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Thrusting in a folded regime: fold accommodation faults in the Ruhr basin, Germany

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Abstract

The Late Carboniferous Ruhr basin in Germany has been described as an authochtonous foreland basin of the Variscan Orogen. The structure of the basin is fold-dominated with fold accommodation faults as secondary elements. Vast and excellently documented 3D mining exposures provide extensive data on the geometry of thrusts and the relationship between thrusting and folding. Stratigraphic throw is the determining factor in the geometry of thrusts and displacement and shortening are functions of throw, material behaviour and bedding dip. Built up on a basic geometric model, a complex system of different fault types can be described, linked regularly to each other and developed during the folding process.

Keywords: Fold accommodation fault; Thrust fault; Variscan Orogenic Foreland; Ruhr basin

1. Introduction: fold accommodation-faults

During recent decades much investigation has been done on the relationship between folding and thrusting within orogenic belts. Most of the models developed for the interpretation of fold and thrust belts focus on kinematics with thrusts as the primary element and folds formed in response to thrust-movement (fault-propagation folds, fault-bend folds etc.; e.g. Rich, 1934; Butler, 1982; Suppe, 1983; Anastasio et al., 1997). Orogenic models, which apply to these structures, are commonly based on the idea of basal detachments (e.g. Dahlstrom, 1970; Boyer and Elliott, 1982; Davis et al., 1983; Morley, 1986; Vann et al., 1986). However, it has been pointed out by several authors (e.g. Mitra, 2002) that thrusts may also be the product of the folding process within an orogen, accommodating strain variations within the tectonised stratigraphic sequence. This type of thrusting has been described as 'fold accommodation faults'. Within this paper, the term 'thrust' is usually used for fold accommodation faults of any type (see Section 7).

According to observations in the Ruhr basin the following criteria seem to be diagnostic for this type of faulting (Drozdzewski and Wrede, 1994):

(1) Fold accommodation faults show a geometric and kinematic relationship to surrounding folds. In particular their strike is generally parallel to the strike of fold-axes and they show a more or less symmetric arrangement to the axial planes of folds.
(2) Fold structures below and above the thrust plane are similar; fold axes can be connected from footwall into the hanging wall block.
(3) Thrusts are isolated and limited in extent and are not normally connected by flats.
(4) They may terminate out-of-bedding, i.e. thrust tips form an angle with bedding and do not necessarily run into bedding-planes.
(5) Their movement always cuts up stratigraphic section.

It is the aim of this paper, primarily based on extensive studies of the structure of the Ruhr Basin in Germany, to contribute to the description of fold accommodation faults as well as to the interpretation of their kinematic evolution.

2. Structure of the Ruhr Basin, Germany

The Ruhr Basin is part of the Variscan Externides in

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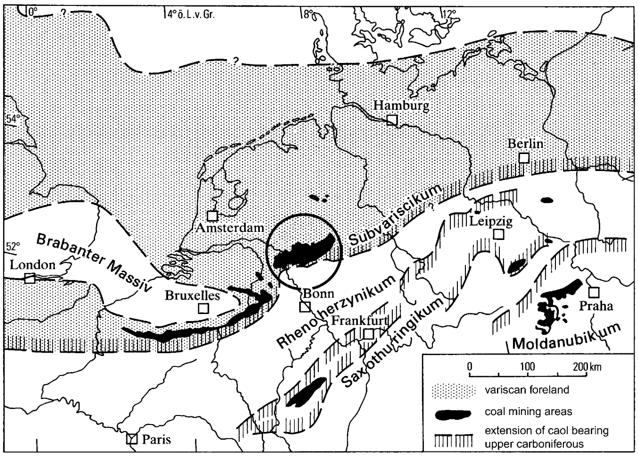

Fig. 1. Location map of the Ruhr basin within the Variscan Foreland.

Central Europe. It crops out at the surface in the southern part and is unconformably covered by Permian–Cretaceous sediments of up to 1000 m thickness in the northern part. It extends over 200 km in a SW–NE direction and is exposed by mining activities over 75 km across the general strike (Figs. 1 and 2). In this basin a sequence of over 5000 m of Upper Carboniferous (Pennsylvanian) coal-bearing, molasse-type sediments conformably overlay Mississippian and Devonian strata. The whole palaeozoic sequence has been folded at the end of the Carboniferous. Orogenic shortening gradually decreases from 40–50% in the south to less than 5% in the north (Wrede, 1987). The Ruhr basin has been described as an authochtonus orogenic foreland (Brix et al., 1988; Drozdzewski, 1993; Drozdzewski and Wrede, 1995). Because of the presence of economic coal seams, the area has been thoroughly mined and today may be one of the best-exposed and documented examples of a fold belt in Europe. Mining exposures and boreholes constrain the geologic structure of the whole area to a depth of 2 km. Mining industry needs have led to the tectonic structure of this area being systematically investigated by the Geological Survey of North Rhine–Westphalia over the last 30 years. Most of the results of these surveys have been published (Drozdzewski and Wrede (1994) with further references) and may well contribute to the discussion on the kinematics of thrusting and folding.

Folding in the Ruhr basin is strongly disharmonic: three tectonic levels (‘stockwerks’) can be distinguished. The upper stockwerk is defined by large synclines with flat bedding and wavelengths of up to some 10 km, intersected

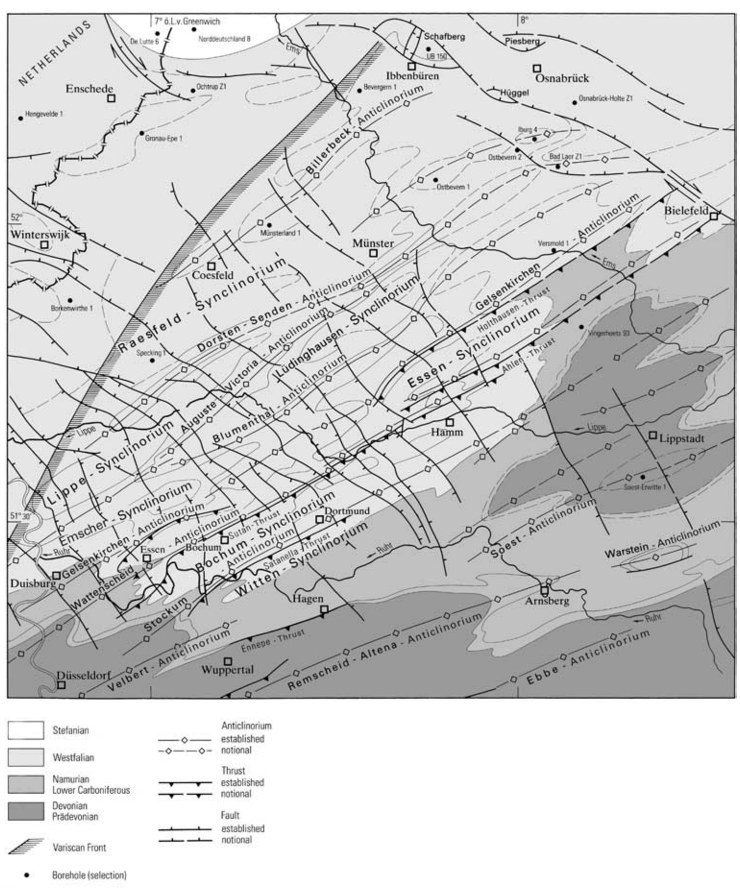

Fig. 2. Structural map of the Ruhr basin (top of the Palaeozoic); hatched band (‘Variscan Front’) indicates outermost remarkable folding.

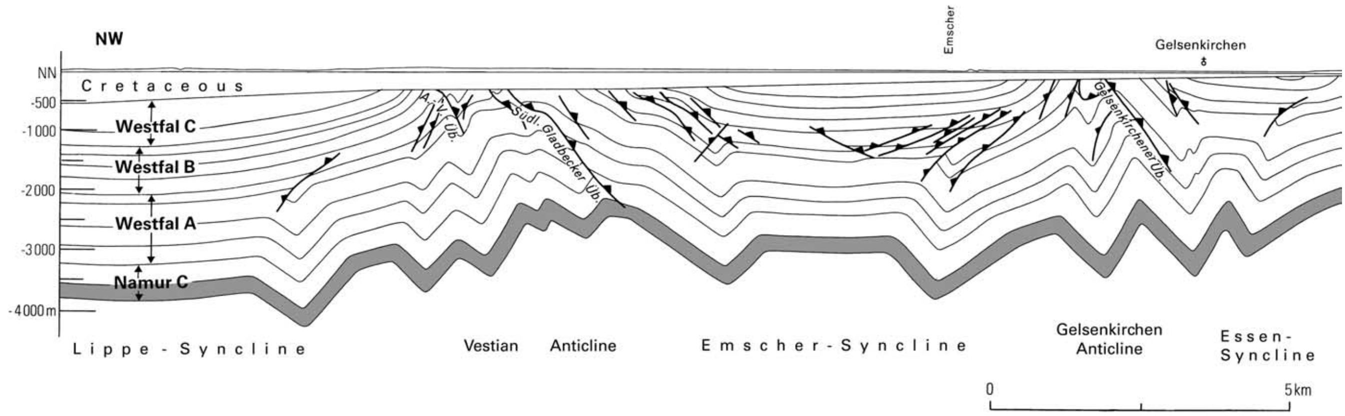

Fig. 3. Typical cross-section of the Ruhr basin: fold dominated tectonics with concentration of thrusts in a middle stockwerk.

by narrow, intensely folded anticlinoria. Larger thrusts, if existing at all, are normally restricted to the limbs of the anticlines. The lower stockwerk displays intense minor folding. The number of folds is far greater than in the upper stockwerk, but amplitudes and wavelengths are less. Larger thrusts do not occur in this stockwerk but they are concentrated in the intermediate stockwerk where they compensate the differences in tectonic style between the upper and the lower stockwerks (Fig. 3). Thrust dimensions range from metres to some tens of kilometres along strike. Displacements and throws occur across a range of scales up to a maximum of 2.5 km and nearly 1000 m, respectively. Isolated thrusts occur at different stratigraphic levels and are not linked, thus no general decoupling of the individual stockwerks takes place. Thrusts are involved in fold geometry: fold axes can be traced from the footwall into the hanging wall of the thrusts, and many thrust-planes are deformed more or less concurringly to folding (Fig. 4). Along strike, transitions between folds and thrusts are frequent.

Orogenic shortening is equal in all three stockwerks; the decrease in the number of folds towards surface is compensated by their increasing size.

The stockwerk distribution in the Ruhr basin is strongly dependent upon a large-scale axes undulation that affects the area. Within axes depressions, the upper stockwerks reach down to relatively old strata, while within axes culminations, they are restricted to relatively young strata. However, it is controlled by neither stratigraphy nor facies. A more detailed discussion of stockwerk tectonics in the Ruhr basin is given by Drozdzewski and Wrede (1994).

The position of the thrusts within the tectonic stockwerk arrangement, as well as various fold–thrust relationships, which will be discussed below, clearly indicate that in the Ruhr basin thrusts are secondary elements in a fold-dominated tectonic environment. Folds in the Ruhr basin

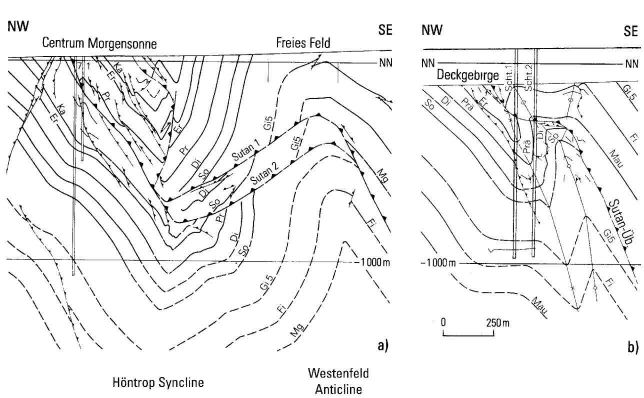

Fig. 4. Thrusts strongly involved in the folding process: ‘Concurringly’ deformed thrust (left: Centrum Morgensonne mine) and ‘non-concurringly’ deformed thrust (right: Graf Schwerin mine). (Ka, Er, Pr, etc.: acronyms for coal seams).

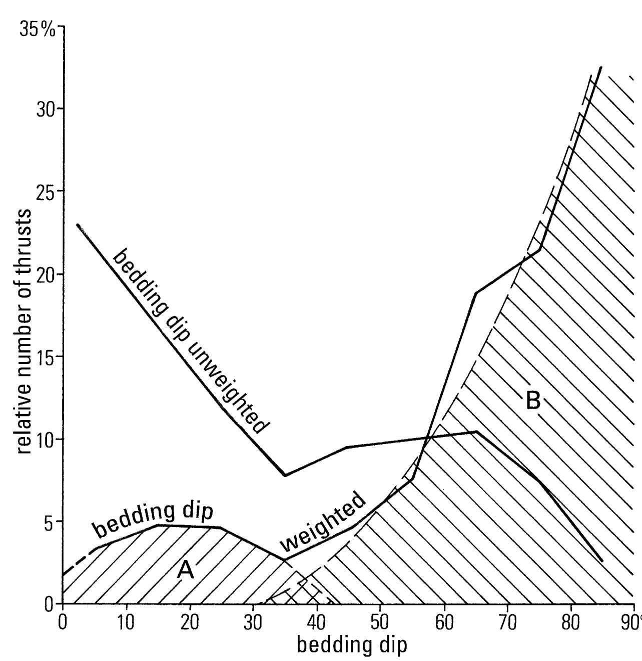

Fig. 5. Relationship between number of thrusts and bedding dips in the Ruhr basin ($n=650$ thrusts); explanation in text.

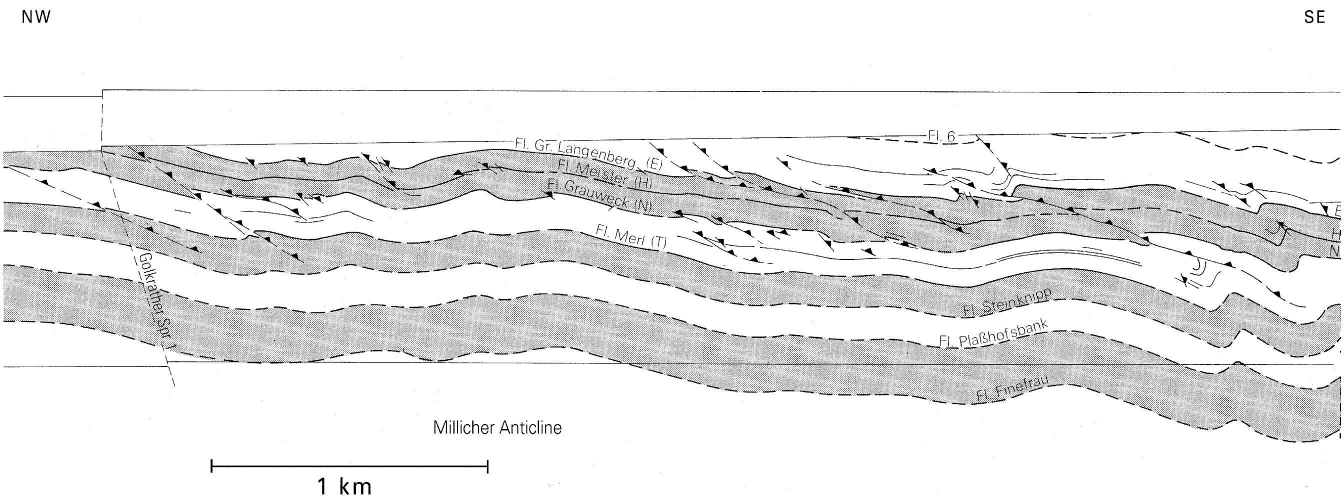

Fig. 6. Thrust belt in the northern foreland of the folded zone. Note that the thrusts die out toward depth in different levels and undisturbed seams have been mined below their footwall tips (solid lines). (Sophia–Jacoba mine).

may be described as flexural slip folds. Bed thicknesses are generally independent from folding and remarkably constant over larger areas.

3. Origin of thrusts and symmetries

A model that suggests folding is the causal process for the development of thrusts should result in a proportional relationship between the intensity of folding and thrusting: increasing folding should result in more and/or larger thrusts.

For the Ruhr basin this question has been investigated by Wrede (1993). In a diagram (Fig. 5) the relative number of thrusts (as percentage of all investigated thrusts; $n=650$ thrusts) was plotted against the respective dip of host strata (in 10° intervals) as a measurement for folding. Surprisingly, the number of thrusts appears to decrease with increasing dip of strata. However, the bedding dips in the Ruhr basin are not random. As more than 50% of strata show dips of <20°, while only 20% of strata are steeper than 35° (Büttner et al., 1985), the graph is rather a function of this relationship than of the thrust–bedding dip relation. Thus, the relative frequency of bedding dips has to be considered and applied to the measurements. The weighted graph resulting from this computation indeed shows at first glance a positive relationship between the number of thrusts and the increase of bedding dip. Closer inspection, however, reveals the existence of two different populations of thrusts: type-A thrusts (ca. 13% of all thrusts) appear in flat-lying

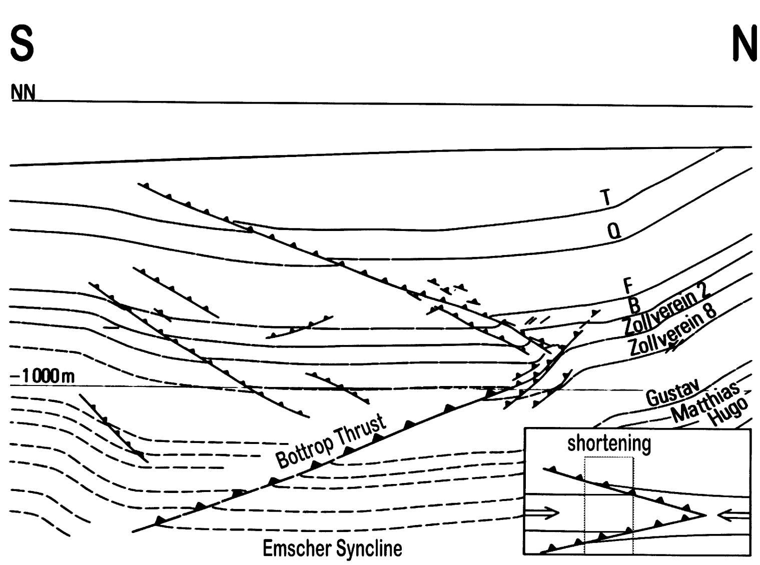

Fig. 7. Bottrop thrust as a large scale example of a 'fish-tail-structure' (Prosper mine) (after Drozdzewski, 1979).

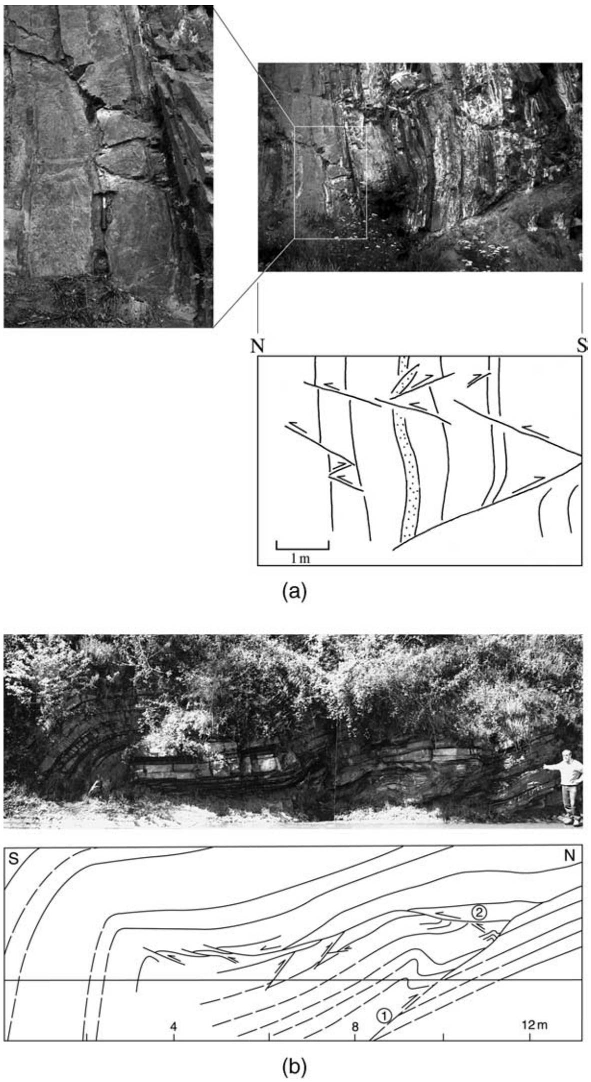

Fig. 8. Fish-tail-structures in different fold positions: (a) multiple fish-tails in a steeply dipping fold-limb (Hagen–Vorhalle Quarry); (b) fish-tail close to the hinge of a box-fold (Herdecke–Schiffswinkel road-cut); 1: northward directed thrust, 2: southward directed 'back' thrust.

strata (bedding dip of $<40°$, with a peak at 20°), while type-B thrusts only develop when bedding dips exceed 30° and then quickly increase in number with increasing folding intensity.

This observation implies two different mechanisms causing the development of thrusts in a fold regime: type-A thrusts substitute folds, i.e. orogenic shortening by folding is substituted by thrusting. This coincides with the observation of mutual transitions of folds and thrusts along strike. Type-B thrusts result from the folding process itself. They compensate volume surpluses within the closing synclines by transport of material to the adjacent anticlines. A remarkable difference exists between type-A and type-B thrusts with respect to their vergence (Drozdzewski and Wrede, 1994, fig. 60): In the Ruhr basin, in which folds show no or only weak vergence towards north(-west), the orientation of type-B thrusts is symmetric: 49% are directed southward and 51% are directed northward. Northward directed thrusts are mainly found on the northern flanks of synclines and southward directed on the southern flanks.

In the population of type-A trusts, however, the ratio between northward and southward directed faults is 62:38. According to field observations, most of the type-A thrusts are concentrated in the northern part of the Ruhr basin, where the intensity of folding is very low (orogenic shortening $<10\%$). Here southward dipping thrusts are frequent, while only very few northward dipping thrusts occur (e.g. Wolf, 1985, fig. 76). As proven by mining exposures, these thrusts are limited in extent, are isolated and do not merge into a common sole thrust (Fig. 6).

The relative minimum in the graph of Fig. 5 between the A- and B-populations suggests that type-A thrusts are relatively young (and cannot predate folding), because it is very unlikely that a number of pre-existing thrusts vanishes completely during the progress of folding. On the other hand, transitions between type-A thrusts and folds along strike prove that type-A thrusts are part of the folding process.

In discussing the symmetries between northward and southward dipping thrusts a special combination of fore- and back-thrusts has to be pointed out, which has been described by Drozdzewski (1979) as 'fish-tail'. At first glance they strongly resemble the thrust patterns that bound tectonic wedges firstly defined by Price (1986) and later described by Martines-Torres et al. (1994) from the Spanish Pyrenees. A single wedge is formed by a floor thrust and a roof thrust, dipping in opposite directions and linked by intersection of their respective hanging wall or footwall tip-line. Several of these wedges may be arranged above each other, forming a zip-like structure. This system of conjugate thrusts with opposing vergences generates a horizontal shortening and a thickening of crust without net transport of material in any direction (Fig. 7).

However, a distinct difference exists between tectonic wedges and the structures observed in the Ruhr basin. The development of tectonic wedges as described from other regions leads to delamination of allochthonous units, limited by décollement sheets.

In the Ruhr basin a combination of a fish-tail and a décollement has never been observed. On the contrary, fish-tails may develop independently from the dip of bedding-planes (which might preferably act as décollements) and are as common in the centre of large box-folds with flat lying strata (Figs. 7 and 8b) as in extremely folded, vertical fold-limbs (Fig. 8a). Fish-tails occur at scales from decimetres to kilometres and, according to an interpretation of the DEKORP-2 N seismic profile, even on a crustal scale (DEKORP Research Group, 1990; Drozdzewski and Wrede, 1994). Fish-tail structures do not only occur in the tectonic

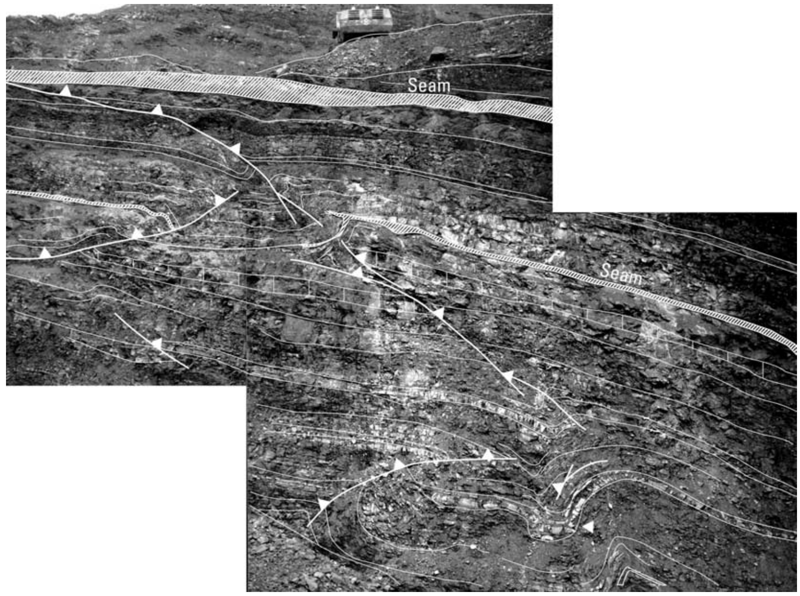

Fig. 9. Fish-tail-structures in East Pit Open Cast Coal Site, Brynamman, South Wales, UK. Situation as in September 1994. Scale: bucket excavator at top.

setting of the Ruhr basin: The South Wales Coal field in Britain in general is characterized by layer-parallel shear with coal seams acting as flats or detachments and predominantly northward directed thrust tectonics. Complex fold/thrust structures are interpreted as frontal thrust ramps induced by deep-seated Variscan thrusts (Frodsham and Gayer, 1997, 1999). Cole et al. (1991) and Cole (1993) likewise interpreted northward-directed thrusts in the East Pit Open Cast Mine as ramps between the coal seams acting as flats. However, ongoing excavation in 1993 unveiled here

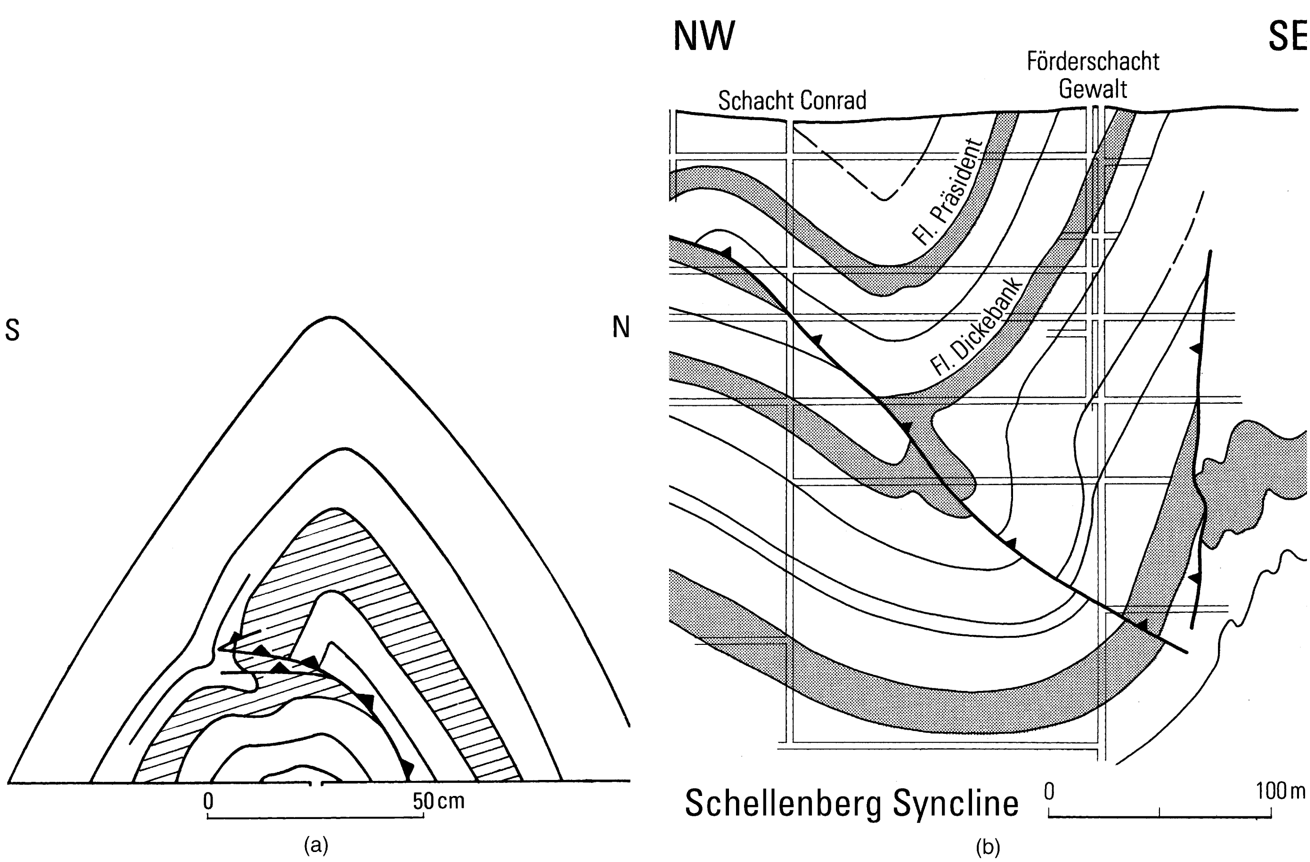

Fig. 10. Hanging wall and footwall tips of thrusts in the Ruhr basin angular to bedding: (a) Tremonia Mine, (b) Gewalt Mine.

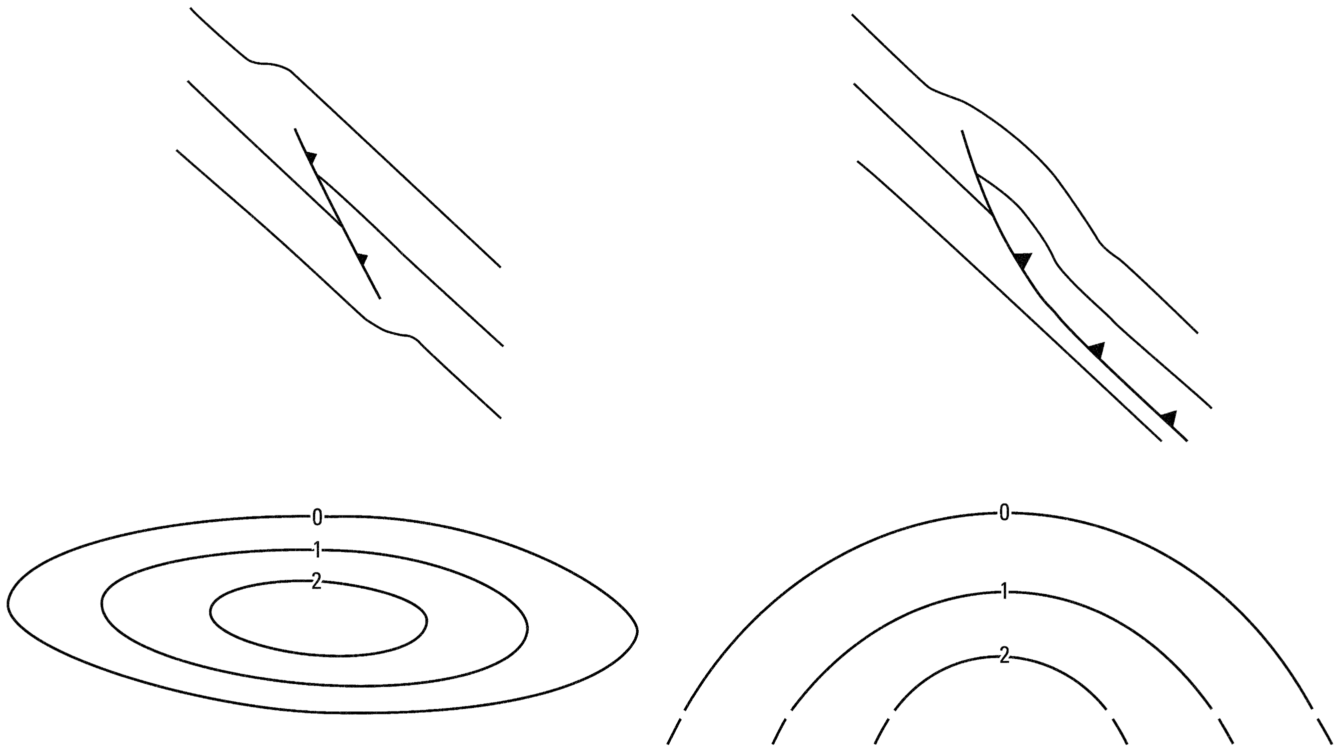

Fig. 11. Displacement variation diagrams for an isolated thrust (left) and a detachment related thrust (right) (after Morley (1994), modified).

a complex system of fore- and back-thrusts that may be interpreted as displaying at least two fish-tails, one upon the other. Towards the footwall a transition of thrust tectonics into a tip fold became visible (Fig. 9). Similar combinations of fore- and back-thrusts have also been described from Nant Helen Open Cast Coal Site (Hathaway and Gayer, 1994).

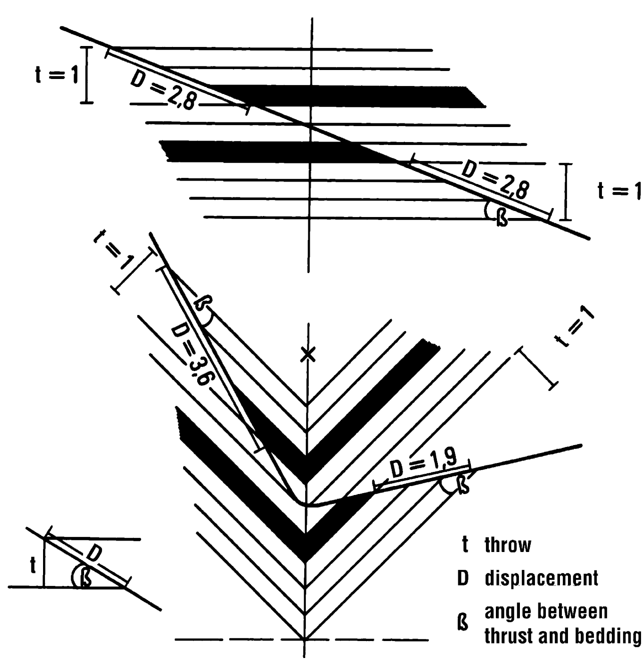

Fig. 12. Variations of displacement (*D*) and angle between thrust and bedding during folding; stratigraphic throw (*t*) remains constant.

Similarities also exist to the wedge thrusts described by Mitra (2002) from Ventura basin, California or structures in the Argentine Andes (Drozdzewski and Mon, 1999).

Many authors describe thrust planes merging with bedding planes in their footwall or hanging wall termination, or at least dying out parallel to bedding. However, a closer inspection of thrust tips in the Ruhr basin, enabled by the excellent exposures, reveals that thrusts (of any scale) may die out angular or even perpendicular to bedding planes (Fig. 10).

4. Displacements and stratigraphic throws

The most common measures for thrusts are either the relative movement of the hanging wall block along the thrust plane (displacement) or the uplift of the hanging wall block perpendicular to bedding (stratigraphic throw).

Fault displacement diagrams (Barnett et al., 1987), generated by plotting fault displacement against width, are a useful tool to distinguish between fold accommodation faults which form closed contour diagrams, and thrusts related to basal detachments, whose contours open at their lower end (Fig. 11).

Gillespie (1991, 1993) adopted this method to investigate displacements of thrusts in the Ruhr basin. His diagrams

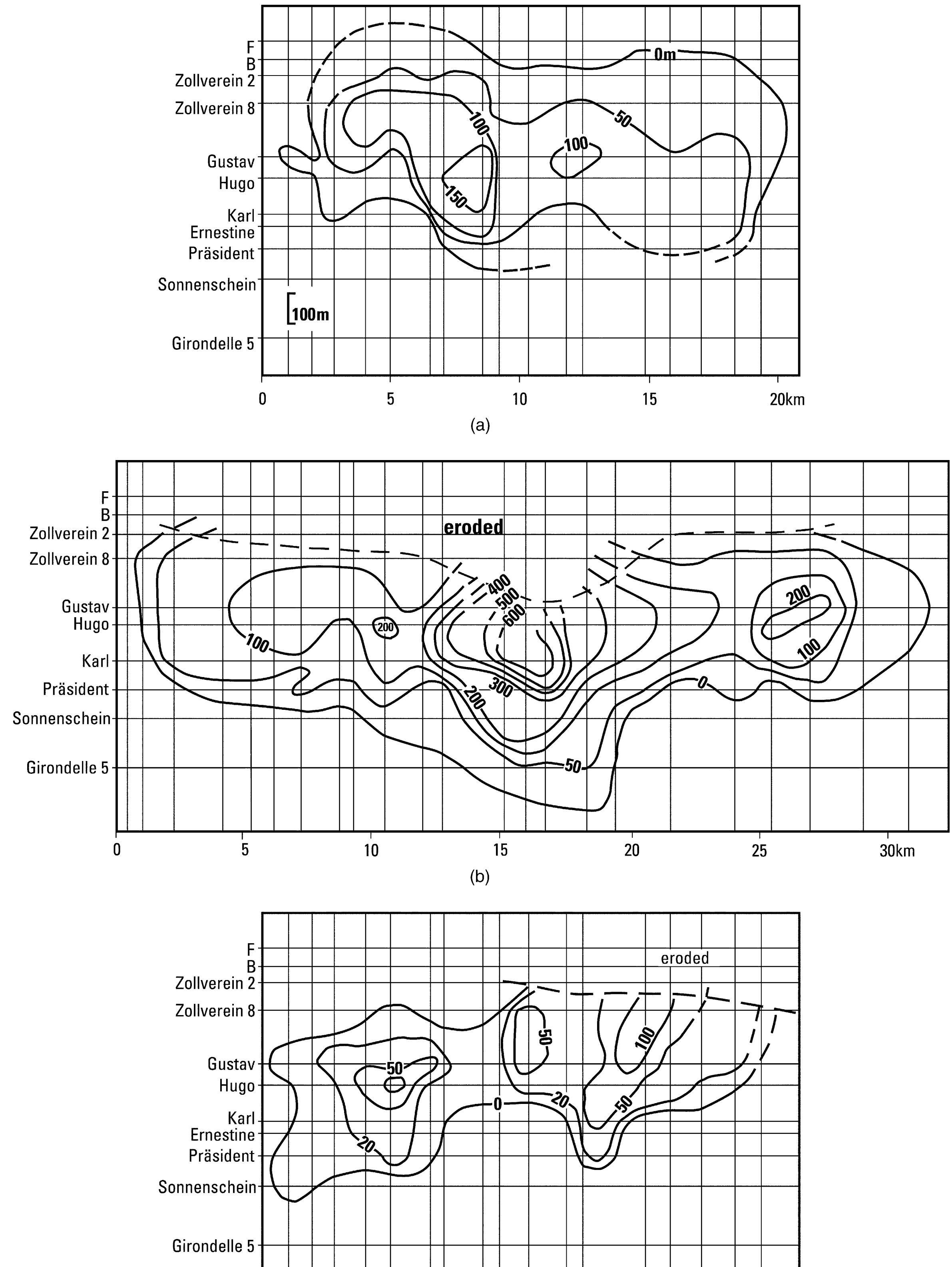

Fig. 13. Throw variation diagrams for different Ruhr basin thrusts (explanation in text): (a) Bottrop Thrust, (b) Langern Thrust, (c) Rheinelbe Thrust.

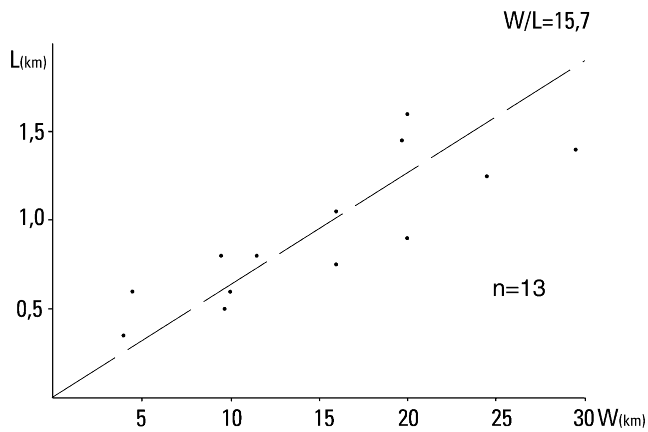

Fig. 14. Relationship between length and width of Ruhr basin thrusts.

clearly show closed contour lines, thus confirming independence of thrusts from detachments or sole thrusts. Gillespie (1993) established a relationship between displacement (D) and width (W) of thrusts over a wide range of scales for the Ruhr basin, South Wales Coalfield and other areas as being approximately $D=aW^{1.4}$, where a is a constant.

However, according to comprehensive observations in the Ruhr basin, displacements are a rather uncertain measure for the 'size' of thrusts. Displacements are strongly influenced by folding. For a constant throw, increasing dips of bedding and thrust result in increasing (or decreasing) displacements (Fig. 12; see Section 6). Therefore, stratigraphic throws characterize the scale of thrusts rather than displacements. Throws are relatively constant over certain regions and only gradually diminish from the peak value towards the fault tips, independent of folding.

Thus, instead of displacement contour diagrams, throw contour diagrams have been plotted for many of the larger thrusts in the Ruhr basin, which are more or less completely exposed. The intersections of the thrust with defined stratigraphic horizons (coal seams) in their correct stratigraphic distance were plotted on the y axis (Fig. 13). Again, the thrusts form closed, concentric structures around one or multiple throw maxima. The existence of multiple maxima may indicate an agglomeration of thrusts from several embryonic structures or, more likely, it reflects strain variations within one element.

From these diagrams it is possible to deduce a width (W) vs. length (L) relationship for the Ruhr basin thrusts. Based on $n=13$ completely exposed thrusts with widths between 4 and 30 km a ratio of

$$W = 15.7(\pm 5)L$$

can be established (Fig. 14). This means that thrust widths in general may be some 15 times greater than thrust lengths. Applied to the largest known thrust in the Ruhr basin, the 'Sutan' thrust with a known width of ca. 80 km, a length of about 5 km can be expected. This does not seem to be unrealistic (Brix et al., 1988; DEKORP Research Group, 1990) and indicates that even large scale thrusts like the 'Sutan' in the Ruhr basin can be regarded as fold accommodation faults.

5. Relationship between bedding dips and fault dips

Drozdzewski (1979) noticed that the angle between bedding planes and thrusts is dependent upon the dip of strata: the steeper the dip of strata, the smaller the angle between strata and thrust. Wrede (1980, 1982, 1993) investigated this problem in more detail and found that not only the angle between thrust and bedding, but also the dip of the thrust itself is dependent on the dip of strata.

The relationship between bedding dip ε (which is variable during the folding process) and thrust dip δ can be deduced from Fig. 15.

If bedding is horizontal, the angle between bedding and thrust β equals δ and can be defined as:

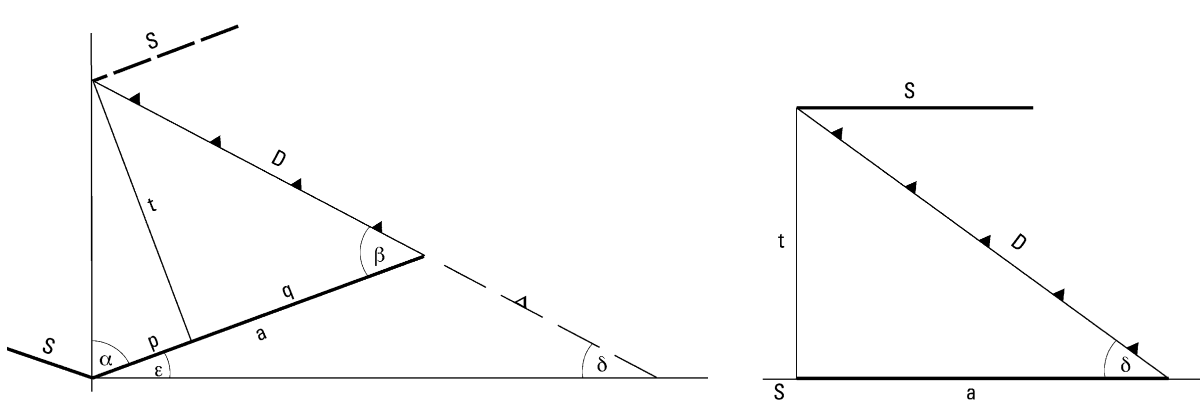

Fig. 15. Basic geometry of an antithetic thrust (S: bedding; D: thrust; for details see text).

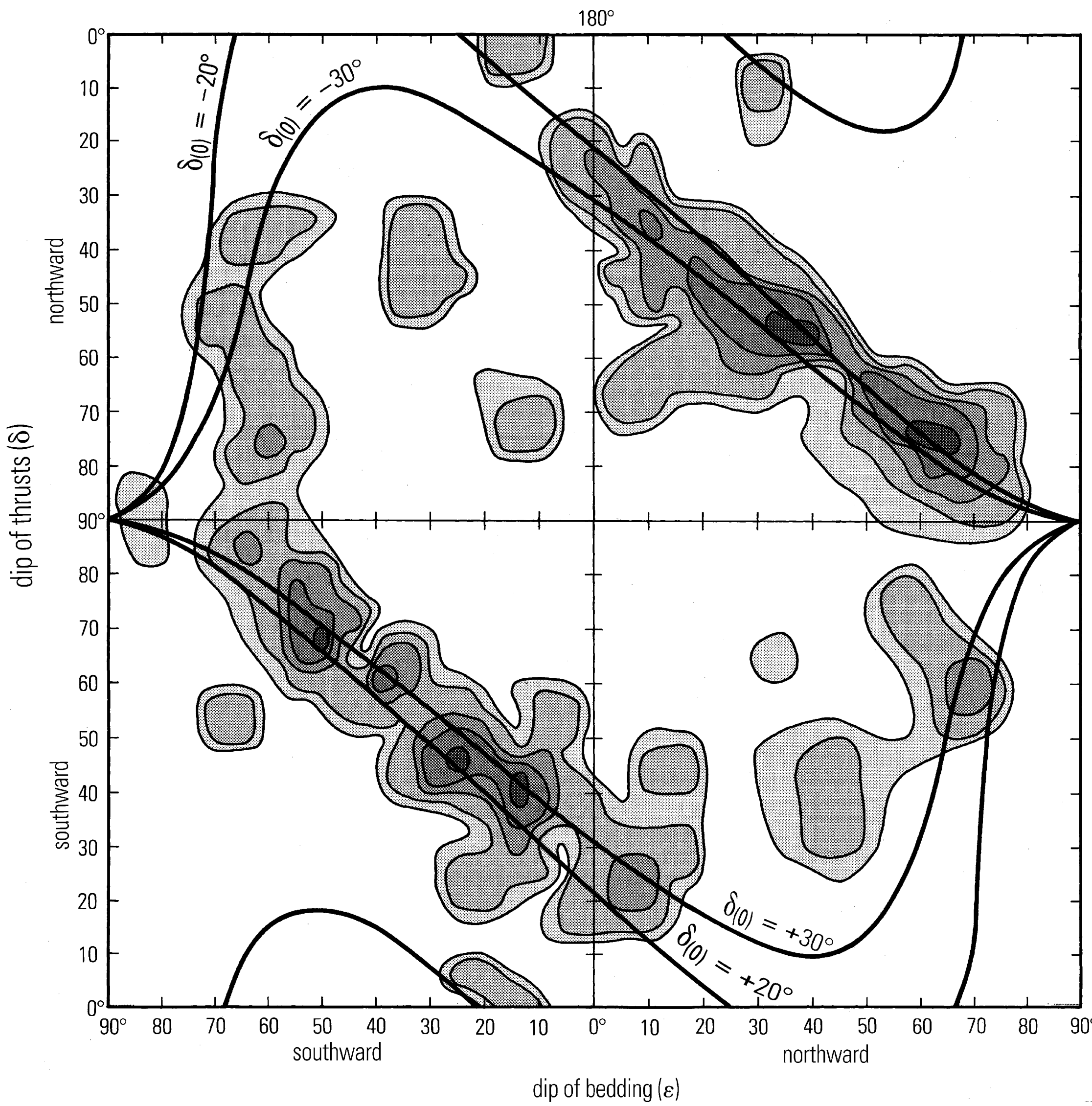

Fig. 16. Relationship between bedding dips and thrust dips in the Ruhr basin considering the respective directions of dip. Calculated relationship for $\delta_{(0)} = \pm 20°/\pm 30°$ ($n = 650$ thrusts).

$$\tan\delta_{(0)} = \frac{t}{a}$$

This angle $\delta_{(0)}$ represents the dip of fractures formed during horizontal compression of untilted beds. It reflects the strength of the material and in the following calculations has been regarded as being a constant for each thrust.

The relationship between bedding dip ε and the angle β between thrust and bedding then can be derived by the following calculation:

$$\tan\delta_{(0)} = \frac{t}{a}$$

$$a = t\cot\delta_{(0)}$$

$$a = p + q$$

$$p = \cot(90° - \varepsilon)t$$

$$q = a - \cot(90° - \varepsilon)t$$

$$q = t\left[\cot\delta_{(0)} - \cot(90° - \varepsilon)\right]$$

$$q = \cot\beta t$$

$$\cot\beta t = t\left[\cot\delta_{(0)} - \cot(90° - \varepsilon)\right]$$

$$\cot\beta = \cot\delta_{(0)} - \cot(90° - \varepsilon)$$

$$\beta = \arctan\frac{1}{\cot\delta_{(0)} - \cot(90° - \varepsilon)}$$

This relationship has been defined for 'antithetic' thrusts (i.e. thrust and bedding are dipping in opposite directions).

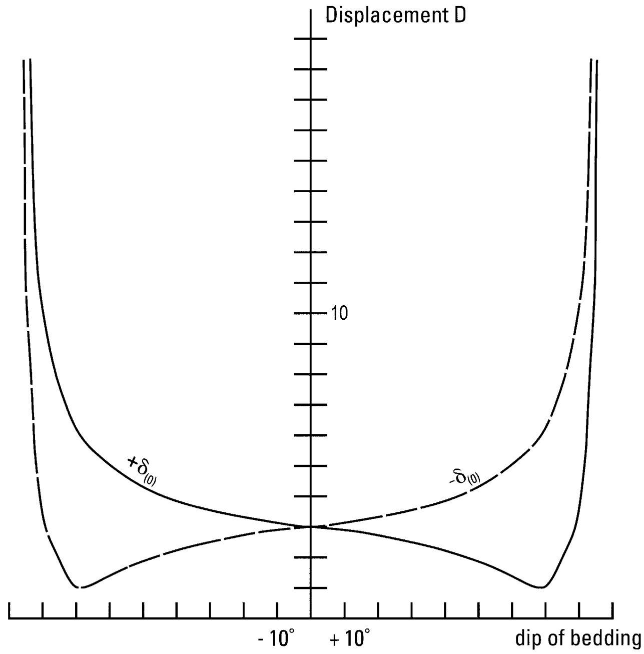

Fig. 17. Relationship between displacement and bedding dip for $\delta_{(0)} = \pm 20°$.

For the case of 'synthetic' thrusts (both elements dip in the same direction), the sign of either δ or ε has to be changed. Within this paper, northward dipping strata are defined by positive ε-values and southward dipping strata by negative. As a consequence, southward dipping thrusts have positive δ-values and northward dipping negative. Therefore the term $\delta_{(0)}$ can also be positive or negative; the sign indicates the direction of dip or (the other way round) the vergence of the thrust: $\delta_{(0)}$ is positive for northward directed thrusts and negative for southward.

The relationship between β and bedding dip ε easily can be transformed into a relationship between bedding dip and dip of the thrust δ:

$$(180° - \beta) + \delta + \varepsilon = 180°$$

$$\delta = \beta - \varepsilon$$

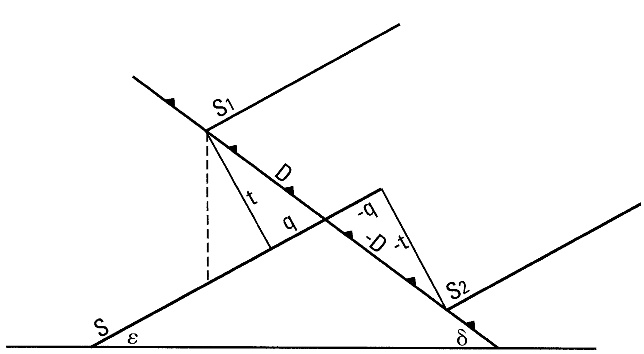

Fig. 18. Sketch for explanation of the terms 'negative displacement' ($-q$) and 'negative throw' ($-t$).

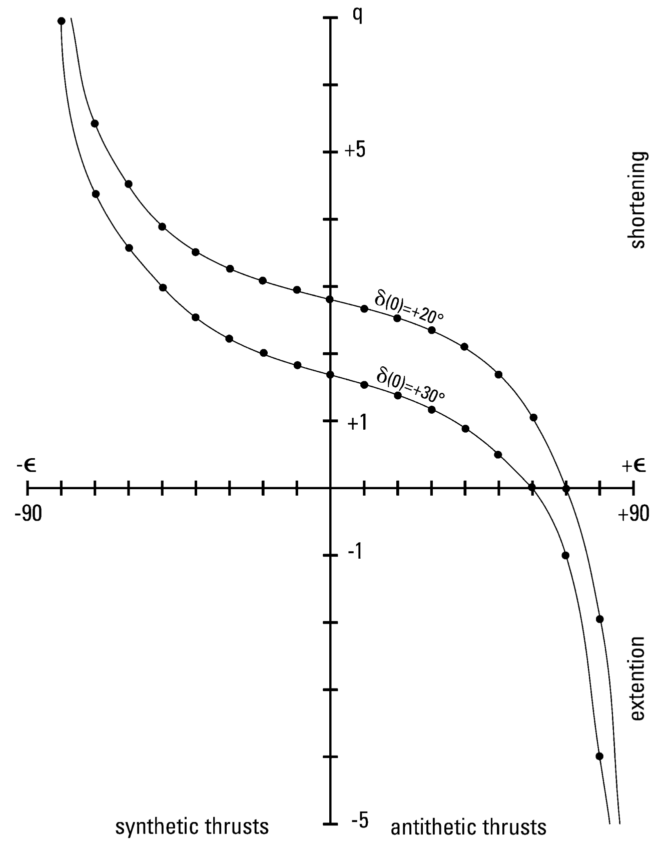

Fig. 19. Relationship between shortening/extension and bedding dips for $\delta_{(0)} = +20°/+30°$.

$$\delta = \arctan \frac{1}{\cot\delta_{(0)} - \cot(90° - \varepsilon)} - \varepsilon$$

It is obvious that the relations for β and δ are independent from the throw of the thrusts (t).

The graphs of the relationship between δ and ε for angles of $\delta_{(0)} = \pm 20°$ and $\delta_{(0)} = \pm 30°$ are given in Fig. 16 and compared with the plots of some 650 thrusts evaluated in the Ruhr basin. The calculated graphs are in good agreement with the distribution of the plots.

In this diagram the directions of dip (northward or southward) of strata and thrusts have been indicated. The diagram is divided into four quadrants; both northward and southward dipping strata with either northward or southward dipping thrusts. Remarkably, in rocks with a small value of $\delta_{(0)}$ ($\delta_{(0)} < 26.5°$) thrusts can change their direction of dip during the folding process. This effect produces the difference between concurringly and non-concurringly deformed thrusts (see Fig. 4 and Section 7).

6. Displacement, shortening and extension

The simple geometric model which was used to describe the relationship between thrust and bedding dips can also be

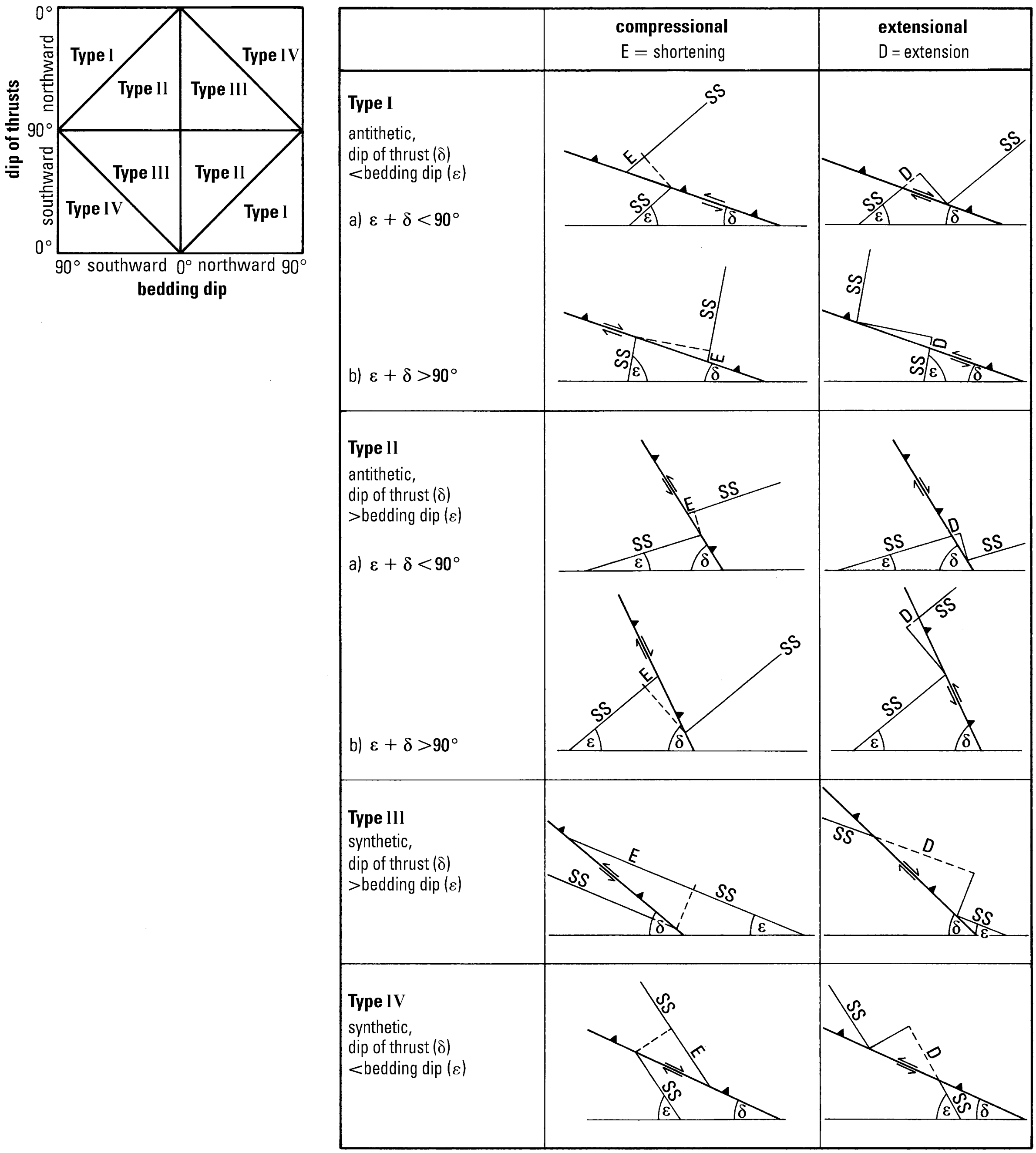

Fig. 20. Thrust types defined by the relationship between bedding dips and thrust dips.

used to calculate the development of thrust displacement which, as already mentioned (Fig. 12), is a function of throw and bedding dip:

$$D^2 = t^2 + q^2$$

$$D^2 = t^2 + t^2\left[\cot\delta_{(0)} - \cot(90^\circ - \varepsilon)\right]^2$$

$$D = t\sqrt{1 + \left[\cot\delta_{(0)} - \cot(90^\circ - \varepsilon)\right]^2} \quad (1)$$

Thus, for a given throw t, the displacement of the thrust is dependent upon the material attribute ($\delta_{(0)}$) and the bedding dip. As the graph of this function (Fig. 17) indicates, the development of displacement on a single thrust is different on different fold-limbs: in the synthetic case (thrust and bedding dip in the same direction: signs of $\delta_{(0)}$ and ε are different) displacement steadily increases with folding. Crossing an axial plane and continuing into the opposite fold limb (antithetic situation: signs of $\delta_{(0)}$ and ε becoming equal) displacement will diminish until a bedding dip of $\varepsilon = 90^\circ - \delta_{(0)}$ and only then increase rapidly again with increasing

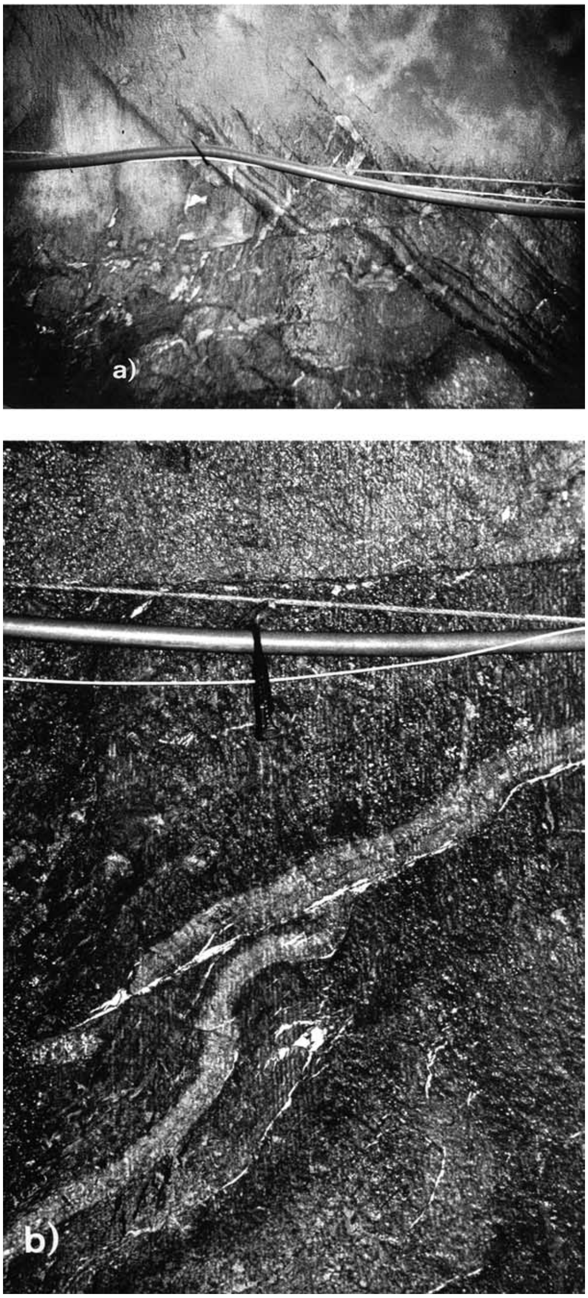

Fig. 21. (a) Extensional thrust (type Ib in Fig. 18). (b) Downthrow thrust (type IV). Sülz Water Carrier near Kürten; Rhenish Mountains, Germany. Scale: Water hose, hammer (ca. 30 cm) in (b).

bedding dip. The different development of the thrust on opposite fold limbs reflects the difference between 'backlimb thrusts' (synthetic thrusts) and 'forelimb thrusts' (antithetic thrusts) as described by Mitra (2002).

Eq. (1) indicates that displacements of thrusts may have positive or negative values. As Fig. 18 demonstrates, negative displacement may be connected with a negative throw, a downthrow of the hanging wall block, and extension instead of shortening (see Section 7).

As explained above, fold accommodation faults may substitute folds and, in general, form as part of a compressional process. Normally they contribute to the orogenic shortening by overlap of strata. The amount of overlap is equal to the term q in Fig. 15. The shortening affected by a thrust is therefore also a function of bedding dip:

$$q = t\left[\cot\delta_{(0)} - \cot(90^\circ - \varepsilon)\right]$$

Again, the graph of this function increases steadily in the synthetic (backlimb) part of the diagram (Fig. 19). For antithetic (forelimb) thrusts, however, shortening decreases with the amount of folding. If the dip of bedding exceeds the amount of $\varepsilon = 90^\circ - \delta_{(0)}$, the amount of q is zero and, with further increasing bedding dip, will become negative. Thus, with increasing folding, an antithetic thrust can be transformed into an extensional fault (see Fig. 21a). Examples of this effect have been described, e.g. by Wrede (1980, pl. 6) and Mitra (2002, fig. 17).

7. Thrust types

The above geometric derivations open up a coherent complex of faults which, aided by the diagram in Fig. 16, can be systematized as follows.

Two of the four quadrants of the diagram contain synthetic thrusts, while the others represent antithetic thrusts. Diagonals within the quadrants separate thrusts with dips smaller or larger than the dips of bedding, respectively. Thus, four types of thrusts can be defined (Fig. 20):

Type I: antithetic, dip of thrust < dip of bedding
Type II: antithetic, dip of thrust > dip of bedding
Type III: synthetic, dip of thrust > dip of bedding
Type IV: synthetic; dip of thrust < dip of bedding

In the cases of type IV and the antithetic types I and II (if $\varepsilon + \delta > 90^\circ$) a downthrow movement of the hanging wall block is necessary for shortening. On the other hand, all four types can be realized as extensional faults as well, as predicted by the root in Eq. (1) for displacement D.

Excellent 3D exposures in the Ruhr basin show that these different types of thrusts occur not only in isolation, but may occur when a single fault changes its character according to its position within the fold. The diagram in Fig. 16 compared with Figs. 4 and 20 clearly illustrates the development of a 'folded thrust': starting with a southward dipping synthetic backlimb situation (type III) the thrust reaches the fold hinge. Here, bedding flattens but the thrust still dips southward (type II). With increasing northward dip of bedding the thrust flattens (type Ia) and finally either an extensional (type Ib) or synthetic downthrow thrust (type IV) may develop. Type IV is the 'concurringly' deformed thrust presented in Fig. 4, while type I is the 'non-concurringly' deformed type. The difference between these types is defined solely by the behaviour of material ($\delta_{(0)}$). Fig. 21 gives outcrop examples of these rarely noticed thrust types as exposed in a water-carrier in the Rhenish Mountains, Germany (Wrede, 1997).

8. Conclusion

Fold accommodation faults are an integral part of the folding process. They develop contemporarily with the folds. In the fold-dominated Ruhr basin they are integrated in a stockwerk arrangement of the tectonic structures. They may substitute folds or are the reaction to volume problems during the folding process. Derivations described above, which are constrained by the 3D exposures in the Ruhr basin reveal that the formation of different thrust types responds to material behaviour and the development of folds (i.e. the change of bedding dip). Relationships between folding and development of thrusts obviously obey basic geometric rules. Comparative investigations of different coal fields and other areas in Europe reveal that—despite all local differences—these rules may be valid in fold belts generally (e.g. Cole, 1993). The definition of these rules in combination with statistic data on the extension of thrusts enables a reliable prediction of the behaviour of thrusts, e.g. in unexposed parts of a minefield or a hydrocarbon reservoir.

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