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The origin of the Basse Normandie duplex, Boulonnais, France

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Abstract—Two Hercynian duplexes are developed in Viséan limestones in the Basse Normandie quarry. The lower duplex is completely exposed in a subvertical quarry wall; the partially exposed upper duplex lies immediately above the lower duplex. The duplexes are both located in the footwall of the Hydrequent thrust which emplaced Devonian clastic sediments above the Viséan limestones. The lower duplex exposes all the internal thrusts, a reference bed of chalky limestone, the roof and floor thrusts, and the duplex tip. The duplex has been graphically restored to its pre-deformation geometry by line-length and area balancing and its resultant geometry is close to the model of Boyer & Elliott. The lower duplex shortened by two different mechanisms, an initial phase of layer-parallel shortening which produced no cleavage, followed by thrust imbrication. The average contraction of the front portion of the duplex was −49% (natural strain) of which −27% is layer-parallel shortening and −22% is thrust imbrication. However, locally the bulk shortening increases from zero at the duplex tip to over −120% in a down-dip direction. The area balancing provides the most accurate estimates of bulk shortening; line-length balance calculations give minimum estimates only. An area balance on the whole of the lower duplex gives a bulk shortening of −84%. An area balance of the upper duplex yields an average contraction of −75% and the total contraction produced by both duplexes is −92%.

INTRODUCTION

THE BASSE NORMANDIE quarry (56003462 French National Grid) is situated in the Boulonnais district of northwestern France near Hydrequent (Fig. 1a). It lies in the Viséan Calcaire Carbonifère Formation of the Ferques inlier (Wallace 1968), and comprises white limestones with dolomitic bands. The Ferques inlier is one of several Palaeozoic inliers in the predominantly Mesozoic Boulonnais (Fig. 1a). The general geology of the inlier was described by Rigaux (1865, 1892), Robinson (1920) and Pruvost & Pringle (1924). More recently Ager & Wallace (1967a, b) have published an updated description of the geology of the Boulonnais, and Wallace (1969) has discussed the detailed sedimentology and palaeoecology of the Devonian rocks of the Ferques inlier. Wallace (1968) compiled regional outcrop and borehole data which demonstrated a number of WNW–ESE Hercynian thrusts in the Palaeozoic rocks beneath the unconformable Mesozoic cover. Bonte (1969), Bouroz (1969) and Delattre *et al.* (1973) have presented a series of cross-sections through the inlier which indicate the emplacement of Palaeozoic thrust sheets (Fig. 1b) north-northeastwards on to the Brabant Massif. Wallace (1969) has noted a number of NNE–SSW dextral wrench faults in the inlier which formed synchronously with the Hercynian thrusting.

One of us (J.R.H.) recognized the miniature lower duplex in the Basse Normandie quarry during a trip to study the palaeoecology of the Viséan limestones. All three authors subsequently investigated the geometry of the structure in detail. Observations collected from the excellently exposed quarry face (Fig. 2a) were supplemented by those from an adjacent railway cutting to the northwest, in which the upper duplex is partially exposed. The lower duplex is developed in the uppermost 2 m of the 10-m thick sequence of limestones deformed by the upper duplex, and is on the foreland side of the latter. In the sequence of beds above the duplexes there is an opposed-dip complex of thrusts, a feature commonly seen above décollement surfaces (Harris & Milici 1977). The Hydrequent thrust crops out to the west of the quarry and carries Upper Devonian (Frasnian) Schistes de Fiennes (Wallace 1969) over the Viséan limestones (Fig. 1b). The duplexes in the limestones beneath the Hydrequent thrust are interpreted as being related to the same deformational event.

There are few good descriptions of duplexes (for a review see Boyer & Elliott 1982). We believe that this is the first description of a duplex where the roof and floor thrusts, all the internal imbricate thrusts, the internal stratigraphy, and the duplex tip are completely exposed (Fig. 2). As a result of a detailed geometric study of the lower duplex we have discovered some pitfalls in the accepted methods of balancing sections (Hossack 1979) and their use in determining bulk strain.

We have used natural strains rather than longitudinal strains throughout this paper for two reasons. Firstly, a 5% difference in natural strain is constant for high or low levels of strain. A 5% difference in longitudinal strain is enormous at high strains in comparison with the same difference at low strains. Secondly, natural strains can be added or subtracted directly which is advantageous when partitioning the bulk strain between different deformation processes.

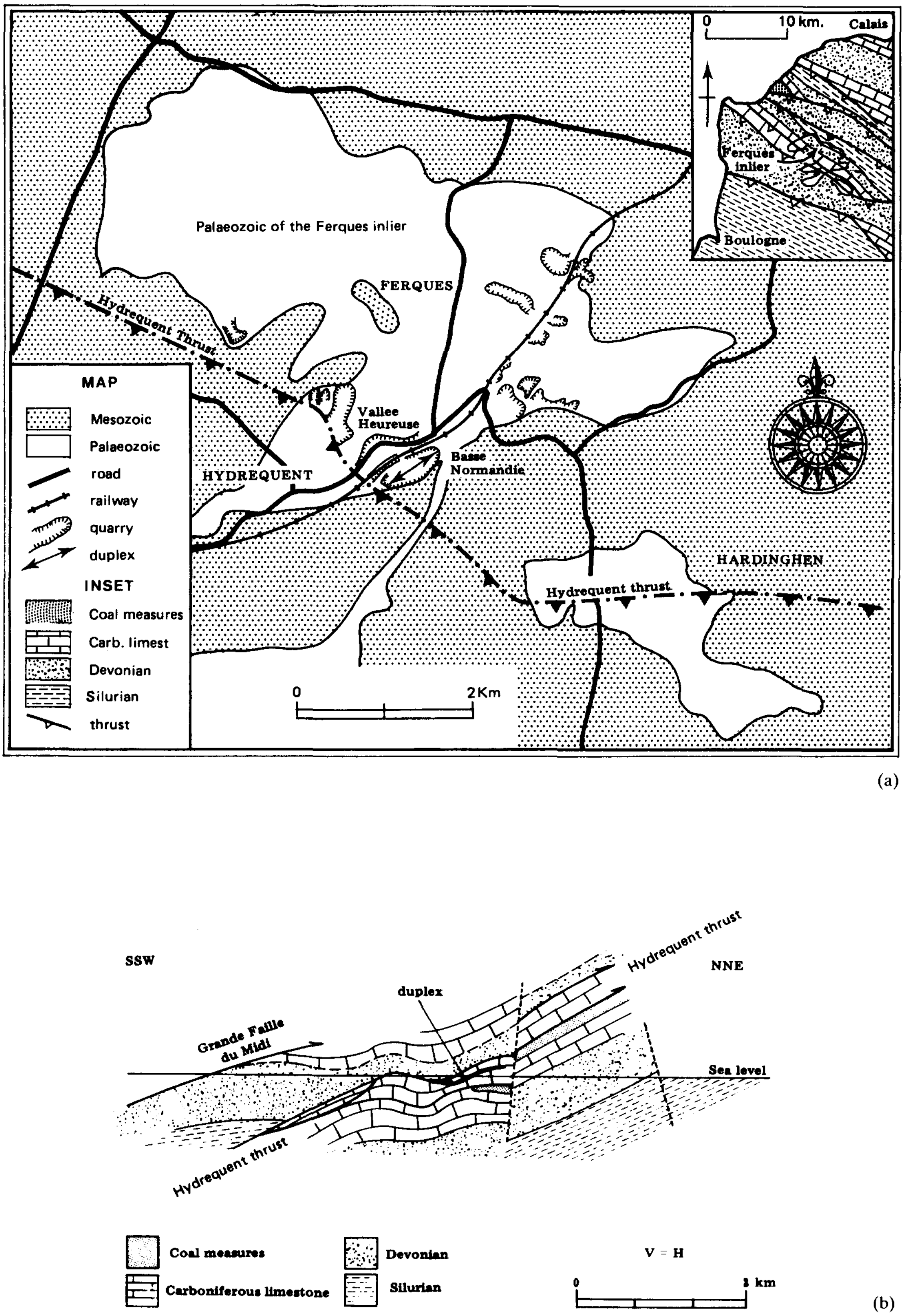
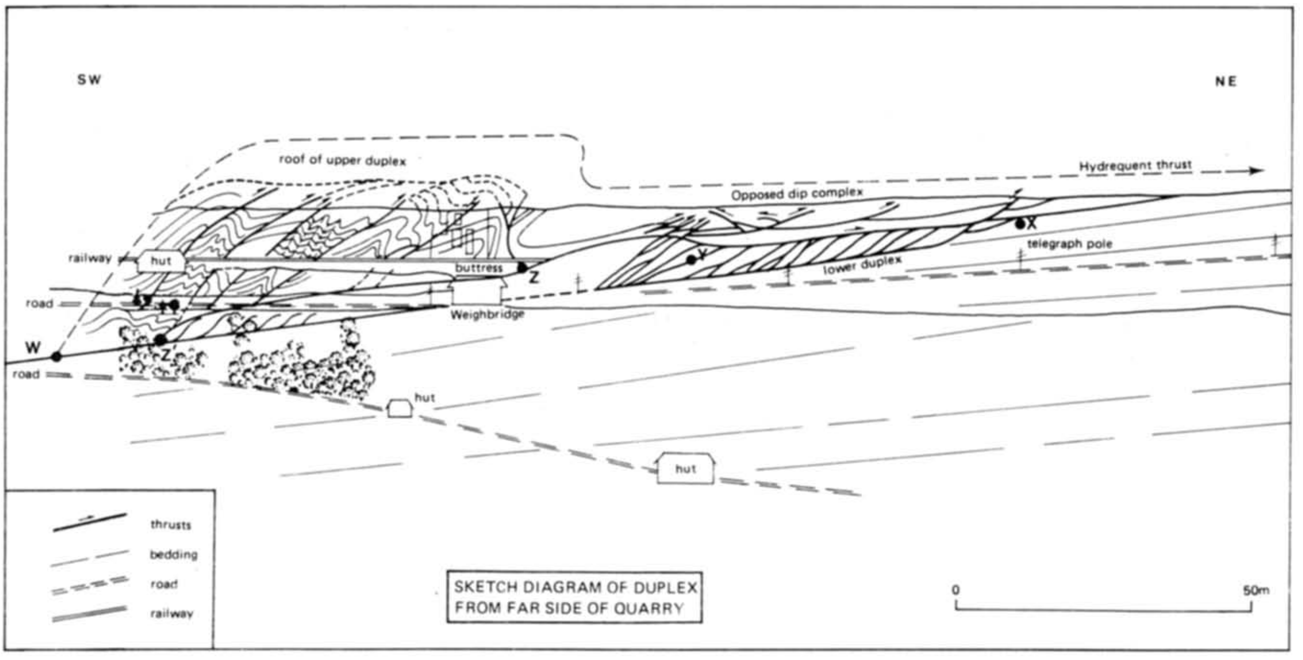


Fig. 1. (a) Geology of the Ferques inlier. Inset: location and subcrop map of the Hercynian thrust belt beneath the Boulonnais Mesozoic cover (after Wallace 1968). (b) Cross-section through the Ferques inlier.

(a)



(b)

Fig. 2. (a) View of the Basse Normandie Quarry. LD, lower duplex; UD, upper duplex; ODC, opposed-dip complex; HT, Hydrequent thrust. (b) Composite profile of the quarry plotted on a down-plunge view based on the photograph shown in (a). W, Z′, Z, Y and X are points referred to in the text. Vertical and horizontal scales are equal.

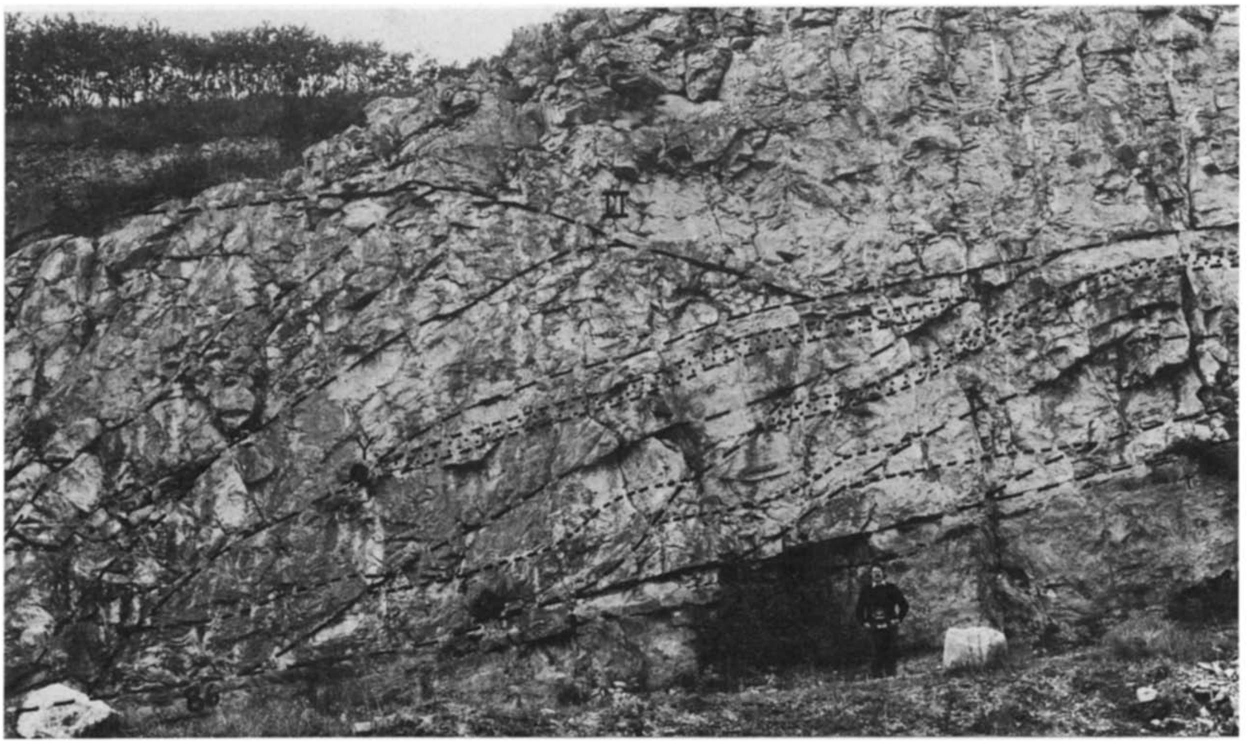


Fig. 4. The hinterland end of the line length balance of the lower duplex (Y) and the second step in the duplex roof thrust (II). The upper marker bed is stippled, the lower is shown enclosed by short dashes. Thrusts are indicated by lines with longer dashes. The horse to the right of Y has developed one of the sub-horses discussed in the text. The number 86 visible in the lower left of the photograph was painted on the rock in connection with quarrying operations.

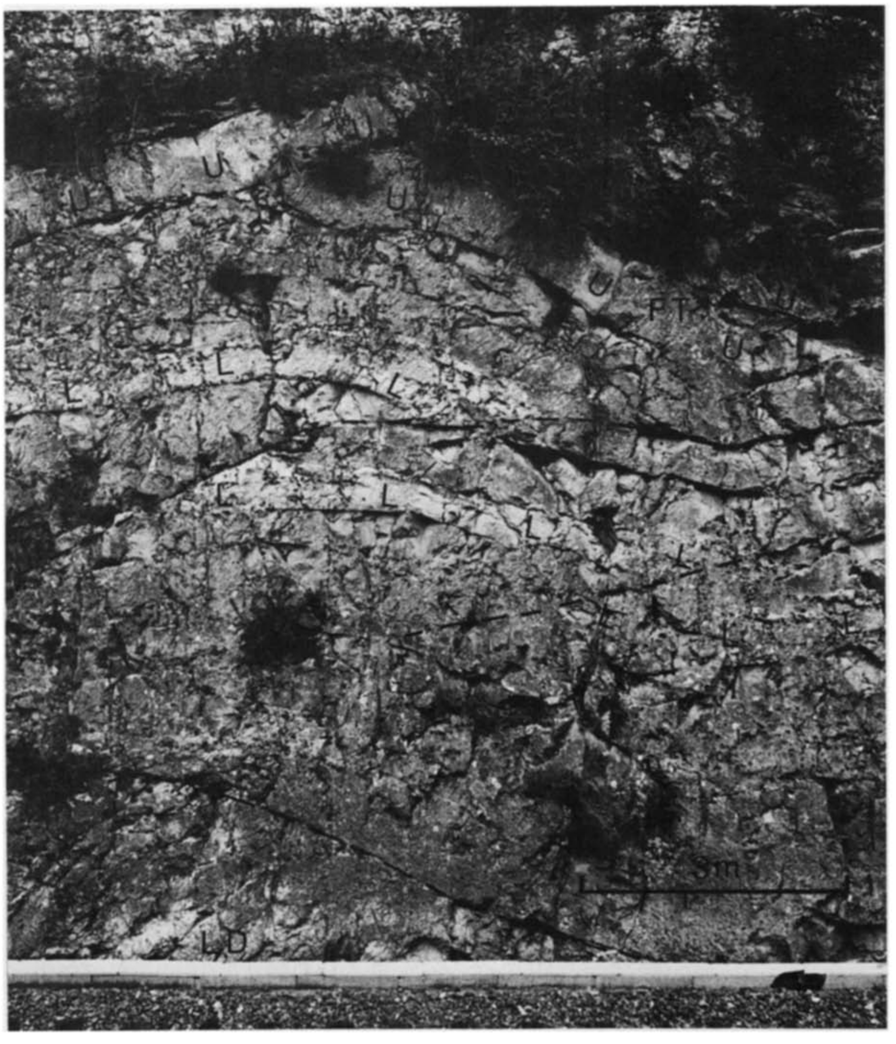


Fig. 10. Portion of the opposed-dip complex showing a number of hinterland-dipping thrusts affecting the upper (U) and lower (L) marker beds. A foreland-dipping thrust (FT) can be seen affecting the upper marker bed. The lower duplex (LD) occurs in the bottom left. This is the position of the lower duplex as visible in Fig. 4.

WHAT IS A DUPLEX?

The term duplex is used to describe an imbricate system within which the subsidiary thrust faults are asymptotic downwards to a floor thrust and upwards to a roof thrust (Boyer & Elliott 1982). These authors recognized three different types of duplex structure. Firstly there is a *hinterland-dipping duplex* which has the subsidiary thrusts dipping away from the foreland and towards the orogenic hinterland (the term hindward for the sense of direction towards a hinterland was introduced by Boyer & Elliott 1982). This is the type that occurs in the Basse Normandie quarry. If the amount of slip along each imbricate thrust is great the duplex horses slide over one another so that they all appear to branch away from more or less the same point to form the second type, called an *antiformal stack duplex*. The Dundonell antiformal stack of the Moine thrust zone is the type locality for this structure (Elliott & Johnson 1980) and the middle portion of the Base Normandie duplex displays a comparable geometry. Thirdly as Boyer & Elliott (1982) suggest if the slip is very great the horses can slide completely over one another to produce an imbricate stack which is a *foreland-dipping duplex*.

All three types of duplex form by the progressive footwall imbrication of a thrust ramp (cf. Fig. 3 and Boyer & Elliott 1982). Slip is transferred progressively from the lower flat (floor thrust) to the upper flat (roof thrust) by the imbricates which develop sequentially from the ramp in the direction of motion of the thrust sheet above the duplex. Boyer & Elliott (1982) have developed a model of a hinterland-dipping duplex in which the folds within the duplex display a kink geometry (Fig. 3). After the development of several imbricates, each horse contains an elongate fold of the bedding within which some parts are parallel to the subsidiary thrusts and other parts are parallel to the roof and floor thrusts. In this model, the angle between the subsidiary thrusts in the middle of the horse and the floor thrust is 30°, the average thickness/length ratio of each horse is 0.2 and the overall bulk shortening is −69%. Natural duplexes depart from this ideal model (Boyer & Elliott 1982, table 1) and can have imbricate floor-thrust angles between 23 and 45° and cause bulk shortening between −34 and −92%. The thrust angle is related to shortening because, as the angle decreases, so does the shortening (Boyer & Elliott 1982).

There are several published examples of hinterland-dipping duplexes [Nevin (1949), Douglas (1952), Fermor & Price (1976) and Gordy *et al.* (1977) from the Canadian Rockies; Gwinn (1970), Boyer (1976) and Boyer & Elliott (1982) from the Appalachians; Peach *et al.* (1907), Bailey (1938), Elliott & Johnson (1980) and Boyer & Elliott(1982) from the Moine thrust zone]. Some of these examples are only partially exposed or their structure has been inferred from borehole or seismic data. The Basse Normandie duplex is on a much smaller scale than the examples cited above and is completely exposed, facilitating detailed geometric study.

THE BASSE NORMANDIE DUPLEXES

The lower duplex is well exposed in a near-vertical cutting along an access road on the northwest side of the quarry (Fig. 2). Immediately behind this quarry face is a parallel railway cutting which displays the structures of the upper duplex and the opposed-dip complex (Fig. 2a). Figure 2(b) is a composite section, which puts together the different sections, plotted on an enlarged down-plunge photographic view taken from the east side of the quarry. There are three different groups of structures in the section.

(1) In the railway cutting to the southwest of the masonry buttress is the folded and imbricate sequence which we call the upper duplex. Imbricate thrusts, hanging- and foot-wall cutoffs and internal folds can be seen. However the floor thrust is hidden in the railway track and the roof thrust has been eroded away. This upper duplex dies out at the position of the buttress in a ramp anticline, and following the model of Boyer & Elliott (1982) we postulate a step in the roof thrust of the upper duplex (Fig. 2).

(2) To the northeast of the buttress the beds in the hanging-wall are structurally conformable in a thrust flat but pass into an opposed-dip complex with foreland- and hinterland-dipping thrusts. Such dip complexes are typical of shortening in beds above décollement surfaces (Harris & Milici 1977). In this case the décollement is the roof thrust to the upper and lower Basse Normandie duplexes.

(3) To the northeast of the weighbridge hut, the lower duplex, the main subject of this paper, is completely exposed along a 70-m long section right to its foreland tip at X (see Figs. 2 & 6). To the southwest of the weighbridge the lower duplex is badly exposed but the floor thrust can be traced into the southwest corner of the main quarry where the thrust branch-line at Z′ (Fig. 2b) marks the hinterland end of the lower duplex. Massive imbricated limestones, characteristic of the lower duplex, are exposed to the northeast of the branch-line (Fig. 4) and folded well-bedded limestones of the upper

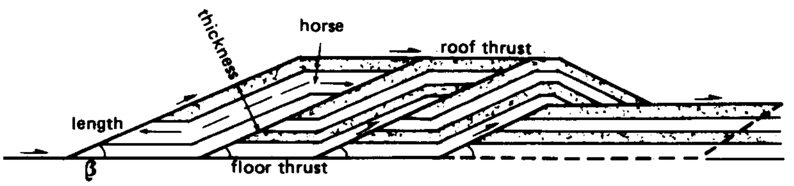


Fig. 3. Duplex model of Boyer & Elliott (1982) in which the internal folds have kink geometry. The angle (β) between the subsidiary thrusts and the floor thrust is 30°, the average thickness/length ratio (t/l) is 0.2 and the bulk shortening is −69%.

duplex are exposed to the southwest. The floor thrust is completely flat and has been projected down-dip to the west where we propose that it joins the Hydrequent thrust in a branch-line (Fig. 2b, w). The roof thrust of the lower duplex has two pronounced steps (visible in Fig. 6), where the structural thickness increases sharply. The foreland portion of the duplex between the second step at Y (Fig. 4) and the tip at X has been studied in detail.

The duplex formed in a series of beds 1.98 m thick before deformation (Fig. 5), containing two marker horizons used to balance the section. This reference section was measured in the foreland beyond the duplex tip (X in Fig. 6). The stratigraphic succession is tectonically thickened within the duplex to initially 3.4 m, and then to over 6.7 m beyond the second step in the roof thrust (Fig. 4). There is no evidence of stratigraphic thickness changes in the beds exposed elsewhere in the quarry and thus all thickening within the duplex is assumed to be tectonic.

Calcite slickenside fibres are visible on some of the lower duplex thrust surfaces and have a vector mean, calculated by computer using the Watson method (Cooper & Nuttall 1981), of 26° plunge to 207°. This implies a transport direction of 027° which is in agreement with the orientation of similar lineations from the upper duplex at the southwest end of the section. A series of folds exposed in the upper duplex (Fig. 2b) trend 115–285°, that is approximately perpendicular to the transport direction inferred from the lineations. The outcrop of the Hydrequent thrust has a trend of 123° (1:50000 Carte Geologique Detaille de la France, Marquise Flle. xxi–3) with a south-southwest dip implying a transport direction up-dip towards 033°. Cross-faults below the thrust, which may be parallel to the transport direction, have a local trend of 034° (Wallace 1969). The trend of the duplex section is 050°, approximately 20° different from the inferred thrust transport direction. However this angle of obliquity will not greatly affect bulk strain calculations on the balanced section of the structure (Cooper 1983).

The lateral persistence of the lower duplex can be demonstrated by its occurrence in the southeast face of the quarry and in the parallel railway cutting behind the quarry. The lower duplex is topographically lower in the railway cutting indicating a slight dip to the northwest. The sequence above the lower duplex is well exposed in the railway cutting and consists of a series of foreland- and hinterland-dipping thrusts which will be discussed later.

BALANCING METHODS IN THE LOWER DUPLEX

We initially photographed the section with a Polaroid camera to produce field slips. The section was also carefully photographed using a tripod mounted camera at a constant distance from the cutting. Considerable overlap was allowed between the frames. The inclination of the camera lens was measured so that each photo-

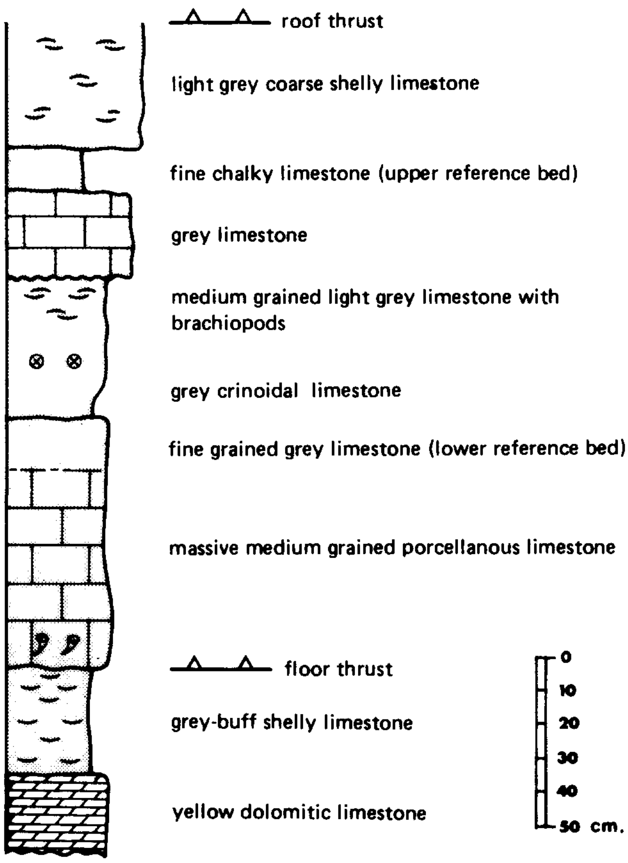


Fig. 5. Stratigraphy of the lower duplex measured at X in Fig. 6. The stratigraphic positions of the roof and floor thrusts are shown in addition to the two reference beds.

graph could be corrected for parallax by printing onto a baseboard tilted at the same angle. Finally the photographs were mounted in a mosaic and a line drawing made. The lower duplex section was then restored to the undeformed state using the constant bed length technique (Dahlstrom 1969, Hossack 1979). As a cross-check, the individual horses in the duplex were area balanced. The horses in the deformed and restored sections were numbered sequentially, cut-out, and weighed with a geochemical balance. The weight of any horse is proportional to its area and differences are accurately determined by the balance. Assuming plane strain, the area (or weight) of a horse must be constant before and after strain. Errors of ±5% were accepted but horses with errors in excess of this were carefully re-drawn to eradicate errors. We feel that this method of cross-checking leads to a more accurate section. Although the section is completely exposed there are still two sources of potential error (Fig. 7). In Fig. 7(a) the thrust cuts up-section through a marker bed and leaves it at point R. However, it is unclear where it intersects the base of the bed; it could be anywhere between points P and Q. Slight errors in determining the point of intersection can produce errors in line length and area balancing. Another error arises from the development of sub-horses (Fig. 7b). Their development is the result of an imbricate thrust refracting into a bedding plane beneath that followed by the roof thrust.

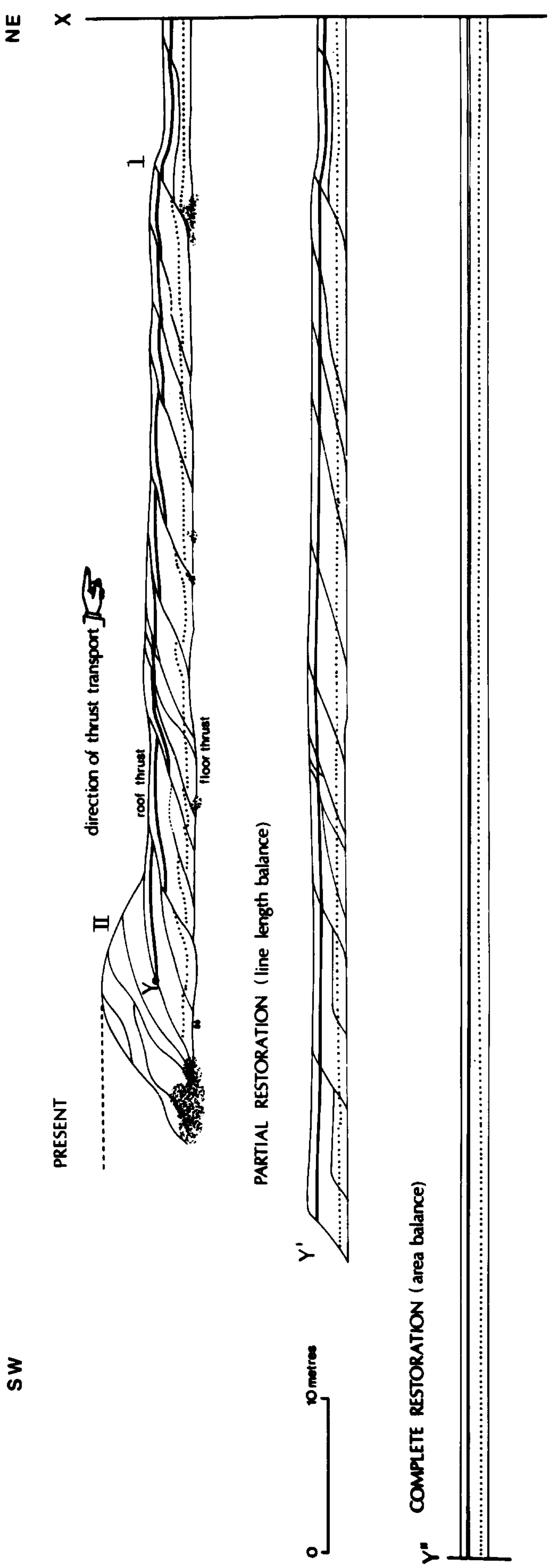


Fig. 6. Present, partially restored and completely restored sections of the Basse Normandie lower duplex between the pin-line X in the foreland and a reference point Y on the upper chalky reference bed. The number 86 represents a number that was painted on the rock face (see Fig. 4) and the stipple indicates bushes.

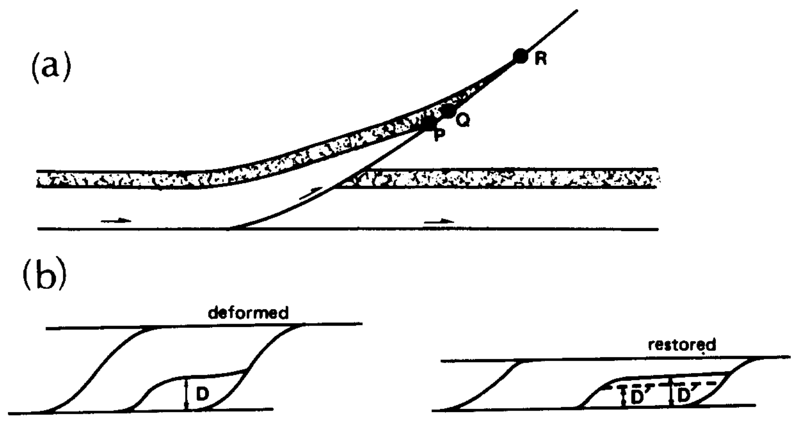


Fig. 7. (a) Difficulty of positioning the lower cut-off (Q) of a reference bed against a thrust. (b) A comparison of a horse restored by area balance where small errors in positioning the height of the horse (D') can induce larger errors in area.

The imbricate thrust is terminated by the next imbricate thrust to develop. Two such sub-horses illustrated in Fig. 6 exploit the same bedding plane. When the horse-sub-horse pair are area balanced any errors cancel out. These are simply due to small errors of measurement from the floor thrust to the sub-horse roof thrust (D and D', Fig. 7b). Although the difference in height may be small the resulting difference in area is greater.

After the final correction of the deformed and partially restored sections the bulk shortening in the section can be calculated. The deformed length of the section (l_1) is 61 m (X–Y Fig. 6), the 'original' length (l_0) is 76 m (X–Y' Fig. 6), both measured in the upper marker bed (Fig. 4).

$$\text{Shortening} = \ln [1 + (l_1 - l_0)/l_0] \times 100$$
$$= -22\%, \text{ where ln = natural log.}$$

However, it is clear from Fig. 6 that line length balancing only partially restores the section. In section X–Y' there is still a marked thickening of the section at the first step in the roof thrust. There is no evidence to suggest that the thickening is primary. Thus, the bulk strain in the section is not solely due to thrusting.

The total bulk strain in the section may be estimated using the excess section area balance method (Hossack 1979, Elliott & Johnson 1980). In these calculations the areas are divided by the original (foreland) thickness of the stratigraphy in the section, in this case 1.98 m. This gives a bulk shortening of −49%, and the present 61 m long duplex section restores to a pre-deformation length of 99.5 m (X–Y" Fig. 6).

The total contraction of the section is −49% of which only −22% is attributed to thrusting. The remaining −27% of contraction is attributed to processes of internal deformation which produced layer-parallel shortening. There is no evidence of cleavage in the duplex but in thin section the carbonate grains are twinned. Part of the internal strain may be accommodated by this process (Groshong 1972): non-plane strain or grain boundary sliding, which leaves no visible evidence, may account for the remainder.

Bed length balancing is generally assumed to give accurate estimates of bulk strain in the absence of cleavage. Where cleavage is present, area balancing must be used to determine the bulk strain. There is a difference of 23.6% in bulk strain estimates from the two methods. Errors of a similar magnitude have been noted by Gwinn (1970) in the Appalachians. We, therefore, recommend that both methods be used, firstly to get an accurate estimate of bulk strain and secondly to investigate which processes have produced that strain.

COMPARISON WITH IDEAL DUPLEX GEOMETRY

Boyer & Elliott (1982) have proposed a theoretical model of a hinterland-dipping duplex, based on a survey of examples in the literature (Fig. 3). The Basse Normandie lower duplex has an average thickness/length ratio for the horses of 0.22 (0.20 ideal) and the average angle between the imbricate thrusts and the floor thrust of 23°, is somewhat less than the 30° of the theoretical model. The overall shortening of the measured part of the duplex is −49% of which only −22% is due to thrusting; this is less than the theoretical value of −69%. A more accurate estimate of the shortening is gained by considering the shortening in successive portions of the duplex from its tip. This shortening is displayed in three ways (Fig. 8). (a) The total shortening calculated by area balancing for each individual horse is plotted against distance from X (Fig. 6). (b) The total shortening calculated by area balancing for successive 10 m intervals from X is plotted against distance. (c) Duplex thickness is plotted against distance from X. The three graphs indicate only small amounts of shortening at the foreland tip which rapidly increases to the first step in the roof thrust (I in Fig. 6). The percentage shortening then increases gradually to the theoretical −69% value at the second step in the roof thrust (II in Fig. 6). The simple plot of duplex thickness against distance (Fig. 6c) illustrates the strain variations very effectively. The maximum thickness attained is 6.64 m, corresponding to a shortening of −123% beyond the second step in the roof thrust. This value is higher than the maximum

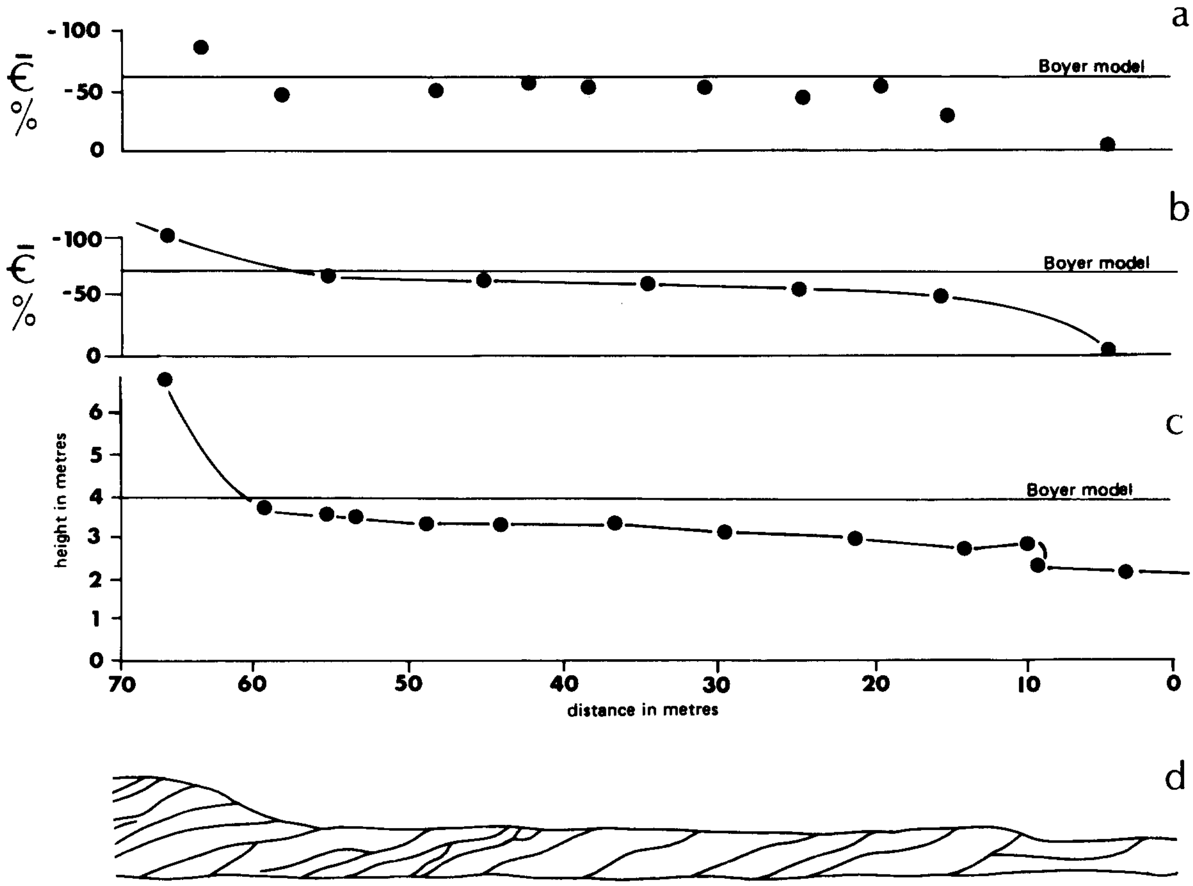


Fig. 8. Shortening estimates in the lower duplex plotted against distance. (a) Shortening calculated in individual horses using area balancing. (b) Shortening calculated for 10-m intervals using area balancing. (c) Duplex structural thickness at different positions. (d) Duplex geometry for comparison.

contraction of −92% quoted by Boyer & Elliott (1982) for the Haig Brook duplex. Because of the high value of contraction at the second step (point Y, Fig. 6a) the thrust slip on each of the imbricates was of the order of the length of each horse. Hence, the horses beyond Y have almost completely slid over one another and consequently seem to branch from the floor thrust at more or less the same point. They have produced a structure similar to the anticlinal stack duplex of Boyer & Elliott (1982). We have not been able to follow the lower duplex structure down-dip from Y in any detail, because we were not able to trace our top marker bed (the fine chalky limestone of Fig. 5) through the duplex. However, we believe that the hinterland end of the duplex is visible at Z′ (Fig. 2) and that we can define the total area of the lower duplex quite accurately. Hence, we have carried out an area balance calculation to estimate the bulk shortening of the whole lower duplex assuming an original stratigraphic thickness of 1.98 m. The present length of the duplex between X and Z′ is 160 m and the restored length 376 m, equivalent to a −85% shortening.

We have suggested that at its propagating tip the lower duplex shortened by two deformation mechanisms: a layer-parallel shortening of −27% and thrust imbrication accounting for −22% shortening. Did these two mechanisms occur simultaneously or did they operate at different times? We propose that they operated at different times with layer-parallel shortening occurring first. Layer-parallel shortening is regarded as an important and early component of strain in the Moine thrust belt (Coward & Kim 1981). Thrust planes normally have a ductile bead or tip which moves ahead of the propagating thrust crack (Elliott 1976). This ductile tip may be a zone of structural damage containing, for example, sigmoidal tension gashes or an anticline–syncline pair. We suggest that a zone of layer-parallel shortening, which could be a potential cleavage front, is another possible indicator of the ductile bead. The layer-parallel shortening bead, now present down-dip of the first roof thrust step, moved through the rock and the imbricate thrusts formed behind, propagating into and thickening the bead. Because strains are non-commutative, the strains have to be removed in the reverse order to restore properly any deformed body. Hence the imbricate thrusts are removed before the layer-parallel shortening in the restored sections (Fig. 6).

THE UPPER DUPLEX

The structures in the rail-cut to the southwest of the weighbridge (Fig. 2), consist of a series of imbricate thrusts and folds. We believe that these structures are also part of another duplex, where the roof thrust is eroded and the floor thrust is hidden beneath the quarry road. It is not possible to trace a continuous stratigraphy through the upper duplex, but the upper chalky reference bed of the lower duplex seems to occur in two of the horses of the upper duplex. This suggests that the 2 m stratigraphic sequence of the lower duplex can be traced into the upper duplex. Our restored section (Fig. 9a) implies that this 2 m represents the uppermost part of the 10 m of imbricated stratigraphy, which we estimate exists in the upper duplex. This estimate is based on 10 m of vertical beds cut-off by the floor thrust of the last horse in the area of the buttress (Z in Fig. 9b and Fig. 3). A comparison with the ideal geometry (Boyer & Elliott 1982) indicates that the width of beds cut-off in the hanging-wall of the horse nearest the foreland (Fig. 3) is trigonometrically related to the thickness of the stratigraphic sequence (or the ramp height) of the duplex. In this case the beds are perpendicular to the thrust and the thickness (t_0) can be measured directly. If we divide the area of the upper duplex (Fig. 2b) by this thickness we can calculate the undeformed length (l_0) of the duplex (Fig. 9a), using the method of the total area balance (Hossack 1979). We estimate that the upper duplex was originally 132 m long and has shortened by −75%. This however is likely to be a minimum estimate, because, like the lower duplex, the upper may have experienced an earlier phase of layer-parallel shortening which we cannot recognize. The roof thrusts of the upper and lower duplexes meet as a leading branch-line at Z′ (Fig. 2b).

THE OPPOSED-DIP COMPLEX

This part of the section occurs in a deep rail-cut to the northeast of the buttress (Fig. 2) and a more detailed diagram is available in Cooper *et al.* (1982). The thrusts are recognized by the repetitions of another, chalky limestone horizon which we believe originally lay above that of the duplexes. The thrusts dip both towards the foreland and the hinterland, forming an opposed-dip complex (Fig. 10). These are commonly observed above décollement surfaces (Harris & Milici 1977). An area balance of the section gives a shortening estimate of −28%, and a line length balance calculation suggests that only −4% of this can be due to layer-parallel shortening. We believe that the detachment beneath is a major slip surface because slip is transferred into this horizon by both the upper and lower duplexes. There is also a major difference in shortening between the structures above and beneath this detachment. The bulk shortening of the 2 duplexes is −92% (Fig. 9) whereas the shortening above the detachment is less than −28%.

THE DEVELOPMENT OF IMBRICATE STRUCTURES IN THE BASSE NORMANDIE QUARRY

We accept that thrusts generally develop in piggy-back sequence and that the higher thrusts are older. Hence the Hydrequent thrust had already carried Devonian sediments over the Viséan limestones of the quarry before the duplexes began to develop in its footwall. To produce the upper duplex we require, following the model of Boyer & Elliott (1982), a footwall ramp in the Hydrequent thrust. The minimum distance for this hidden ramp (W′, Fig. 9) is 508 m down-dip from X which is the sum of the unstrained lengths of the lower and upper duplexes. The pre-deformation length of the upper duplex was over 132 m (W′–Z′, Fig. 9a) with an original stratigraphic thickness of at least 10 m. Imbrication of this area of the footwall produced the hinterland-dipping upper duplex and the 10 m hanging-wall cut-off at Z (Fig. 9b), which allows us to estimate the original thickness of the upper duplex. It is simplest to assume that the −27% layer-parallel shortening of the lower duplex rocks occurred in this strain increment causing the displacement of the reference point Y″ to Y′ relative to the pin-line, X (Figs. 9a & b). During this layer-parallel shortening the lower duplex succession thickened from 1.98 to 2.5 m. The bedding surface to the northeast of Z (Fig. 9b) was by this time a major detachment surface containing the slip transferred by the upper duplex.

The lower duplex then developed from a trailing branch-line just beneath Z′ (Fig. 9b). As suggested above, the original 1.98 m of stratigraphy of the lower duplex formed a continuation of the uppermost part of the upper duplex stratigraphy. The hinterland-dipping lower duplex developed in piggy-back sequence towards the foreland in these beds, producing the additional −22% shortening at the duplex tip. The reference point Y′ moved to Y (relative to the pin-line X, Fig. 9c). The local bulk shortening of the lower duplex however rises from zero at the tip to over −120% at the second step where an antiformal stack duplex has developed. In total the whole of the lower duplex between X and Z″ has contracted by −84%. As the lower duplex is shortened, the upper duplex and the Hydrequent thrust move farther to the northeast by 216 m of slip using the reference point W. It is reasonable to assume that the opposed-dip complex developed simultaneously with the lower duplex resulting in −28% shortening.

Boyer & Elliott (1982) present a duplex model in which the horses within the duplex move one at a time. At any one instant, the frontal horse has to fold over the collapsing ramp and then unfold as the next horse moves. We believe that folding and unfolding is unlikely and can be avoided if several horses form at the same time. The present section (Figs. 3 and 8) shows the shortening in the lower duplex to increase gradually from front to back and not in discrete jumps as required by the Boyer & Elliott model.

There are no more imbricate structures developed in the excellently exposed Viséan limestones beneath the lower duplex. Hence, Fig. 9(c) illustrates the last shortening movement. The total bulk shortening of the lower and upper duplexes and the opposed-dip complex is −92% estimated from the difference in length between Figs. 9(a) & (c).

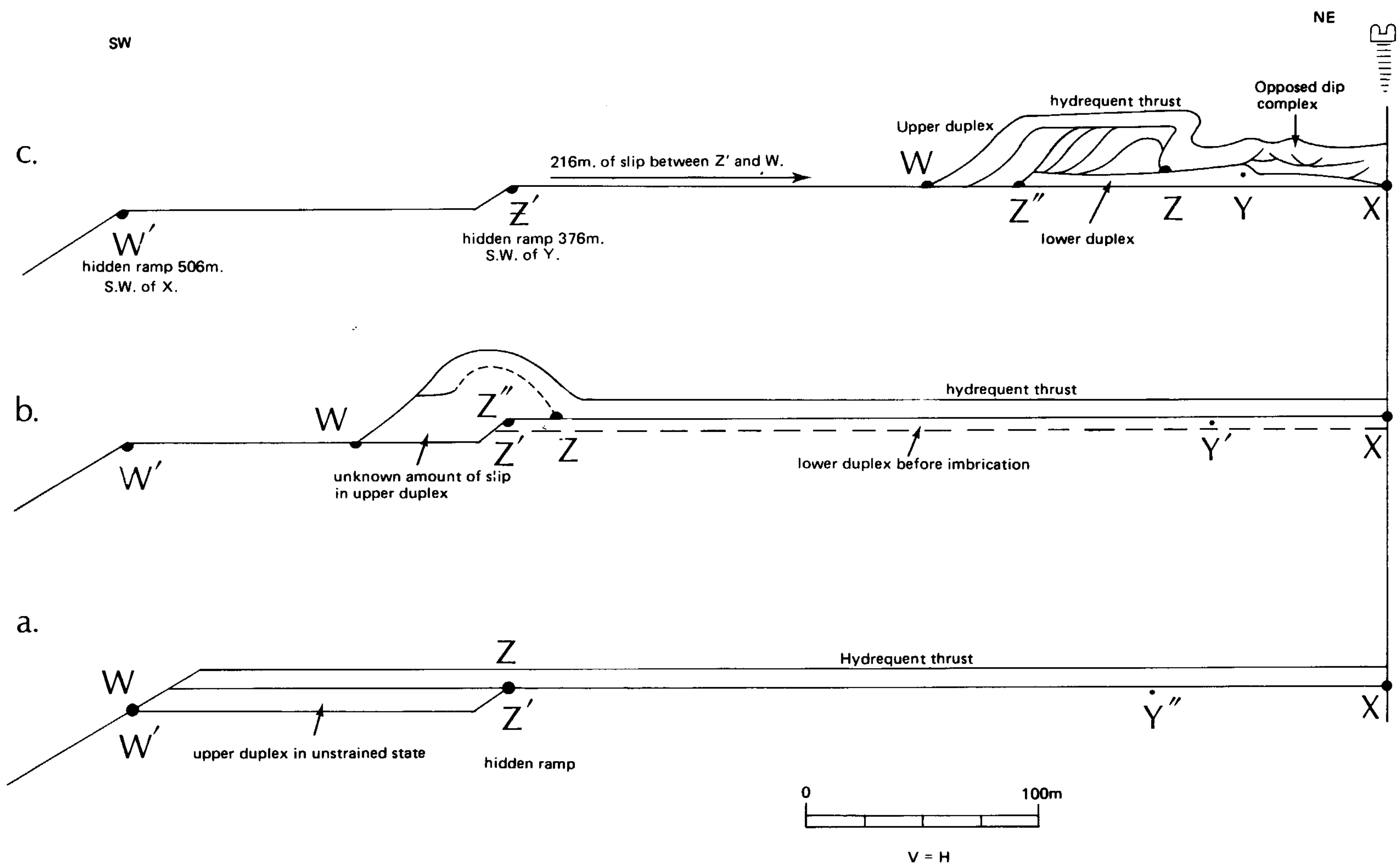


Fig. 9. Sequential development of the Basse Normandie thrust structures. (a) Undeformed section beneath the Hydrequent thrust and the pin-line at X. Y″, Z, Z′, W and W′ are reference points. (b) Imbrication of the upper duplex , offset of Z′ to Z and layer-parallel shortening of the lower duplex. Y″ in (a) is displaced to Y′. (c) Imbrication of the lower duplex and the opposed-dip complex. W and Z move further NE, Y′ in (b) moves to Y. W′ is the suggested position of the footwall ramp in the Hydrequent thrust which produced the lower duplex.

It seems to us significant that the individual shortening increments were, in general, decreasing with time and that they affected thinner units in the sequence. The likely explanation is that the available energy to produce the deformation was gradually decreasing in a decaying differential stress field. These structures were probably formed during the last Hercynian deformation to occur in the area.

DISCUSSION

Drawing a geological cross-section is a complicated process helped by applying several methods. Firstly, when constructing cross-sections a small-scale fully exposed model can aid in drawing larger inferred structures that are less well exposed. The lower duplex helped considerably in the drawing of the structure of the comparatively poorly exposed upper duplex. Secondly, cross-sections should always be balanced by both line length and area techniques. This gives an insight into the tectonic processes which have deformed the sections. Without the application of the two techniques the layer parallel shortening in the lower duplex would never have been recognized. The two techniques also act as a mutual cross-check on the admissibility of the section. Finally it is an advantage to have co-workers when constructing balanced sections. We have balanced and drawn various sections both individually and together and have found that the latter approach yields a more admissible and valid cross-section.

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