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DETRITAL HEAVY MINERALS AS PROVENANCE INDICATORS OF BELGIAN MESO-CENOZOIC SEDIMENTS

by

Jan VAN DER SLUYS [1]

ABSTRACT

The chemical compositions of detritral garnet, epidote and amphiboles from Belgian Meso-Cenozoic sediments, obtained with energy-dispersive X-ray-analysis, have been examined and compared to analysis results from different possible source regions. Five garnet varieties (populations) have been recognized in detrital associations. The two most common populations, Ia and Ib, are mainly originating from Scotland and to a lesser extent from Scandinavia. Population II is derived from the Brabant Massif, whereas population III is originating from the Ardennes. The distribution of these varieties and comparison to results from the North Sea and Hampshire Basins allowed to draw conclusions on provenance of the mentioned deposits.

Varietal studies on epidote and amphiboles have been less fruitful, due to the more limited chemical variation in these minerals.

KEY WORDS

Varietal study, garnet, epidote, amphiboles, energy dispersive analysis, Meso-Cenozoic, Belgium.

SAMENVATTING

De chemische samenstelling van detrietische granaat, epidoot en amfibolen van Belgische Meso-Cenozoïsche sedimenten, bepaald met energie-dispersieve X-straal-analyse, werd onderzocht en vergeleken met analyseresultaten van verschillende mogelijke brongebieden. Vijf granaatvariëteiten (populaties) werden onderscheiden in detrietische associaties.

De twee meest frequente populaties, Ia en Ib, zijn hoofdzakelijk afkomstig van Schotland en in mindere mate van Brabant, terwijl populatie III van de Ardennen afkomstig is.

De verdeling van deze variëteiten en vergelijking met de resultaten uit het Noordzee- en Hampshire Bekken, laten conclusies toe in verband met de herkomst van de bewuste afzettingen.

Variëteitsonderzoek op epidoot en amfibolen was minder succesvol omwille van de eerder beperkte chemische variatie van deze mineralen.

SLEUTELWOORDEN

Variëteitsonderzoek, granaat, epidoot, amfibolen, energie-dispersieve analyse, Meso-Cenozoïcum, België.

RESUME

La composition chimique des grenats, épidotes et amphiboles détritiques dans les

[1] Belgian Geological Survey, Jennerstreet 13 - B-1040 Brussels.

sédiments du Méso-Cénozoique belge, obtenue par analyse aux rayons X par énergie dispersive, a été examinée et comparée aux résultats des différentes régions d'origine. Cinq variétés de grenat (populations) ont été reconnues dans les associations détritiques. Les plus fréquentes, les populations Ia et Ib, sont principalement originaires d'Ecosse, et pour une partie moins importante, de Scandinavie. La population II est issue du Massif du Brabant, tandis que la population III possède plutôt une origine ardennaise.

La répartition de ces variétés et la comparaison aux résultats obtenus dans les bassins de la Mer du Nord et de Hampshire, permettent de tirer des conclusions sur l'origine des dépôts mentionnés.

Les études de variétés exécutées sur des épidotes et amphiboles ont connu moins de succès à cause de la variation limitée de ces minéraux.

MOTS CLES

Etude de variétés, grenat, épidote, amphiboles, analyse aux rayons X par énergie dispersive, Méso-Cénozoïque, Belgique.

1. INTRODUCTION

In the past, provenance studies of detrital sediments were generally carried out by interpreting heavy mineral suites. This approach however, should only be used with the greatest prudence. Several authors pointed out that heavy mineral suites can undergo important changes, due to weathering, hydraulic differentiation and intrastratal solution (Van Andel, 1959 ; Morton, 1985b), so that the detrital suite hardly reflects the original mineral composition of the source region.

Especially intrastratal solution seems to be an important factor, since it can reduce a heavy mineral suite with 20 or 30 different species to one with only a few ultrastable minerals (Morton, 1985b).

A new approach to provenance studies was presented by Morton (1985a), who studied the chemical composition of detrital garnet grains. The different varieties of garnet, having similar hydraulic parameters and chemical behaviour, will react in a similar way to hydraulic differentiation and weathering. It is therefore unlikely that one or different garnet varieties might get enriched in or eliminated from the detrital suite. Detrital garnet compositions therefore reflect the source region.

Using varietal studies on garnet, Morton (1985a) succeeded in showing a Scandinavian and Scottish origin of sandstone from the Jurassic Brent Group, in the North Sea. In more recent publications (1987), the author identified two garnet associations in the Paleocene Forties Formation sandstone, one supplied by Grampian rocks, the other originating from the Northwestern Highlands.

Haughton & Farrow (1989) compared detrital garnet of Midland Valley Old Red Sandstone with garnet from Dalradian metamorphic units. They concluded that garnet in the Old Red Sandstone was supplied by the latter rocks.

All heavy minerals with important chemical substitution are potentially useful in varietal studies : epidote, amphiboles, pyroxenes, staurolite and tourmaline, but minerals other than garnet have had little application in varietal studies : Mange-Rajetzky & Oberhänsli (1982) analysed detrital alcali-amphiboles from Molasse deposits of Savoy and recognized their source region (French Alps - Briançonnais-zone) as well as metamorphic evolutions in that region.

2. SAMPLE PREPARATION AND ANALYSIS

More than 100 samples from Belgian Jurassic, Cretaceous and Tertiary formations have been collected on the field or in collections of the Geological Institute of the State University of Ghent (Van der Sluys, 1990). As far as possible, samples from different occurrences of each lithostratigraphic unit have been chosen, in so far as they contained the mineral concerned.

Heavy minerals were separated from the grain-size fraction 50-500µm using bromoform (d=2.89) for further treatment.

Garnet has been concentrated using electromagnetic separation. In its subfraction, garnet was nearly the only non-opaque mineral, which made it very easy to obtain pure garnet, using a vacuum tweezer for hand-picking and a binocular.

Epidote and amphiboles were concentrated in another magnetic subfraction, and hand-picked to obtain pure epidote, hornblende and actinolite samples.

The grains were mounted with polyester resin on slides, ground and polished. Their chemical composition was determined by single-grain analysis, using a Philips SEM 505 scanning electron microscope with attached energy dispersive system (EDAX). Details of the analyses are discussed for each mineral group separately.

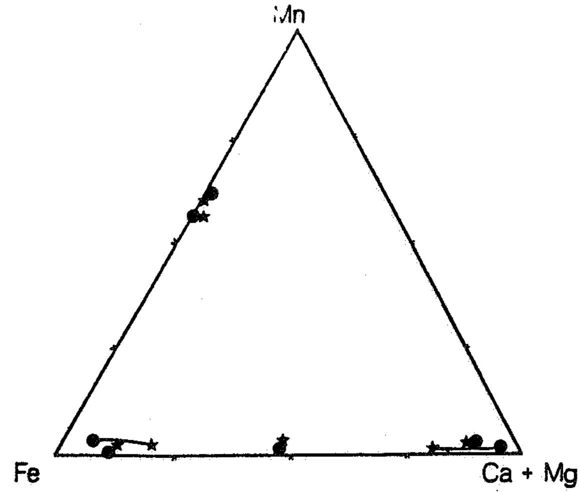

Figure 1 : Comparison between results of classical chemical analysis and EDAX-microprobe of garnet samples (. EDAX ; * AAS).

3. VARIETAL STUDIES OF SOME HEAVY MINERALS

3.1. GARNET

EDAX-analyses have been executed mainly in the semi-quantitative mode, i.e. without reference sample. Even these results are sufficiently accurate as far as the FeO/MnO/CaO/MgO-ratio is considered (fig. 2).

Garnet has been selected because it abounds in various Belgian Meso-Cenozoic deposits (Geets & De Breuck, 1979, 1981, 1983 ; Geets *et al.*, 1981, 1986a, 1986b). On the other hand, the mineral exhibits a large range of chemical compositions, the major varieties being (Deer *et al.*, 1982) :

almandine $Fe_3Al_2Si_3O_{12}$
spessartine $Mn_3Al_2Si_3O_{12}$
pyrope $Mg_3Al_2Si_3O_{12}$
grossular $Ca_3Al_2Si_3O_{12}$
andradite $Ca_3Fe(III)_2Si_3O_{12}$
uvarovite $Ca_3Cr(III)_2Si_3O_{12}$

Other substitutions of trivalent cations by Ti (melanite), V (goldmanite) or rare earth elements (hibschite, schorlomite) appear less often. This wide range of chemical compositions makes garnet very interesting for varietal studies, since these varieties often originate from completely different source rocks.

In a first stage, garnet samples have been mounted on slides and studied by polarisation microscopy.

These preliminary observations allowed recognition of at least two varieties : a pale pink-orange garnet, with little inclusions, and a far less abundant greyish-green garnet, with dusty inclusions. The second type of garnet is dominating in all samples of Cretaceous and Paleocene formations (Hesbaye) and to a lesser extent also in some Eocene deposits and in the Miocene Diest Formation. Other deposits contain exclusively pale pink-orange garnet.

To have an idea of the accuracy of the EDAX analyses, reference garnet samples, with preliminary determined chemical composition (using atomic absorption spectrometry on acid-attacked material), have been analysed with EDAX in the quantitative mode. The

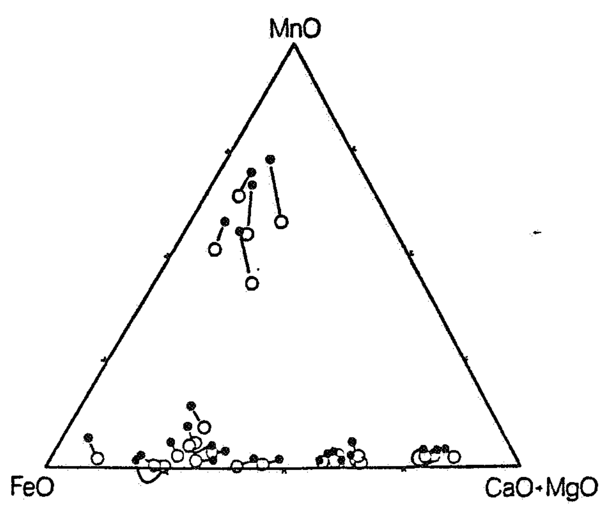

Figure 2 : Comparison between EDAX results of garnet samples, using quantitative (o) and semi-quantitative (.) modes.

results prove to be fairly accurate if the Fe/Mn/Ca/Mg ratio was considered (fig. 1). This ratio is typical for the different Al-garnet varieties.

The high content of Al and the absence of other trivalent cations pointed out that substitution with Fe(III), Cr, V, Mn(III) was negligible. All garnets were of the pyralspite (pyrope-almandine-spessartite) + grossular series.

Results were calculated and plotted in triangular diagrams with FeO/MnO/CaO+MgO and FeO+MnO/CaO/MgO, representing clearly the different chemical varieties.

3.1.1. Results

The analysis results are represented in triangular diagrams per lithostratigraphic unit (figures 3-6).

Five different garnet varieties can be identified, as shown in figure 7 :

1. **Population Ia** : Fe-rich almandine, with FeO/CaO+MgO > 4, MnO/RO < 20 % and MgO > CaO (RO=CaO+MgO+FeO+MnO)
2. **Population Ib** : Ca-rich almandine (grossular-almandine), with FeO/CaO+MgO 3-4, MnO/RO < 20 %, CaO/RO 10-25 % and MgO/RO < 10 %
3. **Population Ic** : grossular-pyrope-almandine, with FeO/CaO+MgO < 3, CaO/RO 25-35 %, MgO/RO < 10 % and MnO > 10 %
4. **Population II** : almandine-spessartine, with MnO/RO 50-75 % and CaO+MgO/RO < 15 %
5. **Population III** : Mn-rich almandine, with MnO/RO 25-40 % and variable CaO and MgO contents

Comparison with the optical properties shows no marked difference for these varieties, except for garnet of population II (spessartine), that seems to be identical to the greyish-green, dull garnet described earlier.

The relative importance of these populations is diverse and varies from unit to unit, as approximatively shown in table I.

During Upper Triassic - Lower Jurassic, population Ib is far the most important garnet variety. This changes drastically in the Cretaceous deposits, where, if they contain any detritus at all (mainly Turonian), the only garnet variety is II (spessartine). In the eastern part of Belgium (Hesbaye), population II remains the unique garnet variety during the Paleocene Heers and Landen Fms. Similar sediments in the west (Hainaut) exhibit a completely different garnet association : the importance of II is strongly reduced, the major population is Ib, with minor contributions of III and Ia.

During the whole Eocene (from the Ieper Fm. to the Kallo Fm.), the content of population Ia is increasing. This population becomes at least as important as Ib, or even more abundant. The other populations, especially III and II still do occur.

In the Brussels Fm. (Middle Eocene), population II and III become again rather important. They decline in the Lede Fm., where also Ia is reduced in comparison with Ib.

A very sharp transition is marked between the Kallo and Zelzate Fms. (limit Eocene-Oligocene). The traditional association of Eocene deposits alters abruptly into an association with a domination of Ib. All other populations nearly disappear.

This domination of Ib over Ia seems to be characteristic for all Oligocene and Neogene deposits. Only the Diest Fm. sands of the Hageland again exhibit a domination of population II, that had almost vanished since the deposition of the Brussels Fm. More to the north (Kempen area) the Diest Fm. shows the "normal" association for Neogene deposits.

The Tertiary deposits of High-Belgium, described earlier by Geets (1984), have a completely different garnet association. These sediments of different marine, littoral or continental origin, generally do not contain garnet. One sample from Ciney-Pessoux however, was very garnet-rich, and the only variety found here turned out to be Ic, a population which is completely unimportant in all other deposits examined.

3.1.2. Comparison with other basins

Samples from Tertiary deposits of South England have been examined as well as literature results from North Sea sediments (Morton, 1982, 1985a, 1987 ; Haughton & Farrow, 1989).

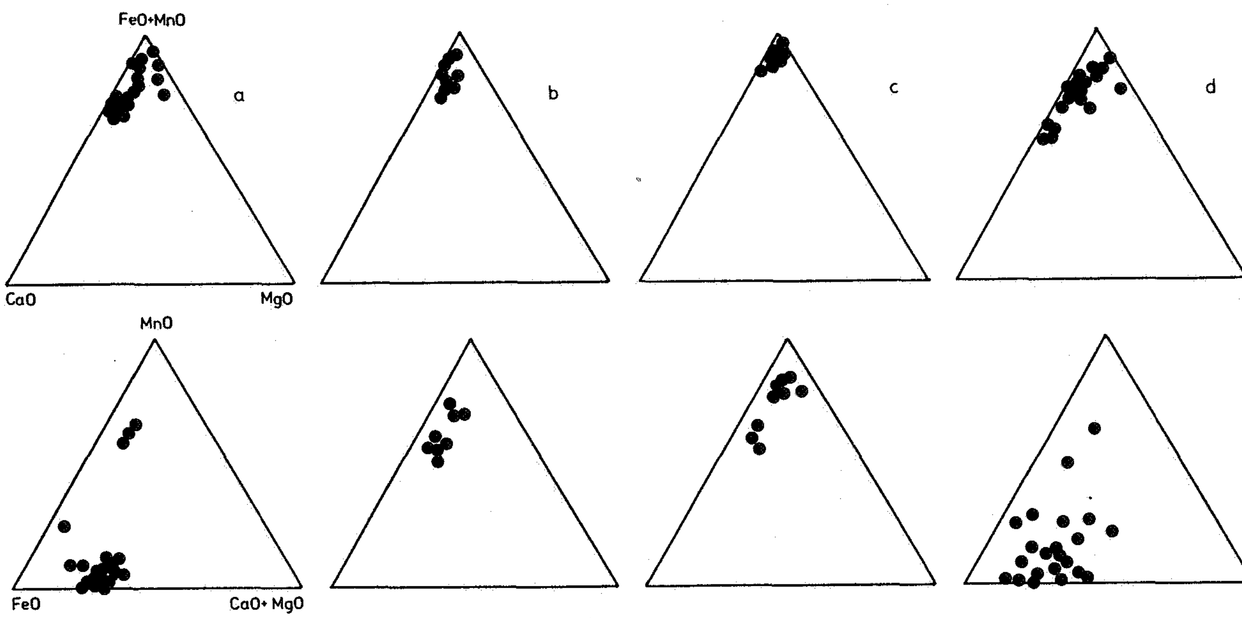

Figure 3 : Triangular diagrams of detrital garnet compositions from Meso-Cenozoic deposits of Belgium : a. Rhetian-Lias (Arlon boring, 219E254), b. Cretaceous (Weald, Turonian/Hainaut ; Senonian, Maastrichtian/Herve, Hesbaye), c. Landen Fm. (Paleocene)/Hesbaye, d. Landen Fm./Hainaut.

Garnets from the Hampshire Basin (fig. 8a-e) and Belgian Tertiary deposits are quite similar. In the Thanet Fm., Ib dominates over Ia, and minor amounts of II and III are present. This view is identical to the garnet associations in the Belgian Landen Fm. (Hainaut facies).

In the Reading Bottom Beds (limit Paleocene-Eocene), population Ia becomes more important. This was also the case in Belgian Eocene deposits. But, while in Belgian Eocene deposits, Ia remains as important Ib, Ia declines again in the Hampshire Basin, so that in the London Clay Fm. as well as in the Bracklesham Group, the importance of Ib is restored. At the end of the sequence, the Barton Fm. is characterised by the disappearing of garnet varieties II and III.

The Paleocene Forties Formation in the Central North Sea contains, according to Morton (1987) two garnet associations (fig. 8f). In the Forties Fan, a rather heterogeneous association is recognized, but the Gannet Fan contains garnet comparable to varieties Ib and Ia, as seen in the Tertiary of Belgium and Hampshire. The Gannet Fan directly originates from Scotland (Grampians).

Another interesting study (Haughton & Farrow, 1989) showed that these associations are also found in the sandstones of the Lower Devonian (Old Red Sandstone) of the Midland Valley (fig. 8g). The authors indicated that the garnet association of the O.R.S. comes from the Dalradian metamorphic rocks of the Grampians (SE Highlands).

These interpretations allow us to conclude that garnet associations of Belgium, Hampshire and North Sea Paleocene deposits (association Ib, Ia) have more or less the same composition, and are probably of the same origin, the source region which supplied already garnet during the deposition of the Old Red Sandstone, the Scottish Grampian Highlands (see also next chapter).

Rhaetian-Lias Gaume (Luxembg.) :	Ib (80) >> II (10, Ia (5), III (5)
Cretaceous	II (100)
Paleocene Heers Fm. ; Landen Fm/Hesbaye : Landen Fm./Hainaut :	II (100) Ib (48) > III (25), Ia (17), II (10)
Eocene Ieper Fm. : Mont-Panisel Fm. : Brussels Fm. Lede Fm. : Kallo Fm. :	Ia≈Ib (39) > III (9), II (8), Ic (5) Ia≈Ib (38) > III (13), II (9) Ia (22), Ib (25), II (25), III (22) Ib (58) > Ia (33), III (6) Ia (44)≈Ib (39) > III (8), II (4), Ic (5)
Oligocene Zelzate Fm. : Tongeren Fm. : Rupel Fm. : Voort Fm. :	Ib (88) >> Ia (12) Ib (57) > Ia (39) Ib (61) > Ia (37) Ib (66) > Ia (20), Ic (7)
Neogene Berchem Fm. : Diest Fm./Hageland : Diest Fm./Kempen : Kattendijk Fm. : Lillo Fm. :	Ib (63) > Ia (33) II (65) >> Ib (12), Ia (12), Ic (9) Ib (60) > Isa (40) Ib (71) > Ia (26) Ib (50), Ia (40)
Tertiary deposits of High-Belgium	Ic (100)

Table 1 : Approximative distribution of garnet populations in Belgian Meso-Cenozoic deposits, calculated on the base of the quantitative and semi-quantitative analyses. Totals not equal to 100 % indicate presence of other, not defined garnet compositions.

3.1.3. Source region determinations

One of the aims of this research was to correlate detrital garnet directly to the possible source regions. This was one of the more difficult parts of our work : though there may be a lot of information about regional geology, structure and tectonics of these regions, detailed information about frequency of minerals and their composition is much scarcer. Eventually, one can only obtain information about the present situation of the source regions, but one hardly knows anything about their situation at the moment of deposition of the sediments mentioned.

Nevertheless, we fairly succeeded in getting an image of different source regions as well. More than 500 analysis results from 170 localities were collected from the literature. They were completed with several analyses of garnet collected on the field. The regions taken under consideration were all massifs in Western and Central Europe with metamorphic and magmatic rocks :

- Brabant Massif
- Stavelot Massif (Ardennes)
- metamorphic zone of Bastogne-Libramont (Ardennes)
- Harz
- Spessart-Odenwald
- Bohemian Massif, Fichtelgebirge, Bavarian Forest
- Black Forest, Vosges
- Massif Central
- Armorican Massif
- Cornwall, Wales
- Scotland, Shetland
- Precambrian and Caledonides of Scandinavia

Analysis results of these regions were plotted in the classic triangular diagrams which we already used for detrital garnet (fig. 9a-h).

Comparison of these results with those of detrital garnet from Belgian Meso-Cenozoic

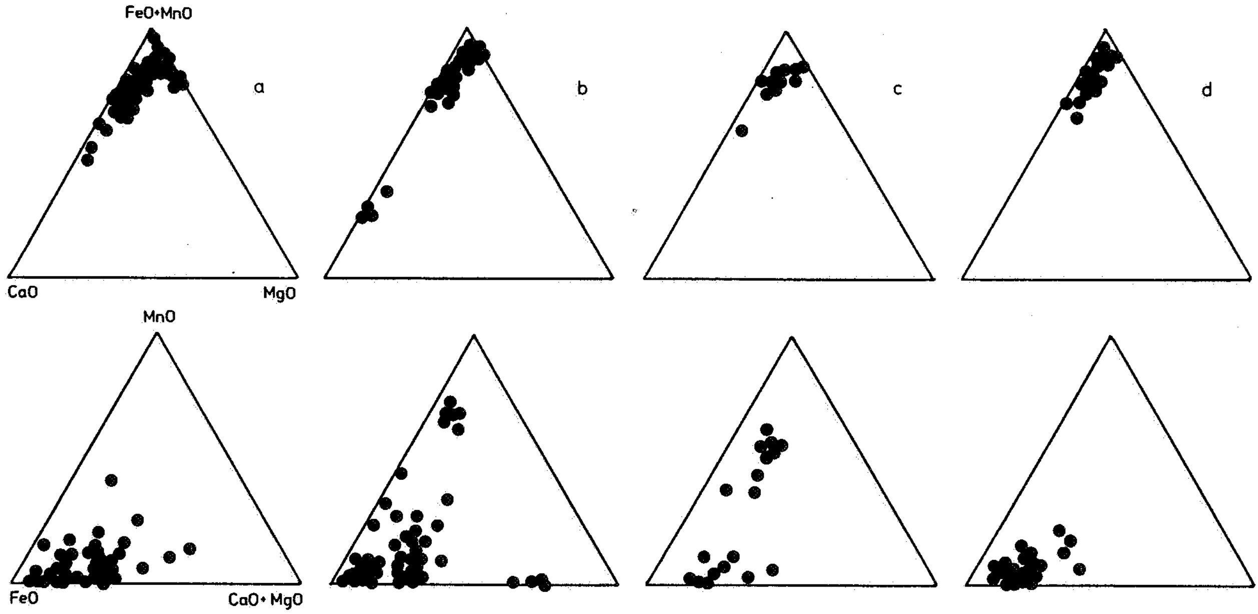

Figure 4 : Triangular diagrams of detrital garnet compositions from Meso-Cenozoic deposits of Belgium : a. Ieper Fm. (L. Eocene), b. Mont-Panisel Fm. (L. Eocene), c. Brussels Fm. (M. Eocene), d. Lede Fm.

sediments leads us to the following conclusions :

Population II is undoubtedly originating from metamorphic rocks of the Brabant Massif. This is the only region considered where spessartine of the same chemical composition occurs, without the presence of other garnet types (as with Spessart e.g., where spessartine and almandine occur). Since in most deposits where II occurs as dominant garnet type, it is not accompanied by other types, only the Brabant Massif can be responsable for this supply. The Stavelot Massif contains spessartine as well, but the iron content is much too low.

Population III can be found in Scottish metamorphic rocks (together with Ia, Ib), and in the metamorphic units of Bastogne-Libramont (Belgium). In this region, de Béthune (1977) described garnet with comparable composition from weakly metamorphic pelitic series.

Population Ib is abundantly found in the Caledonides of Norway, where gneis, eclogites and amphibolites, often very rich in garnet, occur. Garnet of other populations is much scarcer.

In the Scottish Caledonides, and especially in the Grampians, Ib occurs together with Ia, and it has already been said that this association is regularly found back throughout Belgian and South English Paleocene and Eocene deposits, as well as in North Sea Paleocene rocks and in the O.R.Sandstone of the Midland Valley. We can therefore presume a Scottish origin of associations with Ib and Ia.

Population Ia is occurring as the most important garnet species in the Precambrian of South-Scandinavia. It also occurs in the Scottish Grampians, accompanied by Ib.

Garnet of the same composition as in population Ic can be found in different parts of Scandinavian and Scottish Caledonides, but always accompanied by large amounts of Ib and Ia.

All other regions seem to be less probable as source area, since they neither contain garnet varieties that are found back in detrital associations, nor have been able to supply important detrital garnet varieties. This is especially true for Vosges and Black Forest, where metamorphic rocks mainly contain pyrope-rich garnet, being very rare in Belgian Meso-Cenozoic sediments.

It must be emphasized that we only can localize with certitude the ultimate sources of garnet varieties, since it cannot be excluded that part of the garnets (and of the deposit) have been reworked from older sediments.

3.1.4. Specific provenance problems in Belgian Meso-Cenozoic deposits

The first publications, using heavy mineral interpretation for provenance in Belgium were presented by Tavernier in 1947. The author took over the associations recognized earlier by Edelman & Doeglas (1933) in the Netherlands, and described an A-group (rich in garnet, epidote, hornblende, of Scandinavian origin), a B-group (poor in garnet, rich in parametamorphics, of south-eastern origin), and a B-group with garnet, of uncertain origin. Several other authors studied provenance problems and heavy minerals as well (De Breuck, 1959 ; Antun, 1953 ; Laruelle, 1955, 1957). This research yielded undoubtedly valuable results, but the interest in provenance determinations diminished after recognition of the potential errors in interpreting heavy mineral associations.

Interpreting our results, we can draw following conclusions for the provenance of certain Meso-Cenozoic sediments of Belgium :

1) In the Upper-Triassic - Liassic of South Belgium, garnet is mainly composed of population Ib. De Geyter (1976) suggested that garnet was reworked from older Buntsandstein deposits in the Eifel and Ardenne regions. Fransolet (1976) pointed out that this garnet ultimately had a Fennoscandian origin. This seems unlikely, for these Fennoscandian units contain rather garnet of population Ia instead of Ib. Com-

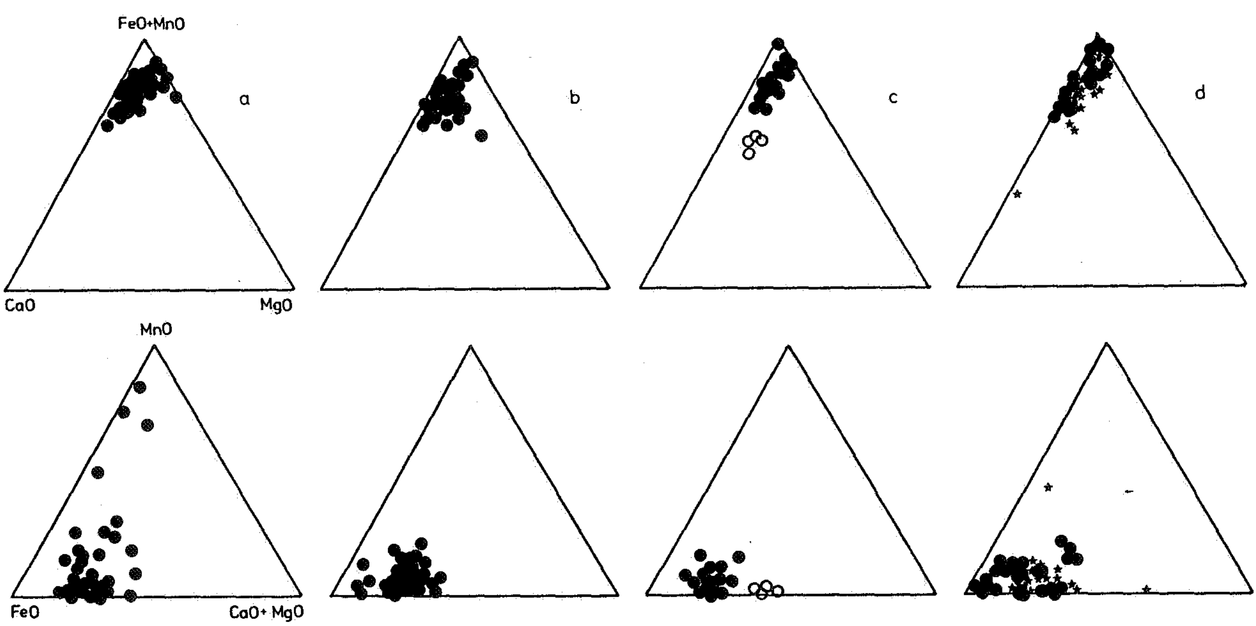

Figure 5 : Triangular diagrams of detrital garnet from Meso-Cenozoic deposits of Belgium : a. Kallo Fm. (U. Eocene), b. Zelzate Fm. (Oligocene), c. Tongeren Fm. (.) and Tertiary Fms. of High-Belgium (o), d. Rupel Fm. (.) and Voort Fm. (*).

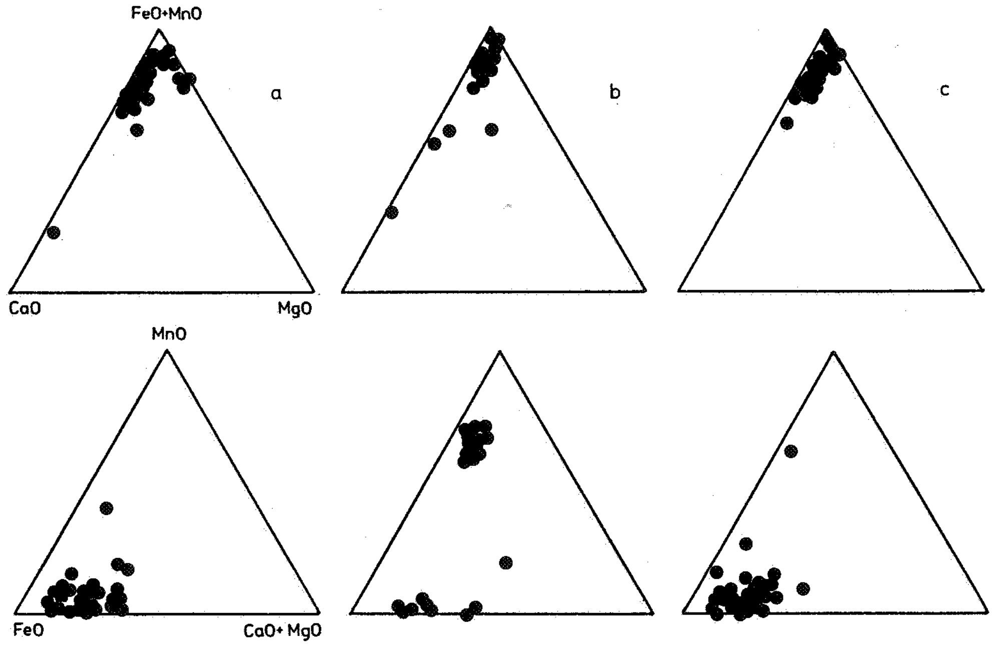

Figure 6 : Triangular diagrams of detrital garnet compositions from Meso-Cenozoic deposits of Belgium : a. Berchem Fm. (Miocene), b. Diest Fm., c. Kattendijk and Lillo Fms. (Pliocene).

parison with Triassic-Jurassic deposits of the northern North Sea (Morton, 1985a, see fig. 8h) indicate a different source region, since the garnet varieties are far from identical.

Vosges and Black Forest could theoretically be considered as source regions, regarding their proximity, but we have shown that garnet of these regions is mainly rich in Mg (pyrope-almandine), and thus different from detrital garnet in the Triassic-Liassic.

We think that garnet has indeed been reworked from earlier Buntsandstein deposits, but that these deposits originate from a southern or southwestern massif. During the deposition of Buntsandstein series, part of the detritus could have been derived from an "Ardenno-Gallian Massif", nowadays largely covered by younger deposits of the Paris Basin. As a matter of fact, metamorphic series occur in and north of the present Morvan massif, and Weber (1973) described garnetiferous amphibolites from boreholes in this region. Unfortunately, no information is available on the chemical composition of these garnets.

The minor contents of II and III are possibly due to less important detritus supply by the Ardennes and the Brabant Massif.

2) The Cretaceous deposits of Hainaut, Hesbaye and Herve contain often very little detrital material. Important garnet contents can only be found in the Turonian and in Senonian Herve sands.

All garnet is of the same type : population II. The few detritus that has therefore been supplied originates exclusively from the Brabant Massif. Allen (1989) notices the presence of high amounts of spessartine in the Weald deposits of SE England.

The abrupt change in garnet associations between the Jurassic and Cretaceous deposits could provide further evidence for an uplift of the Brabant Massif due to Cimmerian tectonism, as recently suggested by Van den Haute & Vercoutere (1989).

3) During the Paleocene, a sharp transition occurs. In the eastern part of the basin (Hesbaye), the supply of population II (possibly reworked from Cretaceous deposits)

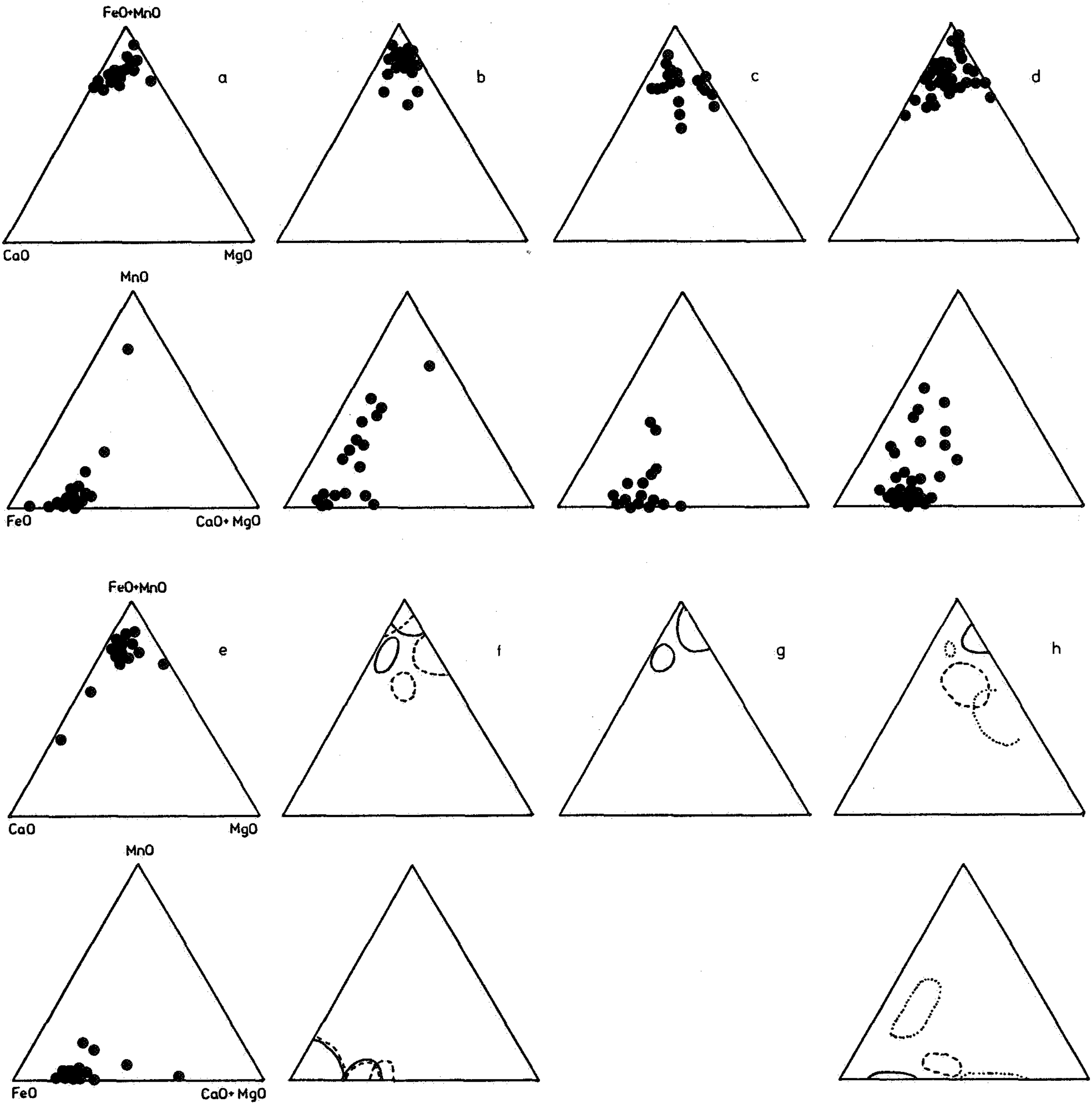

Figure 8 : Triangular diagrams of detrital garnet compositions from South England Tertiary deposits : a. Thanet Fm. (Essex), b. Reading Bottom Beds (Hampshire), c. London Clay Fm. (Hampshire), d. Bracklesham Group (Hampshire), e. Bartom Fm. (Hampshire). f. Detrital garnet compositions from Forties Fm., Central North Sea : ______ Forties association, ---- Gannet association (after Morton, 1987). g. Detrital garnet compositions from Old Red Sandstone grit, Midland Valley, Scotland (after Haughton & Farrow, 1989) h. Detrital garnet compositions from Brent Group sandstone (Middle Jurassic, Northern North Sea) : _____ association 1, ... association 2, ----- association 3 (after Morton, 1985a).

continues, but in the west there is a marked change in detrital supply. Population II diminishes and population Ib is dominating. The resemblance to Thanet Fm. garnet associations of South England and to Forties Fm. associations of the Central North Sea, allows us to suppose an important detrital supply from the Scottish Grampians.

4) In the Hampshire Basin, this association remains present till deposition of the Barton Fm. (apart from a minor interruption in the Reading Bottom Beds, where Ia ≈ Ib). In Belgian Eocene deposits, Ia becomes generally as important as Ib. This indicates a higher supply of Ia, from Fennoscandia, during this period. This additional supply influenced the Hampshire Basin in a far lesser extent, proving its direction (NE).

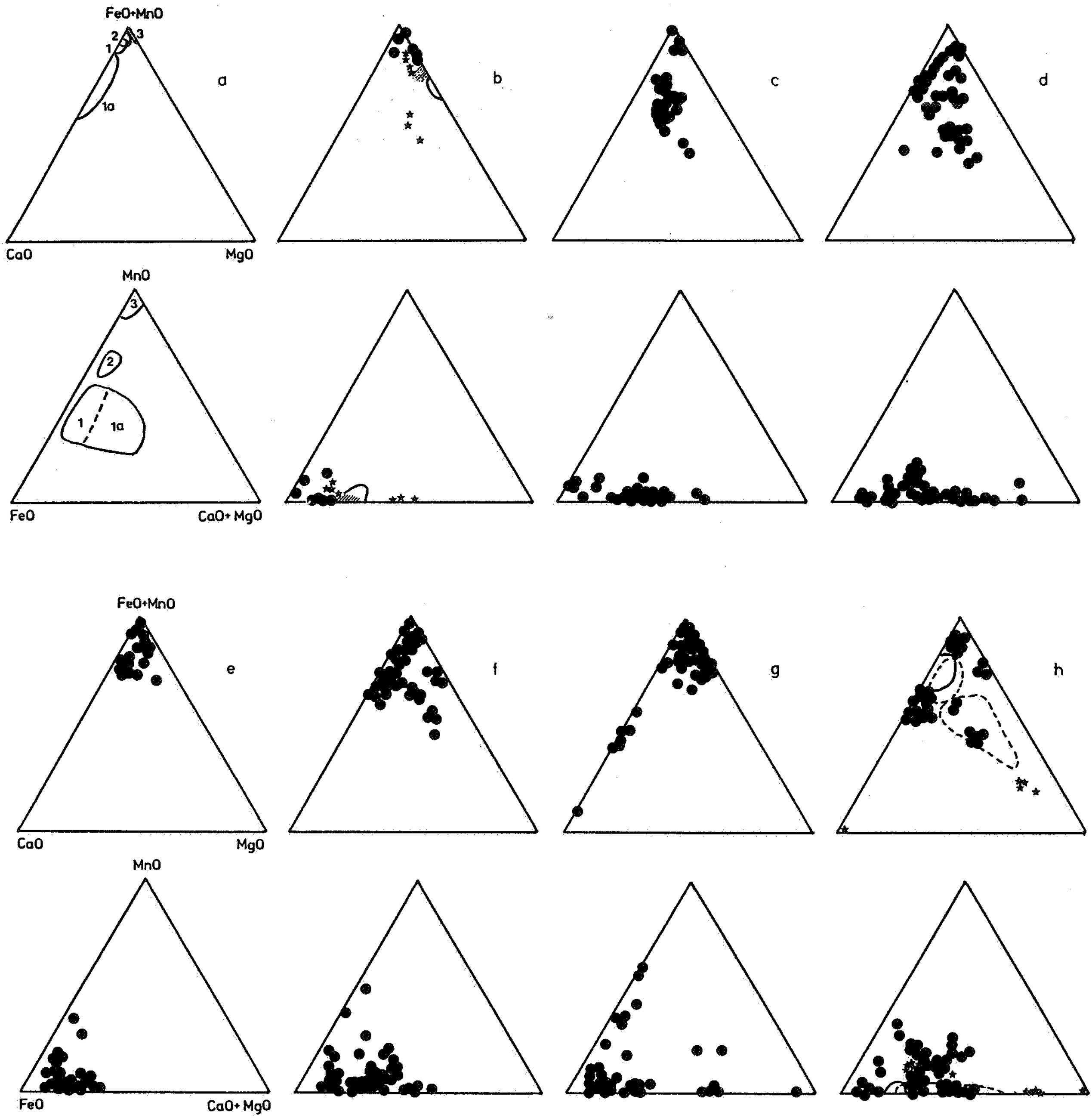

Figure 9 : Garnet geochemistry from potential source regions : a. Bastogne-Libramont metamorphic zone, metapelites (1) ; calcopelitic series (1a) ; Brabant Massif (2) ; Stavelot Massif (3), b. Black Forest (*-) and Vosges (.//), c. Central Massif, d. Armorican Massif, e. Scotland (Grampians), f. Scotland (northwestern Highlands, Shetland), g. Fennoscandian region (Precambrian of South-Scandinavia), h. Scandinavian Caledonides : .- gneiss, granulites, granitic rocks ; *-- amfibolites, eclogites, ultrabasic rocks.

Besides from this major supply, a smaller but continuous supply from the Brabant Massif and the Ardennes is indicated by the presence of II and III. During the deposition of the Brussels Fm., the supply from the Brabant Massif even becomes more important, which is quite understandable, since this formation directly erodes the massif.

5) The deposition of the Zelzate Fm. (transition Eocene-Oligocene) marks another abrupt change in detritus supply : on the one hand Ib is dominating Ia throughout the whole Oligocene-Neogene sequence, and this fact is very striking in the Zelzate Fm. On the other hand, populations II and III disappear nearly completely.

This indicates that the supply by Scottish Grampians continues (Ib, Ia), but that it is accompanied by an additional supply of detrital material rich in garnet Ib (especially in the Zelzate Fm.). This supply is originating from the Scandinavian Caledonides.

The increasing importance of Ib is also accompanied by increasing contents of epidote and hornblende in the heavy fraction. These minerals are also abundant in regions where large amounts of garnet Ib occur.

6) The deposits of the Diest Fm. show a somewhat different association. Sands of the northern facies (Kempen area) seem to have the same garnet association as other Neogene deposits, but the Hageland facies is again rich in population II.

These garnets must have been reworked, since the ultimate source region, the Brabant Massif, was completely covered at the time of deposition. The origin could be the sands of the Brussels Fm., also rich in II, or the Cretaceous deposits, because more to the west, in the Boulonnais region, the Diest Fm. is superposed directly to the Cretaceous.

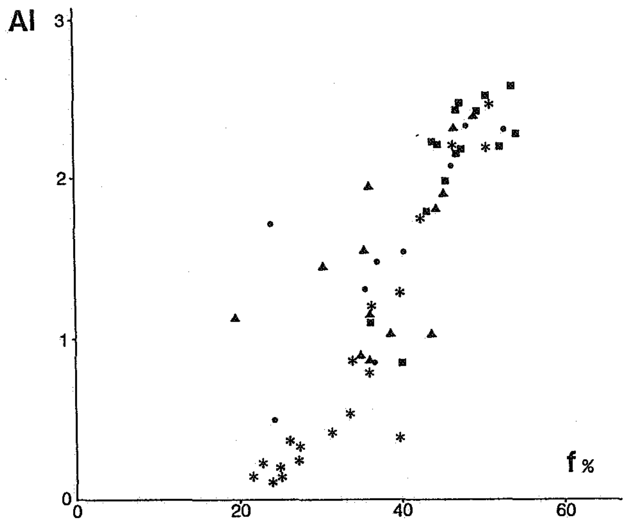

Figure 10 : Al-f-diagram of detrital calcic amphiboles, Belgian Tertiary deposits : ▲ Rumst, Rupel Fm./Boom Clay M. ; • Rumst, Berchem M. ; * Gelrode, Diest Fm. ; ■ Antwerpen, Kattendijk Fm.

7) The Tertiary deposits of High-Belgium are an even more mysterious case. These deposits are generally very poor in garnet, but Geets (1984) indicates a sand from Ciney-Pessoux containing huge amounts of this mineral. The sand seems to have been formed in a coastal, deltaic environment and may be correlated to the Tongeren Fm.

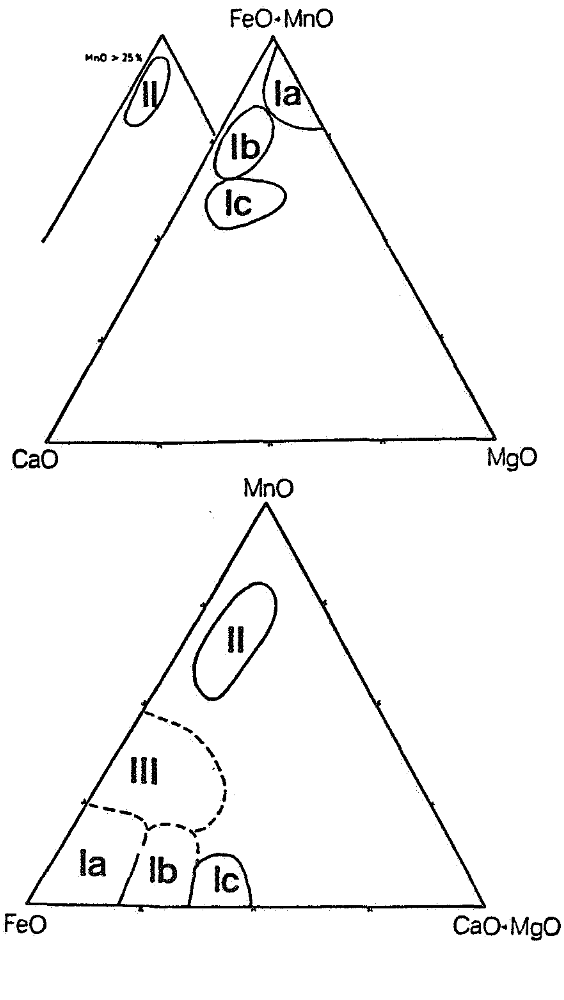

Figure 7 : Schematic overview of detrital garnet populations in Belgian Meso-Cenozoic deposits.

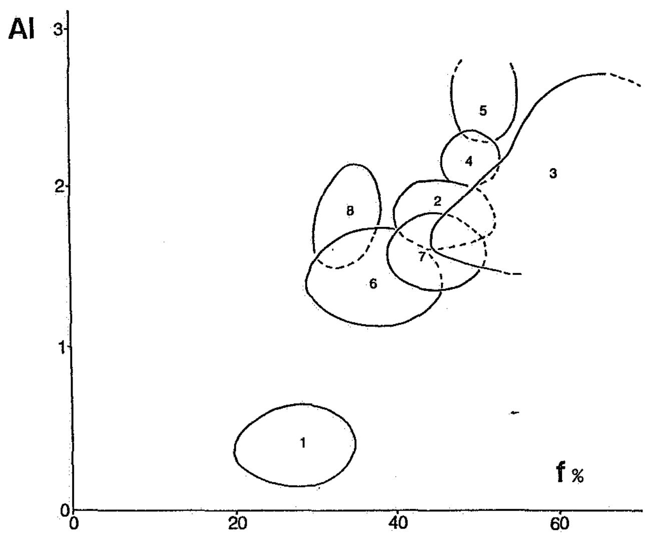

Figure 11 : Al-f-diagram of calcic amphiboles from different magmatic and metamorphic rocks (after Kostyuk & Sobolev, 1969) : 1 = greenschist facies ; 2 = epidote-amphibolite facies ; 3 = amphibolite facies ; 4 = granulite facies ; 5 = kyanite bearing rocks ; 6 = glaucophane schist ; 7 = diorite-quartzdiorite-granodioritic rocks ; 8 = gabbroid rocks.

The only garnet variety is Ic, which is rare in other deposits. Garnet of this chemical composition does not occur in the nearby Ardennes nor in the Brabant Massif. Regarding the position of the deposit, one could presume that the detrital material has been transported by a precursory river Meuse from the Vosges Massif. Yet, garnet of this massif is rich in Mg and not similar to the detrital variety found.

We can therefore find no reasonable explanation for the abundance and the specific type of garnet in the mentioned deposits of Pessoux.

3.2. EPIDOTE-GROUP

As for garnet, epidote samples of different Cenozoic deposits have been examined. Considering the absence or low contents of this group in most units, only 22 samples have been selected. Measurements were carried out by EDAX, using epidote reference samples. Analysis results were presented in $Al_2O_3/Fe_2O_3/CaO$ - diagrams.

The results showed that there is no marked variation in chemical composition of the detrital epidote. All analysed grains have high iron contents and belong to the variety of epidote s.s. (pistacite). Clinozoisite and piemontite are lacking.

Unfortunately, epidote of this composition can be found in a wide range of magmatic and metamorphic rocks. Large amounts of this mineral are reported to occur in the Scandinavian and Scottish Caledonides.

3.3. AMPHIBOLE GROUP

Amphiboles are an important component of Oligocene and even more of Neogene formations of Belgium. The main amphiboles are hornblende and actinolite, other representatives, such as alcali-amphiboles, are much rarer.

From these deposits samples have been selected and analysed. Regarding the rather limited spread of this group, only 4 samples have been analysed. Results have been plotted in $FeO/MgO/Al_2O_3$-diagrams.

The Ca-content seems to be rather constant, Na and K-contents are very low, often below the detection limit, which indicates that nearly all amphiboles belong to the so-called group of calcic amphiboles.

In the diagrams, three groups can be distinguished : a group of Al-poor amphiboles, with chemical compositions comparable to actinolite, a dominating group with higher Al-content, comparable to common hornblende, and a less important group of intermediate composition. Actinolite is only dominant in the Diest Fm., yet the general amphibole content in these deposits is very low.

We also plotted the results in a simplified Al-f-diagram (Kostyuk & Sobolev, 1969 ; fig. 10), where f=Fe+Mn/Fe+Mn+Mg, and compared them to results of the authors (fig. 11). We can conclude that the hornblendes are mainly derived from rocks of the amphibolite-, epidote- amphibolite- and granulite-facies, and from dioritic rocks. The actinolites originate from greenschist-facies rocks.

Comparison with data from different source regions confirms these conclusions. Again, Scotland and especially the Caledonides of Scandinavia are the most probable source regions, since in these areas, amphibole-rich rocks are abundant.

The scarceness of amphiboles in formations older than the Oligocene seems to be related to the lower stability compared to garnet and epidote.

4. CONCLUSION

Garnet is the most interesting mineral for varietal studies, for it shows an important chemical variation and abounds in various Meso-Cenozoic deposits. Energy-dispersive X-ray analysis is fairly accurate to define different garnet varieties, even when used in the semi-quantitative mode.

In the Meso-Cenozoic deposits of Belgium, 5 more or less important garnet "populations" can be distinguished.

Population Ia, of Fennoscandian Precambrian or of Scottish (Grampians) origin, and population Ib, originating from Scottish or Scandinavian Caledonides, are the most important ones. Population Ic, of uncertain origin, is of minor importance.

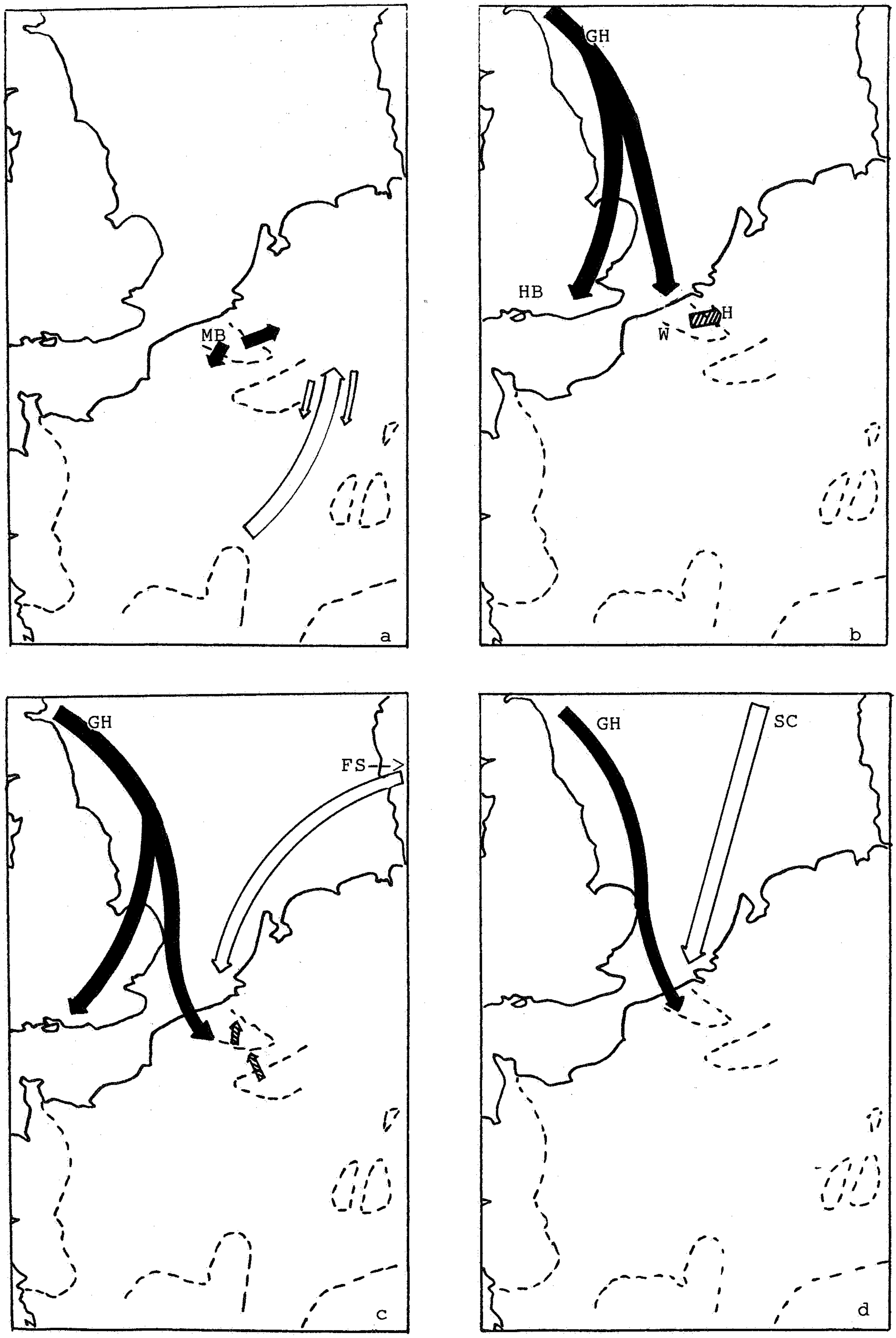

Figure 12 : Detrital supply evolution in the Belgian Basin : a. Lias (white arrow) - Cretaceous (black arrow) ; b. Paleocene (Heers & Landen Fm.) ; c. Eocene ; d. Oligocene - Neogene. MB = Brabant Massif GH = Grampian Highlands FS = Fennoscandia SC = Scandinavian Caledonides HB = Hampshire Basin W = Western Belgium H = Hesbaye.

Population II apparently is derived from the Brabant Massif, whereas population III is identical to garnet of metamorphic rocks of the Ardennes.

Epidote and amphiboles are less interesting, since their chemical variation is less expressed. Nevertheless, it is not excluded that much more information might be gained by studying the minor and trace elements of these minerals.

By means of the results mentioned above, we notice a marked evolution in detrital supply during deposition of the Mesozoic and Tertiary sequence in the Belgian Basin (fig. 12).

The Jurassic detrital deposits of Gaume have probably been reworked from older Buntsandstein deposits. The ultimate source region could have been metamorphic units in the now covered "Ardenno-Gallian Massif". The first deposits of the Cretaceous show an abrupt change : the detritus is now supplied from the Brabant Massif. This is also true during deposition of the Heers and Landen Formations in the eastern part of the Basin (Hesbaye). On the other hand, the Landen Formation in Western Belgium is characterized by a typically Scottish detrital supply, comparable to the one of the Hampshire and North Sea Basins. The Scottish supply continues throughout the whole Tertiary sequence, although from the Oligocene Zelzate Formation on, the supply from the Scandinavian Caledonides considerably increases. Other source regions are of a minor importance during the Eocene. Their influence completely disappears after the Eocene, except for the Diest Formation (Hageland).

Varietal studies prove to be a valuable tool in sediment provenance determinations. The only major problem is the need for detailed information of the source regions (petrology, mineralogy, chemical analyses).

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REFERENCES

ALLEN, P., 1989 - Provenance prospects, aspects and retrospectives : mainly Torridonian and Wealden. *Developments in sedimentary provenance studies*, meeting, London.

ANTUN, P., 1953 - Les associations des minéraux denses du Mésozoïque luxembourgeois. *Ann. Soc. Géol. Belg.*, ***76***: 249-271.

de BETHUNE, S., 1977 - Les minéraux de la zone métamorphique de Libramont. *Serv. Géol. Belg., Prof. Paper* ***142***, 42 p.

DE BREUCK, W., 1959 - Bijdrage tot de kennis van de sediment-petrologie van het Tertiair van België. *Ph. Thesis., R.U.Gent*, unpubl., 141 p.

DEER, W.A., HOWIE, R.A. & ZUSSMAN, J., 1982 - Rock-forming minerals, volume 1a : Orthosilicates. Longman Group, London, 919 p.

DE GEYTER, G., 1976 - De Onder-Lias gesteenten van de boring van Aarlen - een sediment-petrografisch onderzoek. *Belg. Geol. Dienst, Prof. Paper*, ***1976/4***, 90 p.

EDELMAN, C.H. & DOEGLAS, D.J., 1933 - Bijdrage tot de petrologie van het Nederlandsche Tertiair. *Verhand. Geol.-Mijnbouwk. Genootsch.*, ***10***: 1-38.

FIEGER, U. & MÜLLER, W., 1987 - Energy-dispersive X-ray micro-analysis in the scanning electron microscope : an experience report. *N. Jb. Miner.*, ***1***: 1-7.

FRANSOLET, A.M., 1970 - Recherches minéralogiques dans le Permo-Trias des sondages de Campine. *Ann. Soc. Géol. Belg.*, ***93***: 203-245.

GEETS, S., 1984 - Bijdrage tot de kennis van de sedimentpetrologie van Tertiaire afzettingen in Hoog-België. *Belg. Gzol. Dienst, Prof. Paper*, ***213***, 230 p.

GEETS, S. & DE BREUCK, W., 1979 - De zware-mineralen inhoud van Belgische Mesozoïsche en Cenozoïsche afzettingen. A. Trias en Jura. *Natuurwet. Tijdschr.*, ***61***: 89-107.

GEETS, S. & DE BREUCK, W., 1981 - De zware-mineralen inhoud van Belgische Mesozoïsche en Cenozoïsche afzettingen. B. Infra-Cretacische Groep en Krijt. *Natuurwet. Tijdschr.*, **62**: 11-41.

GEETS, S. & DE BREUCK, W., 1983 - De zware-mineralen inhoud van Belgische Mesozoïsche en Cenozoïsche afzettingen. D. Onder-Eoceen. *Natuurwet. Tijdschr.*, **64**: 3-25.

GEETS, S., DE BREUCK, W. & DE GEYTER, G., 1981 - De zware-mineralen inhoud van Belgische Mesozoïsche en Cenozoïsche afzettingen. C. Paleoceen. *Natuurwet. Tijdschr.*, **62**: 139-171.

GEETS, S., DE BREUCK, W. & JACOBS, P., 1986a - De zware-mineralen inhoud van Belgische Mesozoïsche en Cenozoïsche afzettingen. E. Midden-en Boven-Eoceen. *Natuurwet. Tijdschr.*, **67**: 3-25.

GEETS, S., DE BREUCK, W. & JACOBS, P., 1986b - De zware-mineralen inhoud van Belgische Mesozoïsche en Cenozoïsche afzettingen. F.Eo-Oligocene overgangslagen en Oligoceen. *Natuurwet. Tijdschr.*, **68**: 74-128.

HAUGHTON, P. & FARROW, C., 1989 - Compositional variation in Lower Old Red Sandstone detrital garnets from the Midland Valley of Scotland and the Anglo-Welsh Basin. *Geol. Mag.*, **126/4**: 373-396.

KOSTYUK, E.A. & SOBOLEV, V.S., 1969 - Paragenetic types of calciferous amphiboles of metamorphic rocks. *Lithos*, **2**: 67-81.

LARUELLE, J., 1955 - Bijdrage tot de petrologie van de Palaeozoïsche sokkel en van de residuaire deklagen in Hoog-België (I). *Natuurwet. Tijdschr.*, **37**: 209-228.

LARUELLE, J., 1957 - Bijdrage tot de petrologie van de Palaeozoïsche sokkel en van de residuaire deklagen in Hoog-België (II). *Natuurwet. Tijdschr.*, **39**: 82-97.

MANGE-RAJETZKY, M. & OBERHÄNSLI, R., 1982 - Detrital lawsonite and blue sodic amphibole in the Molasse of Savoy, France and their significance in assessing Alpine evolution. *Schweiz. Miner. Petr. Mitt.*, **62**: 415-436.

MORTON, A.C., 1982 - Heavy minerals of Hampshire Basin Palaeogene strata. *Geol. Mag.*, **119/5**: 463-476.

MORTON, A.C., 1985a - A new approach to provenance studies : electron microprobe analysis of detrital garnets from Middle Jurassic sandstones of the northern North Sea. *Sedimentology*, **32**: 553-566.

MORTON, A.C., 1985b - Heavy minerals in provenance studies. *In* : Zuffa, G.G. (Ed.), *Provenance of arenites*. Reidel Publishing Company, Dordrecht, 249-277.

MORTON, A.C., 1987a - Detrital garnets as provenance and correlation indicators in North Sea reservoir sandstones. *In* :Brooks, J. & Glennie, K. (Eds.). *Petroleum Geology of NW Europe*. Graham & Trotman, London, 991-995.

MORTON, A.C., 1987b - Influences of provenance and diagenesis on detrital garnet suites in the Paleocene Forties Sandstone, Central North Sea. *J. Sed. Petrol.*, **57**: 1027-1032.

TAVERNIER, R., 1947 - Aperçu sur la pétrologie des terrains post-paléozoïques de la Belgique. *In* : La géologie des terrains récents dans l'ouest de l'Europe. C.R. Sess. extraord. des Soc. belges Géol. (19-26 septembre 1946)., Hayez Imp., Bruxelles, 69-90.

VAN ANDEL, T.H., 1959 - Reflections on the interpretation of heavy mineral analyses. *J. Sed. Petrol.*, **29**: 153-163.

VAN DEN HAUTE, P. & VERCOUTERE, C., 1989 - Apatite fission-track evidence for a Mesozoic uplift of the Brabant Massif : preliminary results. *Ann. Soc. Géol. Belg.*, **112**: 442-452.

VAN DER SLUYS, J., 1990 - Onderzoek naar mogelijke herkomstgebieden en studie van oppervlaktekenmerken van enkele zware mineralen uit Belgische Meso-Cenozoïsche afzettingen. *Ph. D. Thesis, R.U.Gent*, unpubl., 110 p.

WEBER, C., 1973a - Le socle antétriassique sous la partie sud du Bassin de Paris d'après les données géophysiques (partie I). *Bull. B.R.G.M.*, ***II/3***: 219-292.

WEBER, C., 1973b - Le socle antétriassique sous la partie sud du Bassin de Paris d'après les données géophysiques (partie II). *Bull. B.R.G.M.*, ***II/4***: 293-343.

ZWART, H.J. (Ed.), 1978 - Metamorphic map of Europe. *Subcomm. Cart. Metam. Belts World*, Leiden, 244 p.

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