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REVIEW OF THE SILURIAN IN THE BRABANT MASSIF, BELGIUM.

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(12 figures)

ABSTRACT. – Literature on the Silurian of the Brabant Massif reveals considerable isolated data, mostly on stratigraphy. Own observations in the thick monotonous Silurian of the southern rim have resulted in a detailed lithostratigraphy (Mehaigne area, Sennette Valley, Orneau Valley, Western Flanders). The Llandovery to lower Ludlow sediments are more than 2850 m thick, and mostly turbidites with some intercalated laminated hemipelagites and bentonites. In the central and northern part of the Brabant Massif only a few boreholes have been drilled.

Macrofossils are rare but graptolites provide a good but incomplete coverage. By contrast the organic microfossils, Chitinozoa, have been separated in 80% of the samples. They underwent a very low grade metamorphism of the deep anchizone and estimated heating of over 200-250°C. The rather high frequency is explained by a substantial water depth of the source area of the turbidites, a favourable environment for Chitinozoa. From there they were transported with the sediments in the turbidity currents. A Chitinozoa biozonation in the Brabant Massif has as many zones/subzones as the graptolites.

The roughly E-W trending basin was filled by turbidite fan systems, with a remarkable lateral uniformity observed over several km in the middle and late Wenlock of the Mehaigne area and some lateral variation mainly by downcutting of palaeoflow (S-N), over a few hundreds of meters of distance, in the Gorstian at Ronquières.

Sedimentological, lithological or micropalaeontological cyclicities are observed on the metric, decametric and hectometric scale throughout the column. Some can be assigned to eustatic, regional or local influences. The Silurian sequence forms only a part of a major megacycle spanning the Upper Ordovician till Middle/Upper Devonian. Upper Ordovician sediments with several shallow, shelly and deep, euxinitic intervals are deposited contemporaneous with the most important Caledonian magmatic phase in the Brabant Massif. An ignimbritic event marks the end of explosive volcanism in the Rhuddanian. Turbiditic sedimentation starts shortly above the ignimbrite and continues until Prídolí. Middle or Upper Devonian unconformably covers the Brabant Massif and overlies the major observed Caledonian unconformity.

Data, mainly derived from available literature, is used to demonstrate several Caledonian phases as well as eustatic events within the Brabant Massif.

1 INTRODUCTION.

This review is divided into two parts. The first part deals with previous studies grouped per subject area, such as, litho- and biostratigraphy, sedimentology, megacyclicity, magmatism, structure and metamorphis and per period of research. Data and results derived from our own work has then been added.

In the second part, using valid data from the literature and our own data a hypothetical reconstruction of the sedimentary basin during the Silurian, the tectonic evolution in the Brabant Massif from Cambrian to Devonian and some elements of plate tectonic evolution has been developed.

The evolution of knowledge on the Brabant Massif, especially its Silurian, is sketched below by using those articles containing new data or insights, from the 270 publications consulted. This review begins with literature published early last century, when the basis of the stratigraphy was laid down, and with more occasional work achieved in the first half of this century. Growing interest since 1945 culminated in the monograph on the magmatic rocks by CORIN (1965) and in a milestone monograph on all boreholes in the Brabant Massif with a geological map by LEGRAND (1968).

Five new fields of research have brought, since then, new impetus into the study of the Brabant Massif:

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(a) the biostratigraphy with organic microfossils as acritarchs, discovered by STOCKMANS & WILLIERE in 1963 and Chitinozoa firstly mentioned by MARTIN in 1971. It produced a new tool for accurate dating of monotonous and macrofossil-poor beds of the Lower Palaeozoic;

(b) thus making new detailed fieldwork and lithostratigraphy of outcrop areas and boreholes rewarding;

(c) advances in the sedimentology of e.g. turbidites (KUENEN & MIGLIORINI, 1950; BOUMA, 1962, 1964) or laminated hemipelagites (for an review see DIMBERLINE *et al.* in press) gave new clues for the interpretation of the depositional environment of these deep neritic or bathyal facies;

(d) Renewed geochemical analyses of major elements and new analyses of trace elements in magmatic rocks or sediments allowed the reconstruction of the magmatic history and the retracing of previous source areas of the sediments;

(e) Isotopic age determinations of magmatic or metamorphic events produced absolute dates on which the geological evolution of the Brabant Massif could be pinpointed;

(f) Apatite fission-track measurements on magmatic rocks helped to reconstruct the post-Caledonian history.

2 LOCATION.

The Silurian in the Brabant Massif of Belgium is located mainly on its southern rim, divided from west to east into three parts. Along a central rim and in the north of the Brabant Massif several boreholes also reached the Silurian (fig. 1).

In the southern rim two parts trend WNW-ESE and are situated south of an important structural line Oostduinkerke-Nivelles and north of the Late Caledonian unconformity.

The first part, from the Belgian coast to the river Dender, will be called the "subsurface area of southern Flanders and northern Hainaut" or just "southern Flanders subsurface", with low dips and cartographically younging to the SSE and hence interpreted by LEGRAND (1968) as a monoclinally SSE-dipping structure.

It continues westwards into France, from Bray-Dunes through Licques to Hazebrouck, and has a poorly studied and probably complex structure. The dips are steep and the Silurian occurs as well as the Ordovician (Noordpeene borehole LEGRAND, 1968).

The second part, outcropping in the valleys of the Dender, Senne, Sennette rivers and the Nivelles area is referred to as the "western Silurian outcrop area". The Silurian disappears under the Middle Devonian unconformity west of Nivelles. Generally the layers young to the south with gentle to medium dips, and occasional folds repeat the sequences.

The third part of the southern rim, trending ENE-WSW is bordered to the south by the Middle or Late Devonian unconformity and will be called the "eastern Silurian outcrop area". It lies obliquely over the central axis of the Brabant Massif, which is here largely of Lower Cambrian rocks. It comprises the outcrop areas of the Orneau Valley, Leuze, Cortil-Wodon, Noville-les-bois, Landenne and the Burdinale and the Mehaigne valleys. Eastern and western outcrop areas are separated by an observation gap of sixteen km where the Silurian is probably overlain by Devonian.

Ten km eastward, the most easterly outcrop area of the Brabant Massif at Horion-Hozémont, was previously mapped as Ordovician on the detailed geological map (STAINIER *et al.*, 1899) or Silurian (LEGRAND, 1968). Our own unpublished Chitinozoa studies on two samples confirm the Ordovician age. Further east, at Voroux-Goreux, in a long subcrop gallery, a complex structure of Silurian and Ordovician sediments and volcanic rocks is present.

Silurian is also present, though less extensive and only sparsely known, along a central rim on the Brabant Massif in the Oostende-Roeselare-Nieuwpoort area (fig. 1). Silurian and Ordovician sediments, established palynologically and interbedded with volcanic rocks, alternate in NW-SE strips showing the complex structure of that area (VAN GROOTEL, ms 1990).

In three boreholes north of the main axis of the Brabant Massif (Booischot, Loenhout, Kallo) (LEGRAND, 1963, 1964a, 1968; VANGUESTAINE, ms 1973, and pers. comm. 1989; VAN GROOTEL, ms 1990) and possibly the Knokke borehole (VAN GROOTEL in LAGA & VANDENBERGHE, 1990; VAN GROOTEL, ms 1990) the discovery of graptolites or organic microfossils established the presence of Silurian.

3 HISTORY OF RESEARCH.

3.1 EARLY RESEARCH AND STRATIGRAPHY 1832-1914.

DUMONT described between 1832 and 1857 most sediments in Belgium and the surrounding areas, and laid down the foundations of the stratigraphy and general structure. He defined the Brabant Massif in 1847 on a structural basis as a large anticlinal fold with a core of sediments, initially attributed to the Devonian, but later assigned to the Cambrian and flanked by strips of sediments now considered as Ordovician and

Silurian. Hence in the Brabantian valleys, where the Brabant Massif crops out, the layers young from north to south, a view still broadly accepted. OMALIUS d' HALLOY (1808, 1828) and CAUCHY (1825) had already mentioned some parts of the valleys and DUMONT (1847) was the first to describe several sections along these valleys, e.g. Orneau and Mehaigne.

Stratigraphy was done without fossils in those days, because the meaning of the "occasional organized bodies", called "fossils" from 1820 onwards, were frequently debated either as "age indicators of the strata" or as "inevitably and always leading to errors if used for correlation of sediments" as DUMONT put it. In the period before DARWIN's book on the origin of species (1859), the poorly understood concept of evolution led to confused fossil taxonomy. DUMONT was so opposed to fossils that only after his death (1857) were systematic inventories of fossils and localities in Belgium published. Lack of palaeontological data also resulted in the erroneous correlation of all sediments in the Brabant Massif with the Lower Devonian in the Ardennes, on the basis that both are covered by Middle Devonian limestones and shales. The fossil locality of Grand-Manil, discovered in 1835, was for a long time the only known fossil site in the Brabant Massif. Only after 1860 was it recognized as Upper Ordovician (GOSSELET, 1860a, b, 1863; BARRANDE, 1862).

After the Early Palaeozoic age of the Brabant Massif was established it attracted more interest and this resulted in the first major study on the Ordovician-Silurian by MALAISE (1873). He divided the Lower Palaeozoic into four units. The three lower ones are Cambrian in age, the fourth was named the "Assise" of Gembloux and comprised most of the Ordovician and Silurian. The sections through eight valleys were described.

From his retirement in 1892 until 1910, MALAISE was charged with mapping the Lower Palaeozoic rocks of the Brabant Massif and the "Sambre and Meuse Belt" (often also called "Condroz Ridge") for the detailed geological map on scale 1/40.000. This allowed him to refine the stratigraphy of the Ordovician and Silurian with four successive versions (MALAISE, 1883, 1890, 1900, 1910). The four legends of the detailed geological map of Belgium of 1892, 1896, 1900 and 1909 reproduced the stratigraphy of MALAISE, from 1890 (Conseil de Direction de la carte & Commission géologique, 1892, 1896, 1900, 1909; Conseil géologique, 1929). It was based on lithofacies and fossil content. In 1900 he attributed two type localities in the Orneau Valley (Grand-Manil, Corroy) and one near Nivelles (Monstreux) to each of his three Silurian units. In 1910 he changed the type locality of Monstreux for that of Vichenet in the Orneau Valley and equated them with the three stages of the Silurian in Wales and the Welsh Borderland (Assise of Grand-Manil = Llandovery; Assise of Corroy = Wenlock; Assise of Vichenet = Ludlow).

The type locality of the "Assise of Grand-Manil" is a series of outcrops and quarries on the southern half of the promontory "Try à la Vigne" as far as a quarry close to km 2.450 of the railway. The type locality of the "Assise of Corroy" is situated at the "ancienne poudrière de Corroy" (abandoned powder magazine of Corroy), an old quarry opened to extract building material for a powder magazine of Corroy castle. Built in the quarry itself it exploded at the end of the XVIII century. The type locality of the "Assise of Vichenet" is a long road and railway section (km 3.5 to 4.75) close to the railway stop of Vichenet.

MALAISE's (1910) division of the Lower Palaeozoic was adopted by the fifth edition of the legend of the geological map of Belgium (1929), without however taking into account the author's corrections of 1913 & 1914 (erroneous determinations and typographical errors). It was accepted by most authors, although with diverging interpretations.

Developments in the study of the Variscan in Belgium had important consequences for the study of the Brabant Massif. The Variscan Midi overthrust was already postulated by BRIART & CORNET (1863), but often debated or rejected. When the presence of large thrust faults in the Alps was widely accepted at the International Geological Congress in Vienna in 1903, their existence was also accepted in Belgium through the Ordovician-Silurian outcrop area "Sambre and Meuse Belt" between the Namur and Dinant Basins (LOHEST, 1903; FOURMARIER, 1907, 1921). To check this hypothesis the Sambre and Meuse Belt was more carefully investigated. Studies of MALAISE had revealed that this strip contained many more fossils than the Brabant Massif. After nearly eighty years of research (1832-1914), still no convincing stratigraphy of the Silurian in the Brabant Massif had at that point been established, in large part due to scarcity of fossils and the monotony of the sediments. All new attention then shifted to the Sambre and Meuse Belt which resulted in a new stratigraphy for this area with detailed descriptions of profiles and the fossil inventory of MICHOT (1928a, b, 1929, 1931, 1932a, b, 1934a, b, 1938 & 1944a, b). His division and descriptions still remain unchallenged.

After the death of MALAISE in 1916, the Brabant Massif was for fourty years only occasionally the subject of a stratigraphic study.

3.2 STRATIGRAPHY 1914-1968.

FOURMARIER (1920) saw no lithological difference between the "Assises" of Corroy and Vichenet, and to him only palaeontology could differentiate them. His conclusion was based, however, on limited observations and did not follow exactly the descriptions of MALAISE (1910).

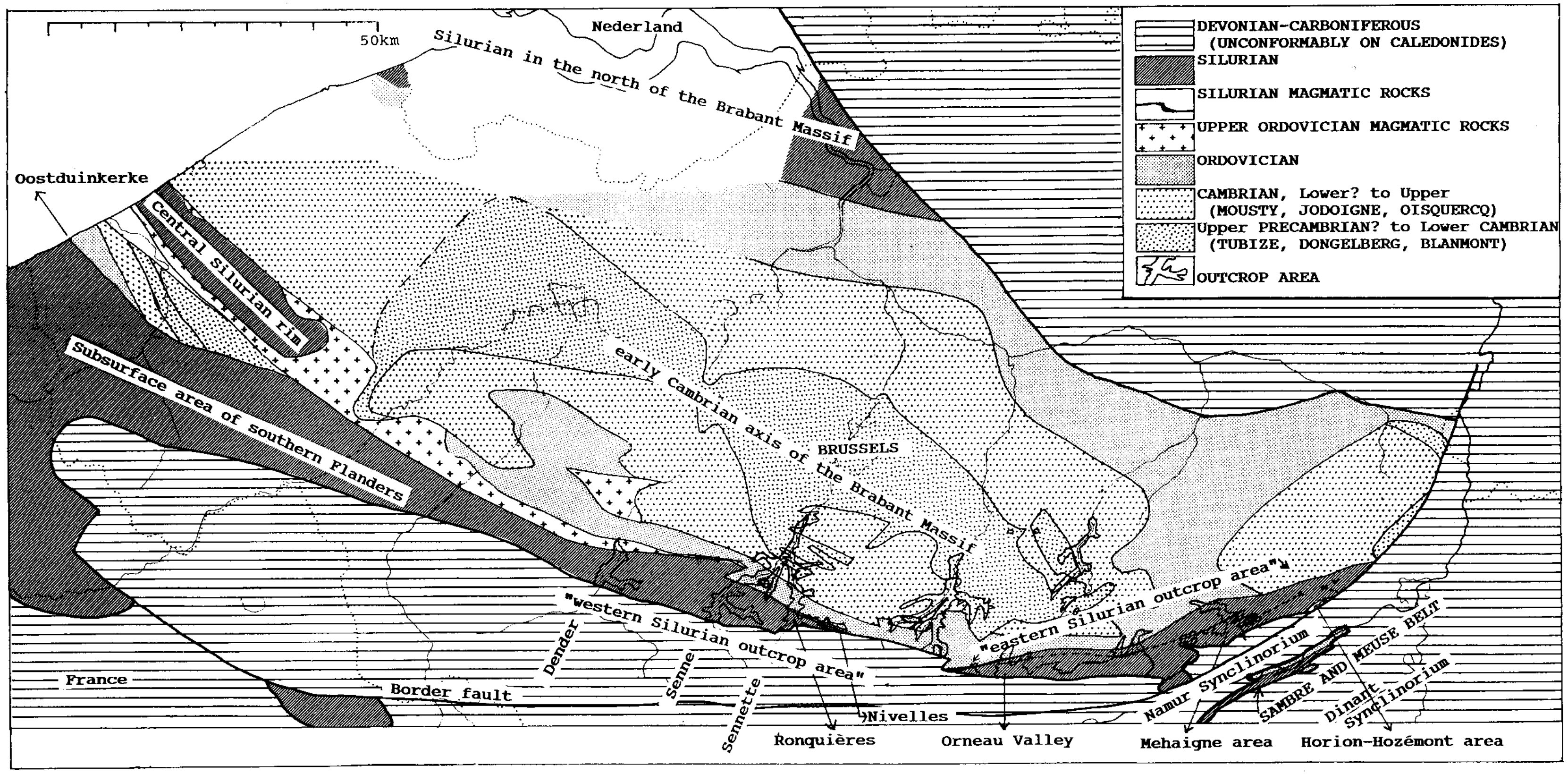

Figure 1a: Geological map of the Brabant Massif after LEGRAND (1968) and VAN GROOTEL (1990) for Western Flanders. Areas with insufficient boreholes data are left blank. The five main Silurian areas in the Brabant Massif are shown, with the names of the main outcrop areas.

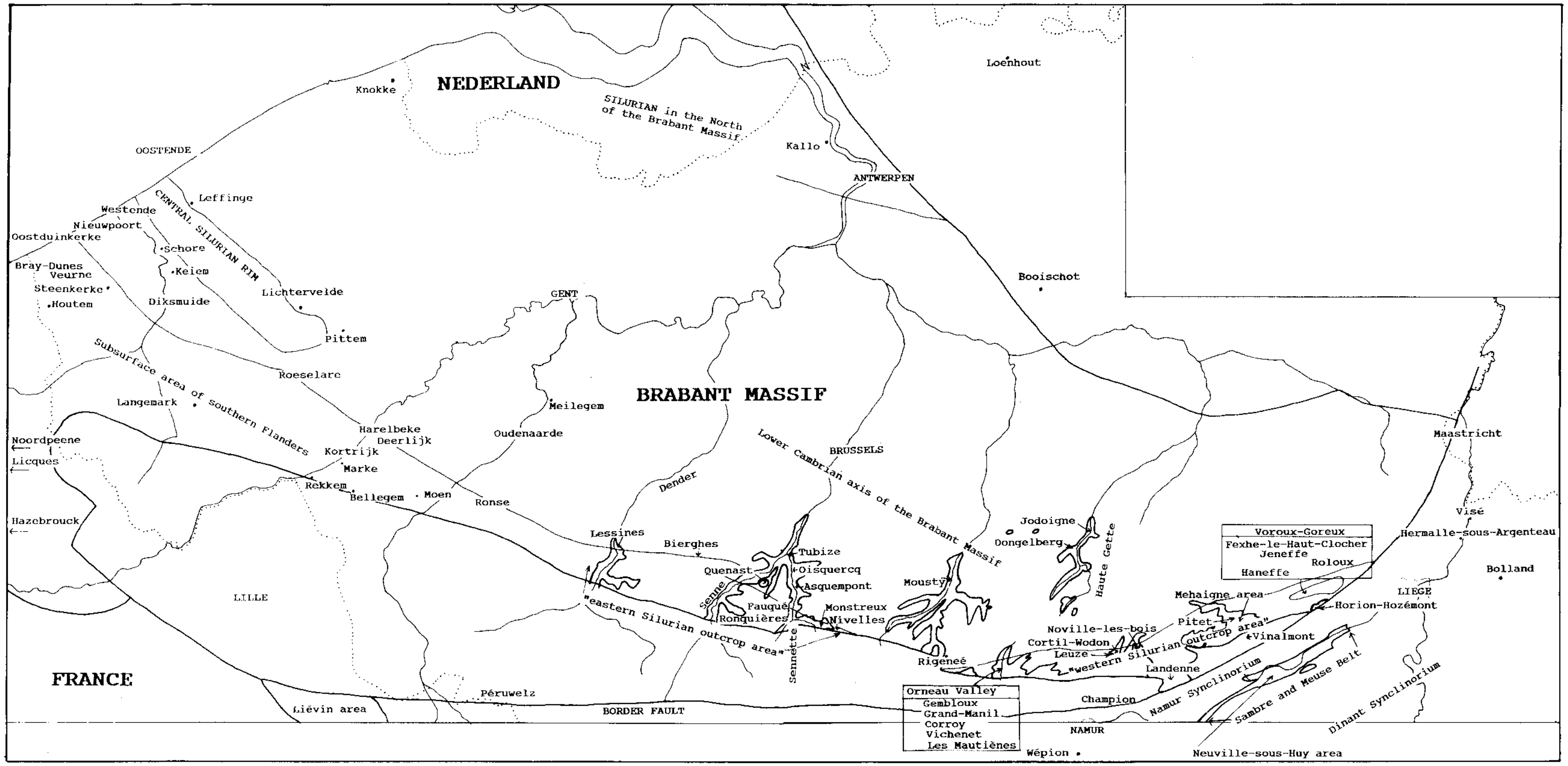

Figure 1b Map with the location of localities mentioned in the text with the main outlines of the Brabant Massif.

MICHOT (1954a) gave an accurate description of all stratigraphical terms as defined by then. In the extensive review on Belgian geology, called the "prodrôme", MICHOT (1954b) gives a mainly stratigraphical synthesis, with some emphasis on the magmatic activity and the palaeoenvironment of the sedimentary basin, based on the literature and his own published work. He also defines in these two works an additional type section for the "Assise" of Corroy after finding Wenlock graptolites in a section lithologically quite different, close to the original type section. He dropped the term "Assise" of Vichenet since the age of that section was unknown and replaced it by "Assise" of Ronquières as "representing" the Ludlow in the Brabant Massif. The large outcrop near the bridge of Ronquières dated by graptolites as the *M. nilssoni* zone, basal Ludlow (LERICHE, 1911; MALAISE, 1913) became the new type section.

LEGRAND (1962a) studied the graptolite-rich borehole of the Lust Brewery in Kortrijk (southern Flanders), where he described three middle and late Llandovery graptolite zones (*M. sedgwicki, M. turriculatus* and *M. crispus*). While restudying the Silurian outcrops of the Orneau Valley, he found in a railway section (km 2.6-2.9) a shaly succession with many quartzite beds devoid of graptolites. They bore, according to him, clear resemblance with the Kortrijk-Lust borehole, 104 km away. Hence, he redefined the type locality of the "Assise" of Grand-Manil in this railway section. Hereby he assumed that the original type locality (MALAISE, 1910), a few hundred meters northwards in the infilled quarry at km 2.45 of the railway, would have displayed the same beds (LEGRAND, 1962b).

He describes two graptolite zones (*M. murchisoni* and *M. riccartonensis*) of an early Wenlock age in the original type locality of the "Assise" of Corroy at the "ancienne poudrière de Corroy". He mentions also two paratype localities for the "Assise" of Corroy: the railway section (km 3.5-3.9) already defined by MICHOT (1954a, b) and the disused quarry "Laid trou de Chênemont", 80 m west of the railway at km 3.7. However, these three sections each show a very different lithology and sedimentology. Hence VERNIERS (1983) named the sequences in these three sections the lower, middle and upper part of the "Assise" of Corroy, awaiting a formal stratigraphic restudy of these type sections.

During major public works for digging the inclined shiplift of Ronquières a section 1.2 km long, about 100 m wide and up to 25 m deep was opened, for a large part in the Silurian. LEGRAND (1967a) described the new sections in detail and incorporated the few hundred meter of Silurian sediments outcropping in the inclined shiplift section in the "Assise" of Ronquières.

Boreholes have been recorded in the Brabant Massif since 1810 (Meilegem). By 1909, 78 boreholes had reached the Caledonian basement, according to the inventory in LEGRAND (1968). By mid-1967, increased industrial demand for pure water, especially since the fifties, led to 337 known boreholes reaching the Brabant Massif (by mid-1988 that number had increased to 603). This new information was studied in the many publications of LEGRAND and summarized in a milestone monograph about the Brabant Massif by LEGRAND in 1968. Besides maps with the topography of the basement, thickness of the red alteration, age and thickness of the post-Permian cover, he also produced the first detailed geological map of the pre-Jurassic Brabant Massif subcrop.

Until the seventies it was common practise for Belgian stratigraphers to use the term "Assise" as the basic unit in stratigraphy with a combined litho-, bio-, and chronostratigraphic meaning. Except in the Silurian of the Mehaigne area and in this volume of proceedings, not one old "Assise" has been redefined to conform to the recommendations of the International Stratigraphic Guide (HEDBERG, 1976). Hence the old term "Assise" will be used hereafter in quotes.

Another peculiarity in the Belgian literature is the use of the term Silurian to cover both the Silurian (sometimes called Got(h)landian) and the Ordovician Systems, although the Ordovician System was defined in its type area in 1879 by LAPWORTH. This French tradition was discontinued in the sixties. Similarly the abandoned term Tarannon(ian) was often used to indicate the Telychian (late Llandovery).

3.3 STRATIGRAPHY SINCE 1969.

3.3.1 LITHOSTRATIGRAPHY.

Although LEGRAND had studied the Brabant Massif extensively from 1948 to 1981, mostly in boreholes, he never defined a stratigraphy for the Silurian in the subcrop. This was rectified by MARTIN (1969a) who defined two units in the southern Flanders subsurface: the "Assise" of Lust, based on the description by LEGRAND (1962a) of the Kortrijk-Lust borehole with an early Telychian age (graptolite zones *M. turriculatus* and *M. crispus*), and the "Assise" of Deerlijk, based on the study of LEGRAND (1966) on the Deerlijk borehole, with a Rhuddanian and Aeronian age.

As explained above, the lithostratigraphic units ("Assise") also had a chronostratigraphical meaning although often fossil dating was lacking. Fig. 2 shows the lithostratigraphic units ("Assises") of the Silurian in the Brabant Massif with their supposed chronostratigraphic position as defined in the literature before 1970.

Detailed field observations since 1971 have been carried out in the thick, monotonous Silurian slate succession and have resulted in a detailed litho- and biostratigraphy in the Mehaigne area (VERNIERS, ms 1976, 1981, 1982, 1983, VERNIERS & RICKARDS, 1979) and in the Sennette Valley around Ronquières (LOUWYE, VAN GROOTEL, VERNIERS (in prep.). A

<table>
<tr><th>SYSTEM</th><th>SERIES</th><th>STAGES</th><th colspan="2">BIOSTRATIGRAPHY</th><th>WESTERN FLANDERS</th><th>RONQUIERES</th><th>ORNEAU</th><th>MEHAIGNE AREA</th></tr>
<tr><td>DEVON.</td><td>LOWER DEVONIAN</td><td>LOCHKOVIAN</td><td colspan="2">Monograptus uniformis</td><td rowspan="18"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td rowspan="28">SILURIAN</td><td>PRIDOLI</td><td></td><td colspan="2">Monograptus ultimus</td></tr>
<tr><td rowspan="5">LUDLOW</td><td rowspan="2">LUDFORDIAN</td><td colspan="2">Bohemograptus</td><td rowspan="5">"ASSISE" OF RONQUIERES</td><td rowspan="5">"ASSISE" OF VICHENET</td><td rowspan="14">"ASSISE" OF CORROY</td></tr>
<tr><td colspan="2">Saetograptus leintwardinensis</td></tr>
<tr><td rowspan="3">GORSTIAN</td><td colspan="2">Pristiograptus tumescens</td></tr>
<tr><td colspan="2">Lobograptus scanicus</td></tr>
<tr><td colspan="2">Neodiversograptus nilssoni</td></tr>
<tr><td rowspan="9">WENLOCK</td><td rowspan="3">HOMERIAN</td><td colspan="2">Monograptus ludensis</td><td rowspan="23"></td><td rowspan="9">"ASSISE" OF CORROY</td></tr>
<tr><td colspan="2">Gothograptus nassa</td></tr>
<tr><td colspan="2">Cyrtograptus lundgreni</td></tr>
<tr><td rowspan="6">SHEINWOODIAN</td><td colspan="2">Cyrtograptus ellesae</td></tr>
<tr><td colspan="2">Cyrtograptus flexilis</td></tr>
<tr><td colspan="2">Cyrtograptus rigidus</td></tr>
<tr><td colspan="2">Monograptus riccartonensis</td></tr>
<tr><td colspan="2">Cyrtograptus murchisoni</td></tr>
<tr><td colspan="2">Cyrtograptus centrifugus</td></tr>
<tr><td rowspan="13">LLANDOVERY</td><td rowspan="4">TELYCHIAN</td><td colspan="2">Monoclimacis crenulata</td><td rowspan="13">"ASSISE" OF GRAND-MANIL</td><td rowspan="13">"ASSISE" OF GRAND-MANIL</td></tr>
<tr><td colspan="2">Monoclimacis griestoniensis</td></tr>
<tr><td colspan="2">Monograptus crispus</td><td rowspan="2">"ASSISE" OF LUST</td></tr>
<tr><td colspan="2">Monograptus turriculatus</td></tr>
<tr><td rowspan="5">AERONIAN</td><td colspan="2">Monograptus sedgwickii</td><td rowspan="9">"ASSISE" OF DEERLIJK</td></tr>
<tr><td colspan="2">Monograptus convolutus</td></tr>
<tr><td rowspan="3">Coronograptus gregarius</td><td>argenteus</td></tr>
<tr><td>magnus</td></tr>
<tr><td>triangulatus</td></tr>
<tr><td rowspan="4">RHUDDANIAN</td><td rowspan="2">Coronograptus cyphus</td><td>cyphus</td></tr>
<tr><td>acinaces</td></tr>
<tr><td colspan="2">Cystograptus vesiculosus = atavus</td></tr>
<tr><td colspan="2">Parakidograptus acuminatus</td></tr>
<tr><td>ORDOV.</td><td>ASHGILL</td><td></td><td colspan="2"></td><td></td><td>"A." OF GEMBLOUX</td><td></td></tr>
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Figure 2 Silurian lithostratigraphic units ("Assises") of the Brabant Massif in each area, as defined in the literature before 1969 (see section 3.1, p. 164-165 for authors).

reconnaissance survey in the Orneau Valley (VERNIERS, 1983), in the valleys of the Dender, Marke, Senne, and in the areas of Monstreux-Nivelles and of Horion-Hozémont added more, partly unpublished, data. Recently VAN GROOTEL (ms 1990) studied the biostratigraphy with Chitinozoa in 19 boreholes in the western part of the Brabant Massif, Those boreholes with available cores were described in detail. Furthermore he described in detail the Chitinozoa from the Ronquières sections.

Based on this renewed field work and after critically assessing the old lithostratigraphy a new preliminary lithostratigraphy for the Silurian of the Brabant Massif is proposed here. Fig. 3 shows the proposed lithostratigraphy based on a uniform time-scale, while fig. 4 shows it in its true thickness. It is preliminary since half the outcrop areas and most of the boreholes still need reexamination. Dip measurements in many boreholes (LEGRAND, 1968) and own field observations suggest a quite continuous section from Ashgill to Ludlow, with a minimum thickness of about 2850 m, with no apparent angular unconformities.

The "Assises" of Grand-Manil, Corroy and Vichenet have not yet been validly defined, under the recommendations of the International Stratigraphic Guide (HEDBERG, 1976). We feel, however, that these "assises" have real significance (VERNIERS, 1983) and that detailed reexamination will merely lead to a modified redefinition.

The "Assises" of Lust and Deerlijk are well defined by MARTIN (1969a) and deserve the status of formations. The restudying of the sedimentology of the old and new boreholes in the southern Flanders subsurface might result in refining or subdivision of these two formations.

The units in the Mehaigne area were informally defined in the spirit of the stratigraphic guide (with the letters MB for Mehaigne-Burdinale followed by numbers) (VERNIERS, 1982; see also fig. 4 and 6). Their formalisation is planned as soon as the type localities and other outcrop areas of the Silurian have all been reexamined and their validity discussed.

The "Assise" of Ronquières was defined in its present form by MICHOT (1954a, b) and extended by LEGRAND (1967a) to include the sediments in the new cutting of the inclined shiplift at Ronquières. It has been restudied in detail sedimentologically and biostratigraphically with graptolites and Chitinozoa, and will be defined as the Ronquières Formation. A different new, underlying unit will also be demonstrated, the Mont Godart Formation (LOUWYE, VAN GROOTEL & VERNIERS, in prep.).

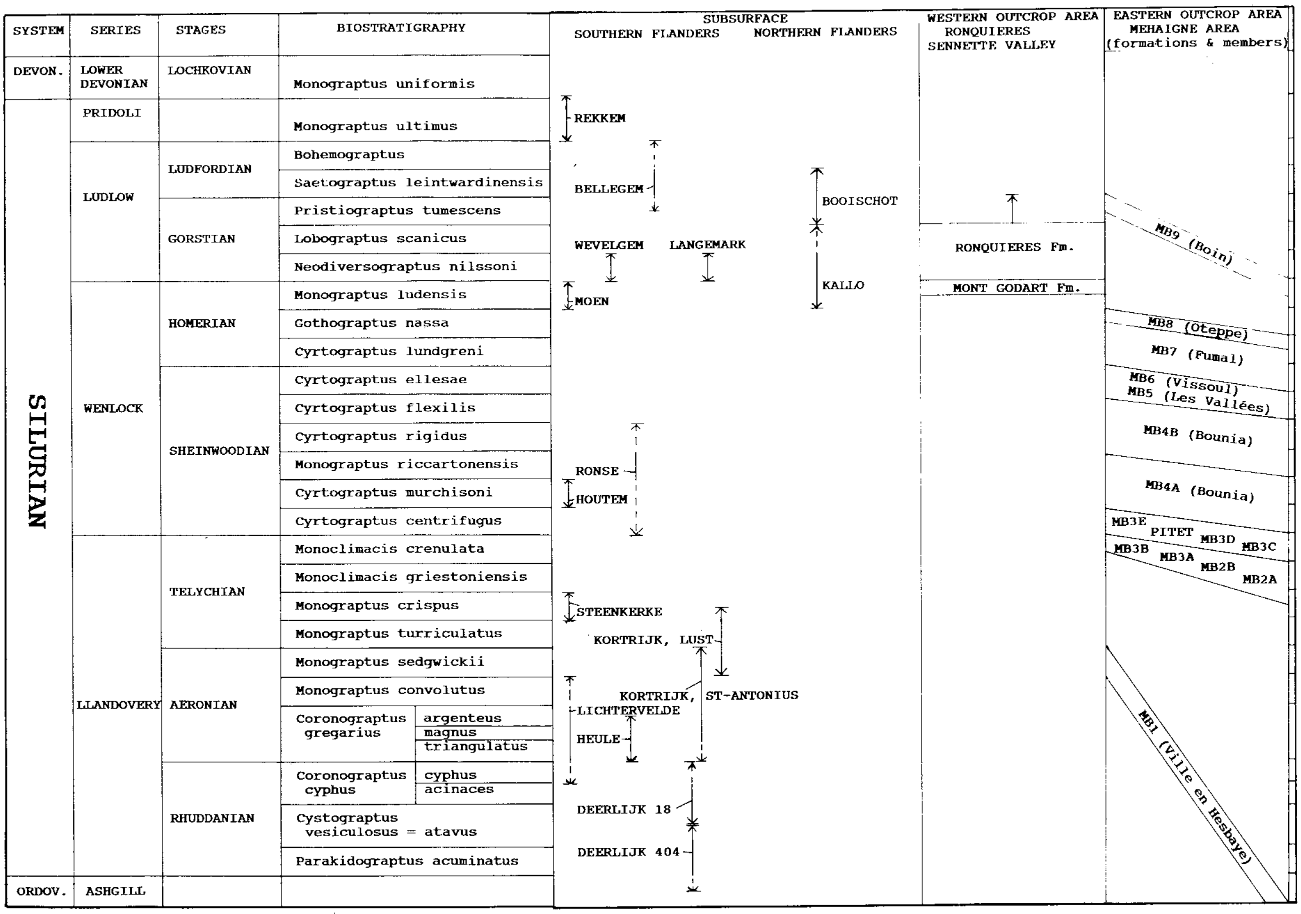


Figure 3 Chronostratigraphic position of Silurian lithostratigraphic units defined since 1969 in the Brabant Massif on a time axis. The oblique lines in the column of the Mehaigne area indicate age brackets, with to the right the oldest and to the left the youngest possible ages for the limits and do not imply diachronic limits.

3.3.2 BIOSTRATIGRAPHY.

An review of the different fossil groups studied or observed in the Silurian of the Brabant Massif is given in fig. 5 together with their stratigraphical position.

3.3.2.1 Acritarchs.

STOCKMANS & WILLIERE (1963) were the first to describe acritarchs in the Brabant Massif in the Kortrijk-Lust borehole. MARTIN (1965, 1969a, b, 1971, 1974) and MARTIN & RICKARDS (1979) analyzed Cambrian, Ordovician and Silurian acritarchs in many boreholes and outcrops from the Brabant Massif as well as from the Sambre and Meuse Belt. MARTIN (1969a) described four acritarch assemblages in the Llandovery and lower Wenlock of the Brabant Massif. Similar studies were undertaken on the Cambrian and Ordovician acritarchs of the Caledonian massifs of the Ardennes by VANGUESTAINE (1967, 1974, 1978a, b, 1986).

Mostly unpublished studies with acritarchs on tens of boreholes in the Brabant Massif (VANGUESTAINE, ms 1973, 1989, 1991; VANGUESTAINE *et al.* 1989) and with Chitinozoa in the Kallo borehole (VAN GROOTEL, ms 1990) showed that the age determinations by LEGRAND (1968) of the Lower Palaeozoic in the Brabant Massif, which had been mainly based on lithology, were often erroneous, especially in greyish siltstone or shale facies. Hence, the future lithostratigraphical divisions and correlations of boreholes in the Brabant Massif should always be checked with palynology.

Palynological studies in the Lower Devonian of Belgium showed a strong contamination with acritarchs from seven Lower Palaeozoic levels (two Cambrian, Tremadoc, Llanvirn, Wenlock, Ludlow-Prídolí and lower Lochkovian). It is supposed that they have eroded out of the Brabant Massif. Their preservation is generally much better than the highly carbonized acritarchs in situ in the Brabant Massif. This suggests that these acritarchs were eroded from the Brabant Massif during the Early Devonian before the Caledonian thermal event affected them (VANGUESTAINE, 1979; ROCHE *et al.*, 1986; STEEMANS, 1989).

3.3.2.2 Chitinozoa.

Chitinozoa were first studied in the Brabant Massif in 1971 in the Caradoc to middle Llandovery of the Deerlijk borehole by MARTIN (1971, 1974). Two biozones were defined in the lower Llandovery (fig. 4). Chitinozoa are also described in some upper Llandovery and lower Wenlock samples from the Sennette Valley by MARTIN & RICKARDS (1979).

In the Mehaigne area Chitinozoa were separated from turbidites, with maturation of the organic material reaching the meta-anthracite stage. The reflectance of the organic matter corresponded to a deep anchizonal metamorphism. Chitinozoa were recovered from 80% of the samples and in spite of the poor preservation a diverse fauna is present. This is explained by the deep neritic environment of the sedimentary basin, a favourable environment for Chitinozoa. Four biozones with nine subzones are described in the uppermost Llandovery to lower Ludlow (VERNIERS & RICKARDS, 1979; VERNIERS, 1981, 1982).

VAN GROOTEL (ms 1990) found in the graptolite dated Ronquières and Mont Godart formations in Ronquières the same Chitinozoa zone as in the highest of the Mehaigne area and could divide it in Ronquières into three subzones. Four Llandovery boreholes of West-Flanders (Lichtervelde, Kortrijk-Lust, Kortrijk/St-Antonius, Steenkerke), also dated by graptolites, showed the presence of 11 biozones in the Aeronian and early Telychian (Llandovery). Chitinozoa associations from two other graptolite dated boreholes (Houtem, Langemark) matched previously described Chitinozoa zones in the Mehaigne and Ronquières. Five undated boreholes were dated with Chitinozoa by correlation with other localities in the Brabant Massif or with Gotland, Baltic Sea. The Bellegem and Rekkem boreholes were placed respectively in the late Ludlow and in the Prídolí. This is the first proven presence of Prídolí in the Brabant Massif.

As a result of these studies the Chitinozoa biozonation in the Silurian of the Brabant Massif now contains 25 biozones or subzones from Llandovery to Ludlow with another one in the Prídolí. The number of Chitinozoa zones is comparable to the number of graptolite zones in the same time span. However more Chitinozoa zones might be present in the several unstudied parts of the Silurian section. The continuous and thick Silurian sections in the Brabant Massif could have been a reference for the graptolite and Chitinozoa biozonation if their preservation had been better.

A correlation of this biostratigraphy with Wales, Welsh Borderland, Gotland, Scania, Estonia, Podolia, Bohemia, Armorican Massif, eastern Canada, Ohio and Kentucky shows, for the Silurian, a clear similarity of the Belgian assemblages with the British, Baltic and Bohemian areas, poorer with the nearby Armorican Massif, and poorest with north African and north American assemblages.

3.3.2.3 Other fossils.

The facies in the Silurian of the Brabant Massif is always deep neritic (see 4.4) with no shallow marine sediments observed yet. Hence:

(a) graptolites are nearly the only macrofossils present and until 1969 the sole basis for biostratigraphical dating (many publications of MALAISE, MAILLEUX, MICHOT, LEGRAND). Most studies with graptolites after 1920 are based on the work of ELLES and WOOD (1901-1918) and might need a revision. Larvae and prosiculae of graptolites are often encountered in palynological preparations as are rhabdosomes in petrographical thin sections (MARTIN, 1971, 1974).
Other fossil groups (fig. 5) are rare to extremely rare;

(b) *Pictonicopila* (organic walled benthic algae often transformed into pyritospheres) are found in many horizons in the two Deerlijk boreholes, studied by MARTIN (1971, 1974), in the borehole of Kortrijk-Lust (Telychian, *M. crispus* zone) (LEGRAND, 1962a, VAN GROOTEL, ms 1990), in the borehole of Houtem (lower Sheinwoodian) (VAN GROOTEL, *ibid.*), in the borehole of Kallo (upper Homerian-lower Ludfordian) (LEGRAND, 1968), in the Ronquières Formation, inclined shiplift section in Ronquières, Gorstian (*N. nilssoni* and *L. scanicus* zones, probably more the latter) (VAN GROOTEL, ms 1990, LOUWYE *et al.*, in prep.), and in Ludfordian of the Bellegem borehole (VAN GROOTEL, ms 1990).

(c) Petrography showed some foraminifers in the *A. acuminatus* zone of the Deerlijk boreholes and

(d) undetermined spicules analogous to those of sponges.

(e) Additionally in the Deerlijk boreholes, in all of the Rhuddanian, some mineralized hexagonal prismatic "niches" are described of probably biogenic origin, and

(f) many spores (MARTIN, 1971, 1974).

Furthermore were found:

(g) one conulate, *Conularia* sp. in the *Monograptus riccartonensis* Zone, lower Wenlock of the Burdinale Valley (VERNIERS, 1983);

(h) a brachiopod cf. *Dayia* sp. found in a supposedly lower Ludlow level in the Moen borehole (LEGRAND, 1968);

(i) fragments of the bivalve *Cardiola* sp. in the Houtem borehole of the *Cyrtograptus murchisoni* Zone, lower Wenlock (LEGRAND, 1968);

(j) orthocone nautiloids of the genus *Orthoceras* spp. in the *M. convolutus* zone (Aeronian) of the Lichtervelde borehole (LEGRAND, 1964b), in the Houtem borehole, lower Wenlock (LEGRAND, 1968) and in the Moen borehole, lower Ludlow;

(k) scolecodonts observed occasionally in palynological preparations in several boreholes

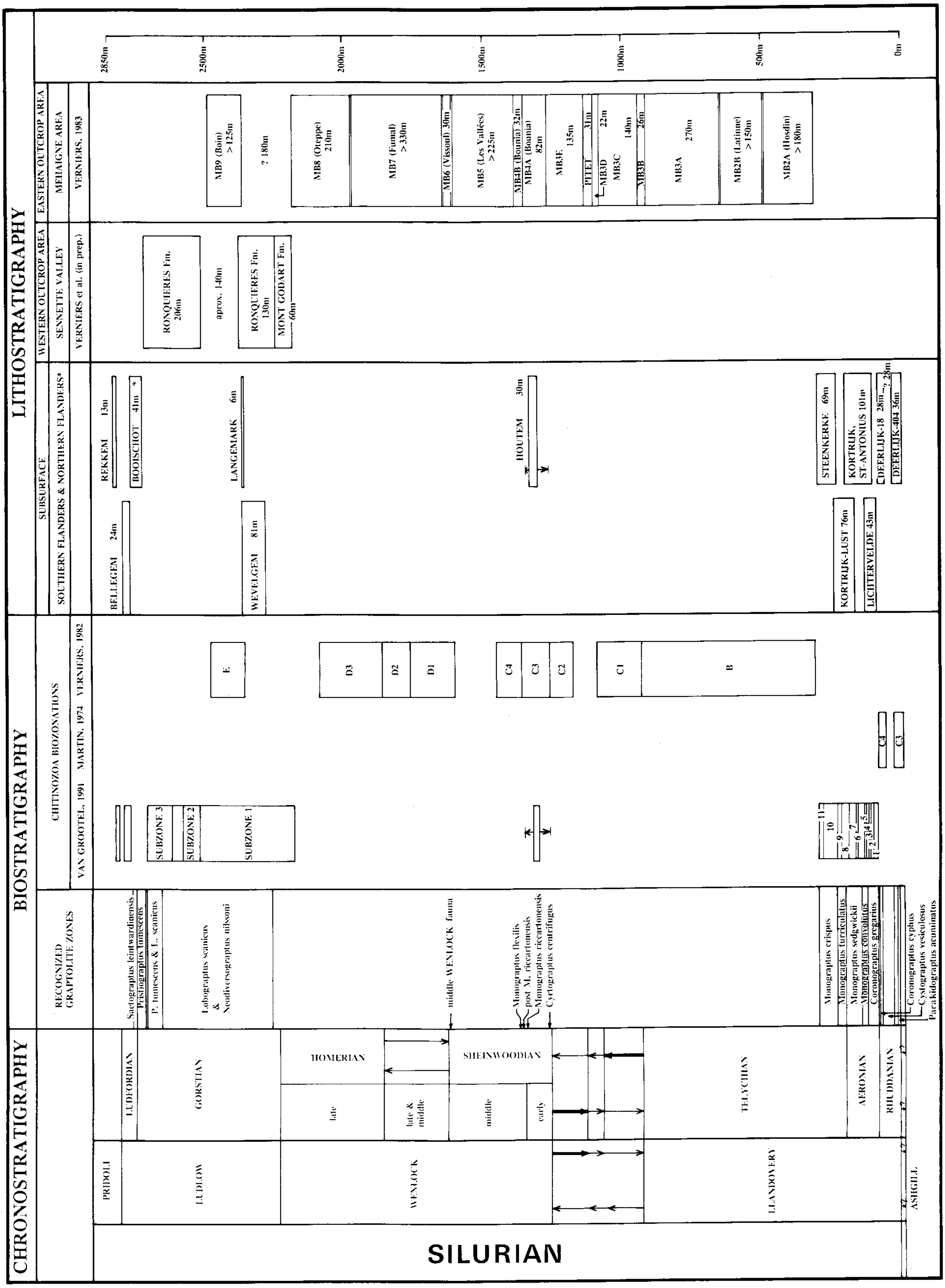


Figure 4 Composite stratigraphical section, based on the real thickness of the Silurian in the studied outcrop and subsurface area with the local formal or informal formation and member names. The recognized graptolite zones and the different Chitinozoa zones are shown, and were used to derive the suggested chronostratigraphy. The location of the Wenlock-Llandovery boundary in the Mehaigne area can be placed according to the Chitinozoa zonation at the base of members MB4A, MB3E, MB3D or MB3C. More detailed Chitinozoa ranges are needed in the type areas of that boundary to decide on its exact location in the Mehaigne area.

throughout the Llandovery of southern Flanders (MARTIN, 1971, 1974; VAN GROOTEL, ms 1990), throughout the Wenlock of the Mehaigne area (VERNIERS, 1982), and in the lower Ludlow of Ronquières (VAN GROOTEL, ms 1990);

(l) crustacean Archaeostraca *Ceratocaris* sp. identified in the Bellegem borehole by RICKARDS in VAN GROOTEL (ms 1990);

(m) a crinoid *Siphocrinites* sp. in the inclined shiplift of Ronquières, lower Ludlow by MORTELMANS in LEGRAND (1967a); and

(n) four periods of bioturbation in the boreholes at Deerlijk-401/2 and -404 (Rhuddanian) (MARTIN, 1971,1974), Houtem (lower Sheinwoodian), Bellegem (upper Ludlow) and Rekkem (Prídolí) (VAN GROOTEL, ms 1990).

3.4 PALAEOECOLOGY.

The presence of the algae *Pictonicopila* at several levels in the Silurian (fig. 5), indicates benthic algal life in oxic conditions at and below the water/sediment interface in a brief interval after the deposition of a turbidite and before that of the laminated hemipelagites (MARTIN, 1971, 1974; VAN GROOTEL, ms 1990). Bioturbation also indicates oxic conditions at the water/sediment interface. Furthermore, *Cardiola* is part of the exaerobic benthos and hence an indication of oxic conditions close to the sea bottom.

Using these four indicators at least seven periods with dominantly oxic conditions at or below the water/sediment interface can be demonstrated: Rhuddanian (*A. acuminatus, C. atavus, and C.*

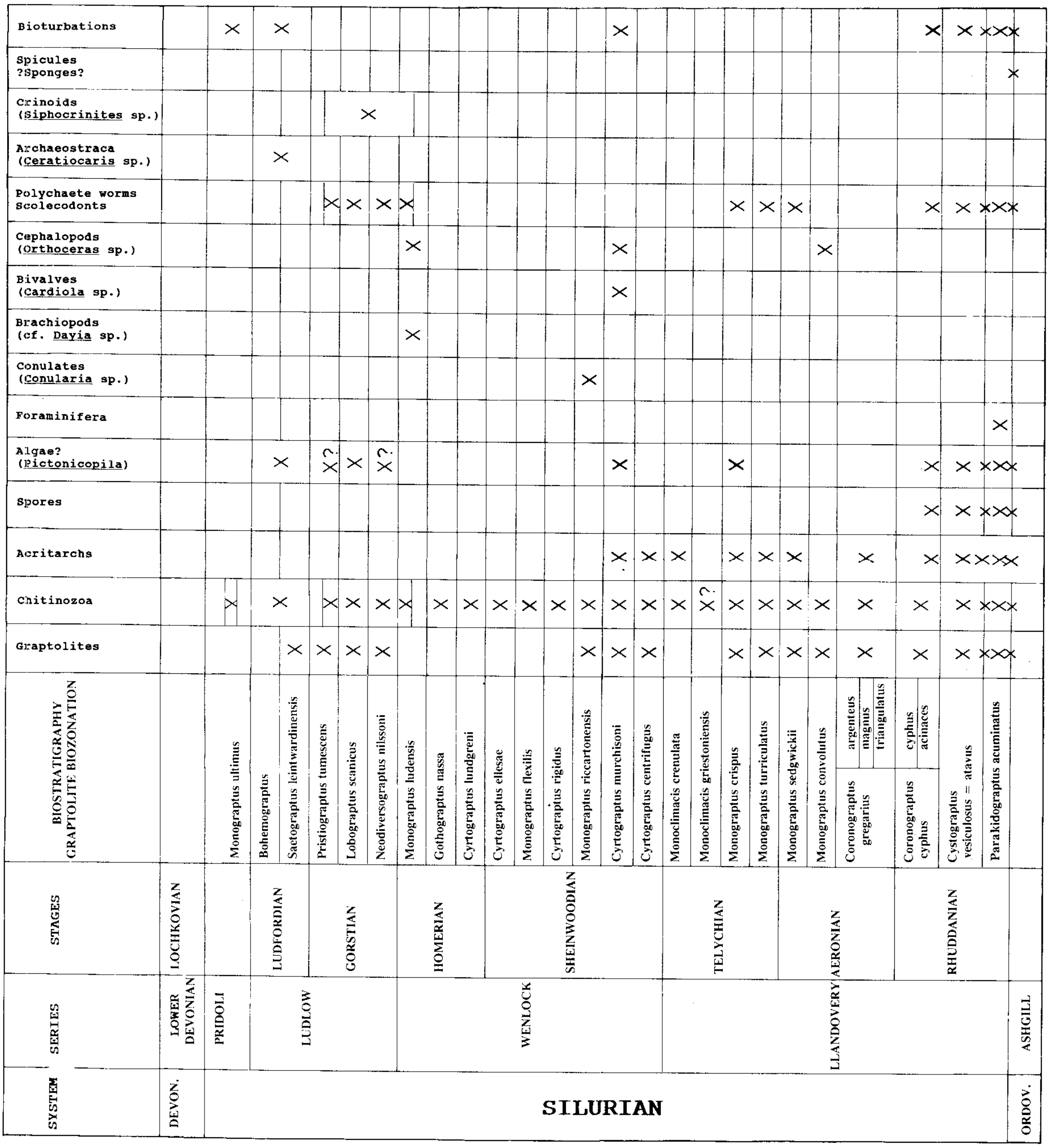


Figure 5 Fossil groups occuring in the Silurian of the Brabant Massif and the stratigraphic levels of these finds. The frequently occurring groups are given below, followed in biological order by the more rarely occurring fossilgroups.

cyphus? zones), a level in the Telychian (*M. crispus* zone); the lower Wenlock (*C. murchisoni* and *M. riccartonensis* zones), the uppermost Wenlock (*M. ludensis*), several levels in the Gorstian, one in the Ludfordian and one in the Prídolí.

Some fossils such as *Conularia, Dayia, Cardiola, Orthoceras, Siphocrinites,* and some species of Chitinozoa (a.o. *Margachitina margaritana, Desmochitina opaca*) show the presence of a "less deep" environment at the following levels: upper Aeronian and lower Telychian, lower Wenlock, uppermost Wenlock and a level in the Gorstian. Since in all these levels graptolites are the dominant group of macrofossils, shallow marine conditions are excluded. On the other hand some Chitinozoa genera (e.g. *Cingulochitina* spp.) or species (*Angochitina longicollis*) indicate deep neritic environments (VERNIERS, 1982), especially in the uppermost Telychian, the upper Sheinwoodian, the lower Homerian and the Gorstian.

3.5 SEDIMENTOLOGY.

In the literature the lithology of the Silurian in the Brabant Massif is mostly vaguely described, e.g. in the Mehaigne area as mentioned in VERNIERS (1983). Before 1958 the following terms were used: shales or slates, "quartzophyllades", "psammites", quartzites, "ampelites" and lutites; sometimes with adjectives as pelitic, quartzitic, cellular, chloritic, calcareous, dolomitic. In 1958 MICHOT introduced a refined classification of clastic rocks studied in thin sections. The new terms such as "psammoschiste", "psammoquartzite", "psammite", "micropsammite" and "micropsammoschiste" were used amongst others by MARTIN (1971, 1974) and VERNIERS (1983).

The sedimentology was nearly never specified or only vaguely so, such as "stratoïde", "zonaire", "feuilleté". MICHOT (1954b) is the first to mention cross bedding.

Given that a turbiditic nature was attributed to most Silurian sediments in the Brabant Massif (MARTIN, 1971; BEUGNIES, 1973; VERNIERS & RICKARDS, 1979; MICHOT, 1980; VERNIERS, 1983) and after comparing the descriptions of formations and outcrops in the literature with our own field observations, we feel that the lithological terms used in the literature could correspond with a specific division in the turbidite model of BOUMA (1962, 1964). The compact division (Te) of the BOUMA sequence was probably always referred to as shales ("schistes") or slates ("phyllades") and probably in some cases also as "quartzophyllades", with adjectives such as chloritic, dolomitic, calcareous, quartzitic, pelitic. Laminated hemipelagites and the upper and lower laminated divisions (Tb and Td) of the BOUMA sequences were probably designated as lamellate psammites ("psammites feuilletés"), very fine psammites or micropsammites, and possibly also as "quartzophyllades". The current ripple laminated divisions (Tc) of the BOUMA sequence were possibly called "stratoid" quartzites or psammoquartzites with cross bedding and the graded divisions (Ta) quartzites, psammoquartzites or psammites. The term zoned ("zonaire") referred at least in the Ronquières Formation to the alternation of compact and laminated layers and hence to the turbiditic or laminated hemipelagic-turbiditic nature of the sediments.

Only in 1966-1967 came the first published descriptions of the sedimentology of Silurian sediments. The rhythmic pattern of the sedimentation in the Silurian was highlighted by LEGRAND (1966) in the Deerlijk-18 and -404 boreholes. LEGRAND (1967a) recorded in the type locality of the Ronquières Formation "silty or sandy centimetric beds interrupt every 20-30cm (the slates) giving it a zoned aspect. Each (of these centimetric beds) consists of tens of straticules of sandy silts alternating with darker clayey straticules." Its formation was explained by sedimentation in a rather deep basin, giving it a uniform distribution, with a continuous clayey sedimentation and discontinuous silt input at rhythmic intervals caused probably by a climatic factor. An eolian silt input is postulated.

The petrography and palaeontogical content in the borehole Deerlijk-404 was studied extensively by MARTIN (1971). A complete rhythmic unit, of centimetric or decimetric scale, consists of five "facies": (fine) psammites, dark grey homogeneous peloshales, slightly laminated peloshales and clearly laminated peloshales, and light grey homogeneous peloshales. The three middle facies are often recurrent. The term peloshales was defined by MICHOT (1958) in a attempt to subdivide fine clastic rocks otherwise called mudstones or slates/shales (see also 3.3).

In the clearly laminated peloshales the laminations are made of alternating light grey laminae (120-300µm thick) passing into dark grey laminae (65-120µm). The difference in colours is not caused by grain size distribution but, in decreasing order, by the amount of colloidal matter, organic matter and pyrite. They characteristically contain abundant trilete spores. MARTIN (1971) explained them as varves caused by annual concentration of colloidal and organic matter and the expression of anoxic environment together with the other two dark facies. These laminated peloshales were called "ampelites" by LEGRAND (1966) and could now be termed laminated hemipelagites.

The light grey homogenous peloshales are rich in acritarchs, Chitinozoa and the only facies where the benthic algae *Pictonicopila dinae* occurs. These peloshales are explained as allochthonous turbidites bringing oxic conditions into the basin. Hence, MARTIN (1971) was the first to postulate a turbiditic

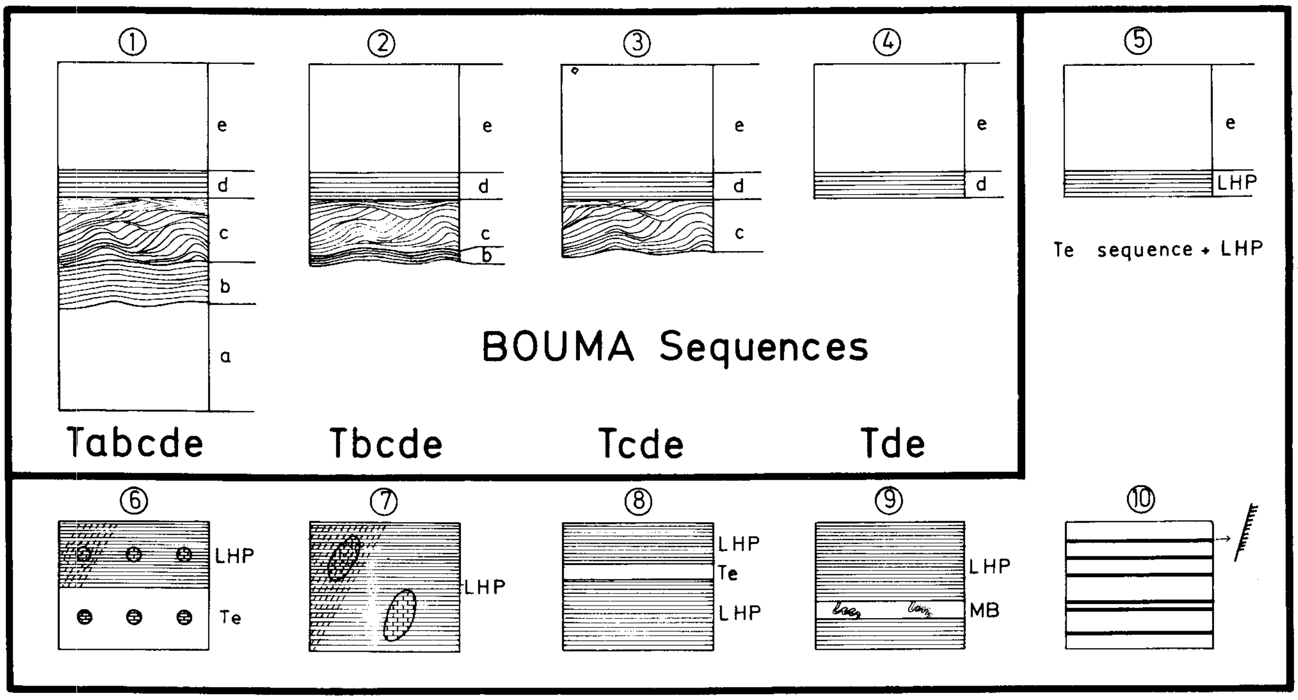


Figure 6 The different sedimentological facies occurring in the Silurian of the Brabant Massif. Different types of complete or incomplete Bouma turbidite sequences with their divisions: a: graded division, b: lower laminated division, c: current ripple division, d: upper laminated division, e: compact sedimentation division (1 to 4); incomplete turbidite sequences alternating with laminated hemipelagites (5); laminated hemipelagites and alternating e divisions of turbidites with cigar-shaped calcareous nodules with slaty cleavage deflected around them (6); laminated hemipelagites with calcareous nodules, bread-shaped with slaty cleavage passing through unreflected (7); minor Te division within laminated hemipelagites (8); laminated hemipelagites with metabentonite and contorted quartz-veins (9). Alternation of dark graptolitic shales, laminated hemipelagites and some fine Te turbidite division (10). 1 to 9: examples from the Ronquières formation (Gorstian, Ludlow), 10 from the Deerlijk boreholes (Rhuddanian, Llandovery).

environment for part of the sediments in the Silurian of the Brabant Massif.

MARTIN (1974) studied the palyno- and microfacies in three Deerlijk boreholes, two Silurian (Deerlijk-18 and -404; the latter already studied in 1971) and an Upper Ordovician (Deerlijk-401/2; not further discussed here). The five facies of the Deerlijk-404 borehole are also present in Deerlijk-18 borehole, with only rarely varves (laminated hemipelagites). The study of the palynofacies showed three groups of taphocoenoses, containing either benthic algae, hexagonal "niches" or neither of these. The presence of benthic algae and "niches" seem to exclude each other. Four environments are proposed: (1) neritic, photic, with benthic algal life, oxic with possible fluctuations, calm sedimentation; (2) aphotic neritic, with "niches", oxic, slow or rapid/agitated sedimentation; (3) neritic, anoxic, formation of varves, calm sedimentation; (4) bathyal, oxic, fine sedimentation without bioturbation.

The fossils have three sources: (1) marine contemporary biocoenoses (some acritarchs, Chitinozoa, graptolites larvas or rhabdosomes and possibly scolecodonts), (2) reworked organisms from older sediments (some acritarchs) and (3) imported continental vegetal remnants (spores).

BEUGNIES (1973) was the first to propose a flysch nature as a whole for the sediments in the Ordovician-Silurian of the Brabant Massif. The turbiditic nature of the Silurian in the Mehaigne has been established since 1972 but only published in 1979 (VERNIERS, ms 1976, VERNIERS & RICKARDS, 1979, VERNIERS, 1981, 1982, 1983). Turbidites were also seen in the Orneau Valley in the upper Llandovery and lower Wenlock by MICHOT (1980) and VERNIERS (1983).

Hence, the facies of the Silurian in the Brabant Massif was deep neritic in all studied boreholes or outcrop areas, either sand-turbidites or mud-turbidites (the latter interlayered with laminated hemipelagites) or pure laminated hemipelagites. To date no shallow neritic facies have been observed.

The different sedimentological types are illustrated in fig. 6. Most common are turbidites of the different Bouma sequences: Tabcde (1), Tbcde (2), Tcde (3), Tde (4), and Te divisions interlayered in laminated hemipelagites (5). Pyritosphaeres can occur in the top five mm of a Te division, in the bottom of a Td division or in the laminated hemipelagites. Laminated hemipelagites are often found interbedded with the less energetic turbidites. In the basal part of the Ronquières Formation a 30.2 m thick series of laminated hemipelagites with some minor invasions of Te turbidites occurs (8). Two types of calcareous nodules occur: cigar-shaped calcareous nodules, (1-3 cm ⌀ x 10-20 cm L) with the slaty cleavage folding around the nodules (6) and bread-shaped calcareous nodules (15-25 cm ⌀ x 5-15 cm H) with the slaty cleavage passing undisturbed through the nodules (7). Cream-coloured very fine grained beds, 1-6.5 cm thick, of metabentonites with a base of coarser grains are found, containing some contorted quartz-veins (9). Black graptolitic shales occur in between the turbidites in the "Assise" of Deerlijk in the boreholes of Deerlijk 18 and 404 and Kortrijk/St-Antonius. They are interpreted as pelagites or sapropelites, rich in graptolites.

Palaeoflow directions in the Silurian sediments of the Mehaigne area, deduced from ripple directions and current ripple lamination within the Tc divisions point quite constantly NNW wards. Groove, flute and other casts were not observed in the mostly small outcrops of that area. It was concluded that the source area of the turbidites was situated somewhere to the SSE (VERNIERS, 1982). This conclusion should be handled with care since there is no other supporting data than these (local) palaeoflow directions. The shapes of the basin and the turbidite system are still largely unknown.

Chitinozoa were mostly sampled in the Te divisions. Their assemblages are mostly deep neritic and reflect the environment of the source area of the turbidites. Hence the deposition area of the turbidites had to be deep neritic or deeper, bathyal. The Chitinozoa and acritarch assemblages are different from those of the Sambre and Meuse Belt (MARTIN, 1969a, b, and unpublished data). Thus it was concluded that the source was probably situated between the Mehaigne and the Sambre and Meuse Belt (VERNIERS, 1982). Here again we should stress that the shape of the basins is unknown and this conclusion can only be tentative.

Unpublished observations by one of the authors (J.V.) in the "Poudrière de Corroy" (Orneau Valley) also concluded a northwards flow direction from ripple direction and current ripple lamination. However flute and groove casts were also observed in an E-W direction, at right angles to the flow direction deduced from cross lamination, a hitherto unexplained phenomenon.

3.6 MEGACYCLICITY.

Several sedimentological, lithological and micropalaeontological cyclicities, on different scales (metric, decametric or hectometric) were detected as a result of detailed lithostratigraphical logging in the Mehaigne area (VERNIERS, 1983) and in Ronquières (LOUWYE *et al.*, in prep.) (fig. 7). They are still on a smaller scale than the megasequences as defined by WOODCOCK (1990) in the Welsh Basin.

Four types of megacyclicity were observed in the Mehaigne area (formations MB2 to MB9, uppermost Llandovery to lower Ludlow)

(1) large cycles with changes in lithology,
(2) large cycles with changes in sedimentology,
(3) small cycles with changes in sedimentology but unchanging lithology,
(4) cyclical changes in the relative proportion of Chitinozoa assemblages.

In the Ronquières Formation in its type area (uppermost Wenlock? to lower Ludlow) only one type of megacyclicity occurs with only sedimentological and no lithological changes. These are mainly the changing energy of the turbidites, the amount of material transported by them, and the frequency and thickness of interstratified laminated hemipelagites (fig. 7).

Several of our observed cycles were also observed in other areas on the same microcontinent or further away. The deep-shallow-deep cycle observed in the uppermost Llandovery and lower to mid-Wenlock in the Mehaigne area is reflected by a marked cycle of increasing-decreasing energetic regime of turbidites and by a cycle with deep-shallow-deep Chitinozoa associations (VERNIERS, 1982). It is remarkably contemporaneous with a similar cycle in the Visby and Högklint Beds and in the basal Slite Marls in Gotland, Baltic sea (LAUFELD 1974, 1979a, b), or in the lower Wenlock (*C. centrifugus* to *M. riccartonensis* Zones) of Wales and Welsh Borderland (BASSETT, 1974; HURST *et al.*, 1978; DIMBERLINE & WOODCOCK, 1987).

Another large shallow-deep-shallow cycle in the Mont Godart and the Ronquières Formations (uppermost Wenlock? to lower Gorstian, Ludlow) reached a prolonged laminated hemipelagic facies at its peak, where several bentonites are preserved. This cycle is contemporaneous with the observed deepening in the basal Elton Beds starting just above the very shallow conditions in the top of the Wenlock limestone in the Welsh Borderland (BASSETT, 1989). It is also possibly contemporaneous with the deepening observed, 1100 km away in the island of Gotland (Baltic Sea), from the shallow Klinteberg limestone/beds to the deeper Hemse beds, close to the Wenlock-Ludlow boundary. The age of that limit however is still debated and possibly diachronous, hence our reservation. It is however noteworthy that these two stratigraphical levels with shallow environments are the only levels in the Brabant Massif where deeper water macrofauna occurs (fig. 5).

The megacyclical variation observed in the Silurian in the Brabant Massif is summarized in fig. 7. More cyclicities are present in the other parts of the Silurian (Llandovery in southern Flanders and outcrop areas), but need detailed stratigraphical logging to be clearly demonstrated. Only after the construction of a composite section through the Silurian in the Brabant

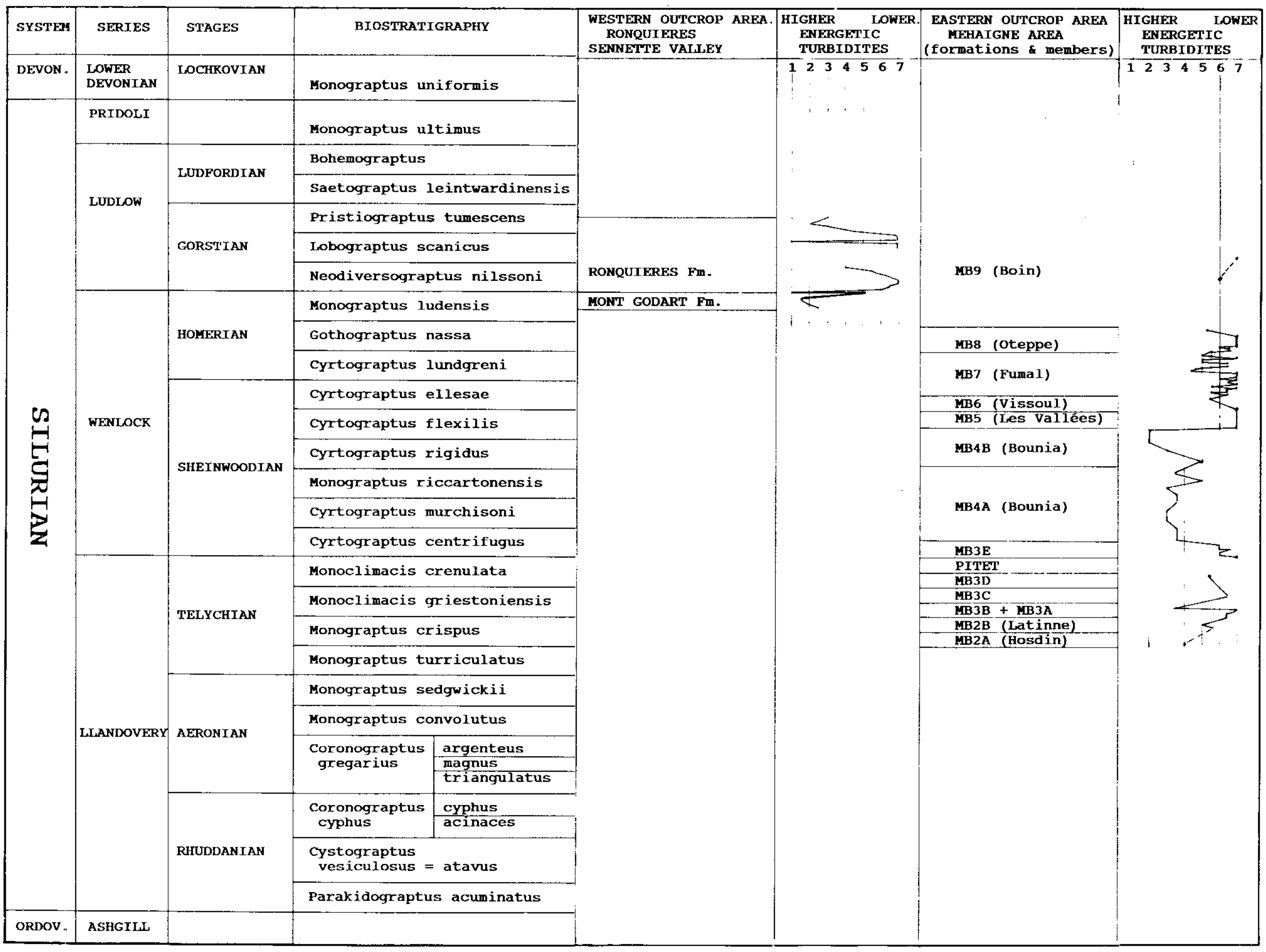


Figure 7 Megacyclical variation in the Silurian of the Brabant Massif in the Mehaigne area and in Ronquières. The parameter indicating the energy of the turbidites was calculated by the relative proportion of each type of Bouma sequences and the thickness of the c-divisions.

Massif will the general megacyclical variation become apparent and possibly correlated with cyclicities observed in other Silurian sequences on the same Wales-Anglia-Brabant (=Eastern Avalonia) microcontinent or further away.

3.7 MAGMATISM

3.7.1 REVIEW OF STUDIES ON THE MAGMATISM

DUMONT had already described most magmatic rocks in the outcrop area of the Brabant Massif and MALAISE (1873) enumerated many new outcrops. They were examined for the first time systematically by de la VALLEE-POUSSIN & RENARD specially in their monograph of 1876. Their accurate field observations are still a great help to present day workers since many quarries and outcrops have disappeared.

A new petrographical study by MORTELMANS on the magmatic rocks of the Brabant Massif appeared in DENAEYER & MORTELMANS (1954). CORIN reviewed the literature on all known outcrops or boreholes, in his monograph of 1965 on the magmatic rocks of Belgium, together with his field observations, petrographical studies and chemical analyses on the major elements.

ANDRE added to the petrography data on major and trace element geochemistry of the magmatic rocks in Belgium, together with isotope ages (ANDRE, ms 1983a, 1983b, 1989; ANDRE & DEUTSCH, 1984, 1985, 1986; ANDRE, DEUTSCH & MICHOT, 1981; ANDRE, HERTOGEN & DEUTSCH, 1986; ANDRE, DEUTSCH & HERTOGEN, 1986).

The age of the extrusives is accurately known by the detailed dating with graptolites or organic microfossils from the interbedded sediments, while the intrusives are only datable with isotopes within large limits of errors. New dating with fossils not only confirmed but described more accurately the west to east shift through time of the magmatic activity in the Brabant Massif, already postulated by CORIN (1965) and ANDRE (ms 1983a) (fig. 8 and 9).

The magmatic activity during the late Ordovician is situated only along a linear WNW trending zone, south of the main axis of the Brabant Massif, between Fauqué (spelled earlier Fauquez) and Westende with

SYSTEM	SERIES	STAGES	BIOSTRATIGRAPHY		SOUTH. FLANDERS SUBSURFACE	WESTERN OUTCROP AREA			EASTERN OUTCROP AREA		SAMBRE-MEUSE	VOLCANIC LEVELS (SILURIAN)
						SENNETTE VALLEY	NIVELLES	ORNEAU	MEHAIGNE AREA	VOROUX-GOROUX	NEUVILLE S/HUY	
DEVON.	LOWER DEVONIAN	LOCHKOVIAN	Monograptus uniformis									
SILURIAN	PRIDOLI		Monograptus ultimus									
	LUDLOW	LUDFORDIAN	Bohemograptus									
			Saetograptus leintwardinensis									
		GORSTIAN	Pristiograptus tumescens									
			Lobograptus scanicus									
			Neodiversograptus nilssoni			Metabentonites of Ronquières						4
	WENLOCK	HOMERIAN	Monograptus ludensis									
			Gothograptus nassa									
			Cyrtograptus lundgreni									
		SHEINWOODIAN	Cyrtograptus ellesae									
			Cyrtograptus flexilis									
			Cyrtograptus rigidus									
			Monograptus riccartonensis								V11	
			Cyrtograptus murchisoni								V10	
			Cyrtograptus centrifugus								V 9	
	LLANDOVERY	TELYCHIAN	Monoclimacis crenulata				Porphyroid of Monstreux	Porphyroid Km 2.809	Volc. sediment. rock of Pitet	Porphyroids, rhyolites	V 2	3
			Monoclimacis griestoniensis								V 8 V7, V6, V5, V4	
			Monograptus crispus								V 3 V 1	
			Monograptus turriculatus									
		AERONIAN	Monograptus sedgwickii									
			Monograptus convolutus		KORTRIJK, ST-ANTONIUS					Pillow lavas, Basalts		2
			Coronograptus gregarius	argenteus								
				magnus								
				triangulatus								
		RHUDDANIAN	Coronograptus cyphus	cyphus								
				acinaces								
			Cystograptus vesiculosus = atavus				Eurite of Nivelles	Ignimbrite of Grand-Manil				1b
			Parakidograptus acuminatus		DEERLIJK 404	Fauqué (Canal)						1a
ORDOV.	ASHGILL					Fauqué (Bois des Rocs)	Porphyroid of Grand-Manil					

Figure 8 Stratigraphic position of the four volcanic horizons in the Silurian for different areas of the Brabant Massif (many publications, see chapter 3.7.2.).

a parallel strip from Pittem to Leffinge. The earliest volcanic activity in the Brabant Massif, if we exclude the magmatic activity in the Tubize group (Lower Cambrian or earlier), started with rhyolites in the coastal area in the early Caradoc (Leffinge borehole) and undifferentiated Caradoc (Keiem and Schore boreholes, VAN GROOTEL, ms 1990).

Further east on the magmatic lineament, around the eruptive centre of Deerlijk (near Kortrijk), magmatic activity with rhyolites, some dacites and andesites, started in the late Caradoc (MARTIN, 1974).

The eruptive centre of Quenast with a major pipe (Quenast) and sill (Bierghes) and several periods of dacitic extrusives (Fauqué) is Ashgill in age. The 800 m thick Lessines sill of acid andesite and dacite intruded, according to isotopic dates during the Silurian (fig. 12). The ages seem to cluster in the later half of the Silurian (Ludlow?), although there are large error limits. Since different proposed absolute timescales are still at variance with one another, they must be approached with caution. A Silurian age is however also suggested by the petrography and geochemistry indicating a cover of at least 1500 m of sediments during the intrusion into Ashgill sediments (ANDRE, pers. comm. 1989; HERBOSCH *et al.* 1991).

3.7.2 STRATIGRAPHIC POSITION OF THE SILURIAN MAGMATIC ROCKS.

Magmatic activity in the Brabant Massif is found in at least four stratigraphical levels of the Silurian (fig. 9). It clearly decreased in activity through time and shifted to the east. It extends from Deerlijk to Voroux-Goreux (near Liège) and possibly more to the ENE as far as Visé, along an arcuate line south of the main axis of the Brabant Massif in its western and central part and crossing that axis in its eastern part.

Level 1a is a siliceous lutite of possible volcanic origin, 1.4 m thick, in the *Akidograptus acuminatus* zone, Rhuddanian, Llandovery in Deerlijk-404 borehole at depth between 165.5m and 166.9m (LEGRAND, 1966). This level deserves to be checked palaeontologically to exclude a possible synchronism with the Grand-Manil ignimbrite.

Level 1b is the "eurite" of Nivelles (DUMONT, 1848, 1854) or rhyolites of Nivelles (ANDRE, ms 1983a, 1983b). The "eurite" of Grand-Manil LAMBOTTE (1836) or ignimbrite of Grand-Manil (ANDRE, ms 1983a, 1983b) is often thought to be the same layer (CORIN, 1965). However the graptolites in Grand-Manil were determined by ELLES in MAILLIEUX (1930) and placed in the *Coronograptus cyphus* zone (Rhuddanian, Llandovery). A sample with graptolites in the kaolinizated volcanic rock from Nivelles was offered by a collector to L. ANDRE and via the authors determined by RICKARDS (pers. comm., 1983). To him it undoubtedly belongs to one graptolite zone lower, the *Cyrtograptus vesiculosus* zone (also Rhuddanian, Llandovery). A (micro)palaeontological restudy should elucidate this divergence. The eruption centre is unknown but its main development is observed between Nivelles and Grand-Manil.

Level 2a is the volcanic complex of Voroux-Goreux, in an eight km long subcrop gallery for water captation, discovered by LOHEST (1911). In the east around Fexhe-le-Haut-Clocher spilitic pillow lavas and basalts (DUMONT, 1832; de la VALLEE-POUSSIN & RENARD, 1876; CORIN, 1935a, b, 1965), were found close to graptolitic shales of the *Monograptus convolutus* zone, Aeronian, Llandovery (MICHOT, 1929). In the middle around Roloux undated diabases and rhyolites and around Jeneffe and Haneffe porphyroids occur similar to these of Pitet (CORIN, 1935a, b), which are dated as latest Llandovery and possibly earliest Wenlock (VERNIERS, 1982). In the security pit at 136 m east of the spilites, graptolites were found by HALET (1911) and described as an (early) Wenlock fauna (MALAISE in HALET, 1911; MALAISE, 1911). The sediments are compared lithologically in an additional note (MALAISE, *ibid.*) with those from outcrops in the Mehaigne area between Fumal and Vinalmont, that VERNIERS (1982, 1983) mapped and dated as middle and upper Wenlock strata. The Voroux-Goreux complex is seen as the third eruptive centre in the Brabant Massif, however with a Llandovery/early Wenlock age. It is supposed to be the source for middle Llandovery to lower Wenlock extrusives in the Brabant Massif and possibly for the nine extrusive layers in the Telychian and three in the lower Wenlock of the Neuville area in the Sambre and Meuse Belt. If all data in the literature prove to be right then a considerable section of Llandovery and Wenlock rocks is present in the Voroux-Goreux complex. This could be expected in an 8 km long subcrop section, with magmatic rocks only observed in parts of it.

Level 2b is a three cm thick tuff of the same age (*Monograptus convolutus* zone, Aeronian, Llandovery) in the Kortrijk/St-Antonius borehole at -258,50 m (LEGRAND, 1981; VAN GROOTEL, ms 1990), 150 km away from Voroux-Goreux.

Level 3 is the "porphyroid" and "eurite" of Pitet (DUMONT, 1848), the rhyolitic complex of Pitet (ANDRE, ms 1983a, 1983b) or the volcano-sedimentary layer of Pitet (VERNIERS, 1983). It is dated by Chitinozoa as uppermost Llandovery or possibly lowest Wenlock (VERNIERS, 1982). It extends into the Burdinale Valley (VERNIERS, 1983) and possibly towards the east into the western part of the Voroux-Goreux complex (CORIN, 1935a, b, 1965), and to the west in Noville-les-Bois, Cortil-Wodon and Leuze (CORIN, 1965), in the volcanoclastic rock in the Orneau Valley at Km 2.785 (cf. fig. 4 of MORTELMANS, 1954; own data) and in the Nivelles

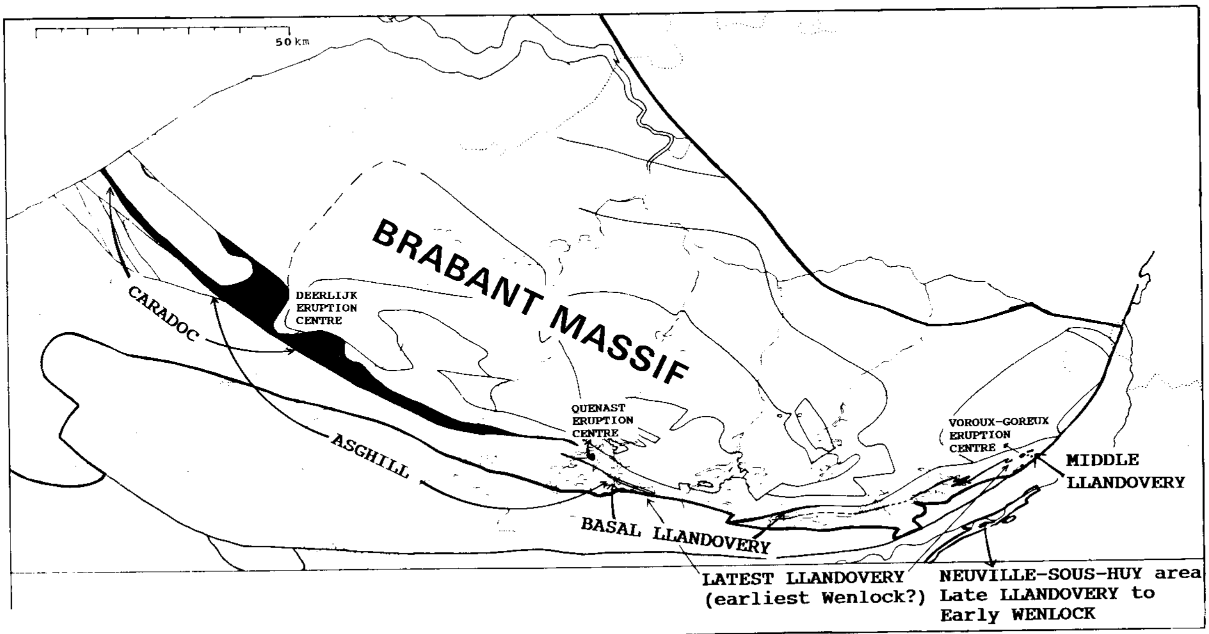


Figure 9 Map with the location of magmatic rocks in the Brabant Massif, the supposed eruption centres and its eastward younging shift.

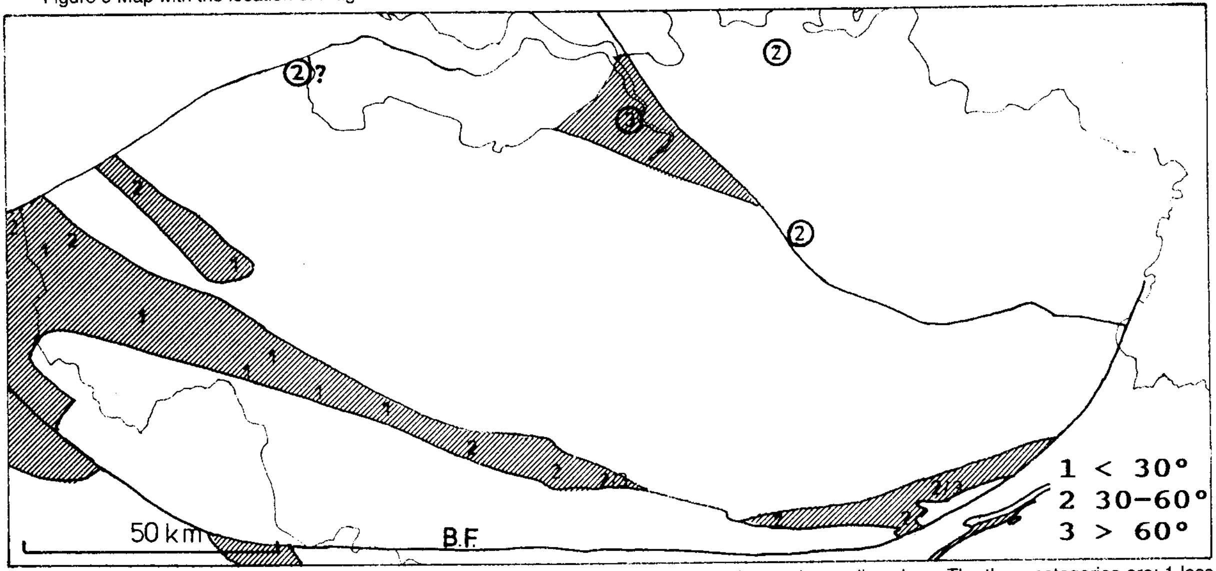


Figure 10 Map with intensity of folding of Silurian strata in the Brabant Massif as measured by maximum dip values. The three categories are: 1 less than 30°, 2: between 30 and 60° and 3 more than 60°. B.F.= Border fault. The pre-Devonian (subsurface) outcrop of the Silurian is marked by westward dipping shading. The question mark at the Knokke borehole indicates its uncertain Silurian age.

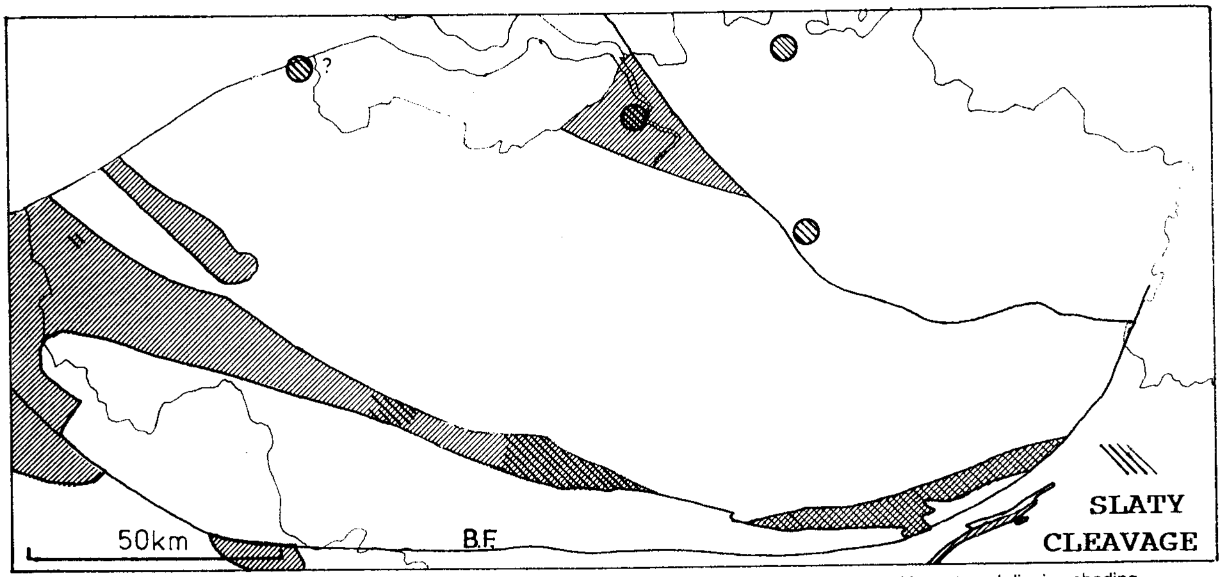


Figure 11 Map with the presence of slaty cleavage in Silurian rocks of the Brabant Massif, marked with eastward dipping shading.

area in the "porphyroid of Monstreux" (DUMONT, 1854; de la VALLEE-POUSSIN & RENARD, 1876; own data).

Level 4 are the seven metabentonites found in laminated hemipelagites of the Ronquières Formation, at Ronquières, dated with graptolites and Chitinozoa as the *Neodiversograptus nilssoni* zone, Gorstian (Ludlow). The very fine grain size suggest a remote source (MALAISE, 1879, arch. GSB; LEGRAND, 1967a; CORIN, 1962, 1964, 1965; VAN DEN HAUTE, pers. comm. 1985).

The undated gabbro of Hozémont is the only intrusive in the Brabant Massif of a tholeiitic type (ANDRE, ms 1983a, 1983b). Its contact with the parent rock was not observed and the closest outcrops of Horion-Hozémont, 1 km away, are dated as Ordovician by Chitinozoa (own unpublished data). It is situated a few hundred meters from the limits of the Brabant Massif formed locally by the "Border Fault" (LEGRAND, 1968), probably an important structural boundary.

In the prolongation of the Brabant Massif between Liège and Visé three boreholes reach magmatic rocks under the Namur Synclinorium. The undated Hermalle-sous-Argenteau borehole has subvertical cineritic tuffs and rhyolites from 338.3 to 353.0 m unconformably below Givetian strata (VANDENVEN *in* GRAULICH *et al.* 1975). Two Visé boreholes reached more than 100 m of gently dipping metarhyolites, unconformably under Middle Devonian strata (GOEMAERE & VANDENVEN, 1989). All three occurrences are as yet undated and tentatively linked with the eruptive centre of Voroux-Goreux and postulated to be early Silurian.

3.8 STUDIES ON STRUCTURE, METAMORPHISM AND TECTONICS.

3.8.1 STRUCTURE & METAMORPHISM.

The Silurian of the Brabant Massif was transformed everywhere to a grade more or less of a "very low metamorphism". Tectonic and metamorphic studies, however, are limited to the occasional mention of strike and dip of stratification, presence of slaty cleavage, folds and faults, measurements of the reflectance of organic matter and of metamorphic mineral such as monazite.

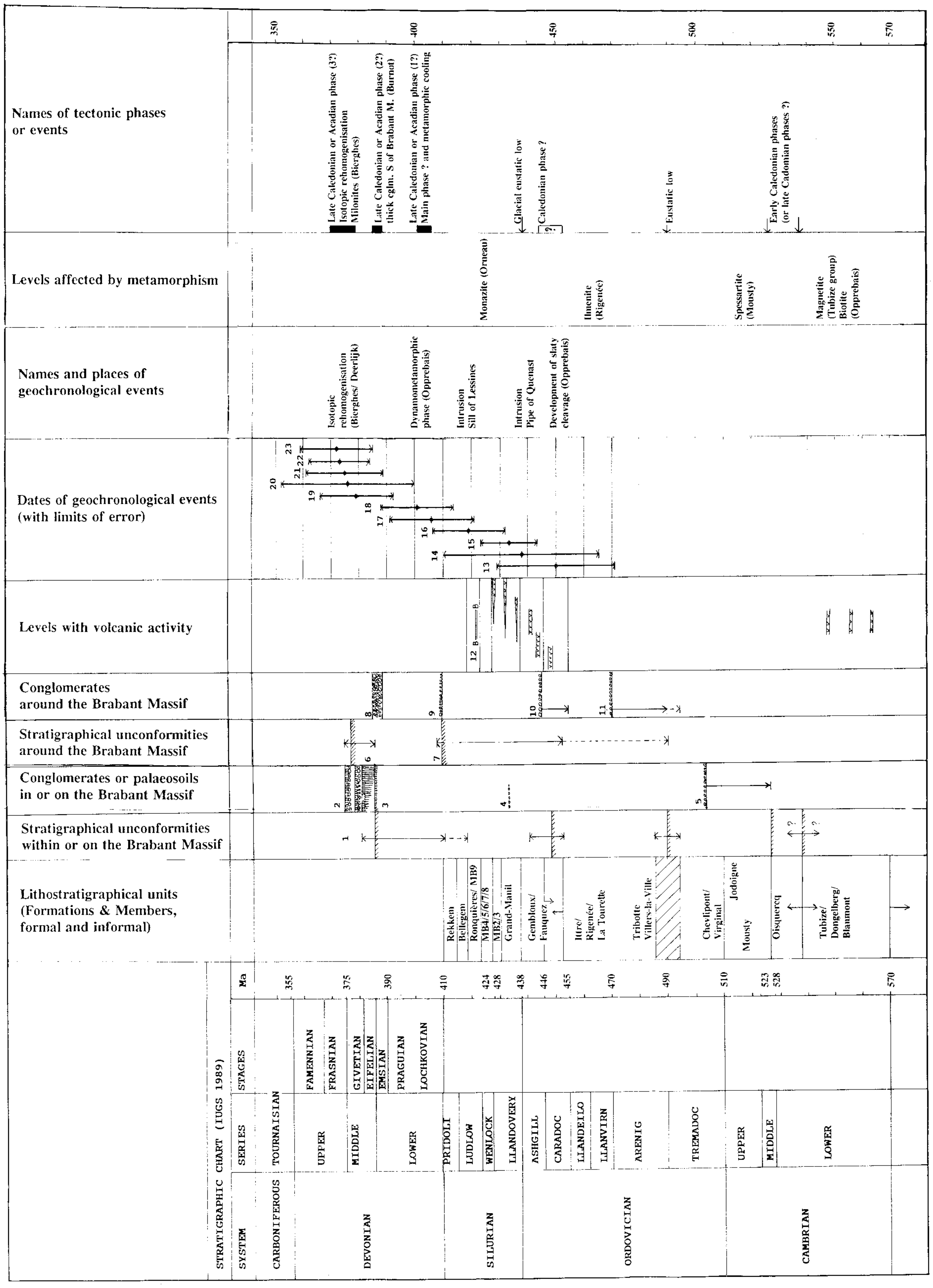
A slaty cleavage is present in the Silurian in the eastern and central part of the Brabant Massif from Hozémont to the Senne Valley. It is absent in the Dender Valley (boreholes studied by HANCE, pers. comm. 1990) and present further west in the boreholes of Ronse (LEGRAND, 1967b, 1968). It is of an axial plane type in the Mehaigne area (VANDENVEN, 1967; VERNIERS, 1983) and of a fan type in the Orneau Valley (MORTELMANS, 1954) and in the Sennette Valley at Ronquières (LEGRAND, 1967a). No slaty cleavage is observed west of the Schelde river except in the upper part (!) of the Steenkerke borehole near Veurne (LEGRAND, 1968). Nor is it present in the Silurian on the central axis of the Brabant Massif between Roeselare, Oostende and Nieuwpoort. In the north of the Brabant Massif, however, the four boreholes with possible Silurian (Knokke, Kallo, Loenhout, and Booischot) all show a slaty cleavage (fig. 10).

The degree of folding, summarized from the literature and the archives of the Geological Survey, and put into three classes (<30°, 30°-60°, >60°) shows a stronger deformation in the central, eastern and northern part, and a lesser deformation in the western part (west of the Dender Valley) (fig. 10). The direction of the strike in the more deformed area, which coincides with the outcrop area, changes from WNW-ESE in the Senne and Sennette valleys through E-W in the Orneau Valley to WSW-ENE in the Mehaigne area.

Until now no crystallinity indices on illite on the Brabant Massif have been published, however, occasional data on the reflectance of the organic matter are known. For instance two samples from the Mehaigne area give a mean reflectance on Chitinozoa and other organic matter alike of 4.0% (limits 2.5-7%). Two samples from the bridge section in Ronquières show a main reflectance of respectively 4.5 and 4.7% (limits 3-8.3%) (SOMERS pers. comm. *in* VERNIERS, 1982 and *in* LOUWYE *et al.*, in prep.). SOMERS (pers. comm. *in* HANCE *et al.*, 1991) and ALLEMAN (ms 1989) also mention measurements of the same order in the Brabant Massif. This data comes from areas where a slaty cleavage is present and show a meta-anthracite maturation stage, corresponding to the deep anchizonal metamorphism.

NONNON (1989) established the presence of metamorphic porphyroblasts of monazite in heavy mineral concentrates from river gravels. In the river gravels of the Brabant Massif it appears to be restricted to areas with Ordovician-Silurian outcrops. This mineral was also demonstrated in thin sections from upper Wenlock slates of the Orneau Valley at Les Mautiènes.

The following metamorphic indicators have been described in pre-Silurian rocks (fig. 12). Magnetite and biotite are abundantly present in the thick and extensive "Assise" of Tubize. ZIMMERLE & OTTEMANN (1971) found in quartzites from this group three metamorphic recrystallisation phases: (1) a pre-slaty cleavage phase with the development of poeciloblastic porphyroblasts of biotite, (2) a second phase with slaty cleavage development and (3) a recrystallisation of biotite rearranging itself along the crenulation cleavage. Ilmenite is described in the Rigeneé Formation and in "Assise" of Mousty and spessartite in the Mg-rich layers of the top part of the "Assise" of Mousty (ROBASZYNSKI & DUPUIS, 1983).


Names of tectonic phases or events
Late Caledonian or Acadian phase (3?)
Isotopic rehomogenisation
Mylonites (Bierghes)
Late Caledonian or Acadian phase (2?)
thick cglm. S of Brabant M. (Burnot)
Late Caledonian or Acadian phase (1?)
Main phase ? and metamorphic cooling
Glacial eustatic low
Caledonian phase ?
Eustatic low
Early Caledonian phases
(or late Cadomian phases ?)
Levels affected by metamorphism
Monazite (Orneau)
Ilmenite (Rigenée)
Spessartite (Mousty)
Magnetite (Tubize group)
Biotite (Opprebais)
Names and places of geochronological events
Isotopic rehomogenisation (Bierghes/ Deerlijk)
Dynamometamorphic phase (Opprebais)
Intrusion Sill of Lessines
Intrusion Pipe of Quenast
Development of slaty cleavage (Opprebais)
Dates of geochronological events (with limits of error)
23
22
21
20
19
18
17
16
15
14
13
Levels with volcanic activity
12
B
Conglomerates around the Brabant Massif
8
9
10
11
Stratigraphical unconformities around the Brabant Massif
6
7
Conglomerates or palaeosoils in or on the Brabant Massif
2
3
4
5
Stratigraphical unconformities within or on the Brabant Massif
1
?
Lithostratigraphical units (Formations & Members, formal and informal)
Rekkem
Bellegem
Ronquières/ MB9
MB4/5/6/7/8
MB2/3
Grand-Manil
Gembloux/ Fauquez
Ittre/ Rigenée/ La Tourelle
Tribotte Villers-la-Ville
Chevlipont/ Virginal
Jodoigne
Mousty
Oisquercq
Tubize/ Dongelberg/ Blanmont
350
400
450
500
550
570
STRATIGRAPHIC CHART (IUGS 1989)
Ma
355
375
390
410
424
428
438
446
455
470
490
510
523
528
570
STAGES
FAMENNIAN
FRASNIAN
GIVETIAN
EIFELIAN
EMSIAN
PRAGUIAN
LOCHKOVIAN
SERIES
TOURNAISIAN
UPPER
MIDDLE
LOWER
PRIDOLI
LUDLOW
WENLOCK
LLANDOVERY
ASHGILL
CARADOC
LLANDEILO
LLANVIRN
ARENIG
TREMADOC
UPPER
MIDDLE
LOWER
SYSTEM
CARBONIFEROUS
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN

Mylonites were described by de la VALLEE-POUSSIN & RENARD (1876 & 1885) and by CORIN & RONCHESNE (1936). ANDRE & DEUTSCH (1985) studied very low-grade metamorphic Sr isotopic resettings of mylonites and other foliated rocks in Bierghes, Harelbeke and Deerlijk. They hypothesized a shear zone extending from Oudenaarde to Bierghes and a contemporaneous deformation around Deerlijk near Kortrijk. They concluded a compressive phase with strike-slip faults in the late Givetian (375 Ma), a very late Caledonian or late Acadian manifestation.

3.8.2 HYPOTHESES ON THE TECTONIC EVOLUTION

Even if structural data available was insufficient and the stratigraphy was only poorly known, many far reaching hypotheses were proposed on the evolution of the sedimentary basin and tectonics, eventually being overtaken by new information. Emphasis in this review is not put on the errors due to overinterpretation but on new ideas, especially those still considered to have some validity.

FOURMARIER improved in his work (presented in 1912 but only published in 1921) the ideas of DUMONT (1848) about the tectonics of the Brabant Massif. He kept the general idea of a large anticlinal fold with a Cambrian core, but postulated the presence of large (Caledonian) overthrusts of this Cambrian core southwards over the Ordovician and Silurian rims. He gave the first detailed description of the folds and faults in each of the valleys of the outcrop area of the Brabant Massif. Since he also observed secondary folds he argued that DUMONT's concept of "southwards younging beds" did not apply in detail. He produced a detailed geological map (1/160.000) of the outcrop area with structural data such as fold axes and faults. KAISIN (1936) did the same for all Lower Palaeozoic massifs in Belgium.

MORTELMANS (1954) described in detail the structures of the Silurian outcrops in the Orneau Valley and saw remnants of the Caledonian as well as the Hercynian orogeny. In 1955 he postulated the structure of the Brabant Massif as a segment of the Caledonian Orogen, built up of a succession of four units or "tectonic massifs", separated from one another by large overthrusts comparable in extent and displacement to the Midi Overthrust. LEGRAND (1961) tried to show with examples from the Brabant Massif that epeirogenetic movements could be sufficient to cause orogeneses with folds and overthrusts.

Mainly based on his own data on the Cambrian massifs in the Ardennes, BEUGNIES (1963, 1964) was the first to propose a hypothetical evolution of the sedimentary basin and tectonic evolution of the Caledonian and Hercynian in Belgium. Some of his observations on the Brabant Massif are at variance with our own observations (e.g. in Ronquières, where he sees south directed tectonic forces, while we observed the opposite).

LEGRAND (1967a) observed sections in the enlarged Brussels-Charleroi canal, especially around Ronquières, and published detailed profiles not only of the inclined shiplift but also from other sections along the canal. Like MORTELMANS (1954) in the Silurian of the Orneau Valley, LEGRAND observed in the Sennette Valley two folding phases separated by a slaty cleavage phase. Since these folds are cut off by

Figure 12 Stratigraphic position of events from Cambrian to Devonian in the Brabant Massif, derived from stratigraphy as unconformities, conglomerates, palaeosoils and levels with volcanic activity in or around the Brabant Massif, from geochronological data, and levels affected by metamorphism, calibrated against the general lithostratigraphy in the Massif and against the absolute time-scale by the IUGS (COWIE & BASSETT, 1989). 1: stratigraphical unconformities within the Massif according to LEGRAND (1968). 2, 3: Ronquières, LEGRAND (1967a). 4: Kortrijk-St.-Antonius LEGRAND (1981). 5: Lessines (DEJONGHE *et al.*, 1989, HERBOSCH *et al.*, 1991). 6. Bolland: stratigraphic gap from late Emsian till Frasnian (MICHOT, 1979; VANGUESTAINE, *et al.*, 1989). 7: Bolland (MICHOT, 1979; VANGUESTAINE, *et al.*, 1989) stratigraphic gap from in the Lochkovian till Llandeilo, Llanvirn or Arenig. 8: Burnot Formation (see BULTYNCK *et al.*, 1991). 9, 10: basal conglomerates in the Bolland borehole, MICHOT (1979). 11: conglomerate in the Wépion borehole (GRAULICH, 1961). 12: B = metabentonites in Ronquières (LOUWYE *et al.*, in prep.). 13: 450 +/-21 Ma (Rb-Sr date on whole rock in the "Assise" of Tubize at Opprebais; J. MICHOT, 1976; ANDRE, DEUTSCH & MICHOT, 1981); 14: 438 +/-28 Ma (Rb-Sr date on whole rock in the porphyry of Quenast; ANDRE, ms 1983a; ANDRE & DEUTSCH, 1985; cf. 439 +/-53 Ma in ANDRE, ms 1983a); 15: 433 +/-10 Ma (U-Pb on zircons in the porphyry of Quenast; ANDRE, ms 1983a; ANDRE & DEUTSCH, 1984, 1985); 16: 419 +/-13 Ma (Rb-Sr date on whole rock for emplacement of sill of Lessines, mean of 423 +/-33 and 414 +/-16 Ma; ANDRE, ms 1983a; ANDRE & DEUTSCH, 1984, 1985); 17: 406 +/-15 Ma (Rb-Sr date on whole rock in a meta-andesite breccia of Izegem: probable age of emplacement, ANDRE, ms 1983a; 404 +/-19 Ma in ANDRE, DEUTSCH & MICHOT, 1981); 18: 401 +/-13 Ma (Rb-Sr date on biotite in the "Assise" of Tubize at Opprebais, MICHOT, FRANSSEN & LEDENT, 1973; ANDRE ms 1983a; ANDRE & DEUTSCH, 1984; 1985); interpreted as a metamorphic event, ANDRE, DEUTSCH & MICHOT, 1981); 19: 379 +/- 13 Ma (Rb-Sr date on whole rock of an ignimbrite from Harelbeke-Deerlijk, ANDRE & DEUTSCH, 1985); previously dated 384 +/- 20 Ma (ANDRE, DEUTSCH & MICHOT, 1981; ANDRE & DEUTSCH, 1984), 387 +/- 20 Ma (ANDRE 1983b) and 377 +/- 13 Ma (ANDRE, ms 1983a); 20: 376 +/-24 Ma (Rb-Sr date on whole rock on the meta-andesite breccia of Izegem, ANDRE, DEUTSCH & MICHOT, 1981); 21: 375 +/- 14 Ma (Rb-Sr date on whole rock in a first sample of the porphyry of Quenast, ANDRE & DEUTSCH 1985); 22: 373 +/-11 Ma (Rb-Sr date on whole rock on a mylonite in the porphyry of Bierghes, ANDRE & DEUTSCH, 1985); 23: 372 +/- 13 Ma (Rb-Sr date on whole rock in a second sample of the porphyry of Quenast, ANDRE & DEUTSCH, 1985).

flat-lying Middle Devonian, he concluded that all tectonic movements were pre-Mid-Devonian and that no Hercynian movements are present in Ronquières. He hypothesized southwards directed movements of nappes via thrust faults (Fauqué fault and the Asquempont fault = Orne fault of BEUGNIES, 1963, 1964) in the interval between the Ludlow and the Middle Devonian.

VANDENVEN (1967) studied the slaty cleavage and kinkbands in the Mehaigne area and the Orneau Valley (eastern outcrop area) and deduced, in that part of the Brabant Massif, the presence of a Variscan reworking of the Caledonian folding and slaty cleavage.

LEGRAND (1968) in his major study on the subsurface of the Brabant Massif postulated the presence of more unconformities than the one widely recognized between Ludlow and Middle Devonian. The dips measured in the boreholes showed a clustering of data around six groups:

(1) "Assise" of Tubize and "Assise" of Dongelberg (Lower Cambrian or earlier);
(2) "Assise" of Oisquercq (Lower Cambrian);
(3) "Assise" of Jodoigne and "Assise" of Mousty (Middle or Upper Cambrian) and the Tremadoc "Assises";
(4) the rest of the lower to middle Ordovician beds;
(5) Ashgill and Silurian beds;
(6) Devonian-Carboniferous.

He concluded that not one but five successive Caledonian phases were active. These angular unconformities are shown on his geological map: e.g. the Ashgill-Silurian beds of the Eastern Silurian outcrop area lie obliquely over the central axis of the Brabant Massif. Consequently he emphasised the tectonic evolution of the Brabant Massif as the result for each unconformity of an alternated stress field, either NNE-SSW compression and ESE-WNW extension or the reverse.

He was the first to map the thickness of the red weathering on the axial part of the Brabant Massif, north of the pre-Silurian fault zone, reaching a thickness of up to 76 m. He argues that the age of peneplanation, kaolinization and reddening is between Westphalian and Albian and by elimination he puts it in the Triassic.

Several faults or fault zones were observed and tentatively dated:

(1) the faulted (tectonized) zone in the Cambrian of the "Haute Gette";
(2) the ante-Silurian fault zone of Diksmuide-Bierghes ("bande failleuse antésilurienne"), a nearly straight fault breccia zone at the southern limit of the Cambrian rocks, seemingly a tangential rift fault with a northern uplift, also limiting the deep red-weathered zone of the Brabant Massif, and later still active during the Cretaceous and early Tertiary;
(3) the border fault ("faille Bordière") running from Bon-Secours (Péruwelz), over Champion (north of Namur) to Maastricht, of a Variscan age with reactivation in the Cretaceous and Tertiary.

MICHOT (1979) observed in the Bolland borehole (situated some 15 km east of the Brabant Massif) Lower Devonian sediments unconformably covering a Cambro-Silurian unit, the former unconformably covered by Frasnian strata. Hence he concluded the presence of two plastic deformation phases. The first one, before deposition of the Lower Devonian in the Bolland borehole, was called the Condruso-Brabantian phase (MICHOT, 1976, 1980), of an early Lochkovian age, which according to him induced the slaty cleavage in the Brabantian domain. A second plastic deformation, called the Bollandian phase, at the end of the early Emsian, produced secondary folds in the Silurian of the southern edge of the Brabant Massif and in the Sambre and Meuse Belt, which he designates the Bollandian ridge. After reinterpreting the Wépion borehole he hypothesizes a thrust fault, the Mosane Fault, also resulting from this Bollandian phase, separating the Brabantian tectofacies with a slaty cleavage, from the Condrusian tectofacies without a slaty cleavage.

Later the Cambro-Silurian of the Bolland borehole was dated as Arenig to Llandeilo (early to middle Ordovician), (VANGUESTAINE, SERVAIS, STEEMANS, unpublished data and 1989).

Apatite fission-track studies of Upper Ordovician magmatic rocks from Fauqué and Bierghes proved that these rocks resided at temperatures exceeding 100° C till the middle Jurassic and only later started to cool down. This necessitates a considerable cover of 3000 m of sediments of middle Jurassic age and older. One has to accept the assumption of PATIJN (1963) that the Brabant Massif was covered by the Middle/Upper Devonian, and much of the Carboniferous, and maybe some Mesozoic to reach that thickness (VAN DEN HAUTE & VERCOUTERE, 1989, 1990).

3.9 PREVIOUS REVIEWS ON THE SILURIAN OF THE BRABANT MASSIF.

BEUGNIES (in WATERLOT, BEUGNIES & BINTZ, 1973) gives a short review, mainly of stratigraphy, but also of basin evolution and tectonics, based on the literature and his own field observations. WALTER (1980) reviews the literature, mainly the stratigraphy, and shows palaeofacies maps of Belgium and adjacent countries for different periods. MICHOT

(1980) gives an extensive synthesis and proposes a hypothesis for a regional scheme of the basinal evolution in the Palaeozoic, based on the literature and his own observations. ROBASZYNSKI & DUPUIS (1983), with many co-workers give a short review of the stratigraphy and basin evolution based on the work of MICHOT and BEUGNIES and of the geochemistry of the magmatic rocks based on ANDRE (ms 1983a).

4 INTERPRETATION.

4.1 EVOLUTION OF THE SEDIMENTARY BASIN DURING THE SILURIAN.

The sedimentary cycle of which the Silurian forms part had started already in Caradoc or Ashgill times, with non-turbiditic sediments with several shallow neritic intervals, e.g. the "grauwacke fossilifère of Grand-Manil" of a probably pre-Hirnantian Ashgill age (LESPERANCE & SHEEHAN, 1988; SHEEHAN, 1988). The remnants of the glacial eustatic low of the Hirnantian have not yet been recognized.

The composite section made from all parts of the southern rim of the Brabant Massif (fig. 3 and 4), allows a first impression of the sedimentology of the Silurian. Caution is needed, however, since many observation gaps are present throughout this composite section. Furthermore, contemporaneous sections at some distance from the reference section are either absent or as yet unstudied. But some appreciation of lateral facies and thickness variations can be made.

All observed Silurian sediments in the Brabant Massif are deep marine, with no shallow marine intervals present. Only at times of eustatic or regional sea-level lows (e.g. early and latest Wenlock) are some less deep conditions present, evidenced by fossils such as *Cardiola* sp., *Orthoceras* sp., *Conularia* sp., *Dayia* sp., etc.. Most sediments are turbidites, interstratified with laminated hemipelagites, some volcano-sedimentary input, and deep neritic sediments in the Rhuddanian and Aeronian.

These latter two stages and the lower part of the Telychian are present in several boreholes in southern Flanders but not observed elsewhere in the Brabant Massif. The sedimentation is rather slow, several tens of meters per graptolite zone, and consists of laminated hemipelagites, deep neritic sediments or thin-bedded turbidites. Very low energy turbidites are already present from the base of the Llandovery (MARTIN, 1971, 1974). Because of the lack of comparative sections, one can only guess whether the same facies and rate of sedimentation prevailed over the rest of the Brabant Massif.

The upper part of the Telychian and most of the Wenlock is observed in the Mehaigne area (eastern outcrop area). Sedimentation is clearly turbiditic with faster sedimentation rates, in the order of several hundreds of meters per graptolite zone. Sedimentation rates are especially high at two periods: during the latest Telychian and during the *C. flexilis*, *C. ellesae* and *C. lundgreni* zones (mid- to late Wenlock). In this latter period laterally very continuous turbidites were deposited, constituting the MB7 formation. Two sections in the Mehaigne area, 2.3 km apart, showed a completely similar 50 m thick succession of turbidites with differences in bed thicknesses of less than 5%.

Within the eastern outcrop area, although not studied yet in detail, the facies and thickness seem rather similar according to our field observations in the Orneau Valley and the Mehaigne area. If one can believe MALAISE (1911) the sedimentology of parts of the Mehaigne area is also similar to the Voroux-Goreux area. On the other hand some differences are apparent between the uppermost Llandovery and Wenlock turbidites of the western outcrop area (Senne & Sennette valleys and Nivelles area) in comparison with the eastern outcrop area.

The lower Ludlow section is only well exposed in the western outcrop area at Ronquières. Sedimentation is still turbiditic but detailed logging (LOUWYE *et al.*, in prep.) shows that the sedimentation can vary laterally over a few hundreds of meters, mainly by downcutting of palaeoflow (S-N). The two very small outcrops with turbidites of similar age in the eastern outcrop area in the Mehaigne area do not allow a detailed comparison.

Short sections in turbidites of the upper Ludlow and Prídolí, encountered in several dispersed boreholes, do not allow a facies comparison either.

Several megacyclical variations are observed (fig. 7). They are present in most of the Llandovery but largely unstudied. Two main shallower water periods are distinguished in the Wenlock, by the higher energy of the turbidites and the appearance of rare macrofossils or the presence of specific Chitinozoa taxa indicating less deep conditions. They alternate with deeper conditions in latest Llandovery and late Sheinwoodian to early Homerian. A deepening-shallowing cycle occurs starting possibly in the latest Wenlock and mostly in the Gorstian. Contemporaneous cycles are also observed in Wales and the Welsh Borderland and in the Baltic sea. Since these fluctuations are restricted to the Eastern Avalonia and Baltica (micro)continents they may not be a response to eustatism. Smaller-scale cyclicities occur in the sedimentology and micropalaeontology, but are as yet unexplained.

The form of the sedimentary basin is still a matter of speculation, because of the small number of detailed sedimentological studies in outcrops or boreholes. In the outcrop area a roughly E-W, quickly subsiding basin could be present, trapping the uppermost Llandovery to lower Ludlow turbidites. This is suggested by the present day outcrop pattern and the roughly E-W directions of the folds. On the other hand, all measured directions of the turbidity currents point northwards. One would have to postulate an unusual model of an E-W trough with many northwards directed turbidite sources and aprons all along its southern edge and not one single turbidite current diverging into the direction of the main trough, as is the case in most turbidite troughs (BOUMA *et al.*, 1985). Alternatively the measured palaeoflow directions, being mainly from ripple cross-lamination, could be at right angles to the main flow that would be indicated by flutes and grooves. Reexamination of all outcrop areas in detail might solve this controversy.

The Silurian occurring north of the Cambrian axis of the Brabant Massif is largely unknown since it is only reached in three boreholes and possibly in a fourth (Knokke). Kallo and Loenhout contain turbidites with intercalated laminated hemipelagites but more stratigraphical and sedimentological study is needed.

The sedimentation of the Silurian in the Sambre and Meuse Belt is considered deep neritic, as in the Brabant Massif. It differs from this latter by its sedimentology which often has graptolitic shales, an apparent lack of turbidites and by much smaller thicknesses of its stratigraphical units. It is tectonically defined by the absence of slaty cleavage (MICHOT, 1954b, 1979; MAES *et al.*, 1979). Renewed detailed sedimentology and biostratigraphy is needed to compare accurately the Silurian from these two structural units.

The presence of Prídolí sediments within the Brabant Massif, supposed by VANGUESTAINE (1979), was proven recently with Chitinozoa in the Rekkem borehole in the southern Flanders subsurface (VAN GROOTEL & VERNIERS, 1989; VAN GROOTEL, ms 1990). They seem to be in stratigraphic continuity with the other Silurian sediments.

One should mention here another occurrence of Prídolí sediments in the Liévin anticline, in northern France, some 30 km south of the Brabant Massif. This is remarkable since the Prídolí here occurs in stratigraphic continuity with the Lower Devonian strata and yet no evidence of the late Caledonian unconformity has been found. It lies just south of an important structural line, the Border Fault.

Nowhere is the Brabant Massif covered by Lower Devonian rocks. They occur however 5 to 30 km southwards, following the southern margin of the Brabant Massif, in the Dinant Synclinorium. There the Lower Devonian sedimentation starts slightly above the Silurian-Devonian boundary, in the spores biozone M in the middle of the lower Lochkovian (STEEMANS, 1989). The hypothesis of LERICHE (1911) that the Gedinnian started in the Prídolí has long been abandoned and was possibly the result of erroneous identifications of fossils (GODEFROID, 1982).

The Brabant Massif itself is covered, above a marked unconformity, by Middle Devonian strata in the south and north and by Upper Devonian strata on its eastern tip from the Mehaigne Valley to Visé (see fig. 5 in MICHOT, 1976).

4.2 TECTONIC EVOLUTION OF THE BRABANT MASSIF FROM CAMBRIAN TO DEVONIAN.

Because little structural geology had been published on the Brabant Massif we can only tentatively deduce the tectonic evolution from other evidence, such as stratigraphical unconformities observed in situ or on map or deduced from dips in boreholes (LEGRAND, 1968), conglomeratic layers and palaeosoils in or around the massif, periods of magmatic activity, the isotopic ages of metamorphic events, emplacement of intrusives or isotopic rehomogenisation and the presence of metamorphic minerals (fig. 12). The degree of folding and the slaty cleavage front in the Silurian are another source of data (fig. 10, 11).

What happens below the Tubize unit of the Lower Cambrian in the Brabant Massif can only be assessed indirectly (see ANDRE, 1991). Above this unit, however, an angular unconformity is observed in the dips between the Tubize and the Oisquercq units and between this latter and the Mousty unit (LEGRAND, 1968). This unconformity is also apparent cartographically on his map. Two metamorphic minerals are observed in the Tubize unit, magnetite and biotite. The conglomerate in the Lessines borehole capping a Mid- and Late Cambrian hiatus (HERBOSCH *et al.*, 1991) could also be related with these events. Possibly these two unconformities are the reflection of two successive tectonic events of an early Caledonian or maybe late Cadomian age. The direction of the fold axes is NW-SE in the outcrop areas. The same direction is observed on the aeromagnetic map (CGG, 1963) above the outcrop or suboutcrop of this unit.

Superficial resemblances exist in lithology, sedimentology and thickness between the Longmyndian Supergroup in the Welsh Borderland (UK), tectonized by the Cadomian orogeny, and the Tubize and Oisquercq units in the Brabant Massif. Recent acritarch studies in both areas however do not confirm or contradict this analogy. Samples in the lowermost formation of the Longmyndian were dated by acritarchs as Vendian, latest Precambrian (DORNING, 1985), while the top of the Oisquercq unit is dated in the Lessines borehole, close to the Early/Middle Cambrian transition (DEJONGHE *et al.*, 1989; HERBOSCH *et al.*, 1991; VANGUESTAINE, 1991).

Another cartographic unconformity observed by LEGRAND (1968) is probably the result of the eustatic low at the Tremadoc/Arenig boundary. A lacuna in sedimentation, with a basal conglomerate above, was observed in the Wépion borehole (GRAULICH, 1961) and proven with acritarchs in the Thyle Valley by MARTIN (1976).

An angular unconformity is also present in the late Ordovician and clearly shown on the geological map of LEGRAND (1968). A geochronological date on the Tubize group in Opprebais (Rb-Sr whole rock date) of 450 +-21 Ma (J. MICHOT, 1976), was later reinterpreted as the time of the flow cleavage formation (ANDRE *et al.*, 1981) and could possibly be put at the same event. Magmatic activity is at its peak in the late Ordovician, before and after the unconformity. In the Sennette Valley Ordovician to lower Caradoc rocks are strongly folded, whereas the Ashgill and Llandovery strata are only gently dipping (LEGRAND, 1967a; MARTIN & RICKARDS, 1979; SERVAIS, 1989, 1991). Unfortunately the contact between the two has not been observed. Middle Ordovician to lower Caradoc (?) turbidites have been observed in the Sennette Valley (SERVAIS, ibid.) and in the Orneau Valley (own unpublished data). These are the still meagre indications of a late Ordovician Caledonian tectonic phase in the Brabant Massif. The direction of the late Ordovician volcanic belt is NNW-SSE. Possibly linked to this phase are the metamorphic minerals ilmenite and spessartite. The conglomerate of Cocriamont of pre-Hirnantian, Ashgill age (LESPERANCE & SHEEHAN, 1988) in the Sambre and Meuse Belt was seen as the evidence of the Caledonian phase in the Ardenne massifs (MICHOT, 1931), but could also have been the result of a tectonic event in the Brabant Massif or in both the latter and the Ardenne Massifs.

There is evidence for two or three late Caledonian phases or also called Acadian phases in the Brabant Massif, in the Lochkovian, the middle and late Emsian and the late Givetian.

The major unconformity in the Brabant Massif observed in many places is situated between the Prídolí and the Eifelian?-Givetian. There are two indications for a first phase. The presence of reworked Cambrian to Silurian and earliest Lochkovian acritarchs in the basal Lower Devonian of the Dinant Synclinorium proves that sedimentation continued in the Brabant Massif until the most basal Devonian (spore biozones Nb, middle of lower Lochkovian, STEEMANS, 1989). Sedimentation started in the Dinant Synclinorium from spore biozone M (lower Lochkovian, STEEMANS, *ibid.*) and marks the start of the erosion in the Brabant Massif. Secondly, the isotopic age of the main dynamometamorphic phase is 401 Ma (MICHOT, FRANSSEN & LEDENT, 1973). This date is situated early in the Early Devonian according to recent timescales (COWIE & BASSETT, 1989), and would correspond to the first Acadian phase. This phase is called the Condrusian-Brabantian phase by MICHOT (1979).

The presence of the extensive Conglomerates of Burnot (middle Emsian to earliest Eifelian, BULTYNCK *et al.*, 1991) in the northern flank of the Dinant Synclinorium indicates a period of erosion and is interpreted as an upheaval of the massif at the end of the main phase. This would be the result of a second Acadian phase and would correspond to the Bollandian phase of MICHOT (1979).

The presence of Lochkovian sediments, however, on folded rocks of the lower to middle Ordovician in the Bolland borehole (MICHOT, *ibid.*; VANGUESTAINE, SERVAIS & STEEMANS, 1989) was considered to indicates the Bollandian phase (MICHOT, 1979). But, because this borehole is situated outside the Brabant Massif in its prolongation, it may not necessarily date events in the Brabant Massif itself. Strictly, this unconformity could represent any phase between the late Ordovician and the Lochkovian. The second unconformity in that borehole, however, covers a hiatus of possibly the latest Early Devonian and the whole Middle Devonian and could be the reflection of the late Caledonian or Acadian phases 2 or 3 (see below).

The intensity of folding and slaty cleavage diminishes westwards from the outcrop area and culminates in the south-eastern end of the Brabant Massif, close to the "Border Fault" (fig. 10 and 11). The trend of the fold axes from this phase is crescent shaped and going east it changes from WNW-ESE through E-W to ENE-WSW, reflected also by the outcrops of Silurian volcanic rocks.

The third late Caledonian or Acadian phase of the late Givetian is evidenced mainly by the consistent data on an isotopic rehomogenisation at the latest Givetian or Givetian/ Frasnian boundary, observed in the mylonite of Bierghes and in the Deerlijk borehole at some distance from the shear zone. This shear stress phase is possibly reflected along the southern border of the Brabant Massif by the synsedimentary faults observed in the Givetian of Ronquières by LEGRAND (1967a) and by the late Givetian local regression (Bois de Bordeaux Formation, Mazy Member, LACROIX in BULTYNCK *et al.*, 1991).

The presence of kinkbands in the Eastern Outcrop area could be the reflection of possibly Acadian phase 2 or 3. However it could be a Variscan tectonic influence in the eastern part of the Brabant Massif (VANDENVEN, 1967).

The study on apatite fission-tracks in some magmatic rocks of the Brabant Massif by VAN DEN HAUTE & VERCOUTERE (1989, 1990) has another important consequence for the age of the deep red colouring, "rubéfaction", (up to 76 m) observed in the top of the Brabant Massif along its central axis. This weathering was mapped by LEGRAND (1968) and he proposed it had a Triassic age (see above), implying that all possible Upper Palaeozoic cover had been eroded away by then. The studies by VAN DEN HAUTE & VERCOUTERE (1989, 1990) exclude Permian and Triassic erosion and weathering. Hence the red colouring of the top of the Brabant Massif can be narrowed down to an interval post-Silurian and pre-Mid-/Late Devonian.

In the Orneau Valley the lowermost beds of the Devonian cover contain Givetian fossils (LACROIX, 1972). In Ronquières, however, LEGRAND (1967a) gives without fossil evidence an Eifelian age for the lowermost cover on top of the red coloured Silurian. However to us, an Eifelian age for the earliest cover of the Brabant Massif is not proven neither at Ronquières nor elsewhere. The rare fossils in Ronquières only indicate a Middle Devonian age and the stratigraphic succession is similar, with some facies change, to the Orneau Valley, where it is Givetian (BULTYNCK *et al.*, 1991).

Observations along its southern rim show Lower Palaeozoic rocks with their top red-coloured, covered by Middle Devonian. Where the Brabant Massif is covered by Upper Devonian no red weathering has been observed in the top of the massif.

The age of the red colouring of the Brabant Massif under the Middle Devonian is either Emsian (LEGRAND, 1967a, 1973) or Eifelian (see above). We propose the same age for the red colouring of the top of the Brabant Massif in other places, where it is not covered by Devonian. This implies a lot of erosion and peneplanation between the Lochkovian (the main deformation phase) and the Emsian-Eifelian, when peneplanation was reached with deep weathering. How this period of stability, necessary for the weathering, relates to the supposed middle and late Emsian upheaval producing the extensive Burnot Conglomerates will remain a question until the ages of respectively the "rubéfaction" and the Burnot Conglomerates are known more accurately.

The late Givetian shear stress phase (Late Caledonian or Acadian phase 3, see above) would then consequently postdates the red colouring. This might explain the restriction of the deep red colouring on the axial zone of the Brabant Massif to the north of the (Givetian) mylonite fault lineament.

4.3 SOME ELEMENTS ON PLATE TECTONIC EVOLUTION.

On most earlier global plate tectonic or palaeogeographical reconstructions of the Early Palaeozoic the Brabant Massif or the Ardenne massifs were not represented. On a smaller scale the connection of the Brabant Massif westwards towards the UK was only poorly known (see summary by WALTER, 1980). PHARAOH *et al.* (1987) review the different hypotheses of a northern or southern connection with, respectively, the Lake District or the Welsh Basin. Their renewed studies on boreholes of the concealed Caledonides of eastern England now suggest a direct connection of the Brabant Massif with this concealed and largely unknown Caledonian foldbelt. The relationship with other pre-Variscan microplates towards the east is discussed extensively by ERDTMANN (1991).

Recent studies on the Brabant Massif can add to the discussion on the plate tectonic evolution of the area. The closing of the ocean between the Eastern Avalonian microcontinent (of which the Midlands microcraton and the Brabant Massif formed a part) and the Baltica microcontinent in Late Ordovician times, is supposed to have happened along the Tornquist line and the Polish trough (see PICKERING *et al.* 1988; ERDTMANN, 1991). Part of the resulting deformation was probably taken up in the Anglo-Brabant Caledonides, since the observed fold directions in the Cambrian (NW-SE) and Ordovician (WNW-ESE) are parallel to the Tornquist line. However, the Acadian phases in the southern part of the Brabant Massif do not seem to follow the same trend. They are directed broadly E-W and cross the main axis of the Brabant Massif (fig. 1). The possibility should not be ruled out that the Late Caledonian or Acadian phases could connect, south of the Midlands microcraton with Pembrokeshire, where Llandovery volcanism was also active.

ANNEXE

List of boreholes discussed in the text, with their corresponding numbers in the archives of the Geological Survey of Belgium.

Bellegem 97E865; Bolland122W260; Booischot 59E146; Deerlijk-18 83E18; Deerlijk-401/2 83E401/2; Deerlijk-404 83E404; Hermalle-sous-Argenteau 122W258; Houtem 50E133; Kallo 27E148; Keiem 51E153; Knokke 11E138; Kortrijk-Lust 83W44; Kortrijk/St-Antonius 83W421; Langemark 66E70; Leffinge36E117; Lessines 113E1015; Lichtervelde 53W57; Loenhout 7E178; Meilegem 85W1; Moen 97E801; Rekkem 96E77; Schore 36E137; Steenkerke 50E134; Visé A and B 122W291 and 122W292.

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