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EARLY VARISCAN, SOFT-SEDIMENT DEFORMATION FEATURES IN THE CHEMIN DE RONDE SECTION AT THE NAMUR CITADEL (BELGIUM)

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(12 figures)

ABSTRACT. A detailed geometrical study of the Chemin de Ronde section at the Namur Citadel (Meuse River side) and an attempt to reconstruct its original sedimentary configuration, demonstrates that these Namurian sediments were affected by (at least) three types of deformation from their deposition onwards until their final incorporation in the Variscan foreland fold-and-thrust belt. Regularly occurring palaeoseismites reflect the onset of the Variscan deformation in the basin at the time of deposition. A major penecontemporaneous, soft-sediment deformation event occurred when the sediments were affected by the early stages of the Variscan orogeny at the tip of the accretionary complex in front of the prograding orogen. Finally, these Namurian rocks underwent a hard-rock deformation at the time these rocks were incorporated in the Variscan foreland fond-and-thrust belt.

The presence of these three types of deformation features in one single outcrop reflects a prograde deformation history over a period of ~30Ma, from penecontemporaneous soft-sediment deformation during and shortly after deposition to hard-rock deformation during the peak stages of orogeny.

KEYWORDS: Namurian, soft-sediment deformation, palaeoseismite, Variscan deformation

SAMENVATTING. Een gedetailleerde studie van de Chemin-de-Rondesectie op de Citadel van Namur (Maaskant) en een poging om de originele sedimentaire configuratie te reconstrueren, heeft ons geleerd dat de Namuriaansedimenten (ten minste) drie vervormingstypes hebben ondergaan van het moment dat deze sedimenten zijn afgezet tot het moment dat ze geïncorporeerd worden in de Variscisch voorland-plooi-breukgordel. Regelmatig voorkomende paleoseismiethorizonten zijn de reflectie van het begin van de Varischische vervorming tijdens de afzetting van deze Namuriaansedimenten. Een belangrijke penecontemporaine sedimentvervormingsstructuur wordt vervolgens gevormd waneer de sedimenten vervormd worden tijdens de initiële fasen van de Variscische orogenese aan het uiteinde van een accretiecomplex dat zich ontwikkeld voor het groeiend orogeen. Uiteindelijk ondergaan deze Namuriaangesteenten de Variscische gesteentevervorming bij de incorporatie in de Variscische voorland-plooi-breukgordel.

De aanwezigheid van drie typen vervormingsstructuren op éénzelfde ontsluiting is de weerspiegeling van de prograde vervormingsgeschiedenis over een periode van ongeveer 30 miljoen jaar, van penecontemporaine sedimentvervorming tijdens en kort na de afzetting van de sedimenten tot gesteentevervorming tijdens de piek van de gebergtevorming.

SLEUTELWOORDEN: Namuriaan, sedimentvervorming, paleoseismiet, Varistische vervorming

1. Introduction

Distinguishing early, soft-sediment deformation features from hard-rock deformation features is not always obvious (Maltman, 1994). Water-saturated sediments often show a rheological behaviour very similar to that of ductily deforming rocks. These particular soft-sediment deformation features commonly originate shortly after the deposition of the sediments (i.e. prior to lithification) and are therefore often referred to as penecontemporaneous deformation features (Bates & Jackson, 1984; Kearey, 1993, Maltman, 1994). At the Namur Citadel (Belgium) the Namurian strata offer a unique opportunity to observe besides typical hard-rock deformation features (e.g. folds, fold-related faults) a number of such penecontemporaneous deformation features reflecting the early stages of the Variscan orogeny.

The outcrops at the Namur Citadel are located some 5 to 6 km north of the surface trace of the Midi-Condroz-Eifel

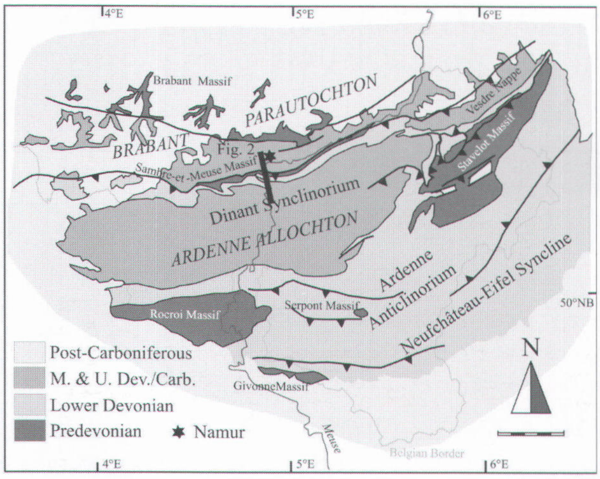

Figure 1. Geological map of the Ardenne showing the location of the Namur Citadel, north of the northern Variscan front thrust.

thrust, the northern front thrust of the Variscan fold-and-thrust belt (i.e. Ardenne Allochthon) (Figs. 1 and 2). The outcropping rocks are Namurian coal-bearing shales and sandstones deposited in a foreland basin. According to Bouckaert (1961, 1967), the particular Chemin de Ronde section (points 14 to 15 on fig. 1 in Bouckaert & Vandenberghe, 1987) belongs to the Namurian A, some 150 m below the Namurian A/B boundary which is equivalent to the Mississippian/Pennsylvanian boundary (~320Ma) (see fig. 2 in Bouckaert and Vandenberghe, 1987).

The structural architecture between the Midi-Condroz-Eifel thrust to the south and the Lower Palaeozoic Brabant Massif to the north consists of three tectonostratigraphic domains (Delmer, 1997; Mansy et al., 1999): (1) the undisturbed Devono-Carboniferous cover of the Brabant Massif, dipping some 20° southwards; (2) the parautochtonous imbricated thrust sheets, mainly consisting of Upper Carboniferous coal-bearing shales; and (3) an out-of-sequence thrust sheet in the direct footwall of the Midi-Condroz-Eifel thrust, referred to as the "Grand Massif Superficiel" by Delmer (1997) (Fig. 2), consisting of Carboniferous and Devonian rocks. This thrust sheet is segmented by several transverse faults leading to different names along strike. In the Namur area this thrust sheet is called the Malonne Massif (see section in Graulich, 1961 and planche IX in Kaisin, 1933).

Vandenberghe & Bouckaert (1984) have interpreted particular features in the Namurian rocks at the Namur Citadel as penecontemporaneous soft-sediment deformational features: diapiric, chaotic shale masses, disrupted strata, and in particular intense folding of finely laminated silty to shaly sandstones below thrust planes (Figs. 3a & 3b). Bouckaert & Vandenberghe (1987) explained the origin of these early deformation features as a consequence of a protracted shortening in the foreland between the Sudetic (~320Ma) and the Asturian (~290Ma) pulses of the Variscan orogeny.

The Asturian deformation in the Namurian rocks has clear hard-rock deformation characteristics as the rocks were buried some 3 to 4 km deep at that time (Adams & Vandenberghe, 1999). Also on the microscopic scale a hard-rock deformation overprint (cleavage development) is clearly present in the penecontemporaneous deformation features (den Brok et al., 1997).

In the present paper we focus on the Chemin de Ronde section at the Namur Citadel (Meuse River side). Based on a detailed geometrical analysis we will demonstrate the presence of at least two types of early, penecon-

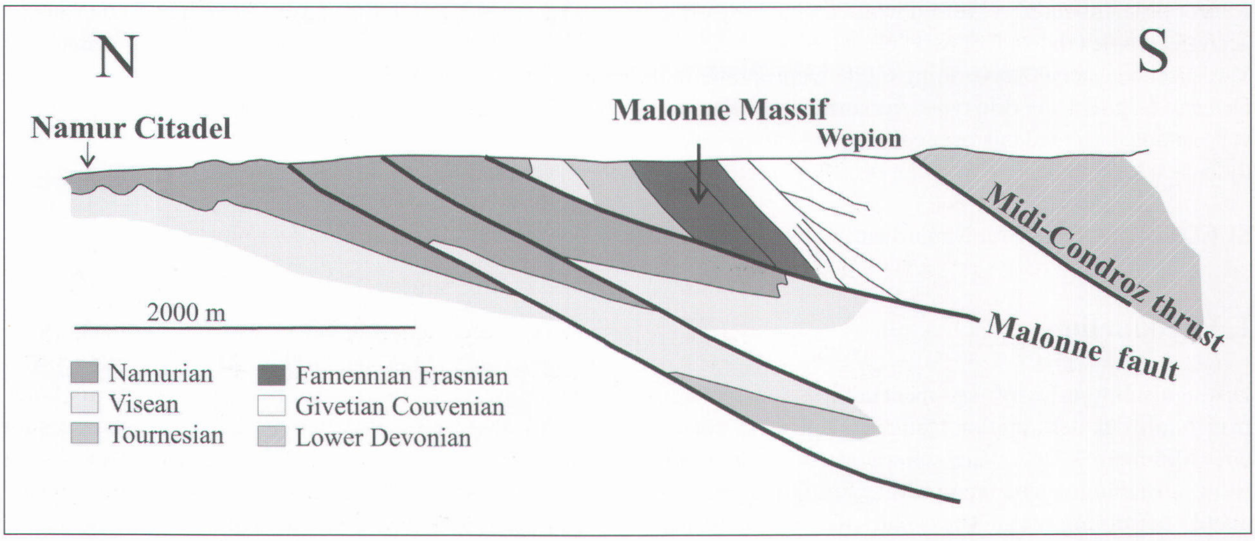

Figure 2. Simplified cross-section along the Meuse River valley south of Namur (see Fig. 1 for location) displaying the structural architecture of the foreland in the footwall of the Midi-Condroz thrust (after Graulich, 1961).

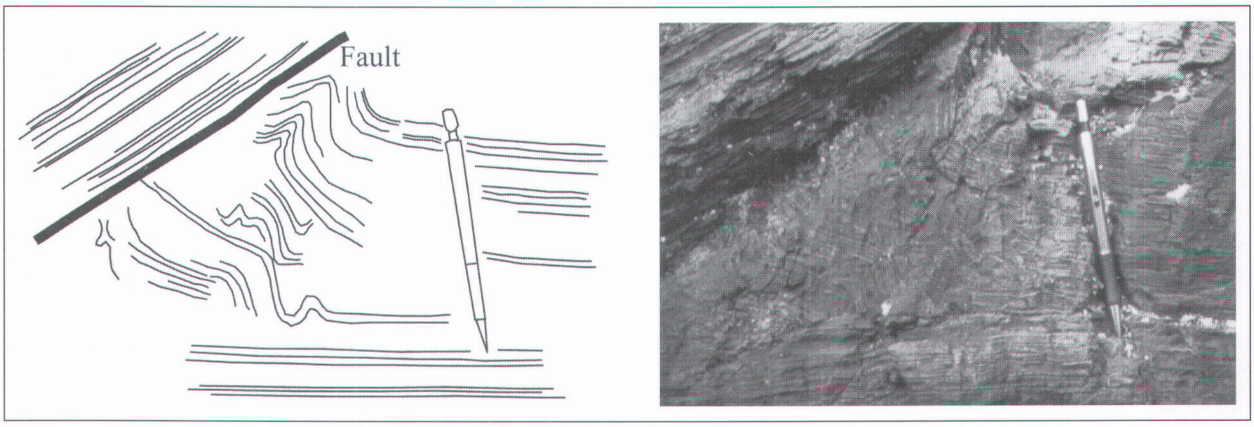

Figure 3. Photograph (a) and associated line drawing (b) of convoluted, finely laminated silty to shaly sediments underlying a fault plane (Route Merveilleuse section at the Citadel described in Vandenberghe & Bouckaert, 1984). The fault plane extends across the whole outcrop (some 20 m visible) (pencil is 15 cm).

temporaneous, soft-sediment deformation features besides the, Asturian, hard-rock deformation features. These three types of deformation features developed in a time span of ~30Ma and reflect a protracted tectonic activity in the foreland basin of the developing Variscan orogeny from the Namurian onwards.

2. The Chemin de Ronde Section

The Chemin de Ronde section, underneath the wall between the Tour des Comtes and Tour des Guetteurs (points 14 and 15 respectively in Bouckaert & Vandenberghe, 1987; Pl I in Kaisin, 1933) can be subdivided in three main parts (Fig. 4):

(1) The northern part (1 in Fig. 4) consists of weakly (25°) southwards dipping cyclic series of sandstones and shales.

(2) In the middle part (2 in Fig. 4) a deformed series of sandstones and shales can be observed, in which a tight chevron fold and a few steeply south-dipping small-offset faults are present (fig. 1 in Vandenberghe & Bouckaert, 1984).

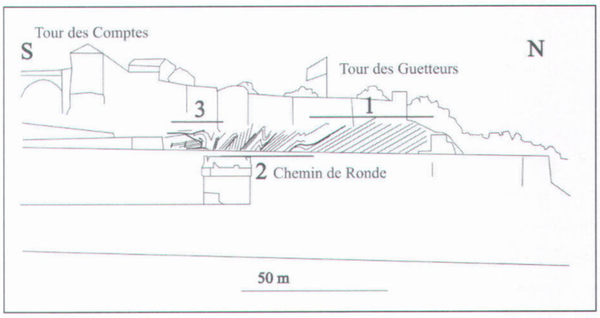

Figure 4. Simplified cross-section of the Chemin de Ronde section. Note the three parts of the section (after Kaisin, 1933).

(3) The southern part (3 in Fig. 4) shows an alternation of sandstones and shales displaying faults and folds with at the southern end of the section again a regularly, weakly (14°) southwards dipping series of dominantly shales. The present paper mainly deals with this southern part of the section (Fig. 5).

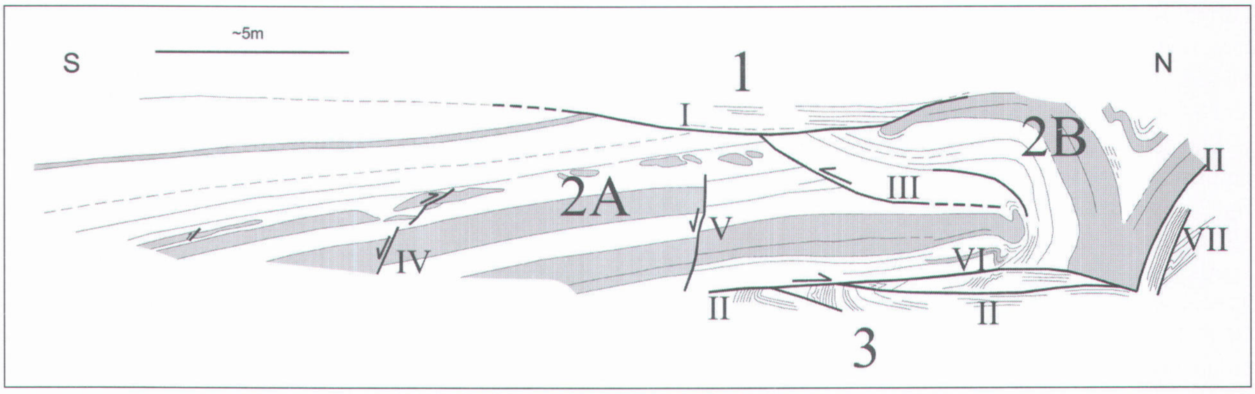

Figure 5. Schematic drawing of the Chemin de Ronde section. The section is subdivided in several units: 1, 2A, 2B and 3. I, II, III, IV, V, VI and VII are abnormal interfaces or fault planes. The dark strata represent the more sandy part of the sedimentary sequence.

The studied part of the section can be subdivided in three units, separated by two, subhorizontal to slightly south-dipping, abnormal interfaces (I and II on Fig. 5):

(1) The unit above the interface I (1 in Fig. 5) shows undisturbed, subhorizontal, finely-laminated shaly series. The interface I is particularly visible as a slight change in dip in otherwise identical thinly laminated rocks. Based on the current observations it can not be concluded whether the interface I is an erosional (infill of a gully) or tectonic (thrust) contact.

(2) The lower unit (3 in Fig. 5), which is barely visible, is composed of finely-laminated sandy shales. In this part, overturned beds underlying the interface II can be observed (Fig. 6 & fig. 3 in Vandenberghe & Bouckaert, 1984). In detail, the overturned laminae display a wavy, convoluted character. The same finely-laminated sediments continue subhorizontally to the north under the V-shaped synform and appear subvertically north of the vertical limb of the folded sandstone layer (Fig. 5), again showing a wavy character. Interface II is clearly of tectonic origin (thrust). Its folded nature clearly indicates that the faulting occurred prior to the (Asturian) folding episode generating the V-shaped synform.

(3) The central unit of the section, bounded by the abnormal interfaces I and II, is the most complicated part of the section and consists of two domains (2A and 2B on Fig. 5) separated by fault III. This fault III is truncated by both interface I and II, thus predating the development of both interfaces. The southern domain (2A), in the footwall of fault III, is composed of regularly weakly southwards dipping shales and sandstones. The middle of domain 2A consists of a sandstone layer, which becomes discontinuous towards the north, displaying contorted ball-type sandstone bodies with a diameter of some tens of cm, and separated by contorted shale (Fig. 7; comparable to the ball-and-pillow structures in Pettijohn & Potter, 1964). The sediments above this sand ball horizon again show an undisturbed nature (Fig. 7).

In the lower part of domain 2A two steeply south-dipping faults (faults IV and V) can be recognised (Figs. 5, 7 and 8). Their displacements (few tens of cm) suggests normal faulting. Both faults end in the sand ball horizon (e.g. fault V in Fig. 7). At the lower northern side of domain 2A, a small fault-bounded block, about a meter long and 0.5 m high, can be observed (between fault II and VI in Fig. 5). This fault horse displays internal asymmetric antiformal layering, overturned to the north (Fig. 9; see fig. 2 in Vandenberghe & Bouckaert, 1984). Above fault VI, a regularly dipping sandstone layer wedges out towards fault III. The wedge tip is back-folded (Fig. 5). The structure of domain 2B, in the hanging wall of fault III (2B) is dominated by the presence of a thick sandstone layer. In the top of domain 2B its attitude is subhorizontal and wedges out. The structure is clearly truncated by the interface I, bringing the laminated shales above the complicated structure. To the north, the sandstone layer suddenly plunges downwards forming an

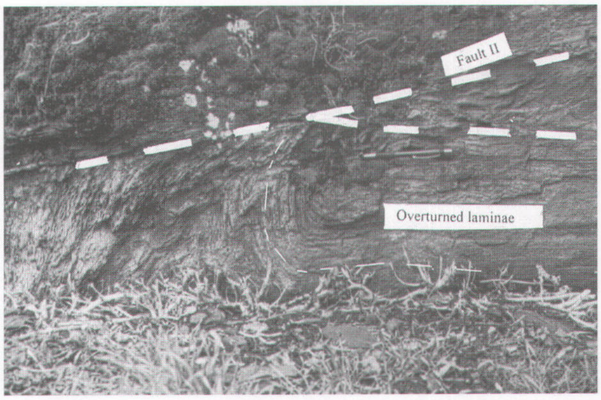

Figure 6. Overturned laminae of the lowest part of the section, underlying the subhorizontal fault II; the overturned geometry shows a relative thrusting to the north (left). Note the wavy character of the overturned laminae (pencil is 15 cm).

Figure 8. Photograph of the normal fault IV on Fig. 5 (hammer is 33 cm).

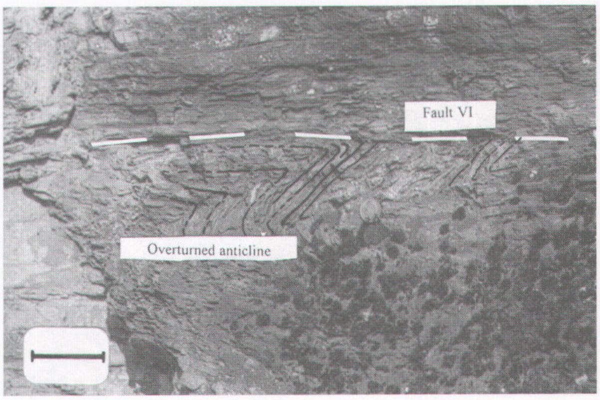

Figure 9. The complicated folded and faulted part of the section. Note the basal part consisting of a small thrusted sheet with internal asymmetric antiformal folds (scalebar is 10 cm).

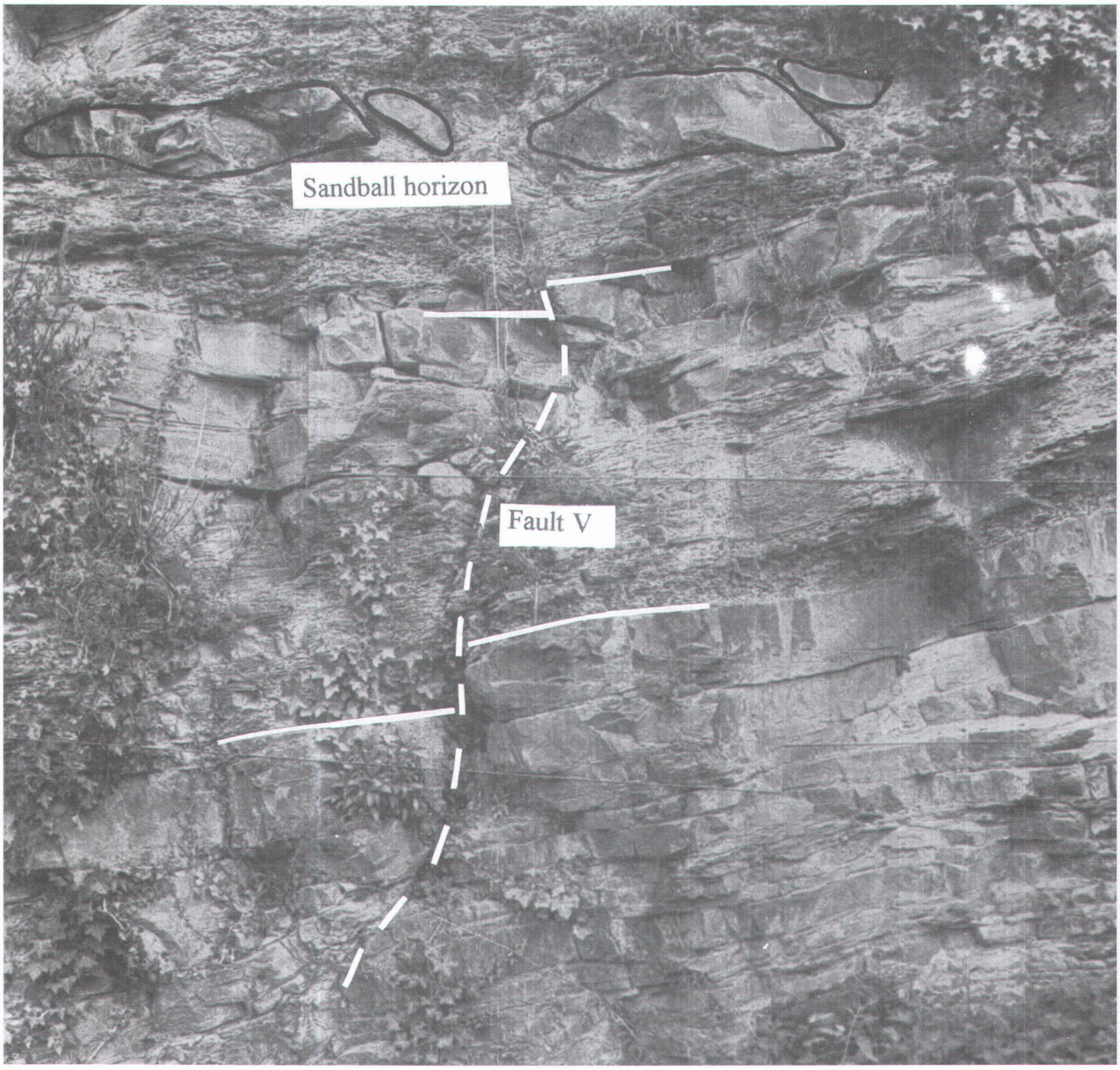

Figure 7. A normal fault (fault V on Fig. 5) can be observed below the disturbed sandstone-sandball layer. This fault ends upwards in the contorted shale between the sandballs. Note that the strata directly overlying the sandballs are again undisturbed (pencil is 15 cm).

asymmetric antiformal structure and ending in a V-shaped synform. The sandstone layer is clearly truncated by fault II, which itself has been folded in the V-shaped synform.

3. Interpretation of the Chemin de Ronde section

3.1. Palaeoseismites

In domain 2A two normal faults (IV and V on fig. 5) are truncated by the same stratigraphical layer. The onlapping of sediment in the hanging wall of both faults, the close spatial relationship to the isolated, sand ball horizon and the undisturbed nature of the layers that overly this sand ball horizon (Fig. 7) indicates that all these features were kinematically linked. Both small-scale normal faults and the disturbed sandstone layer developed in water-saturated sediments prior to the deposition of the overlying, undisturbed layer. This suggests a synsedimentary origin of these features. These features are considered palaeoseismites, caused by the shaking of the Namurian seabed. This earthquake-triggered shaking induced liquefaction of the uppermost sediments (e.g. Marco & Agnon, 1995), resulting in an upward squeezing of mud underlying sandy sediments and the loss of strength in

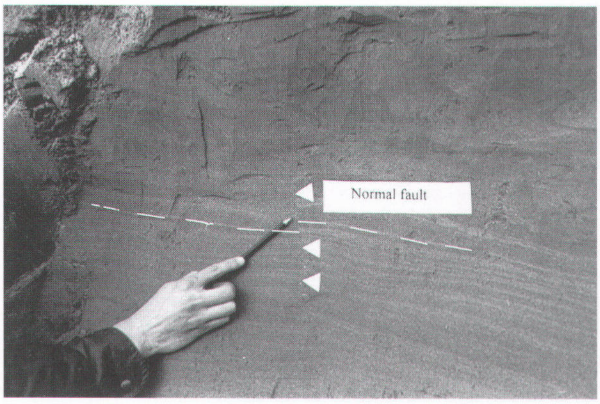

Figure 10. A convoluted bed in fine glauconitic sands interpreted as a seismite (Willems, 1995) underlain by a normal fault with a small offset in the Egem Sands (top Lower Eocene, Ampe pit, Tielt, Belgium) (pencil is 13 cm).

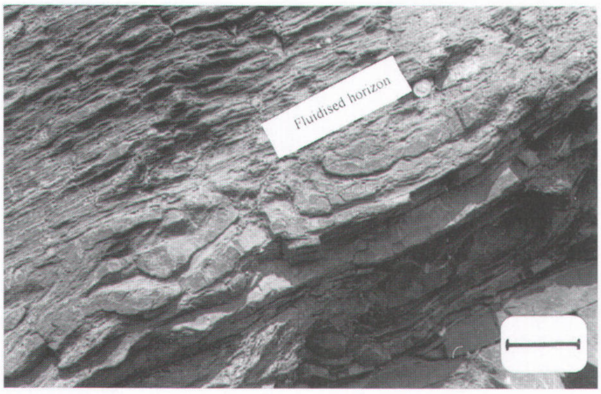

Figure 11. The fluidised bed in the otherwise undeformed part of the Chemin de Ronde section (nr 1 in Fig 4) interpreted as a palaeoseismite (scalebar is 10 cm).

the latter, eventually leading to the formation of the sand balls. Remarkably, a similar situation has been observed in much younger sediments, the Egem Sands of top Lower Eocene in the Ampe pit (Tielt, Belgium). Here, small normal faults can be observed under a convoluted bed, also interpreted as a palaeoseismite (Fig. 10; Willems, 1995). Moreover, in Namurian A sediments less than 100m stratigraphically below the above-mentioned palaeoseismites (in part 1 of the Chemin de Ronde section underneath the Tour des Guetteurs, Fig. 4) another fluidised horizon is present (Fig. 11). The presence of palaeoseismites at different levels in the Namurian A series suggests that during the Namurian the occurrence of seismic events was not incidental but rather common. It is clear that from the Namurian onwards the flysch basin in front of the developing fold-and-thrust belt was affected by the Variscan orogeny.

3.2. Penecontemporaneous deformation features

In the lower unit of the Chemin de Ronde section (3 on Fig. 5), overturned beds, which are truncated by the subhorizontal fault II, can be observed (Fig. 6). This overturning of laminae is likely induced by the movement of the overlying fault II, implying that unit 2 moved relatively to the north with respect to the underlying unit 3. The asymmetry of the small-scale structures in the direct footwall of faults VI and VII (Fig. 5) fits this northwards movement of the overlying sediments. It is clear that faults II, VI and VII represent different segments of the same, folded, fault. In detail the sediments in the direct footwall of fault II show a wavy, convoluted character which is much more easily explained as the result of a soft-sediment deformation of sediments containing still more than 15 to 20% water than as the result of a hard-rock deformation, although microstructural analysis convincingly demonstrates the presence of pressure solution creep (den Brok et al., 1997). A local increase in fluid pressure, building up underneath a small-scale thrust that was cutting off normal diagenetic dewatering paths, could have been responsible for the sediments to deform in a hydroplastic manner (cfr Vandenberghe & Bouckaert, 1984 example at the route Merveilleuse section of the citadel, Figs. 3a and 3b). Contrary to the sand ball horizon, which clearly developed right below the seabed, the hydroplastic behaviour of the unconsolidated layers is considered to have occurred at a deeper level (few metres to few tens of metres below the seabed; Lowe, 1975).

The regularly dipping sandstone layer in the hanging wall of fault VI (Fig. 5) wedges out towards fault III, where the sandstone layer is moreover back-folded. Its attitude implies that domain 2B moved upwards and to the south along fault III with respect to domain 2A (Fig. 5). The thick sandstone layer in domain 2B also wedges out to the south. Lateral wedging out of sandstone layers suggests that sandstone bodies were discontinuous and that apparently not enough sand was available in that part of the Namurian foreland basin to make continuous sand bodies. Consequently mud sedimentation separated the sand bodies. This heterogeneous sediment architecture could eventually have played an important role in the localisation of the deformation.

Although its general attitude is very similar to that of the Asturian hard-rock folding, the asymmetric antiform in domain 2B (Fig. 5) does not comply with the Variscan fold style. Furthermore, the southern extremity of the sandstone layer which forms the antiform seems to have sunk into the underlying shales (Fig. 5). This rather suggests a hydroplastic origin than a hard-rock deformation. Moreover, the burial depth at the time of the Asturian deformation was the deepest ever for these rocks (3 to 4 km, Adams & Vandenberghe, 1999) and lithification and compaction as seen today goes back to that time. Therefore it is suggested that the acme of the Asturian deformation could not produce such hydroplastic deformations as observed in the structures of the Chemin de Ronde section and that a different origin for the formation of these structures is required. The triggering agent of the complex compressional antiformal structure is most likely linked to the palaeogeographical setting of the Namurian sedimentary environment. The penecontemporeneous deformation of these Namurian strata occurred within the foredeep north of the developing Variscan fold-and-thrust belt. During this soft-sediment deformation event, the thrust front of the developing fold-and-thrust belt was located some 100 km to the south (Adams & Vandenberghe, 1999; Bless & Streel, 1976). However, Vandenberghe & Bouckaert (1984) suggested that Varisan tectonics already affected the foreland by e.g. steepening the sea floor of the foredeep inducing massive gravitational sliding.

3.3. Asturian hard-rock deformation

In addition to the structures formed by penecontemporeneous deformation, the Asturian hard-rock deformation has certainly played an important role in the Namurian strata (as exemplified by many structures in the outcrops at the Namur Citadel). This is illustrated by the formation of the V-shaped synform in domain 2B. The refolding of the penecontemporeneously formed basal thrust (faults II, VI and VII) due to the formation of this synform and relatively sharp angle between the horizontal and subvertical limbs are in favour of hard-rock deformation. Therefore, the synform is interpreted as being Asturian in origin. On the outcrops, the Asturian influence on the originally soft-sediment deformational structures in the rocks is also shown by the presence of quartz veins and the development of a pervasive pressure solution cleavage (den Brok et al., 1997).

4. Deformational history

Originally discontinuous sand bars were deposited on a generally muddy, shallow seabed. As discussed above, not enough sand was available to make continuous sand bodies and mud sedimentation separated the sand bodies (Fig. 12a). During sedimentation, earthquake-induced shaking of the seabed (Fig. 12b) lead to the liquefaction of the sediments and resulted in the development of palaeoseismites, two minor normal faults and an isolated disturbed sand ball horizon just above.

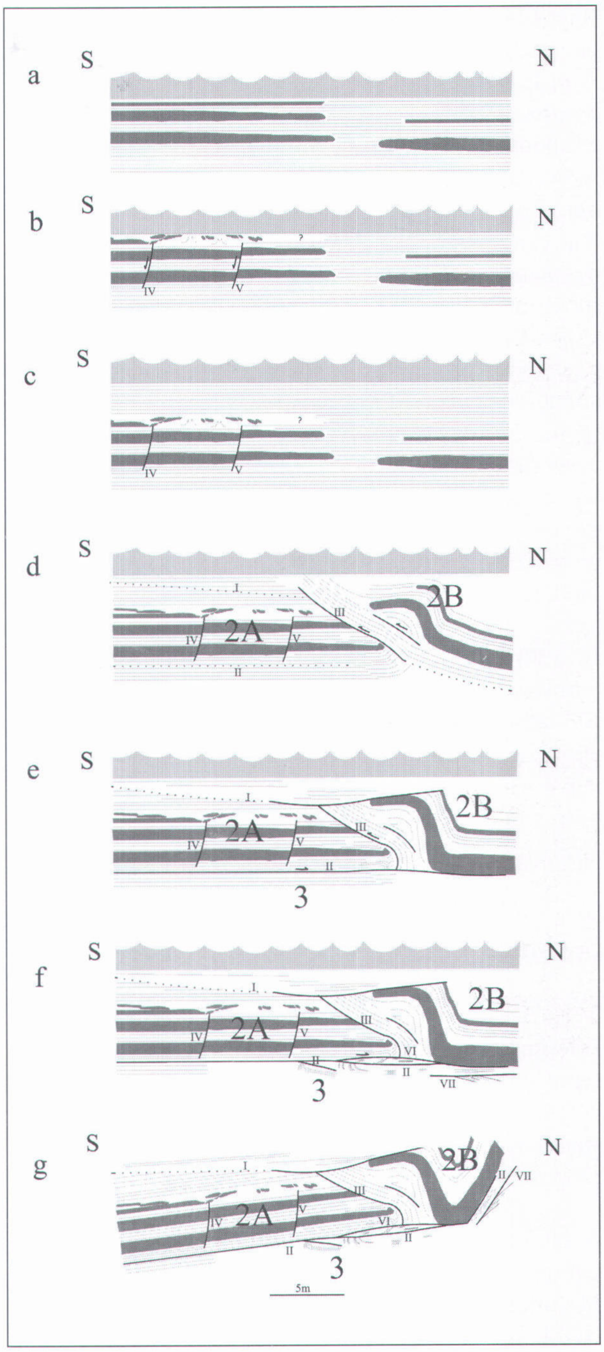

Figure 12. Restored section of the Chemin de Ronde section and evolution model of the deformation structures. The dark strata represent the more sandy part of the sedimentary sequence.

At a deeper level (some tens of metres below the sea bed) hydroplastic soft-sediment deformation was triggered. This penecontemporaneous deformation event caused domain 2A to move to the north relatively with respect to domains 2B (fault III) and the underlying unit 3 (fault II). The emplacement of fault III and the relative movement of domains 2A and 2B was determined by the heterogeneous sediment built up. The absence of sand bodies caused a structural weakness where mud was squeezed upwards so that the southern sand bodies slided underneath the northern bodies, leading to the back folding of the wedge tips (fig. 12d). The folding of the sand layers in domain 2B eventually lead to the blocking of the northwards movement of domain 2A along fault II

(Fig. 12e). The nature of the abnormal interface I remains enigmatic. On the one hand a thrust contact similar to fault II can be considered. On the other hand it can be assumed that a gully eroded a part of the penecontemporaneously developed structure (fig. 12f). Furthermore, the question of the triggering agent remains to date unresolved. Vandenberghe & Bouckaert (1984) suggested that, earthquake-triggered (?), gravitational sliding caused the penecontemporaneous deformation. The northwards movement would in that case imply a northerly palaeoslope of the foredeep basin. This can however be questioned taking into account the palaeogeographical situation of the outcrop area along the northern margin of the Namur basin. Another possibility is that the penecontemporaneous deformation structure reflects the northwards push on a south-dipping slope at the tip of a developing accretionary complex in front of the prograding Variscan fold-and-thrust belt (critical taper model).

In addition to the structures formed by penecontemporeneous deformation, the Asturian hard-rock deformation was responsible for the formation of the sharp synform in domain 2B. The latter resulted in the subvertical positioning of the former subhorizontal penecontemporeneous faults II and VI which were passively taken into this folding (Fig. 12g).

5. Conclusion

The Chemin de Ronde section at the Namur Citadel (Meuse River side) offers the unique opportunity to observe three different types of deformation features. A detailed geometrical analysis has enabled us to understand the deformation history of these structures and to propose a palinspastic restoration of the section.

A sand ball horizon and two related normal faults are interpreted as palaeoseismites formed at the seabed (cf. Molina et al., 1998; Owen, 1987, 1996). Similar fluidized horizons in the same stratigraphical interval demonstrates that at the time of depositions of the Namurian sediments (~320Ma ago) the basin was regularly affected by seismic events, clearly suggesting its instability.

To explain the complex structure, occupying the centre of the Chemin de Ronde section, penecontemporaneous soft-sediment deformation is called upon. The emplacement of this structures was controlled by the failure of a mud zone sandwiched laterally between two sandy sediment bodies. The development of this compressional structure is interpreted to have taken place at the tip of the accretionary complex developing in front of the prograding Variscan orogen.

Finally, after lithification and burial these strongly distorted sediments were incorporated in the frontal parts of the prograding Variscan fold-and-thrust belt (~290Ma).

The presence of these three types of deformation features in one single outcrop reflects the progressive increase in deformation of the sediments in the Namurian foreland basin during the Variscan orogeny. From their deposition onwards (~320Ma) until their final incorporation in the Variscan fold-and-thrust belt (~290Ma), these Namurian sediments were, in a period of ~30Ma, repeatedly affected by Variscan orogeny.

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