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Advanced Java-based application to process thermoluminescence digital color images

Manabu OGATA[1,*], Noriko HASEBE[2], Ayako INAGAKI[1], Noritake ENDO[3]

[1] Graduate School of Natural Science and Technology, Kanazawa University
Kakuma, Kanazawa, 920-1192, Japan

[2] Institute of Natural and Environmental Technology, Kanazawa University
Kakuma, Kanazawa, 920-1192, Japan

[3] College of Science and Engineering, Kanazawa University
Kakuma, Kanazawa, 920-1192, Japan

* *Corresponding author* Email: oga835@gmail.com

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Abstract Dielectric minerals that interact with ionizing radiation emit thermoluminescence when heated. The color of the emitted thermoluminescence varies among different samples, even for the same minerals. TL color analysis can be used to study mineral provenance.
Thermoluminescence color images (TLCI) can be obtained using a digital camera. Inagaki et al. (2010) created a Java application to handle RGB (red-green-blue) information of each pixel. This Java application is able to visually represent thermoluminescence color on a CIE (Commission Internationale de l'Eclairage) chromaticity diagram. Here, we report an improved Java application that enables the numerical treatment of TLCI of various image sizes and resolutions. This application allows for the handling of many digital TLCI in a short time and it is useful for statistical color analyses.

Keywords: thermoluminescence, thermoluminescence color image, mineral provenance

1 Introduction

When dielectric minerals interact with ionizing radiation, semi-stable electron and holetrapping sites are created within the forbidden band. These minerals emit luminescence when heated and this phenomenon is referred to as thermoluminescence (TL). Quartz, feldspar and calcite are known to be TL emitters in the geoscience field. The emitted luminescence intensity is proportional to the accumulated dose given to the mineral by environmental radioisotopes. Therefore, TL can be applied to the dating of archaeological artifacts, volcanic products and sediments (Liritzis et al., 1996; Ganzawa and Ike, 2011; Franklin et al., 1988).

The color of the emitted luminescence varies among samples, even among those of the same minerals. Quartz emits blue or red thermoluminescence depending on its origin (Hashimoto et al., 1986a). TL color analysis can be used to study the provenance of minerals. Hashimoto et al. (1986b) suggested a convenient method to observe thermoluminescence color images (TLCI) of quartz using a commercial camera. Ganzawa and Kubokita (2001) identified a widespread aeolian deposit and tephra by investigating the TL color characteristics on a Munsell color system color chart or a CIE chromaticity diagram that was established by the Commission Internationale de l'Eclairage (CIE). By taking a luminescence photo with a camera, the TL color of each grain can be observed and the TL color can be determined numerically and digitized.

Inagaki et al. (2010) obtained TLCI with a digital camera based on previous work (Hashimoto et al., 1989; Ganzawa and Kubokita, 2001). Earlier studies only evaluated digital TLCI qualitatively by plotting chromaticity diagrams. However, Inagaki et al. (2010) developed a Java application to manipulate RGB information from TLCI. Their software enables the convenient, rapid and statistical analysis of TLCI. Hasebe et al. (2012) applied this program to a core sample recovered from the lake bed sediment. Sequential TLCI numerical information was compared with other analytical data and was discussed as a proxy for environmental changes.

The Java application reported by Inagaki et al. (2010) is restricted to 800×800 pixel image data and its flexibility is thus limited. However, image size may depend on instrumental conditions (e.g. camera and sample heater), camera settings when the image is captured, and the sample size. Therefore, we improved the Java application and applied it to images of different sizes and resolutions to extend the scope of TLCI analyses.

2 Digitization of TLCI

2.1 Numerical conversion

Thermoluminescence digital color images were obtained by the method proposed by Inagaki et al. (2010) and then handled quantitatively and numerically in the CIE color system (Ganzawa and Kubokita, 2001; Fig. 1). The RGB information of each pixel was read in the 0-255 range. To match with visible light, the RGB values were converted to X, Y and Z by the following formula as determined by CIE:

$$X = 2.7689R+1.7517G+1.1302B$$
$$Y = R+4.5907G+0.0601B$$
$$Z = 0.0565G+5.5943B$$

X, Y and Z were then converted to plane coordinate values, x and y.

$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$

These x and y values were plotted on a CIE chromaticity diagram (Fig. 1). On the CIE chromaticity diagram, the colors are represented continuously along the locus: blue, green, yellow, orange and red from short wavelength to long wavelength. Based on previous studies (Hashimoto et al., 1989; Ganzawa and Kubokita, 2001), five color zones are defined and they are blue (B; B≦495 nm), green (G; 495 < G≦565 nm), yellow (Y; 565 < Y≦580 nm), and red (R; 580 nm < R). The fifth color zone is GAP, which is the area formed by connecting the saturated purple line with the standard white line (Fig. 1). Each pixel color is categorized into one of these five color zones.

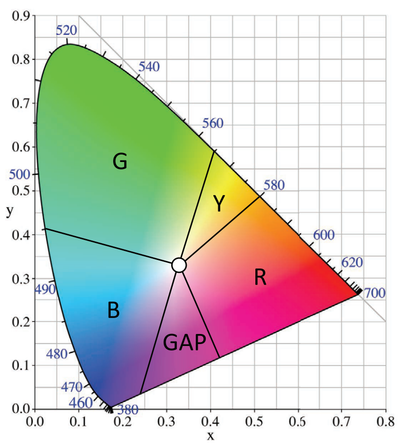


Fig. 1 CIE (Commission Internationale de l'Eclairage) chromaticity diagram and the five color zones defined in this study. B: blue (-495 nm); G: green (495-565 nm); Y: yellow (565-580 nm); R: red (580 nm-); gap: other.

2.2 Application

Inagaki et al. (2010) created a Java application to handle the thermoluminescence digital color image numerically. Java was developed by Sun Microsystems Inc. and is platform -independent. The RGB information of one pixel is read by a method (function) implemented in Java. The application developed by Inagaki et al. (2010) calculated the color information of each pixel (x and y) and the number of pixels in each color zone (blue, green, yellow, red and GAP), and output was as a text file. To visualize the color characteristics, the pixel information is plotted on a CIE chronometry diagram. When several pixels are plotted on the same coordinate, the number of pixels is represented by shading each plotted symbol (darker indicates more). In the application by Inagaki et al. (2010), the point color plotted on the CIE chromaticity diagram is subject to the number of counts. For example, if the number of pixels per coordinate is >100, the color of the plot is black. For >50 it is gray and so on. Therefore, the Java-based application written by Inagaki et al. (2010) can only be applied to TLCI of particular size and/or resolution (applicable to TLCI of 800×800 pixels). If the image size is significantly more than 640,000, the plotted points are always black or vice versa.

We thus report an improved Java-based application for TLCI to evaluate the color characteristics of images of various sizes and resolutions. In this application, the plotted point color depends on the ratio of the number of counts/the number of measured pixels. The pixels are divided into five levels (black, dark gray, gray, light gray and white), and the threshold value for each level (class) can be set by the user. If the ratio of the number of counts/the number of measured pixels is less than the lowest threshold value, no pixel information is plotted although the data is included in the generated text file. Additionally, "the number of measured pixels" (denominator) can be selected as either a black pixels (BP) included-type or a BP excluded-type. For the "BP included-type", all image pixels are used and for the "BP excluded-type" all pixels apart from the black pixels (R+G+B < 30) are used. The BP included-type plot may be useful when the amount of luminous minerals is discussed, while the BP excluded-type plot may be useful to obtain information of color combinations on luminous minerals. This Java application can be used for all image sizes and resolutions.

Additionally, the number of pixels in each color zone (blue, green, yellow, red and gaps) can be counted and output as a text file by our Java application as was the case for the application by Inagaki et al. (2010).

This new application can be downloaded for free from the website of the author's laboratory (http://earth.s.kanazawa-u.ac.jp/chronology/).

2.3 Software usage

To evaluate the use of this new Java application to TLCI of various file sizes and TL colors, we investigated the TLCI of quartz, calcite and feldspar with various resolutions (Fig. 2). The thermoluminescence colors of quartz, calcite and feldspar are blue, red and multiple colors, respectively. The TLCI sizes were 1365×1365 (quartz; Fig. 2(a)), 544×583 (calcite; Fig. 2(b)) and 695×695 (feldspar; Fig. 2 (c)) pixels.

Figure 3 shows the results of the TLCI analysis by the Java application with the BP

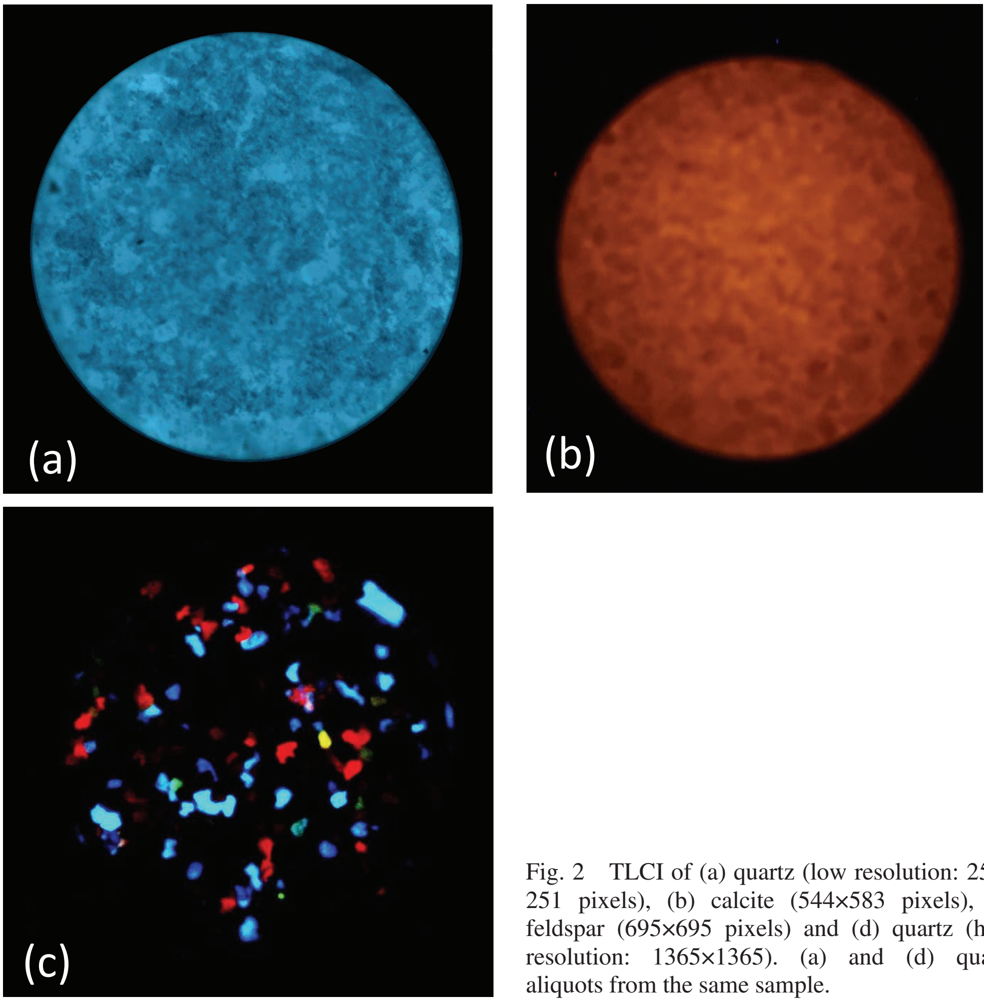


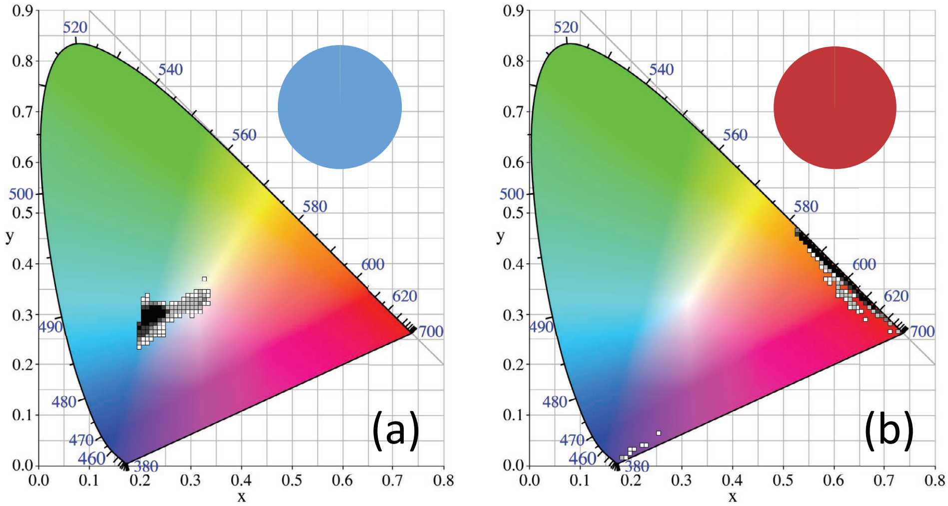
Fig. 2 TLCI of (a) quartz (low resolution: 251× 251 pixels), (b) calcite (544×583 pixels), (c) feldspar (695×695 pixels) and (d) quartz (high resolution: 1365×1365). (a) and (d) quartz aliquots from the same sample.

Table 1 The number of counted color pixels in each color zone obtained from the TLCI analysis.

Sample	Red	Yellow	Green	Blue	GAP	Black	Total
Quartz	103	410	635	1133690	64	728323	1863225
Calcite	184986	0	0	24	6	132136	317152
Feldspar	15537	903	4191	27672	1107	433615	483025

*Red: 580 nm-, Yellow: 565-580 nm, Green: 495-565 nm, Blue: -495 nm, GAP: other zone, and Black: R+G+B < 30.

included-type. The class boundary values used to set the plot (symbol) colors were 0.1, 0.01, 0.005, 0.001 and 0.0001%. The number of pixels in each color zone could be



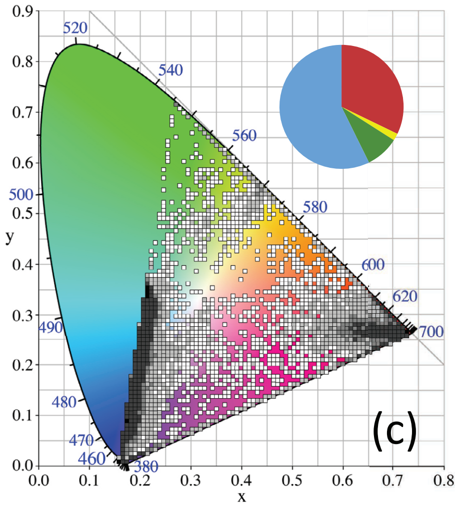


Fig. 3 Results of TLCI analysis using our Java application with the BP included-type. The class boundary values used to set the plot colors that represent the number of pixels were 0.1, 0.01, 0.005, 0.001 and 0.0001%. The analyzed TLCIs are from (a) quartz (Fig. 2(a)), (b) calcite (Fig. 2(b)), (c) feldspar (Fig. 2(c)) and (d) quartz (Fig. 2(d)). Circles show the proportion of each color. Each color comes from the corresponding color zone.

counted and output was as a text file from our Java application (Table 1). Pie charts were drawn using the obtained information and they are shown in Fig. 3 together with a chronometry diagrams. The TLCI information for quartz, with blue TL as shown in Fig. 2(a), was plotted within the blue zone on the CIE chromaticity diagram (Fig. 3(a)). However, the pixels in the TLCI of calcite, with red TL as shown in Fig. 2(b), was plotted within the red zone on the CIE chromaticity diagram (Fig. 3(b)). For feldspar that emitted various colors, the plotted points are widely dispersed over the CIE chromaticity diagram (Fig. 3(c)).

To evaluate the flexibility of this Java application to TLCI of various file sizes, mixture of quartz, which emits blue thermoluminescence (Fig. 2(a)), and calcite, which emits red thermoluminescence (Fig. 2(b)), was prepared and TLCI was investigated (Fig.

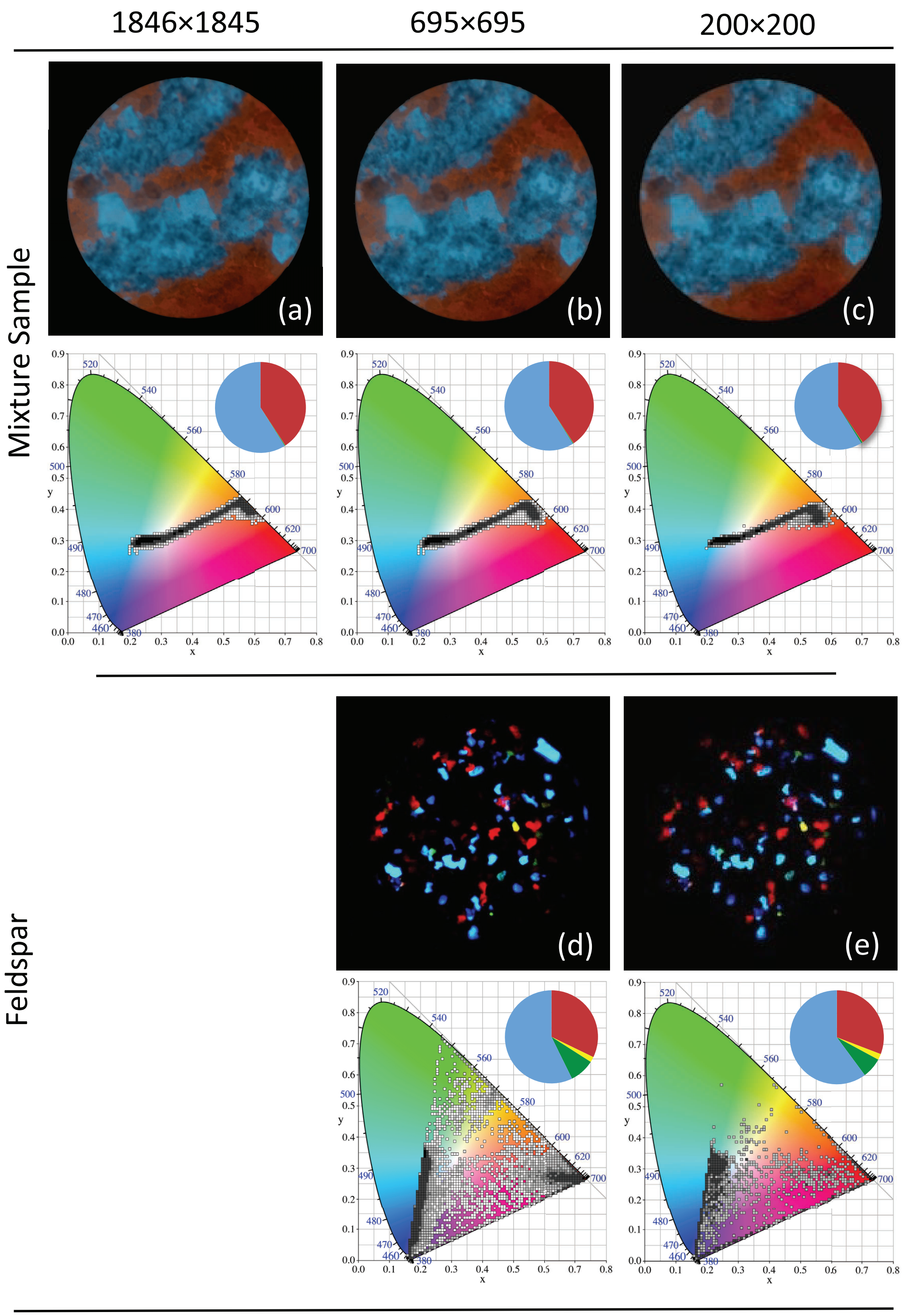


Fig. 4 Results of TLCI analysis with BP excluded type for the mixture sample (quartz and calcite) and feldspar. The class boundary values used to set the plot colors were 1, 0.1, 0.05, 0.01 and 0.001%. For mixture sample, file size is (a) 1846×1845, (b) 695×695 and (c) 200×200. For feldspar, (d) 695×695 and (e) 200×200. Circles show the proportion of each color. Each color comes from the corresponding color zone.

Table 2 The number of counted color pixels in each color zone obtained from the TLCI analyses of mixture sample and feldspar.

Sample		Red (R)	Yellow	Green	Blue (B)	GAP	Black	Total	R/B ratio
Mixture	1846×1845	828602	1272	4572	1197512	45986	1327926	3405870	0.69
	695×695	117704	182	673	170021	6761	187684	483025	0.69
	200×200	9744	26	113	14180	599	15338	40000	0.69
Feldspar	695×695	15537	903	4191	27672	1107	433615	483025	0.56
	200×200	1725	115	391	3366	496	33907	40000	0.51

*R/B ratio was the ratio of the number of red pixels over the number of blue pixels.

4(a)). The original TLCI was 1846×1845 pixels in size. Then resolution was artificially decreased to 695×695 (Fig. 4(b)) and 200×200 (Fig. 4(c)) pixels. The original TLCI of feldspar (Fig. 4(d), the same photo with Fig. 2(c)) was also investigated by artificially decreasing the resolution of TLCI to 200×200 pixels (Fig. 4(e)). The results of TLCI analysis by the Java application with the BP excluded type were also shown in Fig. 4. The class boundary values used to set the plot colors were 1, 0.1, 0.05, 0.01 and 0.001%. The number of pixels in each color zone was shown in Table 2. Pie charts to show numerical information are included in Fig. 4 together with a chronometry diagrams.

For the mixture sample, all TLCIs resulted in similar plots on the CIE chromaticity diagram. TLCI of this sample was dominated by red or blue thermoluminescence (Table 2). The number of red and blue pixels decreased from TLCI of high resolution (1846× 1845) to that of low resolution (200×200). However, the ratios in the number of red pixels over the number of blue pixels (R/B ratio) were almost the same with all resolutions, thus, the color combinations were almost identical for all TLCIs of the mixture sample with difference file size. For feldspar, however, TLCI with high resolution (Fig. 4(d)) resulted in a plot with wider distribution than that with low resolution (Fig. 4(e)). R/B ratio of TLCI with high resolution was higher than that with low resolution. Additionally, the ratio in the number of green against total colored pixels of TLCI was higher in high resolution than in low resolution (Pie charts of Fig. 4(d) and (e)). These differences between two resolutions may be caused by pixels which form the boundary of colored area.

A threshold in resolution of TLCI for a stable result depends on pattern of color distribution in an observed area, which may vary sample to sample depending on luminescence intensity and/or particle size of measured sample. At least the resolution over 200×200 pixels will be necessary to analyze sample with discrete color distribution, as is found in our feldspar image.

The Java application reported here is thus able to reproduce the thermoluminescence color from the TLCI on the CIE chromaticity diagram regardless of image size. It is able to distinguish thermoluminescence color. Although the sizes of these TLCI are different, this work shows that this Java application can be applied to all images. This indicates the flexibility of this Java application.

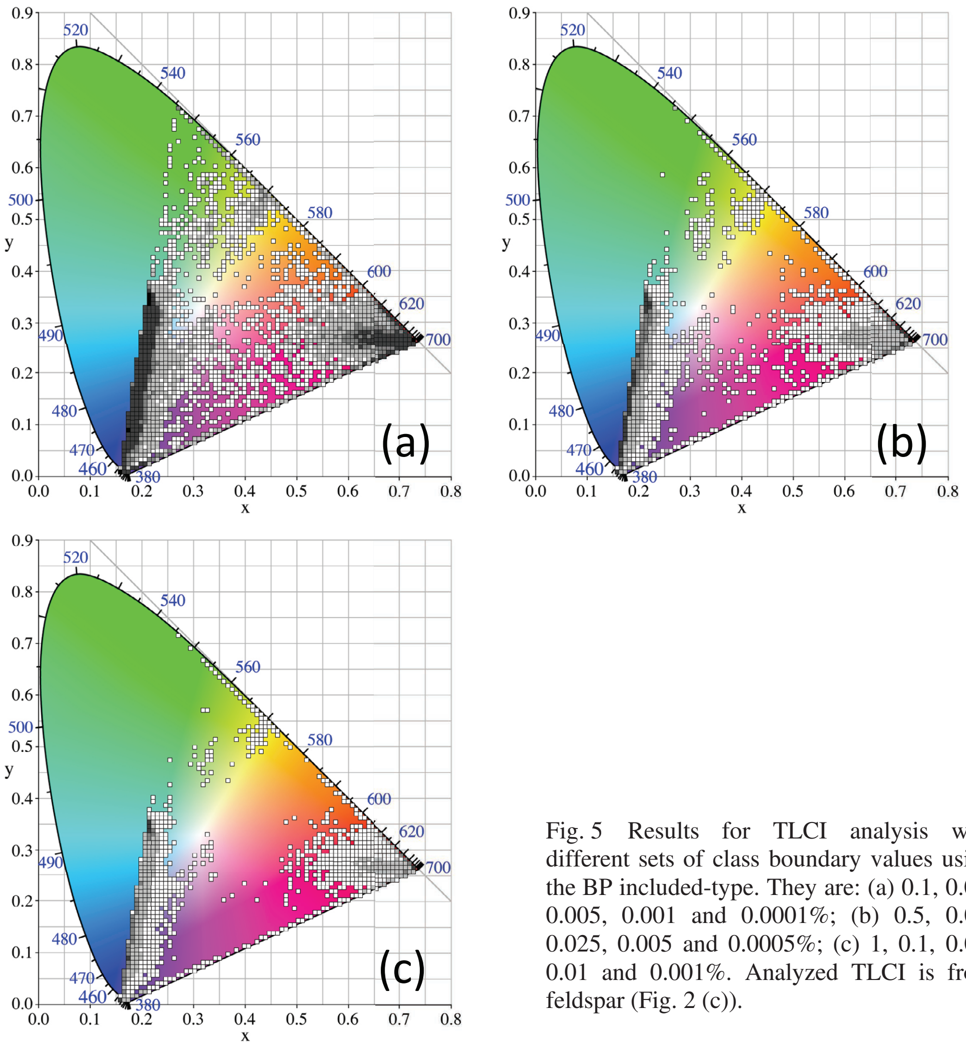


Fig. 5 Results for TLCI analysis with different sets of class boundary values using the BP included-type. They are: (a) 0.1, 0.01, 0.005, 0.001 and 0.0001%; (b) 0.5, 0.05, 0.025, 0.005 and 0.0005%; (c) 1, 0.1, 0.05, 0.01 and 0.001%. Analyzed TLCI is from feldspar (Fig. 2 (c)).

Different sets of class boundary values were evaluated by TLCI of feldspar analyses (Fig. 5). They were: (a) 0.1, 0.01, 0.005, 0.001 and 0.0001; (b) 0.5, 0.05, 0.025, 0.005 and 0.0005; (c) 1, 0.1, 0.05, 0.01 and 0.001. The threshold values increased from pattern (a) to pattern (c). The number of plot points and the darker points decreased from pattern (a) to pattern (c). As the class boundary values increased, the number of plot points decreased and the plot point color became whitish, and vice versa. By setting appropriate threshold values researchers can highlight the TLCI characteristics that support their interpretation.

Figure 6 shows the results of a feldspar TLCI analysis with the BP included-type and the BP excluded-type. The class boundary values used to set the plot colors were 1, 0.1,

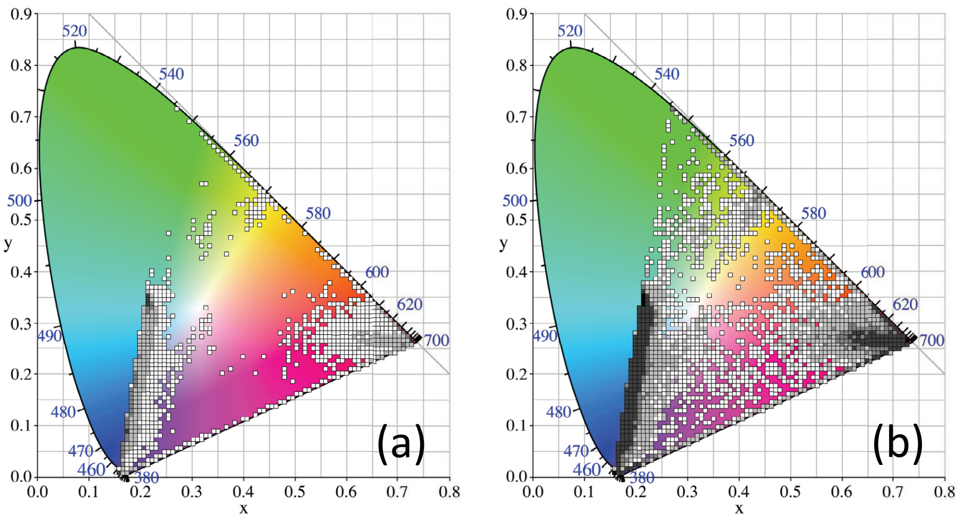


Fig. 6 Results of TLCI analysis with (a) the BP included-type and (b) the BP excluded-type. The analyzed TLCI are from feldspar (Fig. 2(c)). The class boundary values to set the plot colors were 1, 0.1, 0.05, 0.01 and 0.001%.

0.05, 0.01 and 0.001%. A higher number of plot points and dark points were obtained for the BP excluded-type (Fig. 6(b)) for the BP excluded-type removes black pixels (R+G+B < 30) in this Java application. The BP excluded-type only evaluates colored pixels and, therefore, results obtained using the BP excluded-type are independent of the amount of black (or luminescent) pixels in the analyzed image. The BP excluded-type may be useful to obtain information on combinations of luminous minerals. The BP included-type may be useful when the number (or percentage) of luminous minerals is discussed.

3 Conclusion

The Java application reported here is able to visually represent thermoluminescence color on a CIE chromaticity diagram regardless of the image size. A threshold in resolution of TLCI for a stable result depends on pattern of color distribution in an observed area, which may vary sample to sample depending on luminescence intensity and/or particle size of measured sample.

Threshold values for the selection of plot symbol color can be set by the user. Two methods (with or without black pixels) are available to calculate the value required to set symbol color. Feldspar TLCI with the size of 695×695 was investigated by various analytical setting (Method and threshold value); 1) BP included type and threshold values of 0.1, 0.01, 0.005, 0.001 and 0.0001% (Fig.3(c) and Fig.5(a)); 2) BP included type and threshold values of 0.5, 0.05, 0.025, 0.005 and 0.0005% (Fig.5(b)); 3) BP included type and threshold values of 1, 0.1, 0.05, 0.01 and 0.001% (Fig.5(c) and 6(a)); 4) BP excluded type and threshold of 1, 0.1, 0.05, 0.01 and 0.001% (Fig.4(b) and 6(b)). Resultant plots on CIE chromaticity diagram are similar regardless of analytical settings. This suggests that analytical setting of this Java application does not give a significant bias on the plot and TLCI characteristics of feldspar can be represented by plotting the pixel information on the CIE chromaticity diagram.

The numerical treatment of TLCI is still possible as was reported by Inagaki et al. (2010). The application is able to handle many digital TLCI in a short time and is useful for statistical color analyses. Additionally, this application can be applied to thermoluminescence digital image analysis, as well as to other image analyses.

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