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New approach to garnet redistribution during aeolian transport

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Garnet composition within Late Pleistocene (Weichselian) loess and loess-like deposits was studied in 13 samples of sediment heavy mineral fractions from Moravia and Silesia (Czech Republic). Four areas differing in garnet chemistry were identified, and some regional trends in garnet composition changes were documented. The data obtained support the generally accepted conclusion of prevailing westerly winds during Weichselian loess deposition. Metamorphic rocks of the Bohemian Massif together with contributions from igneous (mainly granitic) and sedimentary rocks were indicated as a source for the Weichselian loess and loess-like deposits studied. Local differences in garnet composition depend on the basement source rocks, on prevailing wind direction, on regional geomorphology and on transport distance.

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Key words: Weichselian, Pleistocene, Czech Republic, aeolian sediments, garnet composition, provenance.

INTRODUCTION

The wide compositional range of garnets, leads to their common use as provenance indicators. However, even though their major element chemistry has been known since 1985 (Morton, 1985), they have been very rarely used as provenance indicators for loessic sediments. There are two main reasons why garnet composition is not often used in Quaternary provenance studies. Firstly, the data are inhomogeneous and secondly, sufficient data from provenance source rocks are commonly absent. We demonstrate here that in cases where provenance data are not available, garnet chemistry can be still used as proxies for aeolian sedimentary process. Moravian and Silesian Weichselian loess and loess-like deposits were chosen for this study.

GEOLOGICAL SETTINGS

Loess and loess-like deposits cover more than 20% of the Quaternary surface area in Moravia and Silesia (Fig. 1). Most of these accumulations were deposited during the latest Pleistocene (Late Weichselian, M IS 2) glacial phase (Frechen *et al*., 1999). The average thickness of the youngest Weichselian loess is about 1 to 1.5 m. Garnet-rich loess material was used for provenance studies and also for the study of garnet redistribution across the landscape. The differences between typical South Moravian loess *s.s*. and North Moravian loess-like deposits are in the transparency of the material that reflects carbonate content (Pelíšek, 1949), the different altitudes at which they are found, and different sources (Lisá *et al*., 2005).

Weichselian loess and loess-like deposits in Moravia and Silesia area have been much studied. Detailed sedimentary classifications for local areas were published by Ambrož (1947) and Pelíšek (1949), stratigraphical studies were published by Musil and Valoch (1956), Ložek (1958), Kukla (1961) and Havlíček and Smolíková (1993), provenance studies by Kvítková and Buriánek (2002), Lisá (2004), Lisá *et al*. (2005) and Lisá and Uher (2006). Palaeoclimate studies of the Moravian loess were published by Adamová and Havlíček (1997), Frechen *et al*. (1999), Cílek (2001) and by Adamová *et al*. (2002). However, none of these papers deal with the problem of garnet redistribution.

The most complete source, regarding the garnet chemical composition within the area studied, is by Čopjaková *et al*. (2005). Some other regional publications (Fediuková *et al*.,

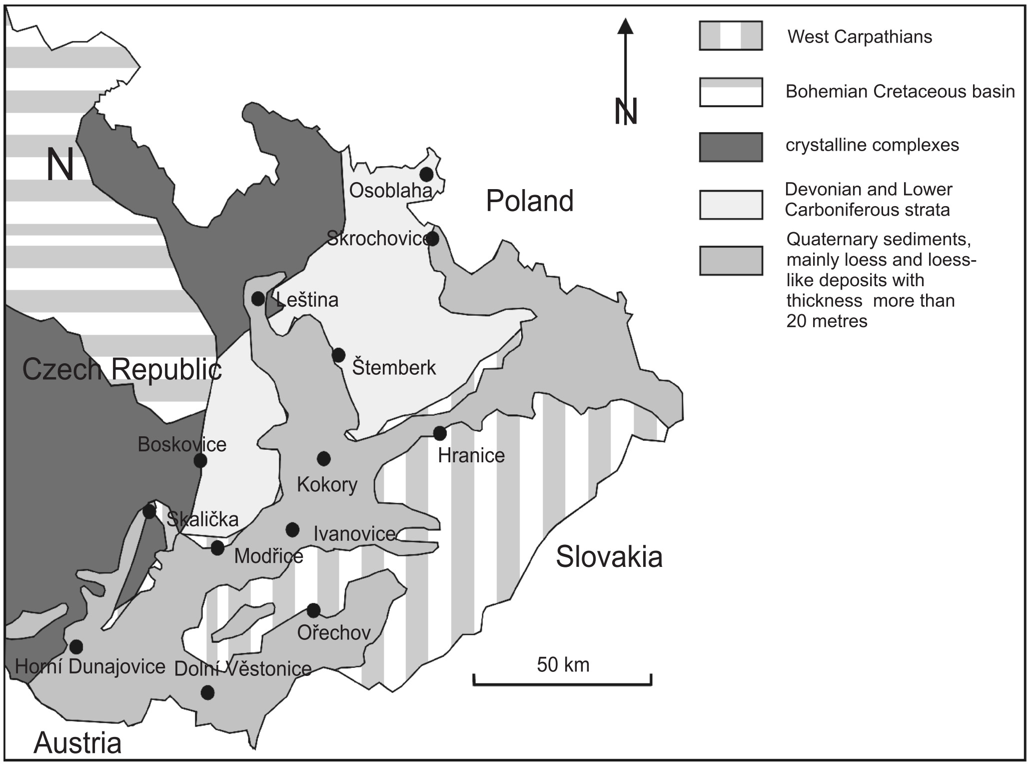

Fig. 1. The distribution of Quaternary, mainly aeolian sediments in Moravia and Silesia and their geological basement, Eastern part of the Czech Republic; location of samples discussed in this paper

1985, Batík and Fediuková, 1992, Nehyba and Buriánek, 2004 and Medaris *et al*., 2005) are used as comparisons in this study.

METHODS

Samples were collected from Weichselian loess sections that have been described by many authors (Macoun *et al*., 1965; Havlíček, 1985; Havlíček and Smolíková, 1993; Adamová and Havlíček, 1995, 1997). In total, 13 sites were selected for detailed garnet analysis (Osoblaha, Skrochovice, Leština, Štemberk, Hranice, Kokory, Boskovice, Skalička, Ivanovice, Modřice, Ořechov, Horní Dunajovice and Dolní Věstonice, Fig. 1).

The most commonly used size fraction in palaeogeographical provenance studies within Moravia, 0.063–0.125 mm, was subjected to the standard procedure of heavy mineral separation in heavy liquid — tetrabromethane of D = 2.96 g/cm^3 (Mange and Mauer, 1992; Mange and Wright 2007). Most of the samples were garnet-rich, so further separation was not necessary. The samples were impregnated with resin and polished. The polished samples were then analysed using a *Cameca SX-100* electron microprobe analyser at the Institute of Geological Sciences (Masaryk University, Brno). The following analytical conditions were used: wavelength-dispersion mode with a beam diameter of 4–5 µm with an accelerating potential of 15 kV and a sample current of 20 nA. A counting time of 20 s was used for all elements. The following standards were used (K_α X-ray lines): wollastonite (Si, Ca), albite (Na), chromite (Cr), Al_2O_3 (Al), MgO (Mg), Fe_2O_3 (Fe), metallic Mn (Mn) and TiO_2 (Ti). Garnet grains separated from the same fraction and mounted on adhesive carbon tape and studied by the same microprobe analyzer were used for micromorphological interpretation. A minimum of three analyses were made, but no zoning was found.

RESULTS

HEAVY MINERAL DISTRIBUTION

The heavy mineral composition is shown in Table 1. Garnets are very abundant in detrital heavy minerals in the fraction studied (0.063–0.250 mm). Their contents range from 5.3% at Ořechov in the south to 44.3% Štemberk in the north. There is no systematic trend in garnet abundance across the area studied, but there is a decrease in garnet from west to east in the south of the area studied and an increase in garnet from west to east in the central and northern parts. A variable proportionality exists between garnet and hornblende quantities (Table 1). The results of the heavy mineral provenance studies have previously been published by Lisá *et al*. (2005).

MAJOR ELEMENT CHEMISTRY OF GARNETS

The garnet chemistry is typified by the predominance of an almandine (Alm) component (Table 2). No pronounced zoning was observed. The garnet with Alm >50% constitutes

Table 1

The concentrations of prevailing non-opaque minerals (%) in the heavy mineral fraction

Locality	Amp	Grt	Zrn	St	Tur	Rt	Ep	Ky	Mnz	Ap	other	
Osoblaha	9.0	34.0	16.7	20.0	3.6	6.7	0.0	5.0	0.2	3.3	1.5	Ttn
Skrochovice	6.6	38.4	7.7	17.4	15.4	10.3	0.0	4.1	0.1	0.0	0.0	
Hranice	8.0	29.3	31.0	0.0	8.0	8.0	9.3	1.3	0.1	0.0	5.0	Cpx
Leština	59.7	24.0	1.9	0.7	0.3	2.5	4.0	0.9	0.3	3.4	2.3	Sil, Ttn
Štemberk	22.4	44.3	4.5	5.0	9.0	1.5	10.1	3.0	0.2	0.0	0.0	
Kokory	57.8	20.3	1.8	1.2	1.2	2.5	3.9	1.2	0.3	3.8	6.0	Sil, Ttn, Cpx
Boskovice	62.5	19.7	3.9	0.5	1.8	0.3	2.5	0.5	0.2	2.1	6.0	Sil, Ttn
Skalička	47.7	24.2	2.9	0.0	5.6	0.0	6.0	0.0	1.2	1.2	0.0	
Modřice	38.6	38.3	1.8	1.8	1.2	2.5	16.6	3.8	2.2	1.9	0.0	
H. Dunajovice	60.2	23.0	1.9	0.9	0.3	2.5	1.7	0.9	0.3	3.4	0.0	
D. Věstonice	61.2	20.9	3.0	0.7	1.8	0.7	2.3	1.4	0.2	2.0	5.8	Sil, Ttn
Ivanovice	31.8	28.8	13.0	3.8	5.0	2.5	6.4	1.3	0.1	5.0	2.3	Cpx
Ořechov	49.5	5.3	15.9	3.9	4.6	11.3	2.0	4.0	0.6	1.4	1.5	Cpx

Amp — amphibole, Grt — garnet, Zrn — zircon, St — staurolite, Tur — tourmaline, Rt — rutile, Ep — epidote, Ky — kyanite, Mnz — monazite, Ap — apatite, Ttn — titanite, Sil — sillimanite, Cpx — Ca clinopyroxene; abbreviations after Kretz (1983)

89%, although groups of garnets can be recognized in which Mg, Mn or Ca components show some differences or anomalies in source provenance rocks. Microchemical analyses of selected detrital garnets from each area are shown in Table 2. Significant differences were found between localities for different parts of Moravia and Silesia. Towards the east, the amount of grossular (Grs) component decreases (Table 2). Another, more significant decrease in this component is a function of latitude in eastern Moravia and Silesia. Towards the south, the Grs component decreases. Another latitude-dependent difference is visible in the western part of Moravia and Silesia (Fig. 2; Table 2). This region is dominated by almandine-rich garnets with variable pyrope (Prp) and spessartine (Sps) components (Table 2). Moravia and Silesia can be divided into four main areas according to such differences: A1, A2, A3 and B1 (see Figs. 2 and 3). Diagrams of relations between Mg/Mn and Ca are demonstrated in Figure 2. These data for garnet distribution in loess of the area studied are shown in four scatter diagrams of Mg/Mn *vs*. Ca (Fig. 2). The first three areas are typified by loess deposits overlying crystalline complexes or surrounded by such complexes. The next two areas have a sedimentary rock basement and a variation of in Grs-rich component garnets can be seen between these two groups. An obvious decrease in the Grs-rich component is visible towards the SE of Moravia. Variations in garnet chemical composition are also visible from north to south. Loess deposits from the southern part of the area studied are typified by a high Mg/Mn ratio (>20; Fig. 3).

MICROMORPHOLOGY OF DETRITAL GARNETS

Garnet grains from the samples studied display typical features of aeolian transport (Fig. 4). This is in contrast with the quartz grains that are more commonly used for micromorphological study (*cf*., Smalley and Cabrera, 1970; Lisá, 2004; Kenig, 2006, 2008; Hladil *et al*., 2008). The garnet grains have a subangular to angular outline, with high to medium relief. There is a noticeable presence of imbricated blocks, large breakage blocks, edge abrasion, and different types of ridges, pits and typical aeolian V-shaped pits or arrows. Most grains are affected by chemical dissolution as documented by solution pits or silica precipitation. Detrital garnets are nearly always found in the form of irregular chips (Fig. 4).

DISCUSSION

The ratio between garnet and hornblende quantities reflects the geological setting of the study area (Lisá *et al*., 2005; Lisá and Uher, 2006). Westerly-lying magmatic and metamorphic Moldanubian rocks, mainly orthogneisses, amphibolites, paragneisses, peridotites, eclogites and granulites (Mísař *et al*., 1983; Fiala *et al*., 1995) produce large amounts of hornblende, garnet and variable amounts of stable heavy minerals such as epidote, apatite or zircon. Towards the east, sedimentary successions of Devonian and Lower Carboniferous age start to appear together with Tertiary deposits of the Carpathian Foredeep. These are connected with large amounts of garnets and other more stable minerals, typical of older strata (Čopjaková *et al*., 2005). Hornblendes are compensated for a more stable mineral — garnet (Table 1). This situation reflects the fact that the studied mineral fraction of loess and loess-like deposits in the conditions of Central Europe (0.063–0.250 mm) were transported at very short distances (Cílek, 2001), mostly about 50 kilometres (Lisá, 2004). Transport was dominantly from the west to the east (Cílek,

Table 2

Typical chemical analyses of garnets from the loess and loess-like localities studied in Moravia and Silesia, Eastern part of the Czech Republic

	Ivanovice/2	Ivanovice/3	Ořechov/4	Ořechov/5	Boskovice/2	Boskovice/8	Leština/3	Leština/5
SiO_2	38.94	38.05	38.98	38.17	37.54	37.36	37.09	37.35
TiO_2	0.22	0.23	0.22	0.37	0.19	0.21	0.33	0.30
Al_2O_3	21.73	21.60	21.70	21.37	20.79	19.89	20.58	20.60
Fe_2O_3	0.00	0.00	0.10	0.00	0.65	0.86	0.89	0.66
FeO	29.42	31.26	25.82	31.04	30.94	21.03	28.04	27.81
MnO	0.67	0.77	0.43	0.38	1.06	16.26	0.56	0.24
MgO	8.43	6.42	9.30	3.74	2.45	2.35	2.60	2.87
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.88	1.47	2.76	5.47	6.89	2.01	9.24	9.18
Total	100.29	99.8	99.31	100.54	100.52	99.97	99.33	99.02
Based on 12 oxygens and with Fe^{2+}/Fe^{3+} calculated assuming full site occupancy								
Si	3.009	2.990	3.007	3.003	2.990	3.025	2.972	2.990
Al^{VI}	0.000	0.010	0.000	0.000	0.010	0.000	0.028	0.010
T-site	3.009	3.000	3.007	3.003	3.000	3.025	3.000	3.000
Al^{VI}	1.979	1.993	1.974	1.983	1.945	1.903	1.920	1.973
Ti	0.013	0.014	0.013	0.022	0.011	0.013	0.020	0.018
Fe^{3+}	0.000	0.000	0.006	0.000	0.039	0.052	0.054	0.040
B-site	1.992	2.007	1.993	2.005	1.995	1.968	1.994	2.031
Fe^{2+}	1.901	2.063	1.666	2.053	2.061	1.424	1.879	1.862
Mn	0.044	0.051	0.028	0.025	0.072	1.115	0.038	0.016
Mg	0.971	0.752	1.070	0.439	0.291	0.284	0.311	0.342
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Zn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.073	0.124	0.228	0.461	0.588	0.174	0.793	0.787
A-site	2.989	2.990	2.992	2.978	3.012	2.997	3.021	3.007
Alm	63.4	69.0	55.3	68.9	68.2	46.2	61.8	61.5
Adr	0.0	0.0	0.3	0.0	2.0	2.7	2.7	2.0
Grs	2.5	4.1	7.4	15.5	17.7	3.3	23.8	24.5
Prp	32.7	25.2	36.0	14.8	9.7	9.7	10.4	11.5
Sps	1.5	1.7	0.9	0.9	2.4	38.1	1.3	0.5

Alm — almandine, Adr — andradite , Grs — grossular, Prp — pyrope, Sps — spessartine; T-site means tetrahedral crystallographic sites in garnet structure, dodecahedral A-site is usually occupied by divalent cations, octahedral B-site is usually occupied by trivalent cations

2001; Adamová *et al*., 2002; Lisá *et al*., 2005) and correspond to contemporary wind directions.

The nature of the geological basement determine overall mineral assemblages as well as garnet compositions. By examining the differences between different geological units it is possible to observe patterns of garnet redistribution within the Moravian and Silesian loess and loess-like deposits and divide them into four main areas named A1, A2, A3 and B1 as described above (Fig. 2). It seems that this redistribution depends not only on the rock basement lithology, but also on selection of garnet types during aeolian transport (*cf*., Čopjaková *et al*., 2005). Aerodynamic and diagenetic effects can be minimized by determining the proportion of stable minerals with similar densities. The index values that best reflect the provenance characteristics (Morton and Hallsworth, 1994) are ATi = 100 × apatite count/(apatite + tourmaline), GZi = 100 × garnet count/(garnet + zircone); RuZi = 100 × rutile count/(rutile + zircone) and Mzi = 100 × count monazite/(monazite + zircone).

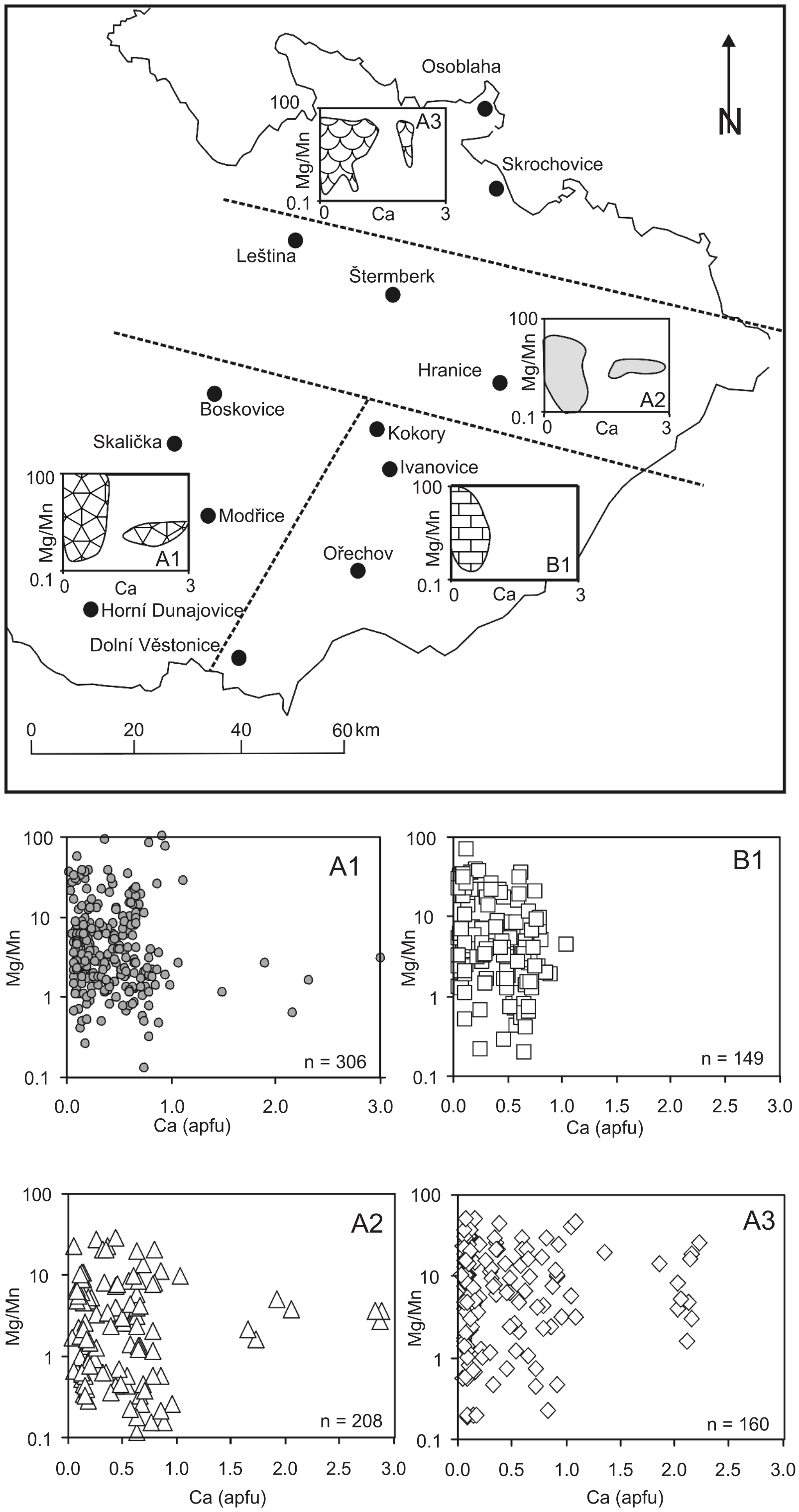

Fig. 2. Diagrams of Mg/Mn *vs*. Ca together with a ternary diagram; this portion is within the loess localities studied from Moravia and Silesia. It is possible to see groups with different garnet chemical compositions

Differences can be found and A1 + B1 groups should be separated from A2 + A3 groups using these indices (Fig. 3). These data support the results published by Lisá *et al*. (2005).

Loess and loess-like deposits with more common almandine-rich garnets are typical mainly of metapelites of the Moravian Nappe (Batík and Fediuková, 1992), paragneisses of the Zábřeh Crystalline Unit (Čopjaková *et al*., 2005) and metamorphic rocks of the Silesicum (Fediuková *et al*., 1985). Low-grossular pyrope-almandine garnets are present in felsic granulites (Čopjaková *et al*., 2005) and pyrope-rich garnets are

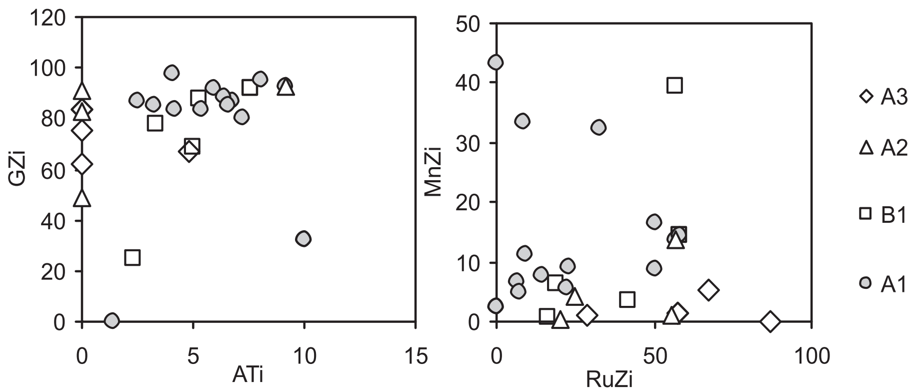

Fig. 3. Diagrams of provenance characteristics according to heavy mineral indices (Morton and Hallsworth, 1994)

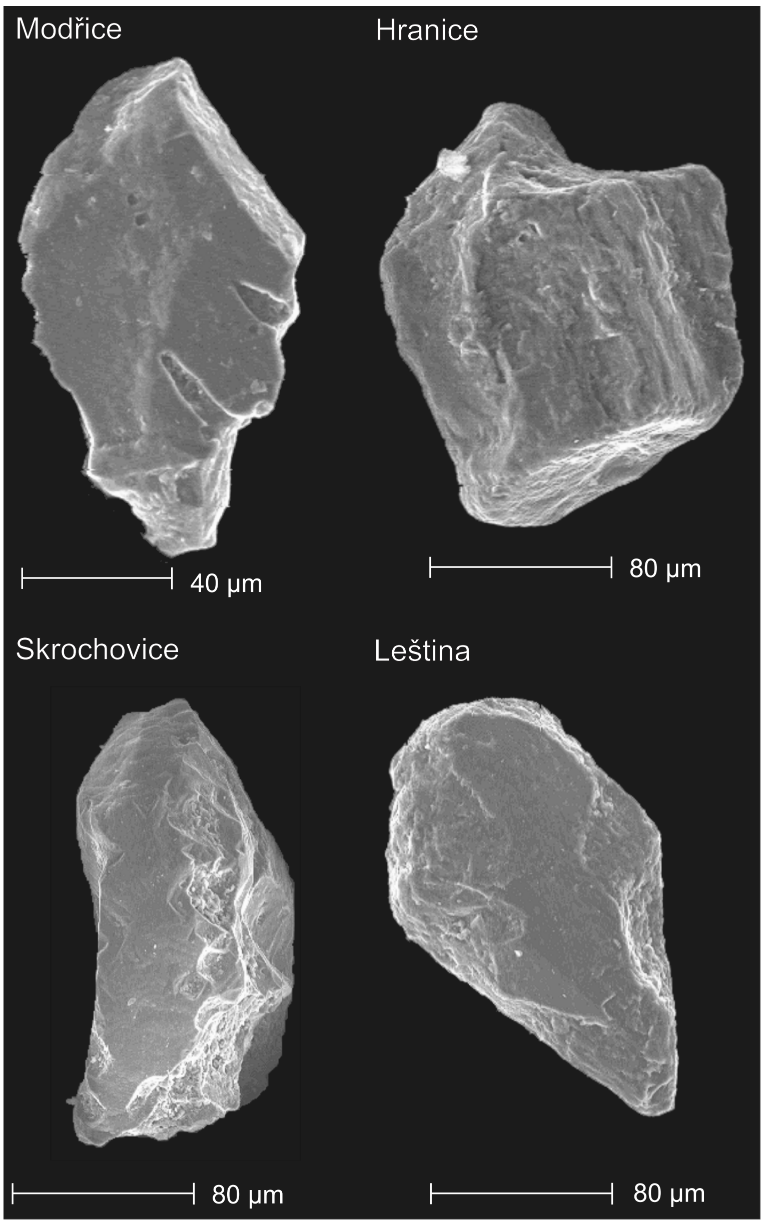

Fig. 4. Garnet grain outlines, morphology and microstructures from selected sites

typical for peridotites from the Moldanubian Zone (Medaris *et al*., 2005). This N–S line primarily covers the main mass of westerly-lying loess and loess-like source rocks. The metamorphic provenance source as a significant part of loess and loess-like deposit material was supported by zircon typology studies (Lisá and Uher, 2006). All sites of loess and loess-like deposits surrounding this line contain variable amounts of garnet with a Grs component (Table 2).

Towards the east, in the provenance area characterized by Tertiary deposits of the Carpathian Foredeep, the amount of Grs-rich garnets rapidly decreases. This is the main trend in loess garnet distribution. This trend could possibly be explained by the fact that the loess material was transported only a limited distance. This explanation fits with the aeolian transport distance results published for this area which are based on radioactivity measurements and abundances of quartz microstructures (Lisá, 2004; Lisá *et al*., 2005). A second explanation for the decreasing amount of Grs-rich garnets towards the east is the changing rock provenance. This is supported by the fact that the garnet geochemical composition of Tertiary deposits from South Moravia is sufficiently variable (Nehyba and Buriánek, 2004); however, garnet grains with a grossular component are very rare in this area. Čopjaková *et al*. (2005) found the same results in the case of Lower Carboniferous Culm strata, where the Grs component is also very rare.

The second trend found in Moravian and Silesian loess and loess-like deposits are the changes in vertical garnet chemical distribution. Garnets with Mg/Mn >20 are present. These types of garnet reflect the presence of different source rocks in the provenance area. Significant differences were found between the A1, A2 and B1 groups. The heavy mineral compositions are very similar for groups A1 and B1 (Fig. 3), as both groups contain garnets with an Mg/Mn ratio of over

30. The only difference between these two groups is the absence of a Grs component in the A1 group. The heavy mineral A2 group differs from the A1 and B1 groups in its composition and also garnet grains from the A2 group differ Mg/Mn ratio, which are not higher than 30. The area A3 contains garnet grains with an Mg/Mn ratio of up to 51.

Areas marked as A1 and A2 have a very similar Ca *versus* Mg/Mn distribution. Garnets in both areas contain a Grs component and have variable amounts of Prp and Grs components. The presumed provenance for these two areas can be seen in rocks lying in southern and central Moravia. The provenance area for southern Moravian loess is probably represented by Moldanubian gneisses, paragneises and migmatites. This mixture of rocks is rich in pyrope and partly also in a spessartine component (Čopjaková *et al*., 2005). The presence of the Grs component is disputable, because some types of rocks are depleted in this component while it is present in others. Source rocks of Central Moravian loess may be represented by the Svratka Zone metapelites, which are mostly rich in Fe with relatively low Mg (unpublished analyses of Novák and Čopjaková in: Čopjaková *et al*., 2005). The area described as A3 probably reflects a source in rocks of the Silesicum. Fediuková *et al*. (1985) distinguished almandine-rich garnets for the Silesicum, but also with variable proportions of Sps and Prp components. Moreover, the same author described Grs-Sps-Alm types of garnets from the Silesicum, originating under conditions of retrograde metamorphism. The widest garnet distribution range (see diagram of Ca *versus* Mg/Mn, Fig. 2) is observed, which reflects a sufficiently wide variability in Silesian garnet chemistry as well as in their source rocks.

Detrital garnets, derived by aeolian process from the source rocks, are mechanically changed into fragments and chips (see Fig. 4). Usually, all grains show some degree of corrosion, but this chemical process is not very marked. There is no evident correlation between the presence of microstructures and the composition of garnets. Čopjaková *et al*. (2005) found the same results in the case of Lower Carboniferous Culm garnets. According to that paper, a low degree of alteration may be suggested by the simultaneous presence of less stable apatite and epidote in heavy mineral assemblages. In the case of loess and loess-like deposits, no significant differences exist in the degree of garnet corrosion between the sites (Fig. 4). This is probably the result of a very recent mechanical erosion and the absence of time for more prominent corrosion processes. It is interesting that the quartz grains from the same samples do not show microstructures that clearly document aeolian transport (Lisá, 2004). The reason for this fact is probably the difference in hardness between quartz and garnet (the hardness of garnet varies from 6.5 to 7.5 while quartz has a hardness of 7). Garnet is shown to be the more informative mineral as regards aeolian transport in this respect.

CONCLUSIONS

The following main conclusions were derived from the data obtained:

1. The use of garnet geochemistry is a new tool for the study of loess deposits and the type of aeolian mineral redistribution.
2. Four different areas in Moravia and Silesia were distinguished based on garnet chemical compositions. These areas reflect different sources of loess material. The aeolian transport distance is recognizable where the almandine component is subdued by other Grs, Prp or Sps components. Such cases are documented by the presence or absence of garnets of anomalous chemical composition.
3. A prevailing westerly wind direction and a short transport distance are best documented in the western part of the study area by the presence of Alm–Prp garnets deflated from Moldanubian metamorphic rocks (especially granulites).
4. The outline (shape, morphology, habitus) of detrital garnets is mostly subangular to angular and reflects aeolian transport more clearly than do quartz grains of the same grain-size category.

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