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The deep structure of the Ardennes Variscan thrust belt from structural and ECORS seismic data

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Abstract—A new crustal tectonic model is proposed for the Ardennes external Variscides of northern France–Belgium on the basis of original microtectonic data, further complemented by revised ECORS deep seismic information. This model is illustrated by both restored and balanced crustal sections that clearly emphasize the direct control exerted by pre-existing extensional structures on the collision-related processes of Variscan deformation. Indeed, the deep structure of the Ardennes belt appears as a continental accretionary prism that thickens south towards the hinterland above a staircase-type basal thrust. Innermost crustal shortening is here assigned to a deeply rooted foreland-directed ramp thrust system soled at depth by a thick ductile decoupling shear zone, actually imaged at about 20 km depth on the ECORS section; this thrust system is bounded upwards by a shallow infra-Devonian roof thrust. To account for the present-day high structural position of the Rocroi Cambrian inlier, as well as for its internal superimposed ductile fabrics, major uplift of a previously sheared crust is assumed to have occurred along a frontal ramp which nucleated on an early S-dipping extensional fault (the Rocroi Fault). According to the ECORS data, the hanging wall of the Rocroi Fault has been translated about 40 km northwards along the Dinant infra-Devonian shallow décollement. This estimate is quite consistent with the 40% stratal shortening undergone at its front by the Devonian detached cover whose thin-skinned fold–thrust structures also reflect the direct influence of early Devonian normal faulting. Basin inversion tectonics are clearly expressed along the frontal thrust zone where the thin Condroz basement sheet is now interpreted as resulting from slicing of the Dinant Décollement through the footwall of a major Lower Devonian extensional fault scarp that separated the Namur shallow shelf from the Dinant downthrowing basin. The present thrust model also implies that the Dinant Décollement extends as a blind thrust beneath the slightly detached Namur Carboniferous coalfield, and that the Midi frontal ramp only represents a minor out-of-sequence thrust reactivating a rotated basement–cover contact.

INTRODUCTION

The existence of large-scale thrusting in the Ardennes Variscan external zone has been postulated, as far back as 1860, by Gosselet on the basis of detailed mapping. It was later confirmed by Fourmarier (1913) along the Midi Fault where the Dinant Devonian unit was assumed to be translated northwards over the Namur Carboniferous syncline (Fig. 1). Then, as a result of renewed interest in Carboniferous coalfields, the Namur-Pas-de-Calais coal-bearing area was largely investigated by extensive mining works (Bouroz 1950, Bouckaert 1967, Delmer 1977), deep boreholes (Graulich 1961, Bouquillon 1984) and commercial shallow seismic (Clément 1963) that clearly demonstrate the presence of imbricate thrust sheets in the footwall of the Midi Fault; the use of thrust tectonics rules has allowed this overall frontal thrust system to be balanced and restored (Houchen 1988). Lastly, the ECORS northern France deep seismic reflection profile, recorded across the concealed western prolongation of the Ardennes Palaeozoic massif (Fig. 1), has emphasized the regional significance of Variscan crustal thrusting by imaging a prominent shallow décollement, about 140 km in length, beneath the Dinant allochthonous unit (Cazes *et al.* 1985, Raoult 1988).

However, although a considerable amount of detailed but often local studies have already been devoted to structural analyses of portions of the Ardennes Variscides, no generalized tectonic interpretation has so far been attempted to describe the entire belt in terms of crustal deformation. That is the principal aim of the present study which is mainly based upon extensive published data, revised ECORS deep seismic information, and also our own microtectonic analyses focused on the Namur syncline, and around the lens-shaped Rocroi inlier. Interpretation of all these data by using modern thrust tectonic concepts brings new important insights for solving such major regional problems as: (1) the kinematics and deep geometry of the Midi frontal thrust; (2) the southward extension of the Namur coalfield beneath the Dinant Nappe; (3) the amount of horizontal displacement along the Dinant Décollement; and (4) the tectonic significance of the Lower Palaeozoic inliers enclosed within the Dinant Devonian unit in the south (Fig. 1).

The resulting model is illustrated by a complete crustal traverse of the orogen, that includes (1) a restored template of the Ardennes basinal domain during Devonian extensional stage, and (2) an original balanced cross-section, about 140 km long, that involves largely the pre-Devonian basement. This section, almost parallel to the N–S transport vector, has been constructed by projecting the Meuse River surface geology onto the ECORS profile which, despite its composite nature, is realistic given the highly cylindrical pattern displayed by the Dinant fold nappe (Fig. 1).

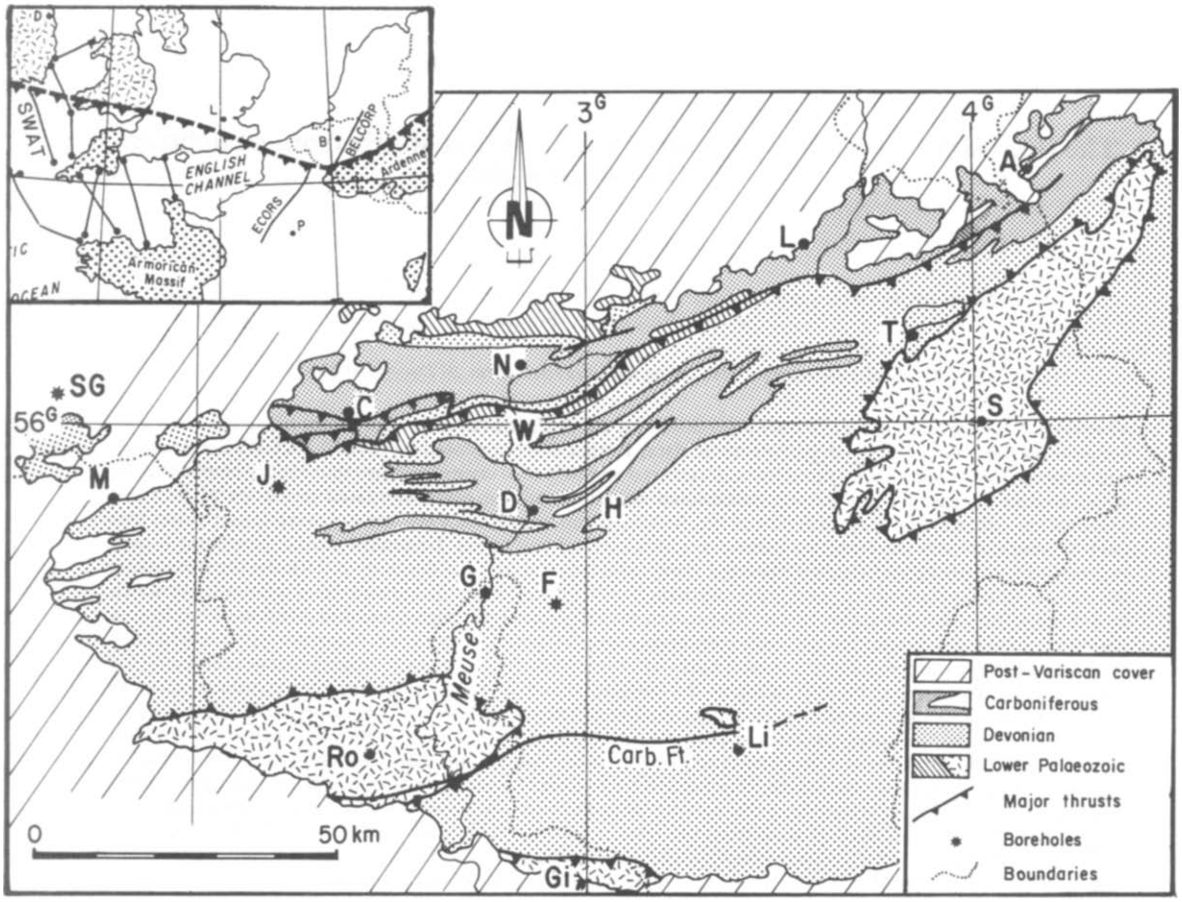

Fig. 1. Geological sketch map of the Ardennes Variscan belt. Inset shows the location of the Ardennes massif in the northern European Variscides. A, Aachen; Carb. Ft, Carbonnière Fault; C, Charleroi; D, Dinant; E, Epinoy; F, Focant; G, Givet; GH, Grand-Halleux; Gi, Givonne; H, Havelange; J, Jeumont; Li, Libramont; M, Maubeuge; N, Namur; R, Rocroi; S, Stavelot; SG, Saint-Ghislain; T, Theux; W, Wépion.

GEOLOGICAL BACKGROUND

As a result of a broadly N–S-trending compression acting at the end of Carboniferous times, the structural framework of the Ardennes E–W elongated belt is arranged into three arc-parallel zones comprising, from north to south (Figs. 1 and 2) : (1) the Brabant Lower Palaeozoic foreland, which has only experienced Caledonian deformation (Michot 1977), and which is unconformably overlain in the south by; (2) the thin Devono-Carboniferous sedimentary wedge of the Namur syncline. This latter includes Middle Devonian to Westphalian C sequences (Waterlot *et al.* 1973) that display a complex sedimentary pattern resulting from superimposed N–S and E–W facies and thickness variations (Colbeaux *et al.* 1977, Becq-Giraudon 1983). The E–W lateral changes are notably reflected in the interfingering of an anhydritic series (Epinoy–St-Ghislain area, Fig. 1) into dominantly carbonate Dinantian deposits (Rouchy *et al.* 1984). In the south, the inverted limb of the Namur overturned syncline is overstepped along the Midi Thrust by; (3) a thin slice of Silurian rocks (the Condroz Unit) assumed to represent the southern allochthonous extent of the Brabant Caledonian basement (Fig. 2a), and which is in turn overridden by the southward-thickening clastic sequences of the Dinant extensive fold nappe (Fourmarier 1954). Further south in the Stavelot, Rocroi and Givonne areas, some other Palaeozoic rocks are exposed as isolated massifs enclosed within the Dinant Devonian succession.

INTERNAL STRUCTURE OF THE DINANT NAPPE

(1) *Structural data*

The most striking feature of the Dinant Nappe is the abrupt tectonic change occurring between the low-strain Upper Palaeozoic series and the highly deformed Cambrian rocks of the Rocroi inlier (Beugnies 1963).

(a) The Rocroi Cambrian flysch-like sequences are involved in a high-strain ductile deformation that can be confidently assigned, in agreement with Hugon's model (1982), to N-directed ductile shearing. In fact, most of the structures range from recumbent to N-overturned syn-cleavage folds with extremely curved hinge lines, thus widely distributed within the E–W-trending pervasive schistosity plane (S_1). They however tend to concentrate towards a conspicuous N170° stretching lineation (L_1) (Fig. 3a) that also represents the direction of regional shearing. The northerly sense of shearing is clearly witnessed by rotational movements occurring

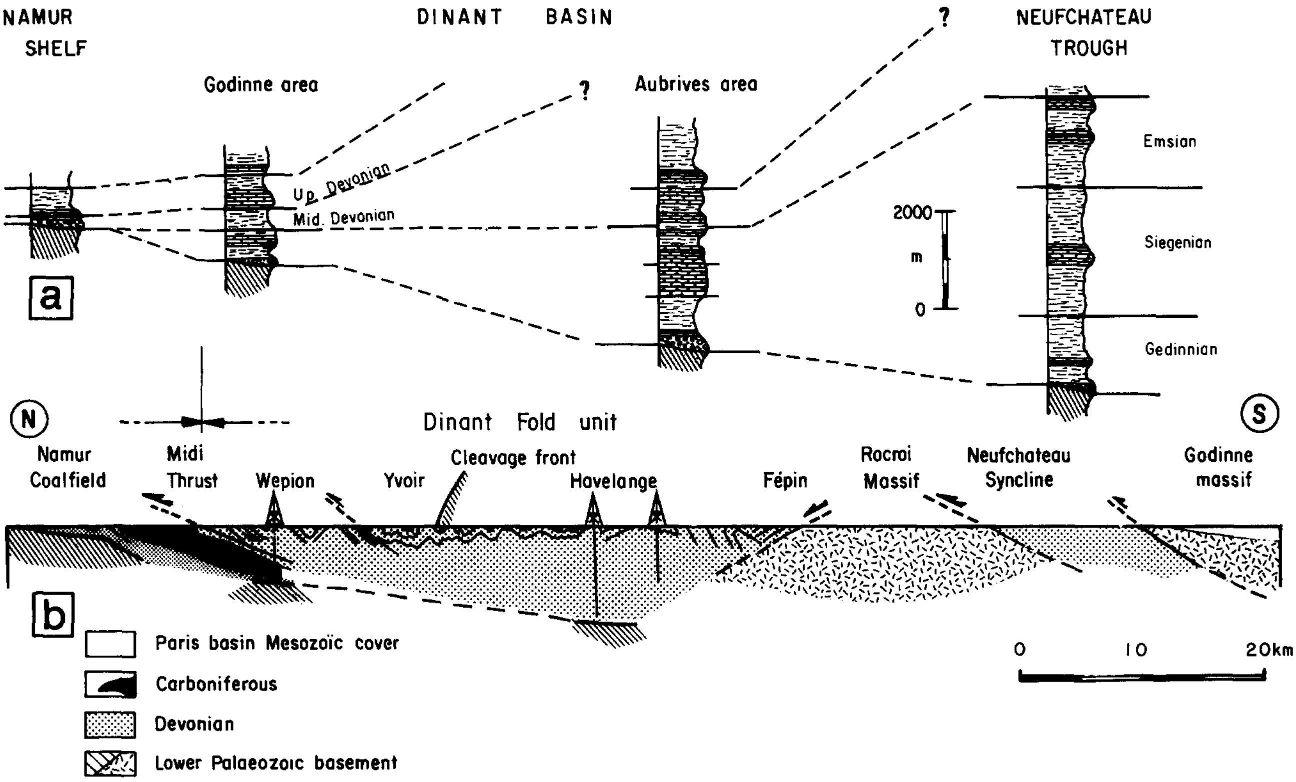

Fig. 2. Major tectono-lithostratigraphic units observed along the Meuse River cross-section (see location in Fig. 1). (a) Simplified lithostratigraphic columns illustrating progressive southerly thickening of Lower Devonian deposits from the Namur to Neufchâteau areas, compiled from Waterlot *et al.* (1973). (b) Diagrammatic structural section showing the main fault-bounded units (the Havelange borehole is projected).

along L_1, and also by the slight angular obliquity of S (cleavage) and C (shear) planes (Fig. 4b).

As clearly shown on the cross-section in Fig. 3(b), the attitude of the schistosity plane changes gradually northwards from moderately S-dipping in the Bogny area, to an almost flat-lying geometry in the Fepin zone (Klein 1980). The origin of this large-scale flattening is discussed below. As microtectonic analyses of thin sections have never provided any evidence for earlier penetrative fabrics overprinted by the prominent shear-related structures, the Rocroi Cambrian series are therefore believed to have experienced only a single deformation, the timing of which remains to be clarified, as well as the way it links up with the moderately strained structures of the overlying Devono-Carboniferous succession.

(b) The structural style of the Devono-Carboniferous is well displayed along the northern part of the Meuse River section where it consists of broad upright to gently overturned synclines and anticlines (Raoult & Meilliez 1985), leading to a large-scale arcuate cylindrical map pattern (Fig. 1). The axial planes of these concentric-type folds are marked within incompetent pelitic layers by a steep and spaced cleavage which vanishes progressively northwards, towards a schistosity front running close to Dinant (Fig. 2b). Along the Fepin–Midi Thrust segment, horizontal bulk shortening has been estimated on top of Givetian limestones as being at least 40%. It is also accommodated, to a lesser extent, by minor N-directed thrusts as in the Yvoir structure (Fig. 2b) (Raoult & Meilliez 1986). In order to carry out a comparative structural analysis of both Cambrian and Devonian basal sequences, detailed fieldwork has been focused along the periphery of the Rocroi inlier where the concept of an 'Ardennes unconformity' was formerly defined (Waterlot 1937). This notion involves a polyphase structural evolution in which a weakly folded Devonian cover rests unconformably upon a previously sheared Caledonian basement. However an alternative model implying a single Variscan deformation has also been proposed (Kaisin 1936, Hugon 1982), and is largely supported in this study by new field evidence acquired along the northern and southern fringes of the Rocroi Massif.

(1) To the south, the contact between Cambrian rocks and the overlying Devonian basal conglomerates is well exposed. In most cases (Bogny, Montcornet, Roches à Corpias sections), it corresponds to a sharp ductile shear plane, weakly inclined to the SE, which separates two conformably superposed units displaying similar high strain deformation. Indeed, the S-dipping cleavage planes developed within the Cambrian quartz-pelitic rocks cut through the sheared contact and pass continuously upwards into the Devonian coarse conglomeratic sequences (Fig. 4b). Though much more competent, these latter also contain well-marked (S) and (C) planes whose angular relationships still indicate a N-directed shear occurring along a persistent N170° stretching lineation defined by intensely elongated clasts and pebbles (Fig. 4). Thus, the 'Ardennes unconformity' model fails to explain the overall observed micro- and macroscopic structures as well as the geological relationships that, on the contrary, testify to a single

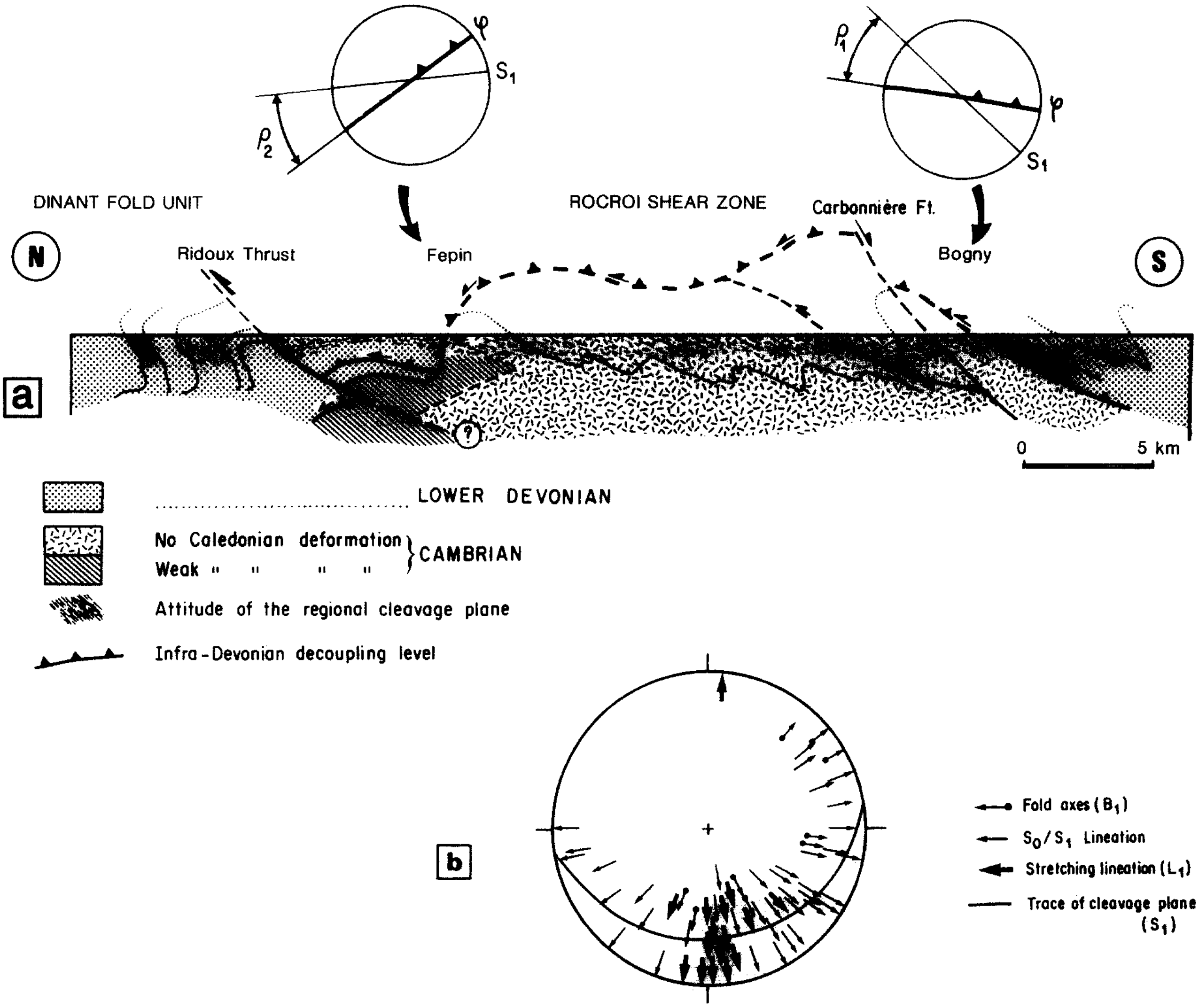

Fig. 3. Structural elements of the Rocroi shear zone. (a) Schematic cross-section showing refolding of early structures as the S_1 cleavage, and the shallow infra-Devonian decoupling level. These two structures keep a constant angular relationship during bulk rotation ($\beta_1 = \beta_2$). Note: (1) the southerly extensional component of the Carbonière Fault, and (2) the existence of a preserved angular unconformity along the northern border of the Rocroi inlier (see discussions in text). The internal folding structure is from Hugon (1982). (b) Lower-hemisphere, equal-area projection of shear-related structures from the Rocroi Cambrian unit.

post-Lower Devonian shear deformation, hence undoubtedly Variscan in age.

This assertion is fully supported by the following additional structural and chronological data. Along the eastern margin of the Rocroi inlier, the S_1 cleavage strikes without any deflection from the Cambrian to the Devonian adjoining rocks (Fig. 1), thus suggesting that this area has only undergone a single syn-cleavage deformation during post-Devonian times; also K–Ar dating of syn-kinematic white micas from the Cambrian Rocroi pelitic schists have yielded ages of 335 ± 7 Ma that clearly indicate a Variscan orogenic event (Piqué *et al.* 1984); lastly, the Rocroi Massif is demonstrably intruded by a swarm of magmatic dykes that are locally intensely folded (Meilliez 1981), and thus pre-date the regional shearing. These intrusions, recently dated as 373 ± 8 Ma (U–Pb zircon) (Gofette *et al.* 1991), can be correlated, in the Libramont area (Fig. 1), with post-Devonian dykes (Beugnies 1963) and also with tonalitic complexes of the Stavelot Massif, dated at 381 ± 16 Ma (Kramm & Buhl 1985). Such dating undoubtedly attests to the Variscan age of the whole Rocroi deformation. Away from the edge of the Rocroi Massif, syn-cleavage structures change gradually southwards through the Neufchâteau syncline as involving younger Devonian sequences (Fig. 2b). In fact, the cleavage (S_1) becomes less penetrative whereas the associated stretching fades progressively, both together reflecting a significant decrease of shear strain in higher structural levels.

(2) The northern rim of the Rocroi inlier exhibits a quite similar structural pattern. Indeed, in the Fépin area (Fig. 2b), the Cambrian pelitic series and its overlying Devonian conglomerates with elongated pebbles, both in a steeply dipping position, are commonly affected by a single flat-lying or weakly N-dipping slaty cleavage (Fig. 3b) that clearly post-dates the basal sheared contact, and that here characterizes a large-scale downward-facing structure (Fig. 3b). By allowing for the bulk rotation undergone by the regional structures, *S* and *C* planes are seen to keep similar angular

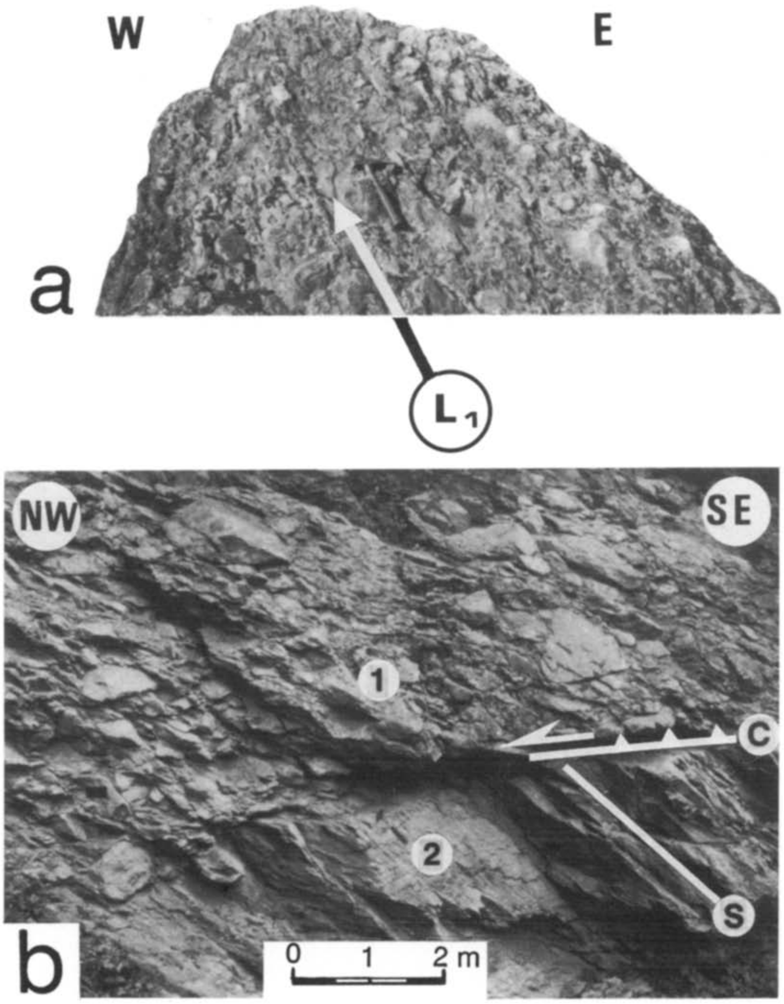

Fig. 4. Evidence of high-strain shearing in Devonian basal conglomerates (Bogny Formation) surrounding the Rocroi Cambrian inlier. (a) Stretched quartzitic pebbles in a coarse clast-supported conglomerate gently inclined to the south (Rocher de l'Hermitage, Bogny, southern border of the Rocroi Massif). (b) Highly sheared contact between conformable Cambrian quartzo-pelitic series (1), and Gedinnian basal conglomerates (2). The two units display a similar high-strain shearing whose northerly vergence is clearly indicated by the obliquity of cleavage (S) and shear (C) planes (Roches à Corpias, southeastern border of the Rocroi Massif).

relationships to those observed along the southern area (Fig. 3b). North of the Fépin border zone, tectonic style changes abruptly throughout the Gedinnian formations as clearly observed along the Meuse Valley section. The intensely cleaved and sheared flat-lying schists that immediately overlie the Fepin conglomerates (Lower Gedinnian Oignies Formation), give way rapidly northwards to moderately deformed shale–quartzite alternations affected only by broad upright folds (Upper Gedinnian St-Hubert Formation). These low strain structures then extend throughout the whole Dinant Unit as far north as the Midi Thrust. The rapid transition between the two tectonically contrasted Gedinnian sequences might be related to a significant N-directed thrust, called here the Ridoux Thrust, although no major stratigraphic break has been so far documented through the inferred transition zone. Some of these structural variations have been considered by Hugon (1982) to indicate a large-scale N-verging shear zone, soled by thick Cambrian high-strained series, and which decreases in intensity upwards within Devonian. However, this kinematic model, restrictively applied on the Rocroi Massif and its immediate borders, does not account for some structural complexities, such as the large-scale flattening displayed by the S_1 cleavage perpendicular to the strike of the belt.

Hence, this previous tectonic model needs to be improved, and broadened in scale in order to explain the overall tectonic environment of the Rocroi Variscan shear zone. Such an attempt is now made by considering the ECORS deep seismic data that are briefly discussed below.

(2) *The ECORS deep seismic data*

Up to now, only one structural interpretation of the ECORS profile has been proposed (Cazes *et al.* 1985, Raoult 1988). Based upon an unmigrated section, this led to an oversimplified thrust model of thin skinned type that did not involve, for example, the internal deformation of the Rocroi Massif which was assigned by these authors to a previous Caledonian orogenic event. That thrust model is dominated by a shallow flat-lying structure—the Dinant Décollement—which was assumed to underlie both the Dinant and the Rocroi units over a distance of about 120 km, from its northern merging line (the Midi Fault) to its root zone located close to the steep Bray Fault (Fig. 5a). A more detailed interpretation of the ECORS profile can be proposed on the basis of a new migrated line-drawing, which is here complemented by additional explosive shot data (Damotte 1988). (All the structures discussed below are shown on Fig. 5a by specific numbers.)

Concerning the Dinant Décollement, it now appears as a more irregular structure comprising, to the north, an almost flat-lying segment located at about 2 s on the two-way travel time section (TWT) between shot points 100–500, e.g. beneath the Devonian of the Dinant Unit (structure 1). Using both published stratigraphic thickness data (Waterlot *et al.* 1973) and currently accepted interval velocities (Devonian, $V = 4.4–4.8$ km s^{-1}; Lower Palaeozoic, $V = 5.5–5.8$ km s^{-1}), it is inferred that the Dinant Décollement would lie in a depth-converted section at about 6–7 km depth, that is approximately the depth of the base of the whole Devonian succession as deduced by Graulich (1982) from the projected Havelange borehole data (Fig. 5a). In addition to the fact that north of the Rocroi Massif no pre-Devonian substratum rocks (except the Condroz slice) are caught up within the Dinant fold–thrust belt, this result strongly suggests that the Dinant Décollement lies close to the basement–cover contact. A similar thrusting pattern is also suggested further north, beneath the Namur external coalfield, by first-hand subsurface commercial data (work in progress). To the south, between shot-points 500–800, e.g. beneath the present-day Rocroi Massif, the Dinant Décollement dips gently to the north before stepping abruptly downwards, at shot point 1150, into a moderately S-dipping structure (structure 2), likely to represent a major Variscan ramp thrust, called here the Rocroi Thrust. It continues down-dip through the upper crust, as far south as point (3), where it flattens and then extends continuously at about 20 km depth (structure 4). This lower décollement underlies a highly reflective portion of crust, with short horizontal and low-amplitude events (structure 5) that can be regarded, in agreement with other previous seismic experiments (Jones & Nur 1984), as flat-lying mylonitic fabrics, here developed within a 5–6 km thick ductile shear zone.

The almost transparent overlying upper crust is transected by S-dipping Variscan thrust-like structures that flatten southwards into the basal shear zone, and that are sealed to the north by the Mesozoic cover of the Paris Basin. One of the more prominent structures, called here the Givonne Thrust (structure 6), would merge, if projected up-dip northwards, close to the western prolongation of the Givonne inlier (Fig. 1), hence suggesting that this later constitutes a Variscan allochthonous basement thrust sheet carried northwards over the Neufchateau Devonian folded series.

Further south, other S-dipping structures occur (structure 7), in close association with either lens-shaped highly reflective packets (structure 8), or almost featureless portions of crust (structure 9). These peculiar seismic signatures are respectively assigned to mafic bodies and granitic intrusions, on the basis of related gravimetric and magnetic anomalies (Galdéano & Guillon 1988), as well as by analogy with similar seismic structures observed elsewhere on well-constrained profiles (SWAT—BIRPS & ECORS 1986 or CHARM—Maguire 1987 sections).

In the northern part of the section, the crust constituting the footwall of the Dinant–Rocroi thrust system is much more transparent, but it still contains two sets of reflections that comprise (1) deep S-inclined Variscan thrust-like structures occurring just beyond the Rocroi ramp (structure 10), and (2) shorter N-dipping events widely scattered through the crust, as far north as the end of the profile (structure 11). The latter are likely to represent the deep trace of S-directed Caledonian struc-

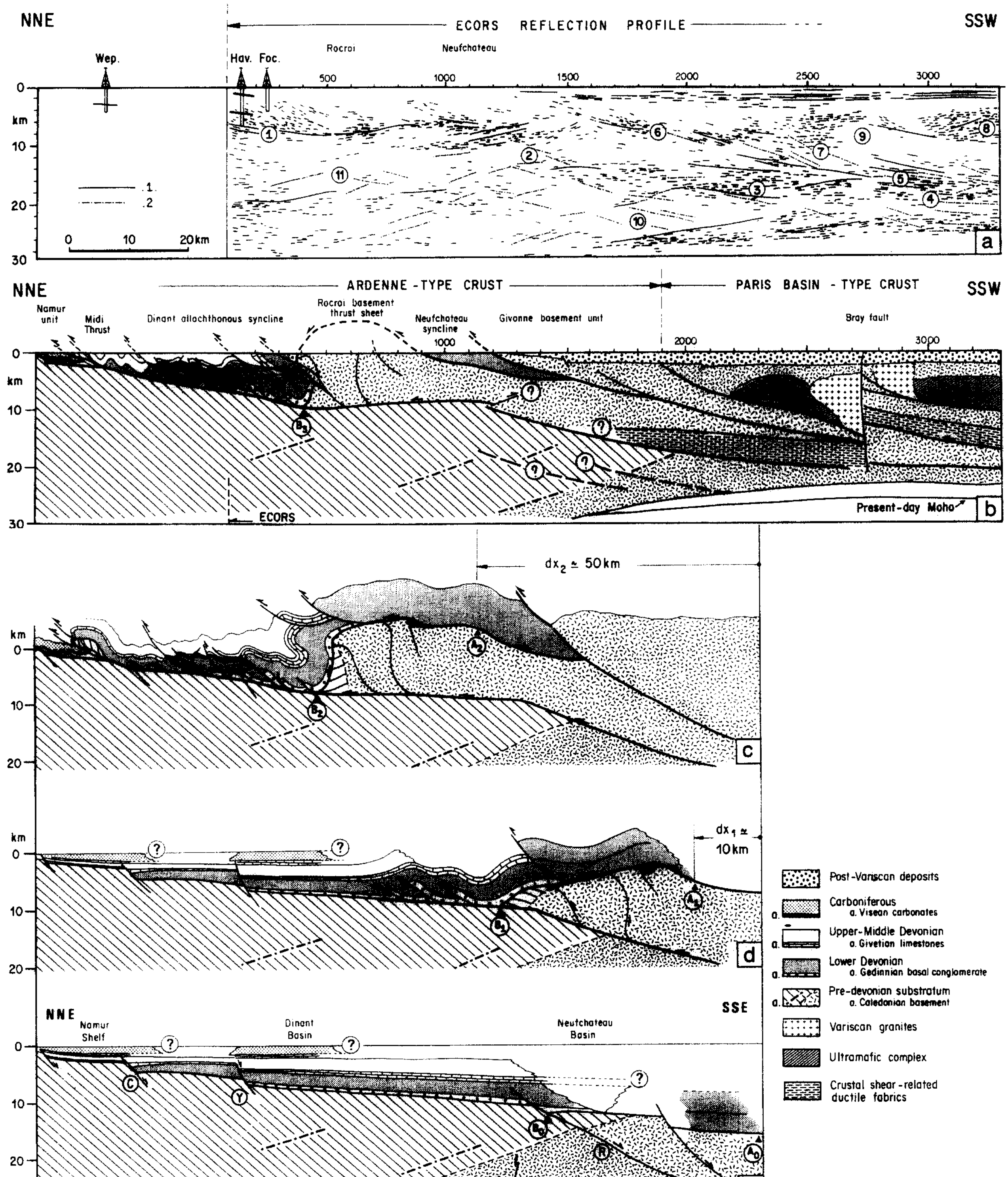

Fig. 5. Deep structure of the Ardennes Variscan fold–thrust belt. (a) Migrated time line-drawing of the northern segment of the ECORS seismic reflection profile. Reflectors provided by (1) a vibroseismic source and (2) a dynamite source. Numbers refer to structures discussed in text. (b)–(e) Evolutionary thrusting sequence through the Ardennes margin along the Namur–Neufchâteau transect, from a final stacked geometry (b) to an early basinal template (e). The shallow structures are constrained by the Meuse River cross-section, and by deep boreholes projected onto the section (Foc, Focant; Hav, Havelange; Wep, Wépion). Section is line balanced only along the Namur–Neufchâteau segment where bulk shortening is estimated at 70 km. The frontal tectonic pattern is discussed below, and the deep structural complexities occurring along the base of the Dinant detached unit (see cross-section of Fig. 7b) are not drawn on the section (b).

tures largely exposed further north in the Brabant Foreland (Michot 1977), and that therefore could testify to the southern extension of the Caledonian autochthonous basement edge beneath the Dinant Devonian detached cover, as far south as the Rocroi frontal ramp.

(3) *Tectonic model*

On the ECORS profile, the portion of crust involved in the Variscan shortening appears as a wedge-shaped zone thickening southwards above a floor thrust that displays a staircase trajectory. According to long-established stratigraphic evidence from the Devono-Carboniferous succession, the Ardennes Variscides are classically considered to represent a previously stretched continental margin dismembered into E–W fault-bounded basins that deepened gradually southwards along S-dipping normal faults (Fourmarier 1954). Some of these syn-depositional structures, like the Yvoir or Condroz faults (Houchen 1988) (Figs. 2 and 5), are clearly marked by abrupt changes in the Devonian stratigraphy.

The ECORS seismic data strongly support such a tectonic model, and furthermore provide additional constraints for the deep crustal geometry of the inferred extensional faulting. In fact, restoring the initial length of the stratigraphy within the Dinant folded unit can be achieved using Givetian limestones, so that the transitional zone between the 6 km-thick Neufchâteau Lower Devonian sequences and the 3 km-thick contemporaneous deposits laid down further north in the Dinant Basin, would be located above the Rocroi S-dipping ramp (Fig. 5e). This ramp is hence likely to represent a reactivated crustal-scale extensional fault along which the Neufchâteau trough was downthrown to the south during Devonian times. Its original listric geometry seems to have been preserved within the pre-Devonian substratum in which it is seen to lie, on the restored section, close to a Caledonian orogenic front that separates a northern Brabant-type deformed basement from a Rocroi-type undeformed substratum to the south (Fig. 5e). This Devonian crustal extension may have once led to the formation of some oceanic crust in the south, as suggested by the occurrence of ophiolitic-like complexes within the Variscan imbricate thrust stack observed at the present-day.

It is beyond the scope of this paper to discuss the plate tectonic setting of the Ardennes margin because such an attempt, still highly controversial (see Meissner *et al.* 1984 or Weber 1984), would require much detailed discussion. Only the intra-continental collision undergone by the outer Ardennes crust, subsequent to ocean consumption, is considered here. Concerning the timing of crustal shortening, regional stratigraphic evidence suggest a diachroneity of deformation through the Ardennes belt with an orogenic wave moving towards the foreland; indeed, thrust-related uplifts might have started as early as the Lower Carboniferous in the southern innermost zones, as inferred from the first arrival of exotic S-derived clastic material in the Namur depositional area (Graulich 1963), while the deformation of this external domain is undoubtedly post-Westphalian in age. Together with a restored width of about 120 km for the Namur–Neufchâteau basinal area, this timing indicates a quite normal forward propagation rate of about 3 cm a^{-1}.

In the innermost zones, crustal shortening was accommodated by a complex deformational process combining both large-scale thrusting with more penetrative ductile shearing at depth. Thrusting was mainly achieved by a synthetic set of S-dipping ramps that penetrated deeply into the basement before soling southwards into a 6–7 km thick low-angle mid-crustal decoupling shear zone actually located at about 20 km depth on the ECORS profile. Crustal shearing is supposed to have propagated to the north through the whole hangingwall of the Rocroi normal fault (Fig. 6), and, according to the present-day surface Rocroi geology, the geometry and kinematics of the shear fabrics may have changed gradually upwards from high-strain flat-lying ductile fabrics in

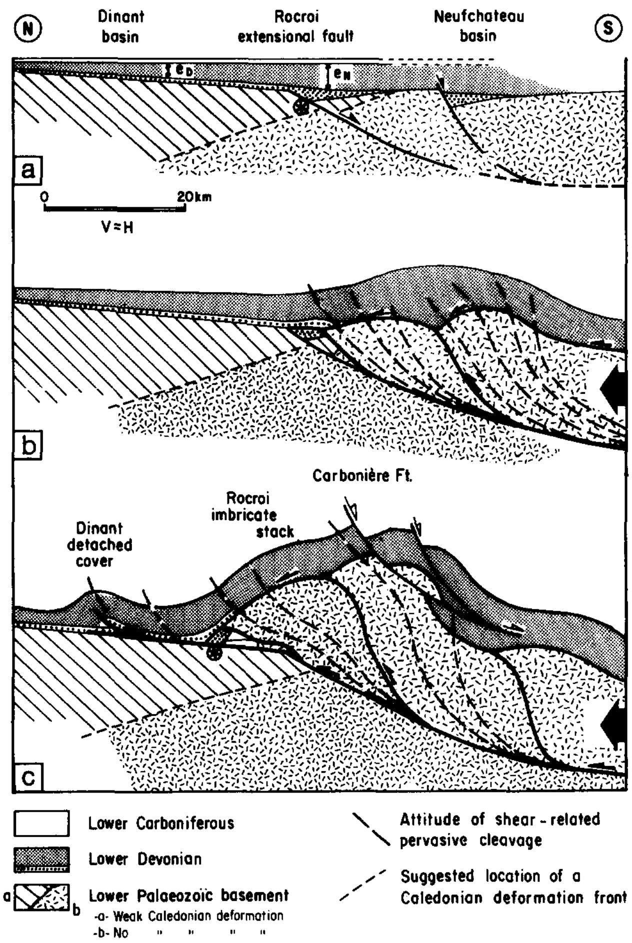

Fig. 6. Sketch sections illustrating evolution of structures developed in the hangingwall of the Rocroi Fault. (a) Devonian extensional template. Thickness data compiled from Waterlot *et al.* (1973) (e_d = 3 km; e_n = 6 km). Only the geometry of the cleavage plane (S_1) and of the Lower Devonian envelope is drawn (the shear-related internal fold structures are not depicted). (b & c) Compressional structures related to early stage of shearing (b), and to ramping (c) along the Rocroi reactivated fault. Note: (1) the progressive downward shallowing of S_1 along a possible ductile decoupling zone, and (2) an unconformable stratigraphic pattern locally preserved along the Rocroi hangingwall ramp (*, present-day northern border of the Rocroi inlier).

the Cambrian strata to progressively steeper and more brittle structures in the overlying Devonian sequences. Prior to cleavage development, some bedding-parallel sliding is likely to have taken place along preferential decoupling zones such as the infra-Devonian shallow basal plane (Roches à Corpias section, Figs. 3 and 4), which may have constituted the roof-thrust of the intra-basement duplex formed at depth by the hinterland-dipping ramps.

The amount of crustal shortening achieved by ductile shearing and thrusting in the innermost zones cannot be estimated due to the lack of any direct control along the southern part of the section, and the absence of good stratigraphic markers in the Rocroi inlier. The high-level granitoids emplaced in the south may originate from this thrust-related crustal overthickening which is no longer imaged on the ECORS profile due to its later remobilization by the layered lower crust.

The overall sequence of crustal thrusting, which is supposed to propagate in a piggy-back way, also admits some 'out of sequence' structures, such as the Givonne Thrust that clearly oversteps the infra-Devonian roof thrust, carrying a basement slice northwards over the Neufchâteau Devonian folded series (Fig. 5b). As commonly stated for many other orogens (Morley 1988), the development of such out-of-sequence thrusts may have been facilitated by pre-existing extensional discontinuities that here display a quite favourable orientation at a high angle to the regional maximum compressive stress. The best example of such reactivation is provided by the Rocroi frontal ramp whose early syn-depositional normal component has also been assessed. In order to account for the present-day high structural position of the Rocroi Cambrian sheared rocks, and also for their large-scale superimposed internal fabrics, the previously sheared hangingwall of the Rocroi listric normal fault is likely to have climbed northwards along the Rocroi reactivated fault, and then to have been stacked and uplifted as a whole. The resulting culmination would have induced the doming of the shallow infra-Devonian roof-thrust, as well as the large-scale arching of earlier ductile fabrics, which are locally involved in downward-facing structures. Hinterland-directed extensional gravity sliding may have also formed at the rear of the thrust imbricates, and it is here suggested that the well-known E–W Carbonnière Fault (Figs. 1, 3a and 6), which was recently interpreted as a post-Variscan normal fault with a southerly downthrow (Beugnies 1983), could instead represent a Variscan thrust-related extensional structure. However, the general thrusting model presented here must be somewhat refined to account for peculiar structures locally observed along the northern border of the Rocroi inlier. They concern Devonian basal conglomerates that rest unconformably upon weakly deformed Cambrian pelites whose broad upright folds, devoid of any pervasive cleavage, are assigned to a slight Caledonian compression (Meilliez 1981). Such a tectonic setting has two major implications for the overall deformation of the Ardennes zone:

(1) as no Caledonian structures have so far been recognized further south in the Cambrian rocks, a Caledonian orogenic front must lie within the Rocroi Massif (Fig. 5), as already assessed from ECORS seismic data;

(2) the fact that both the Devonian and Cambrian rocks locally show very little internal Variscan deformation (i.e. unreactivated unconformity and no evidence of high strain shearing) must be ascribed to their initial location in the Devonian extensional setting. Indeed, the northerly tilt of the Rocroi hangingwall may have later caused the basal décollement to cut up-section stratigraphically northwards into the Devonian, whilst remaining at a constant structural level (Fig. 6); the so-preserved tilted pattern being subsequently translated and rotated northwards as a whole along the reactivated Rocroi Fault during large-scale ramping. On the ECORS profile, the leading edge of the Rocroi Massif lies at about 40 km north of the basement footwall ramp, and that indicates a minimal 40 km northerly translation for the basement wedge along the Dinant shallow décollement. This estimate is fairly consistent with the 40% shortening measured at the front of the advancing slab in the Devonian clastic wedge of the detached Dinant N-overturned syncline. This high-level deformation is hence mostly accommodated by a dominantly low strain fold buckling, and to a lesser extent, by additional N-directed thrusts that formed in two different ways:

(a) flat-lying shear planes develop along the steep Rocroi hangingwall ramp which is intensely disrupted by the inferred Ridoux Thrust, and also by low-angle thrusts identified (Graulich *et al.* 1990) further north in Devonian sequences of the Havelange borehole (Fig. 5). These shears are assumed to root down southwards along the shallow Dinant master décollement;

(b) steeper S-dipping ramp thrusts cut through the gently inclined normal limb of the Dinant syncline where they nucleate along previous Devonian extensional structures, such as the Yvoir or Condroz faults; the related thrusting displacements do not exceed the early normal downthrow (Houchen 1988).

According to this new crustal-scale thrusting model, the Rocroi Cambrian inlier is now regarded as a far-travelled basement wedge, actually occurring as a tectonic window beneath its eroded Devonian detached cover. A quite similar model could also be applied to the nearby Stavelot Cambrian inlier to account for some well-known, but not fully understood, regional structures such as the Theux window (Fig. 1) (work in progress).

Finally, the arcuate Rocroi–Libramont–Stavelot basement-cored zone would represent the northern limit of allochthonous basement thrust sheets rooting down southwards along a major reactivated Devonian extensional fault, rather than a simple anticlinal hinge zone, as classically stated (Dumont 1847).

The frontal tectonics of the Dinant Nappe can now be described in order to define the way it links up to the north with the structures of the Namur external coalfield.

THE FRONTAL THRUST PATTERN

The Dinant Nappe is limited to the north by the rectilinear Midi Thrust, which marks a major lithostratigraphic and strain boundary separating the thick and regularly folded Dinant Devonian sequences from the Namur syncline whose series, totally devoid of Lower Devonian, are involved into a much more complicated fold–thrust system. This is clearly suggested on the tectonic map (Fig. 1), which shows an increasing complexity towards the west: the upright basement-cored folds of the Andenne area giving way in the Wépion zone to N-directed thrust sheets that, in turn, grow in importance further west in the Charleroi area where numerous isolated klippen of Namur-type series overlie Culm folded sequences (Dejonghe *et al.* 1973, Beugnies 1976).

The origin of this E–W anomalous tectonic gradient, quite oblique to the N–S Variscan compression, is not discussed here (work in progress); it should only be said that it probably reflects the influence of early extension-related basinal structures which have long been postulated from stratigraphic evidence (Becq-Giraudon *et al.* 1980, and references cited therein). The frontal tectonics are illustrated here by a single balanced cross-section which, though extending through the Wépion low-strain area, is assumed to be representative of the frontal thrust belt as a whole (Fig. 7b). Mainly constrained by the Meuse Valley geology and the Wépion borehole data, it displays some analogies with Houchen's (1988) thrusting model, although differing significantly in several respects. According to surface geology, the footwall of the Midi Thrust appears as a relatively simple N-overturned syncline whose northern flank, gently inclined to the south, rests unconformably to the north, over the Brabant basement (Figs. 7a & b). To the south, moderately folded Namurian coal-bearing strata are overridden along the Malonne low-angle fault (Graulich 1961) by a steep thrust sheet, composed of a complete Namur-type succession, and issued from slicing of the inverted southern flank. It is, in turn, fringed to the south by a thin slice of Silurian schistose rocks, long known as the Condroz anticline, that gives rise further south to the Dinant Nappe. Given the particular position of the Condroz slice it has been historically considered as a Devonian palaeo-high separating the Namur shallow shelf from the Dinant subsiding basin (Fourmarier 1954). However, due to poor exposure, its structural significance with respect to the frontal thrust pattern, and more especially to the Midi Thrust, is still controversial, giving interpretations which vary from that of an autochthonous basement-cored anticline (Raoult & Meilliez 1985) to that of a blind décollement-related structure (Houchen 1988).

An alternative interpretation is proposed here and illustrated by a couplet of balanced and restored sections (Fig. 7b) that have been constructed from the following observations:

—on the tectonic map (Fig. 1), the Namur syncline is sharply truncated to the south by the Condroz Unit which hence constitutes the immediate hangingwall of the Midi Thrust, and also clearly post-dates the Namur frontal structures;

—a steep S dip, estimated at about 40°, is required for the Midi Thrust to account for its present depth (450 m) in the Wépion borehole (Graulich 1961) which has been drilled at only few hundreds metres south of the thrust emergence line;

—beneath the Namur coalfield, the top of the basement is assumed to display a staircase geometry. Indeed, it has been drilled at 2300 m depth in the Wépion borehole (Graulich 1961), and to account for both surface geology and lithostratigraphic thickness data, it must extend to the north at a moderate angle, and reach the surface via a steep S-dipping fault. As this fault is supposed to have subsequently influenced the Variscan deformation (see discussion below), its present location is directly inferred from surface geology;

—reactivation of the top of the basement as a N-directed shear plane is strongly suggested further west, on reinterpreted commercial seismic lines recorded through the Maubeuge area (Fig. 1) (work in progress). On the other hand, evidence for the deeper intra-basement décollement required by Houchen's (1988) thrust model has not been so far found;

—the initial length of the Namur-type detached sequences has been restored by (1) assuming a minimal amount of fold-related shortening, and (2) estimating the cumulative horizontal displacements achieved along the low-angle shear faults (about 2 km).

On the restored template (Fig. 7e), the Namur shallow shelf would hence extend at least 8 km south of the present Midi Thrust emergence line, before stepping abruptly southwards along the Condroz fault scarp. The southerly downthrow of the top of the basement is estimated at about 1500–2000 m to account for the thickness of Lower Devonian accumulated in the Dinant tilted area (e_d in Fig. 7e) (Waterlot *et al.* 1973).

One of the simplest models to explain the present-day thrust geometry is to invoke significant slicing of the Dinant infra-Devonian décollement through the basement in the footwall of the Condroz normal fault. The extremely narrow surface outcrop of the Condroz thrust sheet probably indicates that only a thin wedge of basement has been caught up into the frontal thrust as a result of rapid ramping of the basal décollement up to the base of the Namur Devonian cover. Subsequent uplift and translation of the whole hangingwall along the basal thrust may have N-rotated steep pre-existing structures and hence favoured dip-slip reverse movement. That is the case for the Condroz fault scarp whose thrust reactivation (Condroz Thrust) is here responsible for the emplacement of the Dinant clastic wedge onto the Namur coalfield.

At that stage, the frontal thrust pattern appears to have been composed of two lithologically contrasting cover sheets (Dinant and Namur), separated by a thin basement wedge (Condroz), and that accommodate quite differently internal shortening: the thick Devonian of the Condroz hangingwall (Dinant Unit) being in-

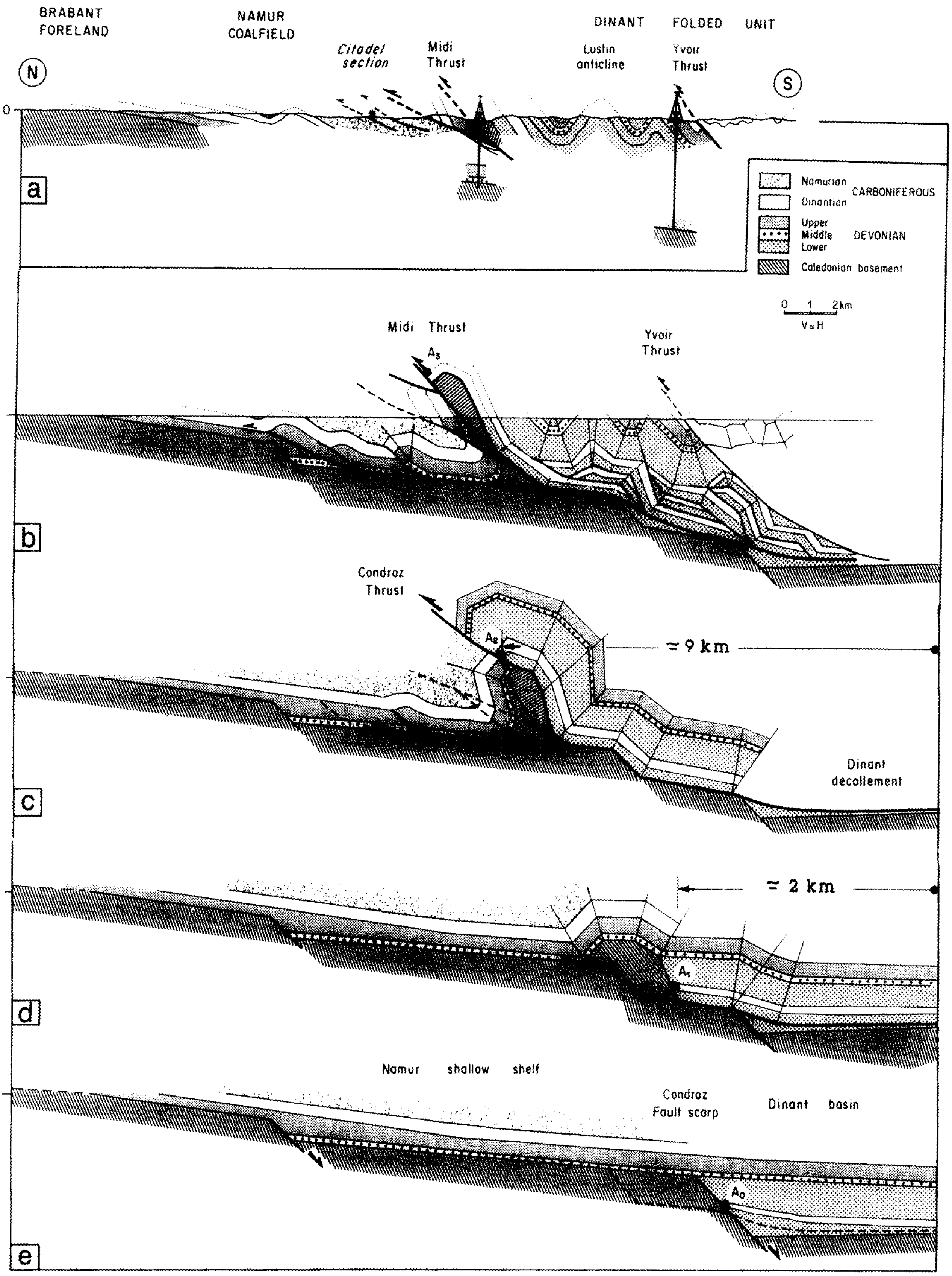

Fig. 7. Structural cross-sections through the Midi thrust zone showing the deep structure of the Namur syncline. (a) Geometrical data, mostly supplied by the Meuse River section and the Wépion borehole (Graulich 1961), and used to constrain the balanced (b) and restored (e) cross-sections.

volved in undisrupted broad upright folds with a wavelength of about 2 km, while the footwall, mainly composed of Namur Carboniferous succession, displays large-scale asymmetric fold structures dismembered by low-angle shear faults in the south. The Namurian coal-bearing strata of the Namur Unit locally show, on restored cross-sections (Namur Citadel section, see location in Fig. 7a), bulk horizontal shortening estimated at about 20%, that suggests some thrust imbricate at depth in Dinantian and Devonian competent strata. As also shown on the section in Fig. 7(b), subsequent ramping of the basal décollement along a still preserved Devonian extensional fault scarp may be responsible for the gentle frontal folds exposed north of Namur.

During final compression, some rotated surfaces are reactivated as out-of-sequence thrusts, such as the Midi Thrust, which is here regarded as resulting only from minor reverse movement along the basement–cover contact of the Condroz wedge. Therefore, despite its prominent character on the present-day tectonic map (Fig. 1), the Midi Thrust would only cause minor uplift of the early Condroz major thrust which was later partly eroded.

Finally, from section balancing, bulk horizontal shortening of the entire Namur Shelf is broadly estimated at about 50% from an initial width of 18 km to a present width of 8 km. That is only a minimum estimate due to the imprecision related to displacements along the Condroz Thrust. In the frontal part of the Dinant Unit, some imbrications are likely to have developed at depth within the Lower Devonian rocks to account for both the present-day surface fold structure, and the inferred depth of the basal décollement (Fig. 7b).

CONCLUSIONS AND DISCUSSION

On the basis of both the ECORS revised deep seismic data and newly acquired microtectonic constraints, a large-scale tectonic model is applied to the entire Ardennes Variscan thrust belt. It is illustrated by a new balanced crustal cross-section, about 140 km in length, that not only provides some clues for the solution of long-lived regional problems, but also displays excellent examples of basin inversion tectonics related to collision.

Concerning the Variscan crustal shortening process, it is here considered to have been mainly achieved in the southern innermost zones by deep basement imbricate stack that developed above a thick ductile shear zone, actually located at about 20 km depth on the ECORS section; its roof-thrust is assumed to have been present close to the infra-Devonian cover contact. The so-defined basement duplex and its detached cover are believed to have been later translated northwards and uplifted as a whole, along a major frontal ramp thrust (the Rocroi Thrust), over an almost unreworked autochthonous Caledonian basement edge. The resulting hangingwall culmination successfully accounts for the present high position of the Rocroi Cambrian basement inlier, as well as for large-scale arching of its early internal structures. The ECORS data also suggest that the Rocroi basement wedge has been translated 40 km northwards along the Dinant infra-Devonian décollement, and that estimate is closely consistent with the 40% frontal shortening experienced by the detached Dinant fold-thrust unit. Though this estimate does not include significant pre-thrusting extension long documented from Devonian stratigraphic evidence (Fourmarier 1954), it is quite valid because it has been measured on sequences that post-date the Lower Devonian extension.

In order to depict this extension-related basinal geometry, a restored crustal cross-section of the Ardennes area has also been constructed by using structural and seismic constraints. This attempt has led to the recognition of two types of basin inversion structures through the Ardennes shortened margin. The first type of inversion mechanism, recognized along the Rocroi frontal ramp thrust, involves simple uplift along a pre-existing normal fault. The initial E–W orientation of this major Devonian extensional fault, as well as its listric shape, assumed to be still imaged on the ECORS line, may have greatly facilitated prominent dip-slip reverse movements during the N–S compression. It is here also suggested that the deep ductile shear zone underlying the basement stack to the south may also represent a reactivated mid-crustal Devonian extensional detachment along which Rocroi-type normal faults were likely to branch. The second type of inversion structures has been identified in the frontal thrust zone, and implies slicing of the Dinant Décollement through the footwall of the Condroz normal fault. The subsequent 6–7 km northerly translation of the Condroz basement wedge and its thick Devonian cover along the shallow sole thrust closely satisfies the 50% bulk frontal shortening undergone by the detached Namur-coalfield. With regard to the whole Variscan thrust pattern, the Midi frontal ramp would only represent a minor out-of-sequence thrust reactivating the rotated pre-existing basement–cover contact, instead of being the emergence line of the Dinant Décollement. Finally, the restored and balanced crustal sections applied to the Ardennes Variscan thrust belt assume a minimum shortening of about 45% from an initial 160 km-long extensional area to a final stacked crust about 90 km in length.

Lastly, some concluding remarks can be now proposed about the crustal structure of the NW European Variscan zone as a whole by comparing, for example, the deep geometry of the Ardennes and SW Britain crusts which have recently both been investigated by deep seismic profiles (ECORS, SWAT and WAM lines) (see inset Fig. 1) (BIRPS & ECORS 1986). The SW Britain traverse has already been fully discussed elsewhere (Le Gall 1990). Though long regarded as two distinct tectonic belts displaying contrasted surface geology and shallow seismic signatures (Brewer 1984, Matthews 1984), the Ardennes and SW Britain Variscides are now assumed to show at depth striking common crustal features that consist of (Fig. 8):

—a thick crustal wedge formed by basement imbricate stack, and intruded by high-level syn-kinematic granites (Cornubian batholith in SW Britain) that may be genetically linked to significant crustal melting at depth. It is overridden to the south, along an inferred suture zone (Lizard Thrust in SW Britain), by an innermost crustal unit (English Channel Unit in SW Britain), whereas it is

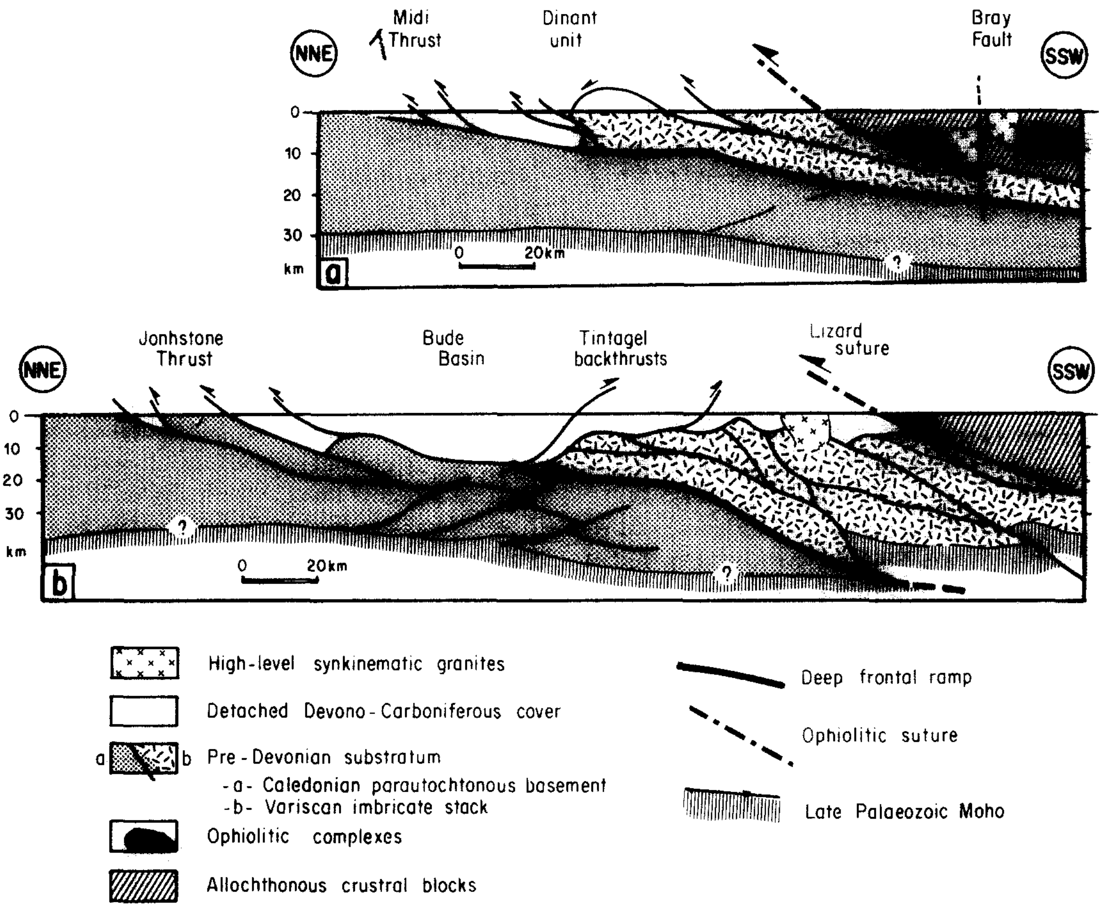

Fig. 8. Crustal sections showing the deep structure of (a) the Ardennes and (b) SW Britain Variscan thrust belts.

emplaced to the north, along a frontal ramp thrust, onto the outer edge of a Caledonian-type autochthonous (Ardennes) or parautochthonous (SW Britain) basement;

—a shallow roof-thrust, lying close to the infra-Devonian contact, and above which the Devono-Carboniferous cover is detached. To the south this master décollement is involved into large-scale upright refolding (Darmouth Antiform in SW Britain) formed above deep ramp-related basement culminations. These uplifted basement rocks are actually exposed (Ardennes), or not (SW Britain) through the cover thrust belt, only as a consequence of differential erosion levels.

Further north, the master décollement is perfectly imaged on the ECORS line as a flat-lying undeformed structure (Ardennes belt), while it is not observed on the SWAT section (British belt), possibly due to its subsequent deformation by deeper thrusts involving the footwall of the basement frontal ramp.

Across the frontal thrust zone, the shallow master décollement dies out as a blind thrust underlying the Carboniferous coalfield series, whereas the frontal thrust merges further south as a late minor out-of-sequence ramp (Johnstone Thrust in SW Wales) cutting through the basement of an early extensional fault scarp (Hancock *et al.* 1981, Coward & Smallwood 1984).

Despite all these strong structural analogies that suggest similar shortening mechanisms for both the Ardennes and SW Britain Variscan crusts, some significant differences nevertheless exist, and generally reflect a more complex geometry for the British zone. For example these complexities consist of: (1) high-strain ductile shearing in most of Devonian in the south; (2) back-thrusts and associated S-directed ductile deformation through the southern rim of the Bude Carboniferous basin (Sanderson 1979); (3) merging of the deep frontal basement-involving ramp (in the Bristol Channel); and (4) a shallow basement–cover imbricate in the footwall of the crustal frontal ramp.

Though these overall structural complexities have already been assigned to a more intense shortening of the SW British Variscan crust, in response to its impingement by the English Channel Block (Le Gall 1990), they could also reflect the direct influence of pre-existing extensional basin geometry. Only further detailed studies could really test this assertion, and therefore permit fruitful comparisons with the Ardennes belt or with other external segments of the Variscan Orogen.

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