Evaluation of garnet discrimination diagrams using geochemical data of garnets derived from various host rocks

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ABSTRACT

This work is an attempt to evaluate six different garnet discrimination diagrams (one binary diagram and five ternary diagrams) commonly used by many researchers. The mineral chemistry of detrital garnet is a useful tool in sedimentary provenance studies, yet there is no clear-cut understanding of what garnet type originates from which host lithology. Several discrimination diagrams exist for garnet showing distinct compositional fields, separated by strict boundaries that are thought to reflect specific types of source rocks. For this study, a large dataset was compiled (N = 3532) encompassing major element compositions of garnets derived from various host lithologies, including metamorphic, igneous, and mantle-derived rocks, in order to test the applicability of the various discrimination schemes. The dataset contains mineral chemical data collected from the literature complemented with some new data (N = 530) from garnet-bearing metamorphic and ultramafic rocks in Austria and Norway. Discrimination of the tested diagrams only works for a small group of garnets derived from mantle rocks, granulite-facies metasedimentary rocks, and felsic igneous rocks. For other garnet types, the assignment to a certain type of host rock remains ambiguous. This is considered insufficient and therefore the evaluated diagrams should be used with great care. We further apply compositional biplot analysis to derive some hints towards future perspectives in detrital garnet discrimination.

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1. Introduction

For more than 25 years, the mineral chemistry of heavy minerals has been widely used to identify, discriminate, and characterise sediment source areas (see recent review in von Eynatten and Dunkl, 2012). Particularly, the heavy mineral garnet can be used for the identification of the potential lithologies exposed in the source area. Garnet is a particular useful mineral in provenance research because of its wide range of major element composition, its high importance in defining metamorphic conditions, and its comparative stability during transport and burial diagenesis (e.g., Wright, 1938; Tröger, 1952; Zemann, 1962; Nandi, 1967; Morton, 1985; Deer et al., 1992). Morton (1985) was the first to undertake detrital garnet provenance analysis using electron microprobe analysis, in a study of Middle Jurassic sandstones from the North Sea. Since then, this method has been widely applied to determine the provenance of sediments (e.g., Haughton and Farrow, 1989; Takeuchi, 1994; von Eynatten and Gaupp, 1999; Sabeen et al., 2002). The chemical composition of garnet depends on host rock bulk composition as well as its pressure and temperature history. Therefore the major, trace, and rare earth element composition of garnet can be

used to analyse the evolution of mantle and crustal rocks (Harangi et al., 2001; Schulze, 2003; Cookenboo and Grütter, 2010; Heimann et al., 2011, and references therein). Certain garnet compositions have been empirically related to specific sources and, therefore, detrital garnet has been increasingly useful in sedimentary provenance analysis (e.g., Morton et al., 2004; Mange and Morton, 2007; Keulen et al., 2008; Aubrecht et al., 2009; Biernacka and Józefiak, 2009; Meinhold et al., 2010; Morton et al., 2011; Wotzlaw et al., 2011; Andò et al., 2013; Suggate and Hall, 2013). Garnet chemistry also has important provenance applications in archaeology, where the mineral chemical composition is used as a fingerprint to trace the source of gemstone garnet, thereby giving insights into ancient trade routes from the Far East to Europe and within Europe (e.g., Farges, 1998; Quast and Schüssler, 2000; Mathis et al., 2008).

Garnet is classified as a group of cubic nesosilicates with the general formula $X_3Y_2Si_3O_{12}$. Altogether, there are fourteen end-member compositions within the garnet group (Grew et al., 2013). The elements Fe^{2+}, Ca^{2+}, Mg^{2+}, and Mn^{2+} are commonly situated in the X position, and Al^{3+}, Fe^{3+}, and Cr^{3+} are usually in the Y position. The most common end-member species are almandine ($Fe_3Al_2Si_3O_{12}$), pyrope ($Mg_3Al_2Si_3O_{12}$), spessartine ($Mn_3Al_2Si_3O_{12}$), grossular ($Ca_3Al_2Si_3O_{12}$), andradite ($Ca_3(Fe,Ti)_2Si_3O_{12}$), and uvarovite ($Ca_3Cr_2Si_3O_{12}$). Natural garnet usually consists of a solid solution of these end-members in

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highly varying proportions. Garnet is a common mineral of a wide variety of metamorphic rocks and rarely occurs as a primary magmatic mineral in igneous rocks and tuffs (e.g., Miller and Stoddard, 1981; Patranabis-Deb et al., 2008). Garnet is also frequent in mantle-derived rocks and is often embedded amongst mineral inclusions in diamonds. In contrast to mantle-derived olivine and pyroxene, garnet is more stable during dispersion and alteration (Pettijohn, 1941; Morton and Hallsworth, 1999; Grütter et al., 2004). Because garnet displays diagnostic compositional characteristics, it is an interesting mineral for diamond exploration (e.g., Nowicki et al., 2003). Garnet can also be a major constituent in the heavy mineral spectra of sediments and sedimentary rocks (e.g., Pettijohn, 1941; Morton, 1985; Takeuchi, 1994; Sabeen et al., 2002).

Although garnet chemical composition is a widely used tool in sedimentary provenance analysis, there is no clear-cut and quantitative understanding of what garnet type originates from which host lithology. A number of discrimination diagrams for garnet have been proposed in the literature. They are mainly binary and ternary diagrams where discrimination fields are drawn as strict boundaries by solid lines and some of them show distinct overlap between discrimination fields (e.g., Harangi et al., 2001; Grütter et al., 2004; Mange and Morton, 2007; Aubrecht et al., 2009). Given the complex controls on garnet composition, such strict boundaries appear to be unlikely. To approach this problem, we compiled a large dataset (N = 3532) based on literature and own data on major element geochemistry of garnet derived from various host lithologies in order to test the reliability of the various discrimination schemes. Finally, future perspectives for a better discrimination of garnets derived from different host rocks are presented using compositional biplot analysis.

2. Garnet sources

2.1. Metamorphic garnet

The majority of garnet occurs in metamorphic rocks covering a broad range of pressure (P) and temperature (T) conditions, and protolith compositions. Metamorphic garnets are commonly characterised through zoning with respect to Fe–Mg–Mn, show resorption zones, and usually have inclusions (e.g., Patranabis-Deb et al., 2008, and references therein). Inclusions in garnet are useful indicators of metamorphic grade. For example, inclusions of omphacite with a high jadeite content point to eclogite-facies host rocks and are also common in ultrahigh-pressure (UHP) metamorphic rocks (Desmons and Smulikowski, 2004; Schmid et al., 2004; Méres et al., 2012). Coesite inclusions in garnet also point to UHP metamorphic conditions (e.g., Wang and Liou, 1991; Wang et al., 1992; Okay, 1993; Cong et al., 1995; Liu and Liou, 1995; Tabata et al., 1998; Petermann et al., 2009). The presence of kyanite and rutile inclusions in pyrope-rich garnet indicates high-pressure origin (Méres et al., 2012). The structure and distribution of inclusions give further information about the formation of a rock. For example, a curvy distribution or snowball structure is often observed in deformed rocks (e.g., Escuder-Viruete et al., 2000).

2.2. Igneous garnet

Primary igneous garnets are rare and can only develop under restricted conditions; hence, they give useful information about the geodynamics of magma genesis and pressure and temperature conditions (e.g., Green, 1977, 1992; Harangi et al., 2001). Their appearance in igneous rocks is often restricted to granitoids and acid volcanic rocks (René and Stelling, 2007). There exist three different theories about the origin of garnet in igneous rocks: (i) formation during partial melting as a restite phase (e.g., White and Chappell, 1977; Vennum and Meyer, 1979; Allan and Clarke, 1981; Stone, 1988), (ii) formation through low-pressure precipitates from a highly fractionated peraluminous granitic melt (e.g., Hall, 1965; Allan and Clarke,

1981; Miller and Stoddard, 1981; Harrison, 1988), or (iii) formation through transportation of high-pressure phenocrysts to the Earth's crust (e.g., Green, 1977; René and Stelling, 2007). Restite means here the solid remain of a plutonic or volcanic rock resulting from partial melting (Chappell and White, 1991; Sheibi et al., 2010). It is important to know if these garnets are of phenocrystic or xenocrystic origin. However, great care must be taken when chemical composition is used to distinguish between phenocrystic and xenocrystic garnets, because they have a wide compositional range depending on bulk-rock composition, mineral assemblages, and P–T conditions (e.g., Spear, 1993; Kawabata and Takafuji, 2005).

Garnet found in pegmatites is commonly a Mn-rich almandine–spessartine solid solution (Manning, 1983). Spessartine-rich almandine–spessartine garnets are stable within a granitic melt at pressures below 5 kbar. With higher Mn content garnet is stable at lower pressures below 1 kbar at 750 °C (Weisbrod, 1974). There exists a relationship between the concentrations of Fe^{2+} and Mn and the geochemical evolution of zoned pegmatite bodies. It has been observed that Mn content increases from the wall to the core whereas Fe^{2+} decreases (Baldwin and von Knorring, 1983; Whitworth, 1992). There is also a correlation between OH in garnets and pegmatite evolution. OH in spessartine–almandine garnets ranges up to 0.1 wt.%, whereas in grossular-rich garnets, OH exists in higher concentrations due to substitution of SiO_4 by O_4H_4 (hydrogarnet substitution) (Arredondo et al., 2001).

As mentioned above, inclusions in garnets can offer clues about their origin. Besides mineral inclusions, there can also be melt inclusions. Their presence in a mineral implies that the mineral grew whilst coexisting with the melt (Kawabata and Takafuji, 2005). The absence of metamorphic inclusions in garnet may point to a magmatic origin. The grain morphology is another important criterion for the origin of a mineral. Euhedral garnets point to rapid ascent of magma and their formation in equilibrium with the host magma (Gilbert and Rogers, 1989; Day et al., 1992; Kawabata and Takafuji, 2005). For example, garnets from the East Kunlun porphyry of the NE Tibetan Plateau show concentric zoning and have a euhedral shape (Yuan et al., 2009).

2.3. Ultramafic and mantle-derived garnet

Garnets in mantle-derived rocks play an important role for diamond exploration (e.g., Nowicki et al., 2003). Eclogite and peridotite garnet xenocrysts and low-Cr megacrysts found in kimberlites represent upper mantle material and hence constitute a source for diamonds (Schulze, 1997). In fact, Cr-pyrope garnet is a minor common mineral in ultramafic rocks but it is also used as an indicator mineral in diamond exploration (Fipke et al., 1995; Seifert and Vrána, 2005). Orogenic garnet peridotites are found within orogenic belts because of subduction and/or late stage continent collision. Cratonic garnet peridotite xenoliths within cratons are usually entrained in ultramafic volcanic rocks and can be related to partial melting of lower mantle and/or mantle plume, whereas off-cratonic garnet peridotite xenoliths are usually preserved in mafic and alkaline volcanic rocks, which occur mostly within the margin of cratons (Su et al., 2011).

The colour of garnets can also be of importance. Seifert and Vrána (2005) studied garnets from the Bohemian Massif, which primarily derived from lherzolites and peridotites, and found that there is a close linkage between colour and Cr_2O_3 content. The garnets with high Cr-content are violet in colour, whilst others are mostly red.

2.4. Detrital garnets

In magmatic and metamorphic petrology, the host rock of garnet is obvious because garnet occurs in situ in the analysed rock specimen. This is not the case in sedimentary petrology where garnet, if present, occurs as an accessory detrital component, i.e. the original paragenesis is not known. Detrital heavy minerals are used for establishing source