

Caesium-rich morganite from Afghanistan and Madagascar

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ABSTRACT: Quite saturated pink beryl of Madagascar and Afghanistan are described. They display densities between 2.91 and 3.10 g/cm³ and RI values up to 1.608 (n_o) and 1.615 (n_o) which exceed the values reported so far in the literature. Chemical analyses reveal very high caesium concentrations (up to 15.18 wt.% Cs₂O). The incorporation of Cs in the structural channels of beryl is mainly coupled with a substitution on the tetrahedrally-coordinated beryllium site. Such stones belong to the so-called tetrahedral beryls. UV-Vis-NIR spectra show manganese and water absorption features typical for morganite. XRD data and Raman spectra reveal a distinct increase in cell parameters (mainly c_0) compared to pure beryl, thus underlining the unusual character of the studied material. While the sample from Afghanistan is semi-transparent, transparent stones are found among the samples from Madagascar. Inclusions consist mainly of fine tubes parallel to the c -axis, flat fluid-filled inclusions parallel to the basal pinacoid, and tension fractures. Based on chemical composition, spectral data and colour saturation we suggest that the simple term morganite be retained to describe the stones, unless a new term is approved by the IMA to recognize the extraordinary composition and structure of the material.

417

Introduction

In mid-2002 a small quantity of pink to raspberry-red beryls were mined in Madagascar (Figure 1). Some time before that, a minor amount of similar specimens had already been found in Afghanistan. Pink to red varieties of beryl have been reported with various names in the gemmological literature. In this paper we intend to describe the new stones and compare them with earlier material of similar colours, i.e. morganite and red beryl. Initial measurements have indicated high values for refractive indices and density, and

therefore we felt it necessary to determine not only the customary gemmological properties, but also to carry out a sound mineralogical investigation including chemical analyses, structural data and spectral characteristics in UV-Vis and NIR.

When the composition of beryl is close to the ideal formula Be₃Al₂Si₆O₁₈, it is considered as n-beryl (normal beryl). The crystal structure of beryl is characterized by Be-O tetrahedra and distorted Al-O octahedra, linked with six Si-O tetrahedra forming a hexagonal ring structure. The stacking of the Si₆O₁₈ rings forms large



Figure 1: Morganite crystals from Madagascar and Afghanistan from left: M2, M1, M3 and A1; faceted stones from Madagascar, from left: M5, M4, M6. The largest faceted stone is 3.025 ct.

structural channels parallel to the crystallographic *c*-axis of the beryl and the structure offers a large number of possible substitutions both on the different lattice sites and in the channels (Deer *et al.*, 1992).

When the main substitution takes place on the octahedral lattice site, commonly occupied by aluminium, we speak of o-beryl (octahedral beryl). Partial substitutions of Al^{3+} by ions such as Fe^{3+} , Cr^{3+} , V^{3+} , or Mn^{3+} are common in this kind of material. Bivalent ions such as Mg^{2+} , Fe^{2+} , Mn^{2+} require a charge compensation that may be satisfied by monovalent alkalis (e.g. Na^+), which are incorporated in the channels of the structure. Most emeralds and aquamarines are o-beryls. When Be^{2+} on the tetrahedral lattice site is partially replaced, we speak of t-beryl (tetrahedral beryl). Based on our investigations it soon became obvious that the new pink beryls belong to this group. Substitution of Be^{2+} by monovalent ions (mainly lithium) requires a charge compensation, which may be realized by introducing a further monovalent ion in the channel structure (Bakakin *et al.*, 1970). The structural channel can accommodate large alkali ions and other large molecules such as H_2O or CO_2 .

Both substitutions, octahedral and tetrahedral, as well as the absorption of ions and molecules in the channels, have the effect of increasing the density and refractive indices of beryl (Cerny and Hawthorne, 1976; Hänni, 1980; Sinkankas, 1981). We can thus assume that beryls with high constants contain more substitute elements and are relatively impure. Data from the literature demonstrate that high constants are usually related to high alkali contents, particularly of the heavy alkalis Cs and Rb (Evans *et al.*, 1966).

Sample description and origin

The present report is based on a small number of samples, which were obtained in March 2002 and January 2003. The first sample (A1) of a surprisingly strong pink colour was presented to one of the authors by Haleem Khan, of Hindukush Mala Gems & Minerals, Pakistan. It consists of a tabular crystal with flat hexagonal hillocks on the basal plane, similar to those described as a consequence of rapid growth by Flamini *et al.* (1983) on red beryl from Utah (Figure 2). The translucent material is more saturated than would be expected in morganite in the gem trade, but it is less saturated than the red beryl from Utah, USA. The sample was reported to have come from

the Deva mine, Paroon Valley (Konar, Nuristan) in Afghanistan (Haleem Khan, pers. comm. 2002). The other samples are from Madagascar and are similar in colour to sample A1. Sample M2 is a flat hexagonal tabular crystal of an orangey-pink colour. Alexander Leuenberger (Switzerland) provided that stone in December 2002. A short time later, five more samples were obtained from Denis Gravier (Le Mineral Brut, St. Jean-le-Vieux, France) during the Tucson Mineral and Gem Show 2003. Two of the samples (M1, M3) consist of rough translucent stones with broken surfaces. Three more samples (M4, M5, M6) are faceted transparent and semi-transparent stones. They are reported to come from Mandrosonoro, approximately 150 km SW of Antsirabe (Central Madagascar). Some dealers give Ambatovita as the local name for the origin of Madagascar samples. The source is described as a pegmatite which also contains danburite, tourmaline and kunzite. The pink beryls are intergrown with lepidolite and amazonite feldspar (F. Danet, pers. comm., 2003). On one of our rough samples dark green tourmaline is also present, and this supports a pegmatitic origin.

As reference samples, red beryl (R1, R2) from the Wah Wah Mountains and Thomas Range, Utah (courtesy Ted and Rex Harris, Delta, 1983), and light pink morganite (R3) from Madagascar (courtesy Werner Spaltenstein, Chanthaburi) were used. Red beryl is well described in the literature (Nassau and Wood, 1968; Hänni, 1980; Flamini *et al.*, 1983; Shigley and Foord, 1984). A remarkable property of the rhyolitic red beryls is their sectorized colour zoning which resembles an hourglass pattern. The prismatic growth sectors are intensely coloured as they attracted more Mn and Fe, while the basal growth sector is pale.

The colours of the faceted samples were compared with the Biesalski Pflanzenfarben-Atlas DIN 6164 colour chart. Since the stones possess a distinct pleochroism (orangey-red and purplish-pink), the perceived colour depends on the orientation selected for the cutting. When viewed in the *c*-axis direction the colour was orangey-pink and described as



Figure 2: From left to right: Morganite from Madagascar (M2), red beryl from Utah (R1), and morganite from Afghanistan (A1).

7.5:3:1 following DIN 6164 (observed in samples M4 and M5). Perpendicular to the *c*-axis the colour is more purplish-pink and described as 10.5:2:1.5 (sample M6).

Specific gravities and refractive indices

Specific gravity (SG), refractive index (RI) and birefringence were determined by usual gemmological testing methods. Both SG and RI of the new material from Afghanistan and Madagascar distinctly exceed the values so far reported in the literature (*Table I*). The birefringence, however, is not affected by these increases. The values for the reference samples (light pink morganite and red beryl) are consistent with those reported in the literature. The increases in SG and RI correlate with the amount of substitution by the heavy alkali ions, Cs and Rb (*Table I*).

UV-Vis spectra

Spectra of morganite and red beryl have been published by Wood and Nassau, 1968; Nassau and Wood, 1968; and Shigley and Foord, 1984. Both pink and red colours in beryl have been attributed to the incorporation of manganese on the aluminium site in the beryl structure, but the situation is complicated by the possibility of two manganese related colour types of beryl,

Table I: Specific gravities, refractive indices and caesium contents of morganites and red beryl.

Sample	SG	RI		Birefringence	Cs ₂ O wt. %	
		<i>n_e</i>	<i>n_o</i>			
pink morganite (Madagascar)	M4	3.103	1.608	1.615	-0.007	14.27
	M5	3.101	1.608	1.615	-0.007	14.63
	M6	3.089	1.604	1.611	-0.007	14.31
pink morganite (Afghanistan)	A1	2.906	1.598	1.606	-0.008	9.70
morganite (Madagascar)	R3	2.760	1.592	1.600	-0.008	1.09
red beryl (Wah Wah, Utah)	R1	2.670	1.564	1.570	-0.006	0.13
red beryl (Thomas Range, Utah)	R2	2.670	1.568	1.575	-0.007	

which are dependent on the valence state of manganese (Mn²⁺ or Mn³⁺) (after Deer *et al.*, 1992 and Wood and Massau, 1968).

In morganite (light pink), bivalent manganese is incorporated probably by substitution for Al according to the formula [Mn²⁺ + alkali⁺ = Al³⁺] where the alkali (e.g. Na⁺, K⁺, Rb⁺, Cs⁺) is in the structural channels of beryl. Other substitutions involving Mn²⁺ may also be possible in morganite. As the concentration of Mn²⁺ generally is much lower than the alkalis in such morganites, the proposed substitution remains essentially based on charge balance and bond length considerations.

In red beryl from Utah trivalent manganese acts as a chromophore element by a simple substitution of Mn³⁺ for Al³⁺ in o-beryl. Platonov *et al.* (1989) have described the spectral characteristics of the two Mn-related colours and underlined a clear difference in pleochroism: morganite exhibits distinct dichroism despite having a weaker colour saturation.

UV-Vis-NIR spectra were recorded on the samples from Afghanistan (A1), Madagascar (M5) and Utah (R1) with a Varian Cary Scan 500 spectrometer, using polarization filters to

obtain o- and ε-absorption spectra (Figure 3). The spectra of samples A1 and M5 showed a strong correlation with spectra reported by Platonov *et al.* (1989) for morganite. In the spectrum of the o-vibration a strong maximum at 570 nm and a general absorption below 370 nm are present. The ε-vibration curve is characterized by a main absorption at 489 nm, with a side peak at 476 nm, and a second maximum at 550 nm, with an absorption edge at 370 nm.

Red beryl from the Wah Wah Mountains, Utah (R1) produced an o-ray spectrum with an absorption maximum at 562 nm, and a peak at 428 nm, with general absorption below 350 nm. The ε-ray spectrum has its maximum at 535 nm, and a very weak peak at 428 nm. The 370 nm peak is absent, and the absorption edge is again at about 350 nm (compare also Shigley and Foord, 1984).

Near infrared (NIR) spectra

The NIR spectra of our samples were studied with a Varian Cary Scan 500 spectrometer between 800 and 2500 nm. A polarization unit could only be used from 250–900 nm. For morganite samples A1 and M2, three main absorption features at 1412 nm (7082 cm⁻¹), 1907 nm (5244 cm⁻¹) and 2267

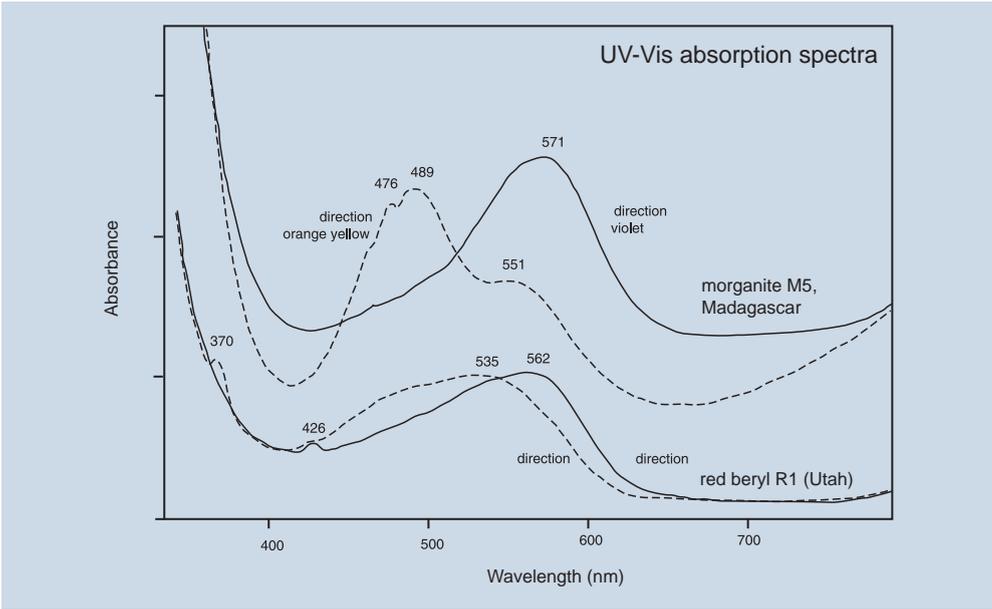


Figure 3: UV-VIS spectra of morganite M5 from Madagascar and red beryl R1 from Utah (USA). The spectra reveal a distinct difference between these two beryl varieties with manganese Mn^{2+} as chromophore in morganite and Mn^{3+} in red beryl.

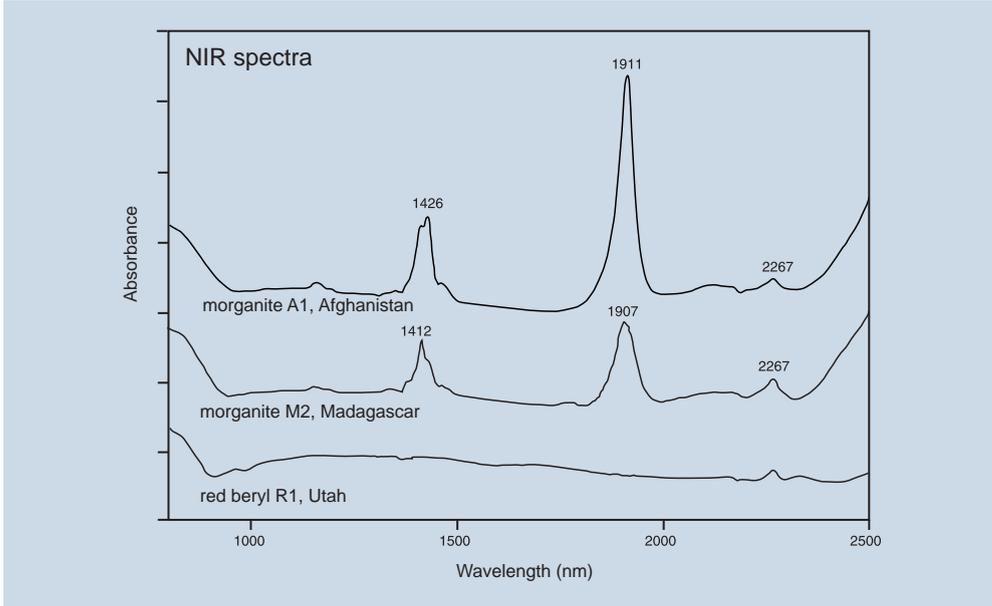


Figure 4: Unpolarized NIR spectra of morganites A1 (Afghanistan), M2 (Madagascar), and red beryl R1 (Utah). Absorption peaks due to water occur at 1420 and 1910 nm in the morganite spectra but are absent in the red beryl spectrum.

Table II: Electron microprobe analyses of morganites from Madagascar and Afghanistan, and red beryl from USA.

Wt. %	Pink morganite				Morganite Madagascar R3	Red beryl Utah, USA R1	
	Madagascar			Afghanistan			
	M4	M5	M6	A1			
BeO*	6.36	6.21	6.28	8.13	11.20	13.78	Be-site
Li ₂ O*	1.84	1.86	1.83	1.35	0.68	0.09	
Cs ₂ O	14.27	14.63	14.31	9.70	1.09	0.13	channel
Na ₂ O	0.56	0.50	0.52	1.15	1.35	0.07	
K ₂ O	0.14	0.16	0.15	0.03	0.07	0.20	
Rb ₂ O	0.38	0.39	0.39	0.14	0.09	0.14	
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	0.11	
CaO	0.17	0.17	0.19	0.98	0.01	b.d.	
Al ₂ O ₃	15.84	15.70	15.62	15.72	17.52	16.59	
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	
V ₂ O ₃	0.05	0.09	0.09	0.06	b.d.	0.04	
Fe ₂ O ₃	0.03	0.03	0.02	0.02	0.02	2.10	
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.27	
MnO	b.d.	b.d.	b.d.	0.02	b.d.	0.29	
Sc ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	
SiO ₂	59.01	58.60	58.42	61.32	64.82	66.91	Si-site
Total	98.65	98.33	97.82	98.60	96.85	100.69	
Normalization to a total of 11 cations							
Be ²⁺	1.552	1.528	1.549	1.910	2.490	2.968	
Li ⁺	0.753	0.765	0.755	0.532	0.298	0.032	
Cs ⁺	0.619	0.639	0.626	0.405	0.043	0.005	
Na ⁺	0.110	0.099	0.103	0.218	0.242	0.012	
K ⁺	0.018	0.020	0.020	0.004	0.009	0.023	
Rb ⁺	0.025	0.026	0.026	0.009	0.005	0.008	
Mg ²⁺	0.000	0.000	0.000	0.000	0.000	0.015	
Ca ²⁺	0.019	0.018	0.021	0.103	0.001	0.000	
Al ³⁺	1.899	1.895	1.890	1.813	1.911	1.753	
Cr ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	
V ³⁺	0.004	0.007	0.008	0.004	0.000	0.003	
Fe ³⁺	0.002	0.002	0.001	0.001	0.001	0.142	
Ti ⁴⁺	0.000	0.000	0.000	0.000	0.000	0.018	
Mn ²⁺	0.000	0.000	0.000	0.001	0.000	0.022	
Sc ³⁺	0.000	0.000	0.000	0.000	0.000	0.000	
Si ⁴⁺	6.000	6.000	6.000	6.000	6.000	6.000	
Total	11.000	11.000	11.000	11.000	11.000	11.000	
H ₂ O*	0.460	0.570	0.749	0.456	0.973	0.000	

N.B. *BeO, Li₂O and H₂O have been calculated. b.d. = below detection limit

nm (4411 cm^{-1}), are present (*Figure 4*). Without polarisation measurements detailed attributions could not be made and the above absorptions could only be attributed to H_2O vibrations in general. H_2O molecules may be present in two perpendicular positions (type I or II) in the beryl channels (Wood and Nassau, 1968; Charoy, 1998). Infrared analysis of beryl sample powder mixed with KBr would allow an identification of water type and this work is planned for the future. According to the literature, however, most of the water molecules in morganites possess a molecular axis parallel to the structural channels in beryl and are type II. The red beryl reference sample did not show molecular response in the NIR spectral range except for a small peak at 2267 nm, which is in agreement with the H_2O -free nature of this material (Nassau and Wood, 1968; Hänni, 1980).

Chemical composition

Preliminary compositions of the new material were obtained from ED-XRF analyses, which indicated major Si, Al and also the presence of minor Fe, Mn, Cs and Rb in all samples (red beryl and morganite).

Quantitative chemical analyses of pink samples A1, M4, M5 and M6, light pink morganite R3 (Madagascar) and a red beryl R1 (Utah, USA) (see *Table II*) were carried out. On each sample six measurements were taken along a traverse of about 3 mm, to gain some information about their homogeneity.

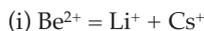
The analyses were carried out with a JEOL-JXA 8600 electron microprobe (Geochemical Laboratory, University of Basel, Switzerland), operated in wavelength-dispersive mode (WDS) at an accelerating potential of 20 kV and a beam current of 20 nA. Fourteen elements were measured on their $\text{K}\alpha_1$ or $\text{L}\alpha_1$ lines, respectively, using well-characterized silicates (pollucite for caesium) and oxides as standards. The raw data were fully corrected for matrix effects by a ZAF-type online procedure. Vanadium was further corrected for peak overlap by caesium $\text{L}\beta_5$.

The measurements revealed (*Table II*) that the pink samples are relatively homogeneous and that the red beryl has zones of different composition. Samples M4, M5 and M6 contain caesium (Cs_2O) up to 15.18 wt.%, which is distinctly higher than reported so far in the literature (11.3 wt.% Cs_2O reported by Evans and Moore, 1966). Specimen A1 is less rich in caesium (Cs_2O up to 10.05 wt.%), whereas morganite with Cs_2O up to 1.25 wt.% and red beryl with Cs_2O up to 0.19 wt.% are in the range commonly determined in such beryls (Deer *et al.*, 1992; Nassau and Wood, 1968). Further R^+ and R^{2+} in pink beryl M4, M5 and M6 are sodium, rubidium, potassium and calcium, whereas magnesium is below detection limit. Compared to this, specimen A1 has higher contents of sodium, but shows lower values for rubidium. Potassium and magnesium are at or below detection limit. Based on these data, the new pink samples from Afghanistan and Madagascar belong to the alkali beryls, further classified as lithian caesian beryls after Deer *et al.* (1992).

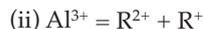
The aluminium concentration is slightly below that required for ideal stoichiometry. This may perhaps be explained by single-site substitutions on the Al-site, but is more likely to be due to the presence of coupled substitution involving caesium. Transition elements, such as iron, chromium, vanadium, titanium and manganese, commonly involved in such substitutions on the Al-site, were only found at the detection limit or below using either the microprobe or the ED XRF. As vanadium had to be corrected for Cs $\text{L}\beta_5$ interference, these values near the detection limit are only indications. We suspect that the pink beryls do not contain any vanadium. Although there is a general consensus that manganese is the chromophore for the pink and red colours in natural beryl (Nassau and Wood, 1968; Deer *et al.*, 1992), only in the red beryl could the manganese be measured quantitatively (*Table II*, column 6). However, UV-Vis spectra of the samples where the manganese was below the detection limit of the electron microprobe contain absorption peaks typical for manganese.

All data were further normalized, on a basis of six silicon atoms per formula unit (pfu), assuming full site occupancy on the tetrahedrally-coordinated Si sites (see *Table II*). Furthermore, beryllium and lithium were calculated for a stoichiometric total of 11 cations, although some Cs-rich beryls with total cations up to 11.25 have been described (Deer *et al.*, 1992).

Since beryllium and lithium contents can not be obtained by means of the electron microprobe, these contents were calculated taking into account any possible substitution mechanisms. Although several single-site and coupled substitutions involving alkalis have been described, most of them are based on unsupported stoichiometry (Wood and Nassau, 1968). Based on the data for the pink beryls, and on charge balance and bond length considerations, the most important substitution mechanism in samples A1, M4, M5 and M6 may be formulated as:



where for charge balance reasons, lithium on the beryllium site (Hawthorne and Cerny, 1977) is coupled with caesium in the channels of the beryl structure. Due to their large ionic size compared to tetrahedrally coordinated beryllium, all alkalis except lithium can only occupy positions in the channels of the beryl structure. This suggests that the other alkalis present (Na^{+} , K^{+} , Rb^{+}) may be charge balanced mostly by a similar mechanism with the possibility of involvement also with a coupled mechanism involving the Al site,



where R^{2+} stands for bivalent ions (Mg^{2+} , Ca^{2+} , Fe^{2+} , Mn^{2+}) and R^{+} stands for monovalent alkalis except lithium (Na , K , Rb).

Usually substitution mechanisms can be confirmed by plotting the quantities of the involved cations against each other in a diagram. A distinct correlation with a

negative slope between Be and Cs would support the most important suggested substitution mechanism in our pink samples. However, as beryllium and lithium have been calculated in relation to the total amount of cations (in our pink samples basically dependent on the caesium concentration), any diagram representing beryllium content plotted against caesium (or lithium) would necessarily produce a very good negative correlation, due to the so-called constant sum effect (Rollinson, 1993). Therefore no correlation diagram is given in this study.

The indicated amounts of beryllium and lithium in *Table II* are necessarily given as approximate concentrations. Light elements can now be measured in gemstones by laser ablation inductively coupled mass spectrometry LA ICP MS, if a small amount of damage on the surface is acceptable (Hänni and Pettke, 2002).

Laser ablation inductively coupled mass spectrometry (LA ICPMS) results, produced after delivery of the manuscript of this paper confirm the presence and quantities of calculated values for BeO and Li_2O . The Afghan sample A1 gave BeO 7.93 wt%, Li_2O 2.30 wt% and Cs_2O 9.21 wt%. The Madagascar sample M3 gave BeO 8.09 wt%, Li_2O 2.04 wt% and Cs_2O 13.85 wt%.

NIR-spectrometry revealed the presence of water in the structural channels of pink beryl from Madagascar and Afghanistan, whereas the sample from Utah showed no water peaks. This was also confirmed by the chemical analyses. Based on total sum considerations, the pink samples A1, M4, M5, and M6 contain $1/2$ H_2O molecule per formula unit. This is in good agreement with published analyses, which mention H_2O concentrations commonly from 0.3 to 0.8 molecules (Charoy, 1998). The light pink morganite specimen contains 1.0 molecules of H_2O per formula unit, whereas the calculated water concentration in the red beryl from Utah is zero, which

again is in good agreement with published figures (Nassau and Wood, 1968; Hänni, 1980).

Crystal structure

Bakakin *et al.* (1970) described a correlation between chemical composition and unit cell parameters of beryl. This was further confirmed by Hänni (1980), who showed that an increase of a_0 in o-beryls was correlated to the extent of substitution on the octahedral Al-site, whereas the c_0 value remained virtually unaffected. The c/a ratio commonly is slightly below 1.0 in such beryls. For alkali (caesium) rich beryl, Sosedko (1957) demonstrated an increase in c_0 related to the content of caesium, with a_0 remaining reasonably constant. They show c/a values slightly above 1.000, as it has been described already by Sosedko (1957) and Charoy (1998) for caesium rich t-beryls (see *Table III*).

Preliminary crystal structure investigations by powder XRD (X-ray diffraction) seem to confirm this correlation.

However, ongoing studies by the authors will clarify if and how the high caesium content affects (enlarges) the crystal structure of these samples. First powder XRD analyses revealed that two of the most important diffraction reflections of beryl are not present in samples M2 and A1.

Raman spectra

The Raman-shift spectra of samples M4, M5, M6 and A1 have been obtained using a Renishaw Raman microprobe. These are compared with spectra from o-beryls (red beryl from Utah, synthetic red beryl and aquamarine) and in *Figure 5* a partial peak shift of the pink caesium-rich specimens compared to the above-mentioned o-beryls can be seen. The pink caesium-rich samples show a distinct peak at 1098 cm^{-1} , which compares with 1069 cm^{-1} of the reference samples. A second but less distinct shift can be observed at 404 cm^{-1} (M4, M5, M6, A1), compared to 394 cm^{-1} for the reference samples. All other peaks are constant or show only minor peak shifts. This may be explained by the fact, that substitution takes

Table III: Cell parameters and contents of Cs and Al.

Beryl variety	Beryl sample	a_0	c_0	c/a	Substitution type	Wt.%		Source
						Cs_2O	Al_2O_3	
morganite	Madagascar M2	9.214	9.280	1.007	tetrahedral	14.4		this study
	Afghanistan A1	9.226	9.243	1.002		9.7		
	Russia 3*	9.200	9.227	1.003	tetrahedral	4.13		Sosedko 1957
	Russia 2*	9.202	9.209	1.001		0.67		
Russia 1*	9.202	9.183	0.998	0.27				
red beryl	Utah R1 light centre	9.214	9.206	0.999	octahedral		17.42	this study
	Utah R1 red rim	9.227	9.205	0.998			15.74	
colourless beryl	Switzerland, Hänni 4	9.211	9.196	0.998	octahedral		18.1	Hänni 1980
aquamarine	Switzerland, Hänni 1	9.233	9.208	0.997	octahedral		15.5	
	Switzerland, Hänni 3	9.257	9.197	0.994			14.6	
	Switzerland, Hänni 3	9.288	9.189	0.989				10.6

* after Deer *et al.*, 1962

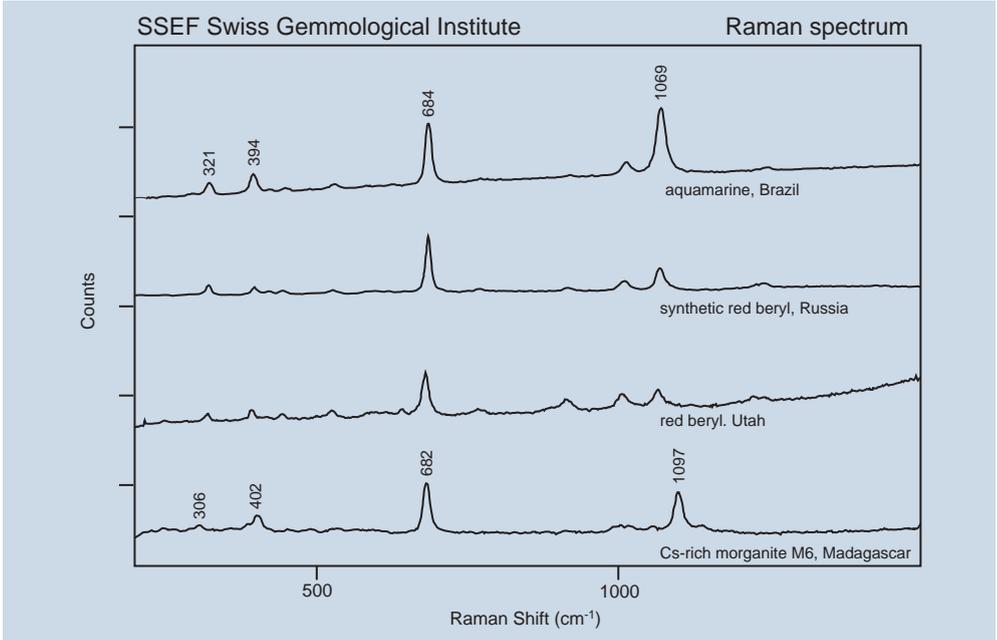


Figure 5: Raman spectra of morganite M6 red beryl R1, synthetic pink beryl (Russia), and aquamarine (Brazil). Cs-rich morganite from Madagascar shows a distinct peak shift at 1098 cm^{-1} compared with the other beryls.

426

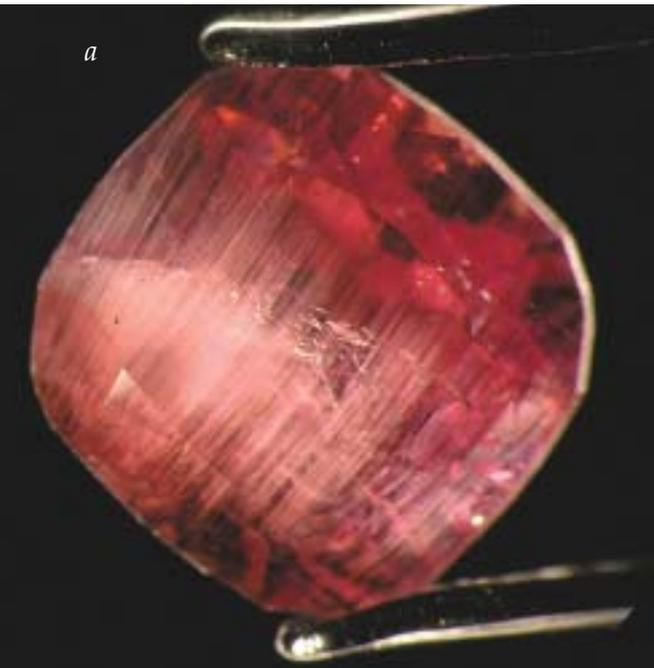


Figure 6: (a) Morganite from Madagascar (M5) with hollow tubes parallel to the c -axis.

(b) Detail of M5 showing hollow tubes parallel to the c -axis, flat fluid inclusions parallel to the basal pinacoid, and tension fractures (magnification $20\times$).

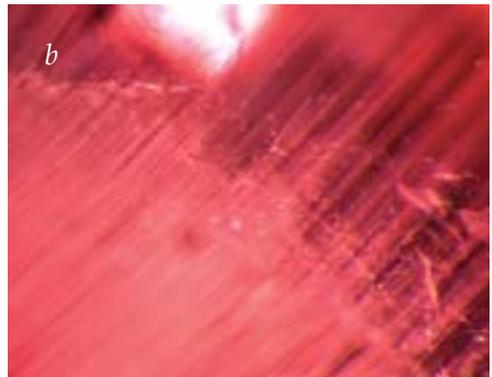




Figure 7: Cat's-eye Cs-rich morganite from Madagascar, provided by D. Gravier (magnification 10×).

place mostly on the Be-site (coupled with incorporation of large alkalis in the structural channels) enlarging locally the structure, whereas the aluminium- and silicon-sites remain virtually unchanged. Further studies will be done to attribute molecular vibrations to their relative Raman peaks.

Inclusions

The specimen from Afghanistan shows strong basal growth zoning and a few tension fractures of conchoidal shape. The samples from Madagascar contain fine tubes parallel to the *c*-axis, and fluid inclusions flattened along the basal plane. The tubes may be so dense in parts that cat's-eye stones may be expected from this source. (Figure 6a, 6b and 7). With only a small number of samples, only a few inclusions have been encountered and a wider range may emerge when more stones are seen.

Comparison with synthetic pink, red or purple beryl

For some years hydrothermally grown red and purple beryl has been available. The

crystals appear in different colours and owe their colours to different chromophore elements. Some of the stones have been described for example by Henn and Milisenda (1999) and Shigley and Foord (1984). None of the synthetic crystals contain Rb or Cs, but are characterized by distinct concentrations of Ti, Mn or Ni (unpublished SSEF analyses).

The oldest commercially available synthetic material seems to be the pink synthetic beryl from Biron (Australia), which contains Ti as a chromophore element (Brown, 1993). Later, crystals with darker



Figure 8: Hydrothermally grown synthetic beryls from Biron (right) and Novosibirsk, Russia (left).

colours appeared; these were produced in Russia (*Figure 8*) and showed distinct contents of Mn, Fe and Ni. Henn and Milisenda (1999) reported on synthetic red beryl from Russia and found that Co^{2+} was the chromophore. For all these hydrothermal synthetic beryls, the reported densities and refractive indices are clearly lower than for natural morganite as described in this study. It should thus not be difficult to distinguish them from natural morganites. Furthermore, in most of the red to purple and pink hydrothermal synthetic material, characteristic chevron-like growth in homogeneities could be expected (Johnson and Koivula, 1997).

Terminology considerations

A number of terms are related and used for rose coloured, pink or red beryls. Not all of them are, however, applied in current gemmological publications. Vorobyevite is a caesium beryl of colourless or pink colour, first described in 1908 from Lipovka, Ural Mountains (Sinkankas, 1981). Rosterite is another name for caesium beryl of colourless or pink colour from Elba, Italy. However, these variety names are nowadays only rarely found in the literature.

Much better known is the term morganite (Sinkankas, 1981), given to pink beryl by G.F. Kunz in 1910 to honour J.P. Morgan. Most authors relate the pink colour to the incorporation of some manganese and, at the same time, mention the presence of Cs, which is however not contributing to the colour. Red beryl from Utah owes its name to the intensity of its redness which is far more saturated than the colour associated with morganite. The weak pleochroism of red beryl compared with morganite is a further hint that colour is not the only difference between these minerals.

The new samples studied from Afghanistan and Madagascar strongly resemble in all aspects the properties attributed to morganite. In the trade the

investigated samples were sold as 'raspberry beryl' or 'pink beryl', rather than morganite. It seems that for the trade the term morganite is related to a weak colour, and this might negatively influence the new material. However, reconsidering the literature, the term morganite has for a long time precisely described the available light to intensely saturated rose to pink beryl varieties with variable amounts of Mn, Cs and Rb, and no fancy name is required to describe these stones. In the CIBJO rules (CIBJO 2002), application of morganite is related to a mineralogical variety, while morganite, pink beryl and red beryl are also mentioned as commercial names.

Discussion

Caesium and lithium are typical lithophile elements involved in formation of minerals in rhyolites (Christiansen *et al.*, 1983) and pegmatites. While these elements are found only in trace levels in the red beryl from Utah, in the samples from Afghanistan and Madagascar they are present in minor to major quantities. The Madagascar samples are particularly rich in caesium and exceed the Cs_2O contents of other beryls reported in the literature. A consequence of the higher Cs contents is the higher RI and SG values, which exceed the values quoted in many gemmological identification tables for morganite.

Several substitution mechanisms are proposed for the incorporation of alkalis and manganese in these samples. It has been confirmed that Mn^{2+} colours these pink beryls in the same way that it does in morganite (Shigley and Foord, 1984; Platonov *et al.*, 1989) whereas red beryl shows a different manganese absorption pattern, which is attributed to Mn^{3+} (Wood and Nassau, 1968; Lehmann, 1978). Preliminary structural data and the Raman-shift spectra support the idea that incorporation of Cs and perhaps other alkalis has caused an increase of cell dimensions mainly along the *c*-axis.

Summarizing, studied morganites from Afghanistan and Madagascar represent an extreme position in respect to all measured data (density, RI, Cs-concentration, cell parameters) compared to any beryls described so far in the literature. The new material might require a new mineral name due to chemical and structural differences to the classical morganite.

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