

COLOR VARIATIONS AND PROPERTIES OF JOHACHIDOLITE FROM MYANMAR

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To learn more about the rare gem material johachidolite, the authors used various analytical techniques to study 15 faceted samples from Myanmar that showed a range of colors: saturated orange, orange, yellow, desaturated yellow, and desaturated green. Both orange/yellow-hued and green samples showed trends for beryllium and the radioactive/radiogenic elements uranium, thorium, and lead. Orange/yellow samples also showed relatively constant rare-earth element (REE) concentrations, but the green samples had higher REE values, especially for the lighter elements.

Johachidolite— CaAlB_3O_7 —is a rare borate mineral named after the Johachido district, North Korea, which is its type locality. Investigations of the Korean material (grains up to 1 mm) showed that it was transparent and colorless or semitransparent and white (see, e.g., Iwase and Saito, 1942; Aristarain and Erd, 1977). In 1998, Harding et al. reported on a relatively large (14.02 ct) pale yellow faceted specimen from Myanmar. The large size of that stone led to speculation that it could potentially be synthetic; however, a lack of information regarding synthesis of Ca-Al borates resulted in the conclusion that the specimen was probably natural. Kawano and Abduriyim (2007) published a compositional analysis of a bicolored rough sample, and showed that elemental concentrations in the two portions were different. Also in 2007, Peretti et al.

published a comprehensive report on johachidolite based on over 500 faceted specimens and 200 rough samples. The purpose of the current article is to present further data and observations on this rare gem material, and offer some new conclusions.

Materials and Methods. In late 2007 and early 2008, Mark Kaufman loaned GIA 14 faceted johachidolites from Myanmar that ranged from 0.11 to 0.95 ct and varied from saturated orange to desaturated green (e.g., figure 1). Two of these specimens exhibited distinct color zoning—orange and desaturated yellow (e.g., figure 1, inset). We also had the opportunity to examine a 0.16 ct faceted stone that was sent to GIA's Carlsbad laboratory for an Identification Report.

Standard gemological testing was conducted on all 15 stones. We also performed energy-dispersive X-ray fluorescence (EDXRF) spectroscopy using a Thermo ARL Quant'X instrument (15 samples), Raman spectroscopy with a Renishaw InVia Raman system (514 nm laser excitation, 2000–100 cm^{-1} scan range, at room temperature; eight samples), and ultraviolet-visible–near infrared (UV-Vis-NIR) absorption spectroscopy using a PerkinElmer Lambda 950 UV/Vis Spectrometer (250–1000 nm scan range; four samples, approximately oriented to alpha and gamma directions using RI values from the table of each stone). Laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) data were gathered for all 14 of the samples loaned to GIA using a Thermo X-Series II ICP-MS attached to a New Wave 213 nm laser ablation system (~10 J/cm² fluence, 40 μm spot, 7 Hz repetition rate, 1.0 liter/min He carrier gas flow rate that mixes with Ar before entering the ICP, and NIST reference standards). One or two random locations on the girdle were sampled by LA-ICP-MS for 12 of the stones, while the two strongly color-zoned stones were each sampled in both the lighter and darker regions. Specimens were separated into five color categories (saturated orange, orange, yellow, desaturated yellow, and desaturated green) for data comparison.

Results and Discussion. Examination of the original 14 stones loaned by Mr. Kaufman showed gemological properties (table 1) that were consistent in RI ($n_\alpha=1.717\text{--}1.718$, $n_\gamma=1.724\text{--}1.725$) and birefringence (0.006–0.008), but

See end of article for About the Authors and Acknowledgments.

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Editor's note: Consistent with its mission, GIA has a vital role in conducting research, characterizing gemstones, and gaining knowledge that leads to the determination of gemstone origins. The gemstones studied in this article are not subject to the 2008 Burmese JADE Act, and their import was in accordance with U.S. law.



Figure 1. These seven johachidolites (0.19–0.95 ct) illustrate the range of colors in the samples from Myanmar examined for this study. From left to right, the samples are J15, J04, J01, J12, J02, J13, and J10. Two of the johachidolites analyzed in this study were distinctly color zoned, as shown in the inset (specimen J14, 0.21 ct). The apparent orange zone on the left side of the stone is actually a reflection of the color from the right side. Courtesy of Mark Kaufman; photos by C. D. Mengason and Robert Weldon (inset).

revealed a range in color, pleochroism, and intensity of fluorescence to long- and short-wave UV radiation. The long-wave fluorescence, in particular, showed a strong correlation with color category (see table 1): The orange samples were generally inert, the yellow specimens had weak-to-moderate blue reactions, and the green samples fluoresced strong blue. Our fluorescence observations were generally consistent with those of Peretti et al. (2007). Hydrostatic SG varied (3.23–3.67; mean = 3.46), but the values were reasonably uniform given the small size of some samples. Data collected for the stone sent in for the Identification Report (sample J06 in table 1) were similar to those from the other 14 samples. Characteristics for all 15 specimens were generally comparable with those reported by Peretti et al. (2007)— $n_\alpha = 1.716\text{--}1.717$, $n_\gamma = 1.725\text{--}1.728$, birefringence = 0.008–0.012, SG = 3.44—although they did not note any pleochroism in their samples. Microscopic examination revealed “fingerprints,” clouds of tiny inclusions, and fractures/cavities.

The Raman spectra were consistent with the published results of Harding et al. (1998) and Peretti et al. (2007). All of our Raman spectra contained the seven peaks specifically cited by Harding et al., but with the 684 cm^{-1} feature sometimes only occurring as a shoulder, rather than a defined peak. Similarly, our spectra showed the strongest Raman scattering in the direction perpendicular to the table (as opposed to perpendicular to the girdle); consequently, we observed the peaks at 1191 and 1112 cm^{-1} (the former most often as a shoulder) referenced by Peretti et al. in all of our table analyses, but not in most of our girdle analyses.

EDXRF analysis identified the presence of the following elements: Al, Ca (in major amounts), Fe (minor), Cu, Zn, Ga, Sr, and U (trace). Six of the 15 samples analyzed contained dramatically elevated levels of Th (J08–J13), two showed minor/trace levels (J14, J15), and the remaining seven had none. These results for Th, as well as for the other trace elements detected by EDXRF, later proved to be consistent with the data from LA-ICP-MS measurements.

Our LA-ICP-MS data showed some interesting results for elemental concentration versus color (again, see table 1).

For some elements, chemical composition was variable and the data did not show any significant trends. However, the concentration of Be clearly decreased from the saturated orange samples through the desaturated yellow ones (figure 2; note that the color-zoned samples are not included), but the green samples did not show any appreciable trend for Be. Pb, Th, and U all showed a different trend—higher concentrations in the desaturated green and desaturated yellow samples relative to the saturated orange, orange, and yellow samples (figure 3; note that U is not shown, merely for brevity).

A representative subset of the REEs (La through Dy in table 1) all exhibited relatively little variation in the orange- and yellow-hued samples, but elevated levels in the green samples (figure 4; note that just La and Sm are

Figure 2. Be concentration decreased from the saturated orange to the desaturated yellow johachidolite samples.

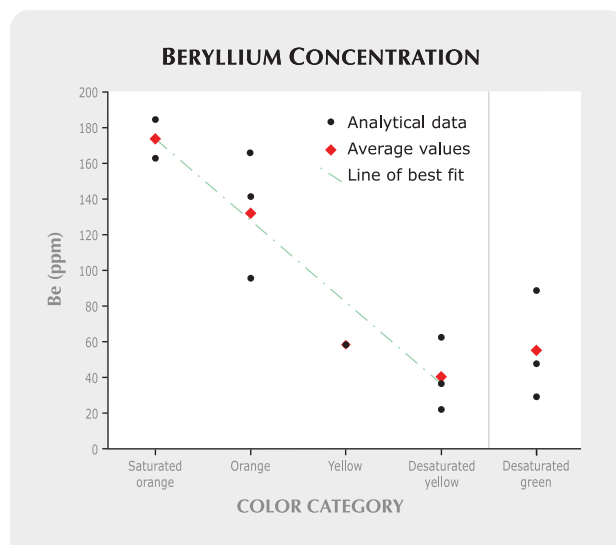


TABLE 1. Gemological properties and trace-element composition of 15 johachidolite samples in five color categories, including two bicolored stones.

Property	Saturated orange			Orange			Yellow
	J01	J02	J03	J04	J05	J06	J07
Weight (ct)	0.21	0.59	0.11	0.19	0.22	0.16	0.17
Color	Medium to medium dark yellowish orange	Medium dark yellowish orange	Medium yellowish orange	Medium orange-yellow	Medium orange-yellow	Medium orange-yellow	Medium light orangy yellow
Color zoning	None	None	None	None	None	None	Minor
Pleochroism	Moderate orange/yellow	Moderate orange/yellow	Moderate orange/yellow	Weak orange/yellow	Moderate orange/yellow	None	Weak orange/yellow
RI							
n_{α}	1.717	1.717	1.717	1.717	1.717	1.718	1.718
n_{γ}	1.725	1.725	1.724	1.725	1.725	1.726	1.725
Birefringence	0.008	0.008	0.007	0.008	0.008	0.008	0.007
SG	3.49	3.46	3.26	3.53	3.56	3.47	3.40
UV fluorescence							
Long-wave	Inert	Inert	Inert	Very weak blue	Inert	Inert	Weak blue
Short-wave	Inert	Inert	Inert	Inert	Inert	Inert	Inert
Trace elements (ppm) ^a							
Be	162.7	184.3	141.2	158.6	95.5	na	58.3
Na	40.2	72.5	78.3	31.9	73.4	na	62.4
Mg	366.5	134.5	50.8	298.8	202.8	na	146.8
Si	533.0	231.2	254.7	327.0	199.6	na	222.2
Ti	3.3	bdl	1.7	5.2	1.5	na	2.7
V	3.1	1.8	0.5	2.0	4.6	na	5.7
Cr	5.1	bdl	1.6	0.3	0.5	na	1.3
Fe	289.1	110.7	86.9	214.3	124.1	na	94.0
Zn	6.8	8.9	0.6	6.8	bdl	na	0.6
Ga	68.0	58.8	23.2	61.7	45.3	na	33.7
Y	2.5	1.1	0.8	1.4	2.2	na	0.7
La	7.6	3.1	1.8	8.7	5.6	na	4.6
Ce	17.9	6.2	3.5	15.6	11.3	na	14.8
Pr	1.9	0.7	bdl	1.5	1.4	na	1.7
Nd	5.0	3.4	1.1	5.2	4.8	na	6.7
Sm	0.6	0.6	bdl	1.1	1.1	na	1.8
Gd	0.7	0.3	bdl	1.0	0.9	na	0.8
Dy	bdl	0.3	bdl	bdl	0.5	na	bdl
Pb	1.0	1.0	0.8	1.8	1.0	na	1.5
Th	20.3	2.4	11.9	9.9	12.7	na	3.7
U	1.8	bdl	0.6	0.9	0.9	na	0.6

^aChemical data were collected by LA-ICP-MS using NIST glass references and represent one spot per sample or the average of two spots per sample. Shaded elements show systematic variations between some color categories. Abbreviations: bdl = below detection limit; na = not analyzed.

shown, again for brevity). Further, when the average rare-earth-element concentration for the green samples was ratioed to the average value for all the orange- and yellow-hued samples, the results (figure 5) clearly indicated an enrichment of the lightest REEs in the green material. Peretti et al. (2007) proposed four different types or generations of johachidolite—based in part on differences in amounts of light and heavy REEs—that varied from light green and light yellow (type 1) to vivid yellow through vivid orange (type 4).

The two distinctly zoned samples (J14 and J15; table 1) showed results consistent with the above observations for the orange and desaturated yellow stones. One of the specimens exhibited a bicolored response to long-wave UV radiation: The desaturated yellow area fluoresced moderate blue, while the orange region was inert; this is in agreement with the fluorescence trend noted for the unzoned samples in those two hues. For both zoned stones, the Be concentration was higher in the orange areas, as opposed to the desaturated yellow areas, while the radioactive elements (i.e., U and Th)

Desaturated yellow			Desaturated green			Orange	Desaturated yellow	Orange	Desaturated yellow
J08	J09	J10	J11	J12	J13	J14		J15	
0.12	0.23	0.95	0.20	0.24	0.60	0.21		0.25	
Extremely light yellow-orange	Extremely light yellow-orange	Light yellow	Extremely light green	Very light yellowish green	Very light yellowish green	Medium orange-yellow	Light yellow-orange	Light-to-medium orange-yellow	Light yellow-orange
None	None	None	None	Minor	None	Distinct		Distinct	
None	None	None	None	None	None	None		None	
1.718	1.718	1.717	1.718	1.718	1.718	1.717		1.717	
1.725	1.724	1.725	1.725	1.725	1.725	1.725		1.725	
0.007	0.006	0.008	0.007	0.007	0.007	0.008		0.008	
3.23	3.43	3.42	3.67	3.60	3.46	3.45		3.44	
Moderate blue	Moderate blue	Moderate blue	Strong blue	Strong blue	Strong blue	Inert	Moderate blue	Weak blue	Weak blue
Inert	Inert	Very weak blue/yellow	Weak blue	Weak blue/yellow	Weak blue/yellow	Inert	Inert	Inert	Inert
36.5	22.0	62.4	29.1	88.6	47.6	109.6	23.5	157.9	46.3
63.8	113.3	31.8	73.3	88.5	25.8	61.6	34.5	19.8	96.1
140.8	103.4	197.0	246.5	603.7	266.6	162.5	54.4	296.9	138.1
255.9	88.4	586.6	212.4	517.0	504.7	242.3	208.9	bdl	139.7
6.1	2.3	bdl	4.0	15.8	2.1	0.6	11.8	bdl	6.0
1.3	3.6	5.9	6.6	5.7	6.9	3.0	3.0	8.1	9.1
1.0	bdl	5.8	0.5	1.6	3.8	0.7	bdl	bdl	bdl
152.7	121.3	273.8	114.9	312.6	240.5	110.3	95.6	57.9	156.9
bdl	0.6	4.9	0.6	5.8	5.4	bdl	bdl	3.0	1.8
59.6	46.8	75.5	45.2	86.3	66.2	40.0	39.1	75.7	85.9
9.1	1.2	4.0	4.3	9.6	4.1	bdl	1.7	1.3	8.1
9.3	3.6	5.5	69.8	19.9	12.3	2.9	6.1	5.2	14.1
17.0	8.0	13.6	131.9	39.6	28.9	6.0	11.6	10.8	25.4
1.5	0.9	1.7	9.6	3.2	3.8	0.6	1.1	1.5	3.2
5.5	3.9	6.2	25.2	10.1	13.0	2.0	3.8	6.7	12.9
1.7	1.4	1.9	5.4	3.4	3.2	bdl	0.7	1.7	3.9
1.6	1.0	1.4	2.8	2.1	2.1	bdl	0.5	1.0	3.9
2.0	bdl	1.1	1.5	2.9	1.4	bdl	bdl	0.8	2.4
2.2	2.2	3.1	4.2	7.4	3.2	bdl	1.0	0.5	2.0
702.3	679.5	1050	1259	3718	1682	2.7	156.7	5.9	488.7
101.5	7.8	28.1	28.2	50.6	31.2	0.7	60.5	1.0	109.0

were less abundant in the orange parts. In addition, the REE concentrations were slightly lower in the orange regions.

Approximately oriented UV-Vis-NIR spectroscopy was performed on four samples from various color categories (orange, yellow, desaturated yellow, and desaturated green); the resultant spectra showed some notable differences in the UV-Vis wavelengths (figure 6). In the visible region, not surprisingly, the transmission windows correlated to sample color. The UV region, however, contained two distinct features: a broad shoulder at ~330–340 nm

(visible only in the spectra for the gamma direction; not shown in figure 6) and, more obviously, a peak at ~375 nm. This peak was strongest in the spectrum of the desaturated green specimen, was smaller through desaturated yellow and yellow, and was absent from the spectrum of the orange sample. While this peak has been reported previously in the literature, its cause is unknown. We noted, however, good correlation between the thorium concentrations and this ~375 nm feature in the UV-Vis spectra; there were greatly elevated Th values in the desaturated

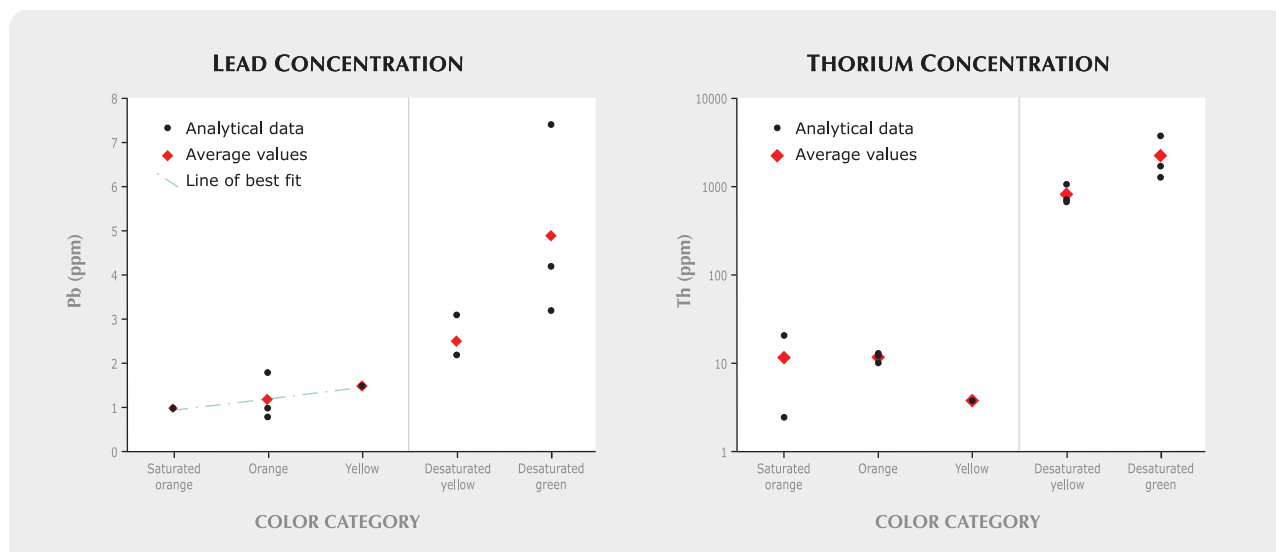


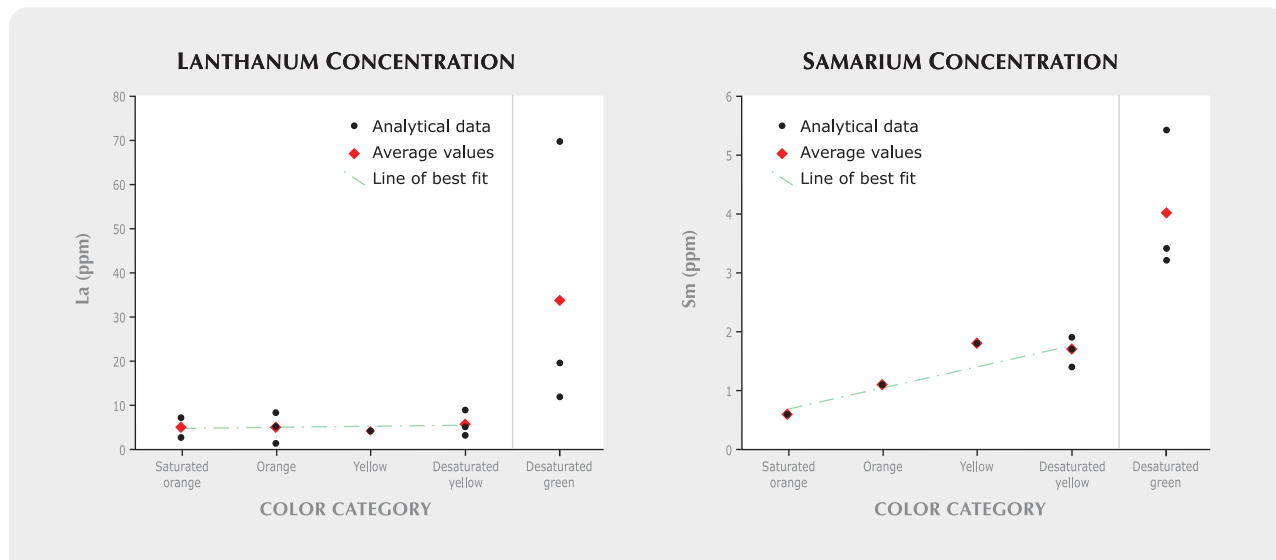
Figure 3. The concentrations of Pb (left) and Th (right; note logarithmic scale) are plotted for johachidolite samples from the various color categories. The desaturated green and desaturated yellow categories show higher concentrations than the others.

green and desaturated yellow samples and much lower Th concentrations in the orange and in most of the yellow stones. Thus, we hypothesize that Th may play an important role in the coloration of johachidolite. More work will be needed to test this observation; other authors have not found a similar correlation between Th and color (Peretti et al., 2007).

The observed trends in our data are in agreement with the results of Kawano and Abduriyim (2007), who performed LA-ICP-MS analysis on a color-zoned rough sam-

ple from Myanmar, and with those of Peretti et al. (2007), who performed LA-ICP-MS analyses on multiple samples, including a color-zoned one. Both studies noted higher concentrations of Be in the more saturated (yellow/yellow-orange) part of the rough compared to the colorless part, and correspondingly lower concentrations of Th and U. Kawano and Abduriyim also found higher concentrations of the REEs in the colorless portion; while our analyses generally detected similar levels for the REEs in the saturated orange through desaturated yellow samples, the

Figure 4. The concentrations of rare-earth elements were fairly constant in all johachidolite colors except for the desaturated green samples, which contained higher levels of these elements. Plotted here are the values for La (left) and Sm (right).



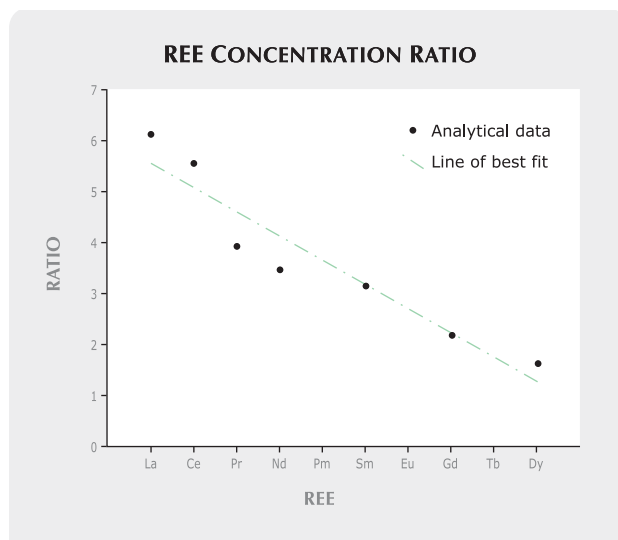


Figure 5. The ratios of average concentrations of REEs in the green samples to those of the orange- and yellow-hued samples show a systematic decrease from the light to the heavy elements. This reflects enrichment of light REEs in the desaturated green material. (Note that data for the rare-earth elements Pm, Eu, and Tb were not included in the analyses.)

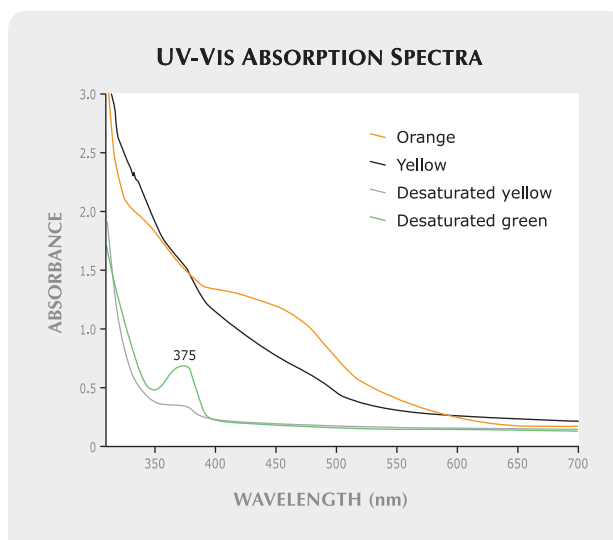


Figure 6. Approximately oriented (α direction) UV-Vis spectra for four of the samples—representative of four of the color categories (orange [J03], yellow [J07], desaturated yellow [J09], and desaturated green [J11])—showed different characteristics. The spectrum for the desaturated green sample has a particularly prominent peak at ~ 375 nm.

desaturated green samples showed clearly elevated concentrations. Also, in our analyses Th showed the greatest variation in concentration from saturated orange (average ~ 11 ppm) to desaturated green (average ~ 2220 ppm); similarly, Kawano and Abduriyim (2007) reported Th concentrations ranging from 30 ppm in the yellow part of their zoned sample to 1590 ppm in the colorless part.

Conclusions. In a study of faceted johachidolites from Myanmar, we found trends in UV fluorescence versus color—with the strongest reaction for the green samples—as well as in trace-element concentrations versus color. Gemological properties were generally consistent with

those presented by other authors, except that we noted pleochroism in some of our samples. Beryllium values decreased from the saturated orange specimens through the desaturated yellow ones, while Pb, Th, and U values all showed elevated concentrations in the green and desaturated yellow samples relative to the saturated orange, orange, and yellow ones. The REEs showed relatively similar concentrations in the orange/yellow specimens, but distinctly elevated levels in the green samples, and also exhibited fractionation (greater amounts of the lighter REEs). Our UV-Vis data suggested a possible link between Th concentration and color, but the cause of color in johachidolite bears further research.

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