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Compositional variation of detrital garnets in Quaternary Rhine, Meuse and Baltic River sediments in the Netherlands

L.A. Tebbens[1], S.B. Kroonenberg[1] & M.W. van den Berg[2]
[1] *Department of Soil Science and Geology, Wageningen Agricultural University, P.O. Box 37, 6700 AA Wageningen, the Netherlands;* [2] *Geological Survey of the Netherlands, c/o DLO-Staring Centrum, P.O. Box 125, 6700 AC Wageningen, the Netherlands*

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Abstract

Electron microprobe analysis of detrital garnets from Quaternary Rhine, Meuse and Baltic River sediments in the Netherlands area is used to trace back the provenance and relative contributions from different source lithologies in each drainage basin.

In the Late Pliocene, high-grade metamorphic almandine- and pyrope-rich garnets from the Vosges and Black Forest dominate the Rhine garnet suite. With the onset of the Pleistocene, the Alpine Foreland Molasse is connected to the Rhine drainage area, supplying grossular- and probably also spessartine-rich garnets. The connection of the Aare and other Alpine tributaries to the Rhine in the Middle Pleistocene (Menapian–Bavelian) finally introduces large amounts of almandine-rich garnets derived from high-grade regionally metamorphosed inner Alpine source lithologies.

The garnet suite of the Meuse sediments almost entirely consists of spessartines and Mn-rich almandines. They are derived from Mn-rich low-grade metamorphic pelites of the Libramont anticlinal region and the Stavelot Massif in the Ardennes. A small association of Mn-poor almandines is ascribed to a Vosges supply from before the capture of the Upper Meuse by the Moselle.

The Baltic River garnet assemblages are characterized by a wide compositional spectrum, indicative of a large differentiated source area. The almandine- and pyrope-rich garnets are most likely derived from the extensive Fennoscandian Shield, while the spessartine-rich specimens are thought to originate from the mid-German Variscan massifs.

Introduction

Heavy mineral analysis has proved to give useful information on the provenance and lithostratigraphy of sediments (e.g. Van Andel 1950, Doppert et al. 1975, Boenigk 1970, 1983). The method is widely used for paleogeographic reconstructions of sedimentary basins or river systems. Up to now paleogeographic and stratigraphic interpretation of heavy mineral analyses focused on mineral assemblages, rather than on compositional variability of individual mineral species. Consequently, the method of distinguishing or tracing back sediments by assessing individual mineral species is still scarcely used (Boenigk 1983). Recently however, Morton (1985, 1991) showed that a compositional study of detrital heavy minerals by means of electron microprobe analysis is one of the most powerful techniques presently applicable to provenance studies. This is based on the fact that in sedimentary rocks many heavy mineral species show a wide compositional range because of their origin from different source lithologies. Since then the technique has been applied to e.g. detrital garnets from sandstones (Morton 1985, 1987, Haughton & Farrow 1989), detrital ilmenite (Basu & Molinaroli 1989) and magnetite (Grigsby 1990, 1992).

This paper deals with the chemical composition of detrital garnets from Late Pliocene

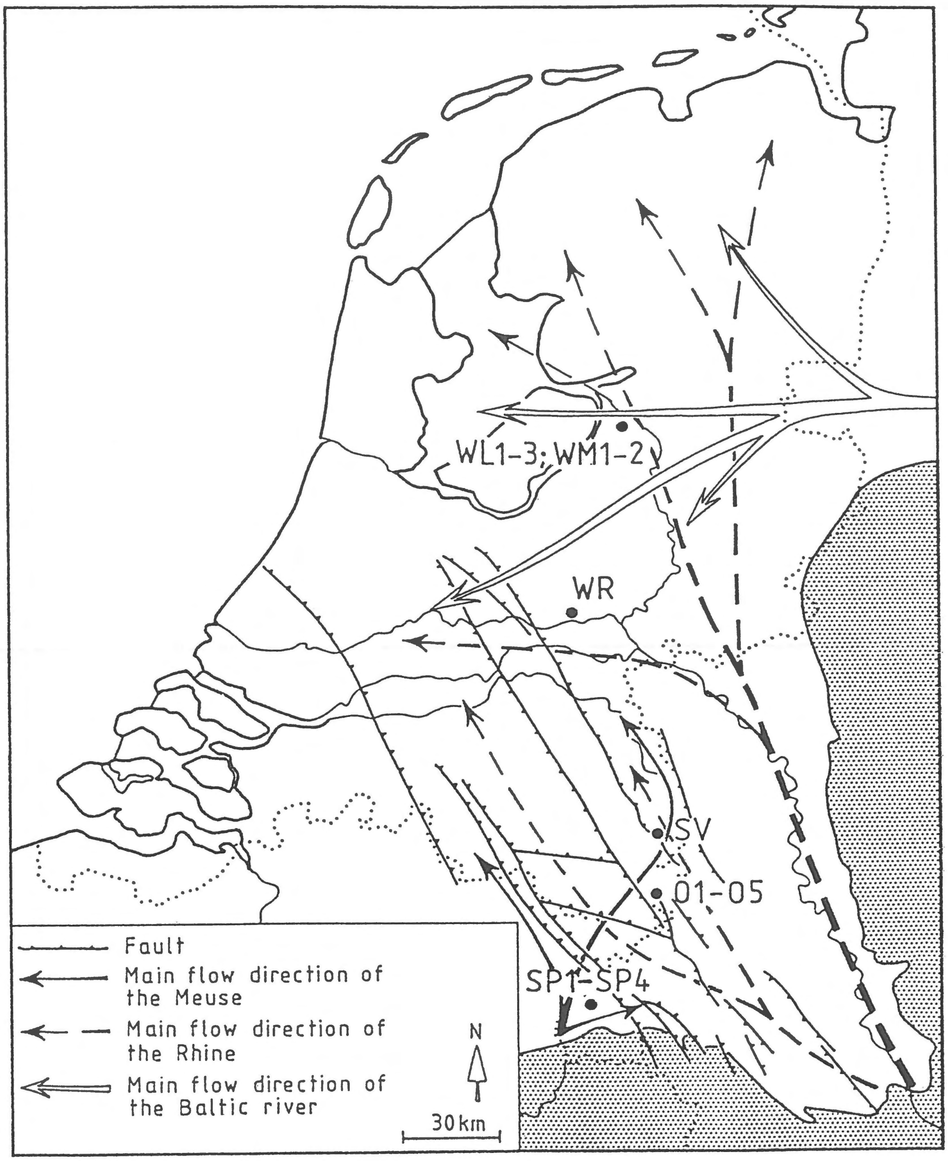
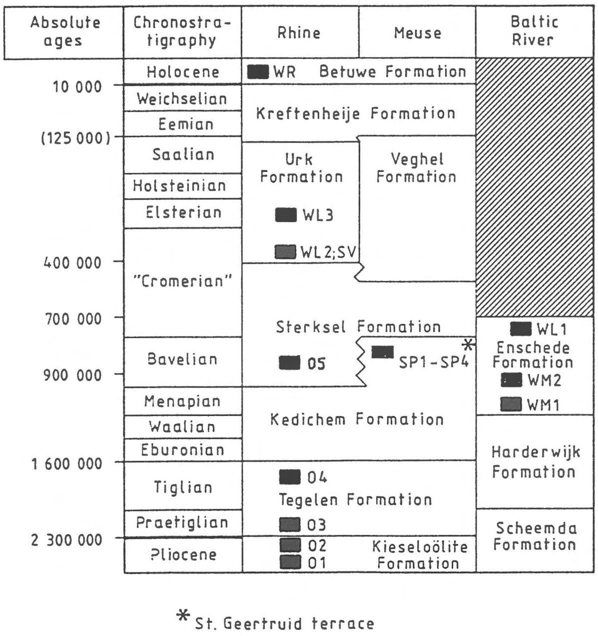


Fig. 1. Map of the Netherlands showing sample sites and main flow directions of the Rhine, Meuse and Baltic River during the Quaternary (after Zagwijn 1975).

and Quaternary fluvial deposits in the Netherlands and a nearby locality in Germany. The garnet group is characterized by six common end-members which form a solid-solution series. Pyrope ($Mg_3Al_2Si_3O_{12}$), almandine ($Fe_3Al_2Si_3O_{12}$) and spessartine ($Mn_3Al_2Si_3O_{12}$) form the pyralspite series, while uvarovite ($Ca_3Cr_2Si_3O_{12}$), grossular ($Ca_3Al_2Si_3O_{12}$) and andradite ($Ca_3Fe_2Si_3O_{12}$) form the ugrandite series. A garnet corresponding in composition with any one end-member is rare however, and the name of a garnet is assigned to the dominant molecular type present (Deer et al. 1982).

Garnet is characteristic of metamorphic rocks and occurs also in some granites, pegmatites and acid volcanic rocks. The bulk chemistry and metamorphic grade of these parent rocks influence garnet composition. Being specifically related to medium and high-grade metamorphic rocks (Deer et al. 1982), almandine- and pyrope-rich garnets also dominate in the sediments that are derived from these rocks. Similarly, spessartine-rich garnets occur in low-grade meta-



*St. Geertruid terrace

Fig. 2. Stratigraphic positions of the samples (stratigraphy after Zagwijn 1985).

morphic rocks and their derivatives. So, generally it can be expected that detrital garnets of fluvial deposits exhibit a clear compositional variation depending on the lithologic characteristics of the drainage area.

In the Netherlands, Quaternary fluvial sediments have been deposited by three major river systems, i.e. the Meuse, the Rhine and the Baltic River (Fig. 1; Zagwijn & Doppert 1978, Zagwijn 1989). The Baltic River was an Early Pleistocene river system, that existed till the early part of the Cromerian (Doppert et al. 1975, Bijlsma 1981, Gibbard 1988). Each of the mentioned river systems is or was typified by a specific drainage area. The Meuse drains low-grade metamorphic rocks of the Ardennes. The drainage area of the Rhine comprises both low-grade metamorphic rocks of the Rhenish Slate Plateau and high-grade metamorphic rocks of crystalline regions in southern Germany, France (Vosges) and the Alps. High-grade metamorphic rocks of the Fennoscandian Shield and the Baltic region occur in the drainage area of the Baltic River, as well as low- to medium-grade rocks in mid-Germany. In the following it will be shown that the characteristics of the Rhine, Meuse and Baltic River drainage areas are reflected in their detrital garnet composition.

Sampling sites

Sample locations were chosen to represent the river systems of the Rhine, the Meuse and the last sedimentation unit of the Baltic River (Fig. 1). Two Late Pliocene and 11 Pleistocene fluvial deposits and one Holocene Rhine sand have been sampled. The stratigraphic positions of the samples are indicated in Fig. 2. For detailed information on the geology and petrology of the sampled sites, one is referred to Boenigk (1970), Zandstra (1971) and Zonneveld (1949).

Rhine sediments have been sampled (O1–O5) in a sandpit near Öbel (Germany, pit 83 in Boenigk 1970). Sample O1 was taken from fine sand layers intercalated in a peat bed beneath the Reuver C clay layer. Samples O2 and O3 were taken from respectively a sand lense in the middle part and a mica-rich sandy gully cut into the upper part of the Reuver C clay layer. This clay layer marks the Plio-Pleistocene transition and includes the lithostratigraphic transition from Kieseloölite to Tegelen Formation (Boenigk 1970, Klostermann 1992). Sample O4 has been taken from the Tegelen Formation, while O5 corresponds to the lowest part of the Sterksel Formation.

In Spaubeek, samples SP1 through SP4 have been taken from the St. Geertruid Meuse terrace (Budel mineral zone; Zonneveld 1949). Attempts to separate garnets from the younger Caberg Meuse terrace in the Belvédère pit near Maastricht were unsuccessful.

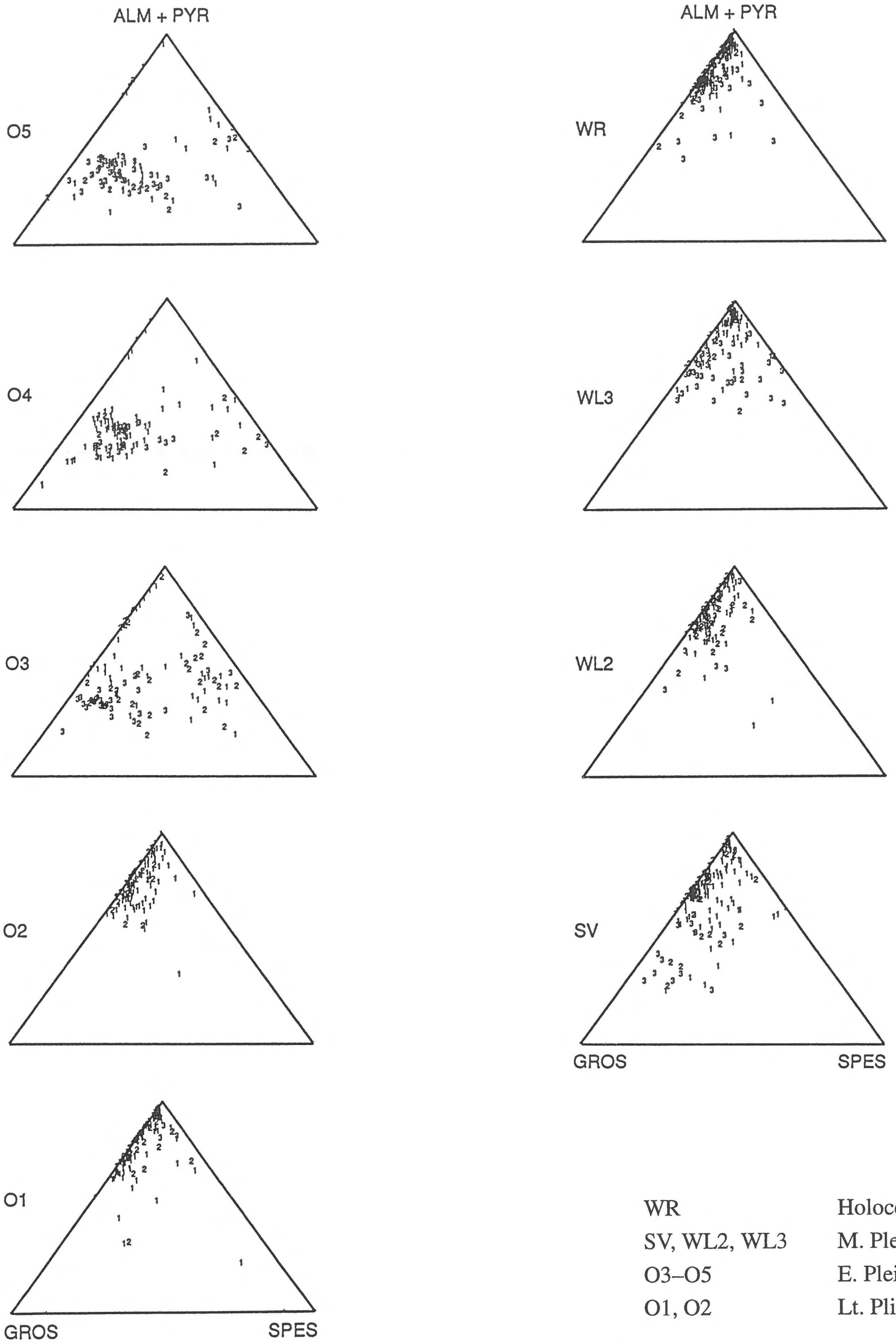
Samples WL1, 2 and 3 form a section taken from ice-pushed sands in the Leemculeweg pit in Wapenveld. WL2 was taken from the 'Green Layer', which is the base of the Urk Formation in the northern Netherlands (Zandstra 1971). WM1 and WM2 have both been taken from the ice-pushed Enschede Formation in the Molenweg pit in Wapenveld. Sample SV originates from the Lingsfort Beds, which form the base of the Urk Formation in the southeastern Netherlands. It was taken in the Driessen pit near Sevenum. For comparison, recent Holocene sand was sampled along the present Rhine in Wageningen (WR).

Materials and methods

Separation and selection of the garnet grains

The samples were air-dried and sieved. From the fraction < 2 mm, calcium carbonate, organic matter and free iron were removed with standard methods. After sieving the samples again, the heavy fraction was sep-

RHINE



WR	Holocene
SV, WL2, WL3	M. Pleistocene
O3–O5	E. Pleistocene
O1, O2	Lt. Pliocene

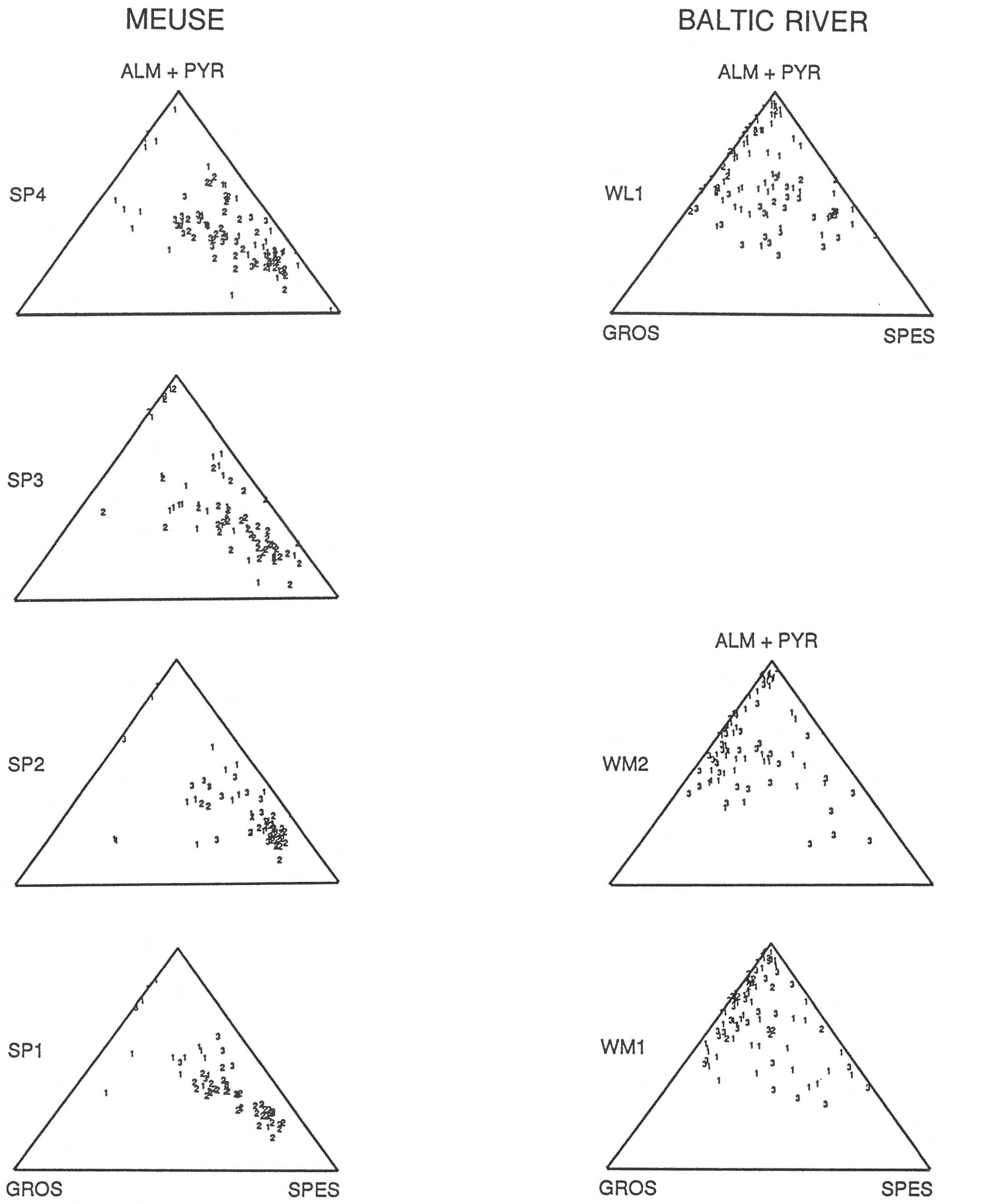


Fig. 3. Fig. 3A (left) and B (above): Ternary plots of detrital garnet composition in relation to grain appearance. Group 1: colourless translucent, group 2: colourless turbid, group 3: coloured, translucent or turbid. Each triangle corner represents 100%. ALM + PYR = almandine + pyrope, SPES = spessartine, GROS = grossular.

arated from the fraction 50–425 μm with bromoform (s.g. = 2.89). The garnets in the heavy fraction were concentrated with methylene iodine (s.g. = 3.325). Finally, a pure garnet concentrate of about 100 grains per sample was obtained by handpicking, making use of the isotropic character of garnet under the polarizing microscope. During the selection procedure crossed nicols and a first-order red plate were used to prevent strongly coloured garnet grains from being preferentially selected. Grain sizes were also selected at random.

In the final handpicked concentrate three groups of garnets were distinguished on the basis of colour and the absence (translucent) or presence of inclusions (turbid): 1) colourless translucent, 2) colourless turbid and 3) coloured, translucent or turbid.

Electron microprobe analysis

The groups of each garnet concentrate were embedded separately from each other in a Spurr epoxy-resin, handpolished and finally coated with carbon. These preparates were attached to aluminium stubs with conducting carbon cement ('Leit-C-Plast').

The elemental composition of all garnet grains has been analysed by means of the energy-dispersive method. The analyses were carried out using a Philips 535 Scanning Electron Microscope (SEM) equipped with an EDAX 9900 energy-dispersive system. The acceleration voltage was 20 kV, with a counting time of 50 s and a scanning surface of $12.5 \times 10\,\mu$m. In order to minimize the effects of zoning, only the cores were analysed. After each 50 grain analyses four Astimex mineral standards were measured.

Due to instrumental drift, variation occurred in the measurement of the peak intensities. Because we used calibration curves based on the daily mean of the standards the calculated weight percentages of all oxides (SiO_2, Al_2O_3, CaO, MnO, FeO en MgO) in a grain can be systematically too high or too low. This caused the totals of the weight percentage in a series of grains in some samples to vary between 70 and 130%. This however had no consequences for the relative proportions of the oxides (e.g. SiO_2/Al_2O_3 in most grains was about 2/3 throughout a day), as systematic variation within one measurement of a grain was the same for all oxides. To eliminate the effect of instrumental drift and to enable comparison with other data, all weight percentages have been recalculated to a total of 100%. Next, the molecular percentages of the end-members of the garnet group were calculated on the basis of 24 oxygen atoms (Deer et al. 1982) for all individual grains. Per sample, the mean of the weight percentages of the oxides of n grains has been calculated for comparison with other data (Table 1).

Substitution of Al by Fe^{3+} is known to occur in grossular-rich garnets, which can result in garnets with appreciable amounts of the andradite end-member molecule (Deer et al. 1982). Grossular garnets reported in Deer et al. (1982) with more than 20% Al_2O_3 generally have less than 5% of the andradite molecule. True andradite garnets have at most 11% Al_2O_3. In this research, the weight percentage Al_2O_3 exceeded 20% in virtually all grains (also in the Ca-rich garnets of samples O3–O5). Substitution of Al by Fe^{3+} and thus the andradite content is therefore considered to be insignificant. Cr and Ti were generally below the detection limits. Consequently, garnet compositions can be described in terms of the four end-members pyrope, almandine, spessartine and grossular.

With the data of the molecular percentages a hierarchical cluster analysis was performed, using the SPSS PC+ software package. The similarity measure was the squared Euclidian distance and the method applied was 'average linkage within group' (Davis 1986, SPSS Inc. 1986). At group level 5, this method empirically yielded the most homogenous clusters. Within the clusters the grains were then grouped according to end-member and the next predominant substitutional molecule.

Results

Plotting the composition of all individual grains of the two or three distinguished groups per sample in triangular end-member scatterdiagrams reveals the occurrence of associations and the relation between garnet composition and grain appearance. This has been done in Figs 3A and B with almandine + pyrope, grossular and spessartine contents as poles. In addition, Fig. 4 shows the percentages of grains of each end-member per sample. In doing so, one obtains a quick insight which end-member is the predominating garnet variety.

Rhine sediments

The ternary diagrams for the Late Pliocene, Early Pleistocene, Middle Pleistocene and Holocene Rhine sediments have been grouped in Fig. 3A. In the diagrams of the Late Pliocene samples O1 and O2, colourless translucent and turbid grains (groups 1 and 2) form a cluster with $Alm + Pyr_{>70}Gr_{0-30}Sp_{0-20}$. High pyrope and almandine percentages occur in O1, resulting in abundant pyrope and almandine garnets (Fig. 4). In O2 however, the almandine percentage has increased at the cost of pyrope.

The ternary plots for the Early Pleistocene samples O3, O4 and O5 show three associations. A small group of colourless grains with high almandine + pyrope and very low spessartine contents is still

Table 1. The average weight percentages of the composing oxides (recalculated to 100%, see text) of n garnet grains per sample

Sample	n	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MnO (%)	FeO (%)	MgO (%)	Total (%)
O1	144	36.05	23.68	6.16	1.59	25.17	7.34	100
O2	129	33.98	22.17	6.95	2.05	32.61	2.23	100
O3	105	34.20	22.15	12.19	8.93	20.34	2.19	100
O4	103	35.86	23.04	15.28	9.06	15.95	0.82	100
O5	101	35.47	23.03	14.71	9.70	15.65	1.44	100
SP1	62	33.27	21.79	5.99	20.90	16.97	1.09	100
SP2	66	34.90	22.94	5.31	23.19	12.49	1.18	100
SP3	74	34.14	22.60	5.04	20.93	15.86	1.44	100
SP4	101	33.37	22.24	5.58	21.84	15.97	0.60	100
SV	174	34.80	22.56	8.19	3.03	28.39	3.04	100
WL1	110	35.34	22.78	7.68	7.78	23.44	2.97	100
WL2	129	35.03	22.54	6.63	2.32	30.65	2.83	100
WL3	146	34.30	21.99	4.51	3.15	32.14	3.91	100
WM1	98	34.88	22.49	6.94	5.38	26.60	3.26	100
WM2	92	35.10	23.36	8.54	6.02	23.71	3.28	100
WR	184	33.12	21.45	6.12	1.63	34.81	2.87	100

present. An association with high grossular contents (Alm + $Pyr_{<50}Gr_{40-70}Sp_{0-35}$) comprises most orange to brown-red garnets (group 3), but also some colourless grains. A third association with moderate to high spessartine content (Alm + $Pyr_{30-65}Gro_{0-30}Sp_{35-70}$) contains predominantly colourless grains. Thus, samples O3, O4 and O5 display an increasing number of spessartine and grossular garnets (Fig. 4), grossular replacing almandine as the predominating garnet variety. On the whole, in the Late Pliocene–Early Pleistocene Öbel section the pyrope and almandine contents decrease from sample O1 to O5, while spessartine and grossular contents increase.

Like in O3–O5, some orange to brown-red garnets in the SV scatterdiagram seem to form a small association, also having higher grossular contents. In the other Middle Pleistocene samples WL2 and WL3 and in the Holocene sample WR, however, no specific relation between garnet composition and grain appearance exists. Both pinkish and colourless grains form an association like in O1 and O2 with Alm + $Pyr_{>70}Gro_{0-30}Sp_{0-20}$. The garnet suite of these samples almost completely consists of almandine (Fig. 4). Only in sample SV grossular still makes up 8%. The Holocene sample (WR) resembles the Urk Formation samples (WL2, WL3 and SV), although the Mn content in the almandine garnets is somewhat lower.

Meuse sediments

In the Spaubeek plots a spessartine-poor association with Alm + $Pyr_{>70}Gro_{0-30}Sp_{0-10}$ and spessartine-rich association with Alm + $Pyr_{<60}Gro_{0-30}Sp_{40-80}$ can be distinguished (SP1–SP4, Fig. 3B). The first association consists of a few colourless translucent grains. In the latter association colourless turbid garnets (group 2) are concentrated in the upper spessartine range (70–80%), while the major part of the colourless translucent (group 1) and brownish-pinkish garnets (group 3) has higher almandine and pyrope contents. Compared to Rhine and Baltic River samples, the spessartine contents in these grains are high. They indicate a great number of spessartine garnets and Mn-rich almandines, while pyrope and grossular garnets are rare (Fig. 4). Within the SP1–4 terrace section, only slight differences can be seen.

Baltic River sediments

The garnet assemblages of samples WL1, WM1 and WM2 show a wide compositional spectrum in which almandine dominates (Figs 3B, 4). Spessartine contents range from 20 to 70% and grossular from 30 to 50%. A Rhine-like association (Alm + $Pyr_{>50}Gro_{0-30}Sp_{0-20}$) is also present. In addition, 8

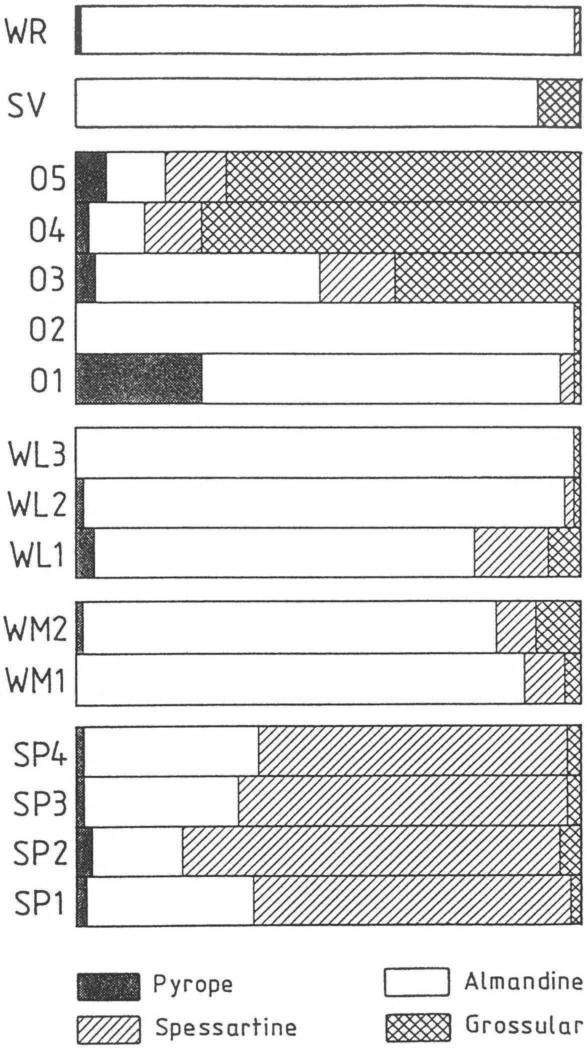


Fig. 4. The number of grains per end-member of the garnet group, expressed as percentages of the total number of grains per sample (Table 1). Each bar corresponds to 100%. Within sections, lowest samples correspond to oldest sediments (Fig. 2).

to 15% (WL1) of the grains are spessartine garnets. The higher spessartine contents in WL1 seem to be related mainly to the brownish-pink grains (group 3). The samples resemble the Middle Pleistocene Rhine samples, but their spessartine content is higher and the almandine content lower. The number of pyrope garnets is surprisingly low, taking into account that high-grade metamorphic garnets were expected in these sediments.

Provenance

Late Pliocene and Early Pleistocene Rhine sediments

The garnets of the Late Pliocene samples O1 and O2 are characterized by an association with high pyrope and almandine, and low spessartine contents, indicative of high-grade metamorphic source rocks (Deer et al. 1982). Nearly all grains are colourless. In his work on the provenance of Rhine sediments, Van Andel (1950) distinguished four garnet varieties. From the two varieties which can be colourless, viz. garnets from the Aare or Vosges provinces, the latter one is the only possible source, as the Aare province was not yet part of the Rhine drainage area during Reuver Clay sedimentation in the Late Pliocene (Quitzow 1974, Gibbard 1988). The Vosges province garnets originate from high-grade metamorphic rocks (gneisses and amphibolites) in the Vosges and the Black Forest region.

The admixture of garnets with high grossular and spessartine contents in the Early Pleistocene samples O3 and O5 (Fig. 4) strongly suggests the impact of a new source area. The grossular association (Fig. 3A, group 3 in O3–O5) predominantly consists of orange to brown-red grains, attributed by Van Andel (1950) to the Aare province. In his view, the Aare province includes both the Tertiary Molasse and part of the Alps.

Sample O3 originates from the upper part of the Reuver C clay, which corresponds to the transition from Late Pliocene to Pleistocene (Boenigk 1978b, Klostermann 1992). At the Plio-Pleistocene boundary the Rhine upper reaches had cut back into the Alpine Foreland Molasse, but not yet into the inner Alps (Boenigk 1970, 1976, 1978a, Gibbard 1988). Garnets with 45–52% grossular, 31–44% almandine and 0–7% andradite have been described from the western Hohe Tauern in Austria (Ackermand et al. 1972). A paleogeographic map (Walter et al. 1992: 399) suggests that this was the main source area for the surficial east Swiss and south German parts of the Foreland Molasse. Thus, a Molasse origin for the grossular garnets in O3–O5 is supported from a lithostratigraphic point of view.

In addition to this, brown-red grossular has been described from calc-silicate hornfelses and metamorphosed marls in the Odenwald (Nickel & Fettel 1979), which is drained by the Rhine tributary Neckar. Grossular also occurs in the Spessart region (Matthes & Okrusch 1965). In this option the occurrence of grossular garnets could also be interpreted as the result of progressive erosion of their respective source areas.

It is doubtful, however, whether these comparatively small geologic units could contribute large enough amounts of garnet to dominate the O3–O5 suites. Furthermore, the Spessart and Odenwald regions already belonged to the Rhine basin during the deposition of the grossular-free O1 and O2 samples (Quitzow 1974), and therefore are unlikely to have had a great impact on garnet composition.

Spessartine-rich garnets are known from skarn deposits, granite, rhyolite, granitic pegmatites and Mn-rich assemblages in relation to metasomatism (Deer et al., 1982). These parageneses however are rather rare in the Rhine drainage area. Low-grade metamorphic rocks from the Rhenish Slate Plateau could also have supplied Mn-rich garnets, analogous to the Meuse supply of Mn-rich garnets from low-grade metamorphics in the Ardennes (see below). However, the major part of the Rhenish Slate Plateau was already drained by the tributaries Main and Neckar during deposition of the spessartine-poor samples O1 and O2 (Quitzow 1974). Probably their garnet contribution was of minor importance. This is corroborated by Van Andel (1950). He mentions the very low heavy mineral content of the Main and the Neckar as compared to Pleistocene Upper Rhine deposits and expects a very small supply of these rivers to the Rhine heavy mineral suite. Therefore, we assume the Mn-rich garnets from samples O3–O5 to originate from the newly drained Foreland Molasse.

Middle Pleistocene and Holocene Rhine sediments

The shift from a grossular-dominated suite in samples O3–O5 to an almandine-dominated suite in the Middle Pleistocene Urk Formation samples SV, WL2 and WL3 indicates that high-grade metamorphic source lithologies began to contribute relatively larger amounts of garnets, possibly in relation to a changed source area. The base of the Urk Formation in the south (Lingsfort Beds, sample SV) seems to form a transition in still having some red-brown grossular garnets. Such grains are lacking in the base of the Urk Formation in the north ('Green Layer', sample WL2).

There are two possibilities to explain the compositional shift. Firstly, the larger amount of high-grade metamorphic garnets could have originated from the Neckar–Main province. They are known to be either directly (Fichtelgebirge) or indirectly (Triassic deposits) derived from the Bohemian Massif (Van Andel 1950). The main uplift period of the Rhenish Slate Plateau coincided with the sedimentation of the Urk Formation (Gibbard 1988; Zagwijn 1989). Therefore, the preponderance of high-grade metamorphic garnets can be attributed to the erosion of rocks or sediments in the Main and Neckar valleys due to uplift of the Rhenish Slate Plateau. However, as already stated above, the Main and Neckar only carry very small quantities of heavy minerals resulting in a minor supply to the Rhine heavy fraction (Van Andel 1950).

Secondly, according to Zagwijn & Doppert (1978), in the Middle Pleistocene the upper course of the Rhine had reached the inner Alpine region, where high-grade metamorphic rocks occur (Trümpy et al. 1980). The exact timing of this event is not agreed upon (Gibbard 1988), but Quitzow (1974) assumes the Aare–Rhine connection to have been established already before deposition of the Younger-Main Terrace (jüngere Hauptterrasse). Boenigk (1976) dates the Aare–Rhine connection not before 900 000 BP. Recently, this was specified by Klostermann (1992) who equates the connection with the deposition of the Younger Main Terrace 2 (jüngere Hauptterrasse 2) from about 850 000 to 760 000 BP (Menapian–Bavelian). Both Boenigk (1976) and Quitzow (1974) describe the event as a substantial enlargement of the Rhine drainage area. The resulting higher sediment discharges (Quitzow 1974) from this new source area could account for the considerable shift in predominating garnet variety. The earliest deposits of the Urk Formation postdate the connection; they date from 400 000 BP (Zagwijn 1986). Therefore, the most likely explanation for the observed change in garnet composition is the establishment of a connection between the Rhine and its Alpine tributaries, with emphasis on the river Aare.

Thus, the Urk Formation garnet suite is likely to have originated from Alpine source lithologies because the garnet supply by the Main and Neckar was of minor importance. This is supported by the fact that Main garnets disappear within 80 km from the Main–Rhine confluence (Van Andel 1950). Furthermore, Main–Neckar province garnets with typically etched facetted surfaces have not been observed in this research and Van Andel concludes the heavy fraction of Holocene sands of the Lower Rhine to be mainly derived from reworked Pleistocene valley deposits of Alpine provenance. In this view the compositional resemblance of the Urk Formation garnet suite with the Holocene Rhine garnets (WR) would also suggest an Alpine (Aare) supply for the Urk samples.

Meuse sediments

The garnets with highest spessartine contents are found among the turbid colourless grains in all samples. Turbid garnets are typical for Meuse sediments. According to Zonneveld (1947, 1953), they originate from the Cambrian metamorphic massifs of Libramont-Bastogne in the Ardennes, which are drained by the Meuse tributaries Lesse and Ourthe. This provenance is confirmed by De Béthune (1977, cited in Deer et al. 1982) who described almandine-spessartines from regionally metamorphosed pelitic rocks in the Libramont anticlinal region. Additionally, Lamens et al. (1986) described low-grade metamorphic spessartine-bearing coticules in the Lower Ordovician of the Stavelot Massif, drained by the Ourthe.

Considering the low-grade metamorphism of the Ardennes region, the occurrence of spessartines and Mn-rich almandines can be well understood. In this respect the additional presence of a high-grade metamorphic association with Mn-poor almandines seems anomalous. Most almandine-rich garnets are colourless and translucent. Zonneveld (1947, 1953) assumes this garnet type ('clear garnet') to have been transported from the Vosges region before the Upper Meuse had been captured by the Moselle near Toul. This capture most probably took place during the Elsterian (Gibbard 1988), but Bosch (1992) presumes it was in the early Saalian. As the Menapian–Bavelian (Felder & Bosch 1989) St. Geertruid terrace predates the capture event, the high-grade metamorphic almandines most likely stem from the Vosges gneisses and amphibolites. A Vosges origin is also suggested by the resemblance of this (small) association with the one in samples O1 and O2.

Summarizing, the presence of a spessartine-rich and a spessartine-poor garnet association in the Spaubeek section indicates contributions from two source areas. Taking the slight differences within the section into account, garnet supplies must have been relatively constant during the deposition of the St. Geertruid terrace.

Baltic River sediments

Considering the heavy mineral and gravel contents, the lower part of the Enschede Formation originates from Scandinavia. In the upper part the north-German part of the river Elbe with its tributaries Saale and Mulde additionally transported components from Thuringia and the Erzgebirge in mid-Germany (Zandstra 1971). Bijlsma (1981) describes the Enschede Formation as a mixture of components from the Fennoscandian Shield and the western part of the Baltic Platform as well as from the German Variscan massifs.

The interpretation of the Baltic assemblages as being derived from the extensive Fennoscandian Shield and the mid-German Variscan massifs, offers a good explanation for the wide compositional spectrum of the Baltic River garnets. The almandines with their appreciable Mg contents (Table 1) indicate high-grade metamorphics, probably from the Fennoscandian Shield where these rocks are wide-spread.

In comparison with WM1 and WM2, sample WL1, from the upper part of the Enschede Formation, is characterized by a relatively large amount of clearly recognizable brown-red spessartines and by a rather high bulk spessartine content. We assume that the supply of high-grade metamorphic garnets decreased and that this resulted in a higher relative contribution of spessartine-rich garnets from mid-German Variscan low-grade metamorphic pelites. This may have been caused by a greater influence of the mid-German rivers during deposition of the upper part of the Enschede Formation (Zandstra 1971). Probably, this resulted from the destruction of the Fennoscandian part of the Baltic River during glacier advance in the Menapian glacial (Bijlsma 1981).

Conclusions

During the course of the Pleistocene the Rhine drainage area was progressively enlarged. This enlargement was accomplished in two stages, which are documented by two major shifts in source lithology supply and hence in detrital garnet composition. In the Late Pliocene the Rhine upper reaches took their rise in high-grade metamorphic rocks of the Vosges and Black Forest region. This is reflected in the garnet assemblages by high almandine and pyrope contents. With the onset of the Pleistocene, the Alpine Foreland Molasse became included in the Rhine drainage area. This first enlargement is accompanied by a substantial admixture of grossular-rich garnets. The greater amount of spessartine-rich garnets might also be attributed to a Molasse supply.

The second stage is the connection of the Alpine tributaries and especially the river Aare to the Rhine system during the Menapian–Bavelian. Their relatively large contribution to the Rhine garnet suite is reflected in a considerable shift in garnet composition. The grossular and spessartine-rich garnets make way for almandine-rich garnets with low Mn contents, derived from high-grade regionally metamorphosed inner Alpine source lithologies. This situation persists up till now. The contribution to the Rhine garnet suite by the main tributaries Main and Neckar is considered insignificant.

The Meuse sediments contain garnets from two source areas. The major part of the garnets consists of Mn-rich almandines and spessartines derived from low-grade metamorphic pelites and coticules. These rocks are found near Libramont–Bastogne and the Stavelot Massif in the Ardennes. A small association comprises almandine- and pyrope-rich garnets with low Mn contents which stem from gneisses and amphibolites in the Vosges region.

The Baltic River garnet assemblages have a wide compositional spectrum, which reflects a large differentiated drainage area. The major part of the garnets is of high-grade metamorphic origin and most likely was supplied by the Fennoscandian Shield. The north-German tributaries probably had a greater influence on garnet supply during the deposition of the youngest Baltic River sediments. This is assumed to be the explanation for the fact that the youngest sample (WL1) contains more spessartine-rich garnets. The spessartine-rich garnets are thought to originate from the mid-German Variscan massifs.

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