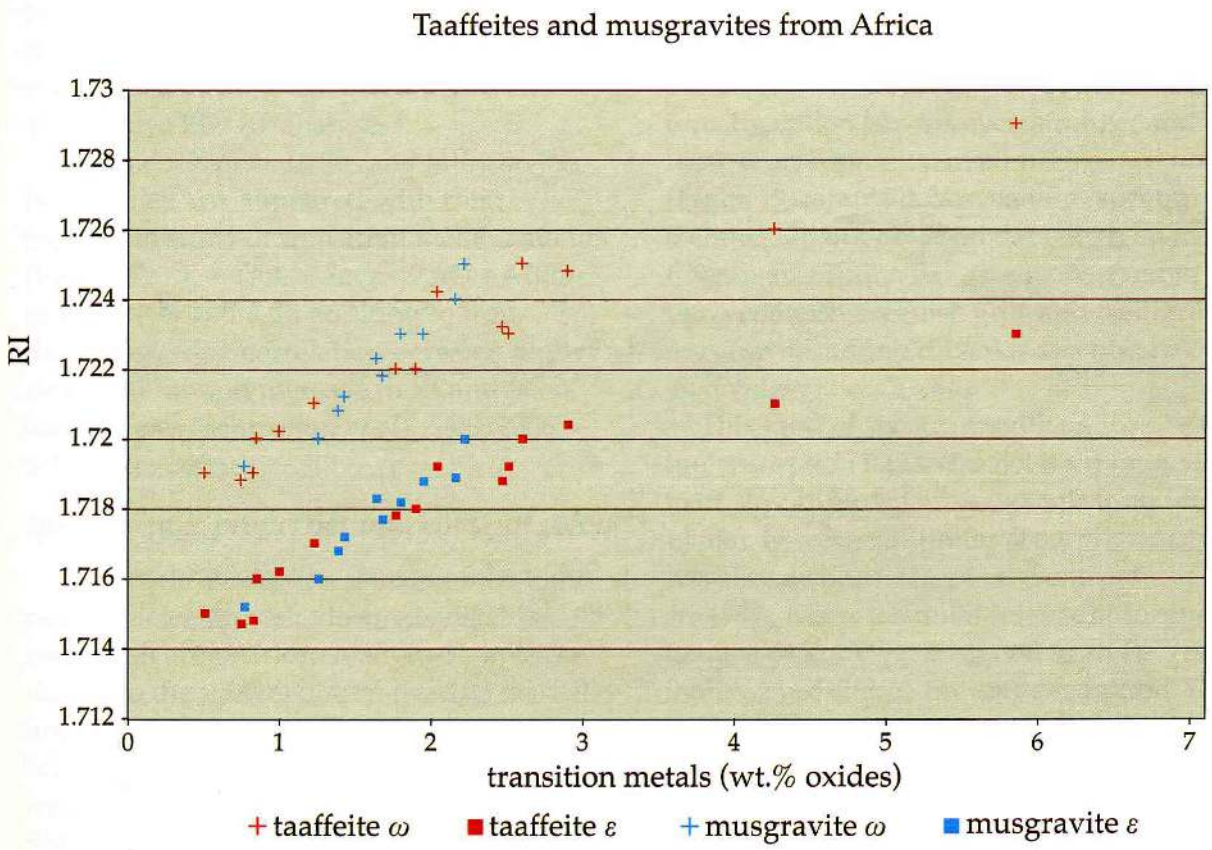

Figure 9b: *A correlation of the sum of transition metal contents with RIs ω and ε indicates the influence of chemical composition on gemmological properties of taaffeite and musgravite samples from Africa (for data see* Table I *and* II*). 'Normal' samples have transition metal contents up to 2.90 wt.%; two zinc-rich taaffeites with trace element contents of 4.26 and 5.85 wt.% are shown on the right of the diagram; the overlap of physical properties for samples of both minerals with similar transition metal contents is evident.*

of 6.08 wt.% BeO for pure musgravite (without iron and zinc contents).

The chemical compositions calculated according to the chemical formula of taaffeite for 16 oxygen atoms and 1 beryllium atom per formula unit is close to ideal cation proportions *(Table I)*. The sum of trivalent cations is close to the theoretical value of 8.000 and the sum of bivalent cations is close to the ideal value of 3.000. These data indicate that only a small fraction of total iron may be present as Fe^{3+} with the majority of iron replacing magnesium as Fe^{2+}. The same applies for musgravite *(Table II)*: the sum of trivalent cations is close to the theoretical value of 6.000 and the sum of bivalent cations is close to the ideal value of 2.000.

From this study, there is no evidence of any intermediate phase with a composition and formula between the two established mineral species, taaffeite and musgravite. The range of chemical composition shown by the 25 samples analysed in the present study is smaller than the range reported by Okano *et al.* (2006) for taaffeite and musgravite samples from Sri Lanka although this is based on semi-quantitative EDXRF analyses.

SGs and RIs of taaffeites and musgravites from Africa are compared with their individual sums of transition metal contents ($V_2O_3 + Cr_2O_3 + TiO_2 + FeO + ZnO + MnO$) in *Figures 9a* and *b*. In addition to iron, there is a strong correlation between higher zinc contents and increase in RI and SG of both species (Schmetzer *et al.*, 2000, 2006; Schmetzer 2005).

Spectroscopic properties and cause of colour

UV-Visible absorption spectra of the light purple, violet, greyish violet, greyish blue and bluish grey African taaffeite samples are similar to the spectra of iron-bearing taaffeites from Sri Lanka as already described by Schmetzer (1983b) and Schmetzer *et al.* (2005a), with the most prominent absorption bands at 629, 581, 557, 472, 458, 385 and 370 nm.

These absorption bands, mostly of low to moderate intensity, are assigned to iron, mostly to Fe^{2+} in tetrahedral coordination, with only the usually low-intensity 629 nm band, assigned to an Fe^{2+}/Fe^{3+} intervalence charge transfer absorption.

The spectra of the light purple, violet and greyish violet musgravites described in this paper *(Figure 10)* show the same absorption maxima and intensity relations for different absorption bands *(Figure 10,* sample H). The spectrum of the intense purple chromium-bearing stone shows a distinct absorption maximum at 557 nm which is assigned to an overlap of the iron-related absorption band at 557 nm with a chromium absorption located in the same spectral range *(Figure 10,* sample B). Chromium-bearing taaffeites from Sri Lanka with a similar absorption maximum at about 550 nm due to chromium have already been described by Schmetzer *et al.* (2000, 2006).

The absorption spectra of bluish grey or greyish blue African musgravites are similar to those of violet samples. Most absorption bands are of low to moderate intensity, but the 629 nm absorption band is more intense *(Figure 10,* sample F). The two bluish greenish grey musgravites (chemical properties see *Table II,* samples I and J) show the same type of spectrum although the 629 nm absorption band is even stronger and there is an additional maximum at 600 nm *(Figure 10,* sample I). Very similar spectra (Schmetzer, unpublished data) with an intense 629 nm absorption have been observed in two yellowish greenish grey and blue-green musgravites from Sri Lanka described recently (Schmetzer *et al.*, 2005d).

This kind of spectrum with an intense 629 nm absorption has so far not been found in taaffeites. In bluish green spinels from Sri Lanka, however, a similar absorption feature has already been described (Schmetzer *et al.*, 1989), where a similar intense absorption band at 645 nm was assigned to an Fe^{2+}/Fe^{3+} intervalence charge transfer absorption. The same cause could also explain the 629 nm absorption band in musgravite, where in addition to ferrous iron (Fe^{2+}), it also contains low concentrations of ferric iron (Fe^{3+}).

A more detailed interpretation of colours, absorption spectra and especially a more complete discussion of the assignment of absorption bands is beyond the scope of the present article.

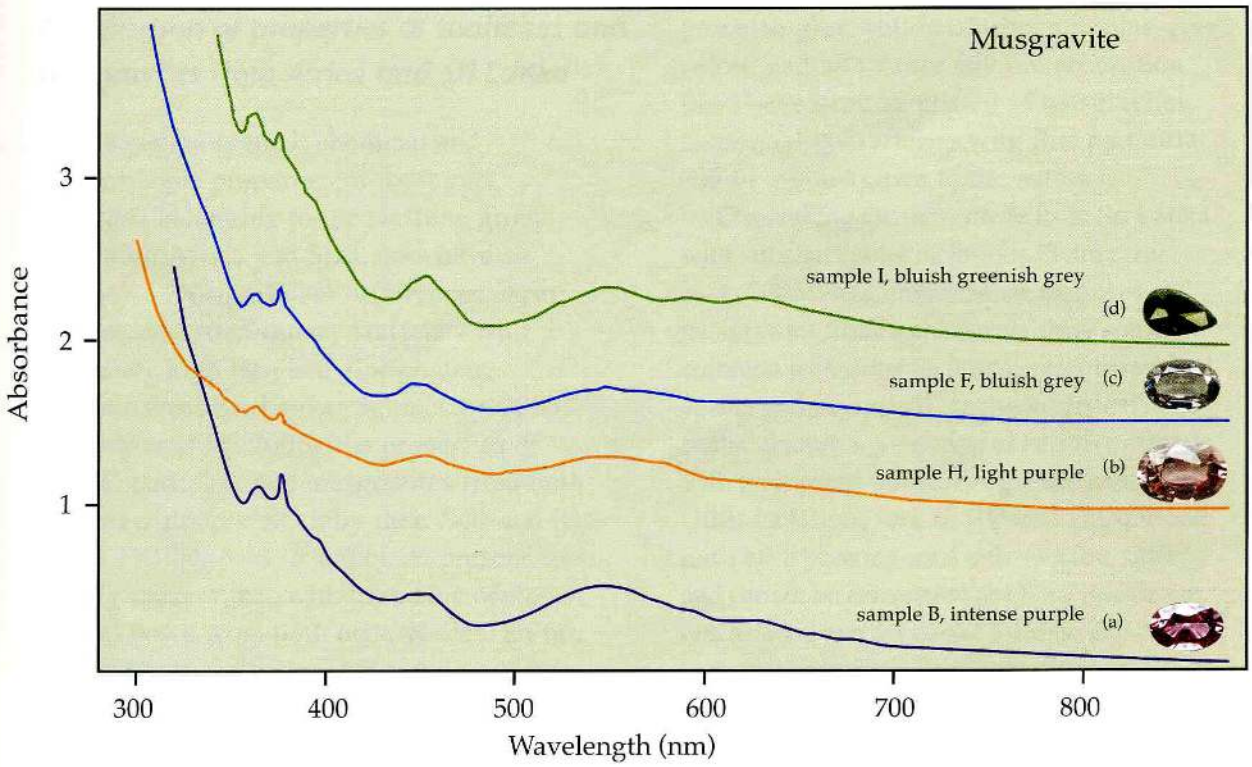

Figure 10: *Absorption spectra of iron- and chromium-bearing musgravites from Africa; from bottom to top: (a) iron- and chromium-bearing musgravite, sample B of* Table II, *intense purple; (b) iron-bearing musgravite, sample H, light purple; (c) iron-bearing musgravite, sample F, bluish grey; (d) iron-bearing musgravite, sample I, bluish greenish grey. The most characteristic iron-related absorption maxima are located at 629, 600, 581, 557, 472, 458, 385 and 370 nm; a chromium absorption band in spectrum (a) is located at about 550 nm; spectra of samples H, F, and I are vertically displaced for clarity. Sample H measures 4.9 x 7.1 mm.*

Discussion

Properties of taaffeites and musgravites from Africa

The taaffeites and musgravites from Africa are characterized by low to moderate iron contents. Two taaffeite samples only show distinct zinc contents of 3.34 and 4.78 wt.% ZnO, but no zinc-rich musgravites have been found. Only one musgravite showed unusual chromium contents of 0.08 wt.% Cr_2O_3.

The variations of RIs and SGs within taaffeites and musgravites are related to their contents of transition metals, i.e. these physical properties mainly increase with increasing iron and zinc contents (see again *Tables I* and *II, Figures 9a* and *b*). However, African taaffeites and musgravites with relatively low transition metal contents have overlapping ranges for these diagnostic gemmological properties. In addition, no significant inclusions or spectroscopic properties have been found which could be usefully combined with standard gemmological methods for a quick distinction of taaffeites from musgravites. Only the bluish greenish grey musgravites show a specific colour and related spectroscopic absorption features which have, so far, not been observed in taaffeites.

Consequently, for an unequivocal determination of faceted gems of the taaffeite group originating from Africa, a combination of sophisticated techniques such as X-ray diffraction (powder or single crystal techniques) and/or quantitative chemical analysis (for example by electron microprobe or LA-ICP-MS) and/or Raman microspectroscopy is needed. This fact is already common knowledge for stones from Sri Lanka.

Comparison of properties of taaffeites and musgravites from Africa and Sri Lanka

The gemmological, chemical and spectroscopic properties of most gem materials belonging to the taaffeite group from both Africa and Sri Lanka have so far shown no significant differences. Apart from some extraordinary taaffeites with extremely high iron and zinc contents reported from Sri Lanka (Schmetzer, 2005; Schmetzer *et al.*, 2006), the properties of normal taaffeites and musgravites from both sources overlap, especially their SGs and RIs (*Table IV*, *Figures 11a* and *b*). At present, gem-quality musgravites with high zinc contents are unknown from both occurrences. So far, all samples from both sources with a bluish greenish grey, yellowish-green or blue-green colour and an intense 629 nm absorption band have been identified as musgravites. Gem-quality taaffeites with that particular colour are unknown to the authors.

Considering the musgravite from Sri Lanka with lamellar spinel inclusions (Schmetzer *et al.*, 2005c) as a unique stone, taaffeites and musgravites from both sources show some common inclusions such as somewhat rounded apatite grains, isolated magnesite crystals and healed fractures consisting of negative crystals with multiphase fillings (magnesite and fluid). Other inclusions such as feldspar, graphite and mica have been reported only in a few stones and cannot be considered as characteristic for one mineral species or one locality. The only inclusions which are relatively common in

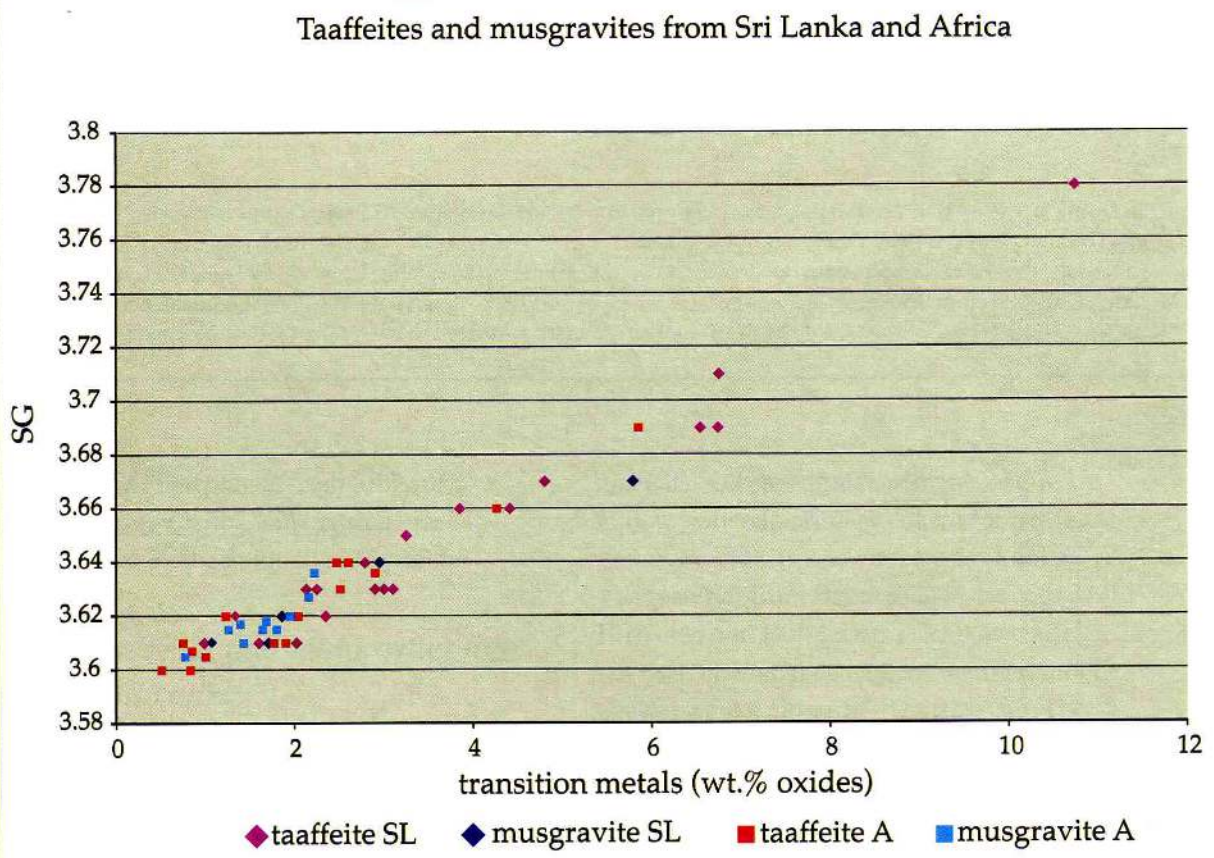

Figure 11a: *A correlation of the sum of transition metal contents with SG indicates the influence of chemical composition on gemmological properties of taaffeite and musgravite samples from Africa (data see* Tables I *and* II*) and Sri Lanka (data see* Table IV*). 'Normal' samples have transition metal contents up to 3.25 wt.%; zinc- and iron-rich specimens have transition metal contents between 3.85 and 10.73 wt.%. The overlap of physical properties for samples of both minerals from both sources with similar transition metal contents is evident. A = Africa, SL = Sri Lanka.*

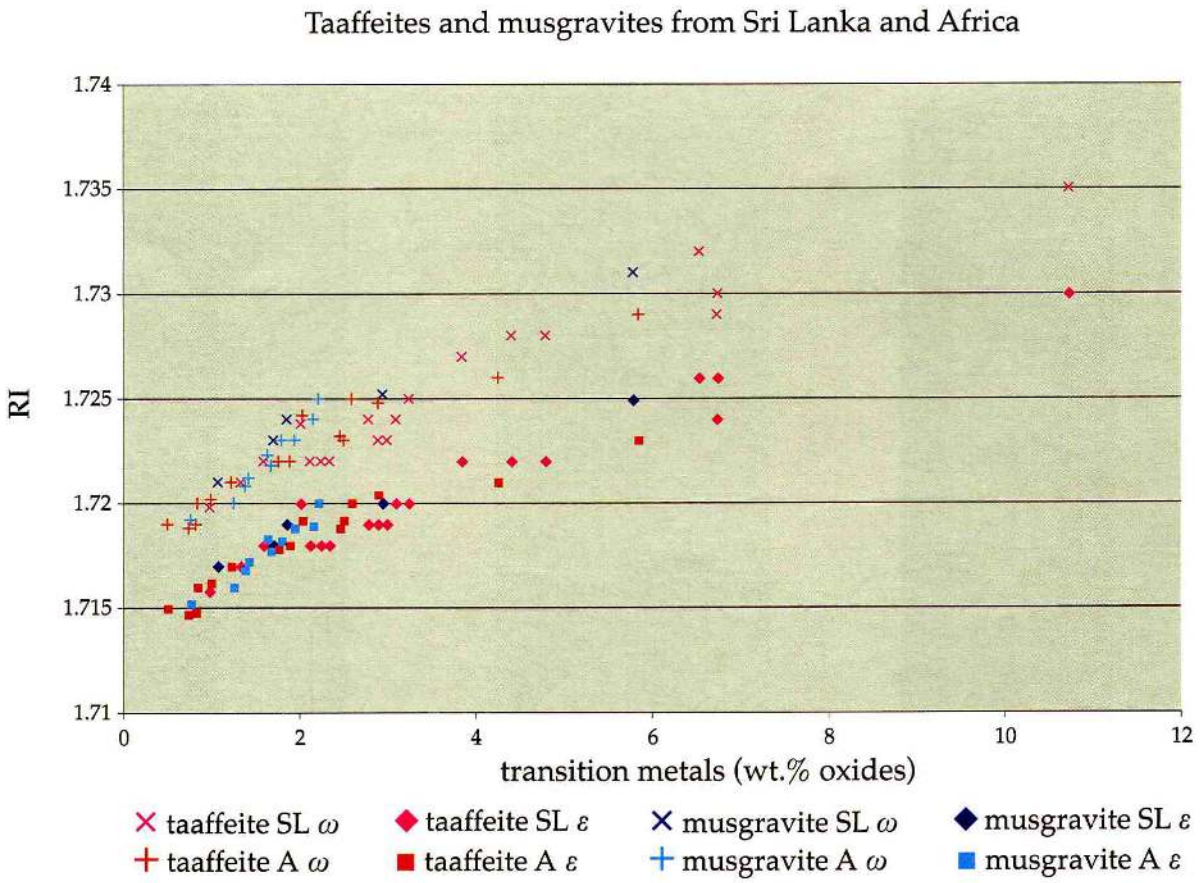

Figure 11b: *A correlation of the sum of transition metal contents with RIs ω and ε indicates the influence of chemical composition on gemmological properties of taaffeite and musgravite samples from Africa (data see* Tables I *and* II*) and Sri Lanka (data see* Table IV*). 'Normal' samples have transition metal contents up to 3.25 wt.%; zinc- and iron-rich specimens have transition metal contents between 3.85 and 10.73 wt.%. The overlap of physical properties for samples of both minerals from both sources with similar transition metal contents is evident. A = Africa, SL = Sri Lanka.*

both taaffeite and musgravite from Sri Lanka are numerous tiny zircons with tension cracks; these have not so far been found in any of the African stones.

Origin of taaffeites and musgravites from Africa and Sri Lanka

General overviews of taaffeite and musgravite occurrences in different host rocks have been given by Grew (2002), Aleksandrov and Senin (2002) and Schmetzer *et al.* (2005d). Phase relationships in the BeO-MgO-Al_2O_3 system, especially of the pseudobinary system chrysoberyl ($BeAl_2O_4$) - spinel ($MgAl_2O_4$), are given by Franz and Morteani (2002). Both minerals are found in various environments, but typical host rocks are magnesian skarns and calc-silicates of metasomatic origin. Up to now only one primary source for taaffeite group minerals is known from Sri Lanka. The material from Bakamuna is described by Fernando and Hofmeister (2000) as taaffeite, but their chemical data (electron microprobe analysis) are a closer fit to musgravite. The material was found in the metasomatic contact zone of a marble with a high-grade metamorphic pelitic gneiss.

The presence of primary magnesite crystals and tiny magnesites in healed feathers within taaffeites and musgravites from Sri Lanka, suggests that their origin may lie in a magnesian skarn or metasomatic calc-silicate host rock (Schmetzer *et al.*, 2005d). A similar metasomatic origin has already been suggested

Table IV: *Range of physical properties and chemical compositions of gem-quality taaffeites and musgravites from Sri Lanka[a] and Africa[b].*

Physical properties

		'Normal' taaffeites Sri Lanka	Iron- and zinc-rich taaffeites Sri Lanka	'Normal' musgravites Sri Lanka	Iron-rich musgravite Sri Lanka	'Normal' taaffeites Africa	Zinc-rich taaffeites Africa	'Normal' musgravites Africa
SG		3.61 – 3.65	3.66 - 3.78	3.61 - 3.64	3.67	3.60 - 3.64	3.66 - 3.69	3.61 - 3.61
RI	ω	1.720 – 1.725	1.727 – 1.735	1.721 – 1.725	1.731	1.719 – 1.725	1.726 – 1.729	1.719 – 1.725
	ε	1.716 – 1.720	1.722 – 1.730	1.717 – 1.720	1.725	1.715 – 1.720	1.721 – 1.723	1.715 – 1.720

Chemical composition (wt.%)

Cr_2O_3	0.01 – 0.21	0.01 – 0.15	0.01 – 0.02	0.01	0.01 – 0.02	0.01	0.01 – 0.08
FeO[c]	0.80 – 2.59	1.40 – 5.62	0.90 – 2.50	4.91	0.31 – 2.79	0.86 – 1.03	0.61 – 2.00
ZnO	0.05 – 1.18	0.07 – 8.87	0.04 – 0.43	0.70	0.04 – 0.17	3.34 – 4.78	0.04 – 0.36
Sum of transition metal contents[d]	0.99 – 3.25	3.85 – 10.73	1.05 – 2.99	5.79	0.51 – 2.90	4.26 – 5.85	0.77 – 2.22

Structural properties and inclusions

	Sri Lanka	Africa
Common	apatites, magnesite crystals, healed feathers with multiphase fillings (fluid and magnesite), zircons with tension cracks	apatites, magnesite crystals, healed feathers with multiphase fillings (fluid and magnesite)
Rare	growth structures and colour zoning, spinel lamellae, graphite, feldspar, mica	mica, black grain with tension cracks

[a]All data from: Schmetzer and Bank (1985), Bank and Henn (1989), Schmetzer *et al.* (2000), Schmetzer *et al.* (2005 a,b,c,d, 2006).
[b]This paper. [c]Total iron calculated as FeO. [d]Calculated as ($Ga_2O_3 + V_2O_3 + Cr_2O_3 + TiO_2 + FeO + ZnO + MnO$).

for Sri Lankan taaffeite by Kampf (1991). A primary source of taaffeite or musgravite in Tanzania is unknown. The similarity of the inclusion patterns of these gem materials from Sri Lanka and Africa, especially the presence of primary magnesite crystals and magnesite as a component of multiphase inclusions in healed feathers, however suggests similar geological conditions in their formation.

Acknowledgements

We are grateful to Mr W. Spaltenstein of Multi Colour Gems, Chantaburi, Thailand, for the loan of the research material for the present study. We also thank Prof. E.S. Grew, University of Maine, Maine, U.S.A., for a critical review of the manuscript.

References

Aleksandrov, S.M., and Senin, V.G., 2002. Genesis and composition of spinellide and related mineral assemblages in greisenized magnesian skarn and dolomite at the Hsianghualing deposit, the People's Republic of China. *Geochemistry International*, **40**(9), 860-73

Anonymous, 1996. Taaffeite found in Tunduru. *Jewellery News Asia*, No. 142, June, 58.

Armbruster, T., 2002. Revised nomenclature of högbomite, nigerite and taaffeite minerals. *European Journal of Mineralogy*, **14**(2), 389-95

Bank, H., and Henn, U., 1989. Changierender Taaffeit aus Sri Lanka. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, **38**(2/3) 89-94

Burford, M., 1998. Gemstones from Tunduru, Tanzania. *Canadian Gemmologist*, **19**(4), 105-10

Demartin, F., Pilati, T., Gramaccioli, C.M., and de Michele, V., 1993. The first occurrence of musgravite as a faceted gemstone. *Journal of Gemmology*, **23**(8), 482-5

Fernando, G.W.A. Rohan, and Hofmeister, W., 2000. Origin of some gem minerals in Sri Lanka: evidence from corundum-spinel-scheelite-taaffeite-bearing rocks. In: Rammlmair, D. et al. (Eds), *Applied mineralogy in research, economy, technology, ecology and culture*. **1**, 293-96. A.A. Balkema publishers, Rotterdam, The Netherlands

Franz, G., and Morteani, G., 2002. Be-minerals: synthesis, stability, and occurrence in metamorphic rocks. In: Grew, E.S. (Ed.), *Beryllium: mineralogy, petrology, and geochemistry*. Min. Soc. of America, Washington. Reviews in Mineralogy & Geochemistry, **50**, 551-89

Grew, E.S.,2002. Beryllium in metamorphic environments (emphasis on aluminous compositions). In: Grew, E.S. (Ed.), *Beryllium: mineralogy, petrology, and geochemistry*. Min. Soc. of America, Washington. Reviews in Mineralogy & Geochemistry, **50**, 487-549

Henn, U., and Milisenda, C.C., 1997. Die Edelsteinvorkommen in Tansania: Die Region Tunduru-Songea. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, **46**(1), 29-43

Johnson, M.L., and Koivula, J.I. (Eds), 1996. Gem News. Gem materials from the new locality at Tunduru, Tanzania. *Gems & Gemology*, **32**(1), 58-9

Johnson, M.L., and Koivula, J.I. (Eds), 1997. Gem News. Tunduru-Songea gem fields in southern Tanzania. *Gems & Gemology*, **33**(4), 305

Kampf, A.R., 1991. Taaffeite crystals. *Mineralogical Record*, **22**(5), 343-7

Kiefert, L., and Schmetzer, K., 1998. Distinction of taaffeite and musgravite. *Journal of Gemmology*, **26**(3), 165-7

McClure, S.F., 2001. Another musgravite. *Gems & Gemology*, **37**(1), 60-2

Milisenda, C.C., Henn, U., and Henn, J., 2001. New gemstone occurrences in the south-west of Madagascar. *Journal of Gemmology*, **27**(7), 385-94

Nuber, B., and Schmetzer, K., 1983. Crystal structure of ternary Be-Mg-Al oxides: taaffeite, $BeMg_3Al_8O_{16}$, and musgravite, $BeMg_2Al_6O_{12}$. *Neues Jahrbuch für Mineralogie Monatshefte*, **1983**(9), 393-402

Okano, M., Kitawaki, H., and Abduriyim, A., 2006. Taaffeite and Musgravite. Website of the Gemmological Association of All Japan http:/www.gaaj-zenhokyo.co.jp/researchroom/2006/2006_10a-01en.html

Schmetzer, K., 1983a. Taaffeite or taprobanite – a problem of mineralogical nomenclature. *Journal of Gemmology*, **18**(7), 623-34

Schmetzer, K., 1983b. Crystal chemistry of natural Be-Mg-Al-oxides: taaffeite, taprobanite, musgravite. *Neues Jahrbuch für Mineralogie Abhandlungen*, **146**(1), 15-28

Schmetzer, K., 2000. Spinel from Ilakaka, Madagascar. *Gems & Gemology*, **36**(2), 169-71

Schmetzer, K., 2005. Rare gemstones from Sri Lanka: some extraordinary taaffeites and musgravites. *GEMMOBASEL 2005, Festschrift in honour of Prof. Dr. Henry A. Hänni*. Rühle-Diebener-Verlag, Stuttgart, pp. 34-7

Schmetzer, K., and Bank, H., 1985. Zincian taaffeite from Sri Lanka. *Journal of Gemmology*, **19**(6), 494-7

Schmetzer, K., Haxel, C., and Amthauer, G., 1989. Colour of natural spinels, gahnospinels and gahnites. *Neues Jahrbuch für Mineralogie Abhandlungen*, **160**(2), 159-80

Schmetzer, K., Kiefert, L., and Bernhardt, H.-J., 2000. Purple to purplish red chromium- bearing taaffeites. *Gems & Gemology*, **36**(1), 50-9

Schmetzer, K., Kiefert, L., Bernhardt, H.-J., Burford, M., and Gunasekara, D.P., 2005a. Iron- and zinc-rich gem-quality taaffeites from Sri Lanka. *Journal of Gemmology*, **29**(5/6), 290-8

Schmetzer, K., Kiefert, L., Bernhardt, H.-J., and Burford, M., 2005b. Two remarkable taaffeite crystals from Sri Lanka. *Journal of Gemmology*, **29**(7/8), 461-6

Schmetzer, K., Kiefert, L., Bernhardt, H.-J., and

Burford, M., 2005c. Gem-quality musgravite from Sri Lanka. *Journal of Gemmology*, **29**(5/6), 281-9

Schmetzer, K., Kiefert, L., Bernhardt, H.-J., and Burford, M., 2005d. Musgravites from Sri Lanka. *Neues Jahrbuch für Mineralogie Abhandlungen*, **181**(3), 265-70

Schmetzer, K., Kiefert, L., Bernhardt, H.-J., and Burford, M., 2006. The variation of gemmological properties and chemical composition of gem-quality taaffeites and musgravites from Sri Lanka. *Australian Gemmologist*, **22**(11), 485-92

Spengler, W., 1983. Burmese parcel reveals rare find. *Jewellery News Asia*, **1**(1), 39