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EOCENE SEDIMENT SUPPLY IN WESTERN BELGIUM AS DETERMINED THROUGH HEAVY MINERAL DISTRIBUTION

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The distribution of heavy minerals in Middle to Upper Eocene deposits of western Belgium is discussed with reference to ternary diagrams based on density (<3.4; 3.4-4.2; >4.2) and mineralogical composition (ubiquist, parametamorphic and garnet-epidote-amphibole-pyroxene groups). A corresponding diamond diagram is used to interpret the transport mode and the energy of the sedimentary environment.
The Aalter Formation (middle Eocene), which was deposited in a quiet to turbulent coastal setting, contains high amounts of ubiquists, parametamorphic minerals and garnets, with a minor epidote and amphibole content. The Maldegem Formation (middle to late Eocene) of deltaic origin, is characterised by the dominance of ubiquists, particularly in the sands and silts. Garnets, parametamorphic minerals and small amounts of epidotes also occur. The heavy mineral distribution of the Zelzate Formation (late Eocene), an intertidal sand flat deposit, is similar to that of the Maldegem Formation, although it contains fewer parametamorphic minerals and more epidote and amphibole.
Intrastratal dissolution of garnet due to subaerial weathering or continuous ground water flows occurred under shallow burial of the Maldegem and Zelzate formations in part of the study area. On the basis of palaeogeographical considerations, it is concluded that the Middle and Upper Eocene sediments were supplied by a precursor of the Rhine-Meuse-Scheldt delta sourced from western European massifs. This is opposed to earlier suggestions assuming a northerly origin from the British Isles or Fennoscandia.

Key words — Eocene, Belgium, heavy minerals, source area, palaeogeography, lithostratigraphy.

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CONTENTS

INTRODUCTION

The study area is situated in northwestern Belgium, between the Belgian-Dutch border, Sint-Niklaas, Brussels, Gent, Oostende and the North Sea (Fig. 1). The Tertiary substratum occurring under a Quaternary cover of varying thickness (usually <5 m, but exceptionally up to 20 m), consists of alternating sand and clay layers of Eocene age. The main physiogeographical units are the following (Fig. 1):

- the 'Hills of Oedelem-Zomergem-Adegem' in the west (elevation +28 m; study area I; boreholes 58 DB 6, 65 DB 3, 132 DB 3, 133 DB 12, 136 DB 1, 136 DB 2, 136 DB 4, 137 DB 4, 137 MB 1 and 137 MB 9);
- the 'Land of Waas' in the east (elevation +35 m; study area II; boreholes 148 DB 2, 148 DB 3, 148 DB 4, 148 DB 5, 148 DB 6 and outcrop 148 E 3);
- the 'Plateau of Brabant' in the south (elevation +80 m; study area III; boreholes 235 DB 1, 235 MB 1, 235 MB 2 and 311 DB 1).

These three study areas occupied different positions in the Eocene North Sea Basin: study area III was situated at the shallow southern border, whereas the other two extended further to the north, in the direction of the deeper open sea.

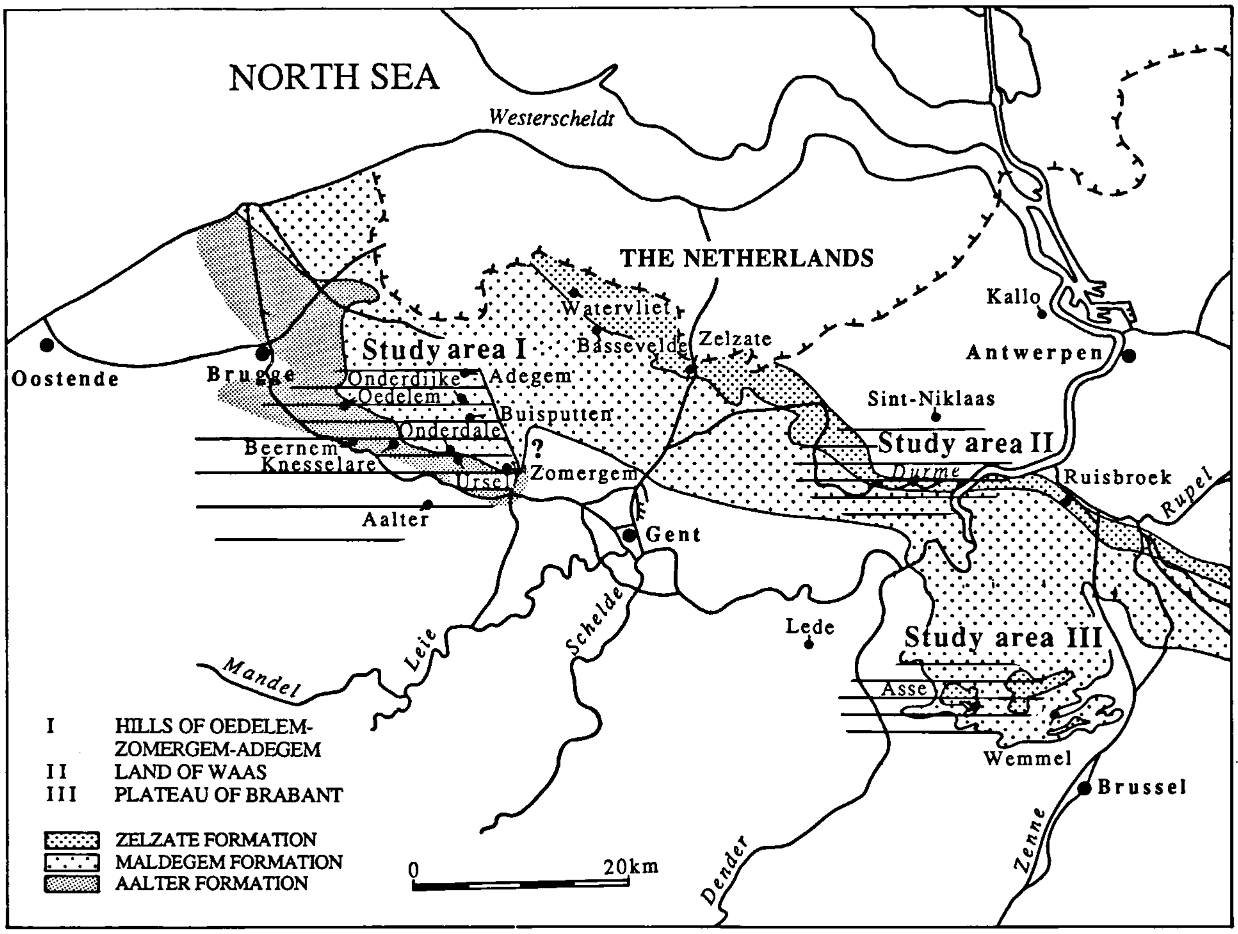

Fig. 1. Geological map showing the location of the study areas I-III.

LITHOSTRATIGRAPHY

Our present knowledge of Eocene stratigraphy in the study area is largely the outcome of research by Rutot (1882a, b), Mourlon (1888), Leriche (1912, 1922) and, more recently, by Gulinck (1965, 1969a, b). The lithostratigraphy of the transitional layers between the Eocene and Oligocene in northwestern Belgium was thoroughly revised by Jacobs (1975). Maréchal & Laga (1988) provided a detailed revision of Palaeogene lithostratigraphy, which currently forms the basis for the new geological map of Belgium, Flanders region (Fig. 2).

— *Lithology*

The type sections of the formations investigated are located in study area I (Jacobs, 1975); they have here been compiled into a synthetic lithostratigraphical log (Figs 3-5).

Aalter Formation

The middle Eocene Aalter Formation of tidal to subtidal and lagoonal origin is restricted to study area I. It comprises mainly glauconitic sandy to slightly clayey sediments, slightly calcareous to highly fossiliferous. Sediment packages are of (pluri)metric thickness (Fig. 3).

1 - Beernem Member: grey-greenish, slightly glauconitic and micaceous, medium-fine to fine clayey sand to sandy clay, slightly calcareous, containing grey-greenish glauconitic thin arenite beds of cemented sediment.

2 - Oedelem Member: pale grey, medium-fine to fine sand, slightly glauconitic and calcareous, with a profusely fossiliferous upper part and a lower part with fewer fossils, but containing shell debris and occasionally large specimens of the bivalve *Megacardita planicosta lerichei* Glibert & van de Poel, 1971. Occasionally three calcarenite horizons occur.

3 - In the Aalter area, the Oedelem Member is represented by a brown - greenish glauconitic, very fine

<table>
<tr><th rowspan="3">SERIES</th><th colspan="3">LITHOSTRATIGRAPHY</th><th rowspan="3">Old stratigraphy</th><th rowspan="3">Symbol old geological maps</th></tr>
<tr><th colspan="3">New names</th></tr>
<tr><th>Group</th><th>Formation</th><th>Member</th></tr>
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<tr><td><u>Watervliet</u></td></tr>
<tr><td><u>Bassevelde</u></td></tr>
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<tr><td><u>Ursel</u></td><td>Asc</td></tr>
<tr><td><u>Asse</u></td><td>Asb-a</td></tr>
<tr><td><u>Wemmel</u></td><td>Wemmelian</td><td>We</td></tr>
<tr><td rowspan="4">Middle Eocene</td><td rowspan="4">Zenne</td><td colspan="2">Lede</td><td>Ledian</td><td>Le</td></tr>
<tr><td>Brussel</td><td>5 Members</td><td>Brusselian</td><td>B</td></tr>
<tr><td rowspan="2"><u>Aalter</u></td><td><u>Oedelem</u></td><td>Upper Paniselian</td><td>P2</td></tr>
<tr><td><u>Beernem</u></td><td colspan="2">not recognised</td></tr>
<tr><td rowspan="9">Lower Eocene</td><td rowspan="9">Ieper</td><td rowspan="3">Gent</td><td>Vlierzele</td><td rowspan="3">Lower Paniselian</td><td>P1d</td></tr>
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<tr><td>Kortemark</td><td rowspan="4">Yc</td></tr>
<tr><td rowspan="4">Kortrijk</td><td>Aalbeke</td></tr>
<tr><td>Moen</td></tr>
<tr><td>Saint-Maur</td></tr>
<tr><td>Mont-Héribu</td><td>Yb-a</td></tr>
</table>

Fig. 2. Eocene lithostratigraphy (simplified and adapted after Maréchal & Laga, 1988) with indication of lithostratigraphic units discussed in the text.

sand, rich in fossils and fossil fragments (mainly of *M. planicosta lerichei*). These are the so-called 'Aalter Sands' and the lateral 'Aalter Sands facies'.

Maldegem Formation

The middle to late Eocene Maldegem Formation displays a clear alternation of massive clays and clayey fine sands of metric to decimetric thickness (Fig. 4). Transitions between all lithostratigraphical units are gradual. Sedimentation took place on the shelf in a shallow marine environment, repeatedly shifting between an open mud shelf and a tidal flat, under influence of river, lagoon, estuarine and delta front sedimentation (Jacobs, 1975; Jacobs & Sevens, 1988).

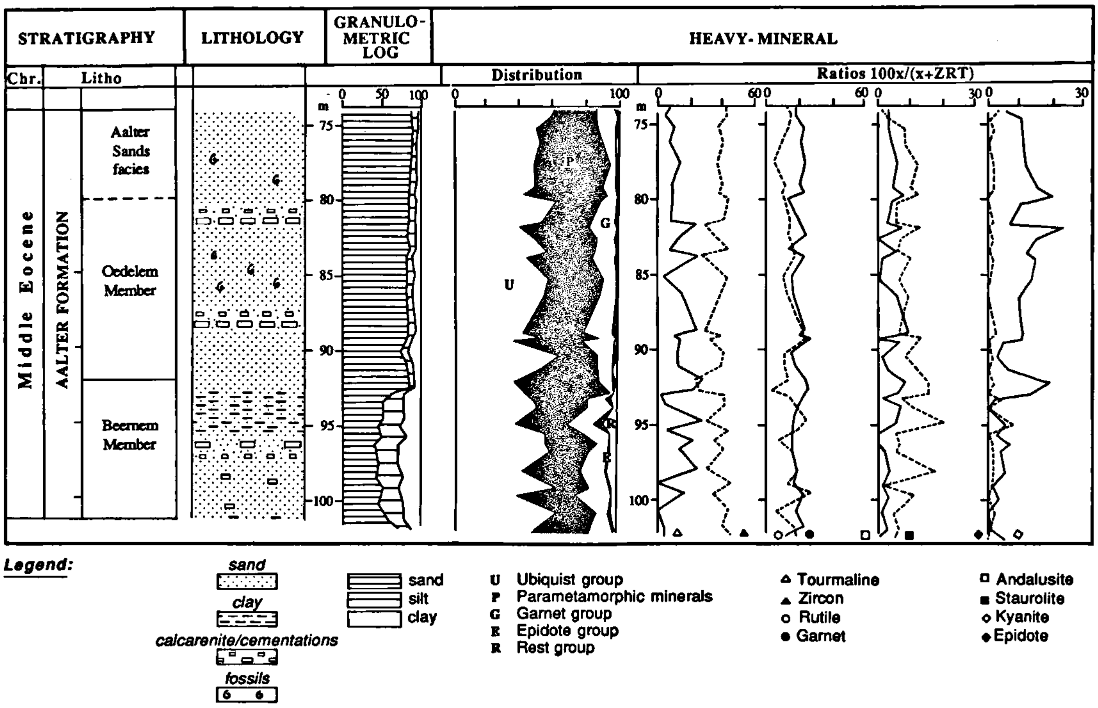

Fig. 3. Aalter Formation: stratigraphy, lithology, grain size (%), heavy mineral distribution (%) and heavy mineral ratios for study area I.

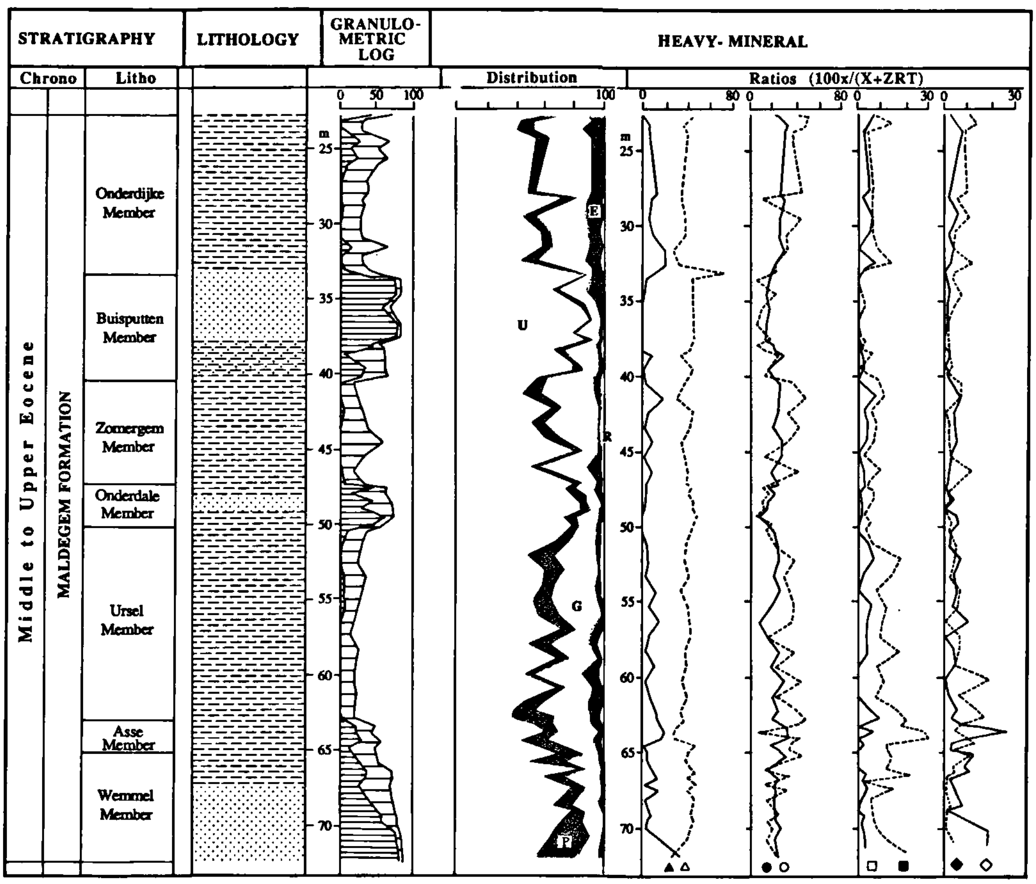

Fig. 4. Maldegem Formation: stratigraphy, lithology, grain size (%), heavy mineral distribution (%) and heavy mineral ratios for study area I.

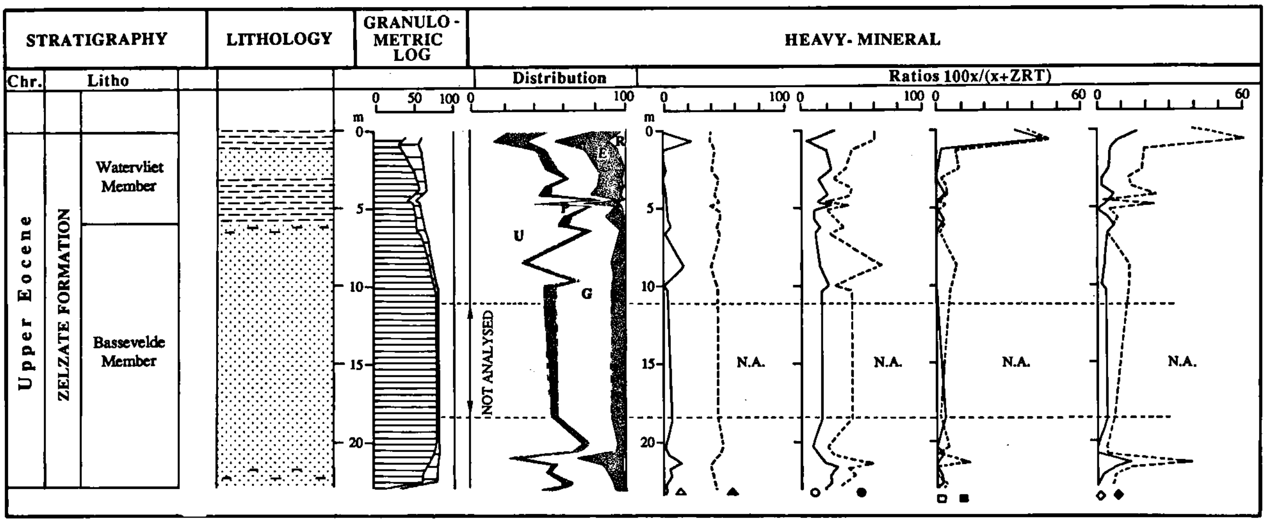

Fig. 5. Zelzate Formation: stratigraphy, lithology, grain size (%), heavy mineral distribution (%) and heavy mineral ratios for study area I.

1 - Wemmel Member: calcareous, grey, glauconitic, silty fine sand at the base, with rounded, small, fossiliferous calcarenite pebbles, milky white quartz grains and shell debris. There is a gradual transition towards a calcareous, bluish grey, heavy clay, glauconitic, with shell debris, the benthic foraminifer *Nummulites wemmelensis* de la Harpe & van den Broeck, 1883 [= *N. orbignyi* (Galeotti, 1837)], and sand intercalations.

2 - Asse Member: greenish grey, heavy clay, glauconitic, calcareous, with pyrite concretions and shell debris, slightly micaceous. The basal part is a distinct glauconitic sand bed, the so-called 'bande noire'.

3 - Ursel Member: homogeneous, grey or bluish grey heavy clay, non-calcareous, with pyrite concretions.

4 - Onderdale Member: homogeneous, greenish grey, medium-fine to fine sand, silty, glauconitic and micaceous, non-calcareous.

5 - Zomergem Member: grey heavy clay, non-calcareous, with pyrite concretions, locally laminated, and sporadically containing fine sand.

6 - Buisputten Member: dark grey to green, silty medium-fine sand, slightly glauconitic and micaceous, non-calcareous, with pyrite concretions.

7 - Onderdijke Member: dark grey, non-calcareous, slightly glauconitic and micaceous, heavy clay, containing at the top several thin, peaty layers, and small burrows, filled with peaty sand.

Zelzate Formation

The late Eocene Zelzate Formation is an alternation of glauconitic, fine sandy to sandy-clayey intertidal sediments of (pluri)metric thickness (Fig. 5).

1 - Bassevelde Member: dark green, silty, medium-fine to fine sand, glauconitic and micaceous, non-calcareous, with pyrite concretions and occasionally thin, friable arenite concretions. In the basal part fine shell debris occurs. On the sharp contact with the underlying Onderdijke Member, small broken and rounded flint and milky white quartz pebbles are found.

2 - Watervliet Member: non-calcareous, micaceous, dark green, glauconitic, sandy clay, with frequent pyrite concretions. There is a gradual transition to the underlying Bassevelde Member.

— *Grain size*

Grain size versus depth plots for all analysed samples of the synthetic lithostratigraphical logs are shown in Figs 3-5. The data are based on Jacobs's (1975) lithostratigraphical study.

In general the basal members of the Maldegem Formation have the finest grain size. The most clayey textures are to be found in the western part of the study area (hills of Oedelem-Zomergem-Adegem); an exception is the Buisputten Member in the Plateau of Brabant region (Jacobs, 1975). There is an overall coarsening-upward trend, with three fining-upward parasequences. The Zelzate Formation also shows a fining-upward trend, while the Aalter Formation displays first a fining-upward, and then a coarsening-upward trend.

HEAVY MINERAL DISTRIBUTION

Line countings of 100 transparent heavy minerals in the total sand fraction (500-50 μm) were carried out for core samples from the type sections of each of the investigated lithostratigraphical units (Jacobs, 1975) and are here summarised in Tables 1 to 12. The results were later plotted for each lithostratigraphical unit in a joint paper (Geets *et al.*, 1985, 1986). Figures 3 to 5 illustrate detailed stratigraphy, lithology, grain size (%), heavy mineral distribution (%) and heavy mineral ratios for the investigated formations in study area I. This area includes the thickest and most complete combined section, consisting of boreholes 65 DB 3, 58 DB 6, 133 DB 12, 132 DB 3 and 136 DB 4 (Jacobs, 1975).

1 - Subdivisions

The studied heavy minerals can be divided mineralogically into seven groups:

- ubiquist (U) group: tourmaline, zircon, rutile, anatase, brookite;
- parametamorphic (P) minerals: andalusite, staurolite, kyanite, sillimanite, chloritoid;
- garnet group: garnet varieties;
- epidote group: epidote varieties, zoisite, clinozoisite;
- pyroxene group: augite, diopside (these are extremely rare);
- amphibole group: hornblende varieties, actinolite, glaucophane, tremolite;
- rest group: apatite, corundum, topaze, titanite, monazite (these are rather rare).

Heavy mineral assemblages reflect source rock composition and thus provenance, and provide information on selection by chemical or mechanical weathering during transport. They also document post-depositional processes like diagenesis or intrastratal solution.

The heavy minerals can also be grouped into different density classes:

- class I: density < 3.4
- class II: density between 3.4 and 4.2
- class III: density > 4.2

The result of choosing these density values is as follows:

- separation of the ubiquists: tourmaline (class I), rutile (class II), zircon (class III);
- separation of the parametamorphic minerals: staurolite and kyanite (class II) from andalusite and sillimanite (class I);
- separation of the garnet group (class II) from the epidote group (class I);
- separation of the amphibole group (class I) from the pyroxene group (class II);

2 - Graphical representations

The mineralogical ternary diagrams of Fig. 6 are based on the percentages of the U-, P- and G-groups. The last-named group in Fig. 6 represents the total of the garnet, epidote, pyroxene and amphibole groups. Different heavy mineral compositions are interpreted to reflect primarily the provenance of the sediments. The density ternary diagrams differentiate sediments by means of the three density classes, and indicate primarily the energy of the transport medium and of the sedimentary environment. The diamond diagrams combine the information on provenance and the energy of the ternary diagrams by plotting the (U + P)- *vs* G-group on two opposite sides of the diagram, and by separating minerals with a density above or below 3.4 on the remaining two sides (Geets & de Breuck, 1979). Examples of such diagrams for the three investigated members are shown in Fig. 6.

Finally, heavy mineral ratios 100x/(x + ZRT) were calculated, x being the percentage of the considered heavy mineral, and ZRT the added zircon, rutile and tourmaline percentages. These ratios, plotted in Figs 3-5, represent for every considered heavy mineral a weighed relative value *vs* the most common ubiquists used as a standard, thus eliminating strong concentration fluctuations.

3 - Compositions

Heavy mineral compositions plotted *vs* depth demonstrate provenance-influenced changes (Figs 3-5).

In the Beernem Member (Table 1), the basal part of the Aalter Formation, half of the ubiquists (67% on average) is zircon. Garnet and parametamorphic minerals both reach 13% on average. Hornblende represents 3%, and epidote occurs sporadically. The strongly varying zircon (10-64%), tourmaline (0-35%) and parametamorphic (3-22%) mineral content illustrate the sedimentary environment to shift from relatively high-energy conditions north of Oedelem (positioned in the top of the diamond diagram) to relatively low ones south of Oedelem (somewhat lower in the diamond diagram published by Geets *et al.*, 1985).

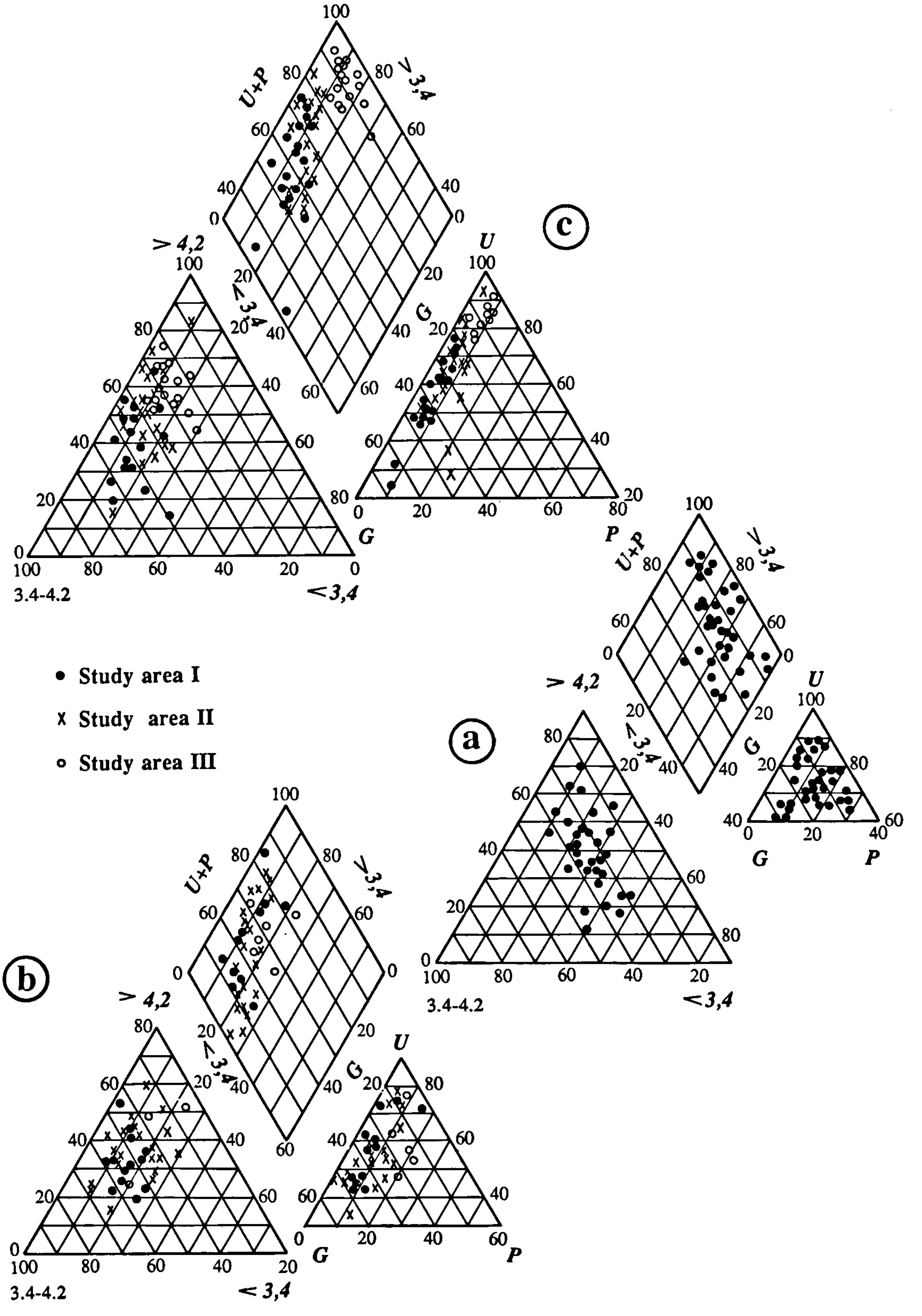

Fig. 6. Heavy mineral distribution diagrams for: A - the Aalter Sands facies (with some additional outcrop data supplied by Geets *et al.*, 1985); B - the Onderdijke Member; C - the Bassevelde Member. In the ternary diagrams: U = ubiquist group, P = parametamorphic group, G = garnet, epidote, pyroxene and amphibole groups together. For diamond diagrams see text under heading 'Graphical representations'. All diagrams are after Geets *et al.* (1985).

Beernem Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	136 DB 1								
		-10,4	47	19	12	11		8	3
		-11,3	58	18	17	1		3	3
		-11,7	55	22	13	1		5	4
		-12,5	55	19	18	1		7	
		-13,3	61	17	13	1		5	3
		-13,7	72	15	9			4	
		-14,5	62	13	15			6	4
		-15,2	69	16	6	2		5	2
		-16,2	61	16	16	3		1	3
		-17,2	65	21	11	1		1	1
		-17,5	80	11	7			1	1
I									
	136 DB 4								
		-17,1	74	8	11	3		1	3
		-17,9	70	13	16				1
		-18,7	50	18	17	4	1	3	7
		-19,3	74	6	16				4
		-19,9	79	10	7	1		3	
		-20,5	74	8	12	1		2	3
		-21,7	61	17	15	1		5	1
		-22,6	80	3	13	1		1	2
		-23,1	60	11	22			2	5
		-24,1	84	5	7	3			1
		-25,1	76	8	15	1			
	average %		66,7	13,4	13,1	1,6	0,0	2,9	2,3

Table 1. Heavy mineral distribution (%) of the Beernem Member (after Jacobs, 1975).

The ubiquist percentage reaches on average 68% in the Oedelem Member (Table 2). Parametamorphic minerals are abundant (17% on average), and garnet decreases slightly to 11%. The strong fluctuations of the heavy mineral percentages of the Oedelem Member, as indicated by their positions in the ternary and diamond diagrams (Geets *et al.*, 1985) suggest the sedimentary environment to have shifted from a quiet setting in the basal part to a more turbulent one in the middle part, to return to a quiet setting in the upper part again.

The Aalter Sands facies (Table 3) contains on average 71% ubiquists with zircon largely dominating over rutile and tourmaline. Parametamorphic minerals are abundant (18% on average). Garnet is only 9%; epidote and amphiboles occur sporadically. The sedimentary environment evolved from a quiet to a more turbulent open coastal setting as the heavy mineral positions shift towards the top of the diamond diagram (Geets *et al.*, 1985) (Fig. 6a).

The Aalter Formation is characterised by a fairly constant high ubiquist percentage (66%, increasing to 71% towards the top), a constant parametamorphic mineral content (13%, increasing towards 18% on average towards the top), a low garnet content (13%, decreasing to 9% at the top) and a decrease of sporadic epidote and amphibole minerals.

Oedelem Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	132 DB 3								
		-13,2	64	29	6				1
		-13,9	57	26	9	4			4
		-14,8	67	24	8	1			
		-16	48	39	8	2		1	1
		-16,6	69	14	12	2			3
		-16,9	71	15	9	1		2	2
		-18,1	66	18	10	1			5
		-19,7	71	12	17				
		-21,3	55	15	19	1		6	4
		-22,3	54	32	8	1		4	1
		-23,2	82	5	11			1	1
		-23,8	82	5	12				1
		-24,7	84	6	9				1
	136 DB 4								
		-3,8	46	10	26	13		2	3
		-4,9	78	5	11	2			4
		-5,6	86	3	7			1	3
		-6,5	76	17	6				1
		-6,7	66	21	12				1
		-7,5	79	9	7	1			4
		-8	84	5	8	1			2
		-8,8	84	5	8	1			2
I		-9,5	59	24	13	2		1	1
		-10,5	53	29	12			5	1
		-11	45	15	35	1		1	3
		-11,6	76	11	7	1			5
		-12,4	86	4	7	1			2
		-13,2	46	36	12	3		2	1
		-13,5	58	24	14			3	1
		-14,5	57	19	15	3		1	5
		-15,4	68	15	10	2		1	4
		-16,7	83	9	6				2
	137 DB 4								
		-5,1	74	15	10				1
		-6,4	73	11	15	1			
		-6,9	55	28	17				
		-7,4	71	17	11	1			
		-8,3	69	17	13				1
		-8,8	65	20	14	1			
		-10	74	16	8				2
		-11	72	18	10				
		-13,3	62	17	18	2			1
		-13,7	72	18	10				
		-13,9	63	15	20			1	1
		-14,6	79	10	10	1			
		-15,5	70	16	9			2	3
		-16,4	58	29	9	1			3
		-17	70	26	2		1		1
	average %		68,0	16,8	11,5	1,1	0,0	0,7	1,8

Table 2. Heavy mineral distribution (%) of the Oedelem Member (after Jacobs, 1975).

The lowermost member (Table 4) of the Maldegem Formation shows a strong dominance of ubiquists (up to 68% on average in study area I) with zircon as a major representative. In study area I, garnet equals the parametamorphic minerals, of which staurolite slightly dominates over kyanite. Due to the fineness of the sediment, the high percentages of small zircons make interpretations of depositional environments hardly meaningful.

In the clayey Asse Member (Table 5), the average percentage of ubiquists decreases in a southeasterly direction, with zircon percentages being more than double those of rutile.

Aalter Sands facies									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	132 DB 3								
		-6,7	78	7	11	2			2
		-7,3	74	12	13				1
I		-8	71	16	11	1			1
		-8,9	73	17	8				2
		-10,1	71	22	3	1			3
		-11,5	66	22	8	1			3
		-12	63	28	6				3
	average %		70,9	17,7	8,6	0,7			2,1

Table 3. Heavy mineral distribution (%) of the Aalter Sands facies (after Jacobs, 1975).

Wemmel Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	132 DB 3								
		-3,8	72	18	5	3		1	1
		-4,3	66	20	11	2			1
		-4,8	67	28	4	1			
		-5,3	74	16	8	1			1
		-5,8	76	16	5	2			1
		-6,3	65	15	14	1		2	3
	133 DB 12								
		-40,8	79	3	13	5			
		-41,2	83	5	9	3			
	136 DB 2								
		-5,2	46	15	32	6			1
I		-6,3	73	15	10	2			
		-6,8	49	24	23	2			2
		-7,3	83	4	12				1
		-7,8	57	14	25			1	3
		-8,5	76	10	11				3
		-9,8	67	12	19	1		1	
		-10,2	80	8	12				
		-11	72	11	14				3
		-11,6	64	25	9				2
		-13	55	28	14	2		1	
	137 MB 1								
		-11,5	69	16	13				2
		-12,2	59	12	28				1
		-12,6	57	12	26	1			4
		-13	72	8	17	2			1
	average %		67,9	14,6	14,5	1,5		0,3	1,3
	235 DB 1								
		-31,3	71	7	15	5		1	1
		-32,5	74	8	11	3			4
		-33,4	54	15	21	9			1
	235 MB 2								
III		-17,5	67	8	20	1		2	2
		-18,3	74	5	15	5			1
		-19,2	51	22	17	8		2	
		-19,5	53	17	20	6		1	7
	311 DB 1								
		-22,8	57	28	11	1			3
		-24	60	9	26	2			3
	average %		62,1	13,2	17,3	4,4		0,7	2,4

Table 4. Heavy mineral distribution (%) of the Wemmel Member (after Jacobs, 1975).

Asse Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	133 DB 12								
		-37,8	51	9	32	4			4
		-38,2	56	21	18	2			3
I		-38,8	70	10	14	2			4
		-39,2	85		15				
		-40,2	83	3	10	3			1
	average %		69,0	8,6	17,8	2,2			2,4
	148 DB 6								
II		-33,5	66	6	23	4			1
	235 DB 1								
		-26,2	66	22	10	1			1
		-27	44	34	17	4			1
		-27,8	57	21	18	2			2
		-28,9	48	19	28	2			3
		-29,5	48	18	29	3			2
		-30,5	51	14	26	4			5
		-30,8	45	26	19	8		2	
	235 MB 2								
		-11,5	58	11	20	8			3
III		-12	62	27	9	1			1
		-13,5	47	27	15	6		1	4
		-14,8	49	21	25	5			
		-16	41	28	22	4		1	4
		-17	58	12	20	7		1	2
	311 DB 1								
		-19,5	67	9	11	2			
		-20,4	57	33	10				
		-21,2	55	28	11	4			2
		-22	53	24	17	5			1
		-22,4	45	30	22	2			1
	average %		53,2	22,6	18,4	3,8		0,3	1,8

Table 5. Heavy mineral distribution (%) of the Asse Member (after Jacobs, 1975).

Garnet dominates over the parametamorphic minerals in study areas I ans II. Epidote is an accessory mineral (4%), while amphiboles only occur sporadically.

Zircon is again the most representative ubiquist in the Ursel Member (Table 6). The parametamorphic minerals vary from 13 to 18% on average; the garnet fluctuates strongly from 18 to 31%. In study area II, the epidote reaches its maximum with 6%. The highest values for the ubiquist content occur in study area III (62%), where the garnet group drops to 18%.

In the Onderdale Member (Table 7), garnet varies greatly between the three study areas (from 10 to 26%), in opposition to parametamorphic minerals. Epidote is accessory. More than 80% of the minerals are ubiquists in study area I. In study area II, the garnet percentage reaches its maximum, strongly fluctuating from 22% in siltier to 2% in sandier sediments in study area III.

The clayey Zomergem Member (Table 8) shows a high ubiquist amount, which, however, is less than in the Onderdale and Buisputten members. Epidote is accessory (4%). In study area II, garnet is abundant (30% on average) and parametamorphic minerals are common (17% on average).

Ursel Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	133 DB 12								
		-24,7	80	4	12	4			
		-25,7	64	8	19	4			5
		-26,7	46	17	29	2		2	4
		-27,7	61	13	24	2			
		-28,7	58	8	28	5			1
		-29,7	52	12	32	3			1
		-30,7	54	14	30				2
		-31,7	74	8	10	6			2
		-32,7	48	14	27	9			2
		-33,7	68	9	19	3			1
		-34,7	40	5	38	12			5
I		-35,7	68	6	19	6			1
		-36,7	48	12	30	8			2
		-37,2	40	15	36	9			
	137 MB 1								
		-2,2	35	21	37	1	1		5
		-2,7	35	27	29				9
		-3,6	29	28	38	1		1	3
		-4,7	27	26	44	1			2
		-6,7	37	25	26	2	2		8
		-7,8	37	22	32	5			4
		-8,9	32	22	41	2			3
		-9,7	30	26	33	1		1	9
	average %		48,3	15,5	28,8	3,9	0,1	0,2	3,1
	148 DB 6								
		-22,7	47	20	26	4			3
		-23,7	47	18	28	4			3
		-24,5	47	10	35	6			2
		-25,3	31	22	38	8			1
II		-26,3	40	13	39	8			
		-27,2	51	13	29	7			
		-28	31	32	34	1		1	1
		-28,3	43	13	34	8			2
		-28,7	50	14	29	6			1
		-30	37	26	19	18			
		-30,8	47	12	31	6			4
		-32	34	28	34				4
	average %		42,1	18,4	31,3	6,3		0,1	1,8
	235 DB 1								
		-21,3	70	6	20	2			2
		-22	69	6	18	4			3
		-23	73	5	15	3			4
		-24	50	17	25	4		2	2
		-24,8	71	3	23	1			2
		-25,3	58	16	22	3			1
		-25,8	91	1	6	2			
	235 MB 2								
III		-8,3	43	19	27	8			3
		-9,3	51	19	20	5			5
		-10	57	6	23	12		1	1
		-11	50	14	24	9		1	2
	311 DB 1								
		-14,7	81	15		2		2	
		-15,8	60	12	22	3		1	2
		-16,7	64	20	11	3		1	1
		-17,3	35	30	24	8		2	1
		-18,3	48	26	21	3			2
		-19	77	11	5	4			3
	average %		61,6	13,3	18,0	4,5		0,6	2,0

Table 6. Heavy mineral distribution (%) of the Ursel Member (after Jacobs, 1975).

Study area III shows the highest ubiquist content (66% on average), but a much lower garnet percentage (only 13%).

As the content of zircon and other dense minerals decreases towards the top, sedimentary conditions in the basal part of the Zomergem Member probably were more turbulent.

Onderdale Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	133 DB 12								
		-22,7	78	9	9	2			2
I		-23,2	85	4	11				
		-23,5	85	8	5	2			
		-24,2	74	8	16	2			
	average %		80,5	7,3	10,3	1,5			0,5
	148 DB 5								
		-24,4	47	10	39	3			1
		-25,5	60	9	27	4			
		-26,5	50	14	27	7			2
		-27	59	10	26	4			1
II									
	148 DB 6								
		-19,2	58	15	22	3		1	1
		-20,3	74	4	20	2			
		-21,4	66	7	26	2			
		-22	62	9	25	4			
	average %		59,4	9,8	26,5	3,6		0,1	0,6
	235 DB 1								
		-15,3	63	9	22	5		1	
		-16,3	55	13	24	6		2	
		-17,3	46	18	26	4		2	4
		-18,7	75	6	17	2			
		-20	68	7	22	1		2	
		-21,2	66	7	21	5		1	
	235 MB 1								
		-12,2	63	13	18	4		2	
		-13,2	66	5	26	3			
III									
	235 MB 2								
		-7,3	60	12	23	5			
		-7,8	70	12	17				1
	311 DB 1								
		-9	82	13	2	2			1
		-9,7	75	16	3	4		1	1
		-10,2	89	6	3	1		1	
		-11,3	73	20	2	4		1	
		-12,3	85	7	5	1		1	1
		-13,3	86	12		2			
		-14,2	79	14	1	3		2	1
	average %		70,6	11,2	13,6	3,1		0,9	0,5

Table 7. Heavy mineral distribution (%) of the Onderdale Member (after Jacobs, 1975).

On average, the Buisputten Member (Table 9) contains 69% ubiquists, 17% garnet and 10% parametamorphic minerals. Amphiboles (mostly hornblende) have only been noted in study areas II and III (up to 4%), while epidote is present in small amounts only (4% on average). In study area I, the ubiquist percentage is somewhat higher (74% on average) and the parametamorphic content somewhat lower (4% on average), in comparison to study area II with a lower ubiquist (57%) and a higher parametamorphic mineral percentage (13%). In the eastern study area III, the ubiquist percentage fluctuates between 35 and 86%, and the parametamorphic minerals become the second most important group.

In the clayey Onderdijke Member (Table 10), the ubiquist group averages 56%. Garnet with 26% on average is the second important heavy mineral group.

Zomergem Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	133 DB 12								
		-14,7	53	6	32	6			3
		-15,8	42	11	38	5			4
		-16,8	65	6	26	2			1
		-17,8	51	8	37	3			1
		-18,8	57	9	27	3			4
		-19,8	82	4	12	2			
		-20,8	47	7	33	9		1	3
		-21,7	75	6	15	3			1
I		-21,9	81	5	10	4			
		-22,2	73	6	14	4			3
	137 MB 9								
		-9,2	52	4	36	2			6
		-9,7	54	11	27	3			5
		-10,2	48	5	35	2			10
		-11,2	48	8	32	2			10
		-11,7	47	12	35	4			2
		-13,2	48	13	30	4			5
	average %		57,7	7,6	27,4	3,6		0,1	3,6
	148 DB 4								
		-19,2	45	18	28	5		2	2
		-19,8	28	18	47	4		2	1
		-20,5	46	14	34	3			3
		-21,4	32	11	52	3		1	1
		-22,4	67	6	22	1			4
		-23,4	65	9	22	2		2	
		-24	37	19	33	8			3
		-25	55	17	17	7		1	3
		-25,3	42	16	30	6		2	4
II									
	148 DB 5								
		-16,2	41	15	34	5		4	1
		-17	42	15	36	4			3
		-18	35	33	27	3		2	
		-18,8	42	24	20	6		2	6
		-19,5	47	20	25	3		4	1
		-21,8	37	23	30	5		1	4
		-22,3	34	26	28	7			5
		-23	43	22	24	9			2
		-23,8	54	9	33	4			
	average %		44,0	17,5	30,1	4,7		1,3	2,4
	235 DB 1								
		-13,8	46	24	23	4			3
		-14,8	58	14	23	5			
	235 MB 1								
		-9,6	66	14	18	1			1
III		-10,8	65	11	16	7			1
		-11,8	44	20	22	9		5	
	311 DB 1								
		-7,2	66	19	5	7		3	
		-8	86	8	1	3		1	1
		-8,8	95	3					2
	average %		65,8	14,1	13,5	4,5		1,1	1,0

Table 8. Heavy mineral distribution (%) of the Zomergem Member (after Jacobs, 1975).

Buisputten Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	133 DB 12								
		-7,7	89		4	7			
		-8,9	68	2	19	11			
		-9,9	84	3	9	4			
		-10,8	92	1	6	1			
		-11,8	80	1	17	2			
		-12,2	89	3	6	1			1
		-12,5	82	2	11	4			1
		-12,8	66	7	23	3			1
		-13,8	80	3	15	2			
		-14,2	80	6	12	2			
I									
	137 MB 9								
		-4,3	76	2	19	1			2
		-4,8	51	7	40	1			1
		-5,3	68	8	20	3			1
		-5,8	74	4	18	2			2
		-6,1	69	8	20	1		1	1
		-6,4	67	9	24				
		-6,8	69	4	20	6			1
		-7,5	83	3	13	1			
		-7,8	66	4	23	4			3
		-8,3	63	6	26	1			4
		-8,7	63	3	30	3			1
	average %		74,2	4,1	17,9	2,9		0,0	0,9
	148 DB 3								
		-20,2	47	19	23	9		1	1
		-21	73	12	12	2			1
		-22	59	11	21	7		1	1
		-22,7	55	15	20	5		2	3
	148 DB 4								
II		-13	78	6	11	3		1	1
		-13,5	49	17	27	4		1	2
		-14,3	58	10	20	5		3	4
		-15,2	53	19	21	4		3	
		-16	72	4	21	2		1	
		-17	56	12	24	6		1	1
		-17,5	68	6	23	2			1
		-17,8	26	20	39	7		4	4
		-18,5	50	18	24	5		2	1
	average %		57,2	13,0	22,0	4,7		1,5	1,5
	235 DB 1								
		-11,2	43	21	32	4			
		-12	35	36	21	5		2	1
		-12,5	56	22	17	2		1	2
		-13,3	61	15	15	4			5
III									
	235 MB 1								
		-6,8	81	16		2			1
		-7,5	86	9		4			1
		-8,7	78	9	6	7			
	average %		62,9	18,3	13,0	4,0		0,4	1,4

Table 9. Heavy mineral distribution (%) of the Buisputten Member (after Jacobs, 1975).

Epidote group minerals fluctuate considerably from 0 to 26% in study area II. The grain size *vs* zircon content diagrams indicate generally less energetic sedimentary environments (Fig. 7b).

In general, the alternating sand and clay layers of the Maldegem Formation in study area I (Fig. 5) show a dominance of ubiquists (especially zircon), which are more abundant in the sandy-silty (up to 80%) than in the clayey sediments (only 50%). In decreasing order, garnets, parametamorphic minerals and small amounts of epidote occur.

In the Bassevelde Member of the Zelzate Formation (Table 11), the ubiquists dominate, their percentages increasing from 56% in study area I in the northwest to 87% in study area III in the southeast. Garnet group minerals are abundant in study areas I and II, but reduced to almost 0% in study area III. Epidote percentages decrease in a southeasterly direction. According to the position of the top zone of the Bassevelde Member near the top of the ternary and diamond diagrams (Fig. 6c), its sedimentary environment was relatively more energetic.

Onderdijke Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	58 DB 6								
		-35,2	60	2	28	8			2
		-35,4	49	4	41	5			1
		-360	43	8	35	12		1	1
		-36,5	57	4	29	8			2
	133 DB 12								
		-2	48	6	35	8			3
		-2,4	75	6	8	10		1	
I		-3,6	47	6	37	10			
		-4,8	57	6	24	8	1	1	3
		-5,8	58	7	25	9			1
		-6,8	44	11	33	10		2	
		-7,3	70	2	19	5		1	3
	137 MB 9								
		-1,6	56	18	23	1			2
		-2,8	46	22	24	3		3	2
		-3,8	72	15	13				
	average %		55,9	8,4	26,7	6,9	0,1	0,6	1,4
	148 DB 2								
		-12,9	50	6	34	9	1		
		-13,2	48		24	26		2	
		-13,6	45	3	28	15		5	4
		-13,8	53	4	26	14		2	1
		-14,2	33	11	36	13		7	
		-14,6	48	6	31	11		4	
		-15,3	50	9	28	10		3	
		-15,8	39	15	22	18		4	2
		-16,4	72	4	17	5			2
		-17	57	10	24	7		1	1
		-17,5	46	9	32	10		2	1
II		-17,8	46	3	30	14		5	2
		-18,2	58	6	22	10	1	1	2
	148 DB 3								
		-13,7	57	20	20	2			1
		-14,8	55	12	28	5			
		-15,8	50	16	31				3
		-16,2	71	8	15	4			2
		-17	64	12	21	3			
		-17,6	76	4	16	3			1
		-18,2	46	16	29	8		1	
		-18,7	55	9	30	5			1
		-19,8	55	8	28	5		2	2
	average %		53,4	8,7	26,0	9,0	0.1	1,8	1.1
	235 DB 1								
III		-10,6	54	21	21	4			
		-10,8	64	10	21	5			
	average %		59,0	15,5	21,0	4,5			

Table 10. Heavy mineral distribution (%) of the Onderdijke Member (after Jacobs, 1975).

In study area I, the Watervliet Member (Table 12) contains on average 40% zircon and 8% rutile. Here, garnet averages 23%, epidote 16% and parametamorphic minerals average 8%. Few hornblendes are present. The ubiquist percentage diminishes towards the top. In study area III, the ubiquist percentage increases to 90%, rutile to 22%. The parametamorphic mineral content equals that of study area I, but the epidote group minerals decrease to 2%.

Bassevelde Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	58 DB 6								
		-26,7	48	7	36	9			
		-27,2	64	3	28	4			1
		-28	76	1	17	2			4
		-28,8	50	7	36	6		1	
		-29	63	3	21	13			
		-30	70	3	22	5			
		-31	48	7	23	22			
		-32,2	59	1	22	16			2
		-32,7	60	4	28	8			
		-33,6	53	4	29	14			
I		-34,2	49	2	38	10			1
		-34,8	59	5	26	8			2
	65 DB 3								
		-26,7	31	4	55	10			
		-26,9	68	1	22	6		1	2
		-27,2	45	5	37	10			3
		-35,2	51	5	35	9			
		-37	72	4	18	5			1
		-37,4	67	4	23	6			
		-37,9	24	8	36	31		1	
	average %		55,6	4,1	29,1	10,2		0,2	0,8
	148 DB 2								
		-2	62	3	24	6		3	2
		-2,7	67	8	15	8		2	
		-3,3	57	8	22	6		2	5
		-4,2	79	1	12	4		2	2
		-6	52	6	25	8		4	5
		-7,6	68	5	20	6			
		-8	73	4	13	8			2
		-8,5	59	6	20	12		2	1
		-9,3	53	6	23	11		6	1
		-10,6	50	4	25	18		1	2
		-11,3	49	10	28	7		5	1
		-11,7	65	8	21	4		2	
II		-12,4	76	4	16	3			1
	148 DB 3								
		-8,4	37	20	37	5		1	
		-9,3	63	9	27	1			
		-10,3	64	10	20	4			2
		-11	68	6	24	1		1	
		-11,7	68	4	24	2			2
		-12,6	55	13	24	7			1
		-13,3	29	22	44	5			
	148 E 5								
		-11,4	91	1	6				2
		-11,8	83		15	1			1
	average %		62,2	7,2	22,1	5,8		1,4	1,4
	235 DB 1								
		-7,3	89	6	1	4			
		-8,2	79	14	1	6			
		-9	81	11	1	6		1	
		-9,8	89	6		3			2
		-10,2	91	4		2		1	2
III									
	235 MB 1								
		-3,2	83	7	1	6		2	1
		-4	90	1	1	7			1
		-5	90	6	1	3			
		-5,7	83	8	1	7			1
		-6,3	91	6		3			
	average %		86,6	6,9	0,7	4,7		0,4	0,7

Table 11. Heavy mineral distribution (%) of the Bassevelde Member (after Jacobs, 1975).

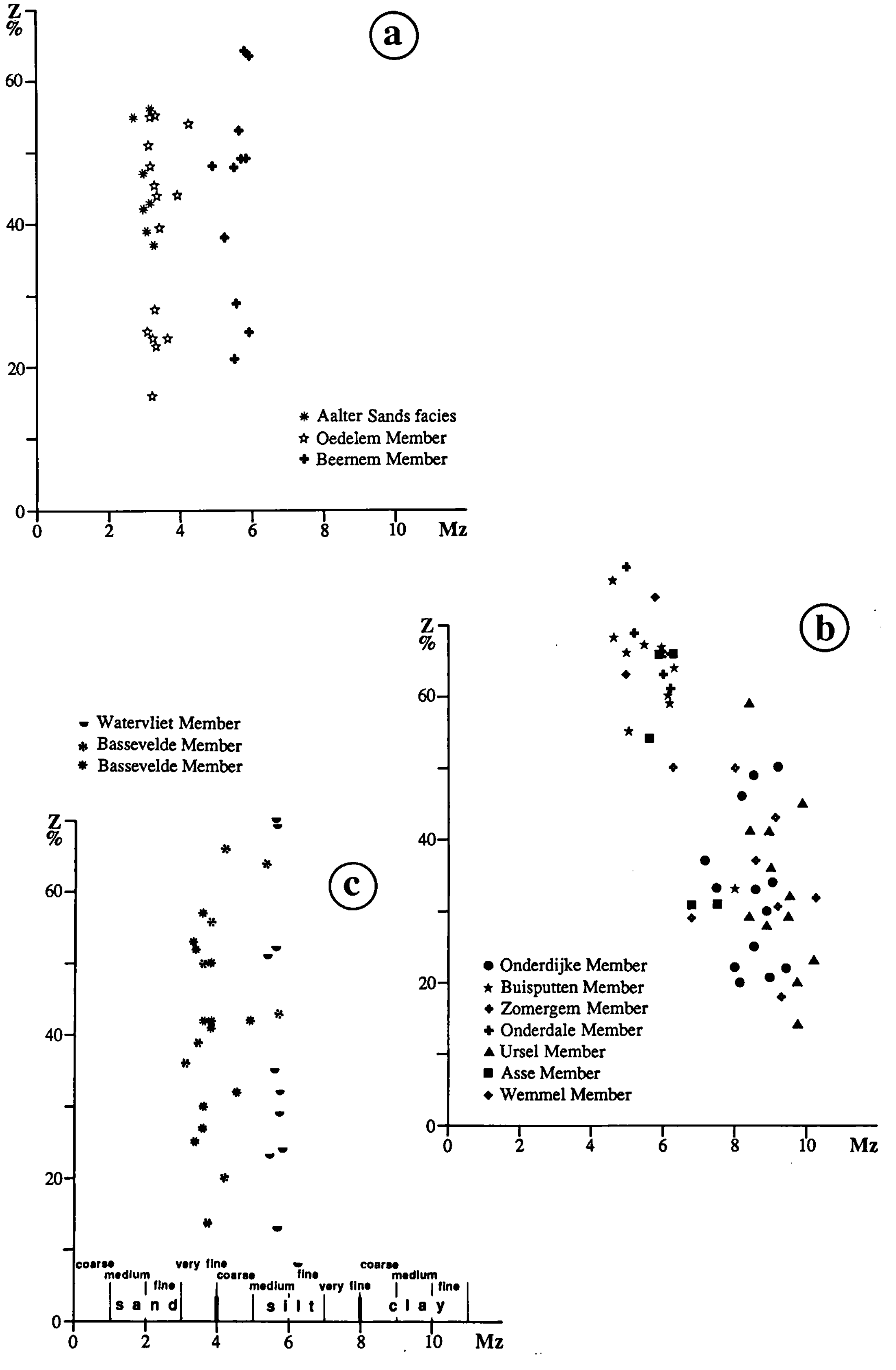

Fig. 7. Mean grain size (Mz in phi-units) *vs* zircon percentage (Z in %) plots for: A - Aalter Formation; B - Maldegem Formation; C - Zelzate Formation, in study area I.

The Zelzate Formation is thus generally characterised by an increase of ubiquists from almost 50% in the west to 90% in the east. It also contains garnet, parametamorphic minerals, epidote and a few amphiboles (Fig. 5).

4 - Quantitative distribution

In general, the weight percentages of the heavy minerals are somewhat higher in the sandy-silty than in the clayey layers (some 0,05 in comparison to 0,02%), although this trend seems to weaken towards the east. In the Maldegem Formation the highest ubiquist percentages, up to 92%, occur in the sand layers. In the Zelzate Formation the ubiquist amount in study area I is significantly lower than in study area III, due to the very low garnet content in the latter area. Garnet percentages in study area III are throughout the stratigraphical column somewhat lower than in both other study areas, but the parametamorphic mineral content is slightly higher. The occurrence of the epidote group is the highest in study area I.

Watervliet Member									
Study area	Well	Depth	Ubiquist	Parametamorphic	Garnet	Epidote	Pyroxene	Amphibole	Rest
	65 DB 3								
		-17,2	22	25	29	20		4	
		-17,5	12	22	17	37		11	1
		-18	38	6	25	23		4	4
		-19,5	48	7	26	18			1
		-20,2	60	2	20	15		2	1
I		-20,6	45	4	30	18		1	2
		-21,1	41	7	26	21			5
		-21,5	80	3	12	5			
		-21,7	40	4	27	23		3	3
		-21,9	76	1	16	5			2
		-22,6	59	5	22	13		1	
		-23,2	55	7	30	8			
		-23,6	73	4	19	4			
	average %		49,9	7,5	23,0	16,2		2,0	1,5
	235 DB 1								
		-2,5	89	10		1			
		-3,2	91	7	1	1			
		-3,8	93	4	2	1			
III		-4,5	93	4	1	2			
		-5,2	94	4	1	1			
		-5,8	92	2	2	4			
		-6,3	90	5	2	2			1
		-6,8	80	9	4	5	1	1	
	average %		90,3	5,6	1,6	2,1	0,1	0,1	0,1

Table 12. Heavy mineral distribution (%) of the Watervliet Member (after Jacobs, 1975).

5 - Grain size influence

The plots of mean grain size *vs* zircon percentage for the Aalter and Zelzate formations in study area I reveal that the zircon content is independent of sediment grain size (Fig. 7a, c). Samples with the same mean grain size have a wide range of zircon percentages. In the Maldegem Formation, on the other hand, a strong negative correlation exists between mean grain size in phi-values and zircon content, which means a positive correlation between mean grain size in μm and zircon content (Fig. 7b). On the graph, two long narrow clusters can be distinguished, characterised by a relatively large spread in zircon percentage for a small range of mean grain size. The first cluster groups most of the samples of the clayey sediments of the Onderdijke, Zomergem, Ursel members as well as part of the Asse Member, while the second cluster groups the sandy sediments of the Buisputten and Onderdale members as well as the remainder of the Asse Member. This supports Pettijohn's (1941) and Blatt & Sutherland's (1969) views that intrastratal solution of heavy minerals in sand bodies that have never been deeply buried, is to be considered a general phenomenon rather than one of local significance only. Minerals which are post-depositionally completely or partly dissolved in sand bodies (and thus responsible for an increasing or fluctuating zircon percentage, as zircon is regarded as one of the most stable heavy minerals), will probably be preserved or present in a higher degree in the impermeable clay bodies, suggesting that clay rather than sand layers should be examined in heavy mineral studies (Blatt & Sutherland, 1969). This hypothesis finds support in the percentage of the more unstable epidote minerals, which is higher in the clayey parts of the Maldegem Formation than in the sandy portions (Fig. 4). Although the Zelzate Formation is in general much sandier and contains considerable amounts of epidote, here too the more clayey part, the Watervliet Member, shows the highest epidote percentages (Fig. 5). The Beernem Member, the most clayey part of the Aalter Formation, contains relatively much hornblende in comparison to the other members (Table 1).

6 - Relative abundance

The ratios of 100x/(x + ZRT) show distinct trends (Figs 3-5). Throughout the section, in general the tourmaline and zircon trends tend to be opposite due to the difference in density (zircon 4.7, tourmaline 3.2).

Predominance of either zircon or tourmaline therefore illustrates opposing conditions of turbulence. Within the Aalter Formation (Fig. 3), the tourmaline ratio hardly reaches a rounded-off value of 10 in the Aalter Sands facies, and strongly oscillates with a maximum in excess of 20 in both other members. Rutile follows a similar trend but with somewhat higher values. The zircon ratio decreases from 40 to 30 at the base of the Oedelem Member, from where it increases again to 40. Garnet oscillates with a maximum of 20. Andalusite, staurolite and epidote ratios are very low (mostly 2 to 3 with a maximum of about 10 for staurolite), but the kyanite ratio increases considerably in the Aalter Sands facies from 5 to 20, remains in general rather high in the Oedelem Member (between 7 and 12) and drops in the Beernem Member, where it averages only 3.

The clayey members of the Maldegem and Zelzate formations (Figs 4, 5) display a tourmaline ratio averaging 10, rutile averaging 25 (invariably > 10) and a zircon ratio in excess of 30. Their andalusite, staurolite, kyanite and epidote ratios oscillate with a maximum of 10, but show a fairly wide spread near the base. Garnet ratios oscillate above 30.

The sand members in the Maldegem and Zelzate formations, and also the sandy intercalations in the clays or the sand-clay transitional zones, show a very low tourmaline ratio (1 to 2, or even 0, the Wemmel Member excepted); the rutile ratio averages 15, and the zircon ratio exceeds 40 (Figs 4, 5). Andalusite, staurolite, kyanite, and epidote ratios attain very low values (maximum 3 to 5). The garnet ratio rarely reaches 20.

In general, the heavy mineral assemblages do not show newly introduced minerals that would affect the heavy mineral percentages. As no deep burial of the sediments occurred, the ratios might rather reflect the influence of intrastratal solution by ground water flows than any other cause of variability with exception for the grain size, the effect of which on small heavy mineral quantities could not be verified. The ratios might therefore indicate preferential dissolution of andalusite, staurolite, kyanite and epidote, and a weaker one for garnet in the confined aquifers of the sand members of the Zelzate and Maldegem formations (van Dyck *et al.*, 1984). In the Aalter Formation, the trends of the ratios are less clear due to the fact that this unit forms only the upper part of a confined aquifer, in which the lateral discontinuous, relatively more impermeable (clayey) Beernem Member occurs, giving rise to less predictable ground water flows with perhaps different geohydrochemical properties.

DISCUSSION

A - Cyclic character of the Maldegem Formation

The heavy mineral distribution of the Maldegem Formation is rather homogeneous and monotonous. The only changes observed might be the result of the changing grain size of the sediment (Figs 4, 7b). The ubiquist percentage increases with increasing grain size, the distribution being dominated by zircon, and to a lesser extent by rutile.

This monotonous distribution can be explained by the repeated reworking of Maldegem Formation sediments, which was controlled by the cyclic character of the sedimentation (Jacobs, 1975, 1978). As deposition shifted from an open marine deltaic sedimentation for the clay members to a tidal flat and lagoonal sedimentation for the sand members, part of the sediments were repeatedly eroded, transported and redeposited within a limited area with minor new sediment supply. Only at the top of the Maldegem Formation and in the Zelzate Formation was new sediment supplied to the basin from continental erosion, as indicated by the slightly increasing amount of minerals of the epidote group (especially zoisite and clinozoisite).

B - Garnet weathering in study area III

In the Onderdale to Watervliet member sediments occurring just beneath the Quaternary loess cover of the 'Plateau of Brabant' region, garnet was dissolved due to intense subaerial weathering of this old exhumation surface during the late Tertiary and early Quaternary. Such dissolution can also be attributed to ground water flows in the sand members involved (Sindowski, 1938; Jacobs, 1975), as indicated by the high garnet content (21% on average) of the clayey Onderdijke Member, which acts as a local impermeable lower boundary.

Earlier studies have revealed that garnet is distinctly less stable under subaerial weathering than under deep burial (exceeding 2000 m), whereas the reverse is true for minerals such as andalusite (Morton, 1984). Deep burial of the Maldegem and Zelzate formations in study area III can be excluded, since the younger Tertiary and Quaternary deposits had only 200 m maximum thickness prior to removal by late Tertiary to Quaternary erosion. The low-pH meteoric (or ground) waters must have affected the garnet minerals, leading to severe or extreme dissolution in the Onderdale, Zomergem, Buisputten, Bassevelde and Watervliet members (Tables 7, 8, 9, 11 and 12).

C - Provenance

Judging from the high garnet content (except in study area III) and from the presence of parametamorphic and epidote group minerals, all associations listed in Tables 1-12 belong to de Breuck's (1959) marine G-province. This province resembles Edelman & Doeglas's (1938) A-province of Lower Eocene sediments in the Belgian Basin. The garnet provenance remains uncertain as different source rock areas, such as the British Isles and Fennoscandia, may be indicated. De Breuck (1959) could not prove a possible northerly origin as proposed by Edelman & Doeglas (1983) for their marine A-province of Lower Tertiary sediments.

The sediments of the Tertiary Belgian continental shelf dip gently to the northeast (Fig. 1). A 'northerly' sediment supply, indicated by heavy mineral studies of early authors, has often been invoked erroneously for the Tertiary Southern Bight of the North Sea, where the transgressions came from the northeast. Several palaeogeographical, mineralogical and sedimentological arguments point rather towards a southerly sediment supply. Alpine uplift of the central and southern European hinterland resulted in the exposure and erosion of metamorphic and/or plutonic terrains, acting as possible source rocks. The Vosges, Black Forest and Odenwald regions consist of intrusive (ultrabasic intrusions, hornblende-, biotite-, two-mica-granites), extrusive (diabases, basalts, keratophyres, gabbrodiorites, tuffs, rhyolites) and regional metamorphic rocks (para-amphibolites, eclogites, mudstone-, graywacke-, quartzite gneisses). In early Cretaceous times, the area of Vosges and Black Forest emerged after a period of Triassic and Jurassic sedimentation (Knetsch, 1963). The siliciclastic Rhenish Massif, permanently emerged since early Permian times, underwent considerable uplift starting in the Berriasian (early Cretaceous) through the Palaeocene and Eocene (Ziegler, 1982).

The fission-track method (van den Haute & Vercoutere, 1989) revealed that the Brabant Massif underwent important uplift and concomitant erosion related to the Cimmerian tectonism which affected large parts of northwestern Europe during the Jurassic. The Brabant Massif, forming a positive counterpart of the subsiding West Netherlands Basin to the north, must have been covered by a considerable overburden of sediments of 3000 m or more, supposedly mainly of late Carboniferous age. This overburden acted as a source for detrital sediments during the Jurassic to late Tertiary uplift, which slowed down with time. The increasing epidote content in the upper Maldegem and lower Zelzate formations, deposited on a thin Upper Cretaceous-Middle Eocene cover on top of the Brabant Massif, might probably be ascribed to the more southerly situated source rocks in the Vosges, Black Forest and Odenwald regions.

As the investigated Eocene sediments cover a timespan from 48.5 to 38 Ma, one might expect variations in heavy mineral percentages to be caused by source rock changes. Recent heavy mineral studies of Palaeogene sandstones of southeast England (Morton, 1982) indicate two distinct assemblages, one dominated by epidote, garnet and hornblende, the other by zircon, with subsidiary rutile, tourmaline, staurolite and kyanite. The latter assemblage is derived from the south, either from the Armorican or the Ardenne-Rhenish massifs. It is contained in lenticular and randomly distributed zircon-rich sand bodies, which represent redeposited older beds rather than sediment influx from elsewhere.

In the early Eocene clayey Saint-Maur, Moen, Aalbeke and Kortemark members (*i.e.* the Flanders Member of authors, former Yc of the Belgian geological map) in Belgium, which correlate with the English London Clay, mean heavy mineral percentages match the zircon-rich assemblages of some of the English Palaeogene sandstones (Geets & de Breuck, 1982). The garnet and epidote percentages, however, are somewhat higher, but this might be due to differences in lithology and methods (for the more clayey Flanders Member in Belgium, the total sand fraction was counted, for the London Clay sand bodies the 63-125 μm fraction).

Morton (1982) derives his more common southeast English epidote-garnet-hornblende association from a north Scottish Highlands source by means of longshore drift. However, this North Sea circulation pattern is disturbed in the Southern Bight by the Artois-Weald updoming, which started in late early Eocene times and deflected the southward oriented longshore currents and even cut off a possible Armorican Massif source. The resulting eastward directed new longshore currents along the southern margin of the North Sea redistributed the Eocene sediments (Mercier-Castiaux *et al.*, 1988).

From the highly rounded character of the ubiquists and parametamorphic minerals in the Belgian early Eocene 'Paniselian' sands, Geets (1969) inferred redeposition to have been an important phenomenon. He rejected provenances such as Fennoscandia for the parametamorphic minerals because the Vosges, Central Massif, Morvan and Armorican Massif are much closer possible source areas. Fennoscandia in fact formed the opposite edge of the North Sea Basin. Ubiquists (especially tourmaline) could have been provided from the Ardenne-Rhenish massifs.

In a comparative chemical analysis of detrital garnet in Belgian Meso-Cainozoic sediments, van der Sluys (1991) distinguished five populations. Two of these originate from the Fennoscandian Precambrian or the Scottish or Scandinavian Caledonides, two are derived from the Brabant Massif and the Ardenne, and the remaining fifth population is of uncertain origin and minor importance. Jurassic detrital sediments show reworking from older Buntsandstein deposits in the south, with metamorphic units in the Ardenne Massif as ultimate source. The oldest Cretaceous deposits have a Brabant Massif origin, and from early Tertiary times onwards western Belgian deposits are characterised by a 'typically Scottish detrital supply comparable to the one of the Hampshire and the North Sea basins' (van der Sluys, 1991, p. 191). In the late Eocene Zelzate Formation the 'supply from the Scandinavian Caledonides considerably increases' (van der Sluys, 1991, p. 191). Van der Sluys's conclusions are unfortunately based on but a single heavy mineral species. Moreover, the chemical composition of the garnets is not known for all possible source regions, of which some have been completely eroded, and the updoming of the Weald-Artois axis, which changed hydrodynamical and sediment-transport conditions considerably, was not taken into account.

During the Eocene, the central North Sea had higher subsidence rates than the southern basin margin (Ziegler, 1988), thus giving rise to sediment thicknesses of up to 2000 m in the depocentre. This depocentre acted as a sediment trap, prohibiting input from the north to reach the southern basin margin, which was characterised by low sedimentation rates, occasionally interrupted by periods of non-deposition (Jacobs & Sevens, 1988). To the north, in the direction of the depocentre, the sediments tend to become finer. Clay-mineralogical analysis (Mercier-Castiaux *et al.*, 1988) has revealed that the detrital clay minerals show a distinct, major, Ardenne and Rhenish massif, *i.e.* southerly influence, triggered by middle to late Eocene tectonic movements. A westerly provenance from the Dieppe-Hampshire Basin or the Armorican Massif played but a minor role.

Palaeogeographical considerations and mineralogical and sedimentological arguments point towards a supply of rather coarse sediments during the Eocene, derived from a southerly source terrain undergoing uplift. Detritus must have been transported into the basin by a northward directed drainage system like a precursor of the Rhine-Meuse-Scheldt delta, depositing the repeatedly reworked tidal flat and delta front sediments prograding on the shelf. Ardenne, Rhenish Massif and large parts of the northwest European continent were drained into the evolving North Sea Basin.

CONCLUSIONS

Over a period of nearly 12.5 Ma only minor changes can be observed in the heavy mineral distribution of Middle and Upper Eocene sediments in western Belgium. This uniform character indicates the repeated reworking of sediments and a permanent but minor sediment supply.

As intrastratal solution might influence the mineralogical composition of the heavy mineral assemblages, special attention should be paid to the heavy mineral content of clayey sediments that might represent a more basinal (or distal) mineralogy, in comparison to sandy sediments that might be characterised by a more hinterland-related (or proximal) mineralogy.

The palaeogeography and sedimentology of the evolving Eocene North Sea Basin suggest derivation of heavy mineral assemblages from southerly sources, resulting from the tectonic uplift of Palaeozoic sedimentary, metamorphic and/or plutonic terrains in western and central Europe, drained to the Southern Bight of the North Sea by a precursor of the modern Rhine-Meuse-Scheldt fluvial system.

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