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NEW SEDIMENTOLOGICAL AND PETROGRAPHICAL OBSERVATIONS ON THE DEVONIAN BURNOT FORMATION IN THE BELGIAN RHENOHERCYNIAN BASIN

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(4 figures, 2 plates)

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ABSTRACT. The sediments of the Emsian/Eifelian Burnot Formation are generally considered to be littoral deposits. New field observations at the stratotype sections at Profondeville confirm these ideas for a part of the deposits and indicate that they bear deltaic and other river mouth characteristics. In other parts of the outcrops the sediments were more likely fluviatile and this has of course some consequences with respect to their provenance.
The first results of a renewed microscopic study indicate (1) the presence of volcanic and thermometamorphic rock fragments in the conglomerates of the Burnot Formation, (2) that these conglomerates were the site of a post-depositional thermal event and that (3) part of the sand-sized grains of quartz and tourmaline that occur in the groundmass of the conglomerates crystallised in situ from mineralising fluids, after the deposition of the rocks. Because of its dual occurrence as crystals in the matrix and as the major constituent of the well-known tourmalinite pebbles, tourmaline is studied in more detail, revealing new evidence with respect to its origin.

KEYWORDS. Burnot Formation, conglomerates, sedimentology, tourmalinite, mineralisation.

1. Introduction

The Burnot Formation, previously known as a part of the northern facies of the Upper Emsian (*le faciès septentrional (de l'Emsien supérieur) ou de Burnot*, e.g., Asselberghs, 1946) is exposed along the northern and northeastern front of the Dinant Allochthon (Fig. 1). Because good guide fossils are lacking it has not been dated yet. Its age is assumed to be latest Emsian but its upper part may even be of early Eifelian age (Stainier, 1994). Lithologically, it consists of conglomerate beds, sometimes a few tens of metres thick, alternating with sandstones, compact siltstones and shales. The sediments are mostly red coloured, but green deposits occur too. The base of the Burnot Formation is distinguished from the underlying Wépion Formation by a several metres thick bed of conglomerates and coarse sandstones. The top of the formation is also composed of a thick conglomerate bed but it cannot always be marked clearly, especially in areas where the overlying Rivière Formation also starts with a conglomeratic sequence (Luc Hance, pers. comm.). Considering the depositional environment of the Burnot Formation, no detailed observations have been made hitherto. Based on the fieldwork of Asselberghs (1946) it is generally classified as littoral deposits.

Tourmalinite pebbles are striking and well-known constituents of the Burnot conglomerates, although the occurrence of these exotic clasts is not restricted to these deposits. They have been observed in conglomeratic rocks of at least eight different Lower and Middle Devonian formations (see Godefroid *et al.,* 1994 and Bultynck *et al.,* 1991 resp.) and their occurrence is known to be highly variable in space. Locally they may constitute up to ten (or more) percent of the rock volume. Because an important part of our paper deals with these tourmalinites, we thougt it is useful to first describe some general features of tourmalinitic rocks and to give a short account on their genesis.

Tourmalinisation is a process by which primary minerals are altered into tourmaline or by which tourmaline is introduced into a pre-existing rock. It can generate minor amounts of tourmaline but also transform a precursor rock into a rock containing up to 80 % of this mineral. When tourmaline constitutes 15 to 20 % or more of the rock volume, the rock may be called a tourmalinite (Slack, 1982). Taking into account the complex chemical composition and the many possible substitutions in the minerals of the tourmaline group (e.g. Hawthorne & Henry, 1999) it may be postulated that, besides Si, only B and Al are truly restrictive in the formation of tourmaline. However, many tourmalines contain significant amounts of Fe and/or Mg and hence it are mainly Al- and Fe, Mg-rich rocks that are transformed into tourmalinites with B being provided by a fluid phase. The process is very often metasomatic,

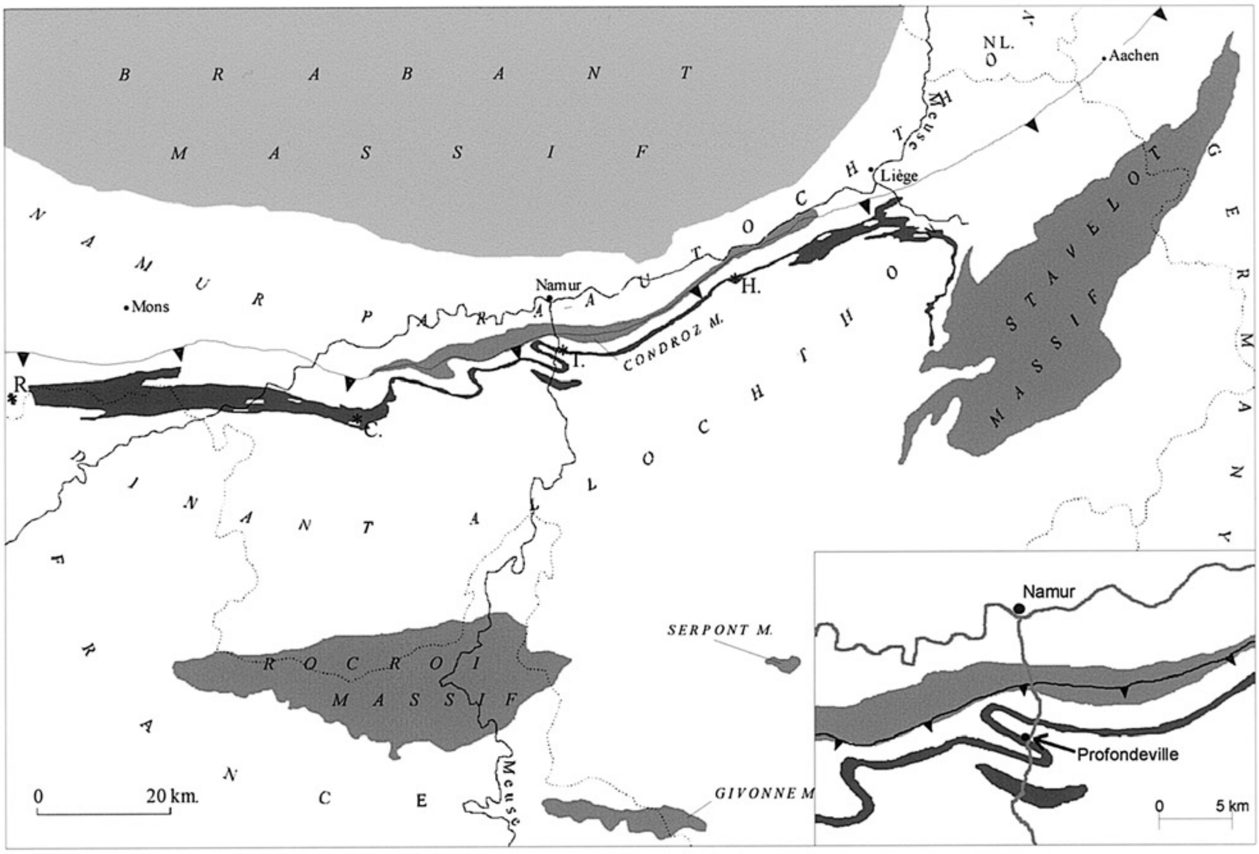

Figure 1. Map of southern Belgium with main tectonic units and outcrop area of the Burnot Formation (dark). 'Caledonides' in dark grey as outcrop, while the lighter-shaded Brabant massif is mainly covered by younger deposits. The thrust zone is the Variscan Front. Marked area in the middle of the map enlarged in inset. Studied localities: in inset: stratotype sections at Profondeville ; others (from West to East): R.: Roisin, T.: Tailfer, H.: Hoyoux valley. Sampling locality of photos B and C (plate 1): C. Cour-sur-Heure.

revealing its unaggressive nature in a way that the original texture is preserved.

Tourmalinisation occurs in different geological frameworks. The most commonly known tourmalinites are those found in contact aureoles around granites, as e.g. in Cornwall (London & Manning, 1995). However, most tourmalinites are formed in other circumstances and result from syngenetic-exhalative replacement processes at the seafloor (e.g., Slack, 1996). In the latter context, tourmalinisation is often accompanied by extensive ore mineralisation (e.g., Slack *et al.,* 2000). Tourmalinisation through boron-metasomatism can also take place under metamorphic conditions (e.g., Frietsch *et al.,* 1997), ranging from low to high grade (Henry & Dutrow, 1996). Finally, closed-system regional metamorphism may also generate tourmaline but only in minor amounts. The boron required for tourmaline formation is released from minerals becoming unstable under the changing conditions of temperature and pressure. In this case, tourmaline occurs either as small newly formed minerals (e.g. Henry & Dutrow, 1996) or as overgrowths on pre-existing detrital tourmaline grains (e.g. Henry & Dutrow, 2001).

Lohest (1885 and 1909) was one of the first investigators who described the Belgian tourmalinites and he noticed a striking variety in textural types. Besides tourmalinites, several Devonian arenitic rocks also appeared to contain individual tourmaline crystals as important accessory minerals and many speculations were made on the genesis and provenance of both these tourmalines and tourmalinites. Based on the fresh appearance of the tourmaline crystals in some arenitic rocks, Barrois (Société géologique de France, 1883) suggested a post-Devonian and post-depositional metasomatic origin related to a granitic intrusion. However, most other early investigators were in favour of a detrital origin and coupled the presence of the tourmaline crystals with that of the tourmalinite pebbles in the coarser deposits. The rounded shape of the tourmalinites apparently left them with little doubt about their detrital character (e.g., Macar 1948). However, the crystalline basement that should have supplied the clasts could never be located and it was supposed to reside somewhere beneath the rocks of the Dinant Allochthon.

Apart from the tourmalinitic clasts in the conglomeratic rocks, no true tourmalinite deposits were found. However, in a petrographic study of the metamorphic rocks of the Ardennes it became clear

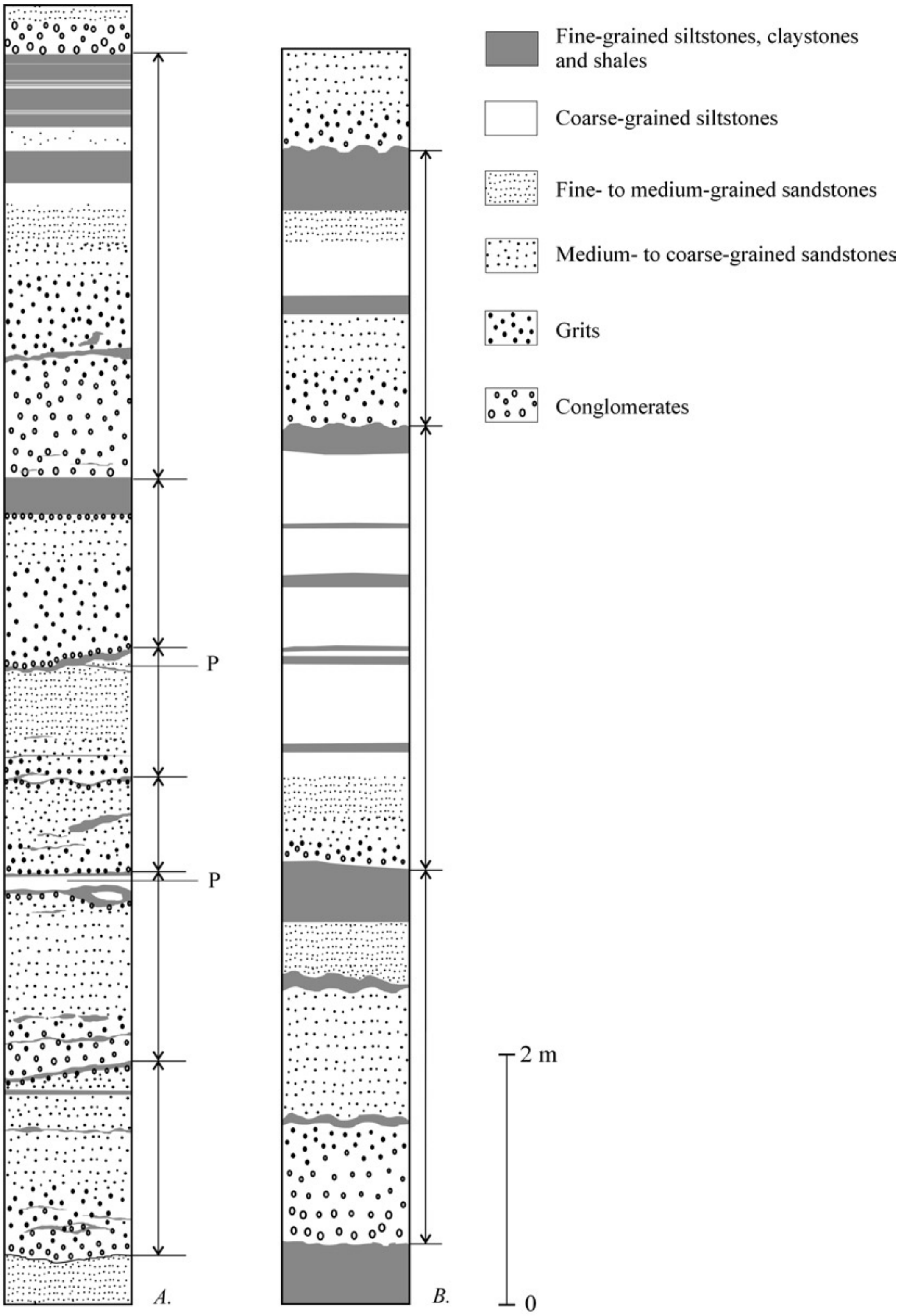

Figure 2. Lithological columns of repetitive sections occurring in the stratotype sections of the Burnot Formation at Profondeville, A (left) section representative for R1 type of deposits, B (right) section representative for R2 type of deposits. Individual cycles are indicated by double arrows to the right of each column. Note that each cycle overlies an erosional contact. In case these contacts are not clearly distinguishable by the different symbols used below and above them, they are indicated by a black undulating line. *'P'* refers to observations of plant fossils.

that tourmaline crystallised as disseminated crystals in hydrothermally altered metamorphic Lower-Devonian slates in association with ilmenite, biotite and zircon (Vandendriessche, 1941). Furthermore, it also formed in quartz-tourmaline veins, particularly along the southern border of the Stavelot massif, a region where tourmalinites are abundant. A review of the vein mineralisations is given by Corin (1965) who concluded that they are pneumatolitic in origin and related to a deep-seated magmatic body that intruded after the deformation of the central Ardennes but before the emplacement of the Dinant Allochthon.

In 1982, Fieremans & De Paepe (1982) reported a petrographical and petrochemical study of a number of tourmalinite pebbles collected from various outcrops, which, unfortunately, they do not specify. However, they presented a detailed description of the tourmalinite textures from which they infered the nature of the precursor rocks affected by the tourmalinisation process. Recently (Corteel & De Paepe, 2003), extended geochemical data of the tourmalinite pebbles have been collected and, based on these data, their genesis could be constrained to a metasomatic replacement by a boron-rich fluid, probably of magmatic origin. Unfortunately, this geochemical characterisation did not shed much further light on the source area of the fragments themselves due to the absence of detailed sedimentological and petrographical data and other information on the depositional environment of the conglomerates. The present insights in this matter indeed still greatly rely on the studies of Asselberghs (1946, 1954).

In this paper, we present some new field observations on the stratotype sections of the Burnot formation at Profondeville in order to obtain more precise constraints on the sedimentary environment of the deposits. In addition, the first results of a new petrographic investigation are given, dealing both with the tourmalinites and with the other constituents of the conglomerates.

2. Observations

2.1 Sedimentological observations

At Profondeville (Fig. 1), the total thickness of the Burnot Formation amounts to about 500 metres and good observations along strike can be made here over several metres. Some parts of the sequence are exposed twice due to the occurrence of an anticline and outcrops along both banks of the Meuse River. Our observations of these exposures enabled us to distinguish four types of sedimentary sequences of which two are rhythmic (R deposits) and two are non-rhythmic (N deposits).

A first type of rhythmic deposits (R1) is dominated by conglomerates and sandstones (Fig. 2A). Each sequence starts with a conglomerate bed overlying an erosional contact and grades upward into sandstones. Complete cycles end with fine-grained compact siltstones or shales at their top. These uppermost pelitic deposits sometimes contain plant fossils that unfortunately are too poorly preserved to be determined. In some of the sandstones oblique-laminations were observed. Centimetre thick claystone beds are also present. They are laterally discontinuous, often undulating and in some cases they grade into lens shaped bodies with a thickness of several decimetres. These claystone beds are considerable in number and often they contain embedded pebbles. Clasts of claystone also occur regularly (Plate 1, A) in the sandstones and coarser grained rocks. Current ripple marks were observed in the sandstones and finer sediments.

The second type of rhythmic deposits (R2) consists mainly of sand- and siltstones (Fig. 2B). They start with a thin conglomerate bed overlying an erosional surface and grade rapidly upward into claystones/shales when complete. The sandstones often exhibit oblique laminations and are regularly interbedded with finer sediments exhibiting current ripple marks. Claystone clasts are rare. Discontinuous claystone beds do occur but less frequently than in R1 deposits.

In the first type of non-rhythmic deposits (N1) the sediments are dominated by sandstones, grits and to a lesser extent, by conglomerates. Compact siltstones and shales are subordinate. In contrast with the rhythmic sequences, oblique bedding is clearly present and locally the sediments coarsen upwards over several decimetres. In some outcrops, decimetre scaled foreset beds, often consisting of gravely lags, were observed. Oblique laminations occur frequently and also erosional contacts have been noticed, though less frequently than in the rhythmic deposits. Clasts and discontinuous beds of claystone on the other hand are rather rare. Compared to those in the rhythmic sections, current ripple marks exhibit mostly a larger amplitude and a longer wavelength.

In contrast with all previous types of deposits, claystones/shales are much more important in the second type of non-rhythmic deposits (N2, Figure 3) and they often show parallel laminations. They consist of a non-rhythmic alternation of shale-(/ compact siltstone-) and sandstone beds, with minor occurrences of grits and conglomerates that sporadically rest upon an erosional contact and that are fining upward over a few metres. No current ripple marks, nor discontinuous beds or clasts of claystones were observed but in a few fine-grained beds plant fossils were found.

The distribution of the four types of deposits throughout the studied parts of the stratotype sections is shown in Figure 4. From this figure it can be seen that there is no systematic variation in sedimentation but only an irregular alternation both stratigraphically and laterally. Noteworthy is the presence of a several metres thick uniform conglomerate bed at the top of the formation. It is exposed along both banks of the Meuse

River and cannot not be attributed to any of the above described types of deposits.

Preliminary observations of other outcrops of the Burnot Formation at Tailfer, Roisin and in the Hoyoux valley (Fig. 1), indicate that in these areas the deposits are similar to those described in the stratotype sections. In the Hoyoux valley, along the small road north of the Hoyoux River between Régissa and the hamlet Marche, an outcrop nearly parallel to the strike shows, not continuously however, the top of the Burnot Formation over several hundreds of metres. At this location, just as in the stratotype sections, it is composed of a several metres thick, quite uniform conglomerate bed. Here, the nature of the outcrop shows that the lateral extent of this conglomerate bed must be at least several hundreds of metres. Also at Roisin, the top of the formation is made up of a several metres thick uniform conglomerate bed.

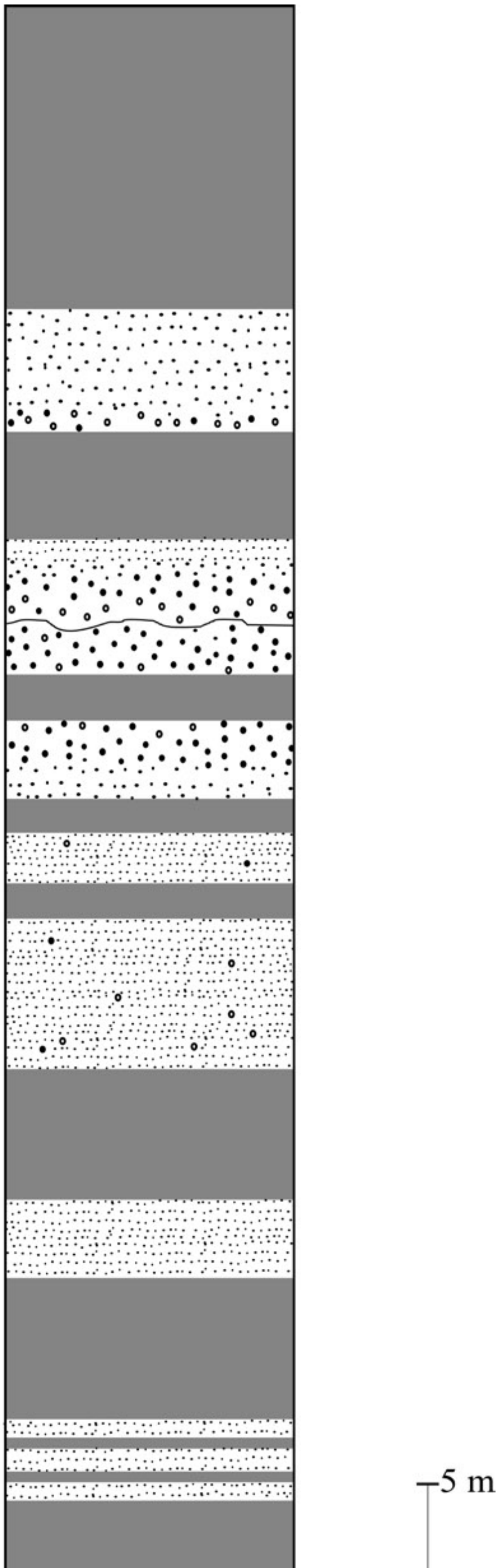

Figure 3. Lithological column of a non-repetitive section (type N2 deposit) occurring in the stratotype sections of the Burnot Formation at Profondeville. Legend as in figure 2.

2.2 Petrographical observations

The petrographic observations are mainly confined to the conglomeratic beds of the rhythmic (R1) deposits, exposed in the northern limb of the anticline, approximately 100 m above the base of the Burnot Formation (Fig. 4). The descriptions and interpretations presented here are based on observations of outcrops, hand specimens and large (9 cm x 6 cm) thin sections. These large sections enabled to obtain a better view on the textural relations between the tourmalinite clasts and the surrounding constituents of the conglomerate. Because our work is still ongoing no definite conclusions will be derived yet. Nevertheless, our observations already revealed some characteristics that have specific implications with respect to the source rocks of the clasts, the post-depositional history of the conglomeratic sediments and the occurrence of tourmaline, all of which, in our opinion, are worthy of discussion in their own right.

The first set of observations deals with the source rocks of the non-tourmalinitic pebbles in the conglomerate. Most pebbles are of fine-grained sandstones, siltstones, cherts, and crystalline quartz but in addition, a number of (previously unnoticed) volcanic rock fragments have been identified. These fragments originate both from pyroclastic deposits and from lavas and they constitute up to a few volume percent of the conglomerate. In hand specimen, the mostly dark, vesicular types (Plate 1, D) are relatively easily recognised but the compact aphanitic specimens are rather inconspicuous. Their volcanic nature is revealed by their microscopic textures that are typical of vitreous tuffs and lavas. Under plain polarised light, the fragments are generally colourless to brown and exhibit irregular flow lines or a more or less pronounced vitriclastic texture due to a dense accumulation of (devitrified) glass shards and dispersed fine angular quartz (Plate 1, E). Under crossed polars a felsitic

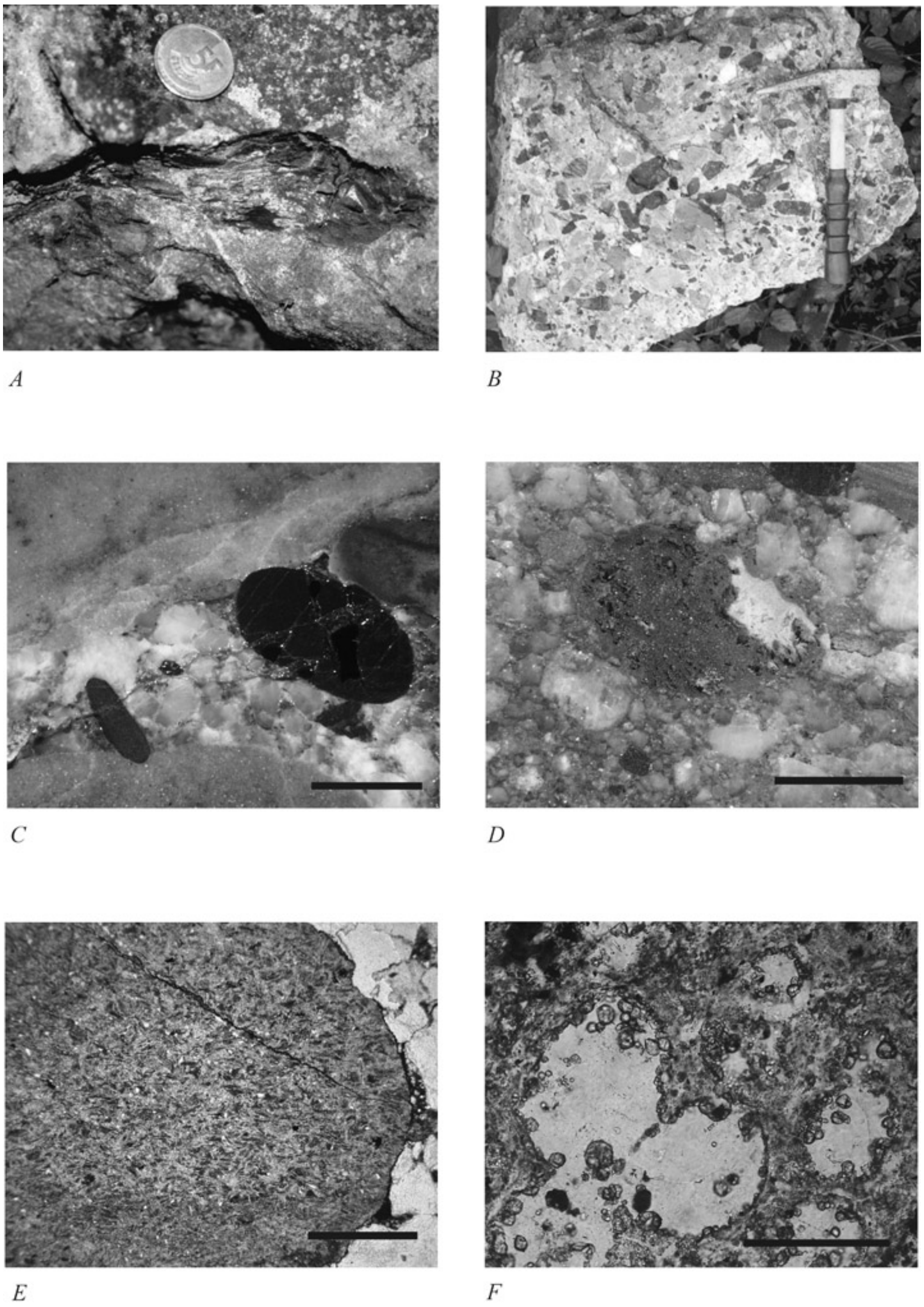

Plate 1. All pictures are from samples taken at Profondeville, unless otherwise mentioned.

Photo A. Deformed red claystone clast in sandstones of an R1 type of deposit.

Photo B. Conglomeratic block from the Burnot Formation at Cour-sur-Heure with a high amount of tourmalinite fragments, showing their variability in shape and size. Note their close association with white quartz that crystallised in the rock in poorly confined veins and patches as a result of a post-depositional invasion of silica bearing fluids.

Photo C. Detail of a cut rock slice sampled at Cour-sur-Heure showing hydrothermal quartz in association with tourmaline and tourmalinite. The dark triangular patch at the bottom right of the large rounded tourmalinite fragment is also composed of tourmaline of somewhat larger grain size and is intergrown with quartz. The tourmaline fragment to the left penetrates both the hydrothermal quartz and a pebble of the conglomerate. The small black spot in the centre is composed of a few larger tourmaline crystals. Note the variegated aspect of the clasts surrounding the tourmalinites and quartz (scale bar = 5 mm).

Photo D. Detail of a cut rock slice showing a fragment of a vesicular volcanic rock. The yellowish patch at the edge of the volcanic fragment is a part of an amygdale filled with cherty, opaline (?) material (scale bar = 5 mm).

Photo E. Fragment of a volcanic rock with a vitriclastic fabric composed of partially flattened and welded glass shards and dispersed minute quartz. The shards are devitrified and crystallised into aggregates of minute grains of high relief with the optical characteristics of tourmaline and/or chlorite (thin section, parallel polars, scale bar = 750 µm)

Photo F. Detail of a thin section showing an amygdaloidal fine-grained rock interpreted to be volcanic in origin and exhibiting incipient metamorphic recrystallisation. The white amygdales are filled with two or three interlocking quartz crystals (only visible with crossed polars). The yellowish grains with high relief scattered throughout the thin section are of garnet (scale bar = 200 μm).

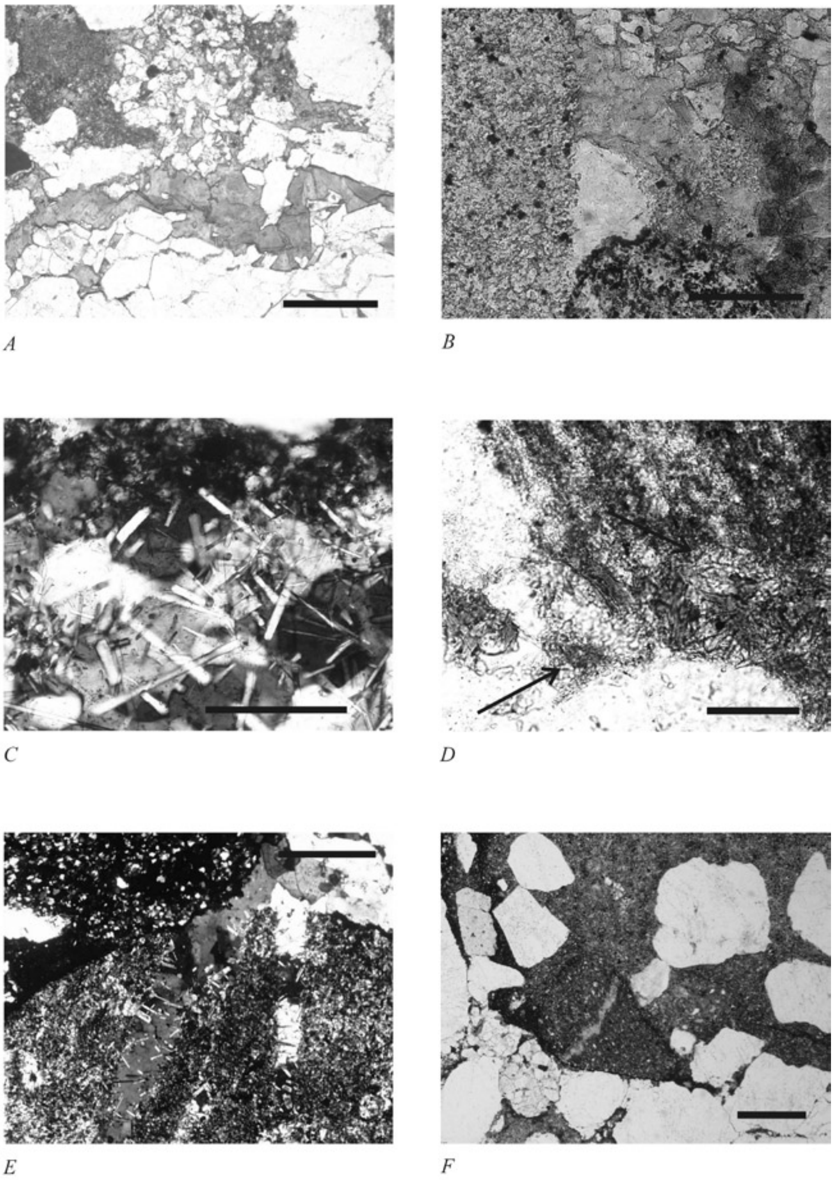

Plate 2. All pictures are from thin sections, all samples taken at Profondeville.

Photo A. (Sub)idiomorphic quartz associated with green chlorite in spherulitic aggregates fills the lower part of this picture. The upper part shows weakly cemented siltstone fragments and very fine-grained clay forming irregular patches throughout the thin section (scale bar = 250 μm).

Photo B. Two pebbles showing clear signs of recrystallisation and grain boundary migration, after their deposition. The pebble to the left is composed of quartz, chlorite and dispersed rutile (dark dots). The pebble at the bottom is composed of quartz and unidentified granular almost opaque crystals. The centre of the picture is taken by quartz and green spherulitic chlorite. At the right there is a group of irregularly zoned blue tourmaline crystals that apparently crystallised in association with chlorite. The grains in the upper part of the picture are of subangular to angular detrital quartz embedded in chlorite (parallel polars, scale bar = 200 µm).

Photo C. Upper part of a quartz-tourmaline fels, composed of granoblastic-polygonal quartz and randomly oriented acicular tourmaline. Note the intergrowth contact between the crystals of the fels and the surrounding fine groundmass composed of fine, partially oxidized chlorite (crossed polars, scale bar = 150 µm).

Photo D. Tourmalinite chert composed of fine-grained olive-green tourmaline (and quartz). The lower left half of the picture shows a vein crosscutting the tourmalinite chert and filled with quartz, coarser tourmaline and allanite. Allanite forms fine dusty brownish grains, both in the centre of the vein and in between the coarser tourmaline (marked with arrows). Note the blue absorption colours of the tourmaline crystals in association with allanite (scale bar = 100 μm).

Photo E. Fine-grained tourmalinite fragment crosscut by veins composed of quartz and needle shaped tourmaline standing at high angles to the vein walls. The quartz of the veins continues into the surrounding «groundmass» quartz, indicating that vein formation and filling was post-depositional. A siltstone fragment cemented by almost opaque material fills the upper left side of the picture (crossed polars, scale bar = 750 µm).

Photo F. Picture showing progressing tourmalinisation in a fine-grained rock, possibly the pelitic groundmass of the conglomerate itself. The rock is composed of minute chlorite, white mica, quartz and brown iron oxides (?). The dark green spot is composed of minute tourmaline crystals. An irregular vein filled with coarser tourmaline prisms cuts it. This vein must have developed almost simultaneously with tourmalinisation. The other elements in the picture are small clasts of siltstone, large quartz grains and chlorite (bottom left; scale bar = 500 μm).

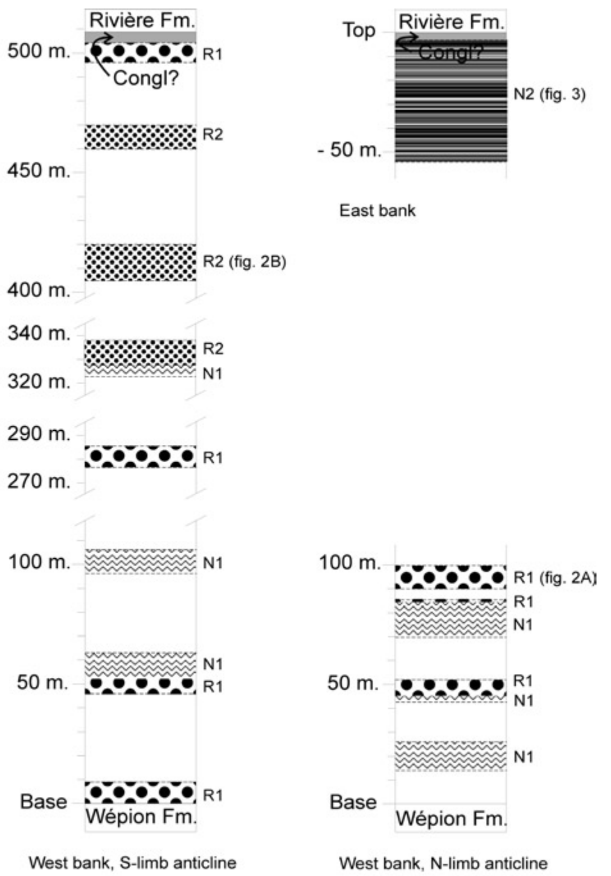

Figure 4. Schematic overview showing the distribution of the four distinguished depositional types throughout the stratotype sections of the Burnot Formation at Profondeville on both river banks. Blank zones refer to parts of the sequence, which were not studied (mostly due to lack of (qualitative) exposure). Note that the scale in the column representing the S-limb of the West bank is not continuous. *'Congl?'* refers to the thick conglomerates that could not be attributed to any of the four distinguished types of deposits.

texture is often observed. Phenocrysts are relatively rare and when absent discrimination from sedimentary chert pebbles is difficult. Of these phenocrysts, only quartz has been preserved while of the mafic minerals (amphibole and/or pyroxene?) and of the feldspars only fine-grained pseudomorphs are left.

In a number of sections, besides volcanic pebbles, also fragments of thermometamophic rocks were observed, often in close association: fragments of pelitic rocks altered into sericite schists, different types of other rocks (including volcanic ones) that developed a fine-grained granoblastic texture or contain small porhyroblasts (garnet and epidote?) (Plate 1, F) and quartzitic pebbles exhibiting grain coarsening and a change of their original fabric into a blocky mosaic texture. Internal recystalisation of the fragments and irregular outlines due to important grain boundary migration affecting their edges can often be observed (Plate 2,B). A supplementary observation that may be mentioned here is the small degree of compaction of the clasts in the conglomerate. The pyroclastic and other textures are quite well preserved and the pelitic clasts do not exhibit any slaty cleavage.

The second set of observations deals with the post-depositional changes that affected the conglomerates. These observations indicate that the rocks were, at least locally, affected by a hydrothermal event. In places, the rocks are quite variegated and invaded by white quartz in irregular veins and patches (Plate 1, B and C). Often the newly formed quartz crosscuts, penetrates and replaces the original clasts. In addition, in places, the original fabric of the rocks appears to be disrupted and transformed into a more open brecciated structure without much sorting and packing. Under the microscope, the quartz crystals have shapes that vary from xenomorphic to idiomorphic. They may exhibit a relatively uniform extinction and internal cracking. Occasionally they contain flakes of white mica and more rarely zircon. They are crowded with fluid inclusions that may form long strings running through several crystals. After quartz, chlorite is the most obvious mineral that is associated with this event. It occurs in various shapes and sizes and may form spherulitic aggregates filling voids between quartz (Plate 2, A). Finally, the local concentration of thermometamorphic rock fragments may also be interpreted as the result of this event, which would imply that these fragments are not detrital as such.

The third set of observations concerns the occurrence of tourmaline and tourmalinite. As is already well known, the tourmalinite content of the conglomerates can be quite variable. Of the rocks observed so far, those showing the most distinct effects of thermal alteration were quite rich in tourmalinite, but we do not want to generalise this statement yet. In hand specimen the tourmalinites are generally aphanitic. Their colour varies from dark grey to black and mainly reflects the relative amount of quartz to tourmaline. Although, in natural (and obviously weathered) exposures, a rounded pebble shape of the tourmalinites is evident, a greater variety in shape appears when fresh rock cuts are observed. The coarse and clastic nature of the rocks renders observation difficult but some pebbles are deeply embayed while others are sharp and angular and still others might be interpreted as merging into each other or give the impression to be plastically deformed (Plate 1,B). Rock fragments that are only partially tourmalinised are also quite frequent and quite a number of tourmalinite pebbles are crosscut by narrow lighter coloured greyish veins. Under the microscope a first and striking feature of the tourmalinites is their variability in fabric indicating that they result from the tourmalinisation of different types of precursor rocks. For almost each lithologic type of pebble found in the conglomerate also a tourmalinised equivalent can be found.

In the majority of the tourmalinite pebbles, tourmaline is present as very fine-grained (< 50 µm) crystals. When they compose the bulk of the rock, they are responsible for its black aphanitic appearance which is typical for a tourmaline chert (Plate 1,C). These cherts do not always exhibit a distinct relict texture. When they do so it is most often finely banded due to submillimetric alternation of silt-sized mostly angular quartz grains and tourmaline rich laminae. This fabric indicates that the original rock was a pelitic sediment (see also Corteel & De Paepe, 2003). The clay-rich layers were apparently transformed into tourmaline while the quartz grains remained relatively intact.

A second type of fine-grained pebbles appears to be derived from volcanic rocks similar to the non-tourmalinised varieties that have been described above. In the vesicular rocks, the vacuoles have been filled with an aggregate of polygonal quartz crystals and tourmaline needles, while in some vitriclastic rocks the shapes of the glass shards can still be discerned. It may be noted here that part of the tourmalinite pebbles studied by Fieremans & De Paepe (1982), were also interpreted as tourmalinised volcanics but the textures they describe are different from those observed here.

Some fragments have a hornfelsic fabric and are composed of groups of randomly oriented tourmaline prisms and needles embedded in and crosscutting a mosaic of granoblastic polygonal quartz crystals (Plate 2, C). This type can be described as a quartz-tourmaline fels. Tourmaline is subordinate to quartz and the presence of tourmaline is inconspicuous in hand specimen. Often, the small tourmaline prisms at the edges of these fragments can be seen to protrude into the surrounding matrix (Plate 2, C). Rutile, mostly idioblastic and randomly-oriented, forms a common accessory in many tourmalinites and also occurs in other rock fragments. Quite a number of clasts are only partially tourmalinised. The most intriguing examples of partial tourmalinisation that we observed were patches of sometimes veined cherty tourmalinite that developed in fine grained irregularly bounded areas that seemed to be original pelitic groundmass material and not some large clast (Plate 2, F).

Veins, generally millimetric to submillimetric in width, may crosscut the tourmalinites. They are composed of quartz and elongated to needle like tourmaline crystals standing at high angles to the vein walls. Some veins may contain other minerals such as allanite, zircon, apatite and even (rare) axinite. While most of the fine-grained tourmaline is pleiochroic in shades of olive green, the vein tourmaline is typically bluish. A striking patchy blue pleiochroism is seen on crystals that are in contact with allanite and hence, at least in this case, it can be ascribed to radiation damage (Plate 2, E). Some veins stop abruptly at the edge of the tourmalinite pebbles. Others, however, do not so and the quartz phase sometimes extends into the surrounding matrix (Plate 2, D) while in other cases the veins are taken over by strings of fluid inclusions running further through the hydrothermal quartz grains surrounding the pebble.

As already mentioned, tourmaline is not only a constituent of the pebbles but it is also found in the groundmass, forming crystals of irregular prismatic shape. It occurs as individual grains that may have sizes of a few hundred µm or in small groups and aggregates that apparently crystallised in the rock after deposition. Their crystallisation seems to be associated with the crystallisation of quartz and chlorite (Plate 2, B). Occasionally large quartz grains were observed to contain groups of tiny tourmaline needles as inclusions. Irregular zoning and brown to bluish absorption colours are common in these tourmalines and in some cases they also crystallised at the edges of tourmalinite fragments forming the bluish grey rims mentioned higher.

3. Discussion

3.1. Sedimentology

Although our field observations are insufficient for a detailed sedimentological interpretation, they allow an evaluation of the general context of the sedimentary environment and they provide some information on the source area of the clasts in the conglomeratic rocks. Several sedimentological features encountered in the N1 deposits support the hypothesis of a littoral sedimentation as proposed by Asselberghs (1946, 1954). Decimetre-scaled current ripple marks, cross-bedded sandstones and foreset beds, all present in N1 sequences, have been described in shore face deposits (e.g. Rosetti, 1997; Niemeyer et al., 1997). On the other hand, foreset beds, be it in much larger dimensions than the ones observed in the Burnot Formation, have also been encountered in prodeltas (e.g. Basilici, 1997; Ulicny, 2001). Coarsening upward, another feature of the N1 sequences, has also been reported for deltaic environments (Kassi et al., 1998).

Further types of sediments generally assumed to be of deltaic origin are fining upward cycles in which conglomerates are of minor importance. The R2 sequences consist completely of such sediments and are quite similar to deposits that have been interpreted as delta channel fills by Kelling & George (1971). The sporadically occurring fining-upward cycles in N2 sections can also be delta channel sediments, while the other parts of these sequences were deposited under a low energy regime. Evidence for such a regime is provided by the parallel nature of the laminations and the absence of features reflecting more energetic conditions (e.g., current ripples, cross bedding and coarse-grained sediments). In general, this type of deposits is generated on either the more distal parts of the shelf or in several types of estuaries. Taking into account the presence of plant fossils in some beds, the latter one is a more likely interpretation for the N2 sediments.

In summary, all observed features in the R2, N1 and N2 deposits suggest a littoral environment in the broadest sense. The R1 deposits on the other hand, cannot be classified as coastal deposits, but are more characteristic for river systems. Allen (1965) attributed a fluviatile environment to the fining upward cycles in the Lower Devonian of the Old Red Continent in Great Britain, which exhibits several similarities with the R1 deposits described above. Also more recently other investigators, e.g. Botha & De Wit (1996), have interpreted similar fining upward cycles as fluviatile channel and sheetflood deposits, respectively corresponding to the coarser and finer grained sediments of the cycles.

The uniform conglomerates forming the top of the deposits at Profondeville, in the Hoyoux valley and at Roisin require a more detailed examination in order to determine their depositional environment. In the present state of our study, two environments can be suggested: a fluviatile environment taking into account the context of the other deposits or an erosive coastal environment, taking into account the great lateral extent of the conglomerates in the Hoyoux valley. The pebbles in the fluviatile R1 deposits may be derived from a distant source area and may be transported over several tens of kilometres by a river system, before they were deposited. Sedimentation of the pebbles around Profondeville took place either in river channels or in and around a river mouth, along a coastline strongly dominated by the presence of the river mouth itself, with deltaic and fluvial channels lying in the vicinity of a low energy estuary, as indicated by the lateral variations at the top of the stratotype sections (Fig. 4). This sedimentary environment exhibits similarities with the present day coastline of the Mono estuary in Benin (Anthony et al., 1996), although finer sediments are more abundant in this estuary than in the Burnot Formation. The alternation of fluviatile, deltaic and near shore deposits finally indicates that several sea level fluctuations occurred during the deposition of the Burnot Formation in Emsian (and earliest Eifelian) times and that during this period, the sedimentary environment remained close to the coastline of the Old Red Continent.

3.2. Petrography

The presence of volcanic clasts in the R1 type conglomerates demonstrates that, during Emsian times, volcanic terranes were exposed and eroded by a drainage system that deposited the clasts in the Burnot formation. The compositional characteristics of the clasts further show that the volcanics are products of subareal eruptions and that, at least in part, they are differentiated rocks probably belonging to the dacite-rhyolite family. They show some compositional and textural similarities with the rocks of the Late Ordovician - Early Silurian volcanic belt running through the southern rim of the Brabant Massif to the north of the Emsian/Eifelian conglomerate beds studied here. Taking into account the general N-S orientation of palaeocurrents (e.g., Steemans, 1989) this suggests that the source area of the pebbles may be searched in this region. Also some of the non-volcanic pebbles could have originated from rocks of this massif. However, pressure cleavage that is thought to have developed in the rocks of the Brabant Massif from Silurian to Eifelian times (Debacker, 2001) is not observed in the pebbles, and this may provide an argument against this hypothesis, unless the source rocks that provided the pebbles evolved at substantially shallower depths within the massif. No source rocks are known to exist in this massif nor for the tourmalinites nor for the (thermo)metamorphic rock fragments, but their existence can obviously not be excluded as only a small of part of the Brabant Massif is known from outcrops and drill cores.

The textures and also the mineralogy of the conglomeratic rocks indicate that a distinct hydrothermal alteration under elevated temperatures took place after the deposition of the conglomerate. The mineralisation phase affected the groundmass and involved the emplacement of quartz, chlorite and bluish tourmaline. In addition, this event may also have produced the thermal metamorphism noticed in part of the rock fragments. Although observed processes, such as grain boundary migration, can equally be explained by diagenesis, the general lack of compaction in the rocks suggests that these processes were rather due to elevated temperature. The mineralogy of the metamorphic clasts would then suggest that metamorphism reached epidote-hornfels conditions. It may be noted here that metamorphism reaching epizonal grades has been recognized in this part of the Dinant Basin by Helsen (1995). According to Fielitz and Mansy (1999) this metamorphism occurred synorogenically during the Late Westphalian due to sedimentary overburden in a piggyback basin forming in front of the uprising Ardennes.

Our observations also carry the question about the origin of the tourmalinites to a different discussion. In the current state of our research, it cannot be ruled out that they are the result of in-situ tourmalinisation during an earlier phase of the described hydrothermal event that also produced the tourmaline in the groundmass of the conglomerates. There are some lines of evidence that may point in this direction and that can be summarized as follows. If detrital, the specific lithologic assemblage of the clasts together with the observation that several fine grained rock fragments are only partially tourmalinised does not support the idea of a long distance transport. To some extent, this is in contradiction with the above made conclusions on the sedimentology of the deposits. On the other hand, these observations can easily be explained by in-situ alteration caused by boron enriched hydrothermal fluids. The strangely shaped tourmalinites could correspond with deformed and tourmalinised claystone clasts from the Burnot formation itself or with crystallisation products out of colloidal tourmalinitic fluids. The latter ones were possibly generated in the pelitic beds of the sedimentary formation and squeezed between the framework elements of the conglomerates. Although less frequently reported, mineralisation from colloids has been suggested as a mechanism for tourmalinisation (Harraz & El-Sharkawy, 2001). The presence of fine-grained tourmaline patches in the pelitic groundmass material can also be seen as an argument for post-depositional tourmalinisation. The minute intergrowths of fine tourmaline needles at the edges of tourmalinite clasts displaying with the surrounding hydrothermal quartz and groundmass may be seen as a further indication for this assumption. Finally, the overall mineralogical composition of the conglomeratic rocks has the characteristics of a single paragenesis (quartz-tourmaline-chlorite-white mica). Regarding temperature conditions, the minerals in the submillimetric veins crosscutting the tourmalinites indicate that temperatures above 300°C were still prevailing during their filling. Hence, although these points are not decisive yet, they are, as stated above, sufficient to reconsider the origin of the tourmalinites.

4. Conclusions

Our field data confirm that at Profondeville, part of the sediments of the Burnot Formation originated in a coastal environment, as previously proposed by Asselberghs (1946). They further allow concluding that many of these deposits exhibit deltaic (and other river mouth) influences. Part of the sediments (the R1 deposits) however are not littoral but river channel and river sheetflood deposits. The source of the clasts of the R1 conglomerates may therefore be more distant than previously assumed.

The petrographic observations reveal the presence of volcanic and thermometamorphic clasts in the Burnot conglomerates. The conglomerates were locally affected by a hydrothermal event associated with an extensive quartz mineralisation with subordinate chlorite and tourmaline. This mineral assemblage shows some similarities with one of the mineralisation stages in quartz veins observed in the southern metamorphic border of the Stavelot Massif (Schroyen & Muchez, 2000) and requires further attention. There is, in our opinion, also evidence suggesting that the tourmalinites (and the metamorphic clasts) in the conglomerates result from the same hydrothermal event. In this point of view, the pebbles represent pseudomorphs after originally pelitic or volcanic clasts or even pseudopebbles resulting from crystallisation out of B-rich fluids. Tourmalinisation should then have occurred in association with the deposition of the tourmaline crystals in the matrix. If this interpretation is correct we may have to acknowledge the occurrence of a large-scale Variscan hydrothermal event involving tourmalinisation throughout the Belgian Rhenohercynian Basin. If not, the post-depositional tourmaline mineralisation is restricted to the crosscutting veins in the pebbles and the crystals in the groundmass. In their paper, Fielitz & Mansy (1999) quote epizonal metamorphism in the area around the Stavelot Massif, where also quite abundant tourmaline and tourmalinites are found. According to these authors this metamorphism was diastathermal and occurred during the Middle to Late Devonian, which is much earlier than the Carboniferous metamorphic phase observed in de central Dinant Allochthon that may be connected with the tourmalinisation of the Burnot conglomerates. Some conflict seems to emerge here, unless the Carboniferous metamorphic phase had a more pronounced hydrothermal character and also locally affected the southern border of the Stavelot Massif without being noticed as such. A thorough and detailed study of the other tourmalinite bearing outcrops of the Devonian of the Belgian Ardennes will undoubtedly shed a further light on this matter.

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