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Heat-treated Be–Mg–Al oxide (originally musgravite or taaffeite)

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ABSTRACT: A heat-treated rough gem mineral from Sri Lanka was examined by gemmological and mineralogical methods. The sample consists of lamellar intergrown taaffeite and beryllium-bearing spinel. Comparing the observed phases and textural patterns with the results of synthesis experiments by Kawakami *et al.* (1986), the formation of the observed phases and their texture may be explained.

Keywords: heat treatment, musgravite, taaffeite, spinel, Sri Lanka

Introduction

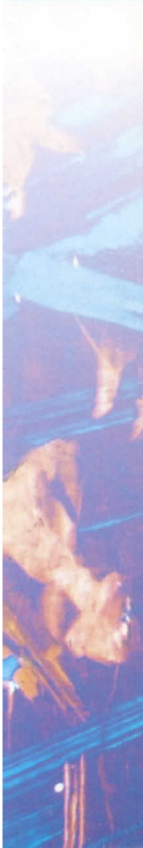
This paper describes the gemmological and mineralogical examination of a rough gem mineral from Sri Lanka. It is shown how a gem mineral determination, which was thought at first to be a normal and simple routine procedure, can become quite complicated and time consuming. It is also shown which determinative steps can be necessary to come to a final and conclusive result.

Experimental results

The sample was first observed in the course of examination of a lot of water-worn rough corundum crystals, originating from Sri Lanka, which had been submitted to commercial heat treatment at about 1650°C by a gem dealer in order to improve the colour of the stones. Within this lot, a somewhat milky-white slightly bluish-to-mauve stone did not show any of the common microscopic features of heat-treated corundum and, thus, a window was polished at the surface of the rough stone for the determination of refractive indices of the birefringent sample.

Figure 1: *Faceted sample of 0.50 ct which was determined as heat-treated Be–Mg–Al oxide (originally musgravite or taaffeite), now consisting of intergrown taaffeite and Be–Mg–Al-spinel. Size of the stone approx. 4.2 x 5.8 mm. Photo by Maha DeMaggio.*

Values of 1.717 to 1.721 indicated that the specimen was either taaffeite, $BeMg_3Al_8O_{16}$, or musgravite, $BeMg_2Al_6O_{12}$. Taaffeite is located at the binary join chrysoberyl $BeAl_2O_4$-spinel $MgAl_2O_4$ at 75% of the spinel end member, whereas musgravite contains



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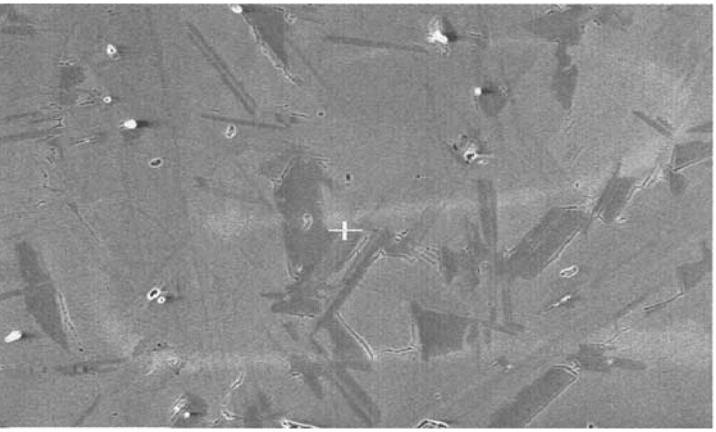
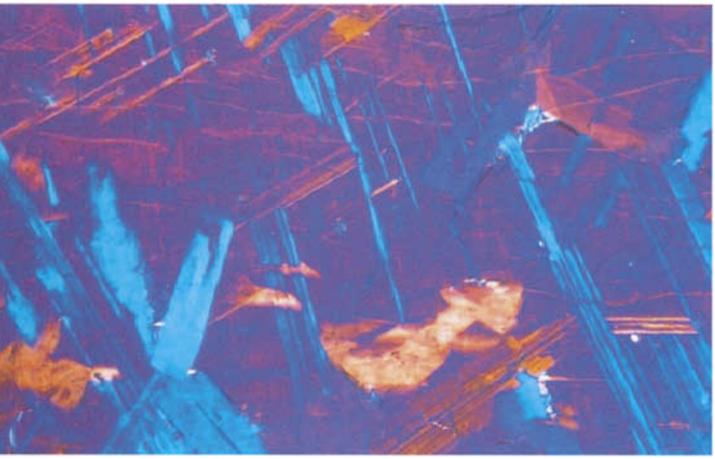


Figure 2: *Back-scattered electron (BSE) image revealing lamellar intergrown spinel (dark) and taaffeite (lighter) areas. The width of the photograph represents 0.47 mm.*

66.7% of the spinel molecule. Both minerals are only rarely found in lots of faceted stones from Sri Lanka, and similarly only a few rough taaffeite crystals of gem quality are known from this country (Schmetzer, 1983a; Kampf, 1991; Demartin *et al.*, 1993).

Figure 3: *Thin section revealing intergrown blue and orange lamellae (representing birefringent taaffeite) and purple areas (representing isotropic spinel and birefringent taaffeite in extinction position). Crossed polarisers with a gypsum plate inserted in the microscope; the width of the microphotograph represents 0.45 mm.*



Problems associated with the distinction of faceted taaffeites and musgravites were recently discussed by Kiefert and Schmetzer (1998). Due to an overlap of gemmological properties, e.g. refractive indices or specific gravity, the distinction of these two minerals needs additional data from, for example, quantitative chemical analysis or X-ray diffraction. Consequently, after cutting two faceted stones of 0.69 and 0.50 ct from the rough sample, one of which is shown in *Figure 1*, small residual fragments of the rough were used for subsequent mineralogical examination.

X-ray powder diffraction analysis was first performed by the Debye-Scherrer technique, but no complete match was found with standard films of taaffeite and musgravite. Subsequently, a Guinier camera was used, which reveals a better resolution of diffraction lines; in addition, this permits three exposures simultaneously, i.e. the examination of the powder pattern of an unknown sample together with two external standards. Consequently, the unknown sample from Sri Lanka was examined together with external standards of an analysed taaffeite from Sri Lanka and an analysed musgravite from Antarctica. As a result, the powder pattern of the unknown sample from Sri Lanka was found to consist of the complete pattern of taaffeite with a number of additional lines which matched the pattern of magnesium–aluminium spinel. The strongest lines of musgravite were not found.

In order to obtain chemical data from the sample, two of the residual fragments mentioned above were polished and submitted to electron microprobe analysis. Although no clear differences between single phases were observable in reflected light, a back-scattered electron (BSE) image (*Figure 2*), performed with the BSE system of the microprobe, revealed a fine lamellar pattern of two intimately intergrown phases. A similar texture was also observed in thin section with crossed polarizers (*Figure 3*).

Quantitative chemical data were obtained from 10 single analysis points for each of the two phases. They indicate a first oxide phase whose composition is almost identical with the theoretical formula of taaffeite and a second oxide with somewhat larger BeO contents and a different Mg:Al ratio. In detail, the average composition of the taaffeite was calculated as $Be_{1.0}Mg_{2.97}Fe_{0.05}Al_{7.98}O_{16}$ (assuming one BeO per formula unit and total iron calculated as FeO), which is almost identical to the ideal formula of taaffeite, $BeMg_3Al_8O_{16}$ (Schmetzer, 1983b; Nuber and Schmetzer, 1983).

Calculating the second phase to 2.0 Al atoms per formula unit (according to the determination of spinel by X-ray powder diffraction), and assuming the difference of divalent cations to be due to beryllium, which cannot be analysed directly by electron microprobe, the formula of the average composition of the 10 microprobe analyses was calculated to be $Be_{0.35}Fe_{0.01}Mg_{0.64}Al_2O_4$ (again assuming total iron as FeO and summing the divalent cations to 1.0). This composition indicates a beryllium-bearing spinel with 65% of the pure magnesium–aluminium end member within the chrysoberyl–spinel join.

In summary, all the evidence indicates that the sample consists of two lamellar intergrown phases: taaffeite and beryllium-bearing spinel.

Discussion

Considering the experimental examinations of the binary system chrysoberyl $BeAl_2O_4$–spinel $MgAl_2O_4$, published by Kawakami *et al.* (1986), the observations described above become understandable. In 1986 taaffeite and musgravite were still regarded as polytypes with an identical chemical composition (the difference in BeO content is only 1.56 wt.%) and, consequently, the phase diagram is somewhat simplified. The general results presented by Kawakami *et al.*, however, are extremely useful in understanding the analytical results obtained from the sample from Sri Lanka.

According to Kawakami *et al.* (1986), both taaffeite and musgravite are incongruently melting compounds. Above an inversion temperature, which is not specified exactly, only a spinel phase and a melt exist. At high temperatures, spinel and chrysoberyl form a solid solution series. This high-temperature compound, i.e. the beryllium-bearing spinel, exsolves taaffeite and/or musgravite lamellae with decrease of temperature.

These phase relationships in the chrysoberyl–spinel system were investigated using the floating-zone technique for crystal growth starting from sintered rods formed from $BeAl_2O_4$ and $MgAl_2O_4$ powders. One experiment was performed with a rod having a starting composition of 37.5% chrysoberyl and 62.5% Mg–Al-spinel. In this run, Kawakami *et al.* (1986) obtained a sample consisting of fine lamellar intergrown taaffeite, musgravite and spinel. These phases were identified by X-ray powder diffraction, but no analytical data, e.g. by electron microprobe, were given and the transition temperatures and extent of intermediate phases still need to be established. It is evident, however, that with a starting composition of 62.5% Mg–Al-spinel and a synthetic end product of taaffeite (which contains a formula percentage of 75% Mg–Al-spinel) and musgravite (which contains a formula percentage of 66.7% Mg–Al-spinel), the resulting intermediate spinel is also a beryllium-bearing phase.

Consequently, the optical pattern of lamellar intergrown phases and the crystalline compounds obtained in the laboratory experiment of Kawakami *et al.* (1986) are consistent with our results. Most probably, during heat treatment of a natural Be–Mg–Al-oxide crystal (musgravite or intergrown musgravite and taaffeite), a beryllium-bearing spinel phase was formed at elevated temperatures. In the course of the cooling process, this high-temperature spinel phase exsolved taaffeite lamellae, but did not transform completely to taaffeite or musgravite. No evidence for the formation of melt was seen at the surface of the rough specimen.

Conclusion

The sample from Sri Lanka was found to be a heat-treated Be–Mg–Al-oxide crystal, most probably musgravite or intergrown musgravite and taaffeite, which now (after heat treatment) consists of intergrown taaffeite and spinel lamellae.

Acknowledgement

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Mineral inclusions in emeralds from different sources

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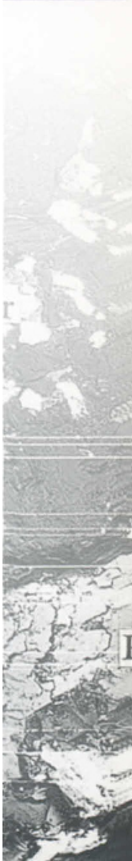
ABSTRACT: Mineral inclusions in emeralds from eleven gem-mining regions and a hydrothermally grown synthetic emerald were chemically analysed with the electron microprobe JEOL JXA-8600. Emerald occurrences in Australia, Brazil, Mozambique, Russia, Tanzania (Lake Manyara) and Zambia belong to 'schist type' deposits. The inclusions comprise micas, talc, pyrophyllite, chlorite, wollastonite, chromite, calcite, dolomite, Fe-oxide, apatite, quartz, pyrite, fluorite and plagioclase. The geological settings for Colombian, Nigerian and Sumbawanga (Tanzania) deposits resulted in related assemblages of solid inclusions in these emeralds (for example, chlorine-rich Al-glauconite, sphalerite, titanium-rich mica, anhydrite and beryllium minerals).

Keywords: electron microprobe, emerald, mineral inclusions



Introduction

Emerald is the most important gemstone of the beryl group (Gübelin, 1974; Sinkankas, 1981; Smith, 1972; Samsonov *et al.*, 1984) and the commercial value of emeralds is affected by many factors, not only by their colour and clarity, but also by their provenance. For the gemmologist the identification of inclusions in gems is of the utmost importance both for their authentification and for the determination of their geological origin (Dele-Dubois and Schubnel, 1987).

A selection of emerald crystals, cut stones and their associated mineral inclusions, from eleven gem-mining regions in Afghanistan, Australia, Brazil, Colombia, Mozambique, Nigeria, Russia, Tanzania, and Zambia, and Biron synthetic emerald were studied using an optical microscope, chemically analysed with an electron microprobe JEOL model JXA-8600 and photographed. This work presents the results of studies of the solid inclusions in these emeralds. Some of the same samples were also studied by a laser Raman microspectrometer DILOR XV (Moroz *et al.*, in press). The study was undertaken to compare the mineral inclusions, characterize distinctions between them and to establish a data base which will enable distinction of emeralds originating from different sources. The electron microprobe technique allows nondestructive chemical analysis of discrete spots across a single crystal, but it has some disadvantages:

(1) with our equipment we cannot measure elements lighter than Na (atomic number 11), so we could not obtain data for Be, a major constituent of berylliium minerals; Li, B, F and water, which can be present in quantities up to several wt%;

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Table I: *Mineral inclusions in emeralds from different deposits.*

Country	*Colombia*	*Nigeria*	*Tanzania*		*Brazil*		*Afghanistan*	*Russia*	*Zambia*		*Australia*	*Mozambique*	*Synthetic*
Locality or deposit	*Muzo*	*Jos*	*Manyara*	*Sumbawanga*	*Carnaiba*	*Santa Terezinha*	*Panjshir*	*Malishevo*	*Kitwe (blue-green)*	*Kitwe (green)*	*Pool*	*Santa Maria*	
No. of samples	2	4	2	2	1	2	3	2	2	3	2	1	2
Fe oxide		●			●			●					●
Fe-Cr oxide							●			●		●	
Fe-Cr-Ni-oxide	●												
Fe-Mn oxide									●				
Sphalerite	●												
Phlogopite			●			●		●	●	●	●	●	
Muscovite					●								
Ti-rich mica				●									
Talc	●		●			●				●			
Chlorite					●								
Pyrophyllite								●					
Glauconite		●	●						●	●			
Illite				●									
Illite-smectite					●								
Margarite								●					
Wollastonite					●								
Apatite										●			
Chromite						●							
Aragonite						●							
Dolomite						●							
Fluorite		●										●	
Anhydrite				●									
Baryte								●					
Pyrite						●							
Albite	●	●	●										●
Quartz	●	●			●					●		●	●
Beryl	●	●					●						
Bertrandite				●		●							
Euclase		●	●	●		●							
Phenakite				●									

NB: The following identifications are unconfirmed: tetrahedrite and tourmaline in Jos emerald, helvine in Sumbawanga, calcite in Panjshir and gypsum in Kitwe emerald.

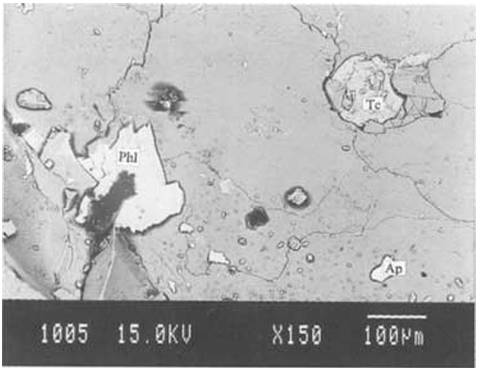

Figure 1: *Inclusions of phlogopite (Phl), talc (Tc) and apatite (Ap) in emerald from Zambia. Image from scanning electron microscope (backscattered electrons)*

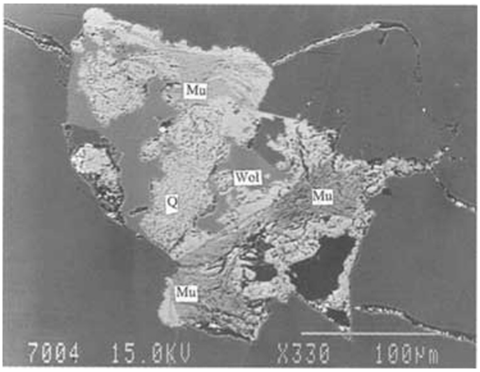

Figure 2: *Wollastonite (Wol), quartz (Q) and muscovite (Mu) aggregate in emerald from Brazil (Carnaìba).*

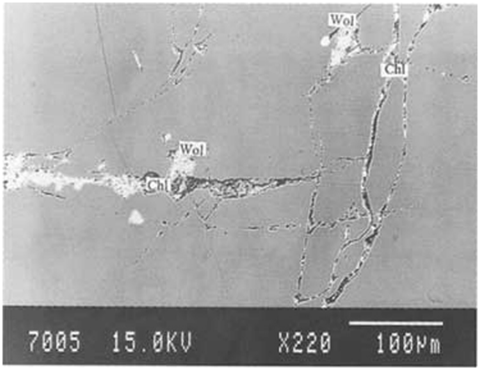

Figure 3: *Chlorite (Chl) and wollastonite (Wol) in flaws in emerald from Brazil (Carnaìba).*

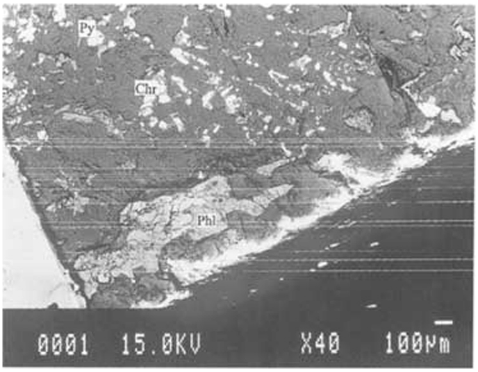

Figure 4: *Inclusions of phlogopite (Phl), aluminochromite (Chr) and pyrite (Py) in emerald from Brazil (Santa Teresinha).*

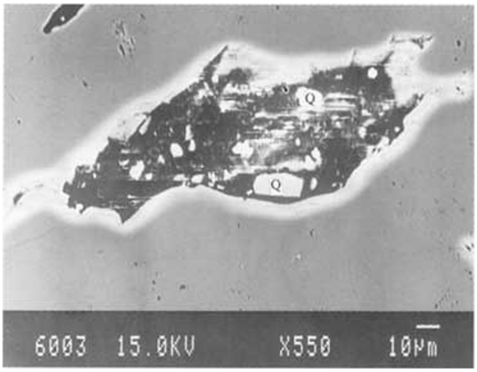

Figure 5: *Quartz (Q) in fluid inclusion in synthetic emerald.*

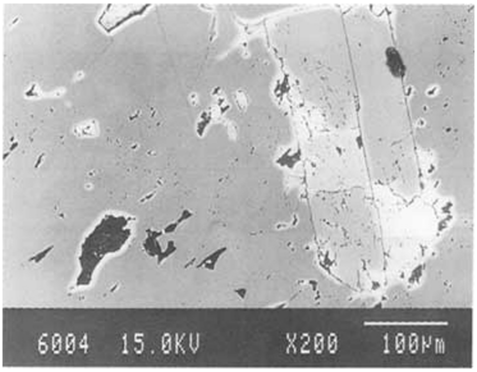

Figure 6: *Albite crystal inclusion in synthetic emerald.*

***Table II:** Crystallochemical formulae of mineral inclusions in emeralds from different deposits (summary of microprobe study)*

Phlogopite		
1	Brazil, Santa Terezinha	$(K_{0.79}Na_{0.002})_{0.792}(Mg_{2.51}Fe_{0.23}Al_{0.36}Cr_{0.02}V_{0.001})_{3.12}[(Si_{3.38}Al_{0.62})_{4.00}O_{10}][OH,F]_2$
2	Tanzania, Lake Manyara	$K_{0.993}(Mg_{2.33}Fe_{0.54}Al_{0.01}Ti_{0.03}Ni_{0.04}Cr_{0.001})_{2.95}[(Si_{2.83}Al_{1.17})_4O_{10}[OH,F,S_{0.045}]_2$
3	Tanzania, Lake Manyara	$(K_{0.71}Na_{0.03}Ca_{0.12}Ce + La_{0.05}Cs_{0.005})_{0.92}(Mg_{2.15}Fe_{0.40}Al_{0.28}Ti_{0.02}Ni_{0.04}Mn_{0.02}Cr_{0.003})_{2.85}$ $[(Si_{2.94}Al_{1.06})_4O_{10}][OH,F,S_{0.05}]_2$
4	Russia, Malishevo	$(K_{0.84}Na_{0.06}Ca_{0.01}Ce + La_{0.04}Cs_{0.01})_{0.96}(Mg_{1.97}Fe_{0.48}Al_{0.29}Ti_{0.03}Mn_{0.03}Cr_{0.01}Cu_{0.01}Co_{0.01})_{2.82}$ $[(Si_{3.06}Al_{0.93})_4O_{10}][OH,F,S_{0.01}]_2$
5	Zambia, Kitwe (in green emerald)	$(K_{0.87}Na_{0.04}Ca_{0.01})_{0.92}(Mg_{2.33}Fe_{0.36}Al_{0.21}Cr_{0.01})_{2.91}[(Si_{3.10}Al_{0.90})_4O_{10}][OH,F]_2$
6	Zambia, Kitwe (in bluish-green emerald)	$(K_{0.67}Na_{0.10}Cs_{0.005})_{0.78}(Mg_{1.29}Fe_{0.77}Al_{0.56}Zn_{0.04}Mn_{0.02}Cu_{0.02}Ti_{0.01}V_{0.004})_{2.71}$ $[(Si_{3.36}Al_{0.64})_4O_{10}][OH,F]_2$
7	Australia, Pool	$(K_{0.73}Na_{0.06}Cs_{0.01})_{0.80}(Mg_{1.40}Fe_{0.54}Al_{0.56}Ti_{0.03}Zn_{0.02}Sn_{0.02}Cr_{0.02})_{2.60}$ $[(Si_{3.44}Al_{0.56})_4O_{10}][OH,F,S_{0.01}]_2$
8	Mozambique, Santa Maria	$(K_{0.41}Na_{0.25}Ca_{0.05})_{0.71}(Al_{0.50}Mg_{1.57}Fe_{0.32}Ti_{0.005}Mn_{0.03}Cr_{0.005})_{2.43}$ $[(Si_{2.82}Al_{0.66}P_{0.52})_4O_{10}][OH,F]_2$
Muscovite		
9	Brazil, Carnaiba	$(K_{0.92}Na_{0.01}Ca_{0.01})_{0.94}(Al_{1.33}Fe_{0.35}Mg_{0.33}Cr_{0.01})_{2.05}[(Si_{3.38}Al_{0.62})_4O_{10}][OH,F]_2$
Titanium-rich mica		
10	Tanzania, Sumbawanga	$(K_{0.65}Na_{0.08}Ca_{0.02})_{0.75}(Ti_{1.00}Al_{0.81}Fe_{0.06}Mg_{0.02}V_{0.03}Cr_{0.002})_{1.92}[(Si_{2.54}Al_{1.46})_4O_{10}][OH]_2$
Margarite		
11	Russia, Malishevo	$(Ca_{0.93}Na_{0.06})_{0.99}Al_2[(Si_{1.79}Al_{1.37}Be_{0.84})_4O_{10}][OH,F]_2$
Mixed-layer illite-smectite		
12	Brazil, Carnaiba	$(K_{0.34}Na_{0.01}Ca_{0.22})_{0.57}(Al_{1.70}Mg_{0.29}Fe_{0.04}Cr_{0.01})_{2.04}[Si_{3.36}Al_{0.64}O_{10}][OH]_2.nH_2O$
Illite		
13	Tanzania, Sumbawanga	$(K_{0.34}Na_{0.019}Ca_{0.02})_{0.38}(Al_{1.86}Mg_{0.10}Fe_{0.046}Mn_{0.01}Cr_{0.02})_{2.04}[(Si_{3.61}Al_{0.39})_4O_{10}][OH]_2.nH_2O$
Al-glauconite		
14	Nigeria, Jos	$(K_{0.42}Na_{0.12}Ca_{0.065}Cs_{0.002})_{0.61}(Al_{1.17}Fe_{0.64}Mg_{0.31}Ti_{0.054}Zn_{0.02}Cr_{0.005})_{2.20}$ $[(Si_{3.5}Al_{0.5})_4O_{10}][OH,Cl,S_{0.05}]_2.nH_2O$
Al-celadonite		
15	Zambia, Kitwe	$(K_{0.28}Na_{0.14}Cs_{0.01})_{0.43}(Al_{1.14}Mg_{0.80}Fe_{0.24}Cr_{0.02}Pb_{0.02}Sn_{0.02}Ni_{0.01}Ti_{0.01})_{2.27}$ $[(Si_{3.97}Al_{0.03})_4O_{10}](OH]_2.nH_2O$
Talc		
16	Brazil, Santa Terezinha	$(Mg_{2.94}Fe_{0.12}Cr_{0.002}Ni_{0.02}Mn_{0.005})_{3.09}[Si_{3.95}O_{10}][OH]_2$
17	Tanzania, Lake Manyara	$(Mg_{3.09}Fe_{0.08})_{3.17}[Si_{3.92}O_{10}][OH]_2$
18	Zambia, Kitwe	$(Mg_{2.49}Fe_{0.34}Al_{0.17}Cr_{0.002}Ca_{0.02}Na_{0.01}K_{0.01})_{2.99}[(Si_{3.92}Al_{0.08})_4O_{10}][OH]_2$
19	Colombia, Muzo	$(Mg_{2.31}Fe_{0.08}Al_{0.17})_{2.56}[Si_{4.16}O_{10}][OH,S_{0.01}]_2$
Pyrophyllite		
20	Russia, Malishevo	$(K_{0.19}Na_{0.11}Cs_{0.001})_{0.30}(Al_{1.31}Mg_{0.53}Fe_{0.18}Cu_{0.01}Cr_{0.01})_{2.04}[Si_{4.07}O_{10}][OH]_2$
Chlorite		
21	Brazil, Carnaiba	$(Mg_{4.47}Fe^{2+}{}_{0.50}Ca_{0.02}Na_{0.01})_{5.00}(Al_{0.68}Fe^{3+}{}_{0.46}Cr_{0.004})_{1.14}[Si_{3.01}Al_{0.99}O_{10}][OH]_8$
Wollastonite		
22	Brazil, Carnaiba	$(Ca_{0.86}Mg_{0.09}Fe_{0.03}Ni_{0.006}Cr_{0.001}Na_{0.01}K_{0.005})_{1.00}[(Si_{1.04}Al_{0.02})_{1.06}O_3]$
Aluminochromite		
23	Brazil, Santa Terezinha	$(Fe_{0.96}Mg_{0.04})(Cr_{1.33}Al_{0.43}Fe_{0.25}V_{0.01})_{2.02}O_4$
Euclase		
24	Tanzania, Lake Manyara	$Be_{1.02}(Al_{0.89}Ti_{0.01}Mg_{0.01}Fe_{0.13})_{1.04}[(Si_{0.93}Be_{0.07})_{1.00}O_4][OH]$

(2) different oxidation states of elements such as iron and vanadium cannot be determined; and

(3) the technique allows chemical analyses only at the surface of a grain.

Nevertheless, the microprobe is being used more frequently in the study of single emerald samples and their solid inclusions; see, for example, Gübelin, 1982; Graziani *et al.*, 1983; Cassedanne and Sauer, 1984; Eidt and Schwarz, 1986; Ringsrud, 1986; Dele-Dubois and Schubnel, 1987; Miyata *et al.*, 1987; Schmetzer *et al.*, 1991; Schwarz *et al.*, 1996 and Moroz, 1997.

Materials and apparatus

The samples in this study were provided by Israel's Emerald Cutters Association. This article presents the results of testing a selection of emerald crystals and faceted emeralds from eleven gem-mining regions ranging from 0.3 (Afghanistan) to 4.39 ct (Brazil, Carnaiba), and Biron synthetic emerald. The samples represent a wide range of colours between bluish-green and yellowish-green. The rough crystals are predominantly euhedral prismatic. Some of the rough and the polished samples have eye-visible colour zoning, with sporadic colourless zones, typically parallel to the prism faces. The diaphaneity of the samples ranged from transparent to translucent, depending on the nature and number of inclusions present. Weak-to-prominent growth structures are present in most of the samples. Most common (especially in Nigerian specimens) were strongly developed straight and angular sequences of prism, basal-pinacoid and pyramid planes.

Mineral inclusions in 28 samples were chemically characterized by use of the electron microprobe JEOL model JXA-8600 Superprobe at the Institute of Earth Sciences, The Hebrew University of Jerusalem. The instrument was equipped with four wavelength-dispersive spectrometers which were used to analyse Mg, Na, Cr and V; the other element contents were measured using an energy-dispersive spectrometer, which displays the entire spectrum (atomic number eleven and above) produced by the spot that was exposed to the beam. The microprobe was operated using 15 kV acceleration voltage with a beam current of 10 nA. The Tracor-Northern Computerized automation system was used to collect and store data, as well as allowing data analysis and presentation. Standards consisted of natural minerals and synthetic materials. We refer the reader to Goldstein *et al.* (1981) for a thorough review of the instrumentation, theory and applications of the technique.

Results and Discussion

The inclusions identified are listed in *Table I* and a selection is shown in *Figures 1–6*. The means of 10–15 microprobe analyses for each species of inclusion for each locality are presented in *Table II* as calculated formulae. The detection limits for elements analysed by microprobe are generally in the range up to two thousand parts per million. Total iron is reported as FeO; vanadium can also occur in multiple valence states but is reported as V_2O_3. It has been possible to identify some beryllium minerals, using calculations based on stoichiometry.

Emerald occurrences in Australia, Brazil, Mozambique, Russia, Tanzania (Lake Manyara) and Zambia belong to so-called 'schist-type' deposits, similar in many respects to those described by Fersman (1925) as emerald-bearing biotite schists in the Ural Mountains; that is, they are located in regions where acidic magmas have penetrated country rocks in the vicinity of basic and ultrabasic rocks. In these situations the beryllium is believed to be derived from acidic intrusions and the chromium appears to have originated from the country rocks (Beus and Mineev, 1974; Kiyevlenko *et al.*, 1974; Moroz, 1978; Sliwa and Nguluwe, 1984; Schwarz and Eidt, 1989; Schwarz, 1991; Laurs *et al.*, 1996; Moroz and Eliezri, 1998). Such emeralds usually occur in phlogopite-biotite rocks which also contain actinolite or tremolite and variable quantities of talc, chlorite, quartz, albite, chromite, ilmenite, magnetite, apatite and fluorite (Moroz, 1978;

1979; 1983; 1996). Some of these minerals occur as inclusions in the emeralds studied and vary in size, with the largest up to 1mm. Usually there is no visible crystallographic orientation of the mineral inclusion distribution within the emerald host crystals. Only the minerals trapped on crystal faces (for example, aragonite, dolomite, or the bertrandite and euclase aggregate on the prism and pinacoid of emerald from Santa Terezinha) during a period of growth interruption show a spatial distribution related to the emerald crystallography. Some of the inclusions are identifiable optically, but many are not and these have been identified by electron probe and Raman microanalyses. The results of the study allow us to distinguish different compositions of the same mineral species in emeralds from different deposits (see the compositions in *Table II*).

Phlogopite is the most common mineral inclusion in these emeralds (*Table I; Figures 1 and 4*), but its composition varies (*Table II, 1–8*). Formulae calculated on a basis of 11 oxygens typically have total numbers of octahedral cations less than the ideal 3.0. The Mg:Fe ratios in phlogopite inclusions in emeralds from Brazil (Santa Terezinha, *Figure 4*), Zambia (*Figure 1*), Tanzania (Manyara), Mozambique and Russia lie in the range 4.1–10.9 with the highest ratio in phlogopite from Santa Terezinha. This ratio in phlogopite inclusions in emeralds from Australia is 2.6 and in bluish-green emerald from Zambia is 1.7. The values of this ratio in phlogopite correlate with relative concentrations of these elements in the host emeralds from these deposits and reflect country rock compositions.

In addition to chromium (0.001–0.02 atoms per three octahedral sites) and titanium (0.03 atoms), several other substitutions are recorded in small amounts for the octahedral sites of phlogopites. The analyses show a few hundredths of an atom of Mn per three octahedral sites in Mozambiquean, Russian, Tanzanian (Manyara) and Zambian phlogopites and there is a coexisting phase of Mn-rich oxide in a Zambian bluish-green emerald (*Table I*). Copper is present in Russian and Zambian phlogopite, nickel in Tanzanian, cobalt in Russian, vanadium in Brazilian and Zambian (from bluish-green emerald) and tin in Australian phlogopite inclusions (*Table II*). Cesium is found in Russian, Australian and Tanzanian phlogopite; the higher values being in phlogopite from the first two deposits. Phlogopite inclusions of tabular habit in emerald from Mozambique (*Table II*, N 8) usually contain appreciable phosphorus concentrations (to 0.52 atoms per four tetrahedral sites). Sulphur occurs in amounts of 0.01–0.05 of an atom in the mica inclusions from Tanzanian, Australian and Russian samples, with the highest value in phlogopite from the first deposit.

Conclusions

Mineral inclusions in emeralds from eleven gem-mining regions were chemically characterized by use of the electron microprobe JEOL JXA-8600.

The emeralds from the Australia, Brazil, Mozambique, Russia, Tanzania (Lake Manyara) and Zambia localities belong to 'schist-type' deposits, and they may contain micas, margarite, aluminiferous glauconite, celadonite, mixed-layer illite-smectite, talc, pyrophyllite, chlorite, wollastonite, aluminochromite, aragonite, calcite, dolomite, Fe-oxides, apatite, quartz, pyrite, anhydrite, fluorite, plagioclase, beryl, euclase and bertrandite. The results of the study allow us to distinguish different compositions of the same mineral species in emeralds from different deposits – for example, mica.

The geological settings for Colombian, Nigerian and Sumbawanga (Tanzania) deposits result in related sets of solid inclusions consisting of chlorine-rich Al-glauconite, essentially a copper–antimony sulfide and tourmaline in Nigerian emerald; sphalerite in Colombian emerald; and titanium-rich mica, illite, anhydrite, helvine, euclase, phenakite and bertrandite in emerald from Sumbawanga.

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Chrome chalcedony – a review

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ABSTRACT: Three chrome chalcedonies from different sources are described. Stones from recent finds in Zimbabwe and Bolivia have refractive indices of 1.530–1.550, rarely with a birefringence up to 0.005. Roman intaglios have refractive indices about 1.540. All have a bright-red reaction under a Chelsea colour filter and show chromium spectra in a hand spectroscope. The intaglios show in addition complete absorption in the blue part of spectrum, caused probably by higher iron contents. Properties of artificially dyed Cr-chalcedony are given for comparison.

Keywords: Bolivia, chrome chalcedony, Roman intaglios, Zimbabwe

Introduction

Cryptocrystalline quartz, chalcedony, has many varieties of which the green chrysoprase, known from several localities, is the most valuable. The oldest known commercial chrysoprase deposit was near Szklary in today's Poland, where the first written report dates from 1425 (Natkaniec-Nowak *et al.*, 1989); the deposit was rediscovered in 1740. Much younger finds are from the Ural Mountains, California and Oregon at the end of the nineteenth century. The most important recent chrysoprase deposits were discovered in the 1960s in Queensland, Australia (Krosch, 1990), in Western Australia, in the states of Goias and Minas Gerais in Brazil and in Sarykulboldy, Kazakhstan (Samsonov and Turingue, 1984).

There is no doubt that chrysoprase is coloured by Ni, which can be contained in amounts up to 5.08% NiO (Barsanov and Jakovleva, 1981). Although the form of Ni is not established beyond doubt, most probably it is bonded in hydrated Ni-silicates (see Webster, 1994) or in tiny particles of the mineral bunsenite, NiO (Barsanov and Jakovleva, 1981). Green opal very similar to chrysoprase is known from Szklary and from Dodoma in Tanzania, where it contains about 1.1% Ni (Schmetzer *et al.*, 1976). Opal can be distinguished by means of its lower refractive index.

Occurrences of chrome chalcedony

Green chalcedony with a high Cr-content was found at first in about 1955 near Mtoroshanga in today's Zimbabwe and called mtorolite (*Figure 1*). Its best

Figure 1: Mtorolite, Zimbabwe, the larger piece is 17 x 9 cm.

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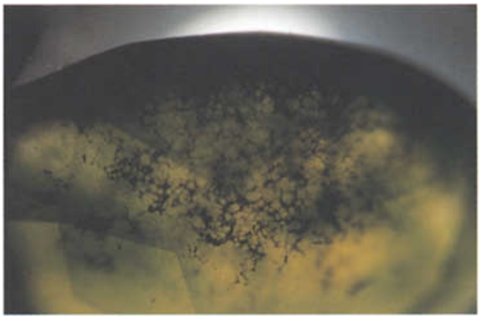

Figure 2: *Chrome chalcedony Bolivia, black net of Fe-oxides (?).*

Figure 3: *Chrome chalcedony Bolivia, yellow-brown Fe-oxides.*

descriptions were written by Phillips and Brown (1989) and Campbell (1955). It comes from the Great Dyke, a huge 500 km long dyke of ultrabasic rock. Mtorolite occurs in a deposit 1.7 km long striking N–S, and is often accompanied by white chalcedony. The best cuttable material came from a small shaft where chrome chalcedony formed three layers with a width of 6–25 mm. The best qualities have already been mined out and at present only low-grade pale green or mottled mtorolite is recovered occasionally as a by-product during the mining of serpentinite for carvings (A. Loke, pers.comm, 1996).

A new occurrence of Cr-chalcedony was found recently in eastern Bolivia (Hyrsl and Petrov, 1998). It is called 'chiquitanite' by local jewellers, from the Chiquitania region of eastern Santa Cruz Department. The chrome chalcedony has a pleasant apple- to dark-green colour and is opaque to translucent (*Figures 2 and 3*). Some stones show a very fine agate-like structure (Figure 4) or a brown 'net' of Fe-oxides. Some parts are coloured more generally brownish by Fe-oxides. The best quality material is facetable and compares favourably with mtorolite. Most of the rough material is exported directly to Brazil and the author found cut chrome chalcedony at the 1995 Munich mineral show described as 'a new find of apatite from Brazil'.

Figure 4: *Chrome chalcedony Bolivia, very fine agate-like layers.*

Figure 5: *Chrome chalcedony Mercury intaglio (coll. W.Mican), 16.9 x 12.5 x 6.8 mm.*

Figure 6: Two intaglios (chrome chalcedony and carnelian) in a necklace from the Museum of Decorative Art, Prague.

A third occurrence of chrome chalcedony is mentioned in the 10th edition of Anderson's *Gem Testing* (1990), revised by E.A. Jobbins. He described Roman cameos and intaglios made from Cr-chalcedony which appeared red under a Chelsea colour filter. Unfortunately, there is no more published information about it. There is one similar intaglio in a private collection of Professor W. Mican in Vienna (*Figure 5*). The gem has dimensions 16.9 x 12.5 x 6.8 mm and weighs 1.820 g. It is apple-green with an uneven colour. Several white spots can be seen inside and a small quantity of brown matrix occurs near the girdle. The gem is an intaglio with the head of the Roman god Mercury and is polished on the other side. Its age is not certain and it could be either Roman or a younger copy.

Another two small light and dark green chrome chalcedony intaglios form part of a necklace in the collection of the Museum of Decorative Arts in Prague, Czech Republic (*Figure 6*). The necklace is probably from the beginning of the nineteenth century, but the Cr-chalcedony intaglios could be much older, because they are more scratched than the others made of carnelian. Two small Cr-chalcedony intaglios were also studied in Prague from a Romanesque reliquary of St Maurus dating from the beginning of the thirteenth century. According to Ondrejova (pers.comm.), both intaglios probably date from the second century AD. They are olive green and emerald green respectively, with n = 1.540, no birefringence, and a specific gravity of 2.58. They show no luminescence in UV, both are red under a Chelsea filter and show Cr-spectra in a hand spectroscope (the emerald green intaglio shows a much sharper line in the red than

Table I: *Gemmological properties of Cr-chalcedonies from different sources*

	Zimbabwe	*Bolivia*	*Intaglio*	*Dyed chalcedony*
Colour	dark green	dark green	dark green	dark green
Diaphaneity	translucent	translucent	translucent	translucent
Hardness	7	7	7	7
RI	1.540	1.530–1.550	1.540	1.532–1.540
Birefringence	0–0.005	0–0.006	–	0–0.005
SG	2.56–2.60	2.56–2.57	2.56	2.56–2.58
UV luminescence:				
LWUV	yellowish	yellowish	very light yellowish	inert
SWUV	pale yellowish in light parts	inert	inert	inert
Chelsea colour filter	Bright red	Bright red	Bright red	Weak brownish-red

Table II: Chemical composition of analysed chalcedonies from Bolivia and Zimbabwe, and artificially coloured chalcedony.

Wt.%	*Cr chalcedony – Bolivia*		*Cr chalcedony – Zimbabwe*		*Artificially coloured chalcedony*	*Detection limits*
	Dark	*Light*	*Dark*	*Light*		
SiO_2	95.90	96.00	93.56	94.38	98.92	0.10
TiO_2	0.09	–	–	–	–	0.07
Al_2O_3	0.09	0.13	0.29	0.18	0.16	0.08
Cr_2O_3	0.36	0.51	0.45	0.21	0.28	0.10
MgO	0.11	0.15	0.30	0.16	–	0.06
MnO	–	–	0.08	–	–	0.08
TOTAL	96.55	96.79	94.68	94.93	99.36	

NB: CaO (0.10 wt.%), FeO (0.10 wt.%), NiO (0.30 wt.%), K_2O (0.05 wt.%) and Na_2O (0.30 wt.%) were sought but below their respective detection limits.

the olive green stone) with complete absorption in the blue part of the spectrum, very similar to the Mercury intaglio which is described later.

Many ancient gems made from Cr-chalcedony are housed in the Cabinet des Medailles in the Bibliotheque Nationale in Paris. Their colours range from emerald-green with a red response under the Chelsea colour filter to light yellowish-green with a pink colour under the Chelsea filter. Their quality ranges from clean translucent to greyish opaque with brown or red networks or spots of Fe-oxides. According to Broustet (pers.comm.), they are mostly from the first to the third century AD, and some could be older. Considering their number (a few dozen) and very different qualities they could come from different parts of the same deposit or from many deposits.

Green chalcedony coloured artificially has usually been dyed by chromium salts. Fortunately, it is easy to distinguish from natural stones by its different reactions under a Chelsea filter and in a hand spectroscope. It also has a typical structure, because grey chalcedony must be cut perpendicular to its fibres to facilitate better permeability for the dye (Webster, 1994). The chemical analysis (*Table II*) shows also that it has a lower content of water than natural chrome chalcedonies.

Gemmological properties

The four materials mentioned above were studied at the same time, including both high- and low-grade chrome chalcedony from Bolivia and Zimbabwe, and their gemmological properties are listed in *Table I*, chemical analyses are reported in *Table II*.

All the chrome chalcedonies are polycrystalline aggregates and they remain light during rotation in a polariscope. Their refractive indices lie between 1.530–1.550 (mostly 1.540) and a few of them exhibit a slight birefringence, caused by its semi-colloidal structure. The most useful property in distinguishing the chrome chalcedonies is their colour under the Chelsea filter. Both natural rough samples and the cut and polished intaglios are bright red under the Chelsea filter, while the artificially coloured Cr-chalcedony is only brownish-red and chrysoprase is nearly inert. The second useful test is to examine them by means of a hand spectroscope. Natural chrome chalcedonies show an emerald-like spectrum with a sharp line (at 684 nm) in the red and an absorption of the yellow and violet parts of the spectrum. The Mercury-gem and the intaglios show, in addition, complete absorption in the blue part of the spectrum, which may well be caused by higher iron contents. The spectrum of artificial Cr-chalcedony typically shows two diffuse lines

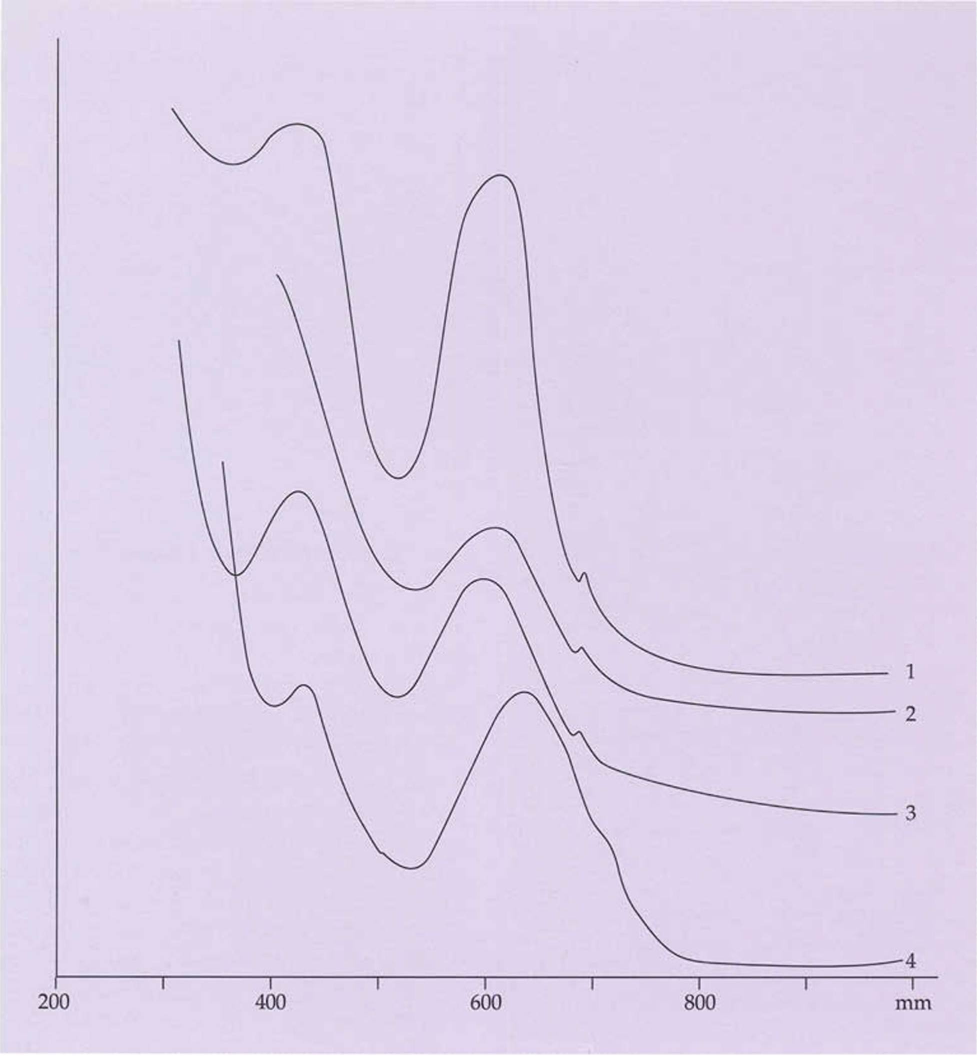

Figure 7: UV-VIS spectral curves of Cr-chalcedony from: 1) Bolivia, 2) Mercury intaglio, 3) Zimbabwe, and of dyed chalcedony 4).

in the red. The curves from the UV-VIS spectrophotometer are shown in *Figure 7*. Surprisingly, artificial Cr-chalcedony is more easily recognised by hand spectroscope, because the two lines in the red show only as weak shoulders on the spectrophotometer trace.

Yellowish fluorescence in SWUV was observed on pale parts of a mtorolite vein, and opal could be present (see *Table I*). Dark mtorolite has much weaker fluorescence than the light variety. Chrysoprase does not usually fluoresce, but Kammerling *et al.* (1990) described greenish-blue fluorescence of chrysoprase from Goias, Brazil. It was stronger in LW than in SWUV.

An attempt to identify the cause of colour was made during a microprobe study. Chromium content in a single specimen ranged from less than 0.10% to 0.95%. Unfortunately in a scanning electron microscope, the back-scattered electron images of the material look homogenous and it means that possible particles of a Cr-mineral are smaller than 100 nm. In some analyses, the Cr content has a positive correlation with contents of Mg and Al, but the results were not statistically significant.

Conclusions

To determine the origin of chrysoprase and chrome chalcedony is an interesting geochemical task. Both originate from Ni–Cr-rich ultrabasic rocks, where Ni is usually bound in olivine and Cr in spinels such as chromite and in pyroxenes such as chrome diopside. Olivine is the most unstable mineral in the ultrabasic rocks (i.e. it weathers first) whereas spinels are almost insoluble. This means that when the olivine weathers first, the SiO_2 is leached out together with Ni and precipitates nearby in fractures to form chrysoprase. Too much circulating water can cause complete leaching of SiO_2 and then no chrysoprase can form. Chrome chalcedony occurs probably after stronger weathering where pyroxenes have been dissolved too, thereby releasing their component Fe, Mg, Cr and Si to recombine under new conditions.

The original locality of the chrome chalcedony used for gems by the Romans is not known and could be very difficult to find. There is no evidence that the Bolivian material was available before recent times. However, the Romans were trading with the East African coast and probably could have obtained material from Zimbabwe, but mtorolite looks completely different from the chrome chalcedony used for Roman intaglios. There must have been another locality which has probably been mined out and forgotten. Two clues could help locate this unknown deposit: one is the relatively rich occurrence of Cr-chalcedony intaglios in the first to third century AD. Their quality fluctuates over a wide range. Older ones are very rare and their dating might even be incorrect. Several examples of Cr-chalcedony intaglios in younger decorative objects may well be a reflection of the very common re-use of antique stones throughout history. For example, the St Maurus reliquary dates from approximately the year 1200 and contains 66 carved gems, most of which are Roman intaglios. There are also possibilities that there was more than one period of mining at the original locality, and that there were later finds of similar stones elsewhere.

The second clue is the origin of Cr-chalcedony in strongly weathered ultrabasic rocks. In the ancient world, the most important accessible areas with such rocks occur in Turkey, Albania and the former Yugoslavia. Recently, Bank *et al.* (1997) described a cuttable green opal from Kutahya in Turkey. It has an RI between 1.438 and 1.442, SG 2.03–2.06 and, according to its spectrum, its colour is caused by trivalent chromium. The occurrence of Cr-chalcedony would be logical in the same region and it might be rediscovered by chance in the future.

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A colorimetric study of the alexandrite effect in gemstones

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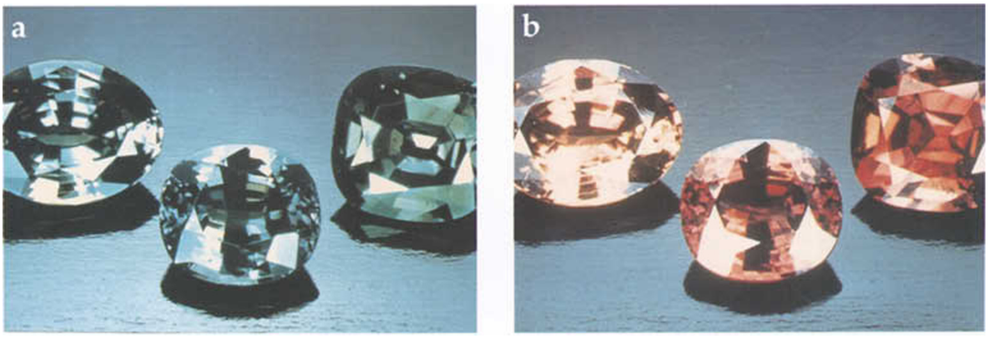
ABSTRACT: The variation in colour hue (the alexandrite effect) for gemstones that change colour under pairs of light sources can be measured by the difference in their calculated CIELAB hue-angle. Depending upon the measured hue-angle and the light sources used, gemstones that exhibit this phenomenon can be grouped into several categories. Colour measurement can provide support for visual observation to help the gemmologist determine if a gemstone displays this behaviour.

Keywords: alexandrite effect, colour, colour appearance, colour change, colour measurement

Introduction

Gemstones that change colour under different light sources are quite valuable and are much sought after in the jewellery trade. On identification reports issued by gem-testing organizations such as the GIA Gem Trade Laboratory, whether or not a gemstone exhibits a colour change can be an important explanatory comment. This phenomenon has been reported in some chrysoberyl (the important variety alexandrite), sapphire, spinel, pyrope-spessartine garnet, zircon, tourmaline and diaspore, to name several of the better-known examples (see, e.g. Schmetzer and Gübelin,

Figure 1: *Three natural alexandrites as seen under two light sources – (a) a fluorescent daylight simulator and (b) an incandescent light. The three gemstones are, from the left, a 1.29 ct stone from Russia, and two stones from the Hematita mine in Brazil (1.06 and 1.32 ct). Photograph by Tino Hammid, copyright GIA.*



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1980a; Scarratt, 1980). It is described as a difference in the colour hue of the gemstone, and not a change in either its colour saturation or colour lightness. Quite pronounced colour changes are known (such as the violet-red to bluish-green change in alexandrite; see *Figure 1*). However, when the colour-hue change is less pronounced, it may be difficult to determine by visual observation whether a gemstone is actually changing colour.

Colour in gemstones is the colour appearance that a person sees. Within the past decade, however, both visual colour comparison instruments, and colour measurement instruments such as colorimeters, spectrophotometers, and imaging spectrophotometers have been introduced into the jewellery trade as an aid for gemstone colour determination (Nelson, 1986; Allaman, 1995). Measuring the colour of a three-dimensional, transparent, faceted gemstone presents challenges in comparison to working with flat, parallel-sided coloured samples. By measuring the interaction of light with a gemstone, the instruments calculate a location of the gem's colour in colour space (which location must then be translated into a word description of the colour to be of practical use in the jewellery trade). However, the question that is often unanswered or unclear when using these measurement instruments is the relation between the colour appearance we see, and the colour appearance of the gemstone that is being measured by the instrument. This is because the colour of a gemstone is due not just to its bodycolour, but also to optical effects due to its size, faceted shape, and other factors. In the table-up orientation, a faceted gemstone exhibits a pattern of colour appearances, and both the human observer viewing the gemstone, and the instrument measuring light coming from the gemstone, may not be 'seeing' the same colour appearance. To date, none of these instruments has yet attained widespread use in the jewellery trade. Nelson (1986) summarized many of the objections in the jewellery trade that have hindered the widespread acceptance of gemstone colour grading systems, and the use of colour comparison and measurement instruments.

The purpose of this article is to report on the results of a colour measurement study of gemstones that change colour under three CIE standard illuminants (theoretical light sources), which represent different types of actual light sources commonly used in the jewellery trade. The goals of this study are:

(1) to further investigate if the calculated colour appearance of a gemstone, obtained by instrumental measurement, can be related to its colour appearance determined by visual observation, as has been suggested by the results of other gemmological studies;

(2) to calculate by colour measurement the colour appearance changes of gemstones under several different pairs of standard illuminants; and

(3) to determine if instrumental colour measurement can assist the gemmologist to decide if a gemstone is changing colour, when the visual appearance of the colour hue change is uncertain.

Background

Colour is one of the most important aspects that make up the beauty of a gemstone. It is a significant contributor to a gemstone's value. Describing this colour in word terms that are widely understood and accepted in the jewellery trade is vital for both effective communication among jewellers and consumers, sustaining integrity in the jewellery trade, and helping to increase gemstone commerce. However, this remains a challenge for jewellers and gemmologists because of:

(1) the difficulty that can occur of describing the colour seen in a gemstone in word terms;

(2) variations in colour description terminology that are used in the trade;

(3) the absence of practical colour-reference standards for visual comparison purposes that effectively simulate the wide range of colours seen in gemstones;

(4) differences in the lighting and viewing conditions under which gemstones and their colour are observed; and

(5) the lack of accepted boundaries in colour space for the ranges of colours of important gemstones (such as the boundary between red ruby and pink sapphire).

Colour is best described in words by means of three attributes – hue (what we normally think of as the colour, such as blue or green), saturation (the depth of the colour, described in terms ranging from, for example, faint to vivid), and lightness (from light to dark). Observation of gemstone colour should be done using controlled lighting and viewing conditions for the most consistent results (the gender, age, colour vision, and physiological state of the observer are also important). Visual colour perception is a complicated phenomenon, but a gemstone's colour appearance arises from a combination of the illumination characteristics of the light source (the actual lamp or bulb), the lighting and viewing conditions used, the light absorbing and transmitting properties of the gemstone itself, and the light detection characteristics of the eye. One example of a procedure for observing and describing colour in gemstones can be found in the article on coloured diamonds by King *et al.* (1994). The scientific basis for observing colour in objects has been standardized and published by the Commission Internationale de L'Éclairage (CIE), an international organization of researchers in the areas of colour science, human vision, and lighting (see CIE, 1986). Descriptions of colour observation and measurement can also be found in standard textbooks such as Billmeyer and Saltzman (1981), Wyszecki and Stiles (1982), Nassau (1983), and Kuehni (1997).

For most gemstone species, a given specimen appears nearly the same colour when seen under different light sources. This results from the extraordinary ability of the human vision system to adapt chromatically over a short time to the changing lighting conditions when viewing an object. Chromatic adaptation means that our eyes adjust when observing an object under different light sources, so that the object's colour often appears nearly constant as the lighting changes (such as an apple that appears red under daylight, incandescent light, and fluorescent light). A good discussion of both vision experiments and the constancy of colour appearance of objects is presented in the article by Land (1959).

Despite colour constancy and the chromatic adaptation of our vision system, some objects do appear to change colour to a certain degree when viewed under different light sources, although we are not normally aware of this change. Colour change in materials seems to have been known at least since the Middle Ages, when Leonardo da Vinci is believed to have first investigated it. This phenomenon has been investigated in some detail by scientists studying colour and colour vision (Ives, 1912; Helson, 1938; Helson and Jeffers, 1940; Judd, 1940; Helson *et al.*, 1952).

Reports on colour-change gemstones are widespread in the gemmological literature (see e.g. Jobbins *et al.*, 1975; Schmetzer and Gübelin, 1980a,b; Scarratt, 1980; Bosshart *et al.*, 1982; Duroc-Danner, 1987; Bank and Henn, 1988, Dharmaratne, 1993; Federman, 1995). For the most part, these articles describe the gem material, and give an explanation of the features in the absorption spectrum that contribute to the colour-change behaviour. Because of its prominent colour change between daylight and incandescent light, the alexandrite variety of chrysoberyl gave its name to the 'alexandrite effect' (White *et al.*, 1967). Although some gemmologists restrict this name only to gems that change from green (or yellowish- to bluish-green) in daylight to red or purplish-red in incandescent light, in the trade this name is often applied to gemstones that change between any two colour hues. At the GIA Gem Trade Laboratory (GIA-GTL), a gemstone that exhibits different hues under different light sources is described as showing a 'colour change' when this behaviour is not typical of all samples of that gem varieties (S. McClure, pers.comm., 1998). Certain purple gemstones, such as amethyst, always display different hues under different light sources; these gemstones are described at GIA-GTL as showing a 'colour shift'.

Some results have also been published on the instrumental measurement of gemstones that exhibit the alexandrite effect. Different gemmological researchers have used several methods to calculate colour information based upon these instrumental measurements.

Schmetzer and Gübelin (1980a) used the difference in calculated dominant wavelength of a colour in the CIE 1931 (x,y) chromaticity diagram to represent the colour change in gem materials when going from daylight to incandescent light. In our opinion, there are several problems with this approach. First, the CIE 1931 (x,y) chromaticity diagram is not a uniform colour space, which means that equal distances between pairs of chromaticity coordinates do not represent equal differences in visual colour perception. Secondly, the change in dominant wavelength does not correspond uniformly to the colour-hue change that a person would see in an object. Finally, their method does not take into account the chromatic adaptation of the human vision system.

Table I: *Colour-change materials examined during this study*

Sample. no.	*Material*	*Observed colour hue*			*Calculated hue-angle*			*Hue-angle change*		
		Incand.	*Daylight*	*Fluor.*	*A*	*D65*	*F7*	*A-D65*	*D65-F7*	*A-F7*
Type 1 colour-change										
1422	Alexandrite, synthetic	P	G	yG	304	200	196	104	4	108
2316	Alexandrite, synthetic	P	G	G	24	136	134	112	2	110
2310	Diaspore	oY	gY	GY	30	82	88	52	6	58
2311	Diaspore	oR	yG	yG	8	138	140	130	2	132
730	Fluorite	V	gB	gB	269	217	213	52	4	56
2467	Garnet	P	gB	gB	292	245	240	47	5	52
2534	Garnet	rO	yO	yO	21	69	87	48	18	66
1369	Sapphire	gY	gY	yG	264	214	228	50	14	36
1326	Sapphire, synthetic	rP	V	P	319	281	267	38	14	52
2161	Spinel, synthetic	yG	G	bG	27	82	91	55	9	64
4644	Sapphire	yG	pV	P	299	273	278	26	5	21
4645	Sapphire, synthetic	pV	V	P	319	284	275	35	9	44
4646	Tourmaline	yG	G	G	84	114	119	30	5	35
Type 2 colour-change										
1327	Glass, synthetic	pR	pR	rO	31	29	64	2	35	33
1366	Glass, synthetic	oR	oY	O	37	36	65	1	29	28
Type 3 colour-change										
1421	Sapphire, synthetic	rP	vP	P+G	316	245	213	71	32	103
Type 4 colour-change										
1116	Garnet	rP	oR	Y	359	14	30	15	16	31
1119	Garnet	oY	oY	G	51	69	76	18	7	25

Codes for colour hues: P – purple, pV – purplish-violet, V – violet, gB – greenish-blue, bG – bluish-green, G – green, yG – yellowish-green, GY – green-yellow, gY – greenish-yellow, oY – orangy-yellow, yO – yellowish-orange, rO – reddish-orange, oR – orangy-red, pR – purplish-red, rP – reddish-purple, vP – purple with a hint of violet

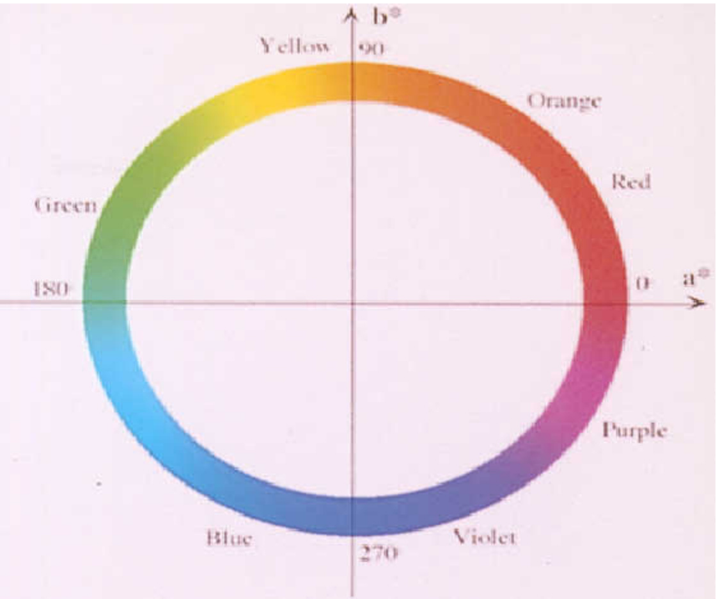

Figure 2: *In the CIELAB colour space, colour hues are arranged around a circle, and their locations can be indicated by the hue-angle (a value up to 360 degrees). These hue-angles can be calculated from the CIELAB coordinates a* and b*, which in turn can be obtained from the measured spectral data. The position a* represents a 0 degree (or 360 degree) hue-angle, and values of the hue-angle increase in a counter-clockwise direction, as shown here.*

Boguth (1990) used a microscope and a multichannel spectrometer to record transmittance colours for an amethyst and an alexandrite, and then employed a method developed by Yonemura to calculate the colour change. This method does take into consideration chromatic adaptation, but the overall approach taken by Boguth still uses the dominant wavelength change to represent the colour change.

Liu *et al.* (1994) used calculated coordinates in the uniform CIELAB colour space to depict the behaviour of colour-change gemstones in terms of differences in their hue-angle and the extent of their colour change. They grouped the studied gemstones into several categories depending upon the pair of light sources used. In the CIELAB colour space, equal measured hue-angle differences approximately represent equal visual-perception hue changes (and take into account chromatic adaptation). The present article summarizes results from this study, presents some additional data, and addresses the three questions mentioned in the introduction. The alexandrite effect is described as a non-colour constancy phenomenon. It is also suggested that the combination of the response of the visual system to the incoming light from the gemstone under the different light sources, and the chromatic adaptation of the human visual system under different light sources, are the cause of the alexandrite effect.

Materials and methods

During this study, a variety of gemstones were re-examined (including natural and synthetic samples) that exhibited colour hue changes ranging from obvious to subtle. *Table I* lists 18 gemstones that are the subject of this article.

Visual observations of the colours of these samples were made independently by the authors both outdoors in daylight in southern California, as well as indoors using incandescent (tungsten filament) and fluorescence (daylight simulator) light sources using a MacBeth Judge II light booth. When outdoors, daylight strikes both the crown and pavilion facets of the gemstone from a number of angles, is reflected within the gemstone, and then it exits. Our observations were made by holding the sample at arm's length (about 60 cm) and looking straight down on the table and crown facets, to judge a colour hue that would be best representative of the overall face-up colour appearance. For the incandescent and fluorescent light sources, observations were made in the light booth that had a neutral grey interior, with the light source directly above the sample at a distance of about 30 cm, and the observer looking at a 45 degree angle from the vertical, and at a distance of about 30 to 45 cm from the gemstone. Again, the representative colour hue was judged from the face-up orientation of the gemstone. In cases where there was a disagreement between observers about a sample's colour hue, the gemstone was examined by both observers together to reach an agreement about the face-up colour appearance and the

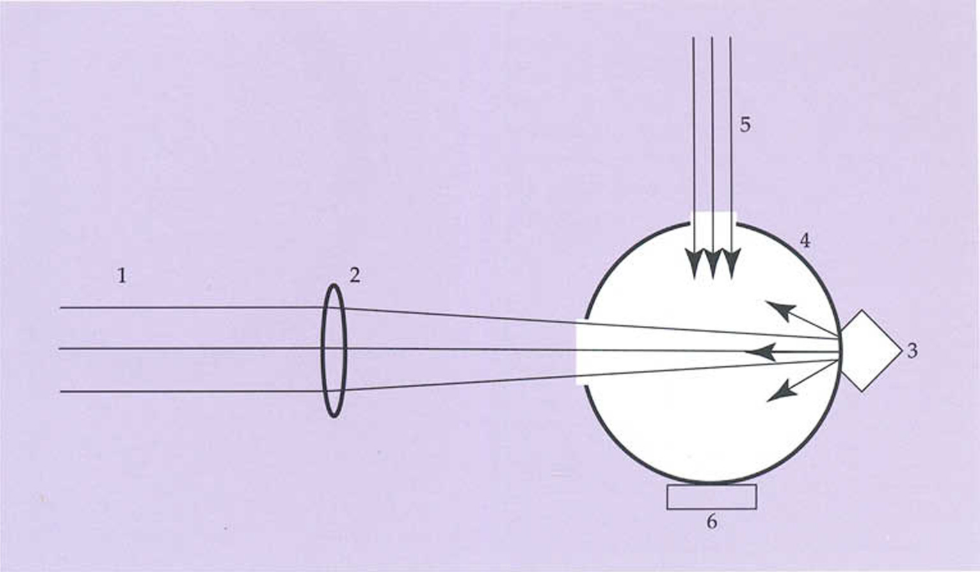

Figure 3: The optical arrangement for measurement of gemstone colour using an integrating sphere mounted in the Hitachi U-4001 spectrophotometer. Numbers refer to: (1) the incident light beam, (2) focusing lens, (3) sample position, with light striking perpendicular to the polished table facet, (4) integrating sphere, (5) reference light beam, and a (6) white reference tile. The measurement resolution is 1 nm. Light striking perpendicular to the table facet is internally reflected within the gemstone; the portion of this light that exits through the table (but not through the crown facets) is captured by the integrating sphere.

hue term(s) to describe this colour. No colour-reference standards were used for visual comparison to our samples. Their colours were described with simple hue terms (such as blue, greenish-yellow, etc.). For the 18 samples, colour-hue changes were seen between one or more pairs of these three light sources, but not necessarily between each pair of sources. A colour change can sometimes be difficult to observe in a gemstone because of its faceted shape, the saturation or lightness of the colour, or the lighting and viewing conditions used.

In the CIELAB colour space, the colour hues are arranged in a circle, and their locations are indicated by an angle (up to 360 degrees), known as the hue-angle (*Figure 2*). Colour measurement data on the hue-angle were calculated from reflectance spectra recorded with an Hitachi U-4001 UV-VIS-NIR spectrophotometer for most of the samples. The wavelength range for these spectra was 300 to 830 nm; a bandwidth of 1 nm and a scan speed of 300 nm per minute were used. *Figure 3* shows the optical arrangement of the measurement experiment. Unpolarized incident light was focused on crown facets of the sample (primarily the table facet) by means of a lens (75 mm focal length); no incident light entered through the pavilion facets. The size of the incident light beam was smaller than the size of the table facet. An integrating sphere mounted within the sample chamber of the spectrophotometer permitted the capturing of most of the light coming from the crown facets of the sample.

Spectra were recorded with the gemstone in the reflectance position (as shown in *Figure 3*), which corresponds closely to how one visually observes a polished coloured gemstone in a face-up orientation. To achieve the closest relation between the observed and the measured colour for a sample, the light source, the gemstone sample, and the 'observer' (either the eye or the instrument detector) were arranged in nearly the same relative positions with respect to one another (although differences existed between how the light struck the sample outdoors and within the spectrophotometer). In the reflectance position, we attempted to capture light that had been transmitted and reflected through the sample. Light specularly reflected from the surface of the table facet left the integrating sphere through the open port, and was not included in calculating the recorded spectra. Thus, our measurement geometry differed slightly from our observation geometry, principally in terms of how the incident light illuminated the sample.

Using the measured reflectance spectral values recorded every 1 nm across the 400–700 nm range, the CIELAB values L*, a*, and b* were calculated. These numbers were then used to calculate the hue-angle (h) of the sample's overall colour appearance by means of a version of the SpectraCalc™ software programme (Galactic Inc.) that was modified by us. The hue-angle (h) is calculated by the following equation:

$$h = \text{arctangent}\ (b^*/a^*)$$

The absolute hue-angle difference (Δh) between two colour hues for the same sample under light sources 1 and 2 is:

$$\Delta h = |h_1 - h_2|$$

This software programme can calculate coordinates of a measured colour:

(1) in several colour spaces (including CIELAB);

(2) using various CIE standard illuminants; and

(3) a 2-degree or a 10-degree standard colorimetric observer (which is a graph of the spectrum of the colour-matching curves of an average group of human observers with normal colour vision, using a 2-degree or a larger 10-degree angular field of view). Because of the small diameters of our samples, the hue-angle calculations reported here were made with a 2-degree standard observer.

In contrast to light sources, which are daylight or actual lamps with measurable spectral power distributions (SPDs), illuminants are not actual lamps, but are mathematically defined SPDs that are routinely used in colour-science calculations. In this study, three CIE standard illuminants were employed to represent the three light sources we used to observed the colour changes in our samples. The SPDs of the three illuminants are shown in *Figure 4*. By calculating the hue-angle of the colour hue of a sample using each of these three illuminants, hue-angle differences between pairs of illuminants could be derived. These calculated differences in hue-angle would then be an indication of the possible extent of a colour change, if any, that could be observed in the sample under the corresponding pair of light sources.

Illuminant A represents light emitted by a 'blackbody' radiator at an absolute colour temperature of 2856 Kelvin (corresponding to an incandescent (tungsten filament) light source). The D illuminants represent one of the several phases of natural daylight, each with a particular correlated colour temperature (such as D65 or D75). Illuminant D65, representing average daylight with a correlated colour temperature of 6504 Kelvin, was used here. The CIE has not recommended an actual light source (a lamp) that corresponds to any of the D illuminants.

Fluorescent daylight simulators are widely used in the jewellery trade for observing the colour of gemstones indoors; they are often the only light source (other than daylight) that is available for gemstone display purposes. As shown in *Figure 4*, although they are commonly referred to as 'daylight simulators', these fluorescent lamps have very different spectral power distributions in comparison to the SPD of natural daylight. The CIE has recommended twelve different F illuminants to represent a variety of typical fluorescent lamps. Illuminant F7, with a correlated colour temperature of 6500 Kelvin and a colour rendering index of 90 (a measure on a scale from 0 to 100 of the accuracy of a light source to correctly render the colour of Munsell

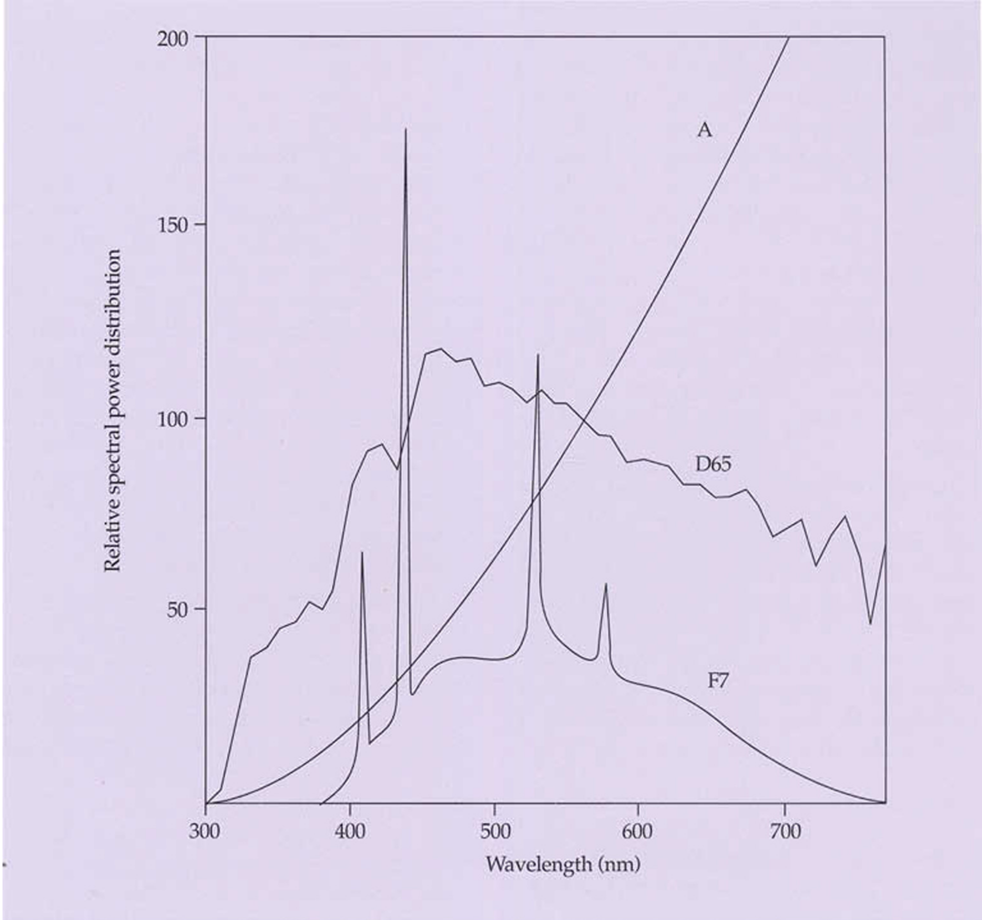

Figure 4: *Comparison of the spectral power distributions (SPDs) of the three CIE standard illuminants used for the colour calculations in this study. An SPD shows the relative portion of energy emitted at each wavelength segment across the electromagnetic spectrum by an illuminant or a light source. The SPD of an actual light source differs from that of the corresponding illuminant; furthermore, the SPD of the former can vary over time as a lamp ages. The SPD of illuminant D65 is very close to that of natural daylight. Illuminants A and F7 are explained in the text.*

samples), was chosen for this study since it is close to the type of fluorescent lamps used by jewellers and gemmologists.

Results

Table I lists the 18 samples included in this study, their colour hue as observed under incandescent and fluorescent lamps and in daylight, and the calculated hue-angles obtained from reflectance spectra for the three corresponding CIE standard illuminants. Comparison of the observed colour hues and the calculated hue-angle values indicates that there is general agreement between our colour observations and the measured data obtained with the spectrophotometer for the 18 samples.

For a given light source, the colour hues of our samples covered a wide range, as did their hue-angles for the corresponding standard illuminants. By comparing the hue-angles of a given sample obtained for different illuminants, the values of the hue-angle difference range up to almost

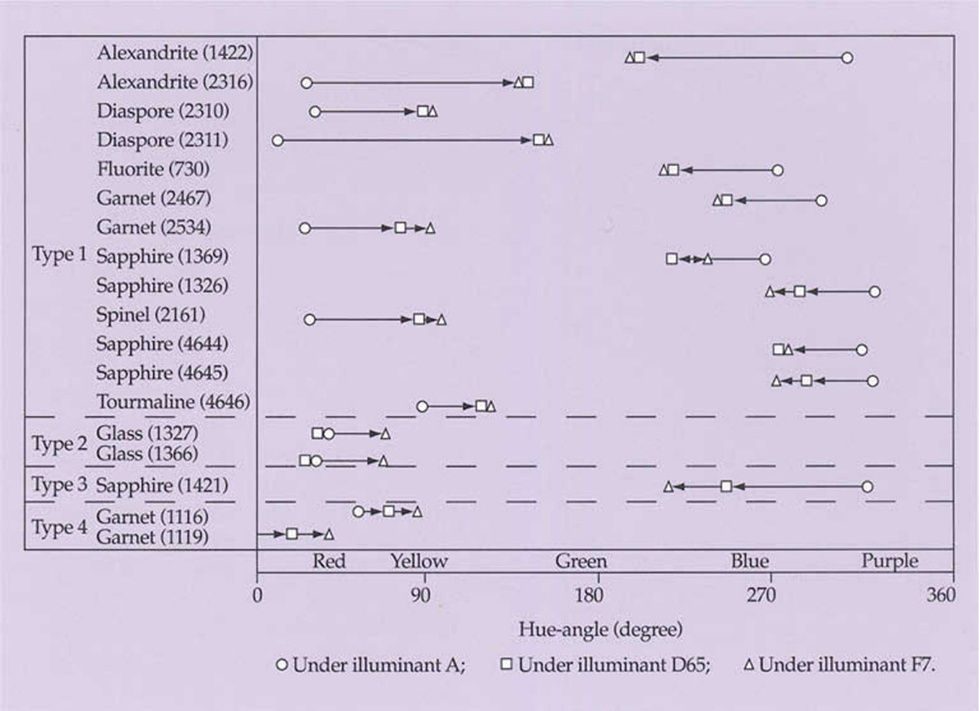

Figure 5: The hue circle depicted as a linear graph to show the direction and extent of colour change as calculated from hue-angle differences for the samples included in this study. For each sample, the measured hue-angles for illuminants A, D65 and F7 are indicated by a circle, a square, and a triangle symbol, respectively. When changing from illuminant A to D65 and F7, the direction of the hue-angle change for each sample is toward the 180 degree value. In general, this corresponds to a gemstone that is more 'red' or 'purple' in incandescent light, and more 'yellow', 'green' or 'blue' in daylight or fluorescent light.

180 degrees (the greatest possible difference). Since in most cases the hue-angles appear to correlate tolerably well with the observed colour hues in our samples, we suggest that the magnitude of the difference in the hue-angle can be used as indication of the extent of colour change that the samples will exhibit between the corresponding light sources.

The data in *Table I* illustrate observations made previously by others that the calculated hue angles of the samples always move in a *direction* toward the 180 degree value (toward a green hue) when the illuminant changed from A to D65 or F7 (corresponding to a change from incandescent to daylight or fluorescent light), as illustrated in *Figure 5*. However, the extent of the hue-angle change, and its location on the hue circle, varied from one sample to the next, as shown in this same figure.

As a test of our colour measurement methodology, we carried out ten repeated colour reflectance measurements of the same sample of a synthetic glass (#2088; a round-brilliant cut weighing 2.55 ct, and measuring 9.3 x 9.3 x 5.6 mm) to check the precision of our results. As shown in *Table II*, the standard deviations in the hue-angle changes for each of the three pairs of illuminants are each less than 4 degrees. These small values indicate that our measurements for this sample are reproducible to establish the colour hue and the hue-angle, since such small variations in hue-angle could not be recognized visually by a person relying on their memory to remember a colour (see Burnham and Clark,

Table II: *Precision of hue-angle measurements.*

Test	*Hue-angle change*		
	A and D65	*D65 and F7*	*A and F7*
1	7.7	63.7	56.0
2	6.5	69.3	62.9
3	6.9	70.7	63.8
4	4.8	61.8	57.0
5	4.1	65.1	61.1
6	5.2	67.2	62.0
7	8.1	70.3	62.2
8	8.8	72.1	63.3
9	6.2	63.8	57.5
10	4.7	63.2	58.5
Mean	6.3	66.7	60.4
Standard Deviation	1.6	3.7	2.9

Calculated differences in hue-angle (measured in degrees in CIELAB colour space) between pairs of illuminants A, D65 and F7, for a colour-change glass (#2088). The hue-angle changes were obtained by ten separate measurements of the reflectance spectra of this glass. Between measurements, the Hitachi spectrophotometer was recalibrated, and the glass sample was repositioned in the instrument.

1960). However, with similar experiments with polished gemstones of smaller diameter (4 mm or less), we found less repeatability with the colour measurements. We attribute this to the difficulty in positioning smaller samples in exactly the same position each time in the spectrophotometer.

While measurement of a sample's colour hue by this method seems promising, we could not correlate the observed colour changes in our samples seen under different light sources to changes in either their saturation or lightness calculated from reflectance spectral data. Based upon our experiments to date, the method discussed here seems best suited for gemstones or other samples that possess relatively saturated colours (with a chroma value of 5 or more in the CIELAB colour space). Samples that exhibit very pale, desaturated colours have hues located near the origin (i.e. the central 'white point') in colour space. While the calculated hue-angle changes of these materials can be artificially very large, these values are meaningless in such instances since any change in their very pale colour would not be perceptible to the eye.

Discussion

Since the CIELAB colour space is a uniform colour-order system, equal differences in hue-angle correspond to equal differences in observed colour hue. Therefore, the hue-angle change in the CIELAB colour space can be used to quantitatively characterize the change in a sample's colour hue for pairs of the three CIE standard illuminants and the corresponding light sources we selected. Use of the instrumental method described here can help support visual observations and the verbal description of a colour-change in gemstones.

One goal of this study was to establish an objective (observer independent) means for determining if a particular gemstone actually changes colour when viewed under different light sources. Based upon a published study of the colour appearance change of opaque Munsell colour chips under different light sources (Helson *et al.*, 1952) and our own experiments with coloured gemstones, we previously selected a 20 degree hue-angle change as our criterion for determining whether a sample would display an observable colour change between a pair of light sources (Liu *et al.*, 1994). If the hue-angle change for a sample between any pair of the three CIE standard illuminants (A, D65, and F7) was equal to or greater than 20 degrees, and the colour saturation of the sample was suitably high (a perceptible saturation of chroma level 5 or higher), we would expect to see a colour change in the sample when viewing it under one and then the other of the corresponding pair of light sources. By subtracting pairs of hue-angle values for the samples listed in *Table I*, it can be seen that all of these samples exhibited a calculated hue-angle change of 20 degrees or more for at least one pair of the three CIE standard illuminants (and in almost all cases,

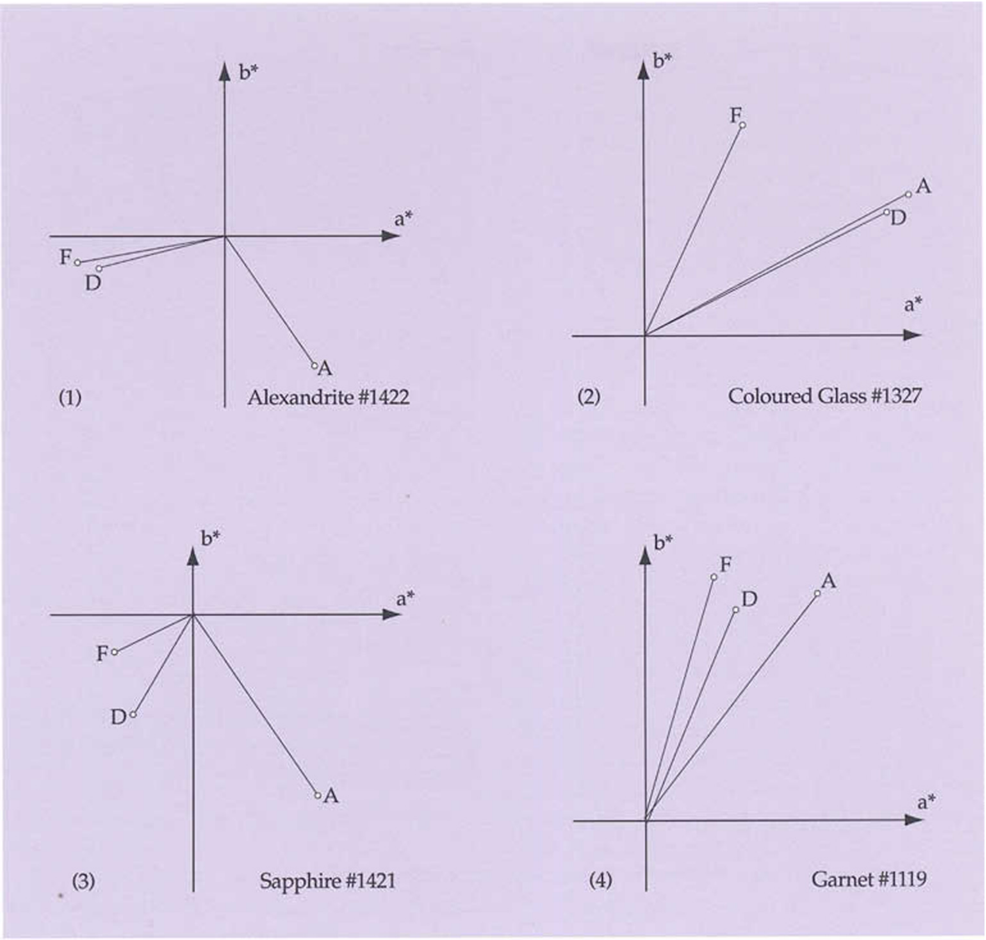

Figure 6: *Hue-angle changes of specific samples, depicted on the a* b* plane of the CIELAB colour space (refer again to Figure 2), for four types of colour change. In each of these sketches, the point marked 'A' represents the hue-angle of the sample for illuminant A, the point marked 'D' is for illuminant D65, and the point marked 'F' is for illuminant F7. The colours of these samples under the different light sources, and the extent of their colour change between pairs of light sources, can be predicted from these sketches. The distance of the point from the origin of the diagram also provides an indication of the saturation of the colour of the particular sample that is represented by the point. These sketches provide a means of illustrating the difference between the types of colour-change behaviour.*

we could see a hue change in the sample between the corresponding light sources). It can also be seen from this table that the hue-angle changes vary up to almost 180 degrees (the maximum value), with a larger hue-angle difference representing a more pronounced change in colour hue. Finally, a sample may exhibit a hue-angle change of 20 degrees or more for one pair of CIE standard illuminants, but not for another pair (i.e. the sample would be expected to change colour between one pair of light sources, but not between another pair).

It should be emphasized that we do not consider the 20 degree hue-angle value as a final or absolute criterion of a colour-hue change in a gemstone. It is an indicator value of the extent of a hue-angle change, above which a colour change could be observed in the samples we examined. If a criterion describing a more obvious colour change is preferred, a 30 degree hue-angle change could be used.

The observation and measurement of colour-change gemstones led Liu *et al.* (1994) to define four categories or types of colour change, based upon the 20 degree hue-angle change criterion and the three CIE standard illuminants listed above. Both illuminants A and D65 can each be considered as approximating a thermal radiator in the visible region of the spectrum. The difference in their SPDs is mainly due to their colour temperature difference (see again *Figure 4*). Illuminants D65 and F7 have the same colour temperature, but different SPDs. Compared to illuminant A, illuminant F7 has both a higher colour temperature and a spectrum that contains sharp emission lines. Therefore, if the hue-angle change between illuminants A and F7 is smaller than 20 degrees, theoretically there is little possibility that the hue-angle changes between A and D65, and between D65 and F7, could be larger than 20 degrees. For this reason, Liu *et al.* (1994) suggested that the hue-angle change for colour-change gemstones should always be greater than 20 degrees for the illuminant pair (A–F7). The criteria for these four categories are summarized in *Table III*. The four types can be described as follows:

Type 1. This category represents the traditional 'alexandrite effect' recognized by gemmologists; it is also the type of colour change found most commonly among our study samples (see *Table I*). It represents a situation of a sample's colour change between illuminants that differ in their SPD and in their colour temperature. Perhaps not surprisingly, this type 1 colour change can be quite pronounced, with colour hues on almost opposite sides of the hue circle (with hue-angle changes approaching 180 degrees).

Type 2. This type of colour change was found in three samples of faceted glass. In this situation, similar colours are seen in the sample under either daylight or incandescent light sources, but a different colour occurs under a fluorescent light source. In this category, the extent of the colour change is more moderate, with hue-angle changes from 40 to 90 degrees for the samples measured so far.

Table III: *The types of colour change for CIE illuminants A, D65 and F7 for conditions where at least one hue-angle change is greater than 20 degrees.*

Type	*Hue-angle changes for each pair of illuminants*		
	A and D65	*D65 and F7*	*A and F7*
Type 1	> 20	< 20	>20
Type 2	< 20	> 20	>20
Type 3	> 20	> 20	>20
Type 4	< 20	< 20	>20
Type 5	< 20	> 20	<20
Type 6	> 20	> 20	<20
Type 7	> 20	< 20	<20

The types of colour change can be defined as to whether the calculated difference in hue-angle (as measured in the CIELAB colour space) is greater or less than 20 degrees for pairs of illuminants A, D65 and F7 as shown here.
Type 5, type 6 and type 7 categories have not yet been encountered based upon hue-angles calculated from reflectance spectra measurements.

Type 3. Samples belonging to this category will exhibit a colour change between any pair of the three illuminants, but the extent of the hue change will be moderate. So far only one synthetic sapphire has been found to display this type of colour change.

Type 4. This type of colour change occurs only between fluorescent and incandescent light sources that have a suitably large colour temperature difference. At best, the extent of the colour change in this category is very weak, with hue-angle changes of only 20 to 30 degrees.

As additional colour-change samples are investigated, we expect to find further representatives of these categories of colour-change behaviour. The diagrams in *Figure 6* illustrate the hue-angle changes or samples that fall into these colour-change categories. *Figure 7* presents three colour-corrected photographs of representative gemstones from this study that are examples of the four colour-change types mentioned above. These

Figure 7: Four representative gem samples are shown under three light sources to illustrate their different colour-change behaviour. Clockwise from the top, the four gem samples are coloured glass, alexandrite, sapphire and garnet. They range in weight from 2–10 ct. The three light sources are (a) incandescent light, (b) natural daylight, and (c) fluorescent light. The three photographs have been colour-corrected using a computer and the Photoshop™ software program to show the correct colours under the different light sources. Original photos by Tino Hammid, copyright Tino Hammid and GIA.

photographs illustrate how different colour changes in gemstones can occur between different light sources.

Conclusion

In this study, we have explored the use of a spectrophotometer for colour measurement to investigate the colour-change behaviour of some gemstones and other materials. Many descriptions of such gemstones have been published, which often give explanations of the spectral causes of this phenomenon. Other gemmological researchers have preceded us in exploring the use of colorimeters and spectrophotometers for gemstone colour measurement, and some of their results have been published. While we cannot claim that our use of a spectrophotometer for gemstone colour measurement is either new or original, we do claim that:

(1) the geometry of colour measurement should approximate as closely as possible the geometry of observing colour in gemstones (as attempted here), if the results of the two methods are to be comparable;

(2) the reflectance measurement geometry gives results that are more consistent with the observation of face-up colour in faceted gemstones, especially for the colour hue (but not necessarily for the colour saturation or colour lightness); and

(3) how colour measurement data are graphically depicted in colour space is important in understanding the relationship between the results of colour measurement and colour observation.

We have shown how the use of the CIELAB uniform colour space to depict hue-angle relationships can be used to develop a minimum hue-angle difference (20 degrees) criterion for samples that would be expected to display a colour-hue change perceptible to the eye. By tabulating hue-angle values for gem materials with three CIE standard illuminants that correspond to the daylight, incandescent, and fluorescent

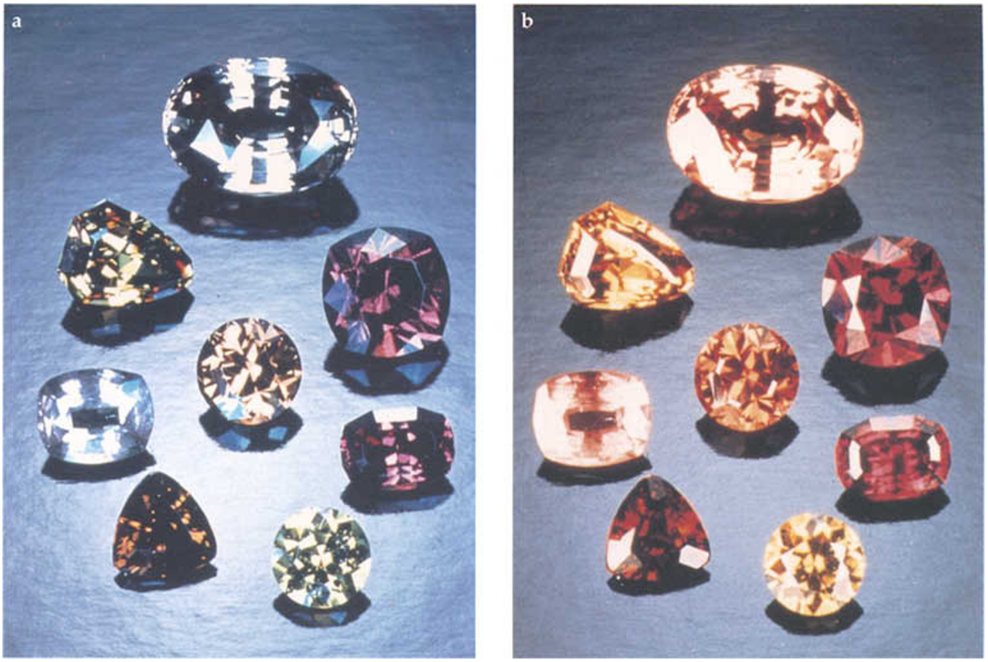

Figure 8: *A group of eight colour-change garnets (0.74 to 5.32 ct) seen under (a) a fluorescent daylight simulator and (b) an incandescent light (right). Photo by Tino Hammid, copyright GIA.*

light sources used in the jewellery trade, we demonstrate that the traditional 'alexandrite effect' is more complicated than previously recognized by gemmologists. Gem samples may not display a change of colour under one pair of light sources, but may display a change between another pair of light sources when their hue-angle difference is greater than 20 degrees. Examples of gemstones are given of the different types of colour-change behaviour, along with criteria that could be used to assign the colour-change behaviour of other gem materials to one of these types. The most practical benefit of this study is to illustrate how colour reflectance measurement data can assist the gemmologist who, when examining a gemstone and thinking it may change colour under different light sources and not wanting to solely rely on his or her colour memory, wishes to have some independent confirmation that the gemstone is actually displaying a colour change, which could increase its market value. Gemstones exhibiting an attractive alexandrite effect, such as the group of garnets shown in *Figure 8*, will always be in demand in the jewellery industry.

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Colour hue change of a gem tourmaline from the Umba Valley, Tanzania

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ABSTRACT: The hue of a tourmaline from the Umba Valley, Tanzania, changes from green to red with increases in path length of light through the material. This hue change phenomenon, called the 'Usambara effect', is different from any colour-change effect previously described in gemstones. Colorimetric methods have been used to analyze this tourmaline. Results of this study suggest that the Usambara effect is a complex phenomenon including effects of both path length and the colour change observed under different light sources (the alexandrite effect).

Keywords: Alexandrite effect, colour, colour change, light, tourmaline, Usambara effect

Introduction

Halvorsen and Jensen (1997) described a reportedly new colour-change effect, which they called the Usambara effect, in gem tourmaline from the Umba Valley, Tanzania. These tourmaline samples are strong yellow- to blue-green when viewed separately in transmitted light, but when two are superimposed over one another, their combined colour becomes red with no change in sample orientation or type of illumination. These authors attributed this effect to a change in the path length of light through the material.

In this study, we re-examined samples of this gem tourmaline, and have analyzed their colour-change behaviour using colorimetric methods as described in Liu *et al.* (1994). Although Halvorsen and Jensen (1997) concluded that the Usambara effect is due to changes in path length, they stated that the observed colours could be mildly modified by the type of illumination, which is the well-known alexandrite effect. We present here a more complete explanation using colorimetric calculations of both effects in this material, and demonstrate how the alexandrite effect predominates over a certain range of sample thicknesses, while the Usambara effect becomes more pronounced as the sample thickness increases beyond this range. According to K. Nassau (pers.comm., 1998), this gem tourmaline provides an interesting example of how several different causes can give rise, either separately or in combination, to colour changes in a gem or mineral.

Materials

Several rough tourmaline crystal fragments from the Umba Valley were examined (*Table I*). Sample #4140 weighs 13.21 ct, has parallel polished surfaces which

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Table I: The properties of the three gem tourmaline samples.

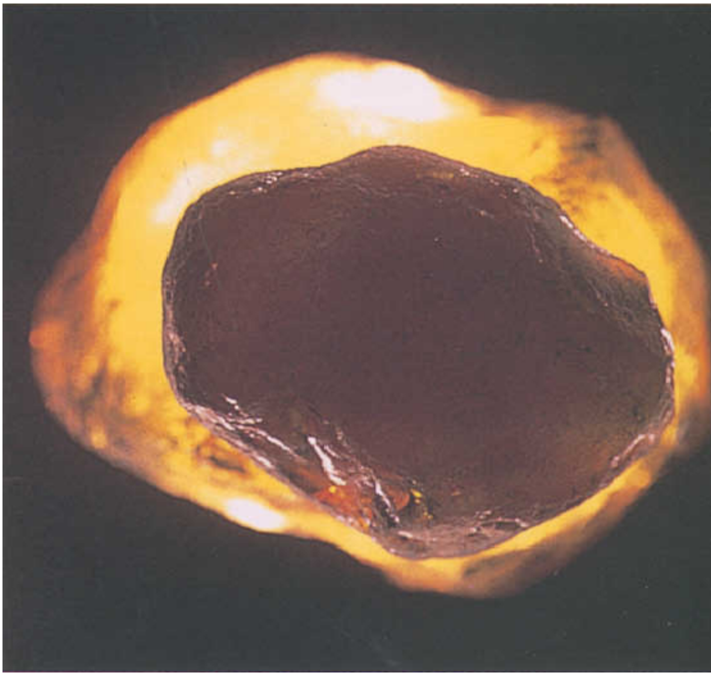
Sample #	*Weight (ct)*	*Colour*[1]	*Thickness*[2]	*Shape*
4140	13.21	Green	6.25	Parallel Surfaces
4427	16.14	Green	6.79	Rough
4428	48.16	Yellowish-green	11.68	Rough

Note: 1. Transmittance colour over a daylight simulator.
2. Maximum thickness in mm.

were specially prepared for this study, and is approximately 6.25 mm thick. The gemmological properties, colours, and spectra of the sample are the same as the samples described by Halvorsen and Jensen (1997). *Figure 1* shows two tourmaline samples viewed by transmitted light over a daylight simulator. Sample #4427 weighs 16.14 ct, and with a maximum thickness about 6.79 mm, its colour appears green. Sample #4428 weighs 48.16 ct, has a maximum thickness about 11.68 mm, and its transmittance colour appears yellowish-green. When sample #4427 is placed on the top of sample # 4428 to increase the total path length, their combined transmittance colour changes to dark red (see *Figure 2*). *Figure 3* shows the spectral transmittance curve of tourmaline sample #4140, which was obtained using a Hitachi U-4001 spectrophotometer with an integrating sphere. A wavelength range from 300 nm to 830 nm was scanned with a wavelength interval of 1 nm. Colorimetric data were obtained using the Spectracalc software from Galactic Industries Corporation.

Figure 1: *Transmittance colours of tourmaline sample #4427 on the left and tourmaline sample #4428 on the right. Photograph by Yan Liu.*

Figure 2: *A dark red total transmittance colour is observed when tourmaline sample #4427 is placed on the top of sample #4428. Photograph by Yan Liu.*



Results

Transmittance Calculations

The intensity of transmitted light can be calculated by Bouguer's law:

$$I(\lambda) = I_0(\lambda)\,p(\lambda)\,e^{-\alpha(\lambda)t} \qquad (1)$$

where λ is the wavelength, $I(\lambda)$ is the intensity of the transmitted light, $I_0(\lambda)$ is

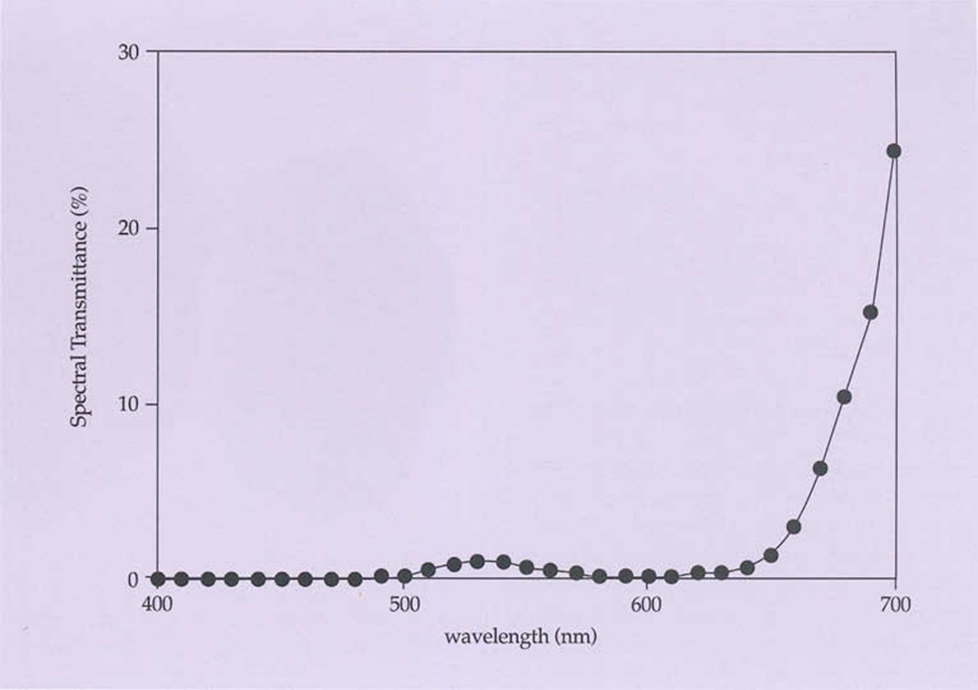


Figure 3: *The measured spectral transmittance curve of tourmaline sample #4140. A weak transmittance band is centred at about 540 nm, and a strong band is located above 650 nm.*

intensity of the incident light, $p(\lambda)$ is reflection factor which takes into account the light loss due to multiple reflections at the parallel surfaces of the specimen (Liu *et al.*, 1991), $\alpha(\lambda)$ is the absorption coefficient of the material, and t is the sample thickness. The measured refractive indices of this tourmaline as reported by Halvorsen and Jensen (1997) are 1.644 and 1.622. Since the dispersion of the tourmaline is relatively small, we used a value of 1.63 as an approximate refractive index in the visible range to calculate the surface reflection factor [calculated by the equation $p = 2n/(n^2 + 1)$], which is about 0.89. The absorption coefficient varies with wavelength. The transmittance $T(\lambda)$ varies exponentially with $\alpha(\lambda)$ multiplied by sample thickness according to the formula:

$$T(\lambda) = 0.89e^{-\alpha(\lambda)t} \qquad (2)$$

If the transmittance is measured for various wavelengths at one known thickness (in this case, the 6.25 mm-thick sample #4140, with results plotted in *Figure* 3), then the absorption coefficient of this tourmaline can be calculated using equation (2) in the form:

$$\alpha(\lambda) = \frac{1n\,(T/0.89)}{6.25}\,mm^{-1} \qquad (3)$$

For the purpose of this study, we wanted to understand the effect of increasing path length on the colour change of this tourmaline, and since only a limited amount of actual gem tourmaline was available from the deposit in the Umba Valley, we used the colorimetric method to calculate colour coordinates for this tourmaline as if it existed in polished pieces of several different thicknesses.

Since the absorption coefficient is a constant for each wavelength, Beer's equation can then be used to calculate the transmittance $T(\lambda)$ for any number of thicknesses of this tourmaline material, as

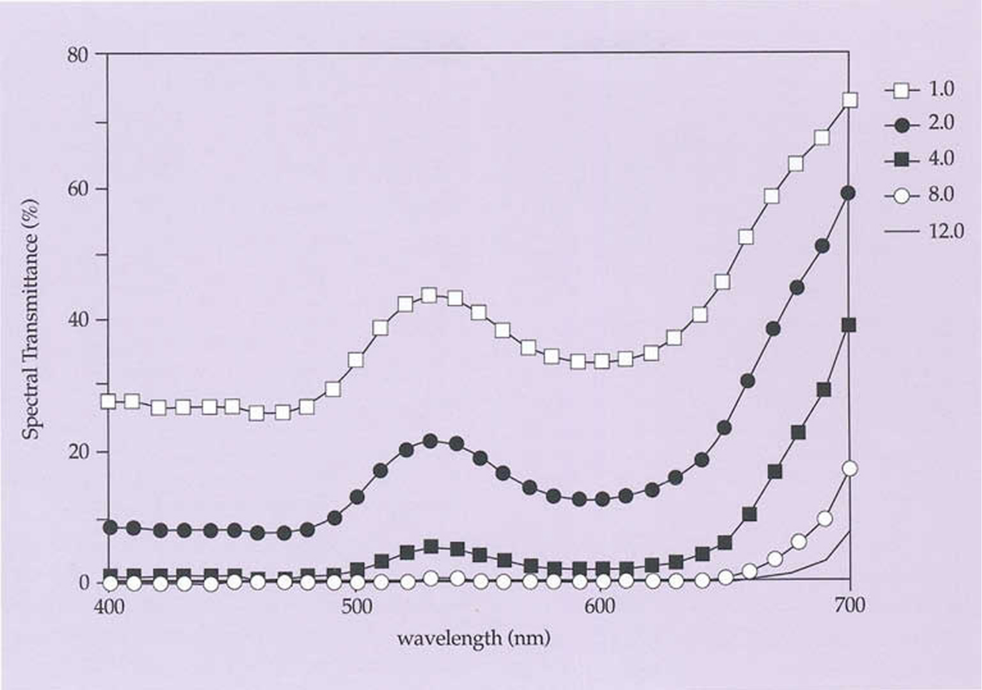


***Figure 4:** The calculated spectral transmittance curves of tourmaline sample #4140, if it could be fashioned into pieces of different thicknesses ranging from 1.0 up to 12.0 mm.*

shown by the curves in *Figure 4* (for 1.0, 2.0, 4.0, 8.0 and 12.0 mm-thick samples). This figure shows that there are two transmittance bands in the visible range, one centred at 540 nm (a middle wavelength band referred to here as the 540 nm band), and the other in the region above 650 nm (a long wavelength band). Since the spectral transmittance of the band centred at 540 nm is reduced much faster than that of the long wavelength band due to Beer's law with increasing sample thickness (or path length), only the long wavelength band is left when the thickness of the tourmaline is over 10 mm.

Colorimetric Calculations

The CIELAB colour space is the most used uniform colour space for representing colour appearance, and equal colour differences approximately represent equal visual colour perception differences. The calculation of L*, a*, and b* is based on the opponent colour vision model and chromatic adaptation:

$$L^* = 116\,(Y/Y_n)^{1/3} - 16$$

$$a^* = 500\,[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}] \qquad (4)$$

$$b^* = 200\,[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

where X, Y, and Z are the CIE tristimulus values of the coloured object calculated from data measured by a colorimeter or spectrophotometer, and X_n, Y_n, and Z_n are the similar values obtained for a standard white object (CIE, 1986). In CIELAB colour space, L* represents lightness; +a* represents 'redness', –a* is 'greenness'; +b* is 'yellowness', and –b* is 'blueness'. The CIELAB colour space includes the von Kries type chromatic adaptation X/X_n, Y/Y_n, and Z/Z_n (CIE, 1986). In the CIELAB colour space, the hue-angle is used to represent the hue of a colour. The hue-angle is given by:

$$h = \arctan\,(b^*/a^*) \qquad (5)$$

Table II: Calculated CIELAB data of tourmaline sample #4140, if it were fashioned into pieces of different sample thicknesses.

t (mm)	*L**	*a**	*b**	C	*h (degrees)*
1.0	67.77	-8.92	14.69	17.19	121.3
2.0	47.24	–12.18	21.27	24.51	119.8
4.0	20.66	–10.47	22.42	24.75	115.0
6.0	5.97	-3.88	8.85	9.66	113.7
8.0	1.38	0.14	2.19	2.20	86.3
10.0	0.37	0.60	0.60	0.85	45.3
12.0	0.12	0.44	0.20	0.48	24.3

Note: t is the thickness, C is the saturation, and h the is hue-angle. Standard D65 illuminant. Maximum chroma is about 24.75 at the thickness of 4.0 mm.

Table III: Hue angle (h) and hue-angle change (Δh) (in degrees) data of tourmaline sample #4140, if it were fashioned into pieces of different sample thicknesses, using CIE standard illuminants D65 and A.

t(mm)	*h(D65)*	*h(A)*	*Δh*
1.0	121.3	102.6	18.7
2.0	119.8	100.5	19.3
4.0	115.0	92.5	22.5
6.0	113.7	70.5	43.2
8.0	86.3	42.2	44.1
10.0	45.3	26.0	19.3
12.0	24.3	19.3	5.0

Note: t is thickness, h(D65) is the hue-angle under illuminant D65, h(A) is the hue-angle under illuminant A, and Δh is the hue-angle change between illuminants D65 and A.

The hue-angle has been used to explain the alexandrite effect (Liu *et al.*, 1994).

Table II shows calculated CIELAB data of the tourmaline sample #4140 using the CIE standard D65 illuminant, which represents average daylight, at different thicknesses. *Figure 5* illustrates the colour trace of the tourmaline sample with changes in the thickness under the D65 illuminant. The hue-angles and hue-angle changes under CIE standard illuminants A and D65 are tabulated in *Table III*. *Figure 6* shows the hue-angle change of the sample with changes in the thickness.

Discussion

This study briefly mentions several important topics relevant to the colour of gemstones:

1. colorimetric calculations,
2. colour change with the change in sample thickness,
3. the alexandrite effect, and
4. colour visual perception.

A discussion involving all four topics is necessary to understand the colour effects observed in this gem tourmaline.

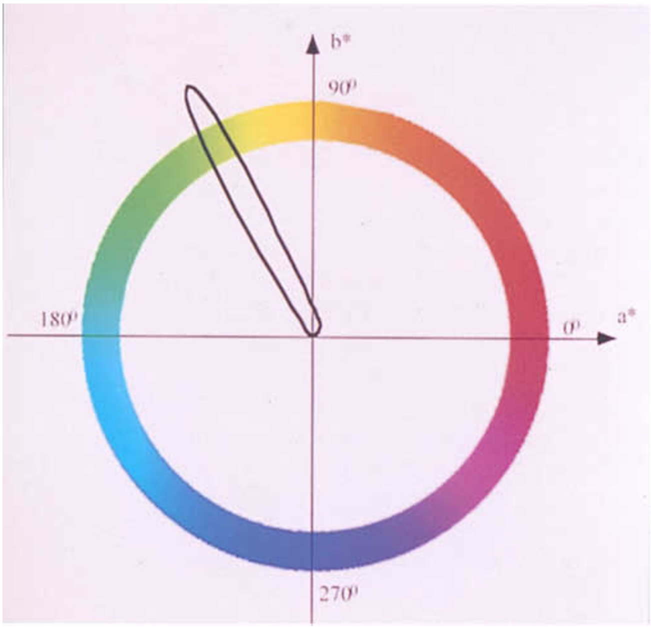


Figure 5: The hue circle and the colour trace of the tourmaline sample #4140 in the CIELAB colour space (plotted according to the hue-angle and saturation values in Table II). Increases in saturation occur with greater distances from the origin. The colour trace moves clockwise from zero saturation for the thickness of 0 mm, to a maximum in saturation of about 25.0 and a hue-angle of about 117.5 degrees for thickness of 3.0, to saturation of 0.85 and hue-angle of 45.3 degrees for thickness of 10.0 mm. When the relative thickness becomes infinite or very thick, the saturation again becomes zero (the sample becomes black).

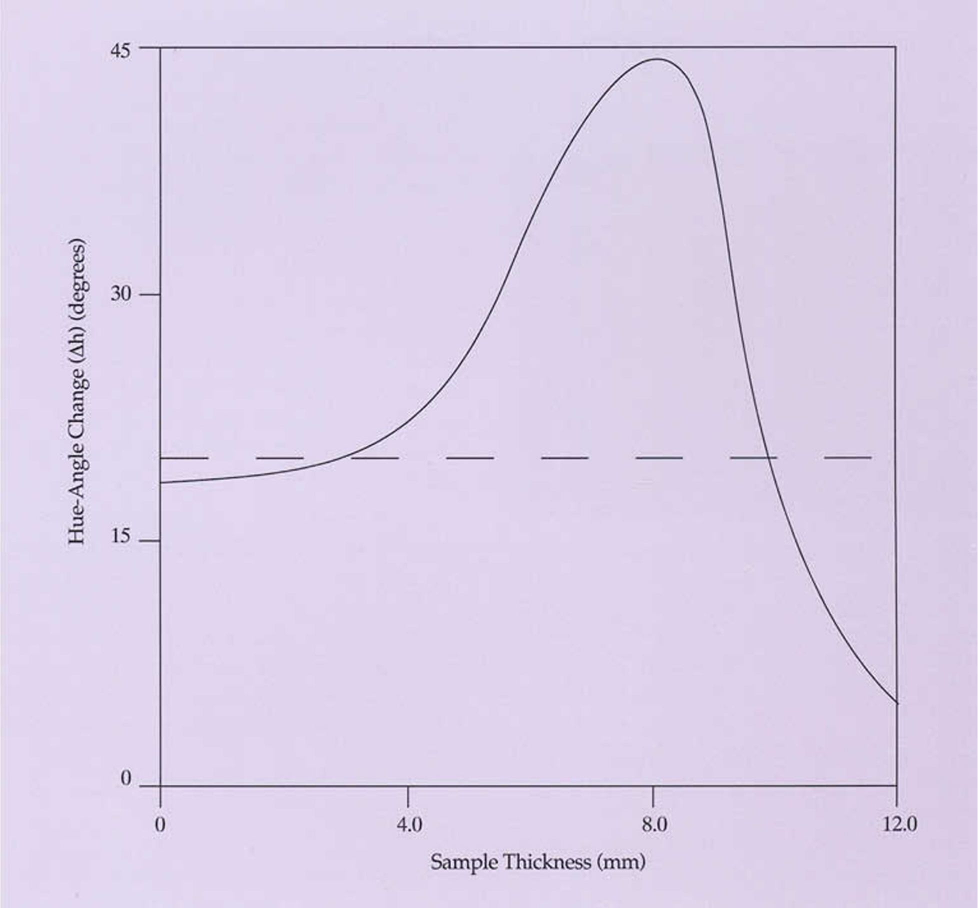


Figure 6: *The hue-angle change of the tourmaline sample between CIE illuminants D65 and A with changes in sample thickness. The dashed line is the 20 degree line. According to a convention proposed by Liu* et al. *(1994), the tourmaline shows an 'alexandrite effect' when the hue-angle change is greater than 20 degrees (for a sample thickness from 3.5 to 9.9 mm when the hue-angle change is above this line).*

Colorimetric calculation

The hue of a gemstone can be accurately represented by the hue-angle in the CIELAB colour space. As such, the calculated hue-angle can be used to investigate colour-change effect in materials (Liu *et al.*, 1994, and previous paper in this issue). From *Table II*, we know that the hue-angle of the tourmaline under D65 illumination decreases as the sample thickness increases. The hue-angle is 121.3 degrees with a thickness of 1.0 mm, and it decreases to 115.0 degrees with the thickness of 4.0 mm. Hue-angles between 121.3 degrees and 115.0 degrees represent the colour range with a yellowish-green hue (again see *Figure 5*). When the thickness increases to 8.0 mm, the hue-angle is 86.3 degrees, which represents yellow. The hue-angle is 45.3 degrees when the thickness is 10.0 mm (an orangy-red hue), and when the thickness is 12.0 mm, the hue-angle is about 24.3 degrees, representing red.

The colour change caused by a light-path change

All coloured materials change colour with changes in thickness or colourant concentration, and most of them also change

Figure 7: *A hue change with colourant concentration or thickness change can be seen in many dyes, such as this commercially available yellow food colour. Its hue changes from yellow, to orange, and to red with increasing colourant concentration. Photograph by Maha DeMaggio.*

hue (Nassau, 1983, 1997; Kuehni, 1997, 111–4). A chrome alum solution appears green in a thinner sample, and purplish-red in a thicker sample, which has been referred to dichromatism (Webster, 1994, p. 678). This phenomenon is similar to the colour change of the gem tourmaline described by Halvorsen and Jensen. *Figure 7* shows the colour change of a common type of food dye (for colouring Easter eggs) with a change in its colourant concentration. For a low concentration, the solution appears yellow. With an increase in concentration, the colour changes from yellow to orange, and then to red. This illustrates a colour-hue change with an increase in colourant concentration (Nassau, 1983). The hue and saturation changes of dye solutions with changes in concentration are usually represented by their *colourant traces,* which are the curves in a CIE colour space connecting the chromatic coordinates of the colourants at different concentrations. For materials other than colourants, similar curves called *colour traces* are used to represent hue and saturation changes with changes in the path length of light through them (Kuehni, 1997, 111–4).

The 'Usambara effect' is typical of the colour change caused by a change in sample thickness or concentration. With increase in the sample thickness of this tourmaline, the 540 nm band becomes smaller and smaller compared to the intensity of the long wavelength band (again see *Figure 5*). The tourmaline, therefore, appears increasingly red the thicker the sample. When the thickness is greater than 10.0 mm, only the long wavelength band is transmitted. The stone appears red as long as the light source has a red component, regardless of the kinds of light sources used. If the light source has no red component, this tourmaline will appear black when its thickness is more than 10.0 mm.

The colour trace curve in *Figure 5* is similar to that of some dyes that change hue and saturation with changes in concentration or thickness (Kuehni, 1997, 111–4). The saturation of the colour of the tourmaline first increases with increases in thickness until it reaches a maximum at about 4.0 mm; then the saturation decreases with increases in thickness.

The alexandrite effect

With increase in the thickness, the hue-angle difference between CIE illuminants D65 and A also changes. According to the 20 degree hue-angle change criterion suggested by Liu *et al.* (1994), the alexandrite effect between CIE illuminants D65 and A is shown by this tourmaline in sample thicknesses between 3.5 and 9.9 mm (again see *Figure 6*), with a maximum alexandrite effect when its thickness is about 8.5 mm.

Human colour perception

Webster (1994, 673, Fig. 31–2) mistakenly referred to the V(λ) function as the 'curve showing the colour response of the normal human eye'. Historically, he and many others incorrectly used it to explain some colour phenomena, such as the alexandrite effect. In fact, the sensitivities of the photoreceptors of the eye depend upon the chromatic adaptation under a particular light source.

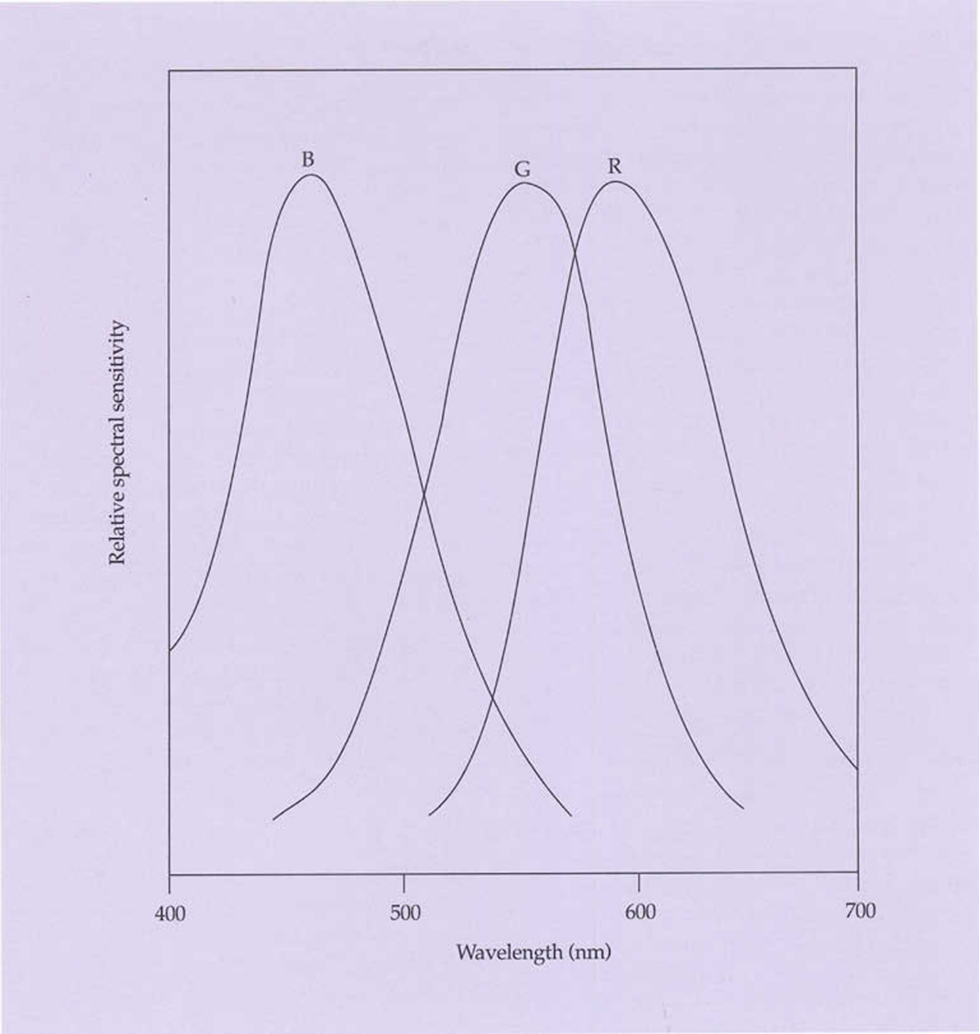


Figure 8: *The normalized spectral sensitivities of the red (R), green (G), and blue (B) cone photoreceptors for human colour vision.*

The human eye has three types of cone photoreceptors (red, green and blue) for colour vision (see *Figure 8*). The sensitivities of the three types of cone photoreceptors depend on adaptation of the eyes to the visual surroundings (Liu, 1996). When the three types of cone photoreceptors receive light from a gemstone, they produce three types of visual signals (R, G, B). These signals are processed though the visual path, and sent to the brain where colour sensations are experienced.

The R, G, and B visual signals can be represented by the CIE tristimulus values X, Y, and Z, which are calculated by the equations

$$X = \int T(\lambda) S(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = \int T(\lambda) S(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = \int T(\lambda) S(\lambda) \bar{z}(\lambda) d\lambda \qquad (6)$$

where $T(\lambda)$ is the spectral transmittance, $S(\lambda)$ is the relative spectral power distribution of the light source, and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the CIE colour-matching functions which correspond to the spectral sensitivities of the cone photoreceptors. The visual signals we experience depend on the integrated effects of the spectral power distribution of the light source, the spectral transmittance of the sample, and the spectral sensitivities of the cone photoreceptors. Therefore, colour perception is determined by four factors: chromaticity adaptation, the spectral sensitivities of the cone photoreceptors, the spectral power distribution of the light source, and the spectral transmittance of the material being observed. A colour phenomenon cannot be explained by relying only on one or two of these factors. This is why, using the two spectral transmittance bands in the spectra of certain gemstones, and the change in spectral power distribution of the light sources, fails fully to explain the cause of the alexandrite effect.

Colour change in this tourmaline

One can explain the colour change of this tourmaline with its thickness change by using the three R, G, and B visual signals, or equally, by the CIE tristimulus values. When the thickness of this sample is very thin (for example, 1.0 mm), the calculated tristimulus values are $X = 33.2$, $Y = 37.7$, and $Z = 29.7$. Since $Y > X$ and $Y > Z$, the green signal Y is dominant, therefore, the sample appears green. When the thickness is medium, $X = 0.15$, $Y = 0.15$, and $Z = 0.01$, therefore, $X = Y$ and Z can be ignored.

Since the red signal X and the green signal Y are equal, the tourmaline appears yellow. When the thickness reaches, for example, 12 mm, $X = 0.023$, $Y = 0.013$, and $Z = 0.000$, we have $X > Y$, and $Z = 0$. The red signal is thus dominant, and the stone appears red.

Using a sample thickness of 8.0 mm and under CIE D65 illuminant, the calculated a* and b* values are: a* = 0.14, and b* = 2.19. Its hue-angle is about 86.3 degrees. Therefore, a 8.0 mm thick tourmaline under daylight appears a slightly orangy-yellow. When it is under an incandescent light, the hue-angle is about 44.1 degrees, thus the tourmaline appears an orangy-red (again see *Figure 5*).

The lightness sensation of the human visual system depends on the spectral luminous efficiency function V(λ) (see *Figure 9*), which was established for photometry (Wyszecki and Stiles, 1982). This function refers to the relative effectiveness of radiant power to stimulate lightness sensation. The luminous efficiency in the short wavelength region is very low, but with an increase in wavelength, the efficiency increases, reaching a maximum at 555 nm, before decreasing with further increase in wavelength. In the long wavelength region, the efficiency again becomes very low. For example, it takes about 90 times the amount of light at 430 nm to produce the same sense of lightness in the human brain as it takes at 555 nm.

Although the V(λ) function is not related to the colour change phenomenon in the tourmaline, it can explain a change in lightness. With an increase in thickness of this tourmaline, the transmittance decreases, and so does the lightness. The lightness L* changes from 100 for 0 mm thickness to 67.77 for 1.0 mm, to 47.24 for 2.0 mm, to 20.66 for 4.0 mm, and to 5.97 for 6.0 mm, and so on (see again *Table II*). The change of the 540 nm band contributes much more than the long wavelength band in the lightness change when the stone is relatively thin, due to both the higher luminous efficiency and faster decrease of transmittance of the 540 nm band compared to that of the long wavelength band.

Different causes that can produce a colour change

To put the colour-change phenomenon described here into perspective, K. Nassau (pers.comm., 1998) suggests that there are four possible causes of this behaviour in gems and minerals. These four causes can be active one or more at a time, and all four appear to play a role in producing the coloration of the tourmalines discussed here. The four causes are:

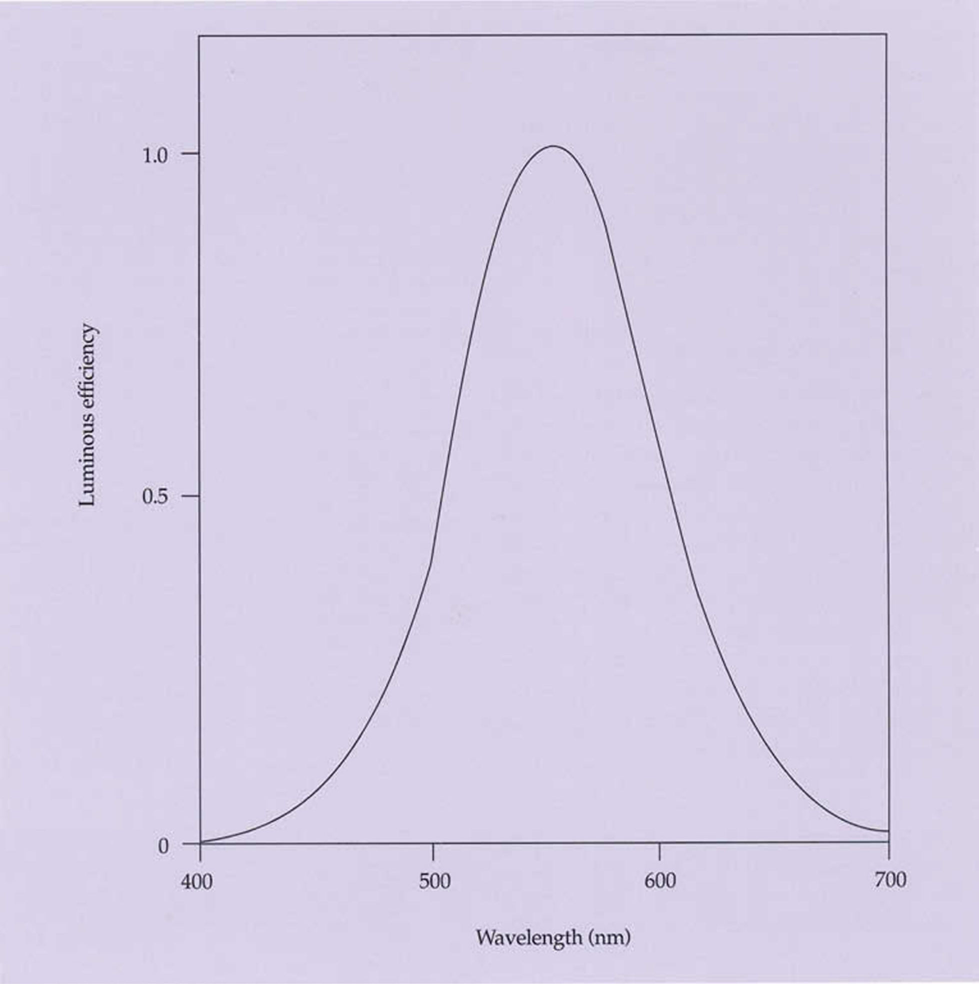


Figure 9: The spectral luminous efficiency function V(λ), which was established for photometry. This function refers to the relative effectiveness of radiant power to stimulate a sensation of lightness.

(A) Pleochroism, which can be seen in anisotropic materials (referred to as dichroism in a uniaxial material, or trichroism in a biaxial material) where the colour varies either with differences in crystallographic orientation of the material, or with polarization observing in one orientation (such as with a dichroscope).

(B) Alexandrite effect, where a material (in one orientation) changes colour when viewed under different light sources, depending upon the light sources used, the spectrum of the material, and the chromatic adaptation of the human visual system.

(C) Colour zoning, due to spatial differences in chemical composition in the material, or to differences in concentration of a particular chemical element, that are seen along one orientation.

All three of these causes are described in mineralogy and gemmology texts.

(D) Usambara effect, where the material changes colour hue due to increasing path length of light through the sample in one orientation.

It is clear from the data reported by Halvorsen and Jensen (1997) and the results described here that the colours of this tourmaline can be attributed to causes B and D (see again *Figure 4*). This Usambara type of colour change itself is difficult to recognize, since it is not often possible to compare the colours of two faceted samples of a suitable gem material that vary significantly in thickness.

Conclusion

The Usambara colour-change effect reported in tourmaline from the Umba Valley, Tanzania, is a complex effect involving two types of colour change: one caused by the 'alexandrite effect' within a certain sample thickness range, and another caused by a change in thickness with consequent lengthening of the light path. The hue changes with differences in the tourmaline sample thickness are caused by spectral transmittance changes. Although the hue change of this tourmaline with thickness is very large, this kind of hue change can happen in any coloured material, particularly in dye solutions with a change of colourant concentration. When the thickness of the tourmaline reaches about 10 mm, only a long wavelength band is transmitted; therefore, the tourmaline appears red under any standard light sources. This material shows the alexandrite effect in samples ranging between about 3.5 and 9.9 mm in thickness. The colour change caused by the change in thickness is light-source independent, but the alexandrite effect shown in a certain thickness range depends upon the light sources used. This effect can be quantified with colorimetric calculations, and the results correspond to the visual colour appearances of the tourmaline in different thicknesses and under different light sources.

Acknowledgments

The authors would like to thank Dr Mary Johnson, manager of research and identification of GIA Gem Trade Laboratory, for her helpful discussions and comments and providing the yellow food dye for the colour-change photo. Earlier versions of this article benefited from the comments of Dr Kurt Nassau and other reviewers.

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Abstracts

Diamonds | Instruments and Techniques
Gems and Minerals | Synthetics and Simulants

Diamonds

Touring the diamond factories of Amsterdam.

A. Barnard. *Australian Gemmologist*, **20**(3), 1998, 98–101, 1 illus. in black-and-white, 1 map.

A report on the tours and facilities offered by seven diamond-polishing operations in the main metropolitan area of Amsterdam (their locations are indicated on the accompanying map). These cutting factories comprise The Amsterdam Diamond Centre (the primary focus here is the retailing of diamonds to the tourist; cutting demonstrations are not conducted continuously, although the centre is open seven days a week), Coster diamonds (guided tours are available five times a day with explanations in several languages), Gassan diamonds (tours of the showrooms are given by a multi-lingual staff, and cutting demonstrations are sometimes offered), Van Moppes Diamonds (tours of the cutting workshops are available; the historic aspect of polishing equipment and techniques is a speciality), Stoeltie Diamonds (tours are conducted regularly in many languages; although the factory is small and may become crowded at times, private tours can be pre-arranged before or after the regular opening hours), Lazare Diamonds (demonstrations of all cutting equipment in use at the other factories, plus the simulation of the cleaving process which these days is seldom used in practice), Singel Diamonds (a small, more intimate operation suitable for those who dislike large tours; a range of diamond-cutting equipment can be seen and staff are willing to demonstrate it. A selection of diamonds is also on view in the display cases.) Admission is free to all tours, and diamonds are available for sale at most cutting factories as well as at diamond wholesalers which are located mainly on the Rokin (the main street in the centre of Amsterdam) or in the surrounding streets. P.G.R.

Testing problems at grass roots level. Fancy coloured diamonds.

I. C. C. Campbell. *South African gemmologist*, **11**(2), 1997, 19–31, illus. in colour.

Review of testing methods for fancy coloured diamonds with special reference to pink stones. M.O'D.

Steine der Erde: Neue permanente mineralogisch-geologisch Ausstellungen im Naturhistorischen Museum Bern.

B. Hofmann and U. Menkveld-Gfeller. *Aufschluss*, **11**, 1998, 329–44.

Diamond crystals and other gem minerals are included in the new display of earth sciences at the Natural History Museum in Bern, Switzerland. M.O'D.

Gem news.

M.L. Johnson and J.I. Koivula (Eds). *Gems & Gemology*, **34**(2), 1998, 134–45, 23 coloured illus.

Recent exploration in Alberta, Canada, has discoverd more than 20 kimberlite pipes, many of which contain diamonds. The largest diamond so far weighs 1.31 ct. Anticipated diamond production in the Northwest Territories, Canada, is estimated at 4.2 mct, making Canada the sixth largest diamond producer (by volume) in the world. J.J.

GIA Gem Trade Lab Notes.

T. Moses, I. Reinitz and S.F. McClure (Eds). *Gems & Gemology*, **34**(2), 127–33, 14 coloured illus.

A 5.75 ct brownish purple-pink marquise brilliant diamond was found to be a coated diamond, with the speckled surface colour readily visible under the microscope. When assessing the colour of coloured diamonds, it is best to do so from the face-up position. A diamond recently submitted had a face-up colour of fancy yellow brown, but the body colour was orange. J.J.

Treated blue diamond.

B. Sechos. *Australian Gemmologist*, **20**(3), 1998, 124, 2 illus. in colour.

The radiation-induced colour of a trilliant-cut 3.78 carat greenish-blue diamond was confirmed by the

Abstractors

R.A. Howie	R.A.H.	M. O'Donoghue	M.O'D.	P.G. Read	P.G.R.
J. Johnson	J.J.	E. Stern	E.S.		

For further information on many of the topics referred to, consult *Mineralogical Abstracts*

ISSN: 1355-4565

diamond's lack of electrical conductivity. The presence of fracture filling was discovered when the stone exhibited the typical purplish 'flash effect' while being examined with a loupe. P.G.R.

CVD diamond: a new engineering material for thermal, dielectric and optical applications.

R.S. Sussmann, J.R. Brandon, S.E. Coe, C.S.J. Pickles, C.G. Sweeney, A. Wasenczuk, C.J.H Wort and C.N. Dodge. *Industrial Diamond Review*, **58**, 1998, 69–77, 5 photographs, 15 graphs, 4 tables, bibl.

Recent advances in the technology and application of diamond synthesised by chemical vapour deposition (CVD) are presented. The properties of large area CVD diamond plates of different grades are synthesised for a range of different applications. These plates can be made up to 160 mm (6.3 in) across and can have a thickness of 2.0 mm; they can also be grown in hemispherical domes up to 70 mm. The strength seems to be lower than that of a single crystal diamond, but considerably higher than other alternatives. The optical properties are as good as those of a best-quality single crystal type IIa. The values for thermal conductivity are similar to those of a single crystal type IIa. E.S.

Gems and Minerals

Mineralien aus dem Westschweizer Jura.

P.J. Andermatt and N. Meisser. *Lapis*, **24**(2), 1999, 13–21 1 map.

Collectable and perhaps facetable crystals of calcite, celestine are among the minerals found in the Jura area of Western Switzerland. M. O'D.

Gemmologie Aktuell.

H. Bank, U. Henn and C.C Milisenda. *Gemmologie, Z. Dt. Gemmol. Ges.*, **47**(3), 1998, 121–28.

Items include garnet cat's-eye from Sri Lanka, star moonstone from India and blue quartz from Madagascar which owes its colour to lazulite inclusions the material is translucent and can be cut into blue cabochons. The Russians are growing bicoloured quartzes esp. amethyst and citrine coloured stones known as ametrines. Synthetic zincite is also being manufactured, red in colour, with a hardness of 4.5–5. Some quartz-feldspar doublets have been found on the market, as have imitations of malachite-azurite; the latter seem to be 'reconstructed', with an SG 3.36 which is lower than the natural material. E.S.

Achat, Karneol und Jaspis aus dem Pechstein von Ebersbach in Sachsen.

W. Beck and U. Thonfeld. *Lapis*, **24**(2), 1999, 35–8.

Ornamental silicas in the form of agate, jasper and carnelian are described from the Ebersbach area of North-West Saxony, Germany, where they occur in volcanic rocks. Moss agate, yellow and amethyst single crystals have also been found. M .O'D.

Gems around Australia – Part 14.

H. Bracewell. *Australian Gemmologist*, **20**(3), 1998, 108–11, 8 illus. in colour, 1 map.

The author describes a visit made some years ago to the Aga Khan emerald mine and its associated workings at Poona in Western Australia. The history of the mine and the stories behind its name and that of the Solomon open pit were related to the author by Ralph Bellairs, the mine's caretaker. Bellairs had a mining lease at the site, and called it 'Emerald Pool'. It was this mine that supplied the low quality emerald that the Biron Corporation used as source material to grow its hydrothermal synthetic 'Pool' emerald. P.G.R.

An ?Australian synthetic opal.

G. Brown. *Australian Gemmologist*, **20**(3), 1998, 112–3, 8 illus. in colour.

A 26 x 15 x 5 mm free-form pendant-mounted translucent black opal was found to have a quite distinctive purplish-brown hue. The opal displayed no evidence of either dark potch or inclusions of pink sandstone that usually characterize Lightning Ridge black opal, and further gemmological inspection revealed the columnar colour structure and 'lizard skin' surface appearance seen in Gilson man-made opal. Subsequent inquiries indicated the possibility that the opal was manufactured in South Australia, and the author warns of the existence of this very effective look-alike in the Australian market. P.G.R.

Topaz, aquamarine and other beryls from Klein Spitzkoppe, Namibia.

B. Cairncross, I.C. Campbell and J.M. Huizenga. *Gems and Gemology*, **34**(2), 1998, 114–25, 19 illus. in colour and 2 tables.

Topaz has been found at Klein Spitzkoppe for over a hundred years, together with beryls and other gem stones. Gem-quality topaz and beryl are found in cavities in the pegmatites that intrude the Klein Spitzkoppe alkali granite, which is Jurassic/Cretaceous in age, or found in alluvium. The major mining is for granite for building purposes while local workers collect the gems. The topaz is typically 0.5 ct to 5 ct, usually colourless (silver topaz) and also pale blue or yellow, but tends to lose its colour if exposed to sunlight. The RI values are relatively low (1.610–1.620), more typically associated with topaz found in rhyolite deposits. The SG values are slightly higher than would be expected and this is thought to be due to a high fluorine content, with a maximum amount of 20.3 wt %. The beryl occurs in various colours and specimens of yellow beryl up to 12 cm long have been recovered. J.J.

Mineralsammeln in Kalifornia.

G. Färber. *Lapis*, **24**(2), 1999, 25–33, 1 map.

Benitoite is described and illustrated among the notable California minerals in a general survey of the state's mineralogy. M.O'D.

Gemmologische Kurzinformationen.

Gemmologie, Z. Dt. Gemmol. Ges., **47**(3), 1998, 167–73.

P.G.R. Dharmaratne reports on some greenish-brown stones from Sri Lanka. The article includes a photograph of a number of similar-looking stones found in parcels in Sri Lanka and the various properties from glass to sapphire, chrysoberyl and zircon are listed in a table. In the parcel described the stones were found to be chrysoberyls.

G. Holzhey describes and illustrates some colourless danburite from Dalnegorsk in Russia.

C.C. Milisenda describes a special exhibition, in the German Gem Museum in Idar, of objects on loan from the Green Vaults in Dresden, mainly objects (bowls, etc.) in serpentine, jasper, marble, alabaster, and rock crystal, made from about 1600 to the first half of the 18th century.
E.S.

Elfenbein: Vom Aussehen bis zur Identifizierung.

V.M.F. Hammer. *Gemmologie, Z. Dt. Gemmol. Ges.*, **47**(3), 1998, 129–46, 14 photographs, 1 X-ray diffraction graph, bibl.

Throughout the ages, teeth, bones, antlers and horns of animals have been used as jewellery. Ivory is the most valuable of these materials and it is therefore important to identify it correctly. Often in the past this was only possible by destroying the object. The author discusses the range of materials classified as ivory and describes their characteristics: African and Indian elephant teeth, also those from the mammoth (fossil ivory). Sometimes there are malformations caused by faulty growth, those from the mammoth being known as elephant pearls. Then there is ivory from hippos, walrus, whale esp. narwhal. Not known as ivory, the teeth of other animals have also been used, such as bear, stag, wild boar and wart hog. There is also 'vegetable ivory', a substance produced by a South American 'phytelephas' palm. The beak of the helmeted hornbill is another source of non-ivory ivory. Other substances used to imitate ivory include bones, antlers and horns. Physical properties and various possibilities of identification are given. E.S.

Raman investigations on two historical objects from Basel Cathedral: the Reliquary Cross and Dorothy Monstrance.

H. A. Hänni, B. Schubiger, L. Kiefert and S. Häberli. *Gems & Gemology*, **34**(2), 1998, 102–13, 15 illus. in colour.

Two fifteenth-century objects, the Reliquary Cross and the Dorothy Monstrance, were examined by the Swiss Gemmological Institute to identify the gems. This was done using a Raman spectroscope and an optical microscope. It was surprising to find in such important works of art that many of the stones were imitations composed of glass and doublets. The doublets were made of glass or quartz with the cement layer coloured. Closed back settings made it difficult to identify the pavilion material. Natural stones included amethyst, citrine, colourless quartz, turquoise, peridot, sapphire, red garnet and pink spinel. Inclusions in the spinel and sapphire suggested a Sri Lankan origin with the turquoise and peridot possibly originating from the Near East. Also identified were engraved carnelian and agate and these were thought to be Greek or Roman in age. J.J.

Achate: zur Diskussion über die Genese, die Farben sowie über seltene Achatqualitäten.

H. Harder. *Aufschluss*, 49, 1998, 325–44.

The origin, form and structure of the chalcedonies are discussed with notes on fashioning and on notable chalcedony artefacts. Reasons for the coloration of natural material are given and numerous types are illustrated.
M.O'D.

Bestrahlte Edelsteine – Grundlagen, Erkennung, Normenklatur.

U. Henn. *Gemmologie, Zeitschr.d.deutsch. Gemmol. Ges*, **47**(3), 1998, 153–66, 8 photographs, 3 tables, bibl.

In 1997 the appearance of radioactive chrysoberyl cat's-eyes stimulated discussion about colour enhancement of gemstones by ionizing radiation. More irradiated gemstones have been found on the south-eastern Asian markets. The author summarizes the background of gemstone irradiation, esp. radioactivity, international units and legal release levels as well as methods of detection and measurement. A distinct part of the article deals with the natural radioactivity of gemstones, the formation of colour centres by ionizing radiation, the artificial irradiation for colour enhancement, identification and nomenclature. In some stones such as orange-coloured corundum or dark-blue beryl the colour tends to fade very quickly. In smoky quartz and red tourmaline causes of the natural colours are identical to the causes of colour in irradiated stones, so it is very difficult to distinguish between naturally and artificially irradiated stones. E.S.

Gem news.

M.L. Johnson and J.I. Koivula (Eds). *Gems & Gemology*, **34**(2), 1998, 134–45, 23 coloured illus.

As no one governs the use of descriptive terms in gemmology, this can lead to problems; the situation with the flame agates, where both the colour and the pattern are important, is described and the names should be applied appropriately. The Benitoite Gem mine in San Benito County, California, has been placed under a 14-month option for evaluation by AZCO Mining Inc, which extends until February 1999, at which time AZCO may elect to purchase the mine. At the 1998 Tucson show, a large aquamarine from Farafangana in Southern Madagascar was exhibited and appeared not to have been heated treated. Light greyish-green six-sided 'trapiche' emeralds from near Mananjary, Madagascar ,were also on show. Pyrope spessartine garnets from Sri Lanka exhibited a colour change from greyish greenish-blue in daylight to either dark greyish-violet or purple in incandescent light. Also on show were yellow, orange and orangy-brown cat's-eye opal from Kasulu, Tanzania. A new locality yielding rubies has been found in the Polar Urals in Siberia but the gem potential of the deposit is not yet known. Star and trapiche blue sapphires have been found in a new alluvial deposit in north-east Madagascar. J.J.

Der Baltische Bernstein.

F. Kauffungen. *Aufschluss*, **11**, 1998, 348–58.

Describes with black-and-white and coloured photographs some of the characteristic inclusions in Baltic amber. A brief account of amber mining is given. M.O'D.

Amazonite in Sri Lankan topaz.

J.I. Koivula and S. Elen. *Australian Gemmologist*, **20**(3), 1998, 106–7, 2 illus. in colour, 1 graph.

Using Raman microspectroscopy, a blue-green crystal inclusion 0.5 mm beneath the surface of a 3.88 ct near-colourless rectangular step-cut Sri Lankan topaz was identified as amazonite. This appears to be the first time a blue-green microcline feldspar has been identified in topaz or in any other transparent material. P.G.R.

Mineralien aus dem Dronning Maud Land, Antarkis.

G. Markl and H. Steen. *Lapis*, **24**(1), 1999, 13–19.

Aquamarine of apparent gem quality, red garnet, topaz, scapolite and topaz are reported from Dronning Maud Land, Antarctica. M. O' D.

GIA Gem Trade Lab notes.

T. Moses, I. Reinitz and S.F. McClure (Eds). *Gems and Gemology*, **34**(2), 1998, 127–33, 14 coloured illus.

A 10.45 ct orange-red cabochon-cut stone, which was full of needle-shaped inclusions, was identified as calcite; the inclusions were thought to be chalcotrichite. A parcel of rubies included one stone that was identified as a diffusion-treated corundum, but whether the original stone was natural or synthetic was undeterminable. A 8.64 ct brownish orangy-red stone from Tunduru, Tanzania, was found to be sapphirine. This is the largest sapphirine reported to date and the first reported sapphirine from Tunduru. J.J.

Separating natural and synthetic rubies on the basis of trace-element chemistry.

S. Muhlmeister, E. Fritsch, J.E. Shigley, B. Devouard and B. M. Laurs. *Gems & Gemology*, **34**(2), 1998, 80–101, 12 coloured illus. and 5 tables.

With the use of an EDXRF spectrometer, the authors found that synthetic rubies contain relatively few trace elements, with the presence of Mo, La, Ni, Pt, Pb and Bi being distinctive to synthetic stones. No single trace element proves that a stone is of natural origin, but an assemblage can help distinguish stones, with concentrations of Ti, V, Fe, and Ca being important, natural rubies usually contain higher quantities of these elements than synthetic stones. Although these results can separate synthetic from natural rubies, the information should be used with caution and combined with traditional methods of gem testing. Rubies from different geological origins can also be distinguished. Rubies from basalt type deposits typically contain little V but moderate to high amounts of Fe, whereas the opposite trends are seen in rubies from marble-hosted deposits, and metasomatic deposits give rise to rubies with a wide variety of trace elements. The information is summarised in very accessible diagrams and useful tables. J.J.

Die Formenwelt der Japaner Zwillinge.

G. Pascher. *Lapis*, **23**(12), 1998, 13–30.

Japan-law twins in rock crystal, citrine and amethyst are eagerly sought by gem crystal collectors. The paper illustrates a number of examples from different localities. M.O'D.

Investigation of the intracrystalline Cr^{3+} distribution in natural and synthetic alexandrites.

H. Rager, A. Khiri-Bakhshandeh and K. Schmetzer. *N. Jb. Miner, Mh.*, 1998, 545–57.

Electron paramagnetic resonance measurements were carried out on three synthetic and five natural alexandrites to ascertain Cr^{3+} distribution over octahedrally co-ordinated Al_I and Al_{II} sites. In all samples Cr^{3+} substitutes the larger Al_{II} sites and a small fraction the smaller Al_I sites. Distribution ratio for the chromium over the Al_{II} and Al_I sites is approximately 3:1 and is very similar for low Cr doping levels of pulled alexandrites. A ratio of approximately 2:1 is found in flux-grown alexandrite. Fe and other additional dopants do not cause a redistribution of Cr over the Al sites in the tested samples.

The Cr^{3+} percentage at Al_{II} sites increases in natural alexandrites. The intensity of the colour change correlates with the total Cr content of a sample. No influence on the colour change by Cr at the Al_I sites was observed. M.O'D.

On the identification of amber and its imitations using Raman spectroscopy – preliminary results.

T.S. Tay, Z.X. Shen and S.L. Yee. *Australian Gemmologist*, **20**(3), 1998, 114–23, 7 illus. in colour, 9 illus. in black-and-white, 5 tables, 3 graphs.

A selection of 173 specimens of amber were examined by conventional gemmological methods, and then by Raman spectroscopy. Compared to the conventional methods, Raman spectroscopy is a fast, accurate and non-destructive technique for the routine testing of amber and its imitations. The strong red and yellow fluorescence that is generated in amber when using a laser operating in the visible range is effectively eliminated by using a near-infrared laser. Preliminary results indicate that Raman spectroscopy can be used to differentiate amber from its imitations (including copal resin) and to identify those imitations. P.G.R.

Composite gems.

A. Thomas. *South African Gemmologist*, **11**(2), 1997, 4–13, illus. in colour.

Illustrated descriptive list of composite ornamental materials, also including cultured and Mabe pearls, false cameos, faked gem rough with matrix, coated and filled stones. M.O'D.

Granate aus der Umgebung von Sao Valéria, Tocantins, Brasilien.

R. Wegner, A. Ramos de Brito, J. Karfunkel, U. Henn and Th. Lind. *Gemmologie, Z. Dt. Gemmol. Ges.*, **47**(3), 1998, 14–52, 7 photographs, 2 tables, 1 graph, bibl.

The garnets are found at Fazenda Balisto, in the Municipio Peixi about 12 miles WSW of Sao Valeria, and are of an unusual amethyst colour, RI 1.792 to 1.798, SG 4.08 to 4.11. Small cut stones possess sufficient transparency and may be called rhodolite garnet because of their blue-violet colour. E.S.

Cat's-eye black opal.

M.S. White. *Australian Gemmologist*, **20**(3), 1998, 126, 2 illus. in colour.

A rare cat's-eye black opal from Lightning Ridge was cut as a semi-translucent brownish-black free-form double cabochon weighing 1.27 ct. What appear under the microscope as 'fibres' (as yet unidentified) which produce the chatoyant effect run at a 40 degree angle to the long axis of the eye. Expert opinion suggests that this is a true cat's-eye phenomenon generated by the internal structure of silica spheres and should not be confused with Brazilian cat's-eye material in which the chatoyant effect is caused by asbestos inclusions. P.G.R.

Instruments and Techniques

The Hodgkinson method, a.k.a. The Hodgkinson method: Clarifying the record.

W.W. Hanneman. *The Australian Gemmologist*, **20**(3), 1998, 103–4.

In response to an article by Hoover, 'The Hodgkinson Method, a.k.a. The eye and prism method: some further adaptations' which appeared in the *Australian Gemmologist*, **20**(1), the author defends his coining of the term the 'Hodgkinson method' for what is more commonly known as 'Visual optics'. He reasons that this non-instrumental confirmation of the identity of a gem was not simply a rediscovery of a method first proposed by Crowningshield and Ellison as claimed by Hoover, but is the result of Hodgkinson's personal experimental observations and the assimilation of well-known observable phenomena. Hanneman's article is preceded by a letter to the editor on the same subject and followed by a 'reply' from Hoover. The arguments put forward by Hanneman and Hoover in their respective letters and articles on this subject appear to be both philosophical and gemmological. The philosophical argument is about whether Hodgkinson is the originator of the method and should have his name associated with it as proposed by Hanneman. The gemmological argument revolves around the question of Hodgkinson's 'Visual optics' being a tool of *confirmative* gemmology as claimed by Hanneman, or a tool of *determinative* gemmology as inferred by Hoover, whose suggested additions to the method simply reinforce this determinative aspect. P.G.R.

Synthetics and Simulants

The 'Biron' synthetic emerald. An update.

G. Brown. *South African gemmologist*, **11**(2), 1997, 53–64.

Describes the Biron hydrothermally-grown emerald with notes on means of identification. Inclusion-free material will need chemical analysis or IR Spectroscopy for certain determination. M.O'D.

Gem news.

M.L. Johnson and J.I. Koivula (Eds). *Gems & Gemology*, *34*(2), 1998, 134–45, 23 coloured illus.

A jadeite boulder appeared complete with its alteration crust and a few polished windows, but when sawn it was found that the windows were thin slices of better coloured green jadeite that had been placed in a fabricated crust. Topaz of pink, orange and red colours had been treated by a sputter-coating process, but the coating was found not to be permanent and was easily scratched. Bluish topaz had been coated with a cobalt-rich material, which could only be scratched with a point of hardness 8 on Mohs' scale. J.J.

Review of synthetic rubies over the years.

A. Kleyenstüber. *South African Gemmologist*, **11**(2), 1997, 38–39, 65–73.

Review of the growth and determination of the main types of synthetic ruby manufactured during the present century. M.O'D.

GIA Gem Trade Lab notes.

T. Moses, I. Reinitz and S.F. McClure (Eds). *Gems & Gemology*, **34**(2), 1998, 127–33, 14 coloured illus.

Nine loose undrilled pearls, together with some beads used in their culturing, were submitted for identification. The beads were dolomite and had been fashioned in South Korea and the pearls had been cultured in Japan. A strand of fairly large black pearls, with a metallic appearance, were found to be cultured pearls that had been dyed, possibly with silver nitrate solution. Six triangular brilliants were thought to be natural green obsidian from Tunduru, Tanzania, but with the aid of FTIR spectroscopy the stones were found to be manufactured glass. A purple cabochon thought to be sugilite, was a dyed quartz aggregate with the colour concentrated around and between the aggregate grains. J.J.

Specious or precious.

J.E.W. Snyman. *South African Gemmologist*, **11**(2), 1997, 40–52, illus. in colour.

Review of hydrothermal and natural emeralds and the means of distinguishing between them. M.O'D.

BOOK REVIEWS

The Crown Jewels: the History of the Coronation Regalia in the Jewel House of the Tower of London.

C. Blair, S. Bury, A. Grimwade, R.R. Harding, E.A. Jobbins, D. King, R.W. Lightbown and K. Scarratt, 1998. Volume I: The History (pp xxiv + 812) and Volume II: The catalogue. The Stationery Office, London, pp xxiv + 630. ISBN 0 11 701359 5. Royal Quarto: quarter bound in leather; edition limited to 650 copies. £1000.00.

These two sumptuously produced volumes, with text and photographs printed on substantial, silk-surfaced paper, record the results of research into the history of the English Coronation and the associated regalia in greater detail than has ever before been possible.

Volume I is concerned entirely with the origins and history of the Coronation ceremony, but it is in Volume II that detailed examination of the Crown Jewels is documented, revealing many discoveries and new insights about the history of the gemstones. Each item has been newly photographed and the team of three gemmologists have taken the opportunity to examine the jewels with sophisticated gemmological techniques. This review will be concerned therefore only with volume II (although the complete set was loaned for the purpose of review).

The catalogue illustrates and describes the regalia, not only the numerous crowns, orbs and sceptres, but also the various swords, plate and textiles. Each chapter begins with a brief 'abstract' giving the size and general appearance of the item, before a general description of the history of the various formats and vicissitudes (as when the plan by the adventurer Thomas Blood in 1671 to steal the Crown Jewels was frustrated, but not before he had battered the arches of the crown with a mallet the better to be concealed beneath his cloak: repair to Crown and Orb £145). The description of each major item is concluded with a 'Gemmological commentary', and it is here that we get a listing of the size and weight of all the major gemstones, including details of their surface imperfections, chips, minor scratches and any visible inclusions.

The Imperial State Crown in brief has 2668 diamonds, 17 sapphires, 11 emeralds and 269 pearls, but interest lies mainly in its larger individual gemstones. The so-called Black Prince's Ruby may have been in the Crown Jewels since around 1367 and for many centuries was described more correctly as a balas ruby. It is actually a large polished crystal (~ 170 ct) of red spinel with three vestigial octahedral faces and was pierced in the Middle Ages for use as a pendant; at the top it supports a small ruby, and on the back of its mounting is a small plaque recording the recent history of the crown. The Stuart sapphire (~ 104 ct) at the rear of the crown (replaced at the front by the Cullinan II diamond) is a fine blue, cut with an oval brilliant crown and step-cut pavilion; at least one of the seven visible crystal inclusions appears to be zircon. The octagonal rose-cut St Edward's sapphire set in the cross is a fine velvety blue (e 1.760, w 1.768); scratches on the crown facets appear to be the result of testing the hardness of the stone, a rather basic form of gem testing, now generally avoided. The large cushion-shaped brilliant on the front of the Crown is the second largest stone (317.40 ct) cut from the Cullinan diamond; it has a maximum diameter of 45.4 mm, is free from internal reflections and its colour-grade in the basket setting compares with a D master stone.

The Cullinan I diamond (530.20 ct), formerly known as the Star of Africa I, is a pear-shaped brilliant mounted in the head of the Sceptre with Cross, and is the largest cut colourless diamond in the world; it weighs 530.20 ct when free from its setting. The rough Cullinan diamond (3025 ct) discovered in the Premier mine, South Africa, was purchased by the Transvaal Government and presented to the reigning monarch, King Edward VII (the package was escorted on board ship to England by armed guards; this, however, was a dummy operation, the diamond being sent by ordinary mail. Both packages arrived safely). The Cullinan was handed over to the firm of Asscher in Amsterdam for cutting and was successfully cleaved into two main pieces weighing 2029.9 and 1068.1 ct. We learn that, contrary to popular legend, the cleaver Joseph Asscher did not faint afterwards; he is reported to have said later that 'No Asscher would faint over an operation on a diamond. He's much more likely to open a bottle of champagne.' The faceting and polishing of the gems cut from the rough Cullinan took three polishers, working 14 hours a day, eight months to complete. There are many other gems in the Sceptre (332 diamonds, 31 rubies, 15 emeralds, 7 sapphires, 6 spinels and an amethyst); the positions of all of these are indicated and it is remarked that although most of the rubies are of a fine purplish-red colour they are accompanied by two spinels in positions where rubies might be expected, and that some or all of the spinels may have been used in the belief that they were rubies. The amethyst 'sphere' (~ 32.8 mm diameter) is composed of two joined hemispheres to form part of the 'monde' at the head of the sceptre; pleochroism is noticeable.

The Crown of Queen Elizabeth the Queen Mother contains some 2800, mainly cushion-shaped, diamonds, but the main feature is the Koh-i-nûr (Mountain of Light) cushion-shaped brilliant. When this stone (186 ct) was ceded to Queen Victoria following the annexation of the Punjab in 1849, its Indian cut was considered to be poor, and it was recut in 1852 to 105.6 ct. It is classified as a type II diamond, and though by modern standards the cut is far from perfect in that the large culet is parallel with the table facet giving the impression of a black hole in the centre of the stone, it is nevertheless described as still being full of 'life'.

There are many other crowns and parts of the regalia described in detail in this outstanding work. Mention must be made of the Sovereign's Orb, for example, which is in gold, set with jewels in enamel settings. In the meticulous detail recorded in the gemmological commentary we learn that the jewels comprise of 365 diamonds, 9 emeralds, 9 sapphires, 13 rubies, one amethyst and one glass! Two or three centuries ago, it was common to hire diamonds and other jewels for use in Coronation ceremonies. Thus, at the Coronation of George II in 1727, diamonds valued at £12,000 were hired for £480 and set in St Edward's Crown and three sceptres. Nowadays the opposite situation applies: the Stuart sapphire originally on the front band of the Imperial State Crown was moved to the back in 1909 to accommodate the Cullinan II diamond in its place, and the 'spare' sapphire previously at the back is now free from the regalia and is displayed in the Martin Tower, Tower of London.

One of the many delights of this work lies in the numerous colour photographs of the regalia, many of the close-up views of the individual stones having been produced by the team of gemmologists, including Alan Jobbins, Ken Scarratt and Roger Harding, and also Frank Greenaway, the photographer from the Natural History Museum. The price of these two magnificent volumes may prevent one from dashing out to buy a set, but this work records for posterity far more details of the gemstones in the regalia than have hitherto been available. We should each try to ensure that it is available for consultation in a nearby university or regional library.

R.A.H.

Jewellery – English/Chinese, Chinese/English dictionary.

Chen Zhonghui, Yan Wei Xuan, C.M. Ou Yang, and Wu Shun Tian. 1998. China University of Geosciences Publishing House, Beijing, P.R. China. pp 310, hardcover. HK $120. ISBN 7 5625 1323 6.

Amazingly useful and comprehensive dictionary found especially useful by this reviewer who (a long time ago) studied the language. Some entries are unexpected but most of those you really want appear to be there. M.O'D.

I gemmologi del mondo raccontano le gemme dal mare Gemmologia Europa VI

CISGEM, 20123 Milano, Italy. (1998) pp 267, Illustrated in colour, softcover. Price on application.

A welcome addition to the literature of maritime ornamental products, this now biennial volume contains papers on pearls and corals from Asia (K. Scarratt), pearls and corals from Australia (G. Brown), gems from African waters (H. Pienaar), formation and composition of gems from the sea-pearls from American waters (C. Hedegaard), gems from British waters (R.R. Harding), gems from French waters (J.P. Poirot), gems from Italian waters (M. Superchi), gems from Italian waters – magic and preciousness in coral manufacturers (C. Ascione), sapphires from Andranondambo, Malagasy (E. Gübelin). Papers are presented in both Italian and English and bibliographies relating to each paper are placed together at the end of the book. There is a good provision of maps and useful short biographies of the authors. The standard of the papers is very high and continues this authoritative and impressive series. M.O'D.

Pearl buying guide. [Third edition]

R. Newman, 1998. International Jewelry Publications, Los Angeles. pp 156, illus. in colour, softcover. US $19.95. ISBN 0 929975 27 8.

At the end of the main text of this most attractive book are quizzes arranged in order of the chapters to which they refer. A quick glance through the questions convinced me that while I knew that most black pearls were not very round, that most black pearls were in fact a dark shade of grey and that 'AAA' quality as applied to pearls has no particular significance, every seller being able to apply any designation desired, most of the remainder of the questions required immediate recourse to the text. This shows how much the book is needed ! This third edition is even better produced than its two predecessors and the text is arranged in a now familiar order, with an introduction showing just why pearls are desirable. Though not really an organic ornamental materials student, this is the book I shall consult on any pearl topic whatsoever. M.O'D.

Saltbush rainbow: the early days at White Cliffs.

G. Rowe, 1998. The author, White Cliffs. pp vi, 57, softcover, Available from Mrs D. Hoffman, Kerara Road, White Cliffs, New South Wales 2836, Australia. $A9.50. ISBN 0 95919 280 8.

In a re-issue with additional photographs of a book first published in 1983, the story of the White Cliffs opal fields of New South Wales is entertainingly told with a wealth of maps and anecdotes. Opal from the area is recorded from at least 1884 though it is not known who made the first discoveries. As well as mining stories, details of community development are recounted, the whole picture being typical of 19th century Australian mining areas. There is a useful bibliography: readers interested in opal history should be keeping a look-out for books such as this as they may have short print-runs.

M.O'D.

Emeralds around the world.

J. R. Sauer, 1992. The author, Rio de Janeiro. pp 160, illus. in colour, hardcover. Price on application.

Well-compiled survey of the world's major emerald deposits with illustrations depicting all kinds of mining scenes as well as examples of cut and rough emeralds from the sources described. A good deal of the information has not appeared in monograph form before. The author promises books on diamonds and ruby.

M.O'D.

Proceedings of the Gemmological Association and Gem Testing Laboratory of Great Britain and Notices

OBITUARY

An appreciation of Miss 'Lena' Willis by David Callaghan

The death of Miss 'Lena' Willis at the age of 99 is the final chapter in the life of a remarkable lady, one who was unique, and one with whom I had the privilege of working for 15 years. From the moment I joined Hancocks in London's West End in 1955, as one of the NAG apprentices, she took me under her wing and gave me the opportunity to learn from her any and all aspects of the jewellery trade, a trade which had become her life.

Miss 'Lena' Willis, taken in 1960 by Vivienne.

Born on 7 December 1899, 'Lena', as she was known to most people, was the eldest daughter in a family of six, having three brothers and two sisters. The family lived in Leigh-on-Sea, Essex, and she lived in that area all her life. Her father held the view that she, as the eldest daughter, should not go out to work but stay and help run the home. She defied her father by going to work as a secretary. Her first job was at a local timber merchant but she found it 'lonely, surrounded by nothing but planks of wood'. She left that job and went to work as secretary to 'Jimmy' Wixley, a local jeweller, and here she really found her niche in life. Mr Wixley was an entrepreneur, a dealer in gems and almost any object sold by the retail jeweller in a county town. He had a love for gem opal and this he passed on to Miss Willis. She really took to the trade and Mr Wixley soon recognized her interest and encouraged her to train further. The Gemmological Diploma of the NAG – to become the FGA in 1931 – was still in its infancy and she had to take the course by correspondence. She qualified in 1930, only the tenth woman to do so. She soon became indispensable to Mr Wixley and when he opened another shop in Westcliff-on-Sea she was appointed manager.

In the 1930s, Hancocks, in common with many small firms, was finding the going very tough and by 1935 was in some difficulty. The company needed a fresh impetus and Mr Wixley was introduced to the then two partners, and so began his 25 years of service until his death in 1959 at the age of 82. At the beginning of World War II his Westcliff-on-Sea business was closed down and the stock transferred to Wigan and Miss Willis went with him to work there. This was not to last long and Mr Wixley returned to Hancocks during the war service of the other partners. Miss Willis joined the Ministry of Supply and her task was to supervise the collection of iron railings and other

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such metal objects from all over East Anglia and the Home Counties during the Government's drive for scrap metal. She began this work in 1941 but in 1942 she answered a carefully worded advertisement in *The Times*. This led to a successful interview on 27 August 1944 with a Lt. Col. O'Hea. He was based in Denham, at Sir Oswald Mosley's home that had been requisitioned at the beginning of the war. Miss Willis transferred there under the direct written order of the Prime Minister, Winston Churchill. It was known as War Station 14 and was, in fact, an arm of MI6. She worked there for the rest of the war.

In 1945 she returned to Hancocks to work alongside her 'old chief' Mr Wixley, and in 1950 she was appointed a Director. Thus she was unique in the history of the firm – the first woman to be appointed a Director and no other woman in the West End jewellery trade had ever reached such a level of responsibility. Why was this so unusual?

The jewellery trade was male dominated and, of all firms in the West End, Hancocks was amongst the most male chauvinistic. Such was the male dominance in the trade that even her own name became masculinized (if there is such a word!). When she first worked for Mr Wixley she would have been referred to as Miss Willis. However, as time progressed and she became indispensable to him, it became appropriate to recognize this. It was not the done thing in those days to refer to someone by their first name, so she became known as 'William'. In turn this was shortened to 'Bill'. This made her an equal, of course, as she now had a man's name! I had always thought it perverse that such a ladylike person should have to suffer this indignity, but recently I realized she took it as a compliment, albeit a very backhanded one!

What was she like as a person? Diminutive in stature, as well as in nickname, 'Lena' Willis was attractive, very ladylike in her manner and dress, generous in every sense of the word, and a sound businesswoman. She was a very fine judge of colour in a gemstone, and had a love of the two 'miracles' of the gem world – pearls and opals. She was a wonderful teacher, and very interested in and encouraging to the young. Without her, Hancocks would not have been the force in the jewellery trade that they became after World War II, and I was the the main beneficiary of her time and knowledge. She gave me every opportunity to stand on my own feet and I felt always that I was working with her and not for her. She retired in 1970 when she had no reason to, other than to give me the opportunity she felt confident I could use. In the portrait taken in 1960 by Vivienne she is shown wearing both pearls and opals. The photograph is not one that flatters her, it shows her as she was and how she appeared every day in business. She is wearing a cultured pearl necklace of carefully graded and matched pearls. The brooch is a basket of flowers and was her favourite. She designed it herself, and the 'basket' is a single piece of precious black opal. The flowers comprised many small pieces of very bright opal, ruby, sapphire, pearl and turquoise – all carefully blended to give a realistic picture.

You will realize that she was retired for very nearly 30 years, during which time she kept herself very active. However, a younger sister with whom she shared a house became very ill. Lena nursed her daily for nearly four years until her death. This took a toll on her own health and she suffered a stroke at the age of 94. This affected her mobility but she recovered well and lived very happily in a rest home for her remaining years. It was only in the last 12 months that her health failed her.

There are now very few people left in the London trade who worked with her either as a buyer or supplier, but her name lives on in those of us lucky enough to have known her. Her love of gemstones and of the trade she passed on to me. Now in my own retirement I look back over 42 very happy and fulfilling years in the trade. My life has been enriched by the generosity, enthusiasm and grace of a unique lady, and I am very fortunate to have worked alongside her.

***

Mr R.K. Bennett, FGA, DGA (D.1978), Winchcombe, died in August 1998.

Mr Matthew S. Potter (D.1980), San Jose, Calif., U.S.A., died on 13 November 1998.

Mr Robert A. Pudner (D.1963), Childwall, Liverpool, died suddenly on 5 March 1999.

Mr Samuel F. Redknap (D.1947 with Distinction), Twickenham, Middlesex, died in January 1999.

NEWS OF FELLOWS

Congratulations to Dr Roger M. Key, FGA, Keyworth, Nottinghamshire, who was awarded an MBE in the 1999 New Year's Honours list. The award was made in connection with his work for the Botswana Geological Survey.

MEMBERS' MEETINGS

London

On 13 January 1999 at the Gem Tutorial Centre, 27 Greville Street, London EC1N 8TN, Andrew Ross, Curator of Fossil Arthropods in the

GIFTS TO THE ASSOCIATION

The Association is most grateful to the following for their gifts for research and teaching purposes:

The Bahrain Promotions and Marketing Board for a copy of the book *Treasures of Bahrain*.

Richard Burton for an 11.93 ct aquamarine.

Luella Woods Dykhuis, FGA, DGA, Tucson, Arizona, U.S.A., for various specimens including agate, coral, ruby in sillimanite, horn and shell, and *The Gem Kingdom* by Paul E. Desautels and *Brazil, Paradise of Gems* by Jules Roger Sauer.

Eddie S.K. Fan of Chui Wah Jewellers, Kowloon, Hong Kong, for two pieces of dyed jadeite.

Alec Farn, FGA, Seaford, East Sussex, for a zircon in memory of Hubert Mornard who died in January 1999 (see *Gem and Jewellery News* 1999, 8 (2), 28).

Sonja Glaser, FGA, Galle, Sri Lanka, for samples of blue apatite, sapphire, spinel and garnet.

Alfred H. Gunn, Dover, Kent, for a set of brass scales.

Janice Kalischer, Finchley, London, for a plastic imitation cameo set in a brooch.

Li Liping, FGA, DGA, China University of Geosciences, Wuhan, P.R. China, for a carved bone flower.

Mrs C.M.Ou Yang, Hong Kong Institute of Gemmology, for a boxed collection of jadeite containing 15 pieces.

Philip Seager, FGA, Didcot, Oxfordshire, for a quantity of back issues of *The Journal of Gemmology*.

E.A. Thomson (Gems) Ltd., London, for 21 garnets, and five packets containing blue and green glass.

Professor Yan Weixuan, FGA, DGA, China University of Geosciences, Wuhan, P.R. China, for a bowenite carving, a row of non-nucleated freshwater pearls, and a corozo nut and carving.

Linda Zhou, Tongji University, Shanghai, P.R. China, for a 'Duschan jade' bangle.

Department of Palaeontology at the Natural History Museum, South Kensington, gave an illustrated lecture on insects in amber.

On 11 March 1999 at the Gem Tutorial Centre, Dr H. Judith Milledge, Emeritus Reader in Crystallography at UCL, gave a lecture entitled *Some current problems in diamond research.*

Midlands Branch

On 29 January 1999 at the Earth Sciences Building, University of Birmingham, Edgbaston, a Bring and Buy evening was held, followed by a quiz.

On 26 February 1999 at the Earth Sciences Building, David Callaghan gave a lecture entitled *Cameos and gemstone carvings.*

On 26 March 1999 at the Earth Sciences Building, James Gosling gave a talk on the fascinating world of miniatures and the beautiful jewelled settings used for their display.

North West Branch

On 17 March 1999 at Church House, Hanover Street, Liverpool 1, Keith Mason gave a lecture entitled *Exotic diamonds.*

Scottish Branch

A Members' Night and Bring and Buy were held on 20 January 1999 at the British Geological Survey, Murchison House, West Mains Road, Edinburgh. A series of short talks was given by members, including one by Alan Hodgkinson on how to identify synthetic moissanite in a parcel of diamonds.

On 17 March 1999 Dr Jeff Harris gave a talk entitled *Diamonds from the crust to the core.*

FORTHCOMING EVENTS

30 April	**Midlands Branch.** ID challenge and AGM
30 April to 2 May	**Scottish Branch.** Annual Conference and AGM. Guest speaker Dr W.W. Hanneman
6 May	**London.** A guide to affordable gemmology. Dr W.Wm. Hanneman
14 May	**London.** Shining examples – the teaching potential of a gemmologist's jewel box. Cecilia Pople
19 May	**North West.** Pearls – romance and fact. Rosamond Clayton
23 May	**Midlands Branch.** Gem Club – Jet. Peggy Hayden
26 June	**Midlands Branch.** Summer supper
28 June	**London.** Annual General Meeting, Reunion of Members and Bring and Buy Sale
14 July	**London.** Demantoid garnet and other new gems and minerals from Namibia. Professor Peter R. Simpson
15 September	**North West Branch.** Photographing gems and their inclusions. John Harris
20 October	**North West Branch.** Window to beauty. Piero Di Bela
31 October	**Annual Conference – New Developments in the Gem World.** Keynote speaker: James Shigley, Director of Research at the GIA, Carlsbad. To be held at the Barbican Centre, London
17 November	**North West Branch.** Annual General Meeting

For further information on the above events contact:

London:	Mary Burland on 0171 404 3334
Midlands Branch:	Gwyn Green on 0121 445 5359
North West Branch:	Deanna Brady on 0151 648 4266
Scottish Branch:	Catriona McInnes on 0131 667 2199

GAGTL WEB SITE
For up-to-the-minute information on GAGTL events
visit our web site on www.gagtl.ac.uk/gagtl

GEM DIAMOND EXAMINATIONS

In January 1999, 55 candidates sat the Gem Diamond Examination, 40 of whom qualified, including three with Distinction. The names of the successful candidates are listed below:

Qualified with Distinction

Chen Chuyiao, Beijing, P.R. China
Chik Wing Sheung, Kowloon, Hong Kong
Zhang Ning, Wuhan, Hubei, P.R. China

Qualified

Ashby-Crane, Robert J., Bratton Fleming, Barnstaple, Devon
Briginshaw, Richard C., Hampstead, London
Cheung Shiu Cheong, Randy, Kowloon, Hong Kong
Deng Xiuquan, Beijing, P.R. China
Dennis, Roger A., Elstree, Hertfordshire
Doucet, Francois L.G., Brockley, London
Dykhuis, Luella Woods, Tucson, Ariz., U.S.A.
Fan Hidy Kit-Ha, Kowloon, Hong Kong
Galdeano, Nerea L., London
Han Xu, Beijing, P.R. China
Hu Yunhua, Beijing, P.R. China
Hunter, Pauline A., Caversfield, Oxfordshire
Kendall, David, Addiscombe, Surrey
Mak Kin Yeung, Kenny, Hong Kong
Konda, Muana Mputu, London
Lee, Martin, South Croydon, Surrey
Li Ki Wing, Alison, Kowloon, Hong Kong
Li Wei, Beijing, P.R. China

Lin Ling, Wuhan, Hubei, P.R. China
Maslik, Magdalena M., Fulham, London
Ng Kwok Wai, Kowloon, Hong Kong
Oldershaw, Cally J. E., Leavesden Green, Hertfordshire
Osband, Peter M., London
Patel, Nita, Newbury, Berkshire
Perez Dorao, Carlos, Golders Green, London
Poon Mei Han, Kowloon, Hong Kong
Qiu Mingjun, Wuhan, Hubei, P.R. China
Qiu Yanping, Wuhan, Hubei, P.R. China
Schatzle-Parisod, Arlette, Basel, Switzerland
Sethi, Barti, London
Sinclair, Gary, London
Sun Haipeng, Wuhan, Hubei, P.R. China
Warshow, Nancy, Nairobi, Kenya
Xie Shirong, Wuhan, Hubei, P.R.China
Yan Yushuang, Beijing, P.R. China
Yang Yong, Wuhan, Hubei, P.R. China
Zhang Jing, Wuhan, Hubei, P.R. China

EXAMINATIONS IN GEMMOLOGY

In the Examinations in Gemmology held worldwide in January 1999, 129 candidates sat the Preliminary Examination of whom 95 qualified. In the Diploma Examination 130 candidates sat of whom 67 qualified.

Diploma

Qualified

Aho, Jouko, Oulu, Finland
Amarasinghe, Ashan S., Rajagiriya, Sri Lanka
Arentsen, Ernst W., Wapse, The Netherlands
Bagri, Abhishek I., Mumbai, India
Bai Chenguang, Guilin, Guangxi, P.R. China
Blampied, Julie K., Trinity, Jersey
Blatherwick, Clare, Hampstead, London
Brown, Vanessa, Sittingbourne, Kent
Chan So Ying, Hong Kong
Chang Kung Jung, Taipei, Taiwan, R.O. China
Chen Shu-Chuan, Taipei, Taiwan, R.O. China
Choi Sun Young Chun, Seoul, Korea
Curran, Rose, Ealing, London
Deljanin, Branko, New York City, New York, U.S.A.
Ding He, Guilin, Guangxi, P.R. China
Edery, Gabrielle J., London
Elen, Shane, Oceanside, Calif., U.S.A.
Finlay, Louden B., London
Garrett, Frances, Sutton, Surrey
Gong Dong, Wuhan, P.R. China
Grech, Carrieann, London
Greenfield, Dawn M., Eynsford, Kent
Grostate, Stephen E., Ashtead, Surrey
Ho Cheuk Fung, Kowloon, Hong Kong
Hsu Feng, Taipei, Taiwan, R.O. China
Hunter, Pauline A., Caversfield, Oxfordshire
Ip Kit Ling, Kowloon, Hong Kong
Ji Yan, Shanghai, P.R. China
Keating, Elaine, Hackney, London
Kilian, Angela M.C., Leidschendam, The Netherlands
Koh Hock Heng, Singapore
Kwon Sung Hae Yoon, Yangon, Myanmar
Lei Wei Hong, Singapore
Li Rutian, Guilin, Guangxi, P.R. China
Lin Ling, Guilin, Guangxi, P.R. China
Lixia Xu, Wuhan, Hubei, P.R. China
Lu Ning, Shanghai, P.R. China
Mafara, Ezekiel M., Harare, Zimbabwe
Mingjun Qiu, Wuhan, Hubei, P.R. China
Mossuto Mori, Maria E., Yangon, Myanmar
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MEETINGS OF THE COUNCIL OF MANAGEMENT

At a meeting of the Council of Management held at 27 Greville Street, London EC1N 8TN, on 26 January 1999, the business transacted included the election of the following:

Fellowship (FGA)

Devon, Jill, Coggeshall, Essex. 1994
Li Xianshu, Tianjin City, P.R. China. 1998
Marr, Peter, Torquay, Devon. 1996
Pfneisl, Thomas, Vienna, Austria, 1986
Richardson, Julia H., London. 1998
Wei Qiong, Wuhan, Hubei, P.R. China. 1998

Ordinary Membership

Atichati, Wilawan, Bangkok, Thailand
Dower, Daniel G., London
Endo, Chihiro, Kyoto City, Kyoto, Japan
Fearnley, Christopher S., Didsbury, Manchester
Fujita, Takashi, Osaka City, Osaka, Japan
Furuta, Atsuko, Kurume-City, Fukuoka Pref., Japan
Halperin, David M., London
Hashimoto, Megumi, Kyoto City, Japan
Hirano, Kiyomi, Kawanishi City, Hyogo Pref., Japan
Kalha, Mahmoud A.M., Linstock, Carlisle
Kataoka, Satomi, Osaka City, Osaka, Japan
Kato, Ayumi, Osaka City, Osaka, Japan
Keat, Ian , Lincoln
Kumagai, Hiromi, Sendai City, Miyagi Pref., Japan
Kuroda, Makiko, Hirakata City, Osaka, Japan
Leverington, Michael, Bexhill on Sea, East Sussex
Matsubara, Midori, Osaka City, Osaka, Japan
Modarres, Pary, Carshalton, Surrey
Morris, Charlene, Duluth, GA, USA
Murai, Shinobu, Osaka, Japan
Rance, Felicity Anne, Windlesham, Surrey
Sakajo, Hiroko, Yao City, Osaka, Japan
Saminpanya, Seriwat, Manchester
Tachibana, Yurika, Chofu City, Tokyo, Japan
Takahashi, Chika, Tokyo, Japan
Tamaki, Yosuke, Sakurai City, Nraa Pref., Japan
Tanaka, Nariko, Tachikawa City, Tokyo, Japan
Tokudaiji, Ayako, Kobe, Hyogo Pref., Japan
Tshiunza, Marcel K., London
Uchida, Tomoko, Hatogaya City, Saitama Pref., Japan
Ueno, Tazumi, Ikoma City, Nara Pref., Japan
Yamanaka, Norio, Takaichi-gun, Nara Pref., Japan
Yamasaki, Yashunori, Akashi City, Hyogo Pref., Japan

At a meeting of the Council of Management held at 27 Greville Street, London EC1N 8TN, on 25 February 1999, the business transacted included the election of the following:

Fellowship (FGA)

Cao Can, Wuhan, Hubei, P.R. China. 1995
Dalsplass, Line, Rasta, Norway. 1998
Han Xiao, Guilin, Guangxi, P.R. China. 1998
Long Chu, Guilin, Guangxi, P.R. China. 1998
Park Chan Won, Taegu, Rep. of Korea. 1998
Yang Sibo, Guilin, Guangxi, P.R. China. 1998

Ordinary Membership

Cintamani, Frank, St. Johns Wood, London
Cross, Alice, Warminster, Wiltshire
Englezos, Antonios, Birmingham
Farrell, Terry, Cambridge
Gaskell, Ben H., London
Giambrone, Roberto, London
Kim Hoon Chong, Camden, London
Oakley, Charles, Ware, Hertfordshire
Odugleh, Ahmed, London
Petrovic, Bilyana, London
Scholz Rittermann, Manfred, Bajamar, Tenerife, Canary Islands
Thackrah, Merle, Great Horkesley, Essex
Vis, Jan, Puttershoek, The Netherlands

Laboratory Membership

Burns the Jewellers, Manchester

At a meeting of the Council of Management held at 27 Greville Street, London EC1N 8TN, on 24 March 1999, the business transacted included the election of the following:

Fellowship and Diamond Membership (FGA DGA)

Owen, Charryn P., Northwich, Cheshire. 1998/1999

Fellowship (FGA)

Ajani, Shilpa Chetan, Bombay, India. 1985
Grostate, Stephen E., Ashtead, Surrey. 1999
Rusch, Louise V., Hatfield, Hertfordshire. 1999
Silverman, Sivan, Waltham, Mass, U.S.A. 1987
Walker, Zoë, Pelsall, Walsall, West Midlands. 1999

Diamond Membership (DGA)

Doucet, Francois L.G., Brockley, London. 1999
Konda, Muana Mputu, London. 1999
Osband, Peter M., London. 1999

Ordinary Membership

Botha, Jacob M.G., Birr, Co. Offaly, Ireland
Chambers, Sara L., Cardiff
Hardiman, Julie C., Chandlers Ford, Hampshire
Lee, Helen, London
Smith, Mark H., Bangkok, Thailand
Woolland, Natalie, Seaton, Devon

TRANSFERS

Ordinary Membership to Fellowship and Diamond Membership (FGA DGA)

Hunter, Pauline A., Caversfield, Oxfordshire. 1999
Sethi, Barti, London. 1999

Fellowship to Fellowship and Diamond Membership (FGA DGA)

Briginshaw, Richard C., Hampstead, London. 1999
Dykhuis, Luella Woods, Tucson, Arizona, U.S.A. 1999
Li Ki Wing, Alison, Kowloon, Hong Kong. 1999
Oldershaw, Cally J.E., Leavesden Green, Hertfordshire. 1999
Patel, Nita, Newbury, Berkshire. 1999
Warshow, Nancy, Nairobi, Kenya. 1999

Diamond Membership to Fellowship and Diamond Membership (FGA DGA)

Keating, Elaine, Hackney, London. 1999

Ordinary Membership to Fellowship (FGA)

Blatherwick, Clare, Hampstead, London. 1999
Brown, Vanessa, Sittingbourne, Kent. 1999
Choi Sun Young Chun, Seoul, Korea. 1999
Curran, Rose, Ealing, London. 1999
Finlay, Louden B., London. 1999
Greenfield, Dawn M., Eynsford, Kent. 1999
Kilian, Angela M.C., Leidschendam, The Netherlands. 1999
Mossuto Mori, Maria E., Yangon, Myanmar. 1999
Muller, Hellen A.D., Wierden, The Netherlands. 1999
Tulo, Karen, Ludwigshafen, Germany. 1999

Ordinary Membership to Diamond Membership (DGA)

Dennis, Roger A., Elstree, Hertfordshire. 1999
Galdeano, Nerea L., Golders Green, London . 1999
Kendall, David C., Addiscombe, Surrey. 1999
Lee, Martin, South Croydon, Surrey. 1999
Maslik, Magdalena M., Fulham, London. 1999
Perez Dorao, Carlos, Golders Green, London. 1999
Sinclair, Gary, London. 1999

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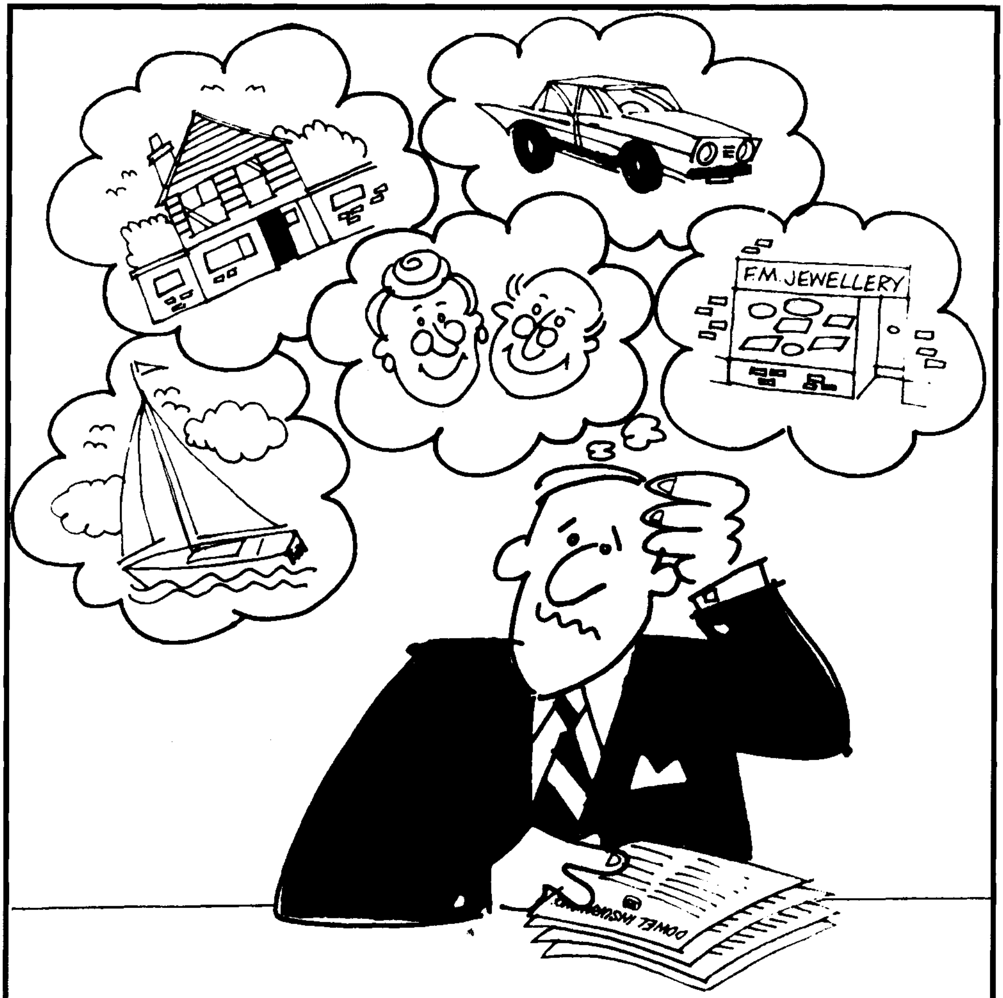
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Books Hughes, R.W., 1990. *Corundum*. Butterworth-Heinemann, London. p. 162

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A sapphire shown under three different light sources to illustrate the colour-change (clockwise from top: fluorescent light, natural daylight and incandescent light). See 'A colorimetric study of the alexandrite effect in gemstones'. pp 371–85.

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