Absorption Spectral Analysis at Gemstones

Uwe G. B. Hollenbach

Abstract

This measurement report presents results of absorption spectral analysis at colored gemstones according to classification of hardness [1]. Characteristic absorptions versus wavelength are measured within the visible spectral range about 400 nm to 750 nm using a SMA Mini Spectrometer from Thunder Optics [2]. The measured spectral data are presented in spectral absorption diagrams and furthermore in spectral color bars. Both of them are computed with the software Spectragryph [3]. In the following sections the motivation of the work, the measurement set up, the illumination and light lunching in gemstones are described. At the end of the explanatory sections a conclusion and an outlook for a further work is given. The experimental achieved results are grouped according to the type of gemstone and tabular placed in the appendix. They will be supplemented and edited over time.

Introduction

Gemology laboratories and institutions invest a lot of money for equipment to analyze natural, synthetic, stacked and treated gemstones. From interest is the experimental proof of all physical, optical, mineralogical and chemical characteristics of gemstones. Hobbyists have typically a low budget and can’t invest so much money for analysis equipment.

In the last few decades more development power was spent in micro optical and optoelectronic systems. Therefore it was possible that more miniature USB diode array spectrometer comes into the marked. But most of inexpensive USB mini spectrometers can’t offer a good spectral resolution which is important for gemstone or mineral analysis. They often designed for quick and raw spectral resolution for industry applications of color or material analysis. For such applications a low resolution of app. 10 nm in the range of visible (VIS) and/or near infrared (NIR) wavelength spectrum is enough. But absorption spectroscopy at gemstones and mineral crystals needs higher resolution which should be app. 10 times better.

To overcome this problem Thunder Optics comes into the marked with USB mini spectrometers with higher performance. The technical specifications especially for detector sensitivity and spectral resolution are improved. In addition also quality and price have a good relationship. That is the fundamental basic and motivation to invest in a USB mini spectrometer from Thunder Optics. Such spectrometers offer the possibility for hobbyists, students and smaller labs to start spectral analysis.

Measurement Set Up

The measurement set up in Fig. 1 used for this work contains a wide band white light source, a spectrometer, an object holder and a netbook with analysis software to compute and illustrate the measured spectral data.

The illumination lamp is a KL1500 from Schott. It contains a Halogen lamp type Xenophot HLX 64 634 EFR 15 V 150 W from Osram with integrated back side mirror reflector. An additional optical element in the lamp system is a heat absorption filter glass followed by a condenser lens.

The lamp light is couplet to a glass fiber bundle of app. 9 mm diameter with polished flat end facet. The fiber bundle is after short distance splitted in two separate glass fiber bundles of 4.5 mm diameter respectively. The typical spectral curve vs. wavelength of the Halogen lamp light is shown in Fig. 2.

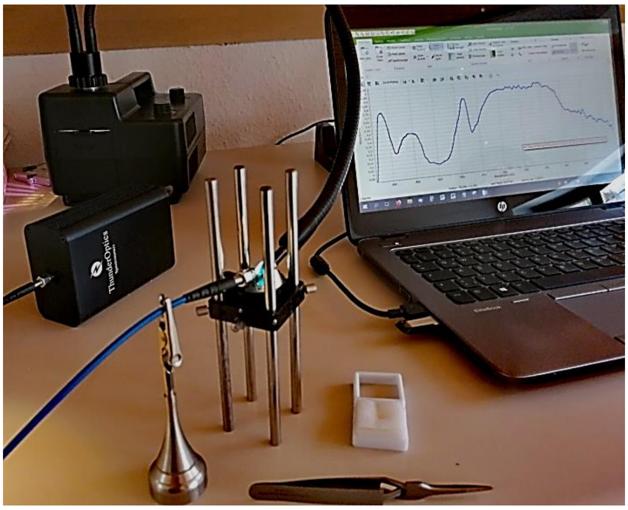

Fig. 1 Measurement set up

A spectral curve of a simple white light emitting diode (LED) is plotted in Fig 3 and can be compared with the spectral plot of the Halogen lamp in Fig. 2.

The comparison between both white light sources within the VIS range between 400 nm to 700 nm demonstrates that the halogen lamp is more homogeneous in her intensity than the LED. Additionally the Halogen lamp has an extended range in the NIR 700-900 nm and can also be used for applications of NIR analysis.

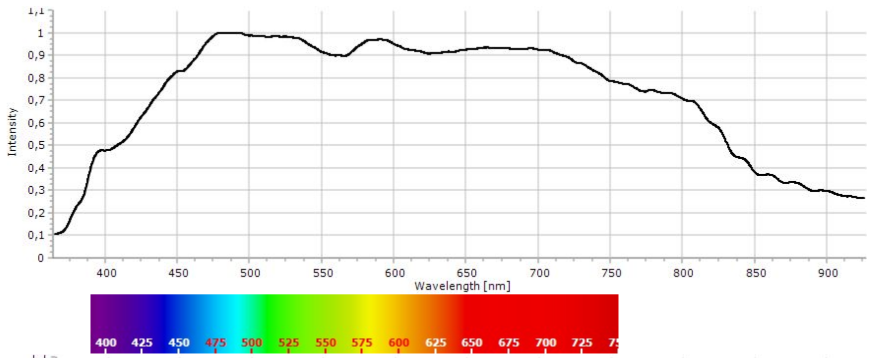

Fig. 2
Spectral intensity line plot of a white light Halogen lamp.
Osram Xenophot HLX 64 634 EFR 15 V 150 W;
The lamp shows a continuous wide band intensity power over the VIS range from 400 to 700 nm;

Spectral diagram & color bar processed by Spectragryph [Ref. 3]

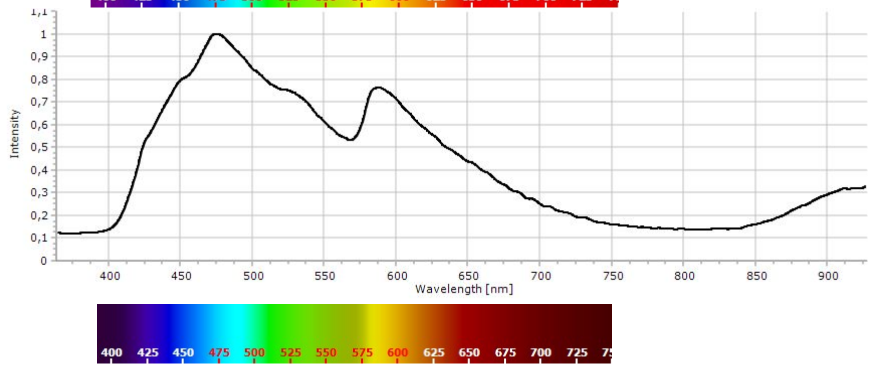

Fig. 3
Spectral intensity line plot of a LED.

Compared with the intensity distribution in the plot of Fig. 2 the LED has less power between 475 to 700

Spectral diagram & color bar processed by Spectragryph [Ref. 3]

The used spectrometer device is an USB SMA-E Mini spectrometer from Thunder Optics. It is calibrated for a VIS-NIR spectral range from 380 nm to 930 nm. The slit width is 100 µm and matched to a multimode fiber of type MMF 100/125 µm core/cladding diameter. The fiber patch cable comes with standard SMA connectors SMA905 on both ends. The length of the fiber cable is about half meter. The free end of the fiber is orientated to the measured gemstone flexible in position while the fiber bundle end illuminates the gemstone in a fixed position. The gemstone is placed on a flat carrier or grabbed in a fife finger spreading spring holder both together are fixed in position.

Illumination and Light Guiding

The illumination and light guiding for a meaningful absorption spectrum in a high contrast is an important experimental part of the work. The light beam guiding through the gemstone must be good adjusted to get enough intrinsic absorption for the characteristic spectral curves vs. wavelength. Disturbed light as shine light, stray light and un-propagated light must be minimized to get best contrast and not saturation on the spectrometer detector unit. Therefore the size of the polished gemstone should be not too small and the proportion between width and height should be in a good relation. That means the relation between pavilion and crown angel should be high enough depends on the refractive index of the gemstone which grants internal total reflection.

If the gemstone lost propagation light by irregular transmission (out coupling) through pavilion facets (so named “windowing”) than could it be the measured light intensity has not the best condition for the absorption analysis.

Fig. 4, Fig. 5 and Fig. 6 show some ray trace sketches computed using the program GemCad [4]. The simulations show this behavior depend of the gemstone proportions and light lunching in different orientations of the gemstone facets.

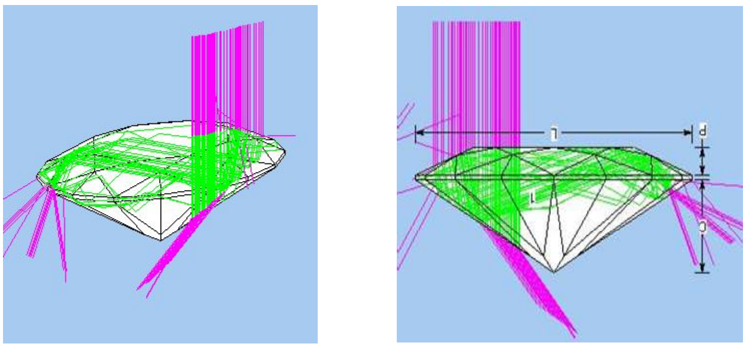

Fig. 4 a. Oval gemstone geometry.
Light lunched from top into the table and crown facets and should be propagate intern **along the long geometrical axis**. The longer the internal light propagation the more characteristic absorption can be measured.
For this orientation the pavilion angle is too small for a refractive index of 1.8. Therefore most of light couples out after a short way. Only a small part of internal propagated light can be used for the measurement.

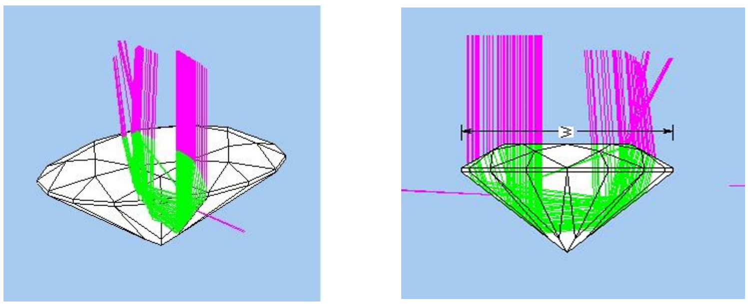

Fig. 4 b. Oval gemstone geometry.
Light lunched from top into the table and crown facets and should be propagate internal **along the short geometrical axis**.

In this orientation the property of the cut is good for internal total reflection by a refractive index of 1.8.
All lunched light couples out on the opposite side of the table and crown facets and can be used for the measurement.

Ray trace and cut designed with GemCad [4]

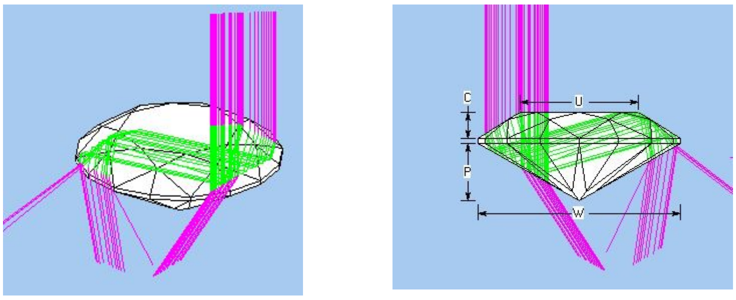

Fig. 5 a. Round gemstone geometry.
Light lunched from top into the table and crown facets and should be propagate by internal total refection. In this case the pavilion angle is only 30° and therefore too small by a refractive index of 1.8. All lunched light couples out through the pavilion facets.
The gemstone shows windowing. Only some light take a longer internal way and may be could be analyzed.

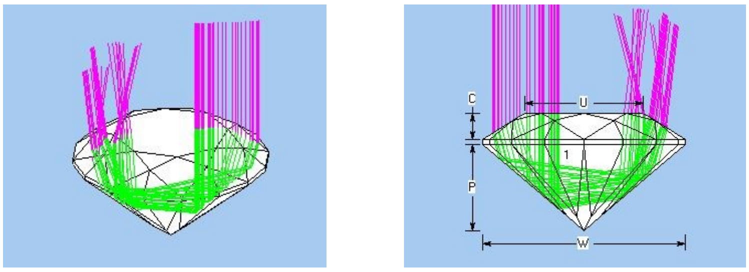

Fig. 5 b. Round gemstone geometry.
Light lunched from top into the table and crown facets and propagate by internal total refection. In this case the pavilion angle is 42° and the refractive index is 1.8. All lunched light couples out at the table and crown facets. The gemstone shows no windowing.
All light take the longest internal way and can be analyzed.

Ray trace and cut designed with GemCad [4]

The orientation in Fig. 6 is much more profitable to use because it is in-depend from the problems described in Fig. 4 and Fig. 5 a. The gemstone is placed upside down on a flat carrier. The lamp light is lunched into the pavilion facets and coupled out from the gemstone on the opposite side of the pavilion facets while the light inside is total reflected at the table facet. Therefor this method is used for all facetted gemstones measured in this report

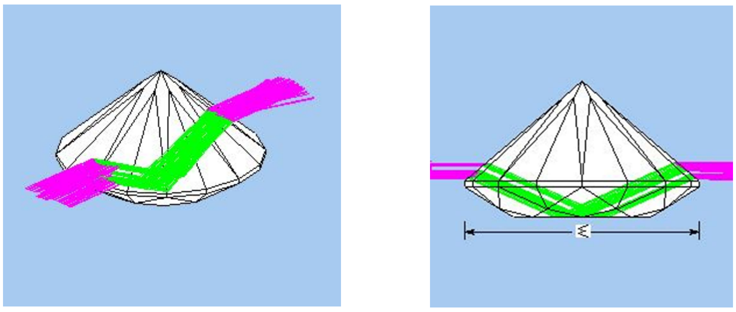

Fig. 6. Round cut.
The light can alternative lunched into the pavilion facets. The light propagates by internal total refection at the table facet. In this case the pavilion angle is 39° and the refractive index is about 1.8. In this simulation all lunched light couples out at the opposite side of the pavilion facets.
The light propagates over a long internal way which is important for intrinsic absorption analysis.

Ray trace and cut designed with GemCad [4]

Experimental Results

In Tables of the appendix grouped according to the type of gemstone series of different colored gemstones are spectral analyzed. The spectral white lamp light is random polarized and not specific coupled into a defined crystal axis of the gemstones. Therefore the resulted spectral absorption curves in the appendix can’t discuss for axis orientated polarization states. All plots are contrast optimized by offset subtraction and normalization of the highest absorption peak within the VIS range. Therefor the visibility a) for small absorption lines and b) for low absorption in nearly colorless or high transparent gemstones (see Petalite, Appendix 12.7, Table 1) can be improved. Also the spectral color bars which are additionally placed below the spectral absorption curves become better visibility about absorption lines and weakly wide absorption bands. The spectral diagrams and color bars vs. wavelength are generated by the software Spectragryph [3].

The visibility of absorption peaks and bands for the measured gemstones are sometimes controlled with a hand held ocular spectrometer from OPL [5].

The spectral curves in the appendix are the results of serial measured gemstones. The plots show characteristic small peaks and/or wide band absorption versus wavelength over the VIS range. The different absorptions vs. wavelengths are understand as typically for different single or groups of gemstones like Diamond, Corundum, Beryllium, Chrysoberyl, Spinel, Topaz, Garnet, Zircon and Tourmaline and a last wide group of rare gemstones, mainly classified by the ranking of hardness. The measured absorption spectral plots can be compared on one hand with reference books [6, 7]. On the other hand they can be compared with spectral line plots which are online presented in the internet [9, 10 and 11].

Reference [6] describes a lot of gemstones in her physical parameters which used for jewelries and/or for a gemstone collection. A table with main and incidental absorption lines for many gemstones is presented. Additionally some colored spectral plots of important gemstones are shown. Reference [9] presents in many more tables measured color spectral bars of special gemstones sorted by colors. Comments for each measured spectral bars are given. Both references give also information about the reason of the characteristic color of the gemstones. Often the color is activated by the free electron transitions or the electron interactions charge transfer (IVCT) with guest metallic ions which are in tiny trace deviations in defect positions of the host crystal matrix. These transition elements mainly could be Titanium, Vanadium, Chromium, Manganese, Iron, Cobalt, Nickel and Copper as pure ore in mix of ions [11]. Depend on the intensity of the color the spectral analysis shows more or less separately characteristic absorption versus the wavelength.

Conclusion and Outlook

Spectral absorption measurements at gemstones with an USB Mini spectrometer from Thunder Optics [2] are presented in this report. The results are graphed in spectral curves vs. wavelength and furthermore in colored spectral bars for each measurement. For data processing and documentation the extensive and powerful software Spectragryph [3] is used. The measurement system and the measurement light guiding are discussed in details. The Appendix 1-12 contains arranged in tables all spectral diagrams from the measured gemstones.

In the future more measurements should be added in the appendix. Furser measurements should be directed on polarization depend spectral analysis if the gemstone has a significant birefringence. Also gemstones with color change effects (key word pleochroism) should be again characterized.

About the Author

Uwe G. B. Hollenbach reached his degree of Diploma in Physic in the year 1985 from University of Paderborn, Germany. 1985 he starts his career as scientist with Carl Zeiss Foundation in the field of wave optics. From 1987 to 2000 he was with IOT – Integrated Optic Technology - a spin-off from Carl Zeiss and Schott – leader of the optical measurement group within the development division in the field of integrated single mode waveguide components based on glass for fiber optical networks. From 2000 to 2017 he was with KIT – Karlsruhe Institute of Technology at IMT – Institute for Microstructure Technology and works in the field of micro optical sensor systems based on polymer formed by LIGA technique. The last ten years with KIT/IMT he was within the micro optical division leader of the micro optical components group. The focus of this development was the demonstration of components of integrated optical single mode waveguide produced by polymer diffusion technique and single mode waveguide structuring by laser direct writing for printed electronic board integration. From 2018 until today the author is retired and now dedicates himself to his hobby in the field of gemology and mineralogy.

References

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[4] GemCad, Gemstone cut design software and ray tracing simulation, www.gemcad.com
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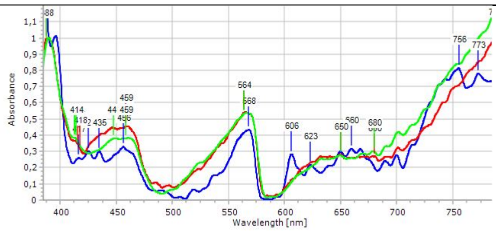
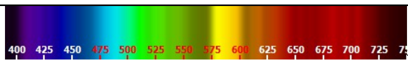
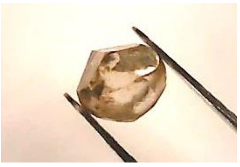
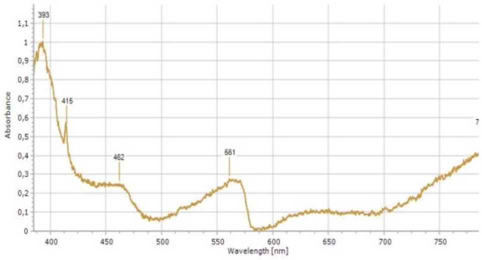
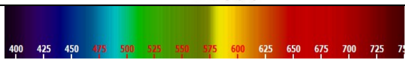
[25] Tay Thye Sun[1], Wilawan Atichat[2], Boontawee Sriprasert[2,3], Thanong Leelawatanasuk2, "Moldavite: Natural or Imitation"
[1]Far East Gemological Laboratory, 400 Orchard Road #03-10, Singapore, 238875; email: fegemlab@singney.com.sg
[2]The Gem and Jewelry Institute of Thailand (Public Organization), Bangkok 10330, Thailand
[3]The Department of Mineral Resources, Bangkok 10400, Thailand

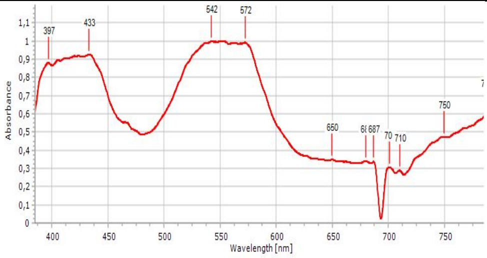
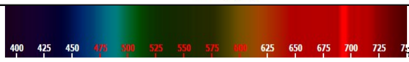
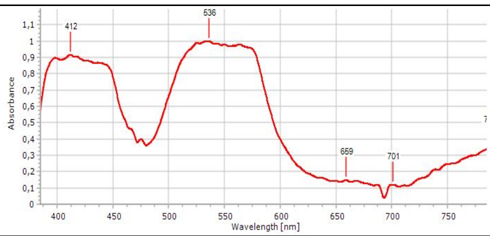
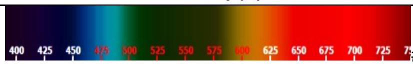
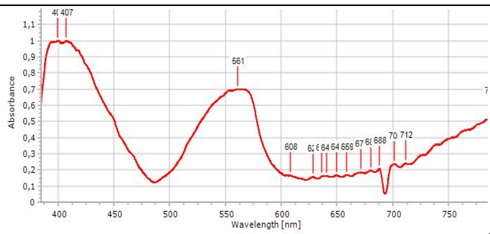
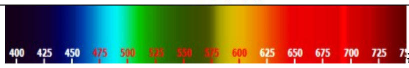
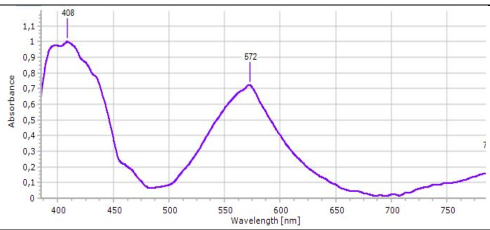
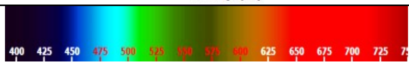
Appendix Overview Table

Appendix 1: Diamond	**Appendix 7: Garnet**
Appendix 2: Corundum	**Appendix 8: Zircon**
Appendix 3: Beryl	**Appendix 9: Tourmaline**
Appendix 4: Chrysoberyl	**Appendix 10: Quartz & Opal**
Appendix 5: Spinel	**Appendix 11: Peridot & Zoisite**
Appendix 6: Topaz	**Appendix 12: Rare Gemstones**

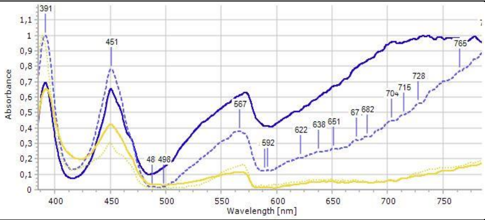
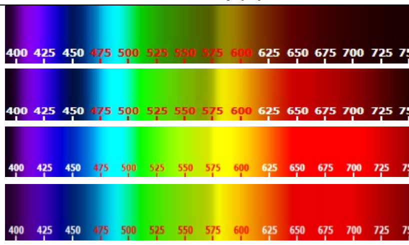
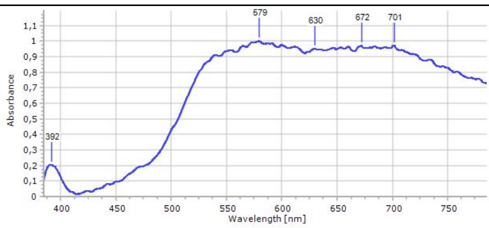
Appendix 1: Absorption spectrums of Diamond gemstones

 **Diamond #1**	 	Diamond, nat. Xtal Octaeder, color less characteristic absorption measured at 388,414 422,435,459,568,606,623,650,660,680 nm other absorption caused by a) inclusions (Fig 1) of Fe-FeO-Fe_3O_4 or Cr_2O_3 associations [21];or b) micro mineral inclusions or grown on the diamond surface (Fig 2) e.g. Olivine, Garnet, Chromite, Diopsite, Rutil etc. [22] c) Nitrogen-vacancy (NV^-) centers [23]
 **Fig 1. Zoom to inclusions in Diamond #1**  **Fig 2. Zoom to surface on Diamond #1**	 #1	— Diamand #1 Xtal color less unpol c-axis — Diamand #1 Xtal color less unpol a,b-axis — Diamand #1 Xtal color less unpol a,b-axis Absorption data about 5-times magnified;
 **Diamand #1b raw Xtal**	 	Diamond, nat. raw Xtal, pale brownish color activation by N [1]; characteristic absorption measured at 393,415,462 and 561 nm Abs. data about 2-times magnified; no data smoothing to see the peak at 415 clear;
	 #1b	— Diamand #1b raw Xtal pale brownish unpol
Appendix 1: Table 1. Absorption spectrums of different colored Diamond gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

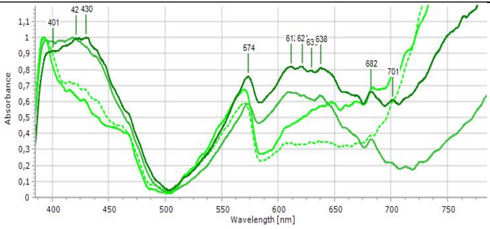
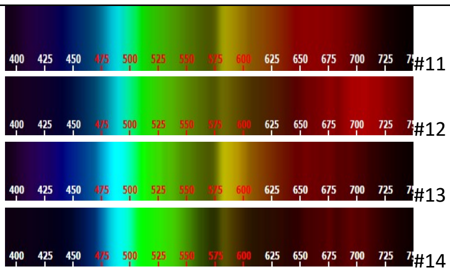
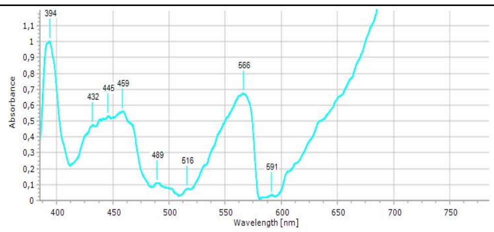
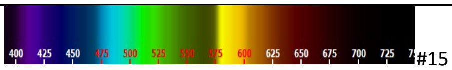
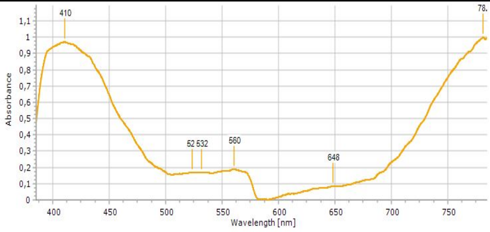
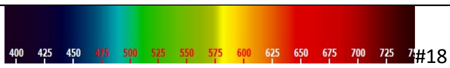
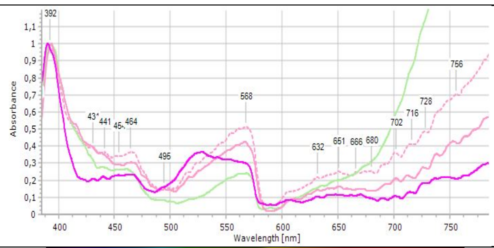
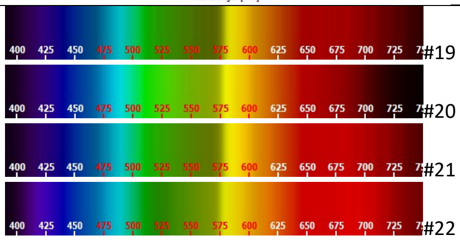
Appendix 2.1: Absorption spectrums of Corundum gemstones

 **Ruby #2**		Corundum; Ruby, violet-red color activation by Cr^{3+} [1],[11]; fluorescence at 693/694 nm characteristic absorption measured at 400-450,500-610 nm
	 #2	— Corundum #2 Ruby red
 **syn. Ruby #182**		Corundum syn.; Ruby, red color activation by Cr^{3+} [1]; weak fluorescence at 693/694 nm characteristic absorption measured at 400-450,500-610 nm
	 #4	— Corundum #4 syn Ruby red
 **Sapphire #8**		Corundum; Sapphire, violet color activation by V [6, 10]; fluorescence at 693/694 nm characteristic absorption measured at 400-450,500-610 nm
	 #8	— Corundum #8 Sapphire violet
 **syn. Sapphire #181**		Corundum; Sapphire, violet color activation by V [6]; characteristic absorption measured at 400-450,500-610 nm
	 #181	— Corundum #181 syn Sapphire violet
Appendix 2.1: Table 1. Absorption spectrums of different colored Corundum gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

Appendix 2.2: Absorption spectrums of Corundum gemstones

 **Sapphire #10**		Corundum; Sapphire, blue and yellow blue color activation by Fe^{2+}-Ti^{4+} and Fe^{2+}-Fe^{3+} intervalance charge transfer [11]; yellow color activation by Fe^{3+} [11]; characteristic absorption measured at 391,451,567 and above 650 nm
 **Sapphire #178**	 #5 #6 #7 #178	— Corundum #5 Sapphire blue -- Corundum #6 Sapphire blue ··· Corundum #7 Sapphire yellow — Corundum #178 Sapphire yellow
 **syn. Sapphire #9**		Corundum syn.; Sapphire, blue characteristic absorption measured at 392 and a wide band above 525 nm (compare with natural Sapphire #5 and #6);
	 #9	— Corundum #9 syn Sapphire blue
Appendix 2.2: Table 1. Absorption spectrums of different colored Corundum gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

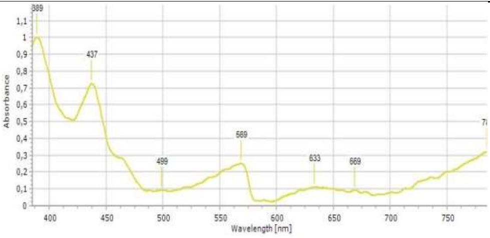
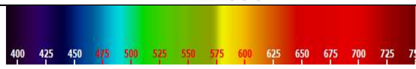
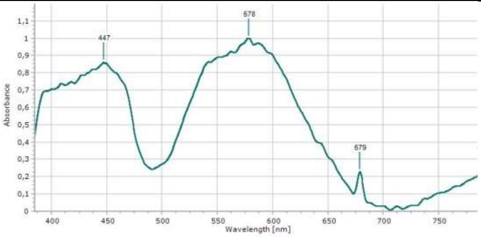
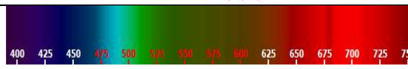
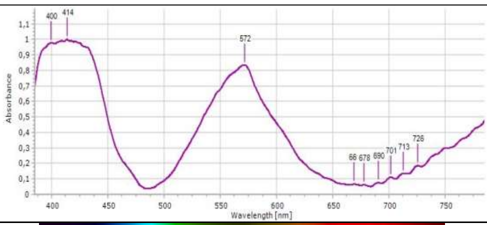
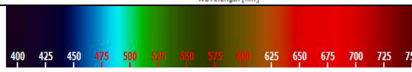
Appendix 3: Absorption spectrums of Beryl gemstones

 **Emerald #11**		Beryl; Emerald, green color activation by Fe^{2+}, Fe^{3+} and also from Cr^{3+} and V^{3+} [11]; characteristic absorption measured at 400-475,550-575 nm and 600-650nm and above 700 nm peaks at 394,421,430,574, 682 and 701 nm
 **Emerald #14**		Beryl #11 Emerald bright green Beryl #12 Emerald green Beryl #13 Emerald bright green Beryl #14 Emerald dark green
 **Aquamarine #15**		Beryl; Aquamarine, bright blue color activation by Fe^{2+} [11]; characteristic absorption measured at 425-575,525 575 nm and peaks 394,432,445,459, 566 and strong above 600 nm
		Beryl #15 Aquamarine bright blue
 **Gold Beryl #18**		Beryl; Gold Beryl, golden-yellow color activation by Fe^{3+} [11]; characteristic absorption measured at 400-450, weak peaks at 560 and strong above 700 nm
		Beryl #18 Gold Beryl golden-yellow
 **Green Beryl #20**		Beryl; a) Morganit, pale pink and b) Green Beryl, pale green a) color activation by Mn^{2+} [11]; b) color activation by Fe^{2+}, Fe^{3+} and V^{3+} characteristic absorption measured at 392,464,568 nm and weak peaks from 630-750 and ; pale green stronger above 700 nm and the more violet lower above 700 nm
 **Morganit #22**		Beryl #19 Morganit pale pink Beryl #20 Green Beryl pale greenish Beryl #21 Morganit pale pink Beryl #22 Morganit pinkish

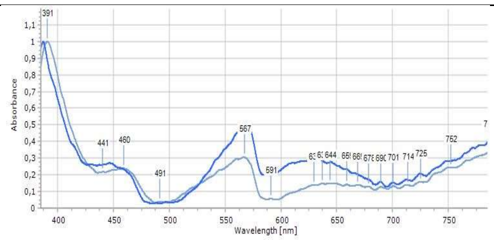
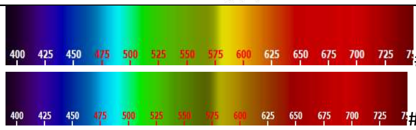
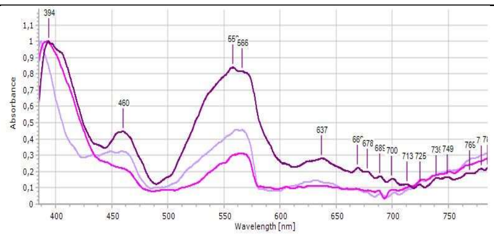
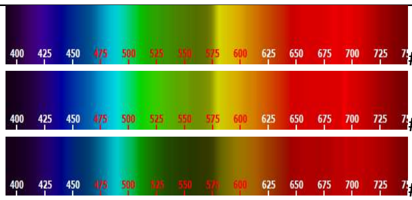
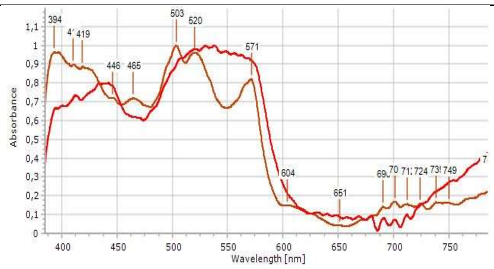
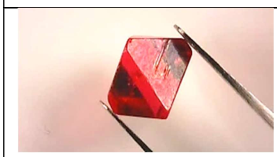
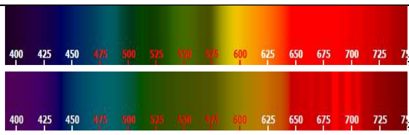
Appendix 3: Table 1. Absorption spectrums of different colored Beryl gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

Appendix 4: Absorption spectrums of Chrysoberyl gemstones

 **Chrysoberyl #23**		Chrysoberyl nat., yellow color activation by Fe^{3+} [11]; characteristic absorption measured at 389,437,569 and 633 nm
	 #23	— Chrysoberyl #23 yellow unpol
 **Alexandrite #24**		Chrysoberyl nat.; Alexandrite dark green-violet, (cold lamp light) color activation by Cr^{3+} [11]; characteristic absorption measured at 390-475,525-625 and a peak at 679 nm
	 #24	— Chrysoberyl #24 dark green-violet opaque
 **Alexandrite #25**		Chrysoberyl syn.; Alexandrite dark violet (warm lamp light) color activation by Cr^{3+} [11]; characteristic absorption measured at 390-450 and 525-600 nm
	 #25	— Chrysoberyl syn #25 Alexandrite dark violet
Appendix 4: Table 1. Absorption spectrums of different colored Chrysoberyl gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

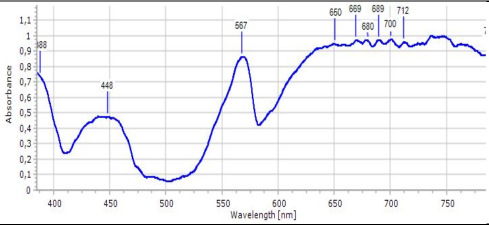
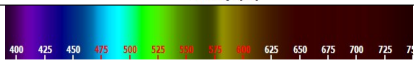
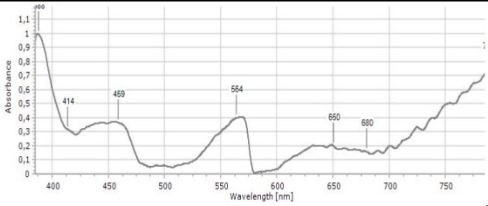
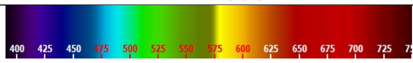
Appendix 5: Absorption spectrums of Spinel gemstones

 **Spinel 176**		Spinel, pale gray blue and blue color activation by Co^{2+} [11]; characteristic absorption measured at 391,441,567 and around 625 nm
 **Spinel #186**	 #176 #185	Spinel #176 bright gray-blue Spinel #185 blue
 **Spinel #174**		Spinel, violet and pinkt violet color activation by Cr^{3+} [11]; pink color activation by Cr^{3+} and Fe^{2+} [11]; characteristic absorption measured at 394,460,561,637nm and weak peaks around 700 nm
 **#Spinel 177**	 #174 #177 #27	Spinel #174 bright violet Spinel #177 bright pink Spinel #27 dark violet
 **Spinel #26**		Spinel; red-brown color activation by Cr^{3+} [11]; characteristic absorption measured at 390-425 and smaller bands around 503,520,571 and weak peaks around 700 nm
 **Spinel #26a nat. Xtal**	 #26 #26a	Spinel #26a nat Xtal red unpol

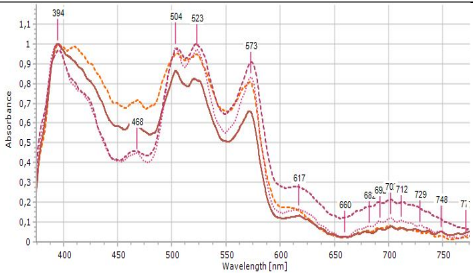
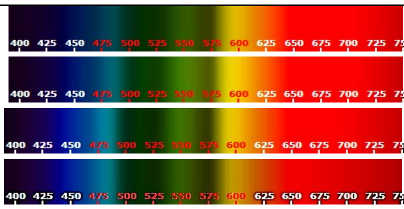
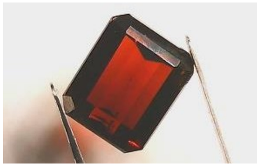
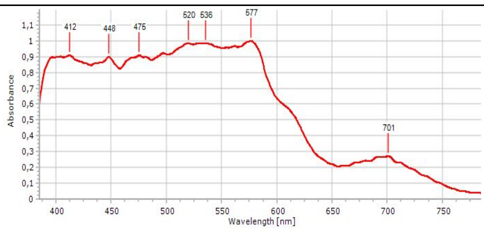
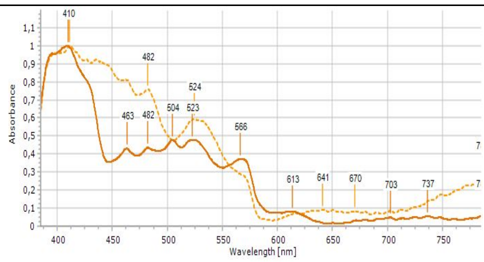
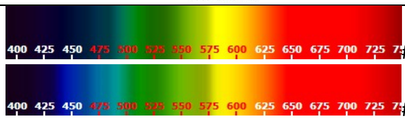
Appendix 5: Table 1. Absorption spectrums of different colored Spinel gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

Appendix 6: Absorption spectrums of Topaz gemstones

 **Topaz #189**		Topaz, blue; color activation by Cr^{3+} [11]; characteristic absorption measured at bands around 388,448,567 and above 625 nm
	 #189	— Topaz #189 blue unpol
 **Topaz #28**		Topaz, pale bluish-color less; characteristic absorption measured at bands around 390,459,564,650 and above 700 nm
	 #28	— Topaz #28 pale bluish-color less unpol
Appendix 6: Table 1. Absorption spectrums of different colored Topaz gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

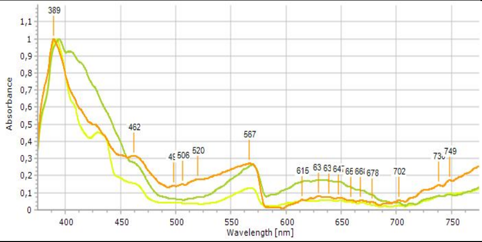
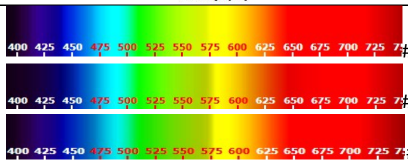
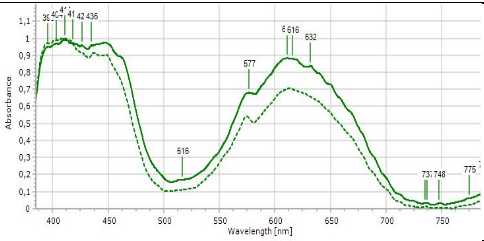
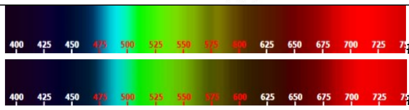
Appendix 7.1: Absorption spectrums of Garnets gemstones

 **Rhodolite #40**		Garnet; Pyrope; Rhodolite, red; brown red; violet red; color activation by Mn^{2+} and Fe^{2+}[11]; Rhodolite is a mix of Pyrope and Almandine with Mg abs. band at 390 nm and Fe abs. band at 500-580; characteristic absorption measured at 394,468,504,523,573,617 nm and around 700 nm;
 **Rhodolite #32**		Garnet #30 Rhodolite red Garnet #40 Rhodolite brown red Garnet #32 Rhodolite violet red Garnet #31 Rhodolite violet red
 Almandine #29		Garnet; Almandine, red-brown; color activation by Fe^{2+} [1]; characteristic absorption measured at a) in a wide band 380-600 nm b) with peaks at 412,448 476 520,577 and 701 nm;
		Garnet #29 Almandine red-brown unpol
 **Manderin #33**		Garnet; Spessartine, red-brown ; Manderin, orange; color activation by Mn^{2+}[11]; characteristic absorption measured at 380-575 with peaks at 410,463,482,504,523 and 566 nm and weakly and 613 nm
 **Spessartine #39**		Garnet #33 Manderin orange unpol Garnet #39 Almandine red-brown unpol

Appendix 7.1: Table 1. Absorption spectrums of different colored Garnet gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

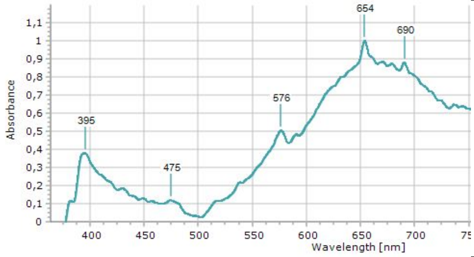
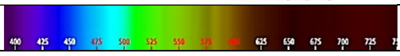
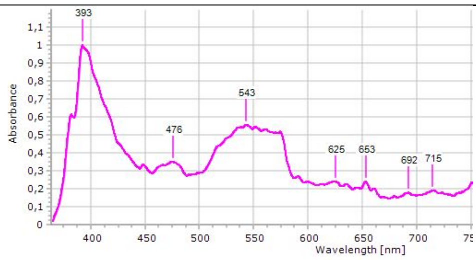
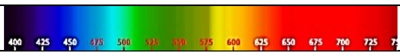
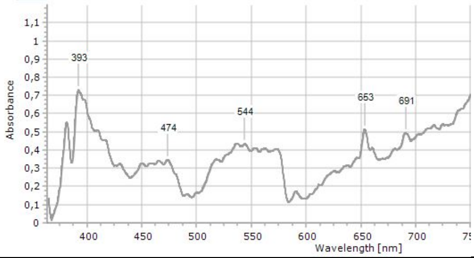
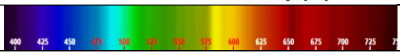
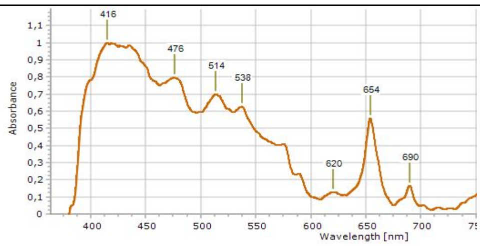
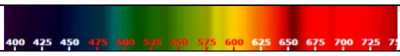
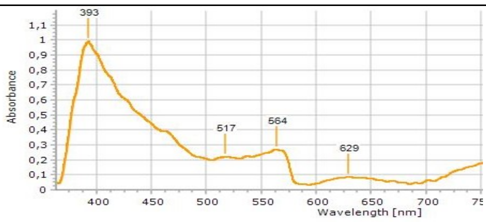
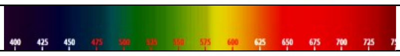
Appendix 7.2: Absorption spectrums of Garnets gemstones

 **Grossular #35**		Garnet; Grossular, bright orange color activation by Fe^{2+} and Fe^{3+} [11]; characteristic absorption measured at 389,431,462,567 and around 630 nm
 **Grossular #34**		Garnet #35 Grossular Garnet #38 Grossular Garnet #34 Grossular
 **Tsavorite #38**		Garnet; Grossular, Tsavorite, green color activation by V^{3+} [11]; characteristic absorption measured at 380-475 and 550-700 nm with peaks at 411,577 and 616 nm
		Garnet #37 Tsavorite green Garnet #36 Tsavorite green

Appendix 7.2: Table 1. Absorption spectrums of different colored Garnet gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

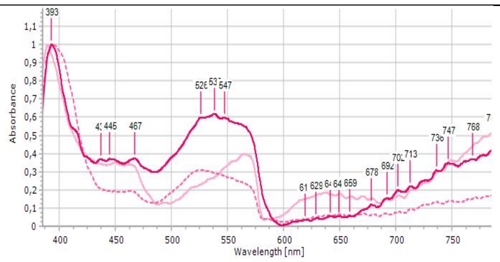
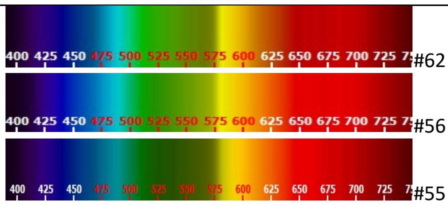
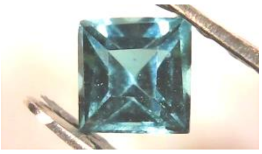
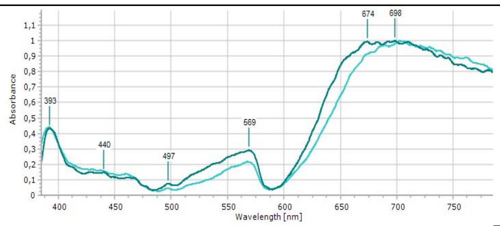
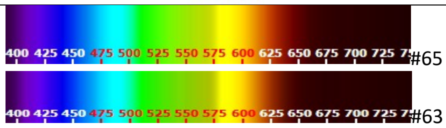
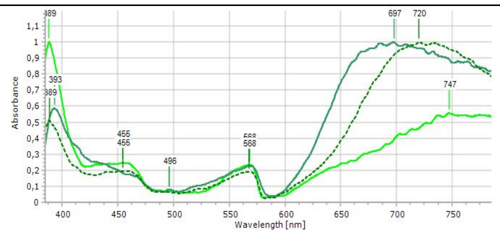
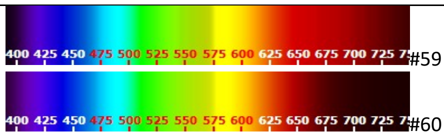
Appendix 8: Absorption spectrums of Zircon gemstones

 **Zircon #173 (Starlit)**	 	Zircon; Starlit blue; color generation by U^{4+} [11]; often refreshed by heat treatment in vacuum [8] characteristic absorption measured at 395,475 and above 550 with peaks at 576,654 and 690 nm;
		#173
 **Hyacinth #51**	 	Zircon; Hyacinth, violet; color generation by radiation damage centers of U^{4+} [11] characteristic absorption measured at 393,476,505-580 nm and weak peaks around 653 nm; more weak absorption lines are visible within the range from 500-650 nm
		#51
 **Jargon #52**	 	Zircon; Jargon, color less; color less if very tiny traces of U^{4+}; becomes more clearness by heat treatment in oxygen flow [11]; characteristic absorption measured at 380,393,450-480,505-580,653 and 691 nm
		#52
 **Hyacinth #50**	 	Zircon; Hyacinth, gold brown color generation by radiation damage centers of U^{4+}; most found crystal color ton in nature [11]; characteristic absorption measured at 390-575, with peaks at 416,476,514,538,620,654 and 690 nm absorption are compared in reference [6] page 45,46,124; Ref [7] and [11]
		#50
 **Hyacinth #170**	 	Zircon; Hyacinth, red brown color generation by radiation damage centers of U^{4+}; most found crystal color ton in nature [11]; characteristic absorption measured at 380-450 with peaks at 393,517,564,629 nm
		#170

Appendix 8: Table 1. Absorption spectrums of different colored Zircon gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

Appendix 9.1: Absorption spectrums of Tourmaline gemstones

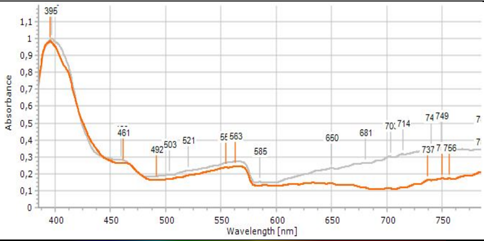
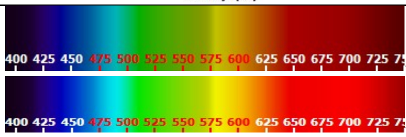
 **Rubellite #55**		Tourmaline; Rubellite, violet color activation by Mn^{2+} [11]; characteristic absorption measured at 393,413,435,467,497,520-570 and above 650 nm
 **Rubellite #56**		Tourmaline#62 Rubellite bright pink Tourmaline #56 Rubellite pink Tourmaline #55 Rubellite dark pink
 **Indigolite #65**		Tourmaline; Indigolite, blue color activation by Fe^{2+} or Cu^{2+} [11]; characteristic absorption measured at 393,440,497,569 and above 625 nm
		Tourmaline #65 Indigolite blue Tourmaline #63 Indigolite blue
 **Verdelite #59**		Tourmaline; Verdelite, green color activation by Fe^{2+}-Ti^{4+} (IVCT) or Fe^{2+}, either Cr^{3+} or V^{3+} alone [11]; characteristic absorption measured at 389,393,455,568 and wide band around 700 nm; stronger above 600 nm the more green to dark green
 **Verdelite #60**		Tourmaline #59 Verdelite bright green Tourmaline #60 Verdelite green Tourmaline #61 Verdelite dark green

Appendix 9.1: Table 1. Absorption spectrums of different colored Tourmaline gemstones

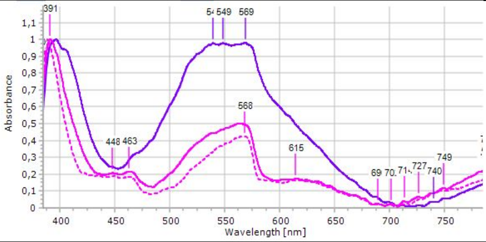
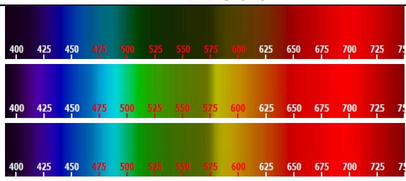
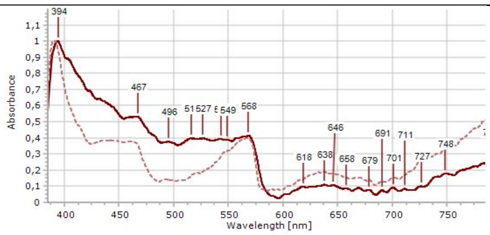
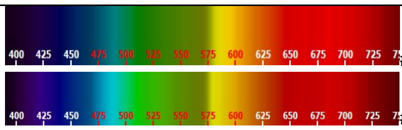
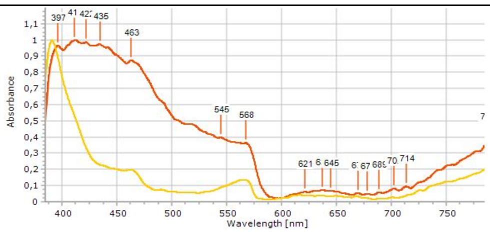
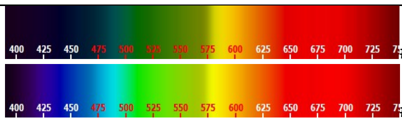
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]

Gemstone pictures created by Uwe G. B. Hollenbach

Appendix 9.2: Absorption spectrums of Tourmaline gemstones

 **Tsilaisite #57**		Tourmaline; a) Dravite, weak brownish and b) Tsilaisite, amber color activation by Mn^{2+}-Ti^{4+} (IVCT) [11]; characteristic absorption measured at 395,461,563 and above 625 nm (only #58)
 **Dravite #58**		Tourmaline #58 Dravite weak brownish unpol Tourmaline #57 Tsilaisite amber unpol
Appendix 9.2: Table 1. Absorption spectrums of different colored Tourmaline gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

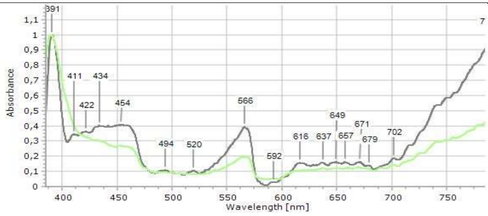
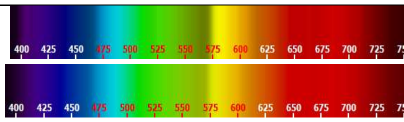
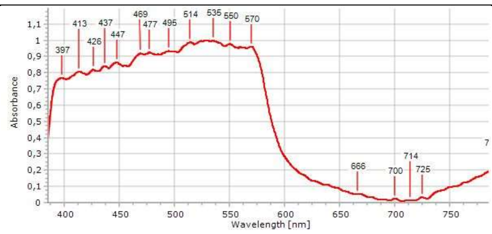
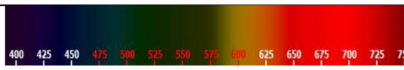
Appendix 10.1: Absorption spectrums of Quartz gemstones

 **Amethyst #71**		Quartz; Amethyst, violet color activation by Fe^{3+} [1] and natural exposer of γ-radiation; characteristic absorption measured at 380-425,448,463 nm and 500-650 (#71) other 380-410,525-575, weakly around 615 (#74 and #187) and all weakly around 700 nm
 **Amethyst #187**	 #71 #74 #187	Quartz #71 Amethyst dark violet unpol Quartz #74 Amethyst bright violet unpol Quartz #187 Amethyst violet unpol
 **Smoky quartz #122**		Quartz; Smoky Quartz color activation by radiation-induced color center pairs of Fe^{2+}-Fe^{4+} (because Fe^{3+} substitutes Si^{4+} [11]); or γ-radiation influences trace elements of Al and Li [20]; characteristic absorption measured at 380-575, around 630 and above 700 nm (#122) and 380-475, around 568 and above 700 nm (#200)
 **Smoky quartz #200**	 #200 #122	Quartz #200 Smoky quartz dark smoky unpol Quartz #122 Smoky quartz pale smoky unpol
 **Quartz #110**		Quartz; Citrine, orange-brown and bright golden color activation by heat treatment of a) Amethyst --> yellow at 470 – 560 °C b) some Smoky quartz --> yellow 200°C [11] characteristic absorption measured at 380-580, and above 700 nm (#110) 380-425, weakly at 463,570 and above 700 nm (#113)
 **Quartz #113**	 #110 #113	Quartz #110 Citrine orange brown unpol Quartz #113 Citrine bright golden unpol

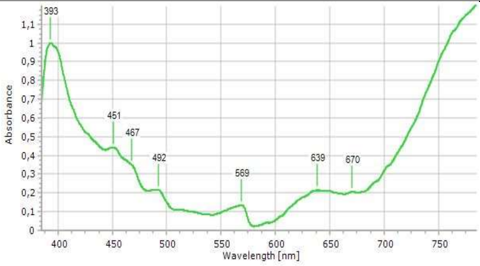
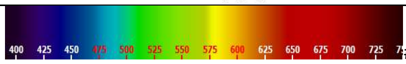
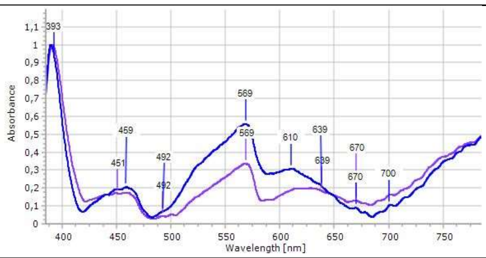
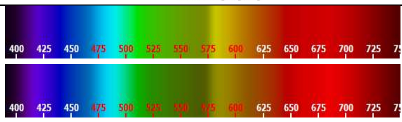
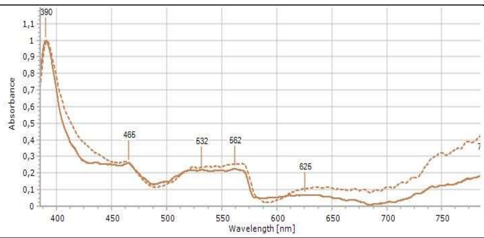
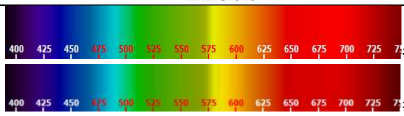
Appendix 10.1: Table 1. Absorption spectrums of different colored Quartz gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

Appendix 10.2: Absorption spectrums of Opal gemstones

 **Quartz #101**		Quartz, color less color activation can influenced by a) trace elements of Al, Li, Na, K, Sb, Ti [1] and b) H-atoms can substitute Si and c) also Fe, Mg was absorbed [20]; Quartz #128; Prasolite pale greenish color activation by Fe^{2+} [1]; characteristic absorption measured at 391, around 430, weakly at 494,520,550-575 around 630 and above 700 nm
	 #101 #128	Quartz #101 Rock crystal color less unpol Quartz #128 Prasiolite pale greenish unpol
 **Fire Opal #129**		Opal; Fire Opal, orange-red color activation by Fe^{3+} which are from nano crystalline Hematite domains [11]; characteristic absorption measured at 480-600 nm
	 #129	Opal #129 Fire opal orange-red unpol
Appendix 10.2: Table 1. Absorption spectrums of different colored Opal gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

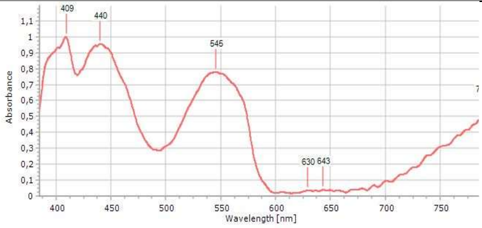
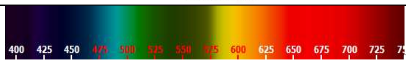
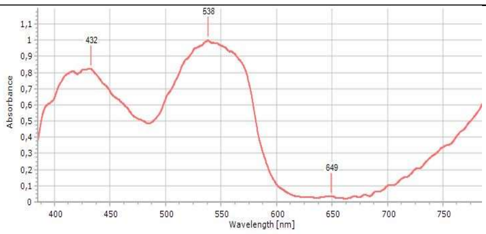
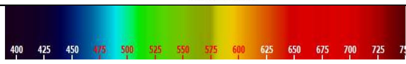
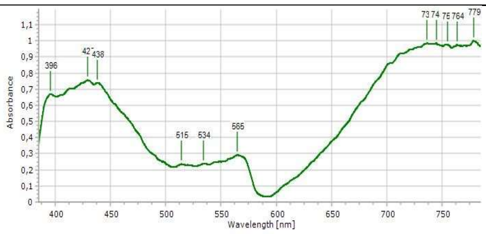
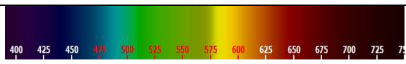
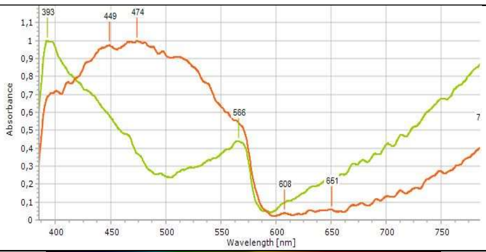
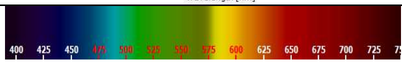
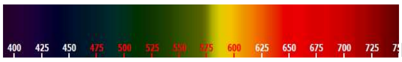
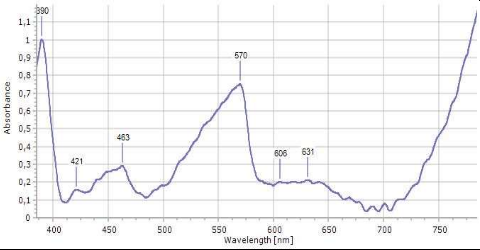
Appendix 11: Absorption spectrums of Peridot & Zoisite gemstones

 **Olivine #130**		Peridot; Olivine, greenish color activation by Fe^{2+} [11]; characteristic absorption measured at 380-475 nm and peaks at 393,451,467,492,599, 639 and above 700 nm
	 #130	Peridot #130 Olivine greenish unpol
 **Tanzanite #133**		Zoisite; Tanzanite, violet-blue color activation by V^{2+} [11] and by natural influence of temperature environment about 600 °C [11] characteristic absorption measured at 393, around 459, 525-575, 610 and above 700 nm
	 #132 #133	Zoisite #132 Tanzanite violet-blue unpol Zoisite #133 Tanzanite violet-blue unpol
 **Tanzanite #165**		Zoisite; Tanzanite, brownish color activation by V^{2+} [11]; characteristic absorption measured at 390,465 nm and weakly 500-575 nm around 625 and above 700 nm
	 #165 #166	Zoisite #165 Tanzanite brownish unpol Zoisite #166 Tanzanite brownish unpol

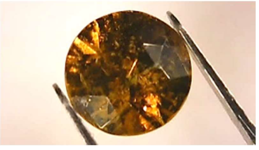
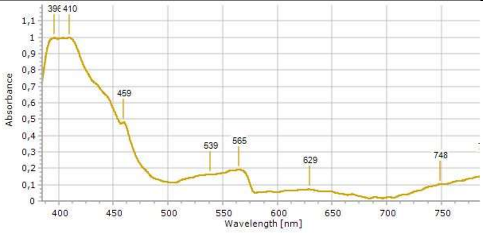
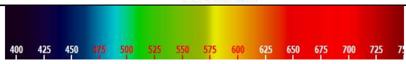
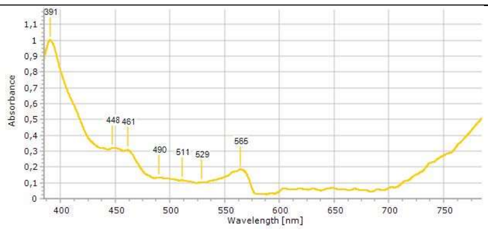
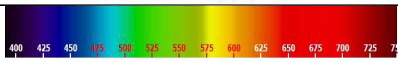
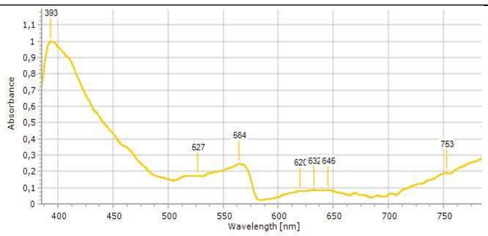
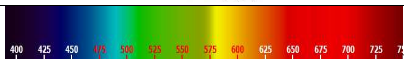
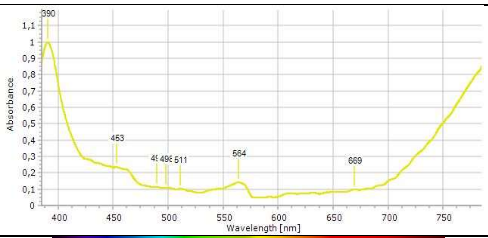
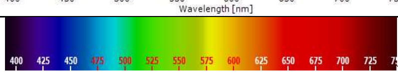
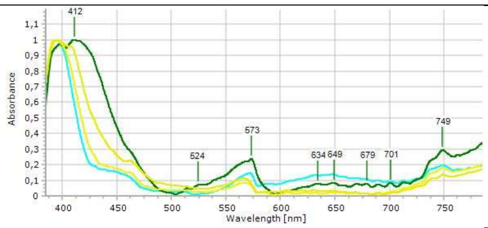
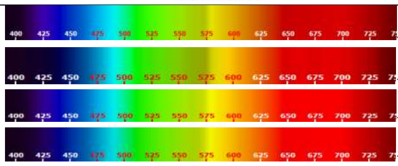
Appendix 11: Table 1. Absorption spectrums of different colored Zoisite gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

Appendix 12.1: Absorption spectrums of rare gemstones

		Rhodochrosite, pink-red color activation by Mn^{2+} [11]; characteristic absorption measured at 380-410,410-475,520-575, with peaks at 409,440,545 and above 700 nm
Rhodochrosite #190		Rhodochrosite #190 pink-red unpol
 **Rhodonite #173**		Rhodonite, pink-red color activation by Mn^{2+} [11]; characteristic absorption measured at 380-425,500-575, with peaks at 432,538 and above 700 nm
		Rhodonite #173 pink-red unpol
 **Moldavite #131**		Moldavite, green color activation by Fe and Mn [24];[25] characteristic absorption measured at 380-475, with peaks at 396,425,438,565 nm and above 600 nm
		Moldavite #131 green unpol
		Andalusite, green-orange-brown green color activation by Mn^{3+} [11]; orange color activation by Fe^{2+} - Ti^{4+} (IVCT) [11]; characteristic absorption measured by 1) green color: at 393,566 nm and above 600 nm 2) orange color: from 385-575 nm and above 600 nm;
Andalusite #134		Andalusite #134 green cross-axis unpol Andalusite #134 orange long axis unpol
 **Cordierite #137**		Cordierite, gray-blue color activation by Fe^{2+} - Fe^{3+} (IVCT) [11]; characteristic absorption measured at 390,421,463,525-575 nm with a peak at 570 nm and weakly around 631 nm and above 700 nm;
		Cordierite #137 gray-blue unpol
Appendix 12.1: Table 1. Absorption spectrums of different colored rare gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		

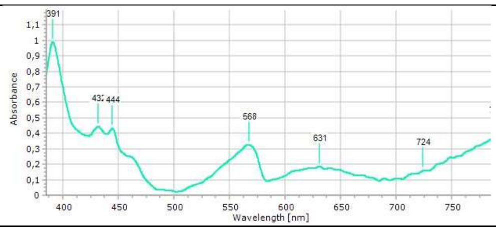
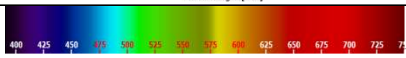
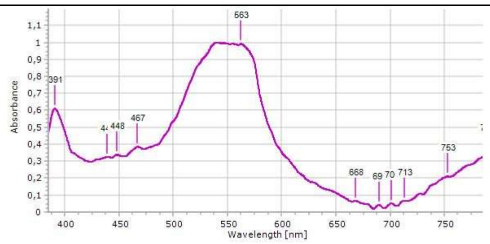
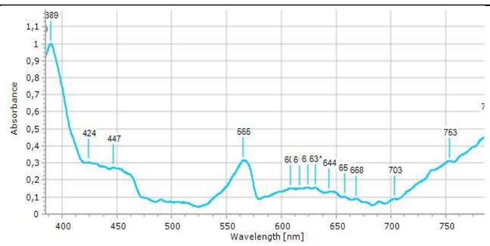
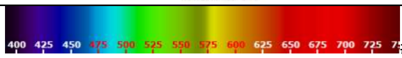
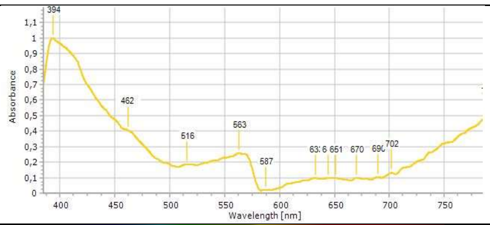
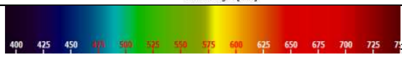
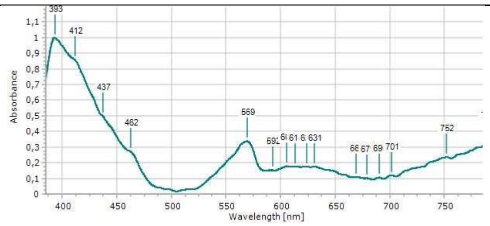
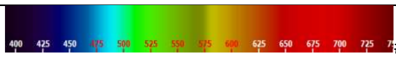
Appendix 12.2: Absorption spectrums of rare gemstones

 **Vesuvianite #138**		Vesuvianite, amber color activation by Fe^{3+} [11]; characteristic absorption measured from 380-450 nm, and peaks at 396,410,459,565 nm and weakly around 629 nm;
	 #138	Vesuvianite #138 amber unpol
 **Sinhalite #139**		Sinhalite, bright yellow color activation by Fe^{2+} [11]; characteristic absorption measured at 391,448,461,565 nm and above 700 nm;
	 #139	Sinhalite #139 bright yellow unpol
 **Scapolite #140**		Scapolite, amber color activation by Fe^{3+} [1]; characteristic absorption measured at 393,527,564 nm and weakly around 632 nm and above 700 nm;
	 #140	Scapolite #140 amber unpol
 **Brasilianite #141**		Brasilianite, greenish-yellow color activation by Fe^{2+} [assumed]; characteristic absorption measured at 393,453,564 nm and weakly around 632 nm and above 700 nm;
	 #141	Brasilianite #141 greenish-yellow unpol
 **Apatite #142**		Apatite, blueish and green, pale yellowish and yellow color activation mostly by Nd and Pr [11] characteristic absorption measured at 400,412,524,573 and 749 nm and weakly around 649 nm;
 **Apatite #145**	 #142 #143 #144 #145	Apatite #142 blueish unpol Apatite #143 green unpol Apatite #144 pale yelloish unpol Apatite #145 yellow unpol

Appendix 12.2: Table 1. Absorption spectrums of different colored rare gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach

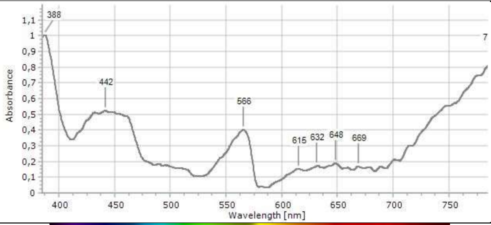
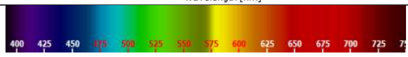
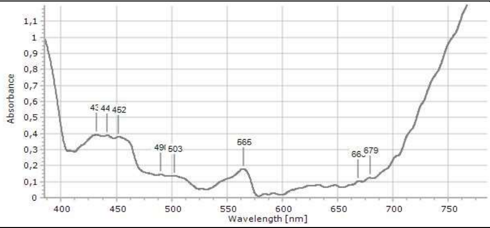
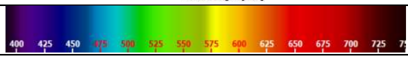
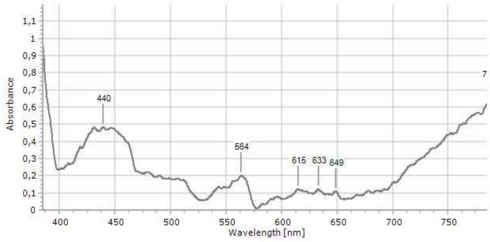
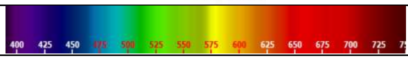
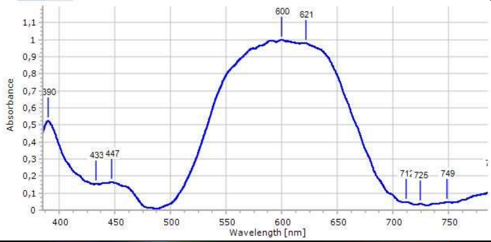
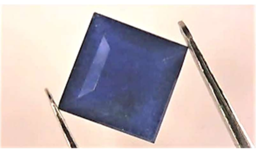
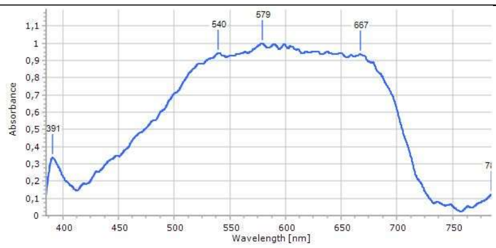
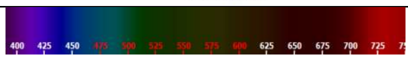
Appendix 12.3: Absorption spectrums of rare gemstones

 **Cyanite #146**		Cyanite, blueish-green orange color activation by Fe^{2+} - Ti^{4+} (IVCT) and Cr^{3+} [9] characteristic absorption measured at 391,432,444,568 nm and weakly around 631 nm and 724 nm;
	 #146	Cyanite #146 blueish unpol
 Fluorite #147		Fluorite, streaky violet color activation by colloidal Ca [11]; characteristic absorption measured at 391,448,467,500-575 nm and weakly around 700 nm (wide band around 850 nm);
	 #147	Fluorite #147 streaky violet unpol
 Fluorite #148		Fluorite, pale blueish color activation by Fe^{2+} and Fe^{3+} complex with Cu and colloidal Ca [1]; characteristic absorption measured at 389,424,447,566 nm and weakly around 625 nm and above 700 nm (wide band around 850 nm);
	 #148	Fluorite #148 pale blueish unpol
 Fluorite #149		Fluorite streaky yellowish color activation by Fe and rare earths elements Eu^{2+}, O_3 and isomorph chlorine additives [1]; characteristic absorption measured at 394,462,516,563 nm and weakly around 650 nm and above 700 nm (wide band around 850 nm);
	 #149	Fluorite #149 yellowish unpol
 Fluorite #150		Fluorite, green color activation by colloidal Ca, Fe^{2+} plus (Mn,Cr,Ni or Cu), Sm^{2+},Sm^{3+} [1]; characteristic absorption measured at 393,437,462,569 nm and weakly around 625 nm and above 700 nm (wide band around 900 nm);
	 #150	Fluorite #150 green unpol

Appendix 12.3: Table 1. Absorption spectrums of different colored rare gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

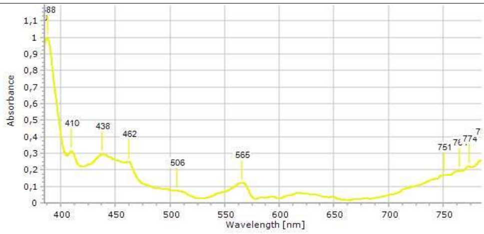
Appendix 12.4: Absorption spectrums of rare gemstones

 **Cerusite #152**		Cerusite, color less characteristic absorption measured at 388 nm around 442,566 nm and weakly around 650 nm and above 700 nm (wide band around 850 nm); Abs. data ~5x magnified
		— Cerusite #152 color less unpol
 **Amblygonite #153**		Amblygonite, color less characteristic absorption measured around 440,566 nm and weakly around 650 nm and above 700 nm (wide band around 825 nm); Abs. data ~5x magnified
		— Amblygonite #153 color less unpol
 **Sanidine #154**		Sanidine, color less characteristic absorption measured around 440 and weakly around 566 nm and 650 nm and above 700 nm (wide band around 900 nm); Abs. data ~5x magnified
		— Sanidine #154 color less unpol
 **Hauynite #155**		Sodalite Group; Hauynite, dark blue color activation by sulfide ions S^{2-} [1],[11] characteristic absorption measured at 390 nm and around 450 and a wide band 525-675 nm centered around 600 nm
		— Hauynite #155 dark blue unpol
 **Sodalite #157**		Sodalite, dark blue color activation by sulfide ions S^{2-} [1],[11] characteristic absorption measured at 391 nm and a wide band 475-725 centered around 600 nm
		— Sodalite #157 blue opaque unpol

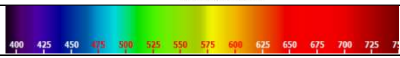
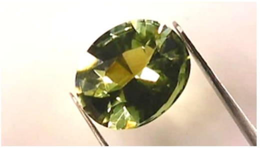
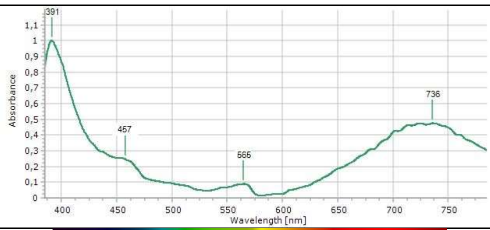
Appendix 12.4: Table 1. Absorption spectrums of different colored rare gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

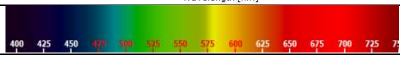
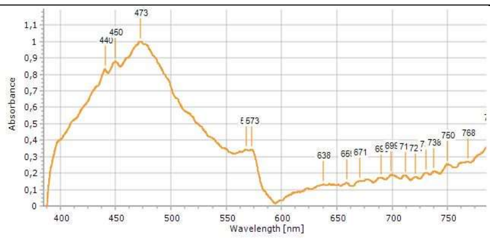
Appendix 12.5: Absorption spectrums of rare gemstones

<table>
<tr><td>
Sillimanite #156</td><td></td><td>Sillimanite, pale yellowish

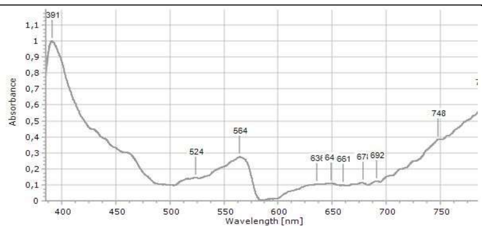
color activation by Uranyl ions $(UO_2)^{2+}$ [1]

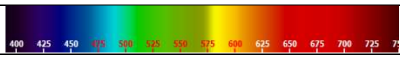
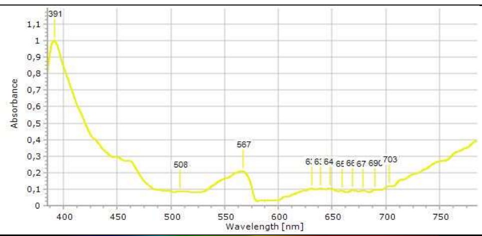
characteristic absorption measured at 388,410 nm and around 450 and weak around 565 nm and above 700 nm</td></tr>
<tr><td></td><td></td><td>Sillimanite #156 pale yellowish unpol</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>
Titanite #159</td><td></td><td>Titanite, yellow-green

color activation by Fe and Cr [11] or rare earths like Ti^{3+}, Sm^{3+}, Eu^{3+}, Nd^{3+} [1]

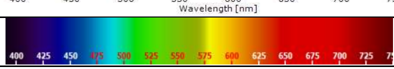
characteristic absorption measured at 391 and weakly at 457 and 565 nm and around 730 nm</td></tr>
<tr><td></td><td></td><td>Titanite #159 yellow-green unpol</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>
Titanite #158</td><td></td><td>Titanite, yellow-green

color activation by Fe and Cr [11] or rare earths like Ti^{3+}, Sm^{3+}, Eu^{3+}, Nd^{3+} [1]

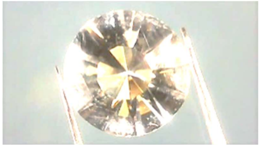
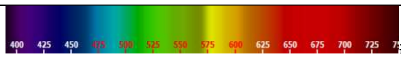
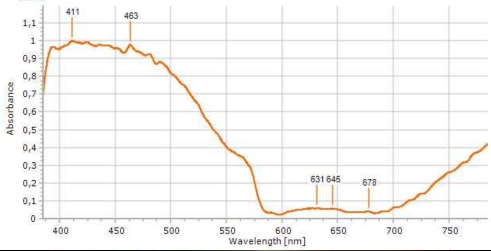
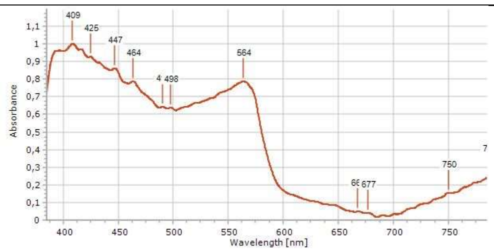
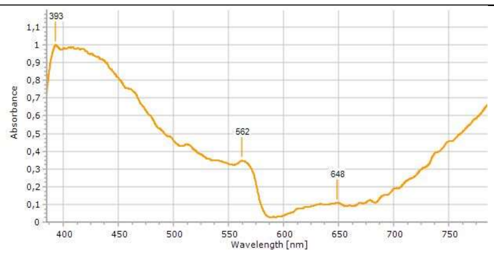
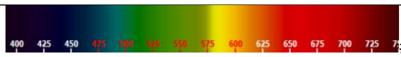
characteristic absorption measured wide band 400-525 with peaks at 440,450,473 and 573 nm and weakly above 600 nm</td></tr>
<tr><td></td><td></td><td>Titanite #158 red-brown unpol S1 0_5P_01</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>
Impact Glass #160</td><td></td><td>Impact Glass, color les

characteristic absorption measured at 391 and weakly at 524 and 564 nm and around 650 nm and around 850 nm</td></tr>
<tr><td></td><td></td><td>Impact Glass #160 color less unpol</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>
Danburite #161</td><td></td><td>Danburite, color less – pale yellowish

color activation by rare earths [11]

characteristic absorption measured at 391 nm and weakly at 506 and 567 nm and around 650 nm and above 700 nm</td></tr>
<tr><td></td><td></td><td>Danburite #161 color pale yellowish unpol</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">**Appendix 12.5: Table 1. Absorption spectrums of different colored rare gemstones**</td></tr>
<tr><td colspan="3">Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach</td></tr>
</table>

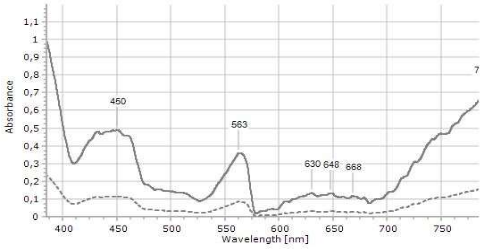
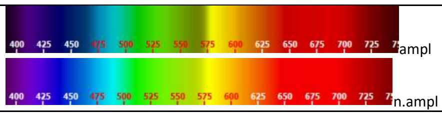
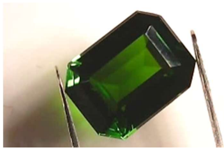
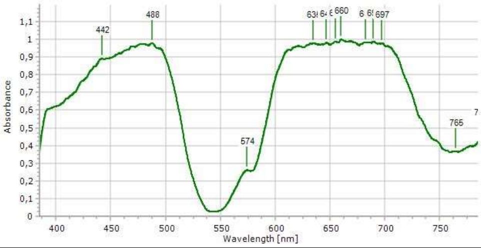
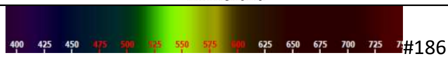
Appendix 12.6: Absorption spectrums of rare gemstones

 **Danburite #162**		Danburite, color less color activation by rare earths [11] characteristic absorption measured around 440,500 and 566 nm and weak around 650 nm and above 700 nm Abs. data ~5x magnified
	 #162	— Danburite #162 color less unpol
 **Clinohumite #163**		Clinohumite, amber color activation by Mn^{2+} [1] characteristic absorption measured at 385-575 nm and weakly around 630 nm and around 825 nm
	 #163	— Clinohumite #163 amber unpol
 **Andesinite #164**		Andesinite, red-brown color activation probably by Mn and Fe characteristic absorption measured at 400-575 nm and above 700 nm
	 #164	— Andesinite #164 red-brown unpol
 **Chondrodite (Brucite) #167**		Chondrodite (Brucite), orange color activation by Mn and Fe [11] characteristic absorption measured at 400-500 and at 562 nm and weakly around 648 nm and above 700 nm
	 #167	— Chondrodite #167 orange unpol

Appendix 12.6: Table 1. Absorption spectrums of different colored rare gemstones

Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3]
Gemstone pictures created by Uwe G. B. Hollenbach

Appendix 12.7: Absorption spectrums of rare gemstones

 **Petalite #175**		Petalite, color less characteristic absorption measured at 400-475 and at 563 nm and around 650 nm and above 700 nm comparison between low absorption spectral data with the contrast improved and magnified Abs. data about 5-times magnification;
		— Petalite #175 color less unpol amplified -- Petalite #175 color less unpol not amplified above: color bar with contrast amplification Below: without contrast amplification
 **Diopside #186**		Diopside, green color activation by Cr^{3+} and Mn^{2+} [11] characteristic absorption measured strong from 400-525 and 575-725 nm
		— Diopside #186 green unpol
Appendix 12.7: Table 1. Absorption spectrums of different colored rare gemstones		
Spectral absorption line graphs and spectral color bars are processed by Spectragryph [Ref. 3] Gemstone pictures created by Uwe G. B. Hollenbach		