

## THE CONCEALED CRYSTALLINE BASEMENT IN BELGIUM AND THE "BRABANTIA" MICROPLATE CONCEPT : CONSTRAINTS FROM THE CALEDONIAN MAGMATIC AND SEDIMENTARY ROCKS

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(13 figures and 2 tables)

**ABSTRACT.** – The presence of a Precambrian crystalline basement beneath the Caledonian sedimentary segment of the Brabant Massif is inferred from several petrological features of the Caledonian magmatic rocks : 1) the occurrence of some gneissic xenoliths; 2) the discovery of old (possibly Archean) inherited zircons; 3) the Sr-Nd isotopic features of the liquid lines of descent ( $+ 0.3 < \epsilon_{Nd}^t < - 4.8$ ;  $- 22 < \epsilon_{Sr}^t < + 59$ ) that imply a two-stage crustal contamination with Rb-depleted and Rb-enriched rocks. They constrain a Brabant basement at least partly older than 1.8 Ga that could extend eastward below the Ardennes Massifs and the Rhenish Massif. The isotopic features of both groups of contaminants are investigated through assimilation-fractional crystallization (AFC) calculations. An important conclusion of these models is the probable occurrence of old Rb-depleted granulitic components in the Brabant crystalline basement. This finding coupled to the seismic unreflectivity of the Brabant crust underscores this basement as an important nucleus in the genesis of the Early Palaeozoic European crust. Some information on the nature of the surface of this basement is also provided by the study of the lithic fragments in the Early Cambrian sediments of the Brabant Massif and the geochemical and Nd isotopic features of the Cambrian-Ordovician fine-grained sediments from the Brabant and Stavelot Massifs. They clearly demonstrate that this surface is made up of two main groups of Precambrian rocks, some juvenile (mantle-derived) late Proterozoic ( $t < 0.9$  Ga) basic intraplate tholeiitic metavolcanites overlying some older ( $T_{DM} > 1.9$  Ga) felsic crystalline rocks.

The strong similarity between the  $\epsilon_{Nd}^t$ - $t$  paths of the Caledonian sedimentary masses from Belgium, southern Britain, Brittany and southern Nova Scotia reveals that all these sediments result from mixtures between similar Late Proterozoic juvenile source units, during the Cambrian, that graded into mature, Early Proterozoic or Archean sources, in the Ordovician. The apparent lack of Sveconorwegian components is at variance with a Baltic Shield provenance while the ubiquitous Pan-African component favours a Gondwana derivation. The various Early Palaeozoic plate tectonic configurations (Baltica Peninsula, Cadomia, Armorica and Avalonia concepts) are reviewed in the light of these new data and the geological constraints from the Belgian Caledonides. These data strongly support the existence of an Ordovician Tornquist Ocean separating Baltica from a Gondwana-derived microplate including most of southern Britain and Belgium that is defined here as the "Brabantia" microplate.

### 1. INTRODUCTION

Palaeomagmatic evidence (André *et al.*, 1986a) suggests that, during Ordovician-Silurian times, Belgium developed as an active arc at the northern edge of a microcontinent that drifted away from Gondwana in the Lower Ordovician to collide with Baltica during the Upper Ordovician (Babin *et al.*, 1980; Van der Voo *et al.*, 1980; Cocks and Fortey, 1982; Perroud *et al.*, 1984). The Precambrian basement that composes this Gondwana detached microplate is partly exposed in Brittany (Pentevrian-Brioverian Craton), S.E. Ireland (Rosslare Complex) and southern Britain (Midlands Microcraton), but it is totally unknown and putative in Belgium.

One of the major results of the well-known ECORS (Bois *et al.*, 1986) and BELCORP (Bouckaert *et al.*, 1988) seismic profiles was to show that the Dinant overthrust covers a thick unreflective basement. Crusts with such poor or no reflectivity are generally cratonic shields that remained undisturbed for a major part of the earth history (e.g. Allmendinger *et al.*, 1987; Meissner, 1987). The Belgian Caledonides are thus inferred to have been developed on an unknown concealed Precambrian basement. The purpose of this study is to review the geological features from the

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Belgian Caledonian rocks that could assess the nature and the age of this putative basement and the original (Cambrian) location of Belgium at the northeastern Gondwana margin (Van der Voo *et al.*, 1980) or at the southwestern edge of the Baltic shield (Paris and Robardet, 1990). These questions will be constrained by : 1) the study of the Caledonian magmatic rocks that possibly interacted with the Precambrian crustal rocks during their ascent; 2) the source-area characterization of the Caledonian sedimentary mass.

## 2. CONSTRAINTS FROM THE CALEDONIAN MAGMATIC ROCKS

Interactions of a mantle-derived magma with the continental crust is a complex, both mechanical and physico-chemical process. The magmatic stopping produces pieces of the crust that are incorporated in the magma as xenoliths or xenocrysts. The physico-chemical interactions result in the melting or chemical interactions of these xenoliths with the magma; they are controlled by the heat capacity of the magma and its saturation with regard to the chemical elements present in the incorporated crustal rocks. As a consequence, a magma generally assimilates the more acidic rocks leaving the more basic ones as xenoliths. So, the reader must be aware that the xenolith population of a magmatic rock is biased towards the more mafic among the stopped rocks, while the assimilated products are biased towards the more felsic ones. The assimilation consumes heat produced by the magmatic crystallization and there is likely to be

a correlation between the advance of the magmatic differentiation by crystal fractionation and the degree of crustal assimilation (Bowen, 1928). Therefore, to define correctly the chemical features of the felsic-biased assimilated rocks necessitates a study of all the rocks that represent the entire liquid line of descent. A representative view of the Precambrian pre-Caledonian basement will thus require a comparative study of the xenoliths, the xenocrysts and the geochemical features of the liquid line of descent.

In Belgium, the Caledonian (Ordovician-Silurian) magmatic activity extends to the four main Caledonian units : the Brabant Massif, the Sambre-Meuse Belt, the Stavelot Massif and the Rocroi Massif. In the Brabant Massif where it is best exposed, two main provinces have been recognized (André *et al.*, 1986a) : a western calc-alkaline province and an eastern tholeiitic province (Fig. 1). To date, most of our magmatic constraints about the Precambrian basement are inferred from the magmatic rocks from the western province where the Early Palaeozoic magmatic activity is concentrated along an arcuate belt along the southern margin of the Brabant Massif (Fig. 1). Three major magmatic centres have been identified : a western, under the Flanders; a central, south of Brussels; an eastern, along the Meuse River. The description of their main features is given in André (1983, 1991).

The recent seismic reflection profile across the Brabant Massif (Bouckaert *et al.*, 1988) shows a lot of reflectors shorter than 1 km that are interpreted, in other areas, as typical for old shield areas with low heat flow (e.g. Meissner, 1987). In particular, there is

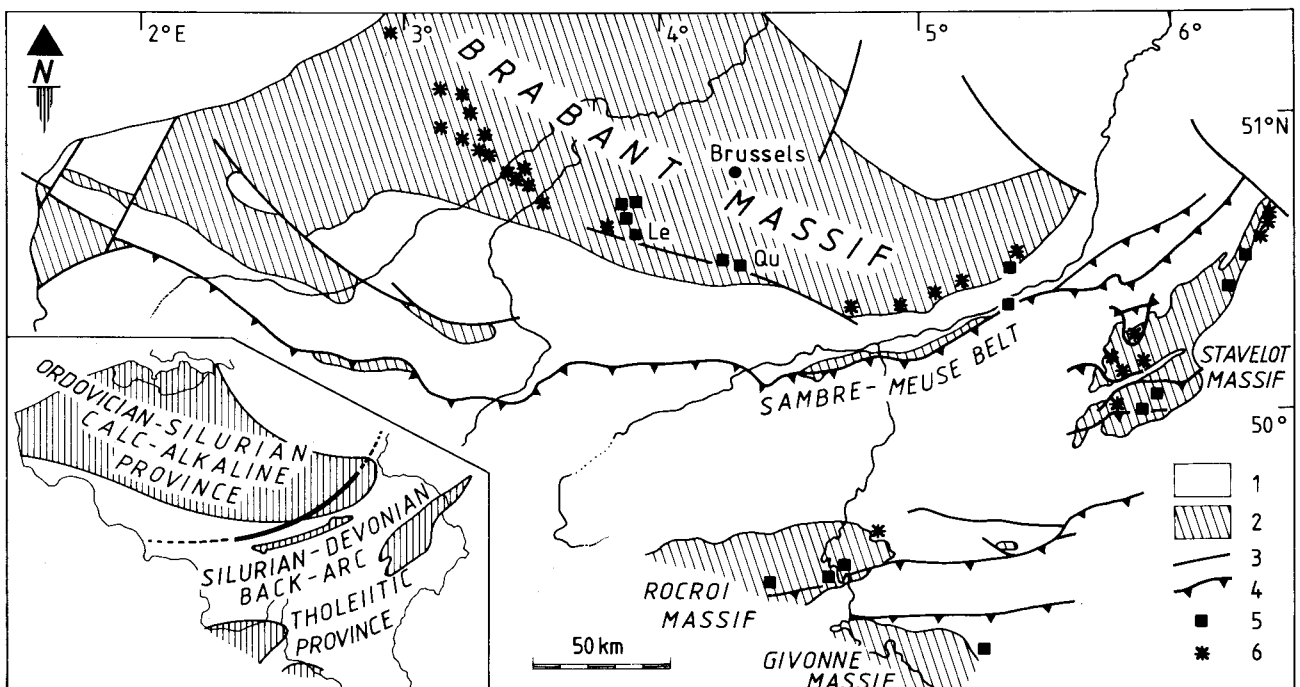


Fig. 1: Tectonic map of Belgium showing : 1) Devonian-Dinantian cover; 2) Early Palaeozoic massifs; 3) faults; 4) thrust faults; 5) intrusive magmatic rocks (Le: Lessines sills; Qu: Quenast plug); 6) volcanic rocks. The inset shows the location and the nature of the magmatic provinces.

no continuous reflector which could be taken as evidence for large scale Caledonian thrust belts and the xenoliths, xenocrysts and geochemical features of the Early Palaeozoic magmatic rocks are thought to characterize the concealed unreflective basement of the Brabant Massif.

### 2.1 The xenoliths

The study of the xenoliths has been carried out on the two best exposures from the central magmatic centre : the Quenast plug and the Lessines sill. The main geological and petrological features of these two porphyritic quartz diorites are described in André and Deutsch (1984, 1986). Except for the rare preservations of relict primary plagioclase, clinopyroxene and hornblende, most original mineralogical features have been obliterated by greenschist facies recrystallizations, related to the late magmatic hydrothermal activity. The crustal xenoliths are relatively rare since they represent less than 5 %

of the total amount of inclusions in the quartz diorites. They can be divided into three groups thought to represent respectively : a) Cadomian or Caledonian metasediments; b) hornfelses formed in thermal aureoles developed around the successive magmatic chambers, where the parental magmas of the Quenast and Lessines quartz diorites have transited during their ascent; c) the Precambrian crystalline basement.

The third group of xenoliths clearly demonstrates that the Caledonian belt of the Brabant Massif was formed upon a crystalline basement. Unfortunately, most of these xenoliths are small (< 10 cm) and have been completely transformed during the late magmatic alteration processes. They have thus little bearing for the determination of the nature of this basement. Two less altered samples found in the biotite zone of the Quenast plug are foliated biotite gneisses possessing a lenticular texture (Fig. 2) expressed by K-feldspar crystals wrapped around by the foliation in a quartzo-feldspathic fabric with biotite.

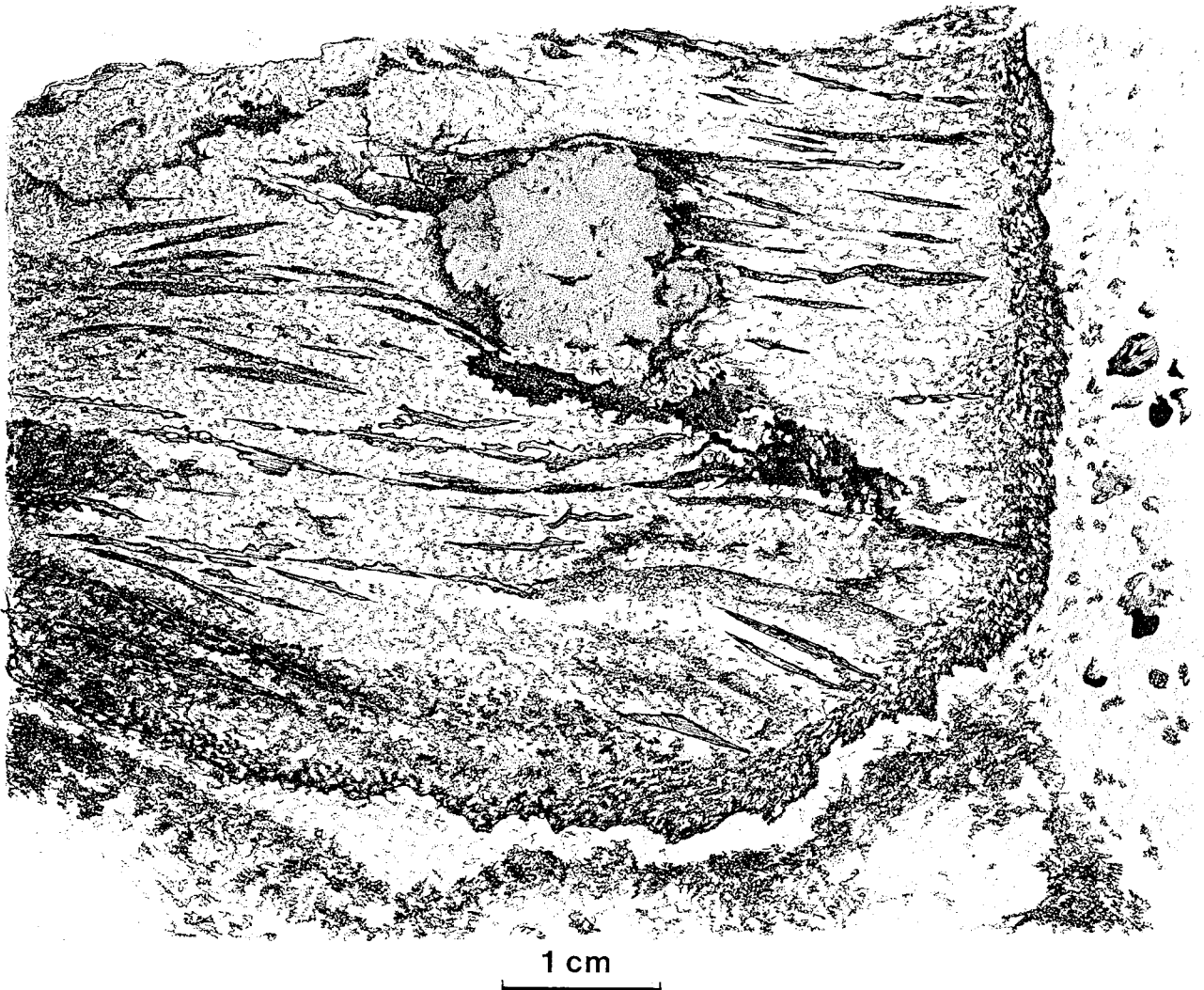


Fig. 2 : A metamorphic xenolith showing some thermal aureole at the contact with the Quenast porphyritic quartz diorite. The planar foliation is marked by the ferromagnesian minerals (biotite, Fe-Ti oxides). The rotation of the K-feldspar porphyroblast is evidenced by the S like orientation of the polygonized biotite flakes.

## 2.2. The xenocrysts

Zircon is the only mineral that has been identified as a xenocrysts (André and Deutsch, 1984). The concordia plot of the Quenast zircons demonstrates at least a two stage evolution for these zircons (André and Deutsch, 1984). Besides a predominant young age component ( $433 \pm 10$  Ma), these zircons bear a memory of an old Precambrian crystallization event (possibly Archean :  $4186 + 995 / - 767$  Ma) which is best preserved in the larger crystals. Such an imprecise upper intercept could represent mixing ages between several sources of different ages and may not be significant in terms of geological events. However, it is noteworthy that similar old Precambrian inherited zircons have also been recognized in the zircon populations of the Devonian intrusions from the Stavelot Massif ( $1928 \pm 64$  Ma, Kramm and Buhl, 1985) and the Rocroi Massif ( $2997 + 640 / - 548$  Ma, Goffette *et al.*, 1991). Thus, a figure of about 1.9 Ga is likely to represent a minimum estimate for the average primary crystallization age of these zircon xenocrysts.

## 2.3 Geochemical features of the liquid lines of descent

### 2.3.1 Results

Two liquid lines of descent have been identified, one for the andesitic to rhyolitic magmas from the western centre, another for the basaltic andesite to dacitic magmas observed in the central centre (André, 1983). Since their parental magmas represent mantle-derived calc-alkaline liquids (André *et al.*, 1986a), their contamination by crustal rocks which bear also, on average, a calc-alkaline signature (Taylor and McLennan, 1985) is undetectable by trace element geochemistry. Sr-Nd isotopes are much more sensitive to crustal contamination and they are used here to define the nature and the age of the crustal contaminant. All the rocks studied exhibit evidence of alteration which may have occurred at various times during the syn-magmatic hydrothermal activity or during the low grade metamorphism associated with the Caledonian orogeny. The effects of these alterations on the Sr-Nd system have been largely discussed in André (1983) and André and Deutsch (1986). The rocks selected for this study are those which isotopic compositions have not significantly been affected by these processes.

The  $^{143}\text{Nd}/^{144}\text{Nd}$  -  $^{87}\text{Sr}/^{86}\text{Sr}$  (Table 1), calculated back to the time of the crystallization and normalised to the chondritic values are plotted in a  $\epsilon_{\text{Nd}}^t$  -  $\epsilon_{\text{Sr}}^t$  diagram (Fig. 3). The basaltic andesitic rocks from the central portion of the arc deviate greatly from the mantle array towards negative  $\epsilon_{\text{Nd}}^t$  -  $\epsilon_{\text{Sr}}^t$ . Such an isotopic composition could result from two mechanisms : 1) a direct derivation from a light rare

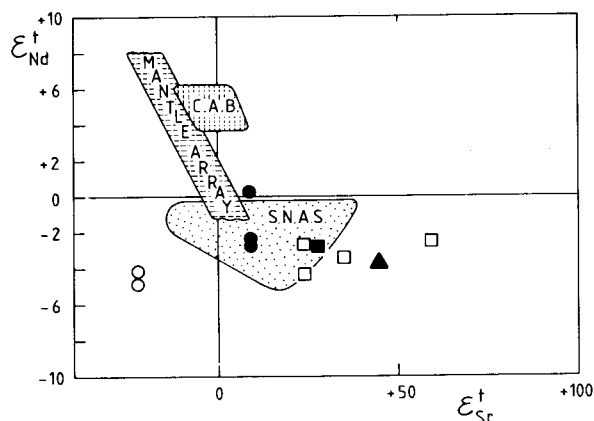


Fig. 3 :  $\epsilon_{\text{Nd}}^t$  -  $\epsilon_{\text{Sr}}^t$  diagram for the calc-alkaline magmatic rocks from the western (closed symbols) and central (open symbols) magmatic centres of the Brabant Massif (circles : basaltic andesites and andesites; squares: dacites, triangles: rhyolites) showing the field of the Ordovician isotopic composition for the mantle array, the calc-alkaline basalts (C.A.B.) and the southwestern Norway Anorthositic Suite (S.N.A.S.). Possible Sr-Nd isotopic features of the mantle reservoirs relevant to the time of crystallization of Brabant magmatic rocks are documented in appendix 2.

earth (LREE) - enriched, Rb-depleted mantle source; 2) a contamination of a LREE-depleted mantle-derived magma by Rb-depleted crustal rocks. Mantle sources with a larger Rb-depletion than normal mantle sources from the mantle array have recently been identified in both suboceanic (Hart *et al.*, 1986) and subcontinental (Anthony *et al.*, 1989) mantles. However, derivation from such a mantle source is implausible because these sources produce alkaline magma with distinctive geochemical characteristics (e.g. pronounced LREE enrichment,  $\text{La}_N/\text{Ta}_N < 1$ ) which are not present in the calc-alkaline magmatic rocks of the Brabant Massif (André *et al.*, 1986a). The second hypothesis is therefore preferred.

The transition by differentiation from the andesite to the more differentiated dacite and rhyolite is characterized by a relatively large increase in  $\epsilon_{\text{Sr}}^t$  values but small variations in  $\epsilon_{\text{Nd}}^t$  values. This points towards a bulk contamination of the residual liquids by supracrustal rocks enriched in radiogenic strontium. The convergence of both liquid lines of descent in the  $\epsilon_{\text{Sr}}^t$  -  $\epsilon_{\text{Nd}}^t$  diagram suggests that their contaminant could have comparable  $\epsilon_{\text{Nd}}^t$  values around minus 4 or lower at the time of the magmatism. André (1983) provides geochemical evidence for an early separation of large quantities of plagioclase during differentiation that significantly modified the Sr-Nd contents of the residual liquids towards enrichment in Nd and depletion in Sr. As a consequence, the Nd isotopic composition of the residual liquid would have been less and less modified by the Nd assimilated during the progressive differentiation while, at the same time, the Sr isotopic composition could have gradually been more and more affected by the Sr added by the

Table 1 : Sr-Nd isotopic data for the Brabant Massif magmatic rocks

Locality and type*	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}^{**}$	$\epsilon_{\text{Nd}}^{\dagger}$	$\epsilon_{\text{Sr}}^{\dagger\dagger}$
Lessines 2/8A (B)	0.1421	$0.51224 \pm 3$	-4.8	$-22 \pm 23$ (1)
Lessines S48-75 (B)	0.1253	$0.51223 \pm 2$	-4.1	$-22 \pm 23$ (1)
Quenast Q7/7 (B)	0.1206	$0.51224 \pm 9$	-3.5	Unknown
Izegem 158.5 (A)	0.1188	$0.51231 \pm 3$	-2.3	$+9 \pm 17$ (2)
Izegem 235 (A)	0.1294	$0.51247 \pm 3$	+0.3	$+9 \pm 17$ (2)
Izegem 251.6 (A)	0.1397	$0.51235 \pm 3$	-2.6	$+9 \pm 17$ (2)
Lessines 2/8 B (D)	0.1203	$0.51230 \pm 2$	-2.5	$+59 \pm 3$ (3)
Quenast Q1/9 (D)	0.1339	$0.51232 \pm 8$	-2.7	$+24 \pm 13$ (4)
Quenast Q6/4 (D)	0.1283	$0.51222 \pm 2$	-4.4	$+24 \pm 13$ (4)
Bierghes B1/9 (D)	0.1283	$0.51227 \pm 4$	-3.4	$+35 \pm 9$ (5)
Roulers 205.5 (D)	0.1114	$0.51224 \pm 3$	-2.7	$+28 \pm 13$ (6)
Deerlijk 193 (R)	0.1364	$0.51227 \pm 3$	-3.8	$+44 \pm 6$ (7)

\* For localities see Fig. 1 in André and Deutsch (1984); Magma types : B=basaltic-andesitic; A= andesitic; D= dacitic; R= rhyolitic.

\*\* For analytical procedures see Weis and Deutsch (1984); between run precision =  $\pm 5 \times 10^{-5}$ , normalised to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$  and Nd standard value of Caltec Nd standard of 0.51193 (Wasserburg *et al.*, 1981).

+ ( $^{143}\text{Nd}/^{144}\text{Nd}$ )<sub>CHUR</sub> = 0.512636; ( $^{147}\text{Sm}/^{144}\text{Nd}$ )<sub>CHUR</sub> = 0.1966

++ References for the isochrone-deduced Sr isotopic data :

1)  $t = 423 \pm 33$  Ma ( $2\sigma_M$ ), ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>0</sub> =  $0.7027 \pm 17$  ( $2\sigma_M$ ) (André and Deutsch, 1986);

2)  $t = 406 \pm 15$  Ma ( $2\sigma_M$ ), ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>0</sub> =  $0.7049 \pm 12$  ( $2\sigma_M$ ) (André 1983);

3)  $t = 414 \pm 16$  Ma ( $2\sigma_M$ ), ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>0</sub> =  $0.7084 \pm 2$  ( $2\sigma_M$ ) (André and Deutsch, 1986);

4)  $t = 433 \pm 10$  Ma (André and Deutsch, 1984), ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>0</sub> =  $0.7059 \pm 9$  ( $2\sigma_M$ ) (André and Deutsch, 1986);

5) Reset initial ratio ( $0.7088 \pm 2$ , André and Deutsch, 1985) calculated back to the time of the intrusion for an average  $^{87}\text{Rb}/^{86}\text{Sr} = 2.5$ ;

6)  $t = 459 \pm 102$  Ma ( $2\sigma_M$ ), ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>0</sub> =  $0.7062 \pm 9$  ( $2\sigma_M$ ) (André, 1983);

7) Reset initial ratio ( $0.7097 \pm 4$ , André and Deutsch, 1985) calculated back to the time of the deposition (Ashgillian) for an average  $^{87}\text{Rb}/^{86}\text{Sr} = 2.7$ .

contaminant. In this context, the limited changes in  $\epsilon_{\text{Nd}}^{\dagger}$  are likely to be due to a contamination balanced by crystal fractionation.

### 2.3.2 Nature of the contaminants

In order to test the crustal contamination of the Caledonian liquid lines of descent and to define the probable Sr-Nd isotopic features of these contaminants, various models of assimilation processes balanced by fractional crystallization (AFC models) have been calculated using the equation of DePaolo (1981a) (see appendix 1).

#### 2.3.2.1 The first stage of contamination

The Rb-poor crustal contaminant can be found in one of the three following groups of rocks : 1) anorthosites; 2) mafic rocks; 3) high pressure Precambrian granulites. A contamination by late Proterozoic anorthositic rocks similar to those of the southwestern Norway Anorthositic Suite (S.N.A.S.) is unlikely because these rocks show Ordovician isotopic signatures in the range (Demaiffe *et al.*, 1986) :  $-5.0 < \epsilon_{\text{Nd}}^{\dagger} < +0.3$ ;  $-12.7 < \epsilon_{\text{Sr}}^{\dagger} < +37$  (Fig. 3). A contamination by a much older anorthositic suite ( $t > 2.0$  Ga) cannot be discounted because, due to their very-low  $^{87}\text{Rb}/^{86}\text{Sr}$  ( $< 0.02$ ), these rocks produce with

time a more and more depleted Sr isotopic signature relative to bulk earth ( $^{87}\text{Rb}/^{86}\text{Sr} < 0.087$ ). Such a contaminant is however improbable because the anorthosites generally have very low Nd content and cannot represent an efficient contaminant for the LREE-enriched calc-alkaline Brabant Massif magmatic liquids.

In the crust, only one group of mafic rocks is significantly depleted in Rb relative to the chondritic value : the tholeiites ( $0.021 < ^{87}\text{Rb}/^{86}\text{Sr} < 0.088$ ; Anderson 1989, table 8.6). However, these rocks are generally Nd depleted relative to Sm and have Sm/Nd ratios lower or slightly higher to those of the chondritic reservoir. Therefore, such a contaminant cannot explain the  $\epsilon_{\text{Nd}}^{\dagger}$  values of the Brabant andesites ( $\epsilon_{\text{Nd}}^{\dagger} = -4$ ) except for very high improbable contamination rates ( $> 50\%$ ) in the case of an old ( $t > 2$  Ga) Nd-enriched tholeiitic contaminant.

Low  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios ( $< 0.06$ ) are common in many Precambrian high pressure granulites (e.g. Tarney and Windley, 1977; Rudnick *et al.*, 1985). This feature is often attributed to "heat producing element (HPE)" depletions accompanying granulite grade metamorphism, with U-Th-K-Rb-losses ascribed to processes such as generation of mobile anatectic melts (Heier, 1973), or migrating fluids generated from dehydration reactions or mantle degassing (Collerson and Fryer, 1978). Since high pressure granulite

terranes are widely believed to compose the lower crust, they represent the most probable contaminant for a picritic magma trapped at the density discontinuity between mantle and crust.

In Europe, geochemical and isotopic information about high pressure granulites are only available from: 1) the granulite facies xenoliths which are carried to the earth's surface by the alkali basalts from the French Massif Central and the Eifel area; 2) the Lewisian granulite terranes from northwestern Scotland. Unfortunately, the isotopic features of these lower crustal xenoliths were shown to result from a mixing process between Caledonian and Hercynian underplate basalts and old Precambrian crustal components (Rudnick and Goldstein, 1990; Downes *et al.*, 1990). Therefore they cannot be representative of a pre-Caledonian high pressure basement. For this

reason, we select the data from the Lewisian gneisses to test the possibility of a lower crustal contamination of the Caledonian basaltic andesites.

AFC models have been calculated (see appendix 2) for variable Sr contents in the magmatic liquid (300, 380, 500 ppm) and different minerals separated using the partition coefficient of Gill (1981) : amphiboles ( $D_{Nd} = 0.62$ ;  $D_{Sr} = 0.23$ ); clinopyroxenes ( $D_{Nd} = 0.5$ ;  $D_{Sr} = 0.08$ ) and plagioclase ( $D_{Nd} = 0.15$ ;  $D_{Sr} = 1.8$ ). The AFC contamination curves for amphibole and clinopyroxene separations are very similar and Fig. 4 only compares the AFC curves for clinopyroxene (Fig. 4A) and plagioclase (Fig. 4B) separations. Whatever the  $r$  ratio may be, the contamination with separation of a large amount of amphibole or clinopyroxene (Fig. 4A) cannot match with the isotopic features of the Brabant basaltic andesites within  $1\sigma$  of their error

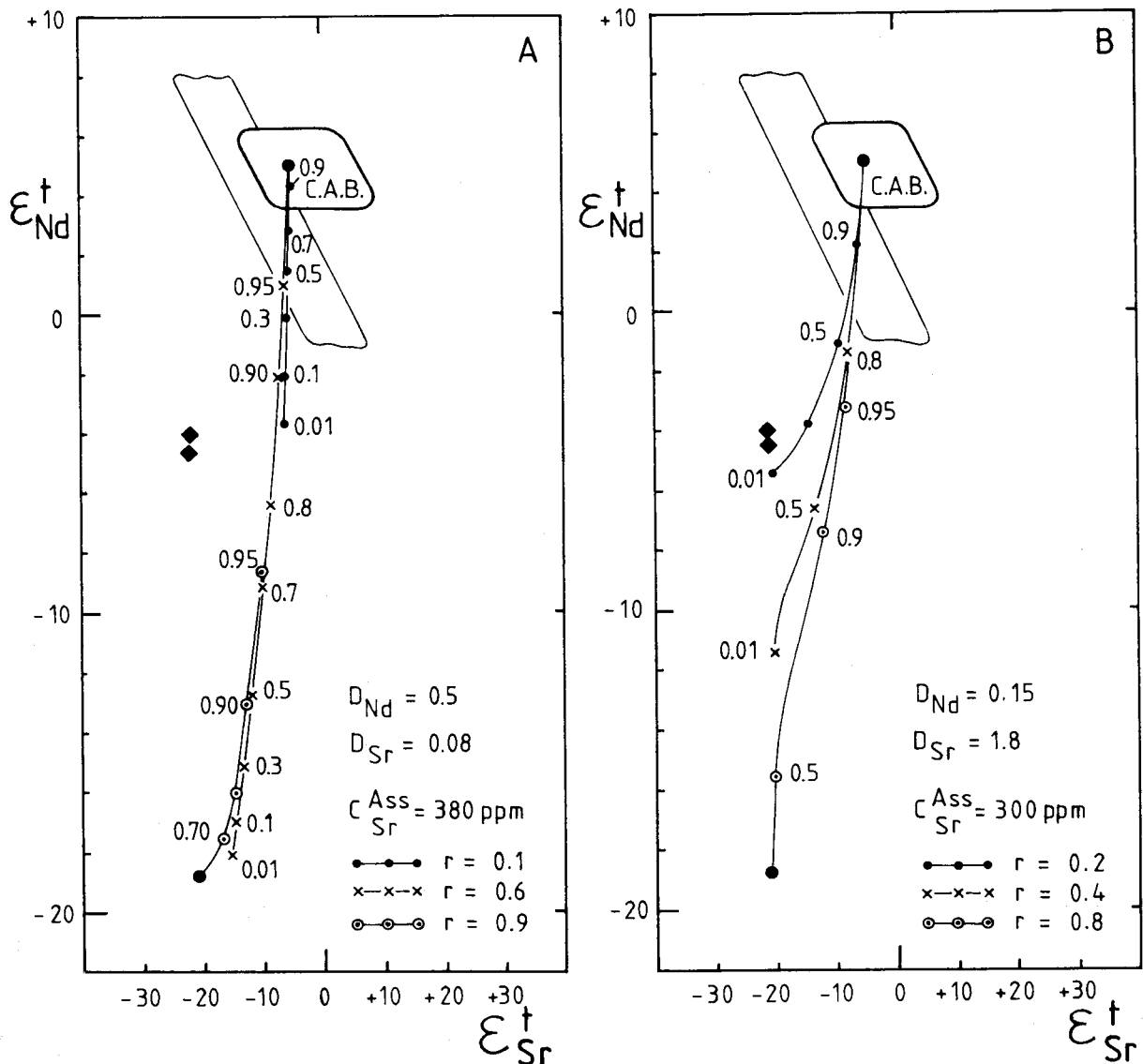


Fig. 4 :  $\epsilon_{Nd}^t$ - $\epsilon_{Sr}^t$  plots showing the values for the Quenast basaltic andesites (black squares) and the AFC mixing hyperbolas for the first stage contamination of the calc-alkaline magmatic rocks from the Brabant Massif using : A) clinopyroxene separations ( $D_{Nd} = 0.5$ ;  $D_{Sr} = 0.08$ ); B) plagioclase separations ( $D_{Nd} = 0.15$ ;  $D_{Sr} = 1.8$ ). The parameters are defined in the text and in the appendixes 1-2. The small numbers along the hyperbolas are the fractions of the remaining liquid. C.A.B. = calc-alkali basalts.

limits (see table 1). In contrast, the AFC curves resulting from the plagioclase separation could fit the data in the analytical error limits for  $0.3 < r < 0.5$ , especially when : 1) the Sr content of the magmatic liquid is lower than 300 ppm; and 2) the  $\epsilon_{Sr}^t$  of the basaltic magma is lower than -5. The curve for  $r < 0.3$  also fits the data but the plagioclase crystallization rate is in every case so high ( $\gg 90\%$ ) that it mismatches with the small negative Eu anomaly of these basaltic andesites (see Fig. 4 in André *et al.*, 1986a). In

contrast, for  $r = 0.4$ , the assimilation and crystallization rates ( $13\% < M_a < 20\%$  ;  $17\% < M_c < 50\%$ ) could remain compatible with the basaltic nature of the rocks and their small negative Eu anomaly if the proportion of residual liquid was high ( $0.7 < f < 0.9$ ). This means an Ordovician  $\epsilon_{Nd}^t$  values  $< -15$  for this contaminant. It must be emphasized that such a  $r$  factor (0.4) is well in agreement with a contamination in the lower crust (see appendix 1). Although this model is too subjective to solve the problem of the

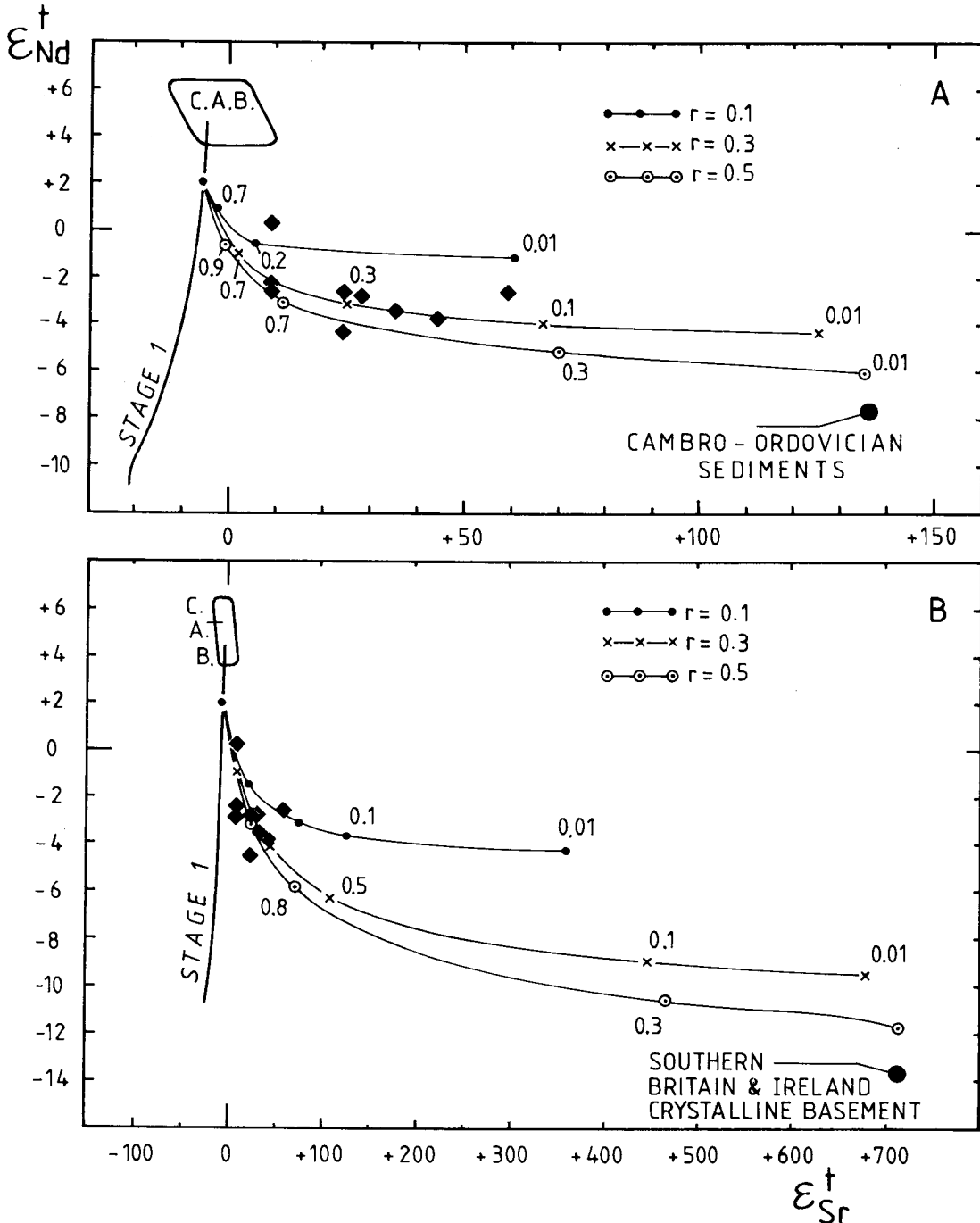


Fig. 5 :  $\epsilon_{Nd}^t$ - $\epsilon_{Sr}^t$  plots showing the values for the andesitic, dacitic and rhyolitic rocks from the Brabant Massif (black squares) and the AFC mixing curves for the second stage contamination of these calc-alkaline magmatic rocks using the Cambrian-Ordovician sediments (A) or the southern Britain and Ireland metamorphic rocks (B) as a contaminant. The parameters are defined in the text and appendixes 1 and 3. The small numbers along the curves are the fractions of the remaining liquid. C.A.B. = calc-alkali basalts.

nature of the crustal mixing partner, it confirms that assimilation of high pressure granulitic materials could have been a major rock forming process in the generation of the Brabant Massif basaltic andesites and it put constraints on the isotopic characteristics of this contaminant ( $\epsilon_{\text{Nd}}^t < -15$ ;  $\epsilon_{\text{Sr}}^t < -20$ ).

### 2.3.2.2 The second stage of contamination

There are two main potential Rb-enriched contaminants for this second stage : the Cambrian-ordovician sediments (C.O.S.) and the Precambrian crystalline basement (P.C.B.). The geochemical characteristics of the C.O.S. are well known and listed in appendix 3. In contrast, the geochemical parameters of the P.C.B. are largely uncertain and therefore subjective. The single constraint concerns its Ordovician Nd isotopic composition that must be more negative than that of the least radiogenic among the Caledonian sediments ( $\epsilon_{\text{Nd}}^t < -10.2$ ), since most of the C.O.S. are supposed to derive from the erosion of the P.C.B. The upper crustal Precambrian crystalline rocks from southern Britain (Rushton schist, Welsh borderland) and S.E. Ireland (Rosslare granitic gneisses) show a  $\epsilon_{\text{Nd}}^t$  signature between -12.2 and -14.2 (Davies *et al.*, 1985) and are thus good candidates for this contaminant. Their geochemical features are described in appendix 3. AFC models have been calculated for these two contaminants and some of the obtained curve patterns have been plotted in Fig. 5 (A et B). These models fit the isotopic data of the differentiated Caledonian magmatic rocks for both contaminants, but they imply very different proportions of residual liquids (f) and contrasted assimilation ( $\dot{M}_a$ ) and crystallization ( $\dot{M}_c$ ) rates, namely (for  $r = 0.3$ ) : P.C.B.:  $0.7 < f < 0.9$ ;  $4 \% < \dot{M}_a < 13 \%$ ;  $13 \% < \dot{M}_c < 43 \%$ ; C.O.S.:  $0.1 < f < 0.7$ ;  $13 \% < \dot{M}_a < 39 \%$ ;  $43 \% < \dot{M}_c < 129 \%$ .

Although the C.O.S. contaminant cannot be discounted, the P.C.B. is a more likely contaminant because : 1) it involves smaller contamination rates compatible with the very small fraction of inherited zircons observed in the Quenast quartz diorites (André and Deutsch, 1984); 2) the P.C.B. contaminant is supported by the existence of some crystalline xenoliths in the Quenast quartz diorite; 3) the geochemical features of the Quenast liquid line of descent suggest a minimum proportion of residual liquid of 25 % for a closed system (André, 1983) and one would expect a much higher value for an open system ( $f \gg 0.25$ ).

## 3. CONSTRAINTS FROM THE CALEDONIAN SEDIMENTARY MASS

In the Brabant Massif, the nature of the Precambrian detrital sources has been identified from

the lithic fragments of the coarse-grained rocks from the Rogissart unit (Assise de Tubize, Early Cambrian ?) by Vanden Auwera and André (1985). These authors described four main petrofacies among the granules : polycrystalline quartzose lithic fragments; greenschist facies metavolcanic rocks; micaschists and gneisses; fragments of metasediments (slates). The Caledonian sedimentary mass is thus inferred to have been derived from a composite Precambrian craton. Otherwise, certain elements (as REEs, Th, Ta, Co) in terrigenous sediments provide an index of the average composition of their provenance (see review in Taylor and McLennan, 1985). So it is possible to trace the average nature of this basement by studying the geochemistry of the Caledonian sedimentary rocks. Moreover, Sm-Nd isotopic analyses of fine-grained clastic sediments are known to provide estimates of the average time (the so-called "model age") since the Sm-Nd components of the sediment became part of the continental crust (Mc Culloch and Wasserburg, 1978). Sm-Nd isotopic systematics of the Caledonian fine-grained sediments could therefore be also employed to address the specific questions of sediment provenance and nature of the pré-Caledonian basement.

The preliminary geochemical and isotopic data recorded on the fine-grained sedimentary rocks from the Brabant Massif (André *et al.*, 1986b) are consistent with a derivation from two major detrital sources : 1) a juvenile metavolcanic source with a depleted-mantle model age ( $T_{\text{DM}}$ ) younger than 1.6 Ga; 2) a long established "granite-gneiss" source with a  $T_{\text{DM}}$  model age higher than 1.9 Ga. The present study provides new insight on the provenance of the Caledonian sedimentary mass. It is divided in two parts. The first reviews the larger geochemical data set that is now available for the slates of the Brabant Massif (André *et al.*, 1986b; André, Herbosch and Hertogen, in preparation) and the Stavelot Massif (André *et al.*, 1987; Burnotte *et al.*, 1989; André and Hertogen, in preparation) with the following objectives : 1) to confirm the preliminary results and determine more precisely the nature of the Brabant Massif source-rocks; 2) to compare the geochemical evolution of the sedimentary mass in the Stavelot and Brabant Massifs in order to detect regional variations in the nature of the detrital sources. Attention is only focused on elements which are known to be quantitatively transferred from the source-rocks into the phyllosilicates (Th, Ta, Hf, REE, Co) and which are thus usually indicative of the chemistry of the detrital sources (Taylor and McLennan, 1985). The samples have been strictly selected according to three criteria : 1) clear chronostratigraphic position; 2) lack of weathering; 3) very-fine grain size (generally  $< 25 \mu\text{m}$ ). The second part concerns some Nd isotopic measurements obtained on several fine-grained sediments from the Stavelot Massif in order to compare the sedimentary source-rocks of the Stavelot



and the Brabant Massifs. These rocks were sampled in the southern border of the Stavelot Massif along the Salm river; their location and description are given in appendix 4.

### 3.1 Geochemical data

The data for the Brabant slates are plotted in a La/Yb versus La diagram (Fig. 6) and a Hf-Th-Co diagram (Fig. 7). These data bring new constraints and new questions, but basically the model of André *et al.*, (1986b) remains unaltered. Indeed, they confirm that :

- 1) these fine-grained sediments exhibit considerable trace element variability ( $16.6 \text{ ppm} < \text{La} < 85.3 \text{ ppm}$ ;  $4 < \text{La}_N/\text{Yb}_N < 14$ ;  $8.9 \text{ ppm} < \text{Th} < 17.1 \text{ ppm}$ ;  $3.1 \text{ ppm} < \text{Hf} < 9.1 \text{ ppm}$ ;  $1.19 \text{ ppm} < \text{Ta} < 3.19 \text{ ppm}$ ;  $1.4 \text{ ppm} < \text{Co} < 36.6 \text{ ppm}$ ) reflecting strong variations in the nature of the Caledonian detrital sources;
- 2) the gradual geochemical evolution of the Cambrian-Ordovician sedimentary mass from low Th-Hf contents in the Early Cambrian to large Th-Hf contents in the Ordovician could be explained in terms of progressive mixtures between two geochemically distinct end members : a Cambrian Th-Hf depleted, Co-enriched mafic source and an Ordovician Th-Hf enriched, Co-depleted felsic source;
- 3) the LREE-enriched patterns of the Early Cambrian slates ( $\text{La}_N/\text{Yb}_N > 4$ ), their lack of heavy rare earth (HREE) fractionation and their small negative Ta anomaly ( $1.2 < \text{La}_N/\text{Ta}_N < 1.6$ ; see Fig. 3 in André *et al.*, 1986b), suggest that their mafic magmatic source-rock was not part of an alkaline sequence ( $\text{La}_N/\text{Ta}_N < 1$ ), a LREE-depleted tholeiitic sequence ( $\text{La}_N/\text{Yb}_N \ll 1$ ) or a calc-alkaline sequence wherein the Ta depletion is much more pronounced ( $\text{La}_N/\text{Ta}_N > 2$ ; e.g. Briquet *et al.*, 1984).

The new geochemical data provide two new facts. Firstly, the dispersion of the data appears to be larger for the REE-enriched sediments than for the REE depleted (Fig. 6). This points to an apparently "unique" mafic end member and a more complex, probably composite, felsic source. Secondly, the Co content roughly decreases with the increase in the La content when the whole data set is considered, but increases with La when the samples are considered according to their deposition age (Fig. 8). This leads to a strong age variation in the Co/La ratios from the Early Cambrian ( $\text{Co}/\text{La} \sim 1$ ) to the Arenigian-Caradocian ( $\text{Co}/\text{La} \sim 0.15$ ). This strongly suggests that the source-rock related evolution of the slate geochemistry is obscured to some degree by sedimentary processes such as weathering, dissolution, transport, deposition or diagenesis. This is not uncommon since, for example, some weathering or depositional controls were noticed on the REE-Co patterns when variations in the tectonic

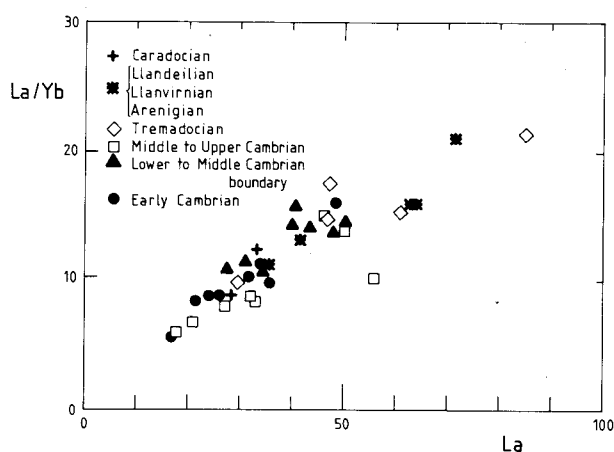


Fig. 6 : La/Yb-La diagram for the fine-grained metasediments from the Brabant Massif.

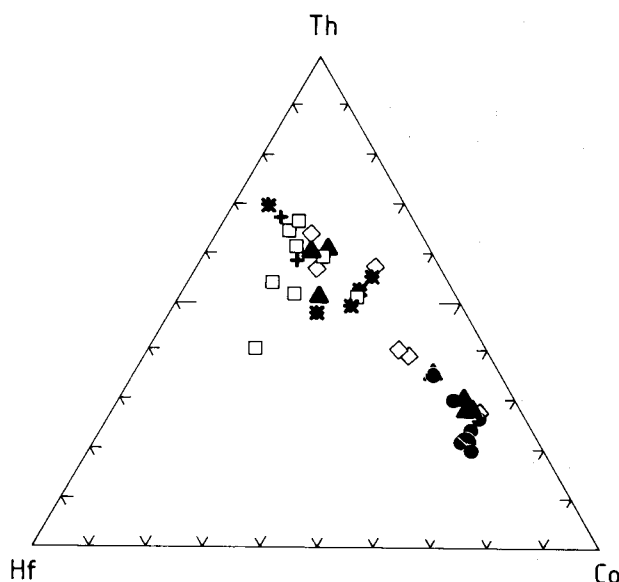


Fig. 7 : Hf-Th-Co diagram for the fine-grained metasediments from the Brabant Massif (symbols as in Fig. 6).

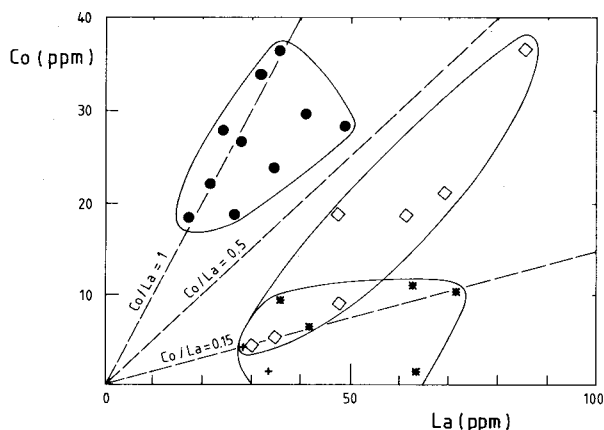


Fig. 8 : Co-La diagram for the fine-grained metasediments from the Brabant Massif (symbols as in Fig. 6).

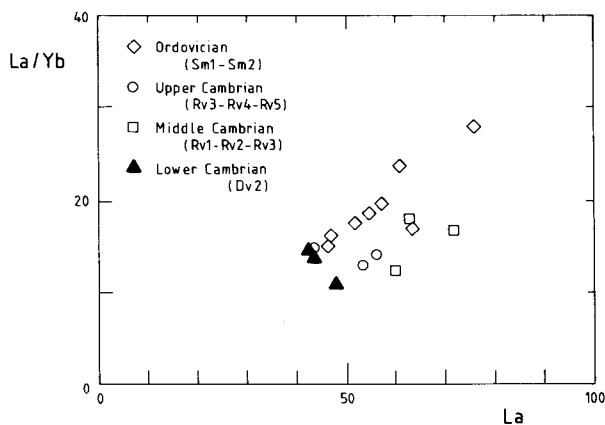


Fig. 9 : La/Yb-La diagram for the fine-grained metasediments from the Stavelot Massif. Lithostratigraphic divisions : Sm = Salmian; Rv = Revinian; Dv = Devillian.

regime changed the weathering intensity or the depositional conditions (Schieber, 1986). In such a context, the nature of the source-rocks can no longer be inferred from the absolute trace element content as proposed by Wildeman and Haskin (1973), Dypvik and Brunfelt (1976) and Taylor and McLennan (1985), but should be identified from the distributions of the trace element ratios. Using this method, the high  $La_N/Yb_N$  ( $\sim 4$ ) and intermediate  $La_N/Ta_N$  (between 1.2 and 1.6) of the Early Cambrian slates (André *et al.* 1986a) suggest a mafic source-rock similar to the modern intraplate continental tholeiites.

The data from the Stavelot fine-grained sediments are also plotted in a La/Yb versus La diagram (Fig. 9) and in a Hf-Th-Co diagram (Fig. 10). Comparison of these figures with Figs. 6-7 clearly indicates similarities and differences between the geochemical features of the Brabant and Stavelot sedimentary masses. Among the similarities it is worth noticing : 1) the LREE-enriched character (see also Fig. 6 in Burnotte *et al.* 1989); 2) the strong differentiation in terms of the Co/Th ratio; 3) the LREE-depletion of the Lower Cambrian slates relative to the Ordovician ones. This reveals that the Stavelot sedimentary mass was also controlled by a change from "mafic" detrital sources in the Lower Cambrian to "felsic" detrital sources in the Ordovician. However, there are three major differences relative to the Brabant slates : 1) the REE differentiation is less pronounced; 2) the spread of data in the La/Yb-La diagram is much wider; 3) the enrichment in Co of the Lower Ordovician Mn-rich beds ("coticles") and red slates. These differences might result from a larger obliteration of the source-rocks geochemical signatures by sedimentary processes. One process could have been the authigenic reactions such as the growth of grey monazites in the Middle and Upper Cambrian formations (Burnotte *et al.*, 1989) and the near-surface diagenetic transformations characterizing the Lower Ordovician (Lamens *et al.*, 1986; André *et al.*, 1987). It is therefore concluded that one must be careful in

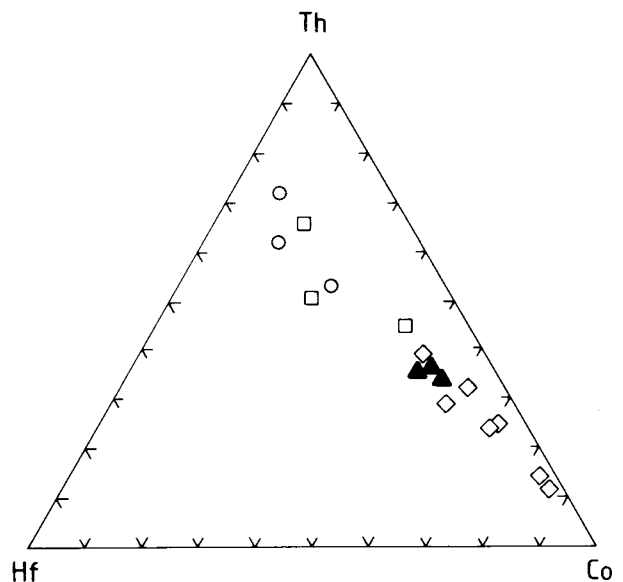


Fig. 10 : Hf-Th-Co diagram for the fine-grained metasediments from the Stavelot Massif (symbols as in Fig. 9).

interpreting the Stavelot slates trace element features in terms of source provenances before the geochemical balance of these authigenic processes has been investigated. In contrast, because Sm and Nd have very similar geochemical properties, they strongly resist fractionation by weathering, erosion, transport, deposition, diagenesis and low-grade metamorphism (see review in DePaolo, 1988). As a consequence, the Sm-Nd isotopic features of a detrital sediment represent a weighted average from its different source-rocks. This explains why a Nd isotopic investigation has been preferred to a trace element inventory in order to address the specific problem of the Stavelot sediment provenances and the nature of its Precambrian crystalline basement.

### 3.2. Nd isotopic data

The  $^{143}\text{Nd}/^{144}\text{Nd}$ , calculated back to the time of deposition and normalised to the chondritic values ( $\epsilon^{143}\text{Nd}$ ), and the model ages of the sedimentary protoliths calculated for bulk earth ( $T_{BE}$ ) or depleted mantle ( $T_{DM}$ ) magma sources are listed in table 2. In the present study, two different symbols are used for either the stratigraphic ages ( $t$ ) or the model age ( $T$ ) in order to avoid any possible confusion. The  $\epsilon^{143}\text{Nd}$  and  $T_{DM}$  values are plotted against La content (Fig. 11) and compared to the trends of the Brabant slates as deduced from André *et al.* (1986b). In Fig. 12, the  $\epsilon^{143}\text{Nd}$  data for the Stavelot and Brabant slates are plotted against the time of deposition and compared with the Cambrian-Ordovician  $\epsilon^{143}\text{Nd}$  data of similar sediments from southern Britain, Brittany and southern Nova Scotia.

There is no correlation between the  $\epsilon^{143}\text{Nd}$  values and the La content for the Stavelot samples. In particular, they do not fit the hyperbolic  $\epsilon^{143}\text{Nd}$ -La mixing curve that

Table 2 : Nd isotopic data for the Stavelot Massif sediments

Sample/Type <sup>X</sup>	Lithostratigraphic <sup>XX</sup> units	Acritarch <sup>+</sup> zones	Series <sup>++</sup>	Age <sup>+++</sup> (Ma)	<sup>147</sup> Sm/ <sup>144</sup> Nd	<sup>143</sup> Nd/ <sup>144</sup> Nd <sup>+</sup> ± 2σ <sub>M</sub>	T <sub>BE</sub> <sup>**</sup> (Ma)	T <sub>DM</sub> <sup>***</sup> (Ma)	ε <sup>t</sup> <sub>Nd</sub>
VI 25/RS	Sm2c	-	L-M.O.	470	0.1106	0.512013 ± 42	1106	1520	- 7.0
VII 3/RS	Sm2a	-	L-M.O.	470	0.1231	0.512094 ± 48	1126	1592	- 6.2
VI 20/C	Sm2b	-	L-M.O.	470	0.0986	0.511999 ± 37	929	1380	- 6.6
TIV 30B/C	Sm2b	-	L-M.O.	470	0.1066	0.511887 ± 50	1269	1642	- 9.3
TIV 27/C	Sm2b	-	L-M.O.	470	0.1244	0.511980 ± 50	1386	1811	- 8.5
VIII 7/SI	Sm1c	Z7	L.O.	490	0.1135	0.512055 ± 42	1068	1499	- 6.2
ST86-11/SI	Rv5	Z6	U.C.	515	0.1104	0.511955 ± 31	1206	1602	- 7.7
ST86-12/SI	Rv4	Z5	U.C.	515	0.1128	0.511983 ± 22	1189	1598	- 7.3
ST86-7/SI	Rv3	Z4	U.C.	515	0.1124	0.511834 ± 21	1452	1817	-10.2
ST86-10/SI	Rv2	Z4	M.C.	525	0.1090	0.511866 ± 18	1340	1710	- 9.2
ST86-9/SI	Rv2	Z2	M.C.	525	0.1063	0.512075 ± 27	949	1371	- 4.9
ST86-8/SI	Rv1	Z1	M.C.	525	0.1128	0.511876 ± 91	1383	1760	- 9.3
ST86-5/SI	Dv2	-	L.C.	540	0.1137	0.512113 ± 86	964	1414	- 4.5
ST86-2/SI	Dv1	-	L.C.	540	0.1151	0.511928 ± 21	1325	1720	- 8.2
ST86-1/SI	Dv1	-	L.C.	540	0.1135	0.512193 ± 29	815	1291	- 2.9

<sup>X</sup> = R.S.: Red shales; C: Coticles; SI: Slates

<sup>XX</sup> = Dv: Devillian; Rv: Revinian; Sm: Salmian

<sup>+</sup> = Biostratigraphy after Vanguetaine (1986)

<sup>++</sup> = L-M.O.: Limit between Lower and Middle Ordovician; L.O.: Lower Ordovician; U.C.: Upper Cambrian; M.C.: Middle Cambrian; L.C.: Lower Cambrian

<sup>+++</sup> = Age interpolated from timescale of Cowie and Bassett (1989)

<sup>\*</sup> = For analytical procedures, see table 1

<sup>\*\*</sup> = Model age calculated using bulk-earth parameters

<sup>\*\*\*</sup> = Model age calculated using depleted mantle parameters of DePaolo (1981b).

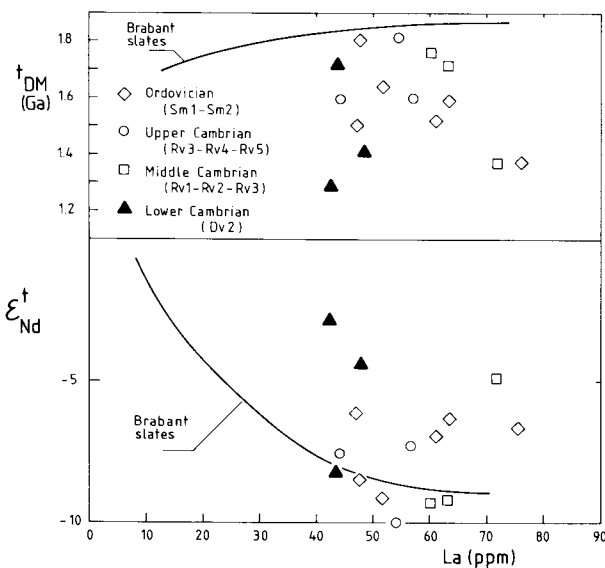


Fig. 11 : T<sub>DM</sub> crustal residence ages and ε<sup>t</sup><sub>Nd</sub> values versus La contents in the Stavelot fine-grained metasediments. The black curves represent the trends for the Brabant slates (data from André *et al.*, 1986b).

characterizes the evolution of the Brabant sedimentary mass. This, together with the trace element data (cf Figs. 9-10), are taken as evidence for one or more of the three following processes : 1) erratic changes in source-rock compositions with time or/and 2) strong weathering of the source-rocks or 3) post-depositional alteration during diagenesis or/and metamorphism on the REE content. The average ε<sup>t</sup><sub>Nd</sub> value is however significantly more radiogenic during the Lower Cambrian (-5.2) than during the Middle Cambrian (-7.8), the Upper Cambrian (-7.5) or the Lower Ordovician (-7.3). This has two important implications. Firstly, this is a clear evidence for an abrupt change in the detrital sources at the end of Lower Cambrian with the replacement of a rather "juvenile" Lower Cambrian source by a rather "mature" source during the Middle Cambrian sedimentation. Secondly, these isotopic data are at variance with a derivation of the Middle and Upper Cambrian sedimentary masses through recycling of some Lower Cambrian sediments rocks as suggested by Von Hoegen *et al.* (1985).

All the Stavelot slates have depleted mantle model ages (T<sub>DM</sub>), younger than the Brabant ones (Fig. 11) with the consequence that their average T<sub>DM</sub> model ages are quite different, 1.56 ± 0.09 Ga and 1.81 ± 0.07 Ga respectively. It is worth noticing that the first value is close to the average model age for the Upper Cambrian and Tremadocian sediments of England

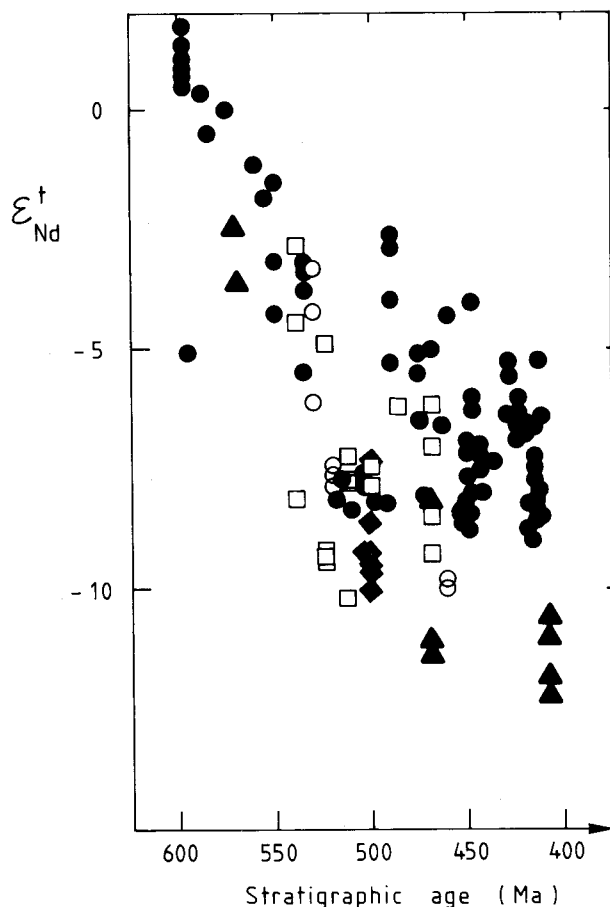


Fig. 12 :  $\epsilon_{Nd}^t$  values plotted against the stratigraphic age of fine-grained metasediments from Brabant Massif (open circles), Stavelot Massif (open squares), southern Britain (solid circles), Brittany (solid triangles), southern Nova Scotia (solid squares). Data from this work, André *et al.* (1986b), Davies *et al.*, (1985), Thorogood (1990), Michard *et al.* (1985) and Clarke and Halliday (1985).

(1.55 Ga <  $T_{DM}$  < 1.66 Ga, O'Nions *et al.*, 1983, Thorogood, 1990), while the second value falls in the range of the mean  $T_{DM}$  model age of the post-Archean sedimentary mass estimated to  $2.0 \pm 0.2$  Ga by Miller *et al.* (1986). This does not necessarily outline a substantial difference in stratigraphic age ( $t$ ) of the source-rocks for the Stavelot and the Brabant sedimentary masses. Indeed, at any time, the  $T_{DM}$  model age is not strictly representative of the mean stratigraphic age ( $t$ ) of the contemporaneous upper crust for two reasons : 1) a relationship exists between model ages and tectonic settings, with passive margins exhibiting considerably older model ages than active settings (McLennan, *et al.*, 1990) due to a preferential input of juvenile materials in the sedimentary masses developed in the fore and continental arcs; 2) the model ages are not equally sensitive to all mantle additions to the crust (see discussions in Michard *et al.*, 1985 and André *et al.*, 1986b) with a better detection of juvenile additions in the form of calc-alkaline basalts than in the form of Mid Ocean Ridge basalts (MORB). The  $\epsilon_{Nd}^t$  values are therefore preferred to the  $T_{DM}$  data in order to analyse

the characteristics of the provenance areas. In the  $\epsilon_{Nd}^t$ - $t$  diagram (Fig. 12), the slates from Brabant and Stavelot Massifs follow a roughly parallel trend with a juvenile input ( $\epsilon_{Nd}^t > -3$ ) in the Lower Cambrian followed by recycling of older crustal segments ( $\epsilon_{Nd}^t < -10$ ) during Upper Cambrian and Ordovician times.

## 4. DISCUSSION

### 4.1. Age and nature of the Precambrian basement in Belgium

As demonstrated above, the major characteristics of the Caledonian sedimentary and magmatic rocks converge to demonstrate the existence of a Precambrian crystalline basement somewhere below the Caledonian and Hercynian segments in Belgium. These are : 1) the crystalline xenoliths and old inherited zircons observed in the magmatic rocks; 2) the Sr-Nd isotopic features of the Brabant calc-alkaline magmatic rocks; 3) the numerous crystalline lithic fragments discovered in the Early Cambrian proximal turbidites of the Brabant Massif; 4) the high crustal residence age ( $1.6 \text{ Ga} < T_{DM} < 2.0 \text{ Ga}$ ) of Ordovician metasediments in the Stavelot and Brabant Massifs. These characteristics put different although complementary constraints on the nature and the age of this basement. The geochemical features of the Cambrian-Ordovician sediments reflect a change in the composition of the Precambrian rocks under erosion. The magmatic rocks record information about the composition of some deeper part of this basement.

#### 4.1.1 Composition of the basement surface

##### 4.1.1.1 Location and rock types

In the Stavelot Massif, the palaeo-currents are dominantly to the North, reflecting a constant northward deepening of the sedimentary basin and southern-southwestern supply areas during the Lower Cambrian (Von Hoegen *et al.*, 1985), the Middle and Upper Cambrian (Walter, 1980) and the Lower Ordovician (Lamens and Geukens, 1985). Therefore, the geochemical and Nd isotopic data of the Stavelot shelf sediments provide information about a basement surface located somewhere to the south of the Stavelot Massif at the time of deposition. Because this massif was probably thrust over the Brabant Massif (Betz *et al.*, 1988) with a net northwestward translation vector of possibly 40 to 120 km (Raoult and Meilliez; 1987), the Stavelot sedimentary mass is inferred to reflect the composition of a Precambrian crystalline basement that was originally located far away to the southeast of the present Stavelot Massif. In the Brabant Massif, the Cambrian-Ordovician palaeogeography has been scarcely investigated and

the rare available palaeo-current directions (cf. Mortelmans, 1955) are uncorrected for tectonic tilting. They are hence insufficient to postulate the position of source-areas. In any case, the Brabant and Stavelot metasediments bring constraints about two Precambrian basements separated, at least, by 150 km.

The  $\epsilon_{\text{Nd}}^t$ -t data (Fig. 12) indicate that, in both basements, the youngest rocks, rather juvenile in composition ( $\epsilon_{\text{Nd}}^t < -3$ ), were removed by erosion during the early stage of deposition while the oldest source rocks ( $\epsilon_{\text{Nd}}^t < -10$ ) were mainly unroofed later in the deposition during the Upper Cambrian and the Ordovician. This establishes that both continental source-areas were stratified with juvenile (mantle-derived) materials overlying older mature rocks. This conclusion is supported by the recent discovery of two major groups of detrital zircons in the Cambrian sandstones from both the Ardennes and Brabant : a first group of colourless, generally rounded to euhedral, U-poor zircons with apparent  $^{207}\text{Pb}/^{235}\text{U}$  ages between 0.53 Ga and 1.65 Ga, and a second group with reddish, generally rounded to very well rounded, U-rich zircons with apparent  $^{207}\text{Pb}/^{235}\text{U}$  ages between 1.75 Ga and 2.4 Ga (Von Hoegen *et al.*, 1990). Considering the predominance of metavolcanic rocks in the Cambrian lithic fragments of the Brabant Massif (Vander Auwera and André, 1985), the continental feeding areas are concluded to be made up of metavolcanic formations overlying older metamorphic rocks.

#### 4.1.1.2 The metavolcanic rocks

The maximum age of the metavolcanites can be deduced from the youngest model age of the Caledonian sediments. As pointed out above, the geochemical characteristics of the Brabant Early Cambrian metasediments favour a continental tholeiitic composition for these Precambrian metavolcanites. This magma type is, at any time, fairly well characterized by Nd isotopic features close to bulk earth values ( $\epsilon_{\text{Nd}}^t = 0$ , see review in DePaolo, 1988) and the crustal residence age of such a magma can better be approximated by  $T_{\text{BE}}$  model ages rather than by  $T_{\text{DM}}$  model ages. The obvious conclusion is that the volcanic precursors of the Brabant Early Cambrian metasediments ( $0.9 < T_{\text{BE}} < 1.2$ , cf. table II of André *et al.*, 1986b) were probably extracted from the mantle less than 0.9 Ga ago and it is likely to be part of a Late Proterozoic or Early Cambrian volcanic sequence. The crustal residence age of some Stavelot Early Cambrian slates ( $1.29 < T_{\text{DM}} < 1.41$  Ga) contrasts with the rather high  $T_{\text{DM}}$  age of coeval Brabant slates ( $T_{\text{DM}} > 1.6$  Ga, André *et al.*, 1986b). This rather young  $T_{\text{DM}}$  could be explained in three ways : 1) a larger juvenile input; 2) a mature input of younger age; 3) a LREE-enriched calc-alkaline juvenile input that could

decrease significantly the  $T_{\text{DM}}$  model age (see discussion in André *et al.*, 1986b). Although the LREE-enriched character of the Stavelot Early Cambrian slates could substantiate the third hypothesis, they are, at present, too a few constraints to permit a firm choice between these three possibilities. Because the LREE-enriched magma type could present highly variable Nd isotopic signatures, above and below the bulk earth value (see review in DePaolo, 1988), we can not make any assumption about the age of the Ardennes juvenile source except that it is younger than 1.3 Ga.

There is no evidence of Lower Cambrian magmatism in Belgium except perhaps for the small Lembeek dyke, the intrusion age of which is still unknown (Denayer and Mortelmans, 1954). In contrast, remains of late Proterozoic volcanism with calc-alkaline and intraplate tholeiitic affinities are ubiquitous within the nearest Precambrian cratonic areas, in both southern Britain (Thorpe *et al.*, 1984; Pharaoh *et al.*, 1987b) and Brittany (Cabanis *et al.*, 1987; Lees *et al.*, 1987). So, referring to the strong similarities in  $\epsilon_{\text{Nd}}^t$ -t paths between the sedimentary masses of southern Britain, Brittany and Belgium (Fig. 12) and to the probable intraplate tholeiitic character of the Brabant metavolcanic source-rock, we argue that the detected Juvenile input in the Early Cambrian from the Brabant and Stavelot Massifs derived from Cadomian volcanic sequences similar to those overlying the Midland and Pentevrian cratons. This view is corroborated by the Late Proterozoic concordant U/Pb age (545 Ma) of a detrital zircon fraction found in the Early Cambrian from the Brabant Massif (Von Hoegen *et al.*, 1990).

#### 4.1.1.3 The metamorphic rocks

A part of the detrital zircon population of the Brabant-Ardennes Cambrian sandstones has been recently documented to derive directly or indirectly from Archean or Early Proterozoic source rocks (Von Hoegen *et al.*, 1990). All the measured  $T_{\text{DM}}$  ages, below or within the range for the entire world preserved sedimentary mass (2.0 Ga; Miller *et al.*, 1986), however suggest that very old crustal materials ( $> 2.5$  Ga) did not significantly contribute to these Caledonian sediments. Archean nuclei were therefore probably insignificant at the surface of the basement exposed to the Caledonian erosion.

As defined above from the geochemical features of the Ordovician Brabant slates, the metamorphic basement surface was a composite of different LREE-Th-Hf-enriched rock-types. The  $T_{\text{DM}}$  ages correspond to a weighted average of several felsic protoliths with different  $T_{\text{DM}}$  and have thus no bearing in terms of the dating of crustal events (crustal growth, crustal accretion or crustal cratonization).

The lithic fragments from the Early Cambrian point to a metamorphic basement made up of schists with

subordinate granite and/or gneissic rocks (Vander Auwera and André, 1985). The Brabant Early Ordovician sediments, that incorporated the largest fraction of these Precambrian felsic components, are strongly enriched in REE relatively to the Post-Archean sediments (see Fig.3 in André *et al.*, 1986b), the uniform REE pattern of which is commonly interpreted as an inheritance from the recycling character of the sedimentary mass (e.g. Veizer and Jansen, 1985). This relative REE enrichment precludes any derivation of these Ordovician sediments from protoliths recycled through several sedimentary cycles. Consequently, the proportion of the parametamorphic rocks in this "Proterozoic" basement surface is thought to be relatively minor to the proportion of orthometamorphic or granitoid rocks.

#### 4.1.2. Composition of the basement deep parts

The ubiquitous finding of ancient (1.9, 3.0, 4.2 Ga) inherited zircons in the magmatic rocks from Belgium is a compelling evidence for the presence of an extensive old basement under the Caledonian-Hercynian belts of Belgium. Another argument for the presence of crustal material already extracted from the mantle in the Archean or the Early Proterozoic is given by the unradiogenic Nd isotopic composition ( $\epsilon_{Nd}^t < -15$ ) of the first-stage contaminant of the Caledonian liquid lines of descent. Indeed, assuming average crustal  $^{147}\text{Sm}/^{144}\text{Nd}$  around 0.12, this  $\epsilon_{Nd}^t$  values implies a minimum extraction age around 2.4 Ga for the contaminant protolith. Additional support comes from the granulite facies xenoliths found in the Pleistocene alkali tuffs from the Eifel area in Germany. There, a three points "isochron" gives an age of  $1.5 \pm 0.1$  Ga that was, previously, interpreted as the age at which the igneous precursor differentiated from the mantle (Stosch and Lugmair, 1984). These rocks are now thought to result from a mixing process between old Proterozoic rocks and Caledonian or Hercynian basalts (Rudnick and Goldstein, 1990) making the 1.5 Ga date to represent a minimum age for the Eifel Proterozoic crustal component.

Gross information about the nature of this Brabant-Ardenne basement can be obtained from the modelling of the crustal contamination of the Caledonian liquid lines of descent. These calculations suggest interactions with both Rb-depleted Early Proterozoic or Archean lower crustal rocks (minimum extraction age around 2.4 Ga, see above) and Rb-enriched Late Proterozoic upper crustal rocks. It is worth noting here that some part of the lower continental crust below the Eifel area are thought to be also characterized by Rb-depleted granulitic rocks (Reys *et al.*, 1987). If confirmed, the presence of some Rb-depleted rocks in the Brabant-Ardenne basement could afford a clue to explain the rather cold and unreflective nature of the Brabant crust (Bouckaert *et*

*al.*, 1988) for two reasons. Firstly, Rb-depleted rocks are often impoverished in heat producing elements like U, Th and K (Heier, 1973). Secondly, there is a possible correlation between the lower crust reflectivity and the heat flow (Klemperer, 1987).

## 4.2 The problematic of the Midlands-Brabant-Ardenne basement

A major Question is to define whether the Precambrian basements from southern Britain ("Midlands" basement) and Belgium ("Brabant-Ardenne" basement) form part of one structural unit or whether they constitute two separate entities. Our apparently convergent data constrain a Brabant-Ardenne basement at least partly older than 1.8 Ga. This age is in the range of : 1) the other exposed Precambrian nuclei in western Europe (the Icartian Block of the Channel Islands dated to 2.0 Ga by Vidal *et al.*, 1981, the southern Bay of Biscay Block dated to 1.9 and 2.7 Ga by Guerrot *et al.*, 1989) and 2) the provenance ages recovered for the detrital zircons of southern Nova Scotia (Krogh and Keppie, 1990), western and central Europe (e.g. Michot and Deutsch, 1970; Grauert *et al.*, 1973; Gebauer *et al.*, 1989, and Belgium (Von Hoegen *et al.*, 1990). In contrast, there is little or no geological, geochemical and isotopic evidence for ancient (>1200 Ma) Precambrian crust under southern Britain (Hampton and Taylor, 1983; Thorpe *et al.*, 1984). From this, we infer that the Midlands-Brabant-Ardenne Precambrian Basement is a composite entity made up of a N.W. block (the Midlands Block) mostly younger than 1.2 Ga and a S.E. block (the Brabant-Ardenne Block) mostly older than 1.8 Ga, both of them overlain by metavolcanic bearing late Proterozoic (< 0.9 Ga) formations. This picture is corroborated by the  $\epsilon_{Nd}^t$ -t path of the Caledonian sedimentary mass (Fig. 12). At any time, the  $\epsilon_{Nd}^t$  values are less radiogenic in Belgium than in southern Britain and the Belgian sediments follow more closely the  $\epsilon_{Nd}^t$ -t evolution of Brittany and Nova Scotia, where 2.0-3.0 Ga source-rocks have been detected.

## 4.3. Implications for the Caledonian plate tectonic configurations

### 4.3.1. Previous models and the "Brabantia" concept

The nature of the geotectonic evolution of the Hercynian orogenic belts of western Europe and their Caledonian precursor in Belgium is an unsolved problem. Most of the modern concepts since the early works of Nicolas (1972), Burrett (1972), Mc Karrow and Ziegler (1972) and Laurent (1972) are based on plate tectonics but they strongly diverge for two main

reasons. Firstly, the lack of convincing proof for any suture inside the Caledonian-Hercynian belts prevents any precise location of the palaeoceanic areas. Secondly, due to ambiguous palaeolatitudes in southern Britain and Wales (Van der Voo, 1988) and a lack of palaeomagmatic data in Belgium, it remains unresolved whether the Ordovician location of southern Britain and Belgium was adjacent to Brittany, whether it was at mid-palaeolatitudes between Brittany and Baltica or it was close to Baltica. Therefore our present objective is to discuss of the plate tectonic models relevant to the Caledonian belts from Belgium, using our news constraints on the nature of the Precambrian crystalline basement.

The modern plate tectonic configurations for Ordovician time fall into four categories : the Baltica Peninsula concept; the Cadomia concept; the Armorica concept; the Avalonia concept. The **Baltica Peninsula** concept was developed by Paris and Robardet (1990) to account for the Early Palaeozoic faunal distributions and palaeoclimatic data. These authors split the tectonostratigraphic units of western Europe into two groups : a northern one, attached to Baltica, and composed by southern Nova Scotia, southern Britain and Belgium (the Baltica Peninsula) and a southern one, made up of the Iberian-Armorican and Bohemian blocks. According to these authors the Baltica Peninsula was part of Baltica long before the Cadomian orogeny. As a variant to that proposal, Matte *et al.* (1990), returned to the plate tectonic configuration of Cogné and Wright (1980). They suggested that a microplate (here called **Cadomia**) composed of southern Nova Scotia, southern Britain and Belgium detached from Gondwana during Late Proterozoic and accreted to Baltica during the Cadomian orogeny after the closure of a Late Proterozoic ocean : (the "Celtic ocean"). The well-known **Armorica** concept was proposed by Van der Voo (1980) to explain discrepancies between the late Devonian palaeomagnetic direction for Africa and Southwestern Europe. This Armorica plate included the Iberian-Armorican regions, Bohemia, Belgium, southern Britain, eastern Newfoundland and southern Nova Scotia. It is supposed to have drifted rapidly northward at the end of the Ordovician (Perroud *et al.*, 1984). This displacement would have corresponded to the closure of the Ordovician Tornquist Ocean that separated Armorica from Baltica (Babin *et al.*, 1980; Cocks and Fortey, 1982) with the consequence of a calc-alkaline magmatism at the northern edge of this plate, in the Brabant Massif (André *et al.*, 1986a). The **Avalonia** concept is a splitting up of the Armorica concept to account for strong Ordovician modifications in ostracod distribution in western Europe (see review in Pickering *et al.*, 1988). According to these faunal constraints, southern Britain and Belgium composed a small microplate called "Eastern Avalonia" that is distinct from "Western Avalonia" (composed by

Eastern Newfoundland and Southern Nova Scotia) and the northern part of Gondwana including Brittany and Bohemia. So, to avoid any confusion between Western and Eastern Avalonia, we propose to reserve the term "Avalonia" for Western Avalonia and to create the name **Brabantia** for the areas that composed "Eastern Avalonia". During Ordovician time, Brabantia moved northward from Gondwana creating a Rheic ocean between it and Gondwana.

#### 4.3.2. Important constraints for Ordovician plate tectonic reconstructions

Any reliable plate tectonic model for the Palaeozoic evolution of western Europe should take into account seven major constraints which are discussed below.

1) It has long been recognized that crustal cratonization (i.e. folding, uplift, erosion and stabilization) occurred sporadically in both Baltica and Gondwana plates, but at different times (Cogné and Wright, 1980). Baltica was built following four major Precambrian orogenic events : Saamian (> 3.1-2.9 Ga), Lopian (2.9-2.6 Ga), Svecokarelian (1.9-1.8 Ga) and Sveconorwegian (1.3-0.9 Ga). In contrast, Gondwana was consolidated during several Archean events (3.3-2.6 Ga) and two Proterozoic orogenic events : Eburnean (2.1-1.9 Ga) and Pan-African (0.73-0.55 Ga) (see review of Cahen *et al.*, 1984 and Krogh and Keppie, 1990). Recently, it was shown that the timing of crustal growth (i.e. extraction from the mantle) differed in Baltica and Gondwana. In Baltica, it was episodic with maxima at 2.7, 1.9 and 1.8 Ga (Condie, 1990), with no isotopic evidence for juvenile inputs during the Sveconorwegian orogenic event (Miller *et al.*, 1986; Condie, 1990). In contrast, in Gondwana, low  $T_{DM}$  ages were detected in the sedimentary masses from eastern Africa (Duyverman *et al.*, 1982; Harris *et al.*, 1984) and central Africa (McDermott and Hawkesworth, 1990), supporting a model with large crustal growth during the Pan-African event. In the  $T_{DM}$ -t diagram (Fig. 13), the Caledonian sediments from southern Britain and Belgium fall within the limits of the envelopes for the evolution trends of eastern Africa and Laurentia-Baltica, suggesting that the two groups of sediment derived from mixtures between similar protoliths of two different ages, one younger than 1.0 Ga, the other older than 2.0 Ga. This, together with  $\epsilon^{1}_{Nd}$ -t paths for sedimentary masses from southern Nova Scotia, southern Britain, Brittany and Belgium (Fig. 12), and the age patterns of detrital zircons in Belgian Cambrian sandstones (Von Hoegen *et al.*, 1990) clearly suggest that Early Proterozoic (or Archean) events and Pan-African events played an important role in the growth of the Midlands-Brabant-Ardenne Precambrian basement. We prefer therefore a derivation of this cratonic nucleus from the northern

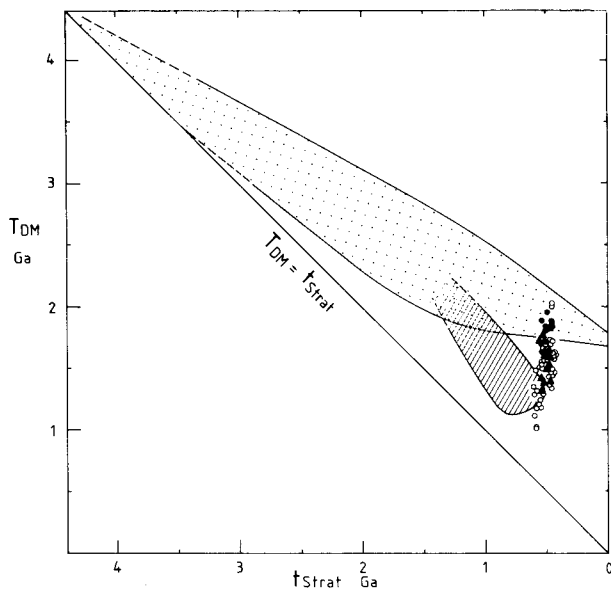


Fig. 13 : Comparative  $T_{DM}$ - $t$  data for Early Palaeozoic metasediments from Belgium (Stavelot = black triangles; Brabant = black circles) and southern Britain (open circles). The stippled envelope corresponds to the trends for the western Canadian shield and the Baltic shield; the shaded envelope shows the trend for northeast Africa (Gondwana) with considerably lower  $T_{DM}$  values.

margin of Gondwana than from the southern margin of Baltica or Laurentia.

2) In north Germany and southern Denmark, the transition zone from the Baltic Shield to the North German Lowlands, limited on its southern margin by the Trans-European Fault, separates two very different crusts (EUGENO'S Working Group, 1988). To the northeast, the thick (40-50 km) crust of the Russo-Baltic Shield is characterized by a shallow Conrad discontinuity between 10 and 14 km. To the southwest, a thinner crust (30-35 km) occurs with a Conrad discontinuity between 16 and 20 km, and beneath it, relatively high seismic velocities up to 7.1-7.3 km/sec. This transition zone probably played a key role in the Phanerozoic structural evolution of western Europe.

3) Two Caledonian deformation belts zones exist between the Baltic Shield and the Rheno-Hercynian Zone of the Hercynian fold belts : the North Sea - North German - Polish (NNP) Caledonides and the Brabant-Ardennes (BA) Caledonides. The Caledonian Deformation Front (CDF) that limits to the North the NNP Caledonides in North Sea, North Germany and Southeast Denmark was traced by absolute age datations in deep boreholes (Frost *et al.*, 1981). A possible eastern prolongation of BA Caledonides was detected from NW-SE trending felsic volcanics and sediments concealed below younger cover in the eastern Midlands (Pharaoh, *et al.*, 1987a). Such a correlation matches better the geological facts than a previous proposal from Ziegler (1984) in favour of a Mid-European Caledonides running from Cornwall to

Belgium, because : 1) the Lochkovian phase of the Caledonian deformation vanishes westward in the Brabant Massif (Michot, 1980); 2) Caledonian fold belts could be assumed to exist north and south of the Thames Estuary from the steep dip in Silurian and Ordovician rocks encountered in boreholes (Watson and Dunning, 1979). The relation between the NNP and BA Caledonides are still unclear. However, the metamorphic grade of the eastern England (EE) Caledonides increases in a north-eastern direction (Pharaoh *et al.*, 1987a), reaching the greenschist facies in the central North Sea (Frost *et al.*, 1981). A similar polarity is seen in the intensity of the cleavage development, suggesting that the NNP and EE fold belts could merge in a unique North European Caledonian fold belt in the central North Sea area.

4) The western and central parts of Brabant Massif were characterized by an important calc-alkaline magmatic activity from the Caradocian until Wenlockian. Mostly acidic or intermediate in composition, it clearly derived by differentiation from some relatively uncommon basaltic andesitic magmas (André, 1983; André *et al.*, 1986a). These basic parental calc-alkaline magmas imply a derivation from a subduction zone. In the eastern part of the Brabant Massif and the Ardennes, bimodal tholeiitic magmatic suites with very similar "back-arc" tholeiitic affinities were recognized (André *et al.*, 1986a). Despite their strong geochemical similarities, these suites show different ages in the eastern Brabant Massif (Silurian, André, 1983) and the Rocroi Massif (Middle Devonian, Goffette *et al.*, 1991). This probably means that the "back-arc" type mantle sources generated by the Ordovician subduction were mobilized at different moments in the Brabant and Ardennes. Nevertheless, the spatial arrangement of the magmatism (Fig. 1) suggests the existence of two constricted subduction related mantle sources : a calc-alkaline one, beneath western and central Brabant Massif; and a back-arc tholeiitic one, to the southeast beneath the Ardennes. This polarity argues for a location of the subducted ocean at the north of the Midlands-Brabant-Ardennes Precambrian basement. Otherwise, a Middle to Late Ordovician acidic to intermediate calc-alkaline volcanic activity has been identified in the concealed Caledonides from eastern England by Pharaoh *et al.* (1991, this volume). The unradiogenic Nd isotopic features of the Brabant calc-alkaline rocks (see above) and their eastern England counterparts ( $-8 < \epsilon_{Nd}^t < +1$ ; Pharaoh *et al.*, 1991, this volume) demonstrate that this magmatism developed on a continental setting, probably as we postulate, at the northern margin of the Midlands-Brabant-Ardennes Precambrian basement. A northwest trending continental magmatic arc may thus extend from the Brabant Massif in Belgium, beneath the North Sea to eastern England. It probably was triggered in response to the closure of a north western Precambrian oceanic area (i.e. the Tornquist ocean or part of it).



5) A remarkable feature of the Belgian Caledonides is the variation in the age of folding. To the southeast, in the Ardennes, the deformation occurred during the Caradocian (Michot, 1980). To the northwest, it took place in the Early Lochkovian (Michot, 1980; André *et al.*, 1981). During the transition between Silurian and Devonian, the tectonic evolution of Belgium appears to undergo a gradual but fundamental change. The regional compressive regime that dominated during the Ordovician and Silurian gradually ceased and gave way to regional extension (Meilliez, 1989). This extensional regime could have begun early in the Silurian with the intraplate tholeiitic basaltic magmatism of the eastern Brabant magmatic centre (André, 1983; André *et al.*, 1986a), but continued until the Middle Devonian with the intraplate tholeiitic magmatism of the Rocroi and Stavelot Massifs (Goffette *et al.*, 1991). At about that time, a major translation shear zone, the Bierghes-Audenaarde fault zone was active in the Brabant Massif (André and Deutsch, 1985).

6) Recent sedimentological investigations in the Stavelot Massif (Walter, 1980; Von Hoegen *et al.* 1985; Lamens and Geukens, 1985) document a deepening of the basin to the northwest throughout the Cambrian and Tremadocian. In combination with the crystalline derivation of the detrital components of these sediments (see above), this illustrates the persistence of a Proterozoic crystalline relief to the southeast. This argues against the opening of a deep marine basin (i.e. the Rheic Ocean) to the south of the Stavelot Massif before the Middle Ordovician. This view is substantiated by the apparent lack of Cambrian-Ordovician continental flood basalts that would suggest an extensional setting for the Rocroi and Stavelot Massifs in the Cambrian and Early Ordovician.

7) Vannier *et al.* (1989) point to a steady increase in faunal similarity between Britain and Baltica throughout the Ordovician, but a decline in similarity between Britain and Ibero-Armorica after Llanvirn-Llandeilian times. According to Paris and Robardet (1990), these differences would have resulted from distinct climatic conditions rather than from geographic separation. In contrast, Cocks and Fortey (1990) show that the Ordovician-Silurian faunal distributions are compatible with the new palaeogeographic reconstructions of Scotese and McKerrow (1990) which illustrate the northward displacement of southern Britain during Late Ordovician and Silurian.

#### 4.3.3. The preferred plate tectonic concept

The Baltica Peninsula concept is incompatible with constraints (1), (2), (3) and (4) and do not bring any satisfactory explanation for an Early Lochkovian deformation limited to the Brabant Massif (constraint 5). Moreover, this concept supposes that, during

Cambrian and Early Ordovician, the Ardennes were located at a passive continental margin at the northern edge of an ocean. This is clearly at variance with constraint (6). This concept is therefore ruled out as a plate tectonic model to explain the Caledonian orogenic belt of western Europe.

The Cadomia concept matches constraints (1) and (2), but fails to explain the development of the NNP, EE and BA Caledonides and the associated arc volcanism (constraints 3 to 5). Moreover, the evolution of the Ardennes as a continental margin from the Late Proterozoic onwards is precluded from the Cambrian northward deepening sedimentary Stavelot basin (constraint 6). Therefore, although accretion and oceanic closure did occur during the Cadomian orogeny (e.g. Pharaoh *et al.*, 1987b; Cabanis *et al.*, 1987), the Late Proterozoic Cadomia plate tectonic concept disagrees with most of our Caledonian constraints.

Both the Armorica and Brabantia concepts fulfill constraints (1), (2), (3), (4) and (5). In particular, the Early Lochkovian deformation in the Brabant Massif is easily explained by the Late Silurian final collision between the Midlands-Brabant-Ardennes craton and the Baltic Shield. Brabantia, unlike Armorica, could in addition justify the Caradocian deformation of the Ardennes Caledonides and the clear Late Ordovician differences in trilobites and brachiopods faunas between Wales-Belgium and Armorica (Paris and Robardet, 1990). Indeed, during the Middle Ordovician, Gondwana (including north Africa, Iberia, Armorica and Bohemia) moved southwards in a rather opposite direction to the drifting Brabantia (Neugebauer, 1989). As a consequence, it is very likely that the region located at the hinge between the two continental blocks, such as the Ardennes (cf. Fig. 16 of Neugebauer, *ibid.*), were displaced and folded along transpression faults or squeezed between opposite moving blocks. In this context, the period of stretching that characterized Belgium during the Silurian-Devonian times is supposed to be the continuation of this opposite movement with a subsequent opening of a narrow Rheic Ocean in the weak zone between Brabantia and Gondwana.

## 5. CONCLUSIONS

The existence of an old Precambrian crystalline basement beneath the Caledonian and Hercynian segments in Belgium is deduced from : (1) the observation of gneissic xenoliths in the Quenast Quartz diorite; (2) the finding of old inherited zircons ( $\geq 1.9$  Ga) in the intrusive magmatic rocks from the Brabant, Stavelot and Rocroi Massifs; (3) the Sr-Nd isotopic features of the Brabant calc-alkaline magmatic suites; (4) the granulite facies xenoliths found in the

Pleistocene alkali tuffs from the Eifel area. The presence of this basement and the calc-alkaline character of the magmatism in the Brabant Massif clearly suggest that Belgium evolved in a continental margin tectonic setting during the Caledonian orogeny.

The  $\epsilon_{\text{Nd}}^t$  and  $T_{\text{DM}}^t$  evolutions of the Early Palaeozoic sedimentary mass in Belgium, southern Britain, Brittany and southern Nova Scotia are very similar. This points to a large input of juvenile material to the crust in these areas during the Late Proterozoic, suggesting these areas were rifted off from Gondwana as microcontinents after the Pan-African cycle. These data conform very well with two different Early Palaeozoic plate configurations: 1) the juxtaposition of Brittany with southern Britain and Belgium in the same Armorica microplate; 2) the location of Brittany, on the one hand, and southern Britain and Belgium, on the other hand, apart of a narrow oceanic domain (the Rheic ocean). In the second configuration, southern Britain and Belgium would compose a small microplate for which the name Brabantia is propounded. The Caradocian deformation of the Ardennes Caledonides and the clear Late Ordovician distinction in trilobite and brachiopod faunas between Wales or Belgium and Brittany, favour the Brabantia microplate concept.

The Precambrian basement of Brabantia microplate, extending from the English Midlands beneath Belgium and the Rhenish Massif, appears to be composite with a N.W Midlands block mostly younger than 1.2 Ga, and a S.E. Brabant-Ardennes block mostly older than 1.8 Ga, both of them overlain by metavolcanics bearing late Proterozoic formations. By its age, the Brabant-Ardennes block has affinities with the Icartian-Bay of Biscay Precambrian nuclei and the source areas of the European detrital zircons. The Sr-Nd isotopic features of the Brabant basaltic andesites and the geochemical characteristics of the Eifel granulitic xenoliths both reveal that this block could be partly made up of high pressure Rb-depleted granulite materials. If confirmed, the presence of these high pressure granulites could afford a clue to explain the rather cold and unreflective nature of the Brabant-Ardennes crust.

The nature of the surface of the Brabantia Precambrian basement was investigated by three different but complementary approaches: 1) the study of the Early Cambrian lithic fragments (Vander Auwera and André, 1985); 2) the U-Pb isotopic analyses of detrital zircons from Early Cambrian sandstones (Von Hoegen *et al.*, 1990); 3) the geochemical features and the Nd isotopic composition of the Cambrian-Ordovician fine grained metasediments (André *et al.*, 1986b and this paper). They indicate that: (1) Archean nuclei were probably insignificantly exposed at the surface of the basement during Early Palaeozoic erosion; (2) the upper part of this basement was stratified with Cadomian ( $t < 0.9$  Ga) tholeiitic metavolcanics overlying older ( $T_{\text{DM}} > 1.9$  Ga) felsic crystalline rocks; (3) the proportion of the

parametamorphic rocks in this older component appears to be relatively minor in comparison to the proportion of the orthometamorphic or granitoid rocks.

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## APPENDIX

### 1. Further details on the assimilation-fractional crystallisation (AFC) model

The models for assimilation balanced by crystal fractionation were calculated using the following equation (DePaolo, 1981a):

$$\epsilon_m = \frac{(r/r-1) (C_a/z) (1-f^z) \epsilon_a + C_m^0 f^z \epsilon_m^0}{(r/r-1) (C_a/z) (1-f^z) + C_m^0 f^z}$$

with  $z = \frac{r+D-1}{r-1}$

where, for a given element, D stands for the bulk partition coefficient in the fractionated mineralogy,  $C_m^0$  for the initial concentration in the magma,  $\epsilon_m$  for chondritic normalised isotopic ratio in the magmatic liquid,  $C_a$  and  $\epsilon_a$  for the concentration and the chondritic normalised isotopic ratio in the assimilated rocks.  $f$  represents the proportion of the residual magmatic liquid.  $r$  is defined as  $\dot{M}_a/\dot{M}_c$ .  $\dot{M}_a$  ( $=dM_a/dt$ ) represents the mass of wallrocks assimilated per unit of time and  $\dot{M}_c$  ( $=dM_c/dt$ ) the rate at which the fractionating phases are effectively separated from the magma. In most geologically plausible conditions, it may be assumed that  $r$  is  $\sim 1$  at deep levels in the lower crust. Due to the larger temperature contrast between magmas and wallrocks,  $r$  will decrease (up to  $r \sim 0.1$ ) when the magma rises to the surface (Taylor, 1980; André, 1983). However, variations in the mineral at the liquidus can produce very different  $r$  factors since the standard enthalpy of melting ( $\Delta H_m$ ) varies from 208.2 cal/g in the case of the olivine down to 67.2 cal/g in the case of anorthite (Robie and Walbaum, 1968). Therefore, at a given level in the crust, the  $r$  factor will be approximately 3 to 4 times lower for plagioclase fractionation than for olivine separation. Thus, in the lower crust,  $r$  factors are plausible between 2 and 0.5, according to the mineral separated.

## 2. Parameters used for stage 1 models

Almost all of the data for modern calc-alkaline basalts (CAB) plot at 1 to 3  $\epsilon_{Nd}$  units lower than the average Mid Ocean Ridge Basalts (M.O.R.B.) data and to the right of the mantle array by as much as 30 units of  $\epsilon_{Sr}$  (DePaolo, 1988). Their average Ordovician counterpart is thus supposed to have the following isotopic signature :

$$(\epsilon_{Nd}^t)_{CAB} = (\epsilon_{Nd}^t)_{MORB} - 2 \epsilon = +7 - 2 = +5$$

$$(\epsilon_{Sr}^t)_{CAB} = (\epsilon_{Sr}^t)_{MORB} + 15 \epsilon = -20 + 15 = -5$$

The data for the Ordovician MORB are deduced from the Nd evolution of the depleted mantle (DePaolo, 1981b) and the Sr isotopic evolution of the Bay of Island ophiolite (Jacobsen et Wasserburg, 1979).

In the models, the Nd content of the contaminated magma was chosen to be lower than the Nd content of the most primitive calc-alkaline basaltic rock from the Brabant Massif (Nd < 10 ppm; André, 1983). Since the Sr content of this rock is unknown due to the late hydrothermal processes, several AFC models were tested using different Sr contents (300, 380 and 500 ppm). The average Sr (387 ppm) and Nd (21 ppm) contents of the Lewisian gneisses are from Dickin (1981). Their Ordovician Nd isotopic composition ( $\epsilon_{Nd}^t = -18.7$ ) has been calculated from an average  $^{147}Sm/^{144}Nd$  of 0.1315 and an initial  $^{143}Sm/^{144}Nd$  of 0.508959 (Hamilton *et al.*, 1979). The Ordovician Sr isotopic ratio ( $\epsilon_{Sr}^t = -20.7$ ) is from Clayburn (1988).

## 3. Parameters used for stage 2 models

The  $\epsilon_{Nd}^t$  range (+ 1 <  $\epsilon_{Nd}^t$  < -4) of the differentiated andesitic, dacitic and rhyolitic rocks would require a basaltic parental magma with  $\epsilon_{Nd}^t > + 1$ . Therefore, the observed basaltic andesite cannot represent this parental magma. The most plausible one must be located on one of the AFC curve that joins these basaltic andesites to the C.A.B. field in Fig. 4B. Let use, for example, the following parameters for this magma :  $\epsilon_{Nd}^t = + 2$ ;  $\epsilon_{Sr}^t = - 5.2$ ; Sr = 380 ppm (andesite average; Gill, 1981); Nd = 10 ppm (Nd content of the less differentiated basaltic andesite; André, 1983) using the partition coefficients for intermediate calc-alkaline magmas of Luhr and Carmichael (1980).

The parameters for the Cambrian-Ordovician sedimentary contaminant was obtained as followed :  $\epsilon_{Nd}^t = - 7.5 \pm 1.3$  ( $2\sigma_M$ ) (average of Cambrian-Ordovician sediments from André *et al.*, 1986b); Sr =  $102 \pm 28$  ppm (average of 17 sediments from the Brabant Massif  $\pm 2\sigma_M$ , André 1983); Nd =  $34.6 \pm 6.1$  ppm (average of the 16 sediments from the Brabant Massif  $\pm 2\sigma_M$  André *et al.*, 1986b). Their Caradocian Sr isotopic signature (André, inédit) is in the range  $+15 < \epsilon_{Sr}^t < +213$  with an average value of :  $+ 136 \pm$

$30$  ( $2\sigma_M$ ). The parameters for the southern Britain and S.E. Ireland upper crustal crystalline rocks are from Davies et al (1985) : Sr =  $167 \pm 169$  ppm ( $2\sigma_M$ ); Nd =  $48.9 \pm 25.3$  ppm ( $2\sigma_M$ );  $\epsilon_{Sr}^t = + 714 \pm 223$  ( $2\sigma_M$ );  $\epsilon_{Nd}^t = - 13.5 \pm 0.6$  ( $2\sigma_M$ ).

## 4. Stavelot slates location

- ST86/1 (X = 259333; Y = 110803) : Dv1 black slates 1 m above the Hourt quartzites; small quarry along the Salmchâteau - Trois-ponts road at 103 km 260; maximum detrital grain size 25  $\mu m$ .
- ST86/2 (X = 259333; Y = 110803) : Dv1 magnetite bearing green slates 5 m above sample ST86/1; maximum detrital grain size 30  $\mu m$ .
- ST86/5 (X = 259133; Y = 115323) : Dv2 black slates from an *Oldhamia* bearing turbiditic sequence at 59 km O20 along the Vielsalm-Trois-ponts railway tracks; maximum detrital grain size : 30  $\mu m$ .
- ST86/8 (X = 258180; Y = 117922) : Brachiopod bearing Rv1 black slates from the acritarch zone 1 at 112 km 100 along the Salmchâteau-Trois-ponts road; maximum detrital grain size : 25  $\mu m$ .
- ST86/9 (X = 257072; Y = 119733) : Black slates from the Rv2 basis and acritarch zone 2 at "Rocher du coeur Fendu"; maximum detrital grain size : 20  $\mu m$ .
- ST86/10 (X = 257320; Y = 121375) : Black slates from the acritarch zone 4 at 25 m below the Rv2-Rv3 limit, car park of the Coo waterfall; maximum detrital grain size : 10  $\mu m$ .
- ST86/11 (X = 254583; Y = 122680) : Rv5 black slates from the acritarch zone 6 at 48 km O20 of the Liège-Luxembourg railway track; maximum detrital grain size : 15  $\mu m$ .
- ST86/12 (X = 251100; Y = 123575) : black slates from the Rv4 and acritarch zone 5; small quarry in a U turn along Stoumont-Remouchamp road at km 16; maximum detrital grain size : 20  $\mu m$ .
- VIII 7 (X = 259775; Y = 108425) : Sm1c green slate; Vielsalm-Rencheux road cut; maximum detrital grain size : 60  $\mu m$ .
- VII 3 (X = 259645; Y = 107648) : Sm2a viridine-braunite bearing red shale; hill slope at 380 m to the SSE of an old quarry; maximum detrital grain size : 30  $\mu m$ .
- VI 20/c (X = 259708; Y = 108218) : Spessartine-chloritoïde bearing green coticule; top of Sm2b; small road cut along the western bank of the Salm river; maximum detrital grain size < 5  $\mu m$ .
- TIV 30b (X = 259737; Y = 108260) : Sm2b spessartine bearing yellow coticule; small road cut along the western bank of the Salm river; maximum detrital grain size < 5  $\mu m$ .

- TIV 27 (X = 259737; Y = 108260) : Sm2b spessartine bearing yellow coticule; small road cut along the western bank of the Salm river; maximum detrital grain size < 5 µm.
- VI 25 (X = 260583; Y = 108175) : Sm2c purplish-blue ottrelite bearing shale; old Cahai quarry; maximum detrital grain size < 15 µm.

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