Pergamon

PII: S0191-8141(97)00078-3

Journal of Structural Geology, Vol. 20, No. 1, pp. 33 to 42, 1998

0191-8141/98 $19.00 + 0.00

The 'Basse-Normandie' duplex (Boulonnais, N France): evidence for an out-of-sequence thrusting overprint

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(*Received* 5 *December* 1996; *accepted in revised form* 20 *September* 1997)

Abstract—The thrust-sheets outcropping in the 'Basse-Normandie' quarry (near the Hydrequent village, Boulonnais, N France) represents an exceptionally well exposed section of the NW European Variscan thrust front. These structures, developed in the footwall of the main Hydrequent thrust, have been often described as a classic example of a duplex structure. Only the lower part of the structure satisfies, however, the geometric and kinematic criteria defining a duplex (and more precisely an intraformational hinterland dipping duplex).

The upper thrust-sheets of the imbricate stack exhibit a much more complex pattern of deformation than a simple piggy-back duplication of the same rock sequence. Restoration of these thrust-sheets (based upon the definition of two marker beds as well as the analyses of fold–thrust relationships and strain markers) argues for a late NE verging thrust event that progressed within the thrust system from the tip of the upper thrust sheets towards the Hydrequent thrust in a local break-back style of thrust propagation. This out-of-sequence thrusting event induced refolding and cross-cutting of the forelimb of a hangingwall anticline developed previously above the footwall ramp of the NNE verging basal thrust of the structure. Within the whole thrust system, the lower duplex represents only a minor structure developed during the initial phase of thrusting in the foreland of the major anticline as a frontal second-order duplex.

The structural data presented in this paper illustrate the tectonic processes acting within the deformed zones lying in the footwall of major thrusts and emphasize the out-of-sequence style of thrust migration that arises from the sequential blocking of thrust propagation towards the foreland. © 1998 Elsevier Science Ltd.

INTRODUCTION

Duplex structures (Dahlstrom, 1970; Boyer and Elliott, 1982) have frequently been invoked in describing the geometry of thrust fronts within mountain belts. These structures, which imply the stacking of horses in between two thrust (or décollement) surfaces, are generally either evidenced by seismic imaging (Mitra, 1986) or inferred by map interpretation of branch lines of thrust systems and by balancing of cross-sections (for example Boyer and Elliott, 1982; Suppe, 1983; Bally *et al.*, 1986; Diegel, 1986; Butler, 1987; Graham *et al.*, 1987). Their recognition at outcrop scale is relatively rare. Few duplex structures have thus been observed directly in the field. Among these, some well known examples in Europe are the Foinaven (Boyer and Elliott, 1982) and the Moine thrust zone duplexes (Butler, 1987; Bowler, 1987) in the Scottish Caledonides, some flexural slip duplexes within fold limbs in N Devon (Tanner, 1992), the Cagalière duplex in the NE Pyrenean foreland (Averbuch *et al.*, 1992; Frizon de Lamotte *et al.*, 1997) and the 'Basse Normandie' duplex in the Boulonnais Variscan thrust front (N France) (Cooper *et al.*, 1983; Ramsay and Huber, 1987).

The latter exceptional imbricate stack exposed in the 'Basse-Normandie' quarry near the village of Hydrequent is the subject of this paper. It is the result of the juxtaposition of numerous decametric thrust sheets of limestones and dolostones of Visean age lying in the footwall of a major Variscan thrust, the Hydrequent thrust. Cooper *et al.* (1983) first recognized this thrust pattern. They interpreted the general geometry as the superposition of two duplexes: a lower one positioned in the more external part and affecting a 2 m thick calcareous sequence and an upper one, thrusted onto the back of the lower duplex, involving an older and thicker calcareous and dolomitic succession. However, they focused their work mainly on the precise restoration of the lower duplex. The latter is less internally deformed than the upper duplex so that it is possible to define and follow a marker bed only in the external part of this lower duplex. On the other hand, only the lower thrust sheets show a clearly exposed roof thrust.

While the duplex geometry of the lower imbricate stack is relatively clear, that for the upper thrust-sheets is not because the roof has been eroded. The piggy-back sequence of deformation imposed by the duplex interpretation of Cooper *et al.* (1983) is also a matter of debate and out-of-sequence movements along the Hydrequent thrust which overrides the upper thrust-sheets have recently been suggested by Mercier and Mansy (1995). These different points will be discussed below on the basis of new structural data acquired in the quarry and also in the adjacent Paleozoic massifs. These observations will lead us to propose an alternative model for the tectonic evolution of the 'Basse-Normandie' thrust complex suggesting that it results from the superimposition of out-of-sequence thrusting upon an earlier thrust-related anticline with a frontal second-order duplex (the lower duplex).

GEOMETRY AND KINEMATICS OF A DUPLEX STRUCTURE

A duplex corresponds geometrically to a set of imbricate horses bordered by two thrust or décollement surfaces: a floor one and a roof one (Fig. 1) (Boyer and Elliott, 1982). These horses result from the duplication of the same lithologic sequence so that the thrust flooring each horse of the duplex branches onto the same décollement zone. Considering an individual horse, the strata and the horse borders become folded as it moves over a thrust ramp (Fig. 1). The resulting geometry is directly dependent on (1) the ramp dip, (2) the amount of slip along the thrust with respect to the internal deformation and (3) the size of the horse. The final geometry of the imbricate stack and the shape of the roof of the duplex is thus primarily the result of the dips and spacing of the subsidiary thrusts as well as the displacement above each of them (Boyer and Elliott, 1982; Mitra, 1986; Mitra and Boyer, 1986; Butler, 1987). The ratio of displacement to the size of the horse is a critical parameter which controls the dip of the imbricates. This parameter is a primary consideration for duplex classification. Duplexes with horses dipping towards the inner part of the thrust system are termed hinterland dipping duplexes (Boyer and Elliott, 1982). Such a geometric pattern requires low displacement on each thrust with regard to the size of the corresponding horse. With increasing displacement, the adjacent horses tend to overlap in antiformal stacks then to slide along their forelimb part giving rise to foreland dipping duplexes (Boyer and Elliott, 1982). Various examples of these geometric patterns are provided by Mitra and Boyer (1986), Diegel (1986) and Butler (1987).

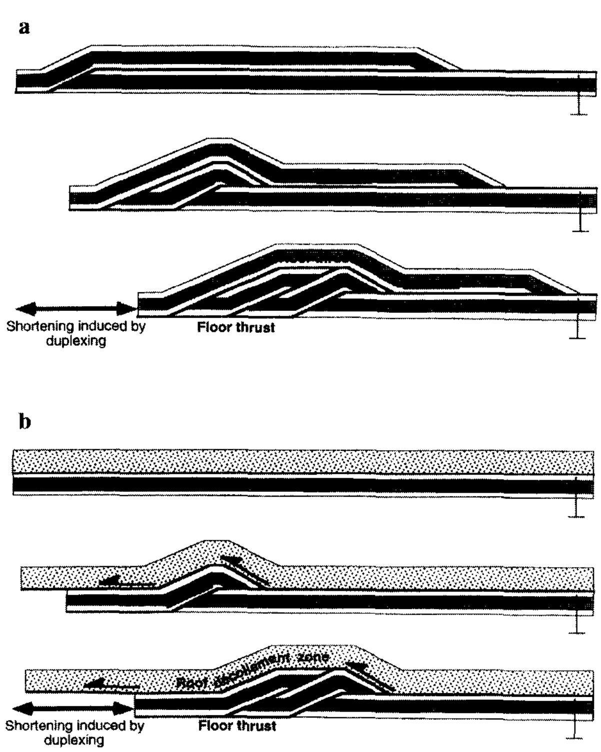

Fig. 1. Sketch diagram showing the sequential development of (a) an allochthonous roof duplex (modified from Boyer and Elliott, 1982) and (b) a para-autochthonous roof duplex with backwards activation of the roof décollement-zone (passive roof duplex).

The nature of the roof border of a duplex may also be various. The roof sequence may be allochthonous as initially described for duplexes (Boyer and Elliott, 1982) or para-autochthonous (for example Mitra, 1986; Kulander and Dean, 1986; Banks and Warburton, 1986; Geiser, 1988). In the first configuration, imbricate stacks develop beneath an initial major thrust (Fig. 1a). Kinematically, subsidiary thrusting above each thrust of the duplex is transferred forward by layer parallel slip along the upper flat. A part of the shortening may be also accommodated by internal deformation at the tip of the thrust (Cooper *et al.*, 1983; Mitra, 1986). In this kinematic evolution, the roof sequence situated above and at the back of the developing horse is pinned to this horse and passively folded. In interbedded imbricate horses, however, the roof border is a décollement zone localized in a particular ductile stratigraphic level situated in between the succession affected by the duplex and the para-autochthonous roof sequence. The kinematics of the roof décollement zone may either transfer displacement towards the foreland in the same manner as the above description (Kulander and Dean, 1986; Morley, 1986; Averbuch *et al.*, 1995) or towards the hinterland (Fig. 1b) (Fallot, 1949; Banks and Warburton, 1986; Price, 1986). The latter configuration has been termed a passive roof duplex (Banks and Warburton, 1986) or an intercutaneous wedge (Fallot, 1949).

The duplex classifications described above deal mostly with different geometrical patterns. A common feature for these geometries is the order in which the individual thrusts are activated. This parameter is very important in controlling the final geometry of the imbricate stack. A general opinion is that true duplexes occur in a foreland-progressing sequence of thrusting (Fig. 1) (Boyer and Elliott, 1982; Butler, 1987). This sequential activation implies the passive transport and folding of the hindward horses. Such a sequence is, however, generally difficult to establish in the field if the horses do not completely overlap. In this respect, it is worth noting that apparent duplex geometries may result from late crosscutting of an earlier fold–thrust situation (Butler, 1987). The sequence of deformation is thus critical in defining a duplex and has to be investigated even if the geometric characters of a duplex appear to be present.

GEOLOGICAL SETTING OF THE 'BASSE-NORMANDIE' THRUST-SHEETS

The 'Basse-Normandie' Variscan thrust sheets are situated in the Boulonnais area which lies in the northernmost part of France, along the eastern side of the English Channel (Fig. 2A). Geologically, the whole

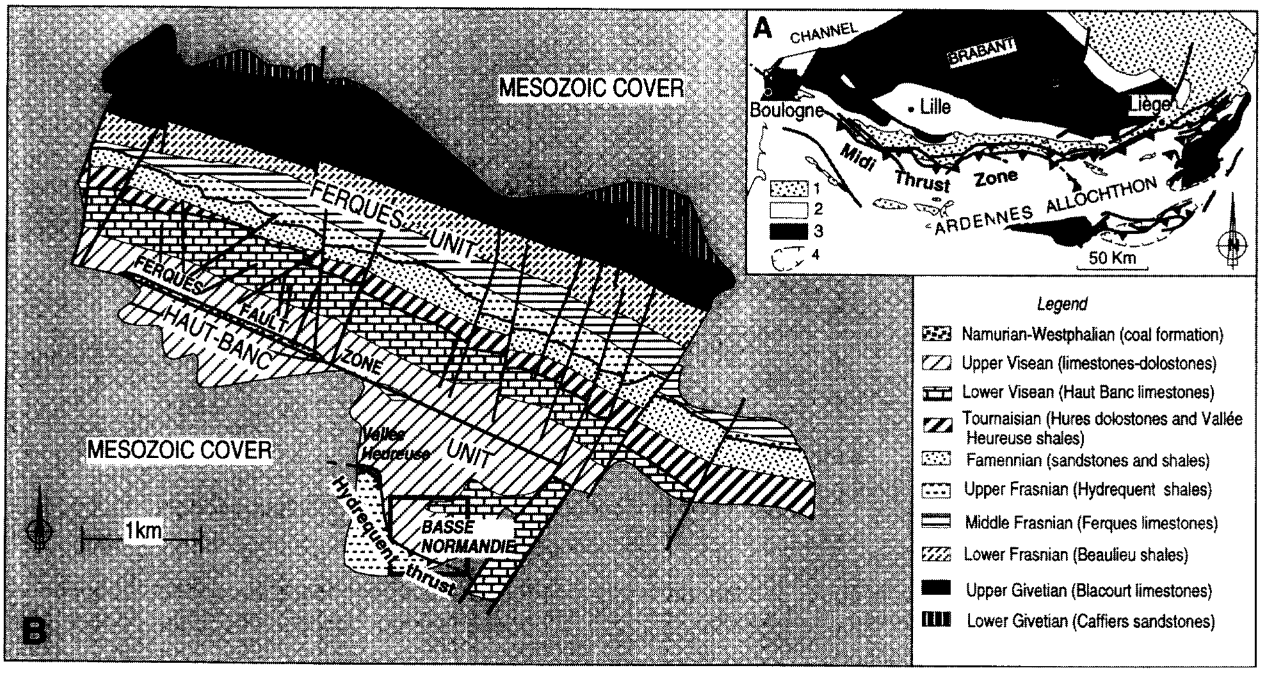

Fig. 2. (A) The location (black square) of the Boulonnais Paleozoic inliers within the tectonic framework of the Variscan thrust front of N France and Belgium. 1. Silesian basin. 2. Devonian to Visean. 3. Cambrian to Silurian rocks (Caledonian substratum). 4. Low-grade metamorphic area. (B) Geological map of the Paleozoic massif of the Boulonnais (after Mansy, in press). The rectangle locates the 'Basse-Normandie' quarry.

region today represents a wide faulted domal structure involving the Upper Cretaceous sedimentary rocks of the Paris Basin. This inverted Alpine domain exhibits within its core an unmetamorphosed Paleozoic sedimentary subtratum (Fig. 2B) folded and thrusted during the Variscan orogeny. The style of the folding-thrusting of this belt as well as the exposure of coal bearing Namuro-Westphalian rocks of a foreland basin setting type show that the Boulonnais massifs form the western tip of the French Variscan thrust front, which is well constrained in the Nord-Pas de Calais coal basin (Fig. 2A) (Bouroz, 1962). The major thrust front (the 'Midi fault' of the Nord-Pas de Calais coal basin) in classic interpretations lies a few kilometres south of the exposed Paleozoic levels, but its location remains poorly constrained. In this respect, the Boulonnais Paleozoic inliers can be considered as the deformed footwall of this major Variscan frontal thrust.

Structurally, the massif may be split into different tectonic units separated cartographically either by thrusts or by late vertical WNW–ESE trending strike-slip faults (Fig. 2B). This geometric configuration is primarily the result of the Variscan stacking of different thrust sheets as shown by an important set of drillholes and coal mining excavations (Fig. 3) (Olry, 1904; Pruvost and Delépine, 1921; Bonte, 1969; Wallace, 1983). The major décollement zone flooring these thrust sheets is likely to be situated within the thick incompetent Silurian shales recognized in the exposed core of the Landrethun culmination, on the Northern border of the Paleozoic massif. This structure, considered classically as autochthonous (for example Colbeaux and Leplat, 1985), is likely to form in fact a thrust related culmination resting upon the unfolded foreland of the London–Brabant massif. The so-defined thrust sheet constitutes the lowermost thrust unit exposed in the Boulonnais area known as the 'Ferques Unit'. To the south, this SW dipping unit ends against Visean subhorizontal layers along a Late Variscan vertical strike–slip fault of regional significance (the Ferques fault). At depth, drillholes show that these gently dipping Visean limestones (defining the 'Haut-Banc Unit') are in fact thrust onto the Namuro-Westphalian coal-bearing rocks roofing the 'Ferques Unit' (Olry, 1904; Pruvost and Delépine, 1921). The 'Haut-Banc' thrust sheet is itself overthrusted on its Southern boundary by the 'Hydrequent' thrust unit composed mainly of Upper Frasnian shales (Fig. 3) as confirmed by boreholes (Pasquet *et al.*, 1983). The contact between these two thrust sheets is defined as the Hydrequent thrust. This major fault contains in its footwall a hectometric deformation zone composed of Tournaisian lenses (in the 'Vallée Heureuse' quarry, W of the study area) and Visean slices which constitute the 'Basse-Normandie' imbricate stack.

In detail, the 'Basse-Normandie' fold–thrust system involves an about 40 m thick calcareous-dolomitic lithostratigraphic succession of Middle Visean age known as the 'Dolomie à *Siphonodendron martini*' (Hoyez, 1970; Colbeaux and Leplat, 1985; Prudhomme *et al.*, 1992). A detailed stratigraphic description has been made of this formation within the 'Basse-Normandie' quarry in the footwall of the imbrications forming the

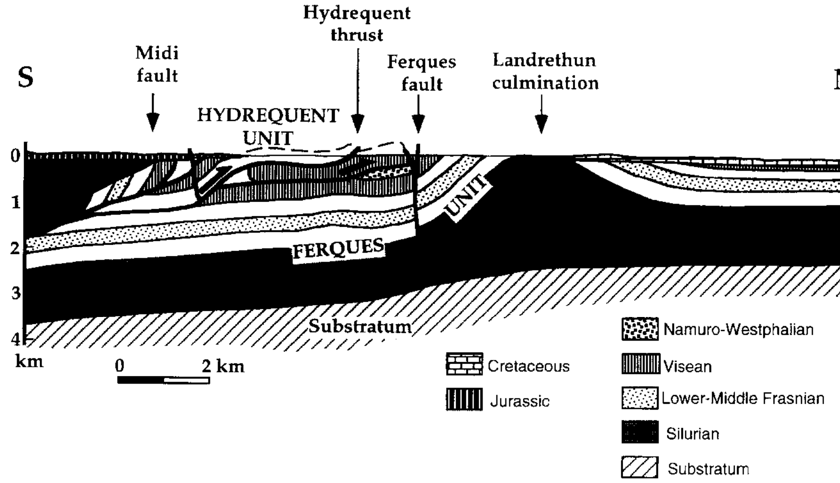

Fig. 3. Synthetic N–S cross-section through the Variscan thrust front of the Boulonnais area based on field and borehole data.

lower duplex (Figs 4 & 5) (Hoyez, 1970). Within the deformed zone, it is difficult to establish, with confidence, the precise stratigraphy due to an intense dislocation of beds. Marker beds have been recognized, however, in the thrust-sheets and in the reference cross section of the undeformed footwall allowing the reconstruction of the global geometry of the 'Basse-Normandie' thrust complex (Fig. 5).

GEOMETRY OF THE IMBRICATE STACK

As previously described by Cooper *et al.* (1983), two different thrust units may be defined within the 'Basse-Normandie' thrust complex (see the geometric reconstitution of Fig. 5 and the interpretative cross-section of Fig. 6). The lower unit (the lower duplex) consists of decametric imbrications of the same lithologic sequence (about 2 m thick) separated by SW dipping thrusts. These thrusts root backwards into a gently SW dipping floor thrust and branch upwards to a roof décollement zone thus defining a set of hinterland dipping intraformational duplications. The roof thrust exhibits a planar gently SW dipping attitude within its external part. Towards the inner part of the stack, it forms a pronounced culmination due to a greater amount of displacement along the underlying thrust surface. Within this zone, the precise geometry of the subsidiary thrusts of the duplex is difficult to decipher. However they seem to exhibit a steeper dip than the more external ones and branch onto the major thrust flooring the thickened zone. Above the roof décollement zone, just at the step surrounding the lower duplex major thickened zone, the roof sequence is affected by a system of NE and SW dipping decametric thrusts (the opposed dip complex of Cooper *et al.*, 1983) inducing its layer parallel shortening (Fig. 6).

The gently SW dipping thrust contact between the lower duplex and the upper thrust sheets (here defined as the upper thrust sheets (UTS) basal thrust) cannot be located precisely in the field. This poor exposure is explained partly by the fact that it branches very rapidly backwards to the lower duplex floor thrust forming the basal thrust of the whole structure and forward to the lower duplex roof décollement zone which forms its initial upper flat (Fig. 6). At the break point between the ramp and the upper décollement zone, the levels situated in the roof of the lower duplex fold into a subvertical wall. The location of this wall suggests that it probably represents the forelimb of a thrust-related anticline associated with the displacement above the UTS basal thrust. Its geometry is complicated by the existence of a complex thickened zone within the roof sequence (? in Figs 5 & 6).

It is not possible to determine the precise geometry of the Hydrequent thrust in the 'Basse-Normandie' quarry

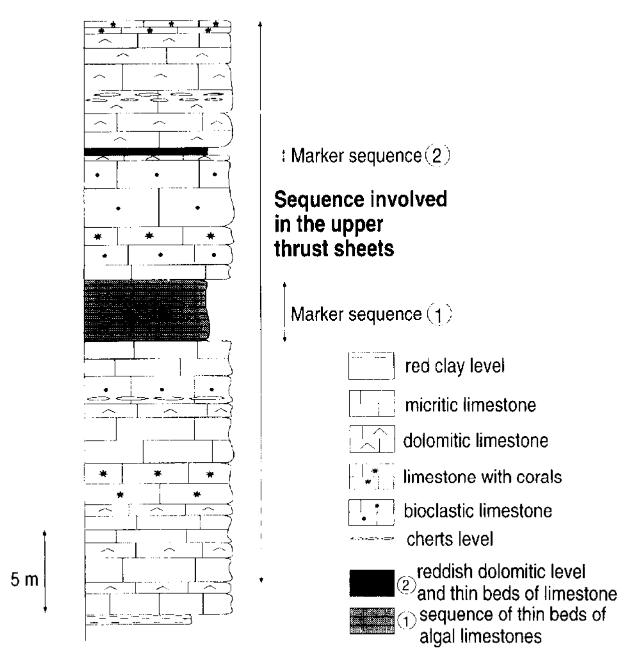

Fig. 4. Stratigraphic column of the sedimentary succession ('dolomie *a Siphonodendron martini*' formation) observed in the direct footwall of the 'Basse-Normandie' imbricate stack (redrawn from Hoyez, 1970).

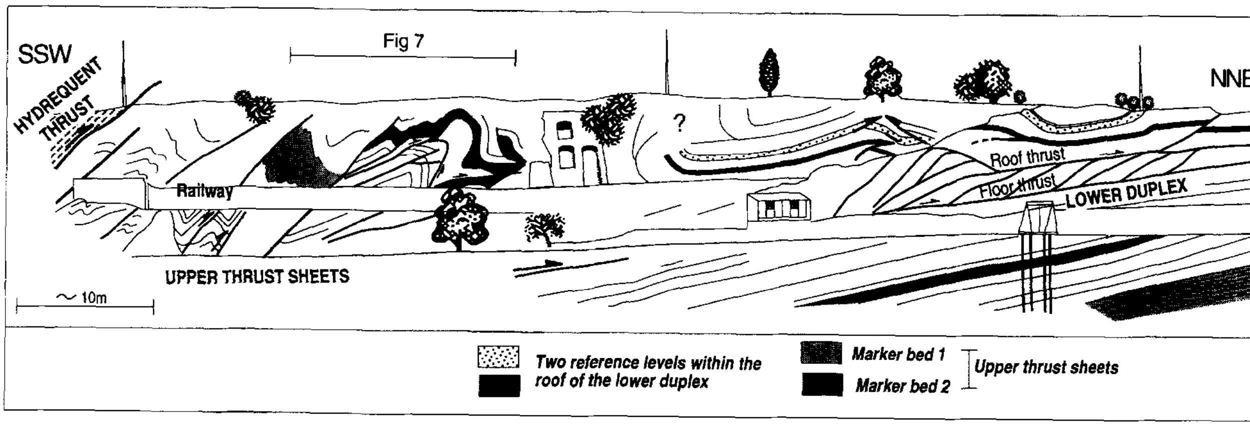

Fig. 5. Geometry of the 'Basse-Normandie' thrust-sheets (drawn from a photographic mossaic).

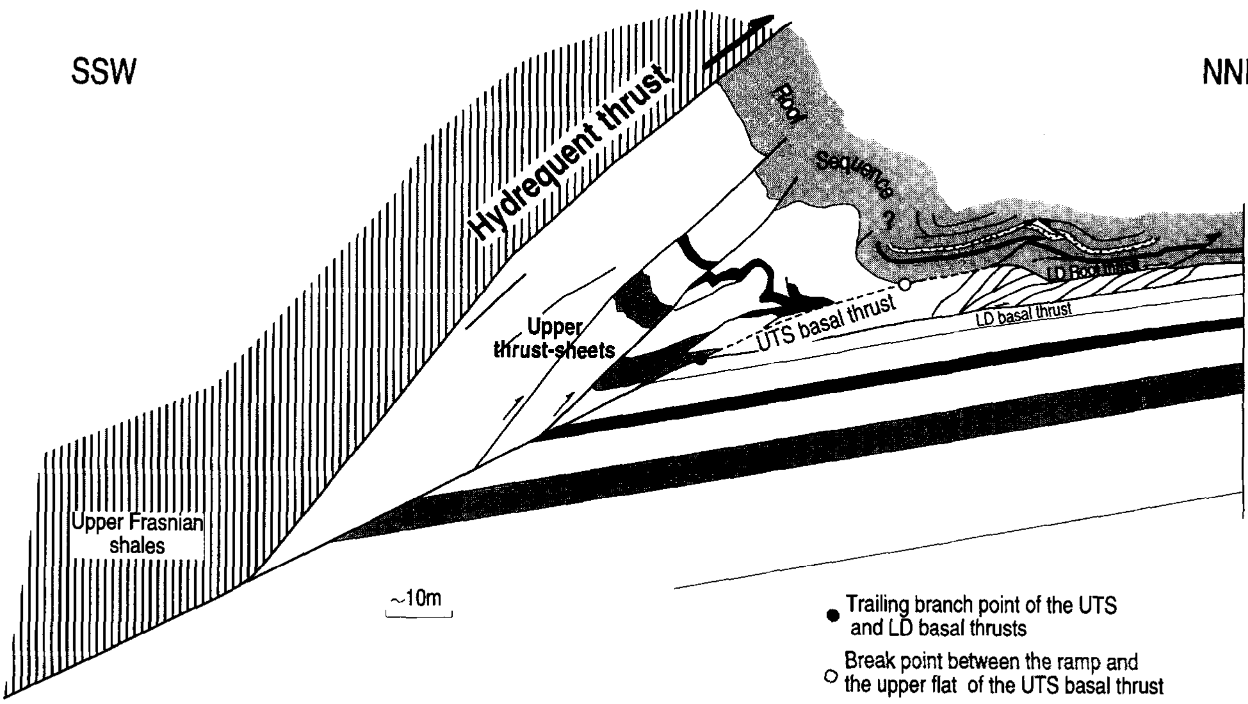

Fig. 6. Interpretative cross-section of the 'Basse-Normandie' thrust sheets.

as it is only observable at the back of the stack with a SW dipping attitude (Fig. 5). It is, however, clear in the exposed section that here is no leading branch line between the UTS basal thrust and the Hydrequent thrust as would be expected in the case of a classic allochthonous roof duplex geometry. This observation is also supported by the along-strike geometry of the Hydrequent thrust. Towards its western extension, within the 'Vallée Heureuse' quarry, it exhibits a southerly dip and affects some younger subhorizontal Visean limestones within its footwall (Pruvost and Delépine, 1921; Mansy, *in press*). Such a lateral attitude does not account for the previously proposed geometry (Cooper *et al.*, 1983), in which the Hydrequent thrust is resting horizontally, folded on top of the 'Basse-Normandie' thrust sheets. These data rather suggest that the SW dipping Hydrequent thrust crosscuts the whole series of the 'Haut-Banc Unit' (Fig. 6).

Within the upper thrust sheets located in between the UTS basal thrust and the Hydrequent thrust, the calcareous and dolomitic levels are highly dislocated and folded. The recognition of two marker beds in the thrust sheets and the undeformed footwall allows however a global geometric reconstruction (Fig. 5). Three major thrust-sheets may be distinguished, each separated by relatively planar SW dipping thrusts with decametric slip. They comprise as a whole a sequence about 35 m thick including the levels forming the lower duplex and the series lying just beneath them. In contrast to the lower duplex, however, the different UTS thrust sheets do not exhibit the same stratigraphic succession. The inner thrust-sheet of the UTS complex involves levels which are characteristic of the base of the sequence (some metres above the red clay level forming the bottom of the lithostratigraphic unit, see Fig. 4). The intermediate thrust-sheet is composed mainly of thin beds that characterize marker bed 1 situated in the middle of the sequence. The more external thrust-sheet of the UTS complex is made of a sequence about 15 m thick comprising the reddish dolomitic rocks of marker bed 2. This sequence and the roof levels of the lower duplex are globally conformable although separated by a badly exposed disharmonic zone. The complete stratigraphic succession is thus observed along the UTS complex with deeper levels being exposed towards the inner part of the stack. This configuration shows that the thrusts bounding the different upper thrust sheets can not be considered as the individual internal thrusts of a duplex. They instead seem to represent late features crosscutting and inducing the refolding of a previous NNE dipping fold limb (Fig. 6).

The geometric data discussed above show that although the duplex geometry of the lower thrust unit is well established, it is not the case for the upper thrust sheets. Indeed, more than a duplex, the geometry of the upper thrust sheets resembles more the forelimb of a hangingwall anticline developed above the UTS basal thrust, cut across by a system of late NE verging thrusts.

KINEMATICS OF THE THRUST SYSTEM

Thrust relationships

The relationships between the folds and thrusts and between the different internal thrusts of the 'Basse-Normandie' thrust sheets are investigated here to establish the kinematics of the resultant imbricate stack. When considering thrust relationships within superposed thrust units, two cases may be encountered:

(1) The upper unit is folded by an underlying frontal (Butler, 1987) or lateral ramp-related anticline (Averbuch *et al.*, 1993) implying a progressive thrusting towards the foreland;

(2) The basal thrust of the upper thrust unit truncates previously folded levels of the bottom thrust-sheet in a breaching style of thrust propagation (Butler, 1987; Morley, 1988).

These basic situations require that both thrusts are not active at the same time. A much more complex situation may evidently arise if the two thrust-sheets are developing synchronously (Morley, 1988; Boyer, 1992).

In any case, the conditions for deciphering the relationships between thrust units are not so common in the field. Concerning the major thrusts of the 'Basse-Normandie' imbricate stack, only the relationships between the two lower ones may be precisely analysed (see Fig. 6) since the Hydrequent unit is not visible at the top of the upper thrust sheets. As previously discussed, the upper thrust sheets basal thrust (the UTS basal thrust) branches forward onto the horizon localizing the lower duplex (LD) roof décollement zone. The latter is likely to resolve part of the UTS basal thrust displacement and to transfer it towards the foreland by layer parallel slip as shown by the NE verging thrusts affecting the roof sequence. It seems rather clear, however, that the shortening affecting the roof sequence in the foreland of the structure does not balance the total displacement above the UTS basal thrust. It appears, therefore, that some important part of the shortening has to be accommodated by internal deformation of the forelimb part of the developing anticline in a fault-propagation style of folding (Suppe and Medwedeff, 1990; Mercier and Mansy, 1995). The existence of the complex thickened zone affecting the roof sequence within the vertical wall (? in Figs 5 & 6) is another argument for such a tectonic style. Nevertheless, the LD roof décollement zone is clearly folded as developing the different imbrications of the lower duplex. On the other hand, no truncation is observed within the folded levels of the LD individual horses. It is thus clear that the UTS basal thrust has been activated mostly before the lower duplex developed in its direct footwall.

Within the lower duplex itself, the individual horses do not overlap except in its internal part where the structural thickness increases strongly. In this position, the subsidiary thrusts of the duplex seem to exhibit a steeper dip than the more external ones suggesting that they have been tilted during their rigid transport upon the lower ramps and thus indicating a progressive thrusting of the LD beds towards the foreland. Movement upon each subsidiary thrust is also only in part transferred to the LD décollement zone (less than 50% of the total shortening) as shown by Cooper *et al.* (1983), the other part being accommodated by layer parallel shortening of the LD beds. Above the décollement zone, just at the step surrounding the LD major thickened zone, the deformation zone with the double verging thrusts probably accommodates part of the shortening transferred from the lower duplex.

The geometric relationships between the Hydrequent thrust and the underlying upper thrust sheets cannot be observed in the 'Basse-Normandie' quarry. There is no leading branch line between the UTS basal thrust and the Hydrequent thrust. It is also not possible to define intersection relationships between the different upper thrust sheets as the bounding thrusts all dip in a similar manner towards the hinterland of the structure (Fig. 5).

In order to characterize the deformation sequence in the upper thrust sheets, fold-faults interactions have been investigated within the two more external thrust sheets. Figure 7 exhibits a scheme for the deformation observed within the latter. It is obvious that the rocks are more strained than within the lower duplex. In detail, rocks are intensively folded with asymmetrical folds showing steeper NE forelimbs. The style of the folds differs in relation to bed thickness. Second order chevron folds are

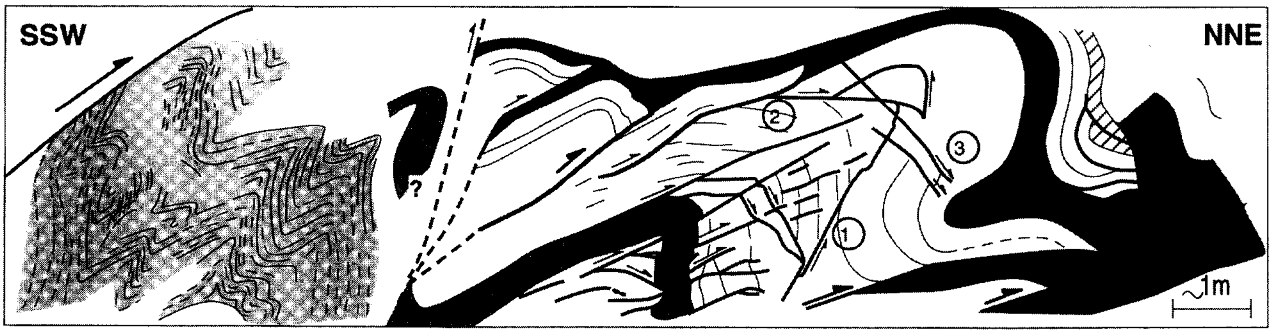

Fig. 7. Geometry of the external part of the upper thrust sheets (drawn from a photographic mossaic). Location is reported in Fig. 5. See text for comments.

thus observable within the thin dolomitic beds of marker bed 1. The most external part of the section is formed by a subvertical wall which represents the south–southwestwards extension of the forelimb of the UTS basal thrust hangingwall anticline. Towards the base of the section, the bedding rapidly becomes horizontal defining a pronounced disharmonic synclinal hinge. This structure develops above two gently SW dipping thrusts that we interpret here to be splays of the UTS basal thrust. These thrusts join in a high strain zone within a dolomitic succession (Fig. 7). This zone is the root of a nearly vertical SW verging backthrust which doubles the vertical wall of the ramp anticline. The core of the resultant structure is highly strained as indicated by minor intraformational thrusts. The global geometry represents a sort of decametric tectonic wedge initiated from the triple thrust junction zone acting as a buttress. This deformation pattern is likely to be indicative of difficulties in the forward propagation of displacement along the UTS basal thrust complex. As a result, numerous faults cross-cutting the folds are observed along the section. Three generations of faults have been defined (Fig. 7):

(1) The first set corresponds to thrusts affecting the limbs of the folds with antithetic vergence towards the hinge. These thrusts are syn-folding features resulting in the accentuation of the fold and thickening of the hinge zone. Such structures are common features in the Variscan folds of the Boulonnais Paleozoic massifs due to the ease in layer parallel displacement along the bedding discontinuities;

(2) The latter structures and the major fold are crosscut by a set of gently SW dipping thrusts. This thrusting event reflects a late NE verging component of shear which is likely to result from the blocking of the UTS basal thrust propagation as commonly observed in the late evolution of thrust-related folds (Butler, 1992; Frizon de Lamotte *et al.*, 1995). The minor thrusts branch onto the steeper thrust bounding at its back the thrust sheet producing a sort of imbricate fan that is interpreted, in such a context, to develop in a break-back sequence of thrusting;

(3) The last generation of faults are gently foreland-dipping normal faults with minor slip. It is worth noting that such faults are quite common in the Nord-Pas de Calais coal basin (Bouroz *et al.*, 1961) which is located within the direct footwall of the major out-of-sequence Midi thrust (Mansy and Meilliez, 1993). These structures are probably the result of the late loading and shearing of the area following the overthrusting of the Hydrequent nappe which represents the final thrust motion in the local break-back sequence of thrusting.

Within the upper thrust sheets, the deformation pattern thus argues for a more complex structural evolution than within the lower duplex. A late event of NE vergent thrusting is evidenced in relation to a change in the ease of forward thrust propagation along the UTS basal thrust zone. Although it is not posssible to determine the relationships between the higher thrusts, these data suggest, in agreement with the geometric considerations discussed above, that the upper thrust sheets are the result of out-of-sequence deformation of a previous fold forelimb.

Analysis of strain markers

In order to characterize better the kinematics of deformation, strain markers have been investigated within the upper thrust-sheets and the lower duplex. As only part of the structure is accessible, this study is not exhaustive (the UTS basal thrust displacement is, for example, not constrained).

No cleavage is visible along the 'Basse Normandie' section nor within the adjacent quarries of Visean limestone. Cleavage has only been observed in the 'Vallée Heureuse' quarry within Tournaisian calcareous shales situated in a mylonitic zone beneath the Hydrequent thrust. There, cleavage dips 65° towards the N215° (SW) and minor fold axes trend around N140°. Within the 'Basse-Normandie' thrust sheets, strain markers are mostly fold axes and bedding attitude as well as striations on fault planes (mostly shear fibres of calcite). These kinematic data are presented in Fig. 8. It is evident that there is little difference in movement direction between the upper thrust sheets and the lower duplex. In the lower duplex (Fig. 8a) and the upper thrust sheets (Fig. 8b),

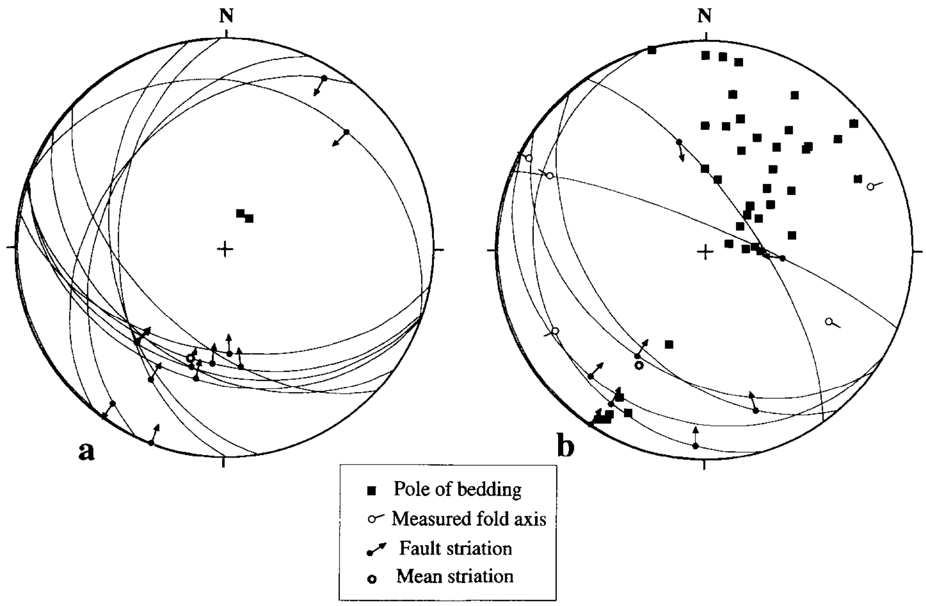

Fig. 8. Stereograms (lower hemisphere, equal area) of strain markers within (a) the lower duplex and (b) the upper thrust sheets.

kinematic data are relatively scattered showing N–S to NE–SW directions of movement. In the lower duplex, although these two directions are seen, the N–S to NNE–SSW movements (mean striation N195°) seem to be the most significant particularly along the SSW dipping subsidiary thrusts of the stack. In the upper thrust sheets, a complex distribution of the structural elements may be observed. Within the striation pattern, the NE–SW direction is more pronounced (mean N209°). Most bedding poles are distributed along this plane of movement in agreement with the orientation of the major fold axes (around N300°). A second population of compressive structures is, however, evident. The latter is characterized mostly by *ca* N070° trending folds which may explain the scatter of bedding poles towards the N–NNW direction (Fig. 8b). It is unclear whether these folds are second (or first) generation frontal folds or if they are only oblique–lateral structures in relation to the rapid plunge of the structure towards the NW. In any case, the major compressive event within the upper thrust-sheets is NE–SW directed, parallel to the orientation of shortening in the mylonitic zone beneath the Hydrequent thrust. Although the kinematic indicators do not give a clear picture, this direction seems slightly oblique to the thrust transport evidenced within the lower duplex which is more N–S directed.

We suggest here that such a slight deviation is the result of diachronous deformation within the lower duplex and the upper thrust sheets, the latter resulting from the late evolution of the hangingwall anticline developed above the UTS basal thrust. The induced clockwise rotation of thrust transport (from N–S to NE–SW) is consistent with the existence of Late Paleozoic left-lateral N110° trending faults (for example the Ferques fault) associated with a N060° direction of shortening.

DISCUSSION AND CONCLUSIONS

Although the 'Basse-Normandie' duplex is often cited as a classic duplex structure, the structural data presented here show that the tectonic development of the whole thrust stack is much more complex than a simple piggy-back duplication. The lower set of imbrications which was carefully analysed by Cooper *et al.* (1983) corresponds undoubtedly to an intraformational duplex structure but finally represents only a secondary structure with regards to the entire thrust complex. By contrast to this lower duplex, the upper thrust sheets of the 'Basse-Normandie' thrust complex exhibit neither the geometric nor the kinematic characters of a duplex. Instead they seem to represent the product of the late evolution of a NNE dipping forelimb of an hangingwall anticline developed above the basal thrust of the system. The lower duplex thus appears as a minor duplex developed in the frontal zone of a more important thrust related anticline accommodating displacement transferred towards the foreland (Fig. 9). During this event, the direction of transport is likely to be towards the NNE as indicated by striations recorded along the subsidiary thrusts of the duplex.

The main outcome of this study is the field evidence for the out-of-sequence evolution of the internal folds and thrusts of the upper thrust sheets and the Hydrequent thrust. Fold-thrust relationships as well as the deformation pattern observed within the upper thrust sheets argue for a local break-back sequence of thrusting in which thrusts sequentially cross-cut the forelimb of the basal thrust related anticline (Fig. 9). Such an evolution is likely to be linked to the difficulty of propagation of the upper thrust sheets basal thrust as shown by the intense deformation observed at its tip. The sequence of

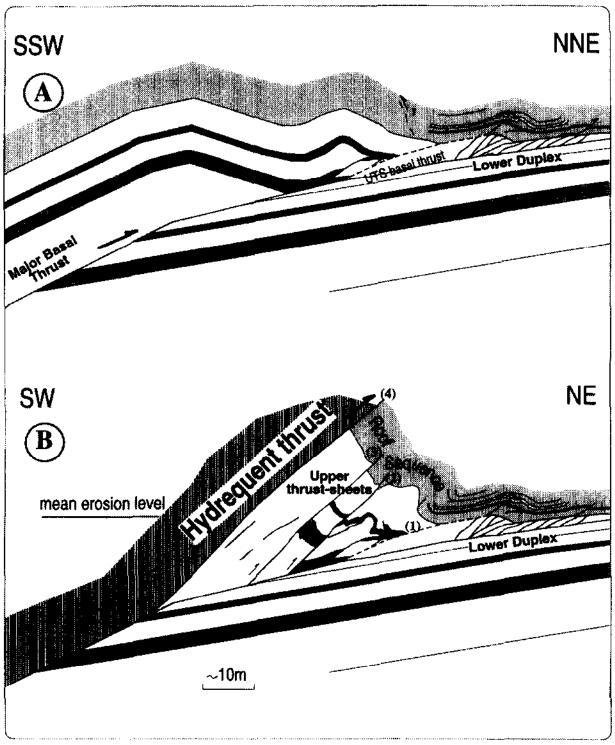

Fig. 9. A model for development of the 'Basse-Normandie' thrust-sheets. (A) Formation of an hangingwall anticline upon the basal thrust of the thrust system with a frontal second-order duplex accommodating forward transfer of displacement. (B) Out-of-sequence thrusting event within the upper thrust sheets and along the Hydrequent thrust inducing the refolding and cross-cutting of the previous situation.

thrusting is punctuated by the activation of the major Hydrequent thrust which emerged from the footwall ramp of the initial fold-thrust structure. Kinematic indicators argue for a late NE verging transport, slightly oblique to the initial shortening direction, which is believed here to be the result of a clockwise rotation of regional thrust transport.

This sequence of deformation, observed at the hectometric scale within the 'Basse-Normandie' thrust system, may well be representative of the processes acting along major Variscan structures such as the 'Midi thrust' as already suggested for other segments of the Western Europe Variscan thrust front (e.g. Mercier *et al.*, 1994). In such a respect, the UTS thrust-sheets could represent the equivalent of the thrust-sheets which appear systematically in a reverse position in the direct footwall of the 'Midi thrust' (Raoult and Meilliez, 1987).

In a more general way, the data presented here emphasize the out-of-sequence mode of thrust propagation which induces both the foreland migration of displacement by layer parallel slip and reactivation of transported fault zones. Such a sequence has been shown in recent times both by numerical modelling (Chalaron and Mugnier, 1993) and field work (e.g. Morley, 1988; Averbuch *et al.*, 1995) to be a widespread style of deformation in fold-thrust belts. Mechanical discontinuities of décollement zones as well as syntectonic sedimentation or erosion (Vinour *et al.*, 1996) are likely to be decisive parameters in controlling this sequence. These points require however further field characterization and modelling for a better understanding of fold-thrust belt kinematics.

Acknowledgements—This is a contribution from the URA CNRS 719 'Sédimentologie et Géodynamique'. The authors wish to thank the 'Vallée Heureuse' quarries for the permission to study the 'Basse-Normandie' section. We also thank A. Prudhomme, J. Lamarche, C. Phalempin and J.-D. Legrand for their help during the field work and M. Bocquet for technical support in the figures. D. Frizon de Lamotte, G. Manby, C. Morley, R. Lisle and an anonymous reviewer are gratefully acknowledged for their constructive comments on earlier versions of this paper and the improvement of the English.

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