

Can cathodoluminescence of feldspar be used as provenance indicator?



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ABSTRACT

We have studied feldspar from crystalline rocks for its textural and spectral cathodoluminescence (CL) characteristics with the aim to reveal their provenance potential. We analyzed ca. 60 rock samples of plutonic, volcanic, metamorphic, and pegmatitic origin from different continents and of 16 Ma to 2 Ga age for their feldspar CL textures and ca. 1200 feldspar crystals from these rocks for their CL color spectra. Among the analyzed rocks, igneous feldspar is most commonly zoned, whereby oscillatory zoning can be confirmed to be typical for volcanic plagioclase. The volcanic plagioclase also less commonly contains twin lamellae that are visible in CL light than crystals from other rock types. Alkali feldspar, particularly from igneous and pegmatitic rocks, was noted to be most affected by alteration features, visible as dark spots, lines and irregular areas. The size of all textural features of up to ca. 150 μm , in combination with possible alteration in both the source area and the sedimentary system, makes the CL textures of feldspar possible to use for qualitative provenance research only. We observed alkali feldspar mostly to luminesce in a bluish color and sometimes in red, and plagioclase in green to yellow. The corresponding CL spectra are dominated by three apparent intensity peaks at 440–520 nm (mainly blue), 540–620 nm (mainly green) and 680–740 nm (red to infrared). A dominance of the peak in the green wavelength interval over the blue one for plagioclase makes CL particularly useful for the differentiation of plagioclase from alkali feldspar. An apparent peak position in red to infrared at <710 nm for plagioclase mainly is present in mafic rocks. Present-day coastal sand from Peru containing feldspar with the red to infrared peak position mainly exceeding 725 nm for northern Peruvian sand and a larger variety for sand from southern Peru illustrates a discriminative effect of different source areas. We conclude that the provenance application particularly can reveal first-cycle input from mafic rocks and source variations for detritus from arid areas that has been affected by little feldspar alteration.

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1. Introduction

Feldspar has been used as a provenance indicator for over fifty years (e.g., Pittman, 1963; Trevena and Nash, 1981; Parsons et al., 2005). Nevertheless, provenance studies commonly rely on the quantitative light- and heavy-mineral petrographic, the whole-rock chemical, and/or the element-chemical and isotopic composition of individual, stable mineral phases such as zircon (e.g., Dickinson and Suczek, 1979; McLennan et al., 1990; Morton and Hallsworth, 1994; Fedo et al., 2003). For quartz arenite particularly the combination of quartz and zircon investigations, e.g., with cathodoluminescence (CL), and U–Pb dating, has a high potential (Augustsson et al., 2011). Feldspar generally largely is ignored as a provenance indicator, partly because it is more unstable than quartz and the most abundant heavy minerals. Nevertheless, feldspar is the most common mineral group in the continental crust, it occurs in both igneous and metamorphic rocks, and it forms both in mafic and felsic rock types. It is one of the most common minerals in sedimentary

rocks and it rarely lacks in siliciclastic sandstone. Opposed to feldspar, more stable minerals may survive many sedimentary recycling phases and therefore do not necessarily give information about first-cycle sources. Hence, if the weathering and diagenetic effect can be taken into account (e.g., Fedo et al., 1995; Wilkinson et al., 2001), the wide spreading of feldspar is an excellent condition for use in source-rock investigations.

Despite its long history, only few provenance studies deal with feldspar, but during the last decade several methods have been suggested for provenance research. Traditional and new approaches include investigation on twinning and zoning (Pittman, 1963, 1970), microtextures (Parsons et al., 2005), major element composition (Trevena and Nash, 1979, 1981; Maynard, 1984), trace element composition (Trevena and Nash, 1981; Götze, 1998; Tulloch and Palin, 2012), Ar–Ar ages (Chetel et al., 2005), Pb-isotopic composition (Tyrrell et al., 2006; Flowerdew et al., 2013), as well as trilinearity, and CL colors (Richter and Zinkernagel, 1975). We are not aware of any studies using the CL characteristics of feldspar for provenance after the attempt by Richter and Zinkernagel (1975). Boggs and Krinsley (2006) similarly noted a lack of literature about the relationship between provenance and CL colors and CL textures in feldspar. Nevertheless, Kastner (1971), Götze et al.

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(2000), Boggs and Krinsley (2006), and González-Acebrón and Götze (2012) state that CL of feldspar can be used in provenance research (Table 1). This situation is markedly different to quartz for which several studies have shown a clear relationship between CL characteristics and provenance (e.g., Zinkernagel, 1978; Bernet and Bassett, 2005; Augustsson and Reker, 2012).

In this study, we present CL characteristics of plagioclase and alkali feldspar in order to reveal their relevance for provenance research. We present CL textures, colors, and corresponding wavelength spectra of feldspar from plutonic, volcanic, metamorphic, and pegmatitic rocks of different age and world-wide origin. The most promising characteristics are discussed in light of possible alterations during weathering and diagenesis in order to give realistic implications for provenance studies.

2. Cathodoluminescence characteristics of feldspar

The CL signal of feldspar is one to several magnitudes stronger than for quartz. This makes the application of the technique more straightforward than for quartz. Optically, numerous CL colors have been reported for natural feldspar. Most studies agree that yellowish green is most common, and unique, for plagioclase and that alkali feldspar often luminesces in blue shades (e.g., Sippel, 1968; Marshall, 1988; this study). Furthermore plagioclase colors include red and different yellow to green and blue shades (e.g., Smith and Stenstrom, 1965; Sippel, 1968; Götze, 2012). Alkali feldspar also has been observed to luminesce in pink to purple, and in brown (e.g., Smith and Stenstrom, 1965; Sippel, 1968; Richter and Zinkernagel, 1975). Authigenic feldspar commonly luminesces weakly, often resulting in a brownish color (e.g., Walker and Burley, 1991; Richter et al., 2002; Boggs and Krinsley, 2006). Parsons et al. (2005) report a complete lack of luminescence for authigenic feldspar, but this probably refers to its optical appearance (cf. Walker and Burley, 1991; González-Acebrón and Götze, 2012).

The different CL colors can be explained by intensity variations in few emission bands in the corresponding color wavelength spectra. The spectra usually are dominated by three broad *apparent* peaks (i.e., the peak position as read directly from the wavelength spectra without deconvolution of the spectra) with different relative intensities, leading to the different visual colors. The intensity peaks are caused by several activators and hence are the result of a combination of several emission bands: (1) Emission in the blue with a maximum at 450–500 nm mainly can be related to electron holes on $\text{Al}^{3+}-\text{O}^{2-}-\text{Al}^{3+}$ bridges caused by Al^{3+} substitution for Si^{4+} but also other activators exist that cause the wavelength at maximum emission to vary (e.g., Finch and Klein, 1999; Götze et al., 2000 and references therein; Słaby et al., 2008). Intense emission bands in the blue are most common in alkali feldspar (Götze et al., 2000; Słaby et al., 2008). (2) An emission band in the green wavelength, with a maximum at ca. 560 nm, is related to Mn^{2+} substitution (e.g., Geake et al., 1971; Mora and Ramseyer, 1992). This emission center is most distinct for plagioclase because Mn^{2+} fits better in the crystal lattice of plagioclase than of alkali feldspar (Götze et al., 2000). (3) An emission band in the red to near-

infrared wavelengths with a maximum around 700 nm for both plagioclase and alkali feldspar is caused by Fe^{3+} substitution for Al^{3+} (e.g., Geake et al., 1973; White et al., 1986; Finch and Klein, 1999). In addition to the three main emission centers, several others in the ultraviolet (<400 nm), visible light, and infrared wavelengths (>700 nm) may cause further peaks that are observed less frequently (Götze et al., 2000 and references therein). Of these, emission bands at ca. 420 nm and 860 nm that are related to Eu^{2+} and Pb^{2+} substitutions are common (Götze et al., 1999; Erfurt, 2003). Incorporation of the different activators and the resulting CL properties are caused by the growth and recrystallization conditions for feldspar.

Alkali feldspar usually is dominated by the peaks in the blue and red to near-infrared wavelength ranges, whereas plagioclase spectra mainly have distinctive peaks in the green and red to near-infrared wavelength interval, although the peak in the blue also can be prominent (Fig. 1). It has been reported that the absolute position of the peak in the red to near-infrared wavelength interval depends on the Na content for both alkali feldspar and plagioclase (Sippel and Spencer, 1970). Its position is reported to vary from ca. 680 nm for almost pure anorthite to ca. 740 nm for albite-rich plagioclase (An_{5-40} ; Geake et al., 1973; Mora and Ramseyer, 1992; Götze et al., 2000; Krbetschek et al., 2002). Similarly alkali feldspar of almost pure orthoclase composition reveals its peak at ca. 700 nm, with a linear trend up to ca. 730 nm for almost pure albite, including a plateau at 710–715 nm for the immiscibility gap at Or_{20-80} (Götze et al., 2000; Kayama et al., 2010). Hence, the color-dependent wavelength spectra of feldspar have potential for source-rock discrimination (Table 1).

The CL intensity varies depending on the crystal orientation because the CL signal of feldspar is polarized (e.g., Smith and Stenstrom, 1965; Sippel, 1971; Kaus, 2002). Therefore, twin lamellae often are visible and zoning frequently occurs (e.g., Smith and Stenstrom, 1965; Lee et al., 2007; Götze, 2012; this study). Boggs and Krinsley (2006) assume that zoning indicates an igneous origin. Hence, also the CL textures of feldspar may be provenance-indicative.

3. Methods

We examined a total of 812 plagioclase and 400 alkali feldspar crystals from 62 rock samples (on average 20 crystals per sample) of which 27 are plutonic (398 plagioclase crystals, 141 alkali feldspar crystals), 25 are metamorphic (342 plagioclase and 163 alkali feldspar crystals), 6 are volcanic (46 plagioclase and 45 alkali feldspar crystals), and 4 are pegmatitic (26 plagioclase and 51 alkali feldspar crystals). The samples

Table 1
Possible provenance-relevant CL properties in feldspar (previous studies).

Property	Feldspar type	Description	Ref. ¹
Zoning	Unspecified	Indicates an igneous origin	1
CL color	Unspecified	No details given	2, 3
CL intensity	Unspecified	No details given	2
Position of red to IR emission band	Plagioclase	Varies with albite–anorthite composition	2, 4
Position of red to IR emission band	Alkali feldspar	Varies with orthoclase–albite composition	2, 5

¹ References: (1) Boggs and Krinsley (2006); (2) Götze et al. (2000); (3) Kastner (1971), González-Acebrón and Götze (2012); (4) Geake et al. (1973), Mora and Ramseyer (1992); (5) Kayama et al. (2010).

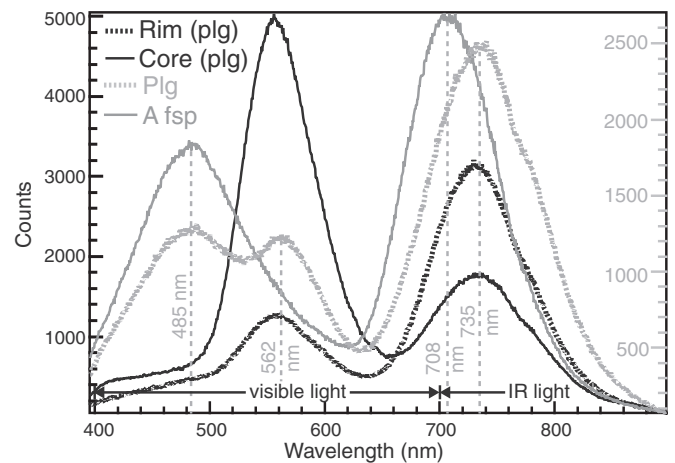


Fig. 1. Typical spectra for plagioclase and alkali feldspar from tonalite APT-4.3 (gray) with the wavelengths for the intensity maxima of the apparent peaks marked, and spectra for zoned plagioclase with a brighter core than rim from granite 97-052 for the green-luminescent core and the darker rim (black). Note the overlap between the different peaks in all spectra.

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