# Diamond and coesite inclusions in detrital garnet of the Saxonian Erzgebirge, Germany

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**ABSTRACT**

Local occurrences of coesite- and diamond-bearing rocks in the central Erzgebirge (northwestern Bohemian Massif, Germany) reveal ultrahigh-pressure (UHP) metamorphic conditions during the Variscan orogeny. Although UHP metamorphism supposedly affected a wider area, implying that rocks which equilibrated under UHP conditions occur dispersed in large volumes of high-pressure country rock gneisses, mineralogical evidence is scarce. Here we applied the new concept of capturing the distribution and characteristics of UHP rocks by analyzing inclusions in detrital garnet. Out of 700 inclusion-bearing garnets from seven modern sand samples from creeks draining the UHP area around the Saidenbach reservoir, we detected 26 garnets containing 46 mainly monomineralic coesite inclusions and 22 garnets containing 41 diamond inclusions. Combining these results with geochemical classification of the host garnets, we show that (1) coesite-bearing rocks are common and comprise eclogites as well as felsic gneisses, (2) small inclusion size is a necessary precondition for the preservation of monomineralic coesite,

and (3) for the first time, diamond-bearing crustal rocks can be detected by analyzing the detrital record. Our results highlight the potential of this novel application of sedimentary provenance tools to UHP research, and the necessity to look at the micrometer scale to find evidence in the form of preserved UHP minerals.

## INTRODUCTION

The "gneiss–eclogite unit" of the Saxonian Erzgebirge, located in the northwestern Bohemian Massif (Germany), was subjected to ultrahigh-pressure (UHP) metamorphic conditions during the Variscan orogeny. This unit is predominantly composed of ortho- and paragneisses with numerous lenses of eclogite and a few lenses of peridotite (e.g., Liati and Gebauer, 2009). It is exposed in the central Erzgebirge and has received considerable attention because diamond inclusions have been found in several host minerals in lenses of paragneiss located at the eastern shore of the Saidenbach reservoir (e.g., Nasdala and Massonne, 2000; Dobrzhinetskaya et al., 2013; Fig. 1). In addition, coesite occurs mainly as a relict mineral in bimineralic coesite/quartz inclusions in an eclogite at the northern shore of the reservoir (Massonne, 2001; O'Brien and Ziemann, 2008) and granulite blocks ~4.5 km further east (Marschall et al., 2009). Even though UHP metamorphic conditions are inferred for several eclogites in the area based on geothermobarometry (e.g., Massonne, 2011) and polycrystalline quartz inclusions interpreted as pseudomorphs after coesite (e.g., Schmädicke et al., 1992), mineralogical evidence in the form of preserved coesite and/or diamond is lacking except for the very local occurrences mentioned.

The commonly applied approach when searching for evidence of UHP metamorphism, i.e., sampling potential crystalline rocks (mainly eclogites), preparing thin sections, and looking for typical structures resulting from the coesite-to-quartz transformation, suffers in several respects, as outlined by Schönig et al. (2018a). Monomineralic coesite inclusions are prone to be overlooked because they are typically small (<20 µm) and do not show the distinct features of bimineralic coesite/quartz inclusions (e.g., Parkinson and Katayama, 1999). Additionally, the large volumes of felsic lithologies (mainly gneisses) surrounding the eclogitic lenses in most UHP terranes are commonly retrogressed and/or not affected by UHP metamorphism and can be only tested selectively. For the Gneiss–Eclogite Unit south of the Erzgebirge, Kotková et al. (2011) already showed that at least some of the felsic to intermediate-composition metamorphic rocks contain coesite and diamond. Thus, one could expect that mafic as well as felsic UHP rocks are widely distributed in the high-pressure country rocks of the area. In the vicinity of the Saidenbach reservoir, these country rocks yield geothermobarometric results below the coesite stability field (e.g., Massonne, 2011).

Schönig et al. (2018a) introduced a complementary approach to capture the distribution and characteristics of UHP rocks by identifying monomineralic coesite inclusions in detrital garnet. This allows for screening a mixture of garnets from lithologies exposed in the sampled catchments. Here we applied this concept and present mineral inclusion data of 700 inclusion-bearing detrital garnets in order to determine (1) whether coesite-bearing rocks in the central Erzgebirge can be traced by analyzing the detritus, and whether these include felsic lithologies; (2) whether diamond-bearing rocks supply significant amounts of diamond-bearing garnets to the sedimentary system, and whether these rocks are widespread or locally restricted; (3) whether the analyzed inclusion size plays a crucial role when searching for UHP minerals; and (4) whether the technique of tracing UHP metamorphism at the catchment scale can be also applied to larger catchments than those tested before.

## SAMPLES AND METHODS

Seven modern sand samples were taken from tributaries draining the area around the Saidenbach reservoir in the central Erzgebirge (Fig. 1). Samples JS-Erz-3s, -5s, -6s, -8s, and -9s are from creeks draining into the reservoir; sample site JS-Erz-3s is located upstream of the coesite-bearing eclogite described by Massonne (2001) and O'Brien and Ziemann (2008), and sample site JS-Erz-8s is slightly downstream from the coesite-bearing granulite blocks described by Marschall et al. (2009), and sample site JS-Erz-9s is very proximal to the diamond-bearing paragneiss lenses at the eastern shore of the reservoir (Nasdala and Massonne, 2000). Sample JS-Erz-13s is derived from a creek north of the reservoir, which drains into the Flöha River and encompasses fewer eclogites in the catchment. Sample JS-Erz-14s was collected from the Flöha River ~3 km farther downstream, representing a much larger catchment (>500 $km^2$) than the other samples (Table 1).

The 125–250 µm heavy mineral fraction was separated and mounted using standard techniques, and polished with $Al_2O_3$ to eliminate any possibility of contamination with diamond abrasives. Mineral inclusions ≥2 µm in detrital garnets were identified by Raman spectroscopy and the main band positions of UHP inclusions were determined to estimate remnant inclusion pressures. Only garnets with visible inclusions ≥2 µm were analyzed, making it necessary to screen 138 to 209 garnets per sample to achieve the target of 100 inclusion-bearing grains per sample (Table 1). The geochemical composition of all inclusion-bearing garnets was determined by electron microprobe analysis (EMPA). Additional details on samples and methods are given in the GSA Data Repository[1].

## MINERAL INCLUSIONS

Forty-six coesite inclusions are present in 26 of the analyzed garnets. Coesite-bearing garnets occur in sample JS-Erz-3s and to a lesser extent in samples JS-Erz-5s, -8s, -13s, and -14s (Table 1). The inclusions are 1.5–20.0 µm in size (longest axis in plane view), colorless, and typically spheroidal to spherical in shape (Fig. 2A). However, some of the inclusions have an angular shape. The majority of the coesite inclusions (39 out of 46) are monomineralic, ≤13.0 µm in size, and show no fracturing of the garnet host (coesites 13–15 in Fig. 2A). In contrast, the Raman spectra of seven coesite inclusions, all >13.0 µm, show a significant quartz component that increases towards the inclusion/host boundary (coesite 16 in Fig. 2A). A filigree of partially healed fine fractures commonly surrounds these inclusions. Coesite inclusions in single garnets co-exist with inclusions of rutile, apatite and/or monazite, zircon, quartz, omphacite, kyanite, carbonates, graphite, micas, and plagioclase (Table DR2). The coesite main band is located at 520–525 $cm^{-1}$ (Table DR3), significantly shifted from the position at room pressure (520–521 $cm^{-1}$), indicating that the inclusions preserve significant stress as a result of entrapment at UHP metamorphic conditions. Band positions which deviate to a lesser extent from those of a free crystal are restricted to inclusions that are exposed at the garnet surface.

Forty-one diamond inclusions were detected in 22 garnets from sample JS-Erz-9s (Table 1). These diamond inclusions are 2.5–20.0 µm in size, typically slightly yellow to grey in color, and have an irregular shape (e.g., diamond 21 in Fig. 2B). Few diamond inclusions are spheroidal, colorless and occasionally have well-developed crystal faces (e.g., diamond 20 in Fig. 2B). Twenty-two out of 41 diamond inclusions are monomineralic, whereas 19 diamonds occur in polyphase inclusions with phyllosilicates, rutile, graphite, quartz, plagioclase, and apatite and/or monazite. Diamond inclusions in the single garnets co-exist with inclusions of rutile, graphite, phyllosilicates, quartz, apatite and/or monazite, cristobalite, and kyanite (Table DR2). The diamond main band is located at 1331–1335 $cm^{-1}$ (Table DR4), indicating inclusion pressures of up to ~1.3 GPa (Tardieu et al., 1990). As a general trend, inclusions that exhibit pressures near atmospheric conditions are restricted to diamonds exposed at the garnet surface or that occur in polyphase inclusions, whereas the highest overpressures are attained from inclusions completely enclosed by garnet. This is in good agreement with theory and has recently been demonstrated by experimental and numerical approaches (e.g., Campomenosi et al., 2018).

In addition to the UHP minerals, omphacite occurs as inclusion in garnet of all samples, except the diamond-bearing sample (JS-Erz-9s), with proportions being highest in samples JS-Erz-5s and -6s, intermediate in JS-Erz-3s and -8s, and low in JS-Erz-13s and -14s (Table 1).

## GARNET CHEMISTRY

Detrital garnets in sample JS-Erz-14s (largest catchment) show the largest spread in composition, comprising garnets from all local crystalline rocks, with the exception of high-Mg eclogites (Fig. 3A, DR1A). This spread is similar in sample JS-Erz-13s, but here low-Mg garnet is less common, and two distinct maxima are present, representing garnet resembling those from local eclogites and diamond-bearing paragneisses. The other samples show even fewer low-Mg garnets, and one and/or both of the maxima are more pronounced. Although several garnets higher in Ca and lower in Mg are present in sample JS-Erz-9s, the majority shows the characteristics of garnet from diamond-bearing paragneiss, whereas garnets of sample JS-Erz-8s also show characteristics of eclogitic garnets. The latter are prominent in samples JS-Erz-3s, -5s, and -6s.

The coesite-bearing garnets show the same two maxima with a higher concentration of eclogitic garnets (Fig. 3C, DR1C). Sample JS-Erz-3s only contains coesite-bearing garnets with an eclogitic affinity, whereas samples JS-Erz-5s and -8s only contain coesite-bearing garnets derived from rocks similar to the diamond-bearing paragneisses, and in samples JS-Erz-13s and -14s both types occur. In contrast, the diamond-bearing garnets resemble the composition of garnets from the diamond-bearing paragneisses (Fig. 3D, DR1D). Omphacite-bearing garnets show compositions similar to those of garnets from local eclogites (Fig. 3B, DR1B).

## DISCUSSION

The widespread occurrence of coesite inclusions in detrital garnets of creeks draining the area around the Saidenbach reservoir indicates that UHP metamorphic rocks are distributed over the investigated area. Although these UHP rocks are volumetrically subordinate to the high-pressure country rock gneisses, the detrital fraction is enriched in garnets sourced from the UHP rocks due to the concentration of garnets from the freshest rocks with highest chance of finding UHP inclusions and their higher modal garnet content. This explains the mineralogical evidence for UHP metamorphism recorded in significant proportions of ~4% from all screened garnets and ~7% from the inclusion-bearing garnets, respectively.

Furthermore, the compositional distribution of detrital coesite-bearing garnets point to more than one source lithology. One population (~77%) most likely derives from eclogites, as indicated by similar compositions of garnets from local eclogites, the co-existence of omphacite inclusions in some of the grains (Schönig et al., 2018b), similar composition to other detrital garnets containing omphacite inclusions, and by their highest abundance in sample JS-Erz-3s where eclogites are common in the catchment area. The other population (~19%) most likely derives from the more felsic gneisses based on similar composition to garnet from the diamond-bearing paragneisses, the absence of omphacite inclusions, and the preferred occurrence in samples from creeks which mainly drain felsic lithologies, i.e., JS-Erz-5s, -8s, and -13s. Thus coesite inclusions in this rock type are probably more common than would be expected from occasional descriptions of pseudomorphs after coesite in the known diamond-bearing paragneisses at the eastern shore of the Saidenbach reservoir (Massonne and Nasdala, 2003) and from the absence of coesite inclusions in detrital garnets of sample JS-Erz-9s, which mainly originated from these rocks. One coesite-bearing garnet from JS-Erz-13s shows a lower Mg-content than garnets from both eclogites and paragneisses. Although an eclogitic affinity of this garnet is very likely (Tolosana-Delgado et al., 2018; Fig. DR1), it cannot be assigned to a specific source rock.

The observation that coesite inclusions $\leq$13 µm are monomineralic and show significant inclusion overpressures without fracturing of the garnet host is in accordance with observations of other monomineralic coesite inclusions in garnet (Schönig et al., 2018a), whereas inclusions >13 µm are bimineralic (coesite + quartz) and commonly show a filigree of fine fractures, which is in accordance with other similar-sized coesite inclusions in garnet (Korsakov et al., 2007). This underlines inclusion size as important factor for the preservation of coesite.

Diamond-bearing garnets in sample JS-Erz-9s are in all probability sourced from the diamond-bearing paragneiss lenses, based on similar garnet composition, the typical polyphase mineral inclusions (Stöckhert et al., 2009), and the proximal sampling locality. The high abundance of diamond inclusions in detrital garnets shows that diamond-grade UHP rocks effectively transfer UHP signatures to the sedimentary record. However, based on the 138 to 209 garnets analyzed per sample, there is no evidence for the presence of diamond-bearing rocks in the other catchments, suggesting that no other diamond-bearing rocks occur in the vicinity of the Saidenbach reservoir, although similar rocks containing coesite are present. An unusual feature of the enclosed diamonds is the remnant inclusion pressure of up to ~1.3 GPa and the co-existence with graphite and quartz (no coesite) in some polyphase inclusions, similar to observations by Kotková et al. (2011). Because the thermoelastic properties of diamond entrapped during garnet growth in the diamond stability field should result in remnant inclusion pressures around zero, elastic re-equilibration of at least some of the diamond inclusions in the stability field of quartz and graphite is suggested, confirming pressure reduction at high temperatures (Ferrero and Angel, 2018).

## CONCLUSIONS

The mineral inclusion data combined with geochemical composition of the detrital host garnets shows that (1) coesite-bearing rocks in the central Erzgebirge are common and include mafic and felsic lithologies, indicating that UHP metamorphic rocks are distributed over the entire study area; (2) high proportions of detrital garnets derived from the diamond-bearing paragneisses contain diamond inclusions, which represents the first report of metamorphic diamond inclusions in detrital mineral grains, and the diamond-bearing lithologies appear restricted to the known paragneiss lenses at the eastern shore of the Saidenbach reservoir; (3) analyzing small inclusions ≤20 μm is crucial for the identification of UHP metamorphic rocks and these may have been commonly overlooked to date; and (4) overall, the applied method is appropriate to detect UHP metamorphic rocks even in large catchments based on the two most prominent and unequivocal indicator minerals coesite and diamond.

## APPENDIX

DR1 including Table DR1 (samples and methods) and Figure DR1 (chemical garnet classification), Table DR2 (mineral inclusions), Table DR3 (coesite inclusions), Table DR4 (diamond inclusions), Table DR5 (EMPA of detrital garnets), Table DR6 (garnet chemistry of local crystalline rocks).

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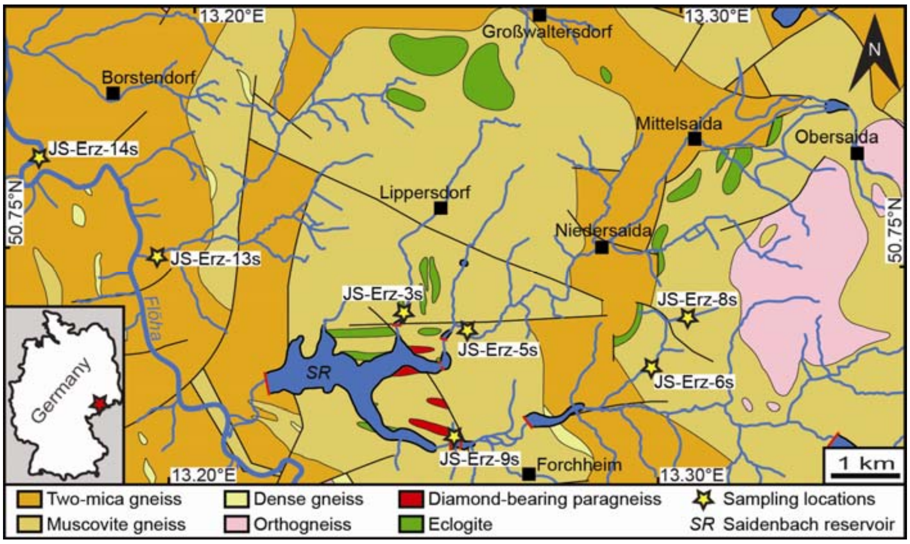


**Figure 1.** Geological map of the area around the Saidenbach reservoir in the central Erzgebirge (northwestern Bohemian Massif, Germany) with sampling locations. Inset shows the location marked by the red asterisk. Geological units adopted from the Saxon State Office for Environment, Agriculture and Geology (http://www.geoportal.sachsen.de) and supplemented by occurrences of eclogites and diamond-bearing paragneisses after Massonne (2001). Sampling locations are marked by yellow asterisks and coordinates are given in Table DR1.

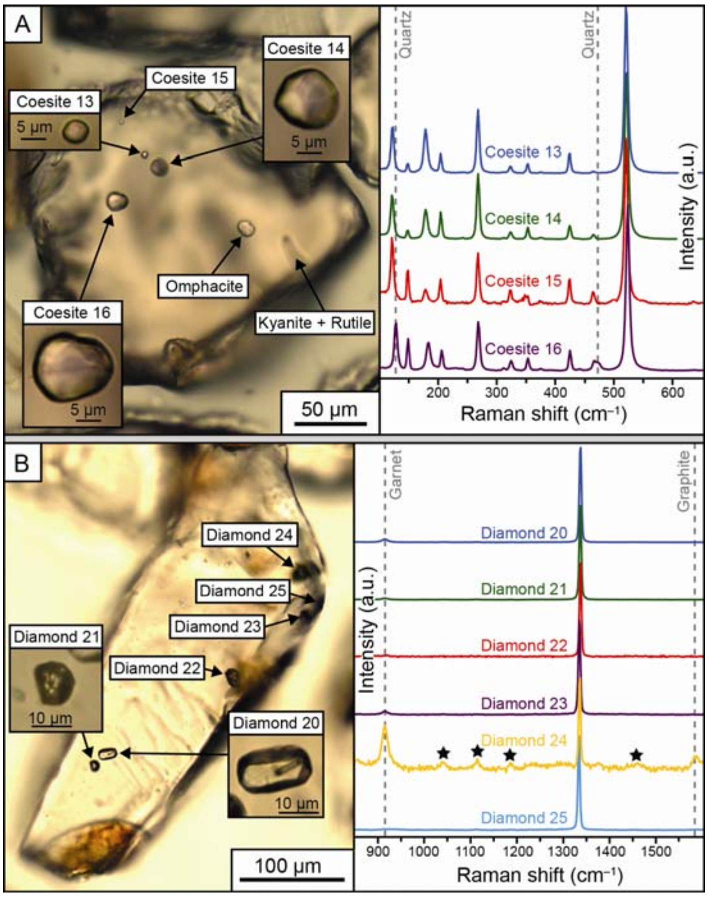


**Figure 2.** Coesite and diamond inclusions in detrital garnet. A: Photomicrograph of garnet number 90 from sample JS-Erz-3s with four coesite inclusions, an omphacite and a kyanite + rutile inclusion, and corresponding Raman spectra of the coesite inclusions. Quartz band positions are given as dashed lines, showing that the larger coesite inclusion 16 (15.5 × 13.0 µm) contains small amounts of quartz. B: Photomicrograph of garnet number 88 from sample JS-Erz-9s with six diamond inclusions and corresponding Raman spectra. Diamond 20 shows an exceptional inclusion shape with well-developed crystal faces. It is colorless and contains a rutile needle. In contrast, diamonds 21–25 show the common irregular inclusion shape with a slightly yellow color. Raman main band positions of the garnet host and graphite (only present in diamond 24) are given as dashed lines. Asterisks mark band positions of the embedding medium (epoxy). a.u.—arbitrary units.

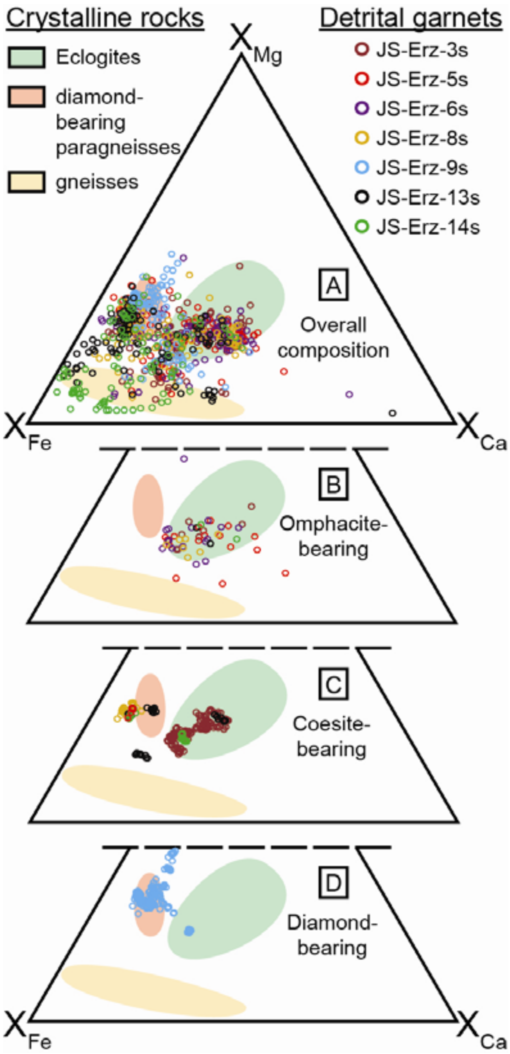


**Figure 3.** Chemical composition of detrital garnets in molar proportions of the Mg-, Fe-, and Ca-endmembers. The full dataset is given in Table DR5 and additional classification using a multivariate discrimination scheme (Tolosana-Delgado et al., 2018) is shown in Fig. DR1. A: All detrital garnets (n = 696; one spot per grain). B: Omphacite-bearing garnets (n = 51; one spot per grain). C: Coesite-bearing garnets (n = 234; 9 spots per grain). D: Diamond-bearing garnets (n = 198; 9 spots per grain). For comparison, garnet data of local crystalline rocks are shown as envelopes (Table DR6).

[1]GSA Data Repository item 201Xxxx, **[DR1 including Table DR1 (samples and methods) and Figure DR1 (chemical garnet classification), Table DR2 (mineral inclusions), Table DR3 (coesite inclusions), Table DR4 (diamond inclusions), Table DR5 (EMPA of detrital garnets), Table DR6 (garnet chemistry of local crystalline rocks)],** is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. OMPHACITE-, DIAMOND- AND COESITE-BEARING GARNETS FROM THE SAXONIAN ERZGEBIRGE, GERMANY

| **Sample** | **Catchment size ($km^2$)** | **Screened garnets (*n*)** | **Inclusion-bearing garnets (*n*)** | **Inclusion-bearing garnets (%)** | **Omphacite-bearing garnets (*n*)** | **Diamond-bearing garnets (*n*)** | **Diamond inclusions (*n*)** | **Coesite-bearing garnets (*n*)** | **Coesite inclusions (*n*)** | **UHP garnets (%)*** |
|---|---|---|---|---|---|---|---|---|---|---|
| JS-Erz-3s | <5 | 200 | 100 | 50 | 8 | 0 | 0 | 17 | 33 | 9 |
| JS-Erz-5s | <20 | 209 | 100 | 48 | 17 | 0 | 0 | 1 | 2 | 1 |
| JS-Erz-6s | <5 | 172 | 100 | 58 | 16 | 0 | 0 | 0 | 0 | 0 |
| JS-Erz-8s | <1 | 200 | 100 | 50 | 7 | 0 | 0 | 2 | 3 | 1 |
| JS-Erz-9s | <1 | 166 | 100 | 60 | 0 | 22 | 41 | 0 | 0 | 13 |
| JS-Erz-13s | <20 | 160 | 100 | 63 | 2 | 0 | 0 | 4 | 5 | 3 |
| JS-Erz-14s | >500 | 138 | 100 | 72 | 2 | 0 | 0 | 2 | 3 | 1 |
| **total** | | **1245** | **700** | **56** | **52** | **22** | **41** | **26** | **46** | **4** |

*percentage of diamond- and coesite-bearing garnets from all screened garnets (UHP—ultrahigh-pressure).