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# Linked fault families in basin formation

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**Abstract**—Recent models of faulting tectonics in basins and passive margins have emphasized the linked nature of faults in a way that is analogous to that developed for thrust regimes. A linked fault system requires three components; ramps, flats and sidewalls or transfers. Basins that are the result of other processes are not considered in this contribution, and the examples used are drawn from the Midland Valley and Northumberland basins of the U.K. where existing mapping by the British Geological Survey as well as field work undertaken by the author indicate that such models are appropriate.

This paper summarizes the geometric features and constraints of such models and emphasizes the role of each of the three critical components of a linked system. For large deformations that result in the formation of major extensional and strike-slip basins, the principal geometries can be understood by reference to regionally and locally balanced fault models that involve detachment, ramp and sidewall or transfer elements. Tip strains, and both lateral and vertical accommodation zones are included in the general model but these probably account for less than 10% of the total upper crustal strain. The basic analysis of a linked basin system requires the transfer of displacement on and between the fault and shear zone components.

The geometry of the stratigraphic units is used to deduce the active linkage on the fault system. In oblique-slip systems and where the dominant extensional ramp is connected to oblique transfer and detachment systems, lateral and sidewall sub-basins and intra-basin uplifts occur as part of continuing slip on the fault system. These control facies distribution and depocentre evolution.

The existence of a basin-forming linked system frequently controls later deformation of basins and margins, and an appreciation of basin growth faults and stratigraphic geometry is essential in the interpretation of inverted basins and orogenic belts involving supracrustal formations.

## INTRODUCTION

DAHLSTROM (1969) gave the first comprehensive account of the geometric analysis of thrust stacks using balanced section techniques. He showed that much of the deformation in thrust-fold belts could be understood as a linked system of faults consisting of low-angle detachments and ramps which formed sequentially. A balanced section is one which can be restored by translation on the mapped faults to the pre-thrusting cross-sectional geometry. To do this Dahlstrom introduced the concept of a regional or pre-faulting position from which depths to detachment could be calculated by an equivalence or balance between area of uplift and area lost between the detachment and the regional as the section shortened. At its simplest a balanced section requires several assumptions to be made (Hossack 1979). Firstly the section must be in the transport direction (i.e. strain must be plane) and area must be conserved. For the majority of upper crustal rocks involved in thrusting much if not all of the deformation can be best understood in this way, and one of the principal tools is to assume conservation of bed length and to assume that all of the deformation is accomplished by 'fault-bend' folding during translation of the thrust sheets (see Suppe 1983).

Geologically, of course, few deformations are plane strain and area is frequently not conserved in detail as faults die out, recrystallization takes place and ductile strains become involved. Many workers in thrust belts have refined Dahlstrom's concepts but despite these efforts his basic approach remains valid at all scales from a few centimetres to hundreds of kilometres (e.g. Coward 1983).

The same principles were applied to extensional basins by Gibbs (1983, 1984) and a series of basic geometric models involving linked flat and ramp extensional faults produced. In order to construct these models and to deduce the linked fault system from stratigraphic data on geo-seismic sections or field maps Gibbs proposed that it is more appropriate to use area rather than bed length conservation due to the fact that stratigraphic growth and hence original bed length variations are normal in basins. Area balance techniques allow growth and eroded sequences to be restored step by step. The effects of compaction can also be modelled where appropriate.

The simplest approach involves the geometric assumption of vertical simple shear commonly referred to as the 'Chevron construction'. No claim is made that sediments deform in the hangingwall extensional fault by any process of vertical shear but that this geometrical assumption closely approximates to the observed relationship between fault shape and stratigraphy. It therefore provides a useful interpretative tool which can be used with confidence in many cases. It has the further advantages of being easy to use and to visualize the relationship between fault and fold.

The Chevron technique does not require that the order of faulting be known or that sections be drawn without vertical exaggeration. Several other methods have been championed as being 'geologically more realistic' but all have similar constraints and some predict very strange effects (see Davison 1986, Wheeler 1987, Williams & Vann 1987). In the author's experience the original Chevron construction should be used in the first instance and then, if the data give sufficient control, other approaches can be used to test the sensitivity of the interpretation. For example the Chevron method can be generalized by varying the shear angle (see White *et al.* 1986) and it may be possible to calibrate the method by iterative restoration or fault construction using a range of shear values.

## LARGE-SCALE LINKED SYSTEMS

Following models derived from the Basin and Range province (see in particular Wernicke 1981, 1985, Wernicke & Burchfiel 1982), Lister *et al.* (1986a,b), Beach (1987) and Gibbs (1987) proposed that for most basins and passive margins with significant extensions ($\beta > 1.2$, McKenzie 1979), fault and detachment linked systems will dominate and account for the bulk of the strain. In this type of model the basins will be asymmetric and all faults linked to a master detachment. The resulting geometry can be understood by applying balanced section techniques. At a crustal scale this means that the displacement can be drawn as a linked fault system where the mid to lower crustal extension is represented by a shear zone narrow enough to be represented on the section as a fault (Fig. 1). In some cases deep seismic profiles provide clear evidence that such continuous zones are the most likely interpretation (Allmendinger *et al.* 1983, Warner 1985). Elsewhere it is possible to interpret the same data without a linked fault system (cf. Klemperer & White in press) where strain in the lower crust is taken up by a ductile pure shear (Fig. 2) rather than on a detachment or shear zone (Coward 1986). As the diagram shows the strains must be compatible as the two 'pin lines' move apart and hence the deformation between the upper and lower crust is linked, albeit with differences in the deformation style and mechanism.

Dahlstrom's paper also pointed out the role of tear faults and 'transfer zones' in linking displacement along strike so that serial balanced sections and hence balanced maps (Coward & Enfield 1986) could be constructed. These strike- or oblique-slip components of the linked system (Fig. 3) are essential if displacement is to be maintained or varies systematically. Bally (1981) recognized the significance of analogous structures in basin growth and Gibbs (1984) formally suggested the the term 'transfer fault' be adopted for tear fault components which form part of an extensional basin system. In extension the transfer fault slips in the opposite direction to its mapped offset and this geometric feature (shared with transform faults) allows this class of fault to be identified in the field and on maps.

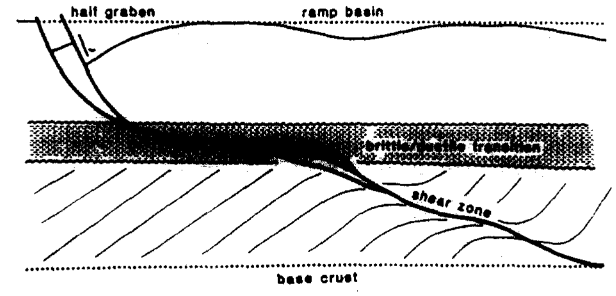

Fig. 1. Linked fault model for through going simple shear of the crust. The effect on the hangingwall geometry of a fault or broad zone of ductile shear is the same. Although the model is shown for the crust it is geometrically valid at all scales.

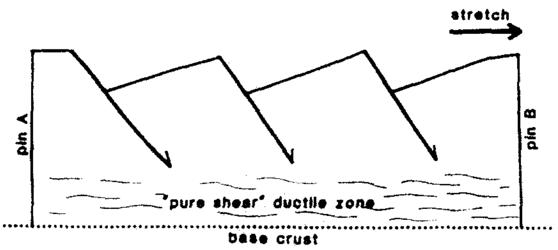

Fig. 2. Extension faults in upper crust overlying homogeneous pure shear of lower crust. Note, however, that extension or stretch between the 'pin lines' is balanced and therefore linked mechanically.

A number of authors have developed the concept of extensional arrays linked to transfer faults (e.g. Lister *et al.* 1986a,b, Etheridge *et al.* 1987) to form completely linked fault arrays where slip is conserved across transfer faults which form boundaries to the extensional compartments. Rosendahl *et al.* (1986) described characteristic 'accommodation zones' between the terminations of major extensional graben forming faults from the East African rift system. Various combinations of these structures have been described with fault or detachment dip maintained across the accommodation zone or in some cases with the detachment polarity reversing (Fig. 4). Morley (in press) points out that the East African system generally has low extension compared with a passive margin or major extensional basin such as the North Sea. He believes that the extension faults themselves need not necessarily be linked up as slip surfaces and will have ductile beads or accommodation zones as they die out laterally as well as downwards into more distributed strain. Systems which consist of extension faults dying out along strike can be analysed by looking at displacement maps of the complete array. The key factor is that strain must be transferred smoothly throughout the system on a combination of slip on faults and compatible

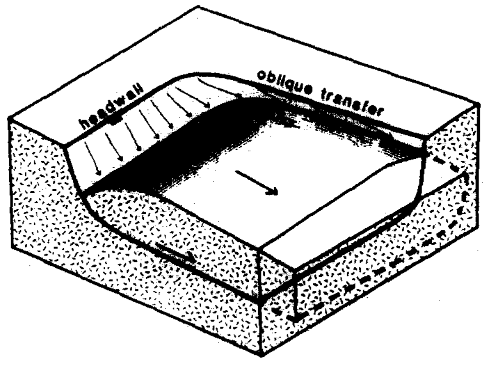

Fig. 3. General model for linked extension in three dimensions. The steep 'headwall' of the extensional fault joins a flat detachment at depth and is bounded along strike by a transfer fault sharing the same detachment. In this case the transfer is oblique and roll-over into the transfer occurs.

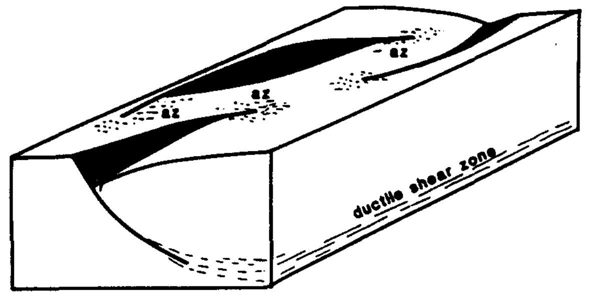

Fig. 4. Accommodation zone (az) model for extension. Faults pass down-dip into a zone of ductile shear and die out laterally in zones of distributed strain. Synthetic and antithetic accommodation zones are possible. In the latter case the polarity of the half graben changes.

ductile strains. Although this truism is well understood it is frequently not reflected in the way in which map or cross-sectional data are presented.

Hence we have two end-members for extensional fault systems, those which are dominated by linked fault systems where all displacement transfer is on faults, and those where displacement is transferred by other compatible deformation mechanisms. In reality both will coexist and a balanced map or section could well contain both elements. Attempts to balance sections invariably highlight such problems which must be resolved either with a linked fault model or another acceptable geological solution.

## LINKED SYSTEMS AT INTERMEDIATE AND SMALL SCALES

Basins and parts of basins forming completely linked systems can provide models of general use to exploration and production geologists in the minerals and petroleum industry. In analysing field or seismic data the interpreter is faced with the problem of building up and visualizing the fault system, its effect on the pre-existing basement and on the consequent development of the stratigraphic infill to the basin. In order to do this balanced models have to be created not just in two but also in three dimensions.

The following discussion describes and illustrates with block diagrams the necessary three-dimensional linked fault elements. These models are simplified cartoons derived from the detailed analysis of several basins using a variety of data and tested for geometric balance. To assist in understanding the models examples of each of the structures have been identified in onshore U.K. basins where existing detailed maps are available to which reference can be made. The examples come from the Midland Valley of Scotland (Fig. 5) and the Carlisle Basin of northern England (see Gibbs 1989). These are Devonian and Carboniferous basins with a late inversion history. Maps of the basins are well constrained by British Geological Survey (Institute of Geological Sciences) and more recent industry data. Detachment depths calculated using the Chevron method correlate well with geophysical evidence (Dentith & Hall in press), and maps at all scales as well as exposures in opencast workings demonstrate almost ideal linked systems. The models discussed in this analysis are not intended to be a complete description of these U.K. basins but rather to illustrate general solutions.

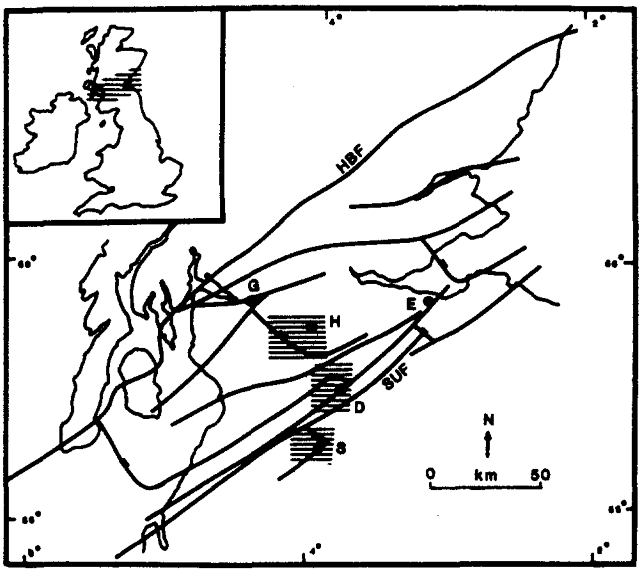

Fig. 5. Location map for the Midland Valley of Scotland. Shaded areas on the main map give locations of Figs. 6 (H), 15 (S) and 17 (D). HBF = Highland Boundary Fault; G = Glasgow; H = Hamilton; D = Douglas; S = Sanquhar; SUF = Southern Uplands Fault.

The basic elements of a linked fault system are shown in Fig. 3. The extensional normal fault joins a detachment and is bound laterally by a transfer fault which passes its displacement to the next extensional component. The transfer fault is shown as oblique to the transport direction. As the hangingwall block moves a small element of extensional roll-over towards the transfer fault is produced. Where the transfer fault is parallel to transport (Gibbs 1984) no vertical throw except in the area of the roll-over is apparent. It is therefore possible to use the orientation of the transfer faults as an indication of transport direction. Commonly the transfer faults will be parallel to transport as in Fig. 6. In this case stratigraphic boundaries will show little or no strike change across the transfer fault. Where, however, the transfer fault is oblique, a marginal or lateral basin (Fig. 6) will be formed. These can be distinguished from synclines formed over detachment ramps (Figs. 6–8) by comparing the effects of transfer faults with slightly different trends on the map (Fig. 6). The key feature to look for is evidence of a strike swing or dip change on approaching the transfer fault.

A section constructed parallel to transport in the Motherwell Basin (Fig. 6) illustrates how this map may look in cross-section. Details of the stratigraphy are given on IGS Sheet 23 and regional estimates of the top and base of the Old Red Sandstone (ORS) are discussed by Dentith & Hall (in press) using both regional geology and seismic data (the MAVIS survey). The regional for the base of the Coal Measures was selected from along strike projects and regional control and the fault profile was constructed using a computerized balance program (BSP). Detachment depths averaged over a number of

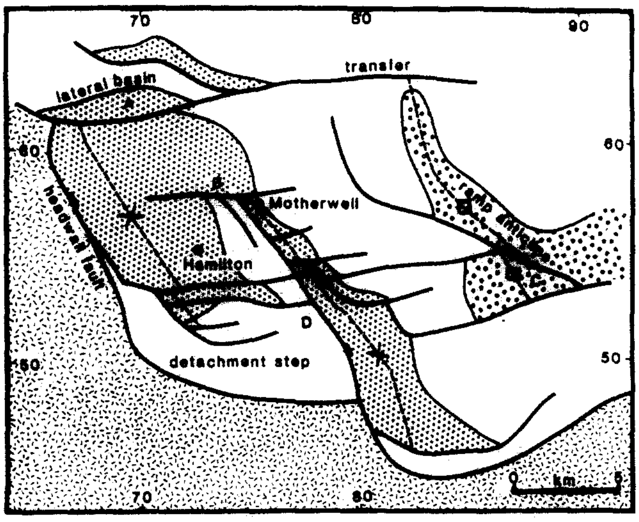

Fig. 6. Map of Hamilton and Motherwell Basin. A—lateral basin (Fig. 8); B—detachment step, see Figs. 10 and 11; C—oblique ramp see Figs. 7 and 8; D—detachment acts as roof to lower extension system. In the hangingwall open circles are older than the unshaded rocks and dots represent the youngest (see Barren Red Measures on Fig. 9). Footwall rocks (stippled) are undifferentiated.

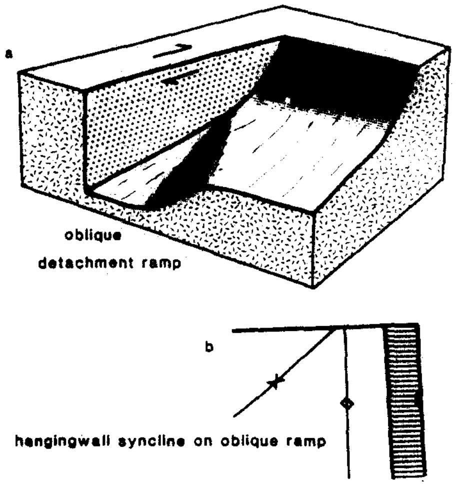

Fig. 7. (a) Cartoon of oblique ramp on detachment with a shared transfer fault. (b) Map of principal elements in (a).

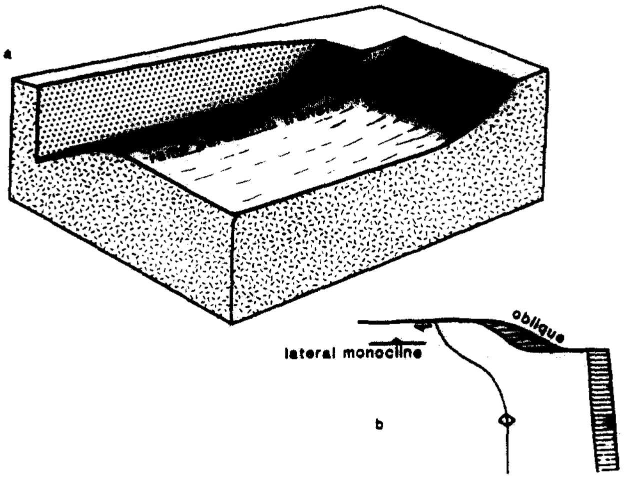

Fig. 8. (a) Cartoon of ramp parallel to transport direction and transfer step on the detachment headwall. (b) Schematic map of (a).

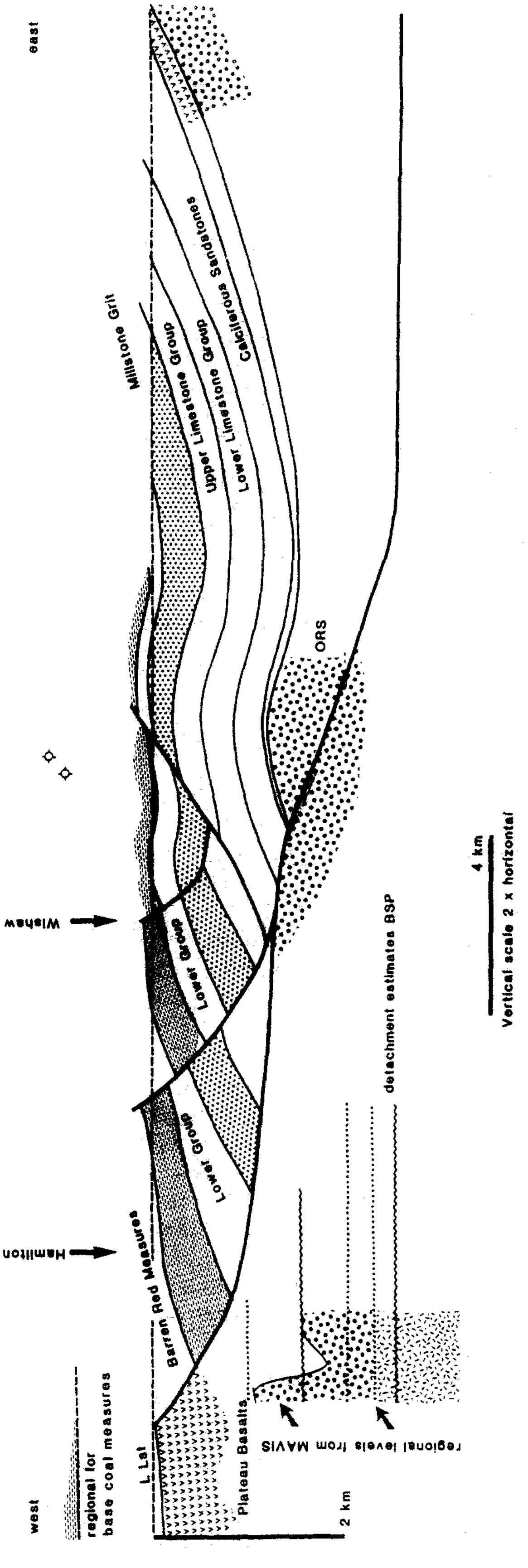

Fig. 9. Cross-section through the area shown in Fig. 6. The line of section is parallel to the transfer faults and runs through the town of Hamilton. See text for details.

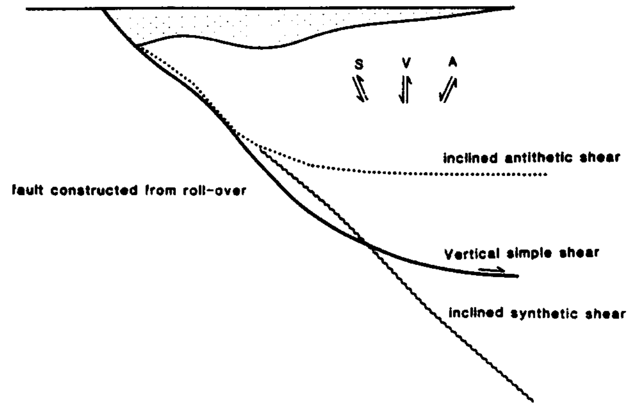

Fig. 10. Fault constructed from roll-over and excess basin area shown with dotted ornament. Note anticline and syncline in the hangingwall are generated by movement across a gently stepped fault surface. Shallower fault constructed using a 60° antithetically inclined shear model (A). Solid line constructed using vertical simple shear (V) and wavy line using 60° synthetic shear (S). Detachment depth using synthetic shear is very deep (off the bottom of the page!) and steps in the fault plane producing hangingwall folds have very low amplitudes.

sections are indicated by wavy lines. A vertical shear model was used which was calibrated using field data from open cast mines in the area. The predicted position of stratigraphy on the ramp in mid section is constrained by two oil wells near Motherwell (Fig. 6). With the constraints imposed by local and regional control a range of detachment estimates are possible due largely to uncertainty in choosing the regional (dotted lines on the section represent alternative detachment estimates).

In the general case the extensional fault may consist of a series of steep and shallower dipping elements (ramps and flats). As the hangingwall moves across these ramps a hangingwall, or ramp syncline, will be generated which enables the position and shape of the ramp at depth to be deduced from the geometry either on the map or from a cross-sectional profile of a stratigraphic marker. Choice of an appropriate hangingwall model is critical in assessing depth of detachment. Different models will give the same number of ramps and flats in the fault surface but their position and amplitude will change dramatically (Fig. 10).

The transfer faults may share one or more of the detachment flats. In the simplest case where the transfer fault in the hangingwall offsets the ramp, but not the detachment, there will be an offset in the roll-over anticline, but not in any structure associated with down-dip ramps on the detachment (Fig. 11). Where, however, the transfer forms a lateral ramp or step to the detachment flat (Fig. 12) it will form an along-strike termination to ramp synclines and anticlines as well as the roll-over anticline. In this way it is possible to deduce the position, extent and relative geometry of steps in the detachment surface both down-dip and along strike of the extensional fault. The map of the Motherwell Basin (Fig. 6) shows several combinations of detachment ramps and lateral detachment steps (sidewalls), illustrating most of the general features of a linked transfer and detachment system built up with an array of simple components such as those in Figs. 11 and 12.

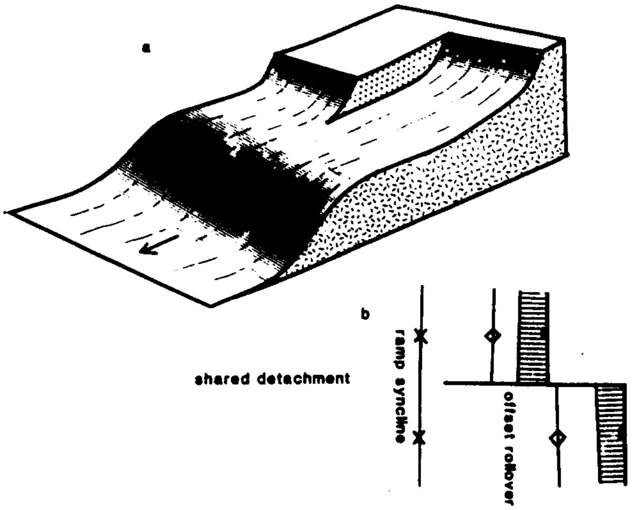

Fig. 11. (a) Cartoon of transfer on shared detachment giving on (b) an offset of roll-over but a continuous ramp syncline down-dip.

Extensional compartments with different structural polarity are linked by transfer faults (Figs. 2 and 13). These are analogous to Rosendahl's 'flip-flop' or back-to-back changes along the East African Rift (Rosendahl *et al.* 1986). In Fig. 13 we can see that the basic elements of this system have a 'fixed' block which is lower plate or footwall to one detachment system and hangingwall to the other. On the fixed block both the transfer fault and the detachment will have tip lines beyond which no displacement takes place. The translated block will be completely detached. In the most general case the detachment surface may underlie both the fixed and translated block of Fig. 13 and both will move away from some marker along the axis of the basin. Resolution of which block has moved must then take into account regional considerations.

An example of a transfer fault separating compartments with different structural polarity is shown in Fig. 14 from the Carlisle Basin (IGS Sheet 23) to the north of the English Lake District. In this case the Lowling and Roe Beck faults form a linked extension system with a reverse polarity compartment to the north. The left-lateral (sinistral) offset of the half graben across a right-

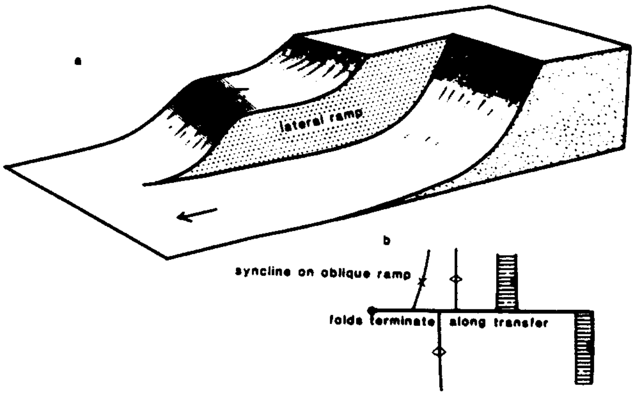

Fig. 12. (a) Transfer step to detachment along which folds on the upper system will terminate (b) and see also the oblique syncline on the ramp of the higher detachment.

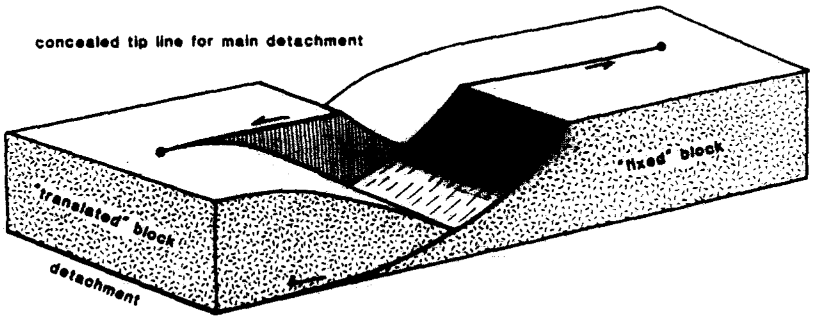

Fig. 13. Block diagram for extensional system with reversed polarity. The extension fault furthest from the reader has a concealed tip line joining that of the transfer fault on the 'fixed block'.

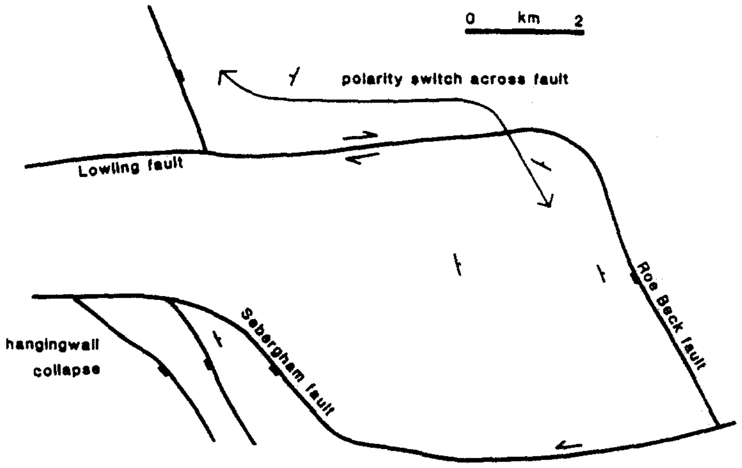

Fig. 14. Simplified map of Lowling and Roe Beck fault system showing switched polarity across transfer fault as in Fig. 13. Note hangingwall collapse over oblique detachment step (Sebergham Fault) see Fig. 12.

lateral slipping (dextral) fault is clear. In the Roe Beck compartment, the Sebergham Fault is a linked transfer and an oblique extension step similar to that on Fig. 12 is present in the southwest with collapse of the hangingwall above the detachment of the Sebergham Fault.

Wherever any part of the detachment system or transfer sidewall is not orthogonal or parallel to transport, oblique faults and folds will form. One of the ramps in Fig. 12 is oblique with a resulting oblique syncline above the ramp. Figure 7 illustrates the general model with a detachment ramp running at about 45° to the transfer direction. The strike swing in the axis of the ramp anticline to the east of Motherwell (Fig. 6) is in response to such an oblique detachment ramp, in this case associated with an oblique transfer.

Detachment ramps parallel to the transfer faults (i.e. that trend parallel to the slip direction) are associated with simple monoclinal flexures close to the ramps. Two of these are apparent in the Sanquhar area (Fig. 15) where they are picked out by strike changes in the basement cover contact. In this basin these ramps are not associated with significant overlying transfer faults in the hangingwall although the larger, southern ramp forms a transfer fault to the headwall of the extensional detachment.

Both the extensional and transfer faults may develop duplex structures. The basic elements are shown in Fig. 16. A releasing bend (Woodcock & Fischer 1986) in the transfer fault produces a vertical or steeply-plunging transfer duplex as shown in the diagram and these will tend to map out as a 'string of beads' as they move away and the bend collapses backwards (see also Fig. 17). Duplexes on the detachment surface are frequently associated with ramps (Gibbs 1984). On the emergent ramp they form the ubiquitous terraced horsts and riders seen on most basin margins (Fig. 15). Ramp duplexes on concealed ramps are also probably very common but are difficult to interpret in basins which are not fully dissected or strongly inverted. Complex shallow ramp synclines will form above such ramp collapse structures and these have been convincingly demonstrated (McClay & Ellis 1987, Ellis & McClay 1988) using sand and clay analogue models. Note that in the McClay & Ellis' models, slip on the fault surface is conserved by the apparatus and some dilation takes place so a geometric restoration must take this into account. Their models do not 'prove' that this is the general approach that should be applied to real rocks, as the ramp–flat nature of the fault is imposed as a boundary condition, and deformation is accomplished by pulling a plastic sheet down the fault surface. On the detachment surface itself transport parallel detachment ramps generate detachment mullions (Fig. 16).

The small Douglas Basin (Fig. 17) shows very clearly the development of a duplex along its transfer margin, and duplexes are also present on constraining bends of

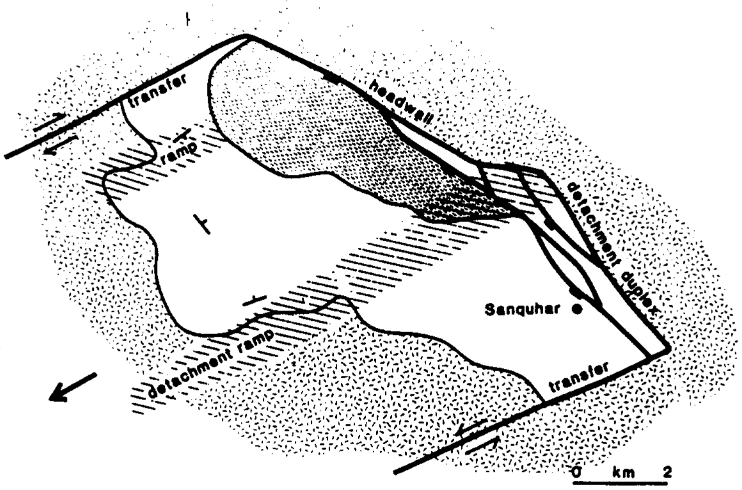

Fig. 15. Map of the Sanquhar Coal Basin showing detachment ramps parallel to the transport direction and an emergent ramp or headwall duplex just to the east of Sanquhar.

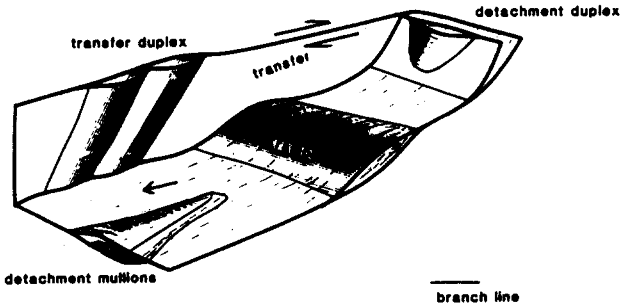

Fig. 16. Composite cartoon of principal extensional elements of a linked system.

the transfer fault. These were associated with uplift and inversion of basement during basin growth. A syncline strongly oblique to the basin margin (cf. Fig. 7) is present in the hangingwall of the basin and it is thought that this has formed above an oblique ramp. A simplified diagram of the linked fault system for the Douglas basin would be similar to that shown in Fig. 16.

A balanced longitudinal section of the Douglas Basin is shown in Fig. 18. In addition to the published map the construction and model used in generating this section have been calibrated using small-scale linked fault systems which were exposed during opencast mining. Two further sections (Fig. 19) are shown. These are at right angles to Fig. 18 and it is clear that they do not balance in the section plane. The stacked faults at depth are similar to those seen in similarly orientated outcrops in mines and in this case have been constructed from serial balanced sections in the transport direction.

Transfer faults bounding extensional compartments such as the Douglas Basin change along their length from pure strike-slip displacement outside the extensional compartment (Fig. 20) to more or less normal faults towards their tip-line termination. The block diagram (Fig. 20) shows how the various slip and functional components are distributed. The front face of the diagram (Fig. 20) represents the fault surface where in the

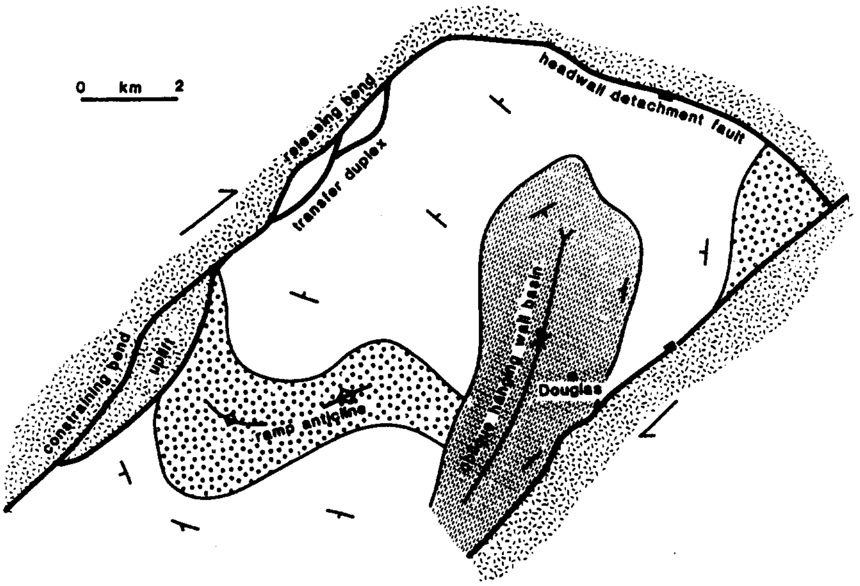

Fig. 17. Map of the Douglas Basin showing transfer duplex (Fig. 16) and oblique folds over steps on the detachment fault (see Figs. 7 and 12).

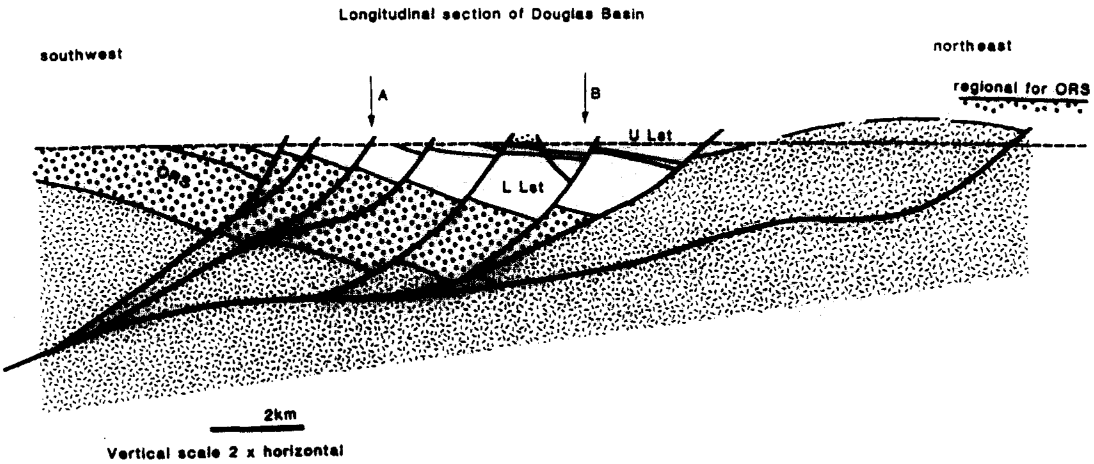

Fig. 18. Cross-section of the Douglas Basin drawn parallel to transport along the basin axis. Details of the section are discussed in the text.

footwall block to the extensional compartment ('C') slip is horizontal. Where the transfer fault is in contact with the hangingwall the rocks in the roll-over move with it but drop down and therefore show relative vertical displacements. In the diagram a vertical simple shear (Chevron) construction has been used so that the relative displacement is vertical and the tip-line is also vertical. An inclined shear assumption would give inclined relative displacements.

The intermediate part of the slip surface ('B' in the diagram) represents the part of the fault which has been translated into contact with the hangingwall and will therefore change from horizontal to vertical displacement. The arrows in the diagram on the other two fault faces represent finite particle displacement paths (for vertical simple shear).

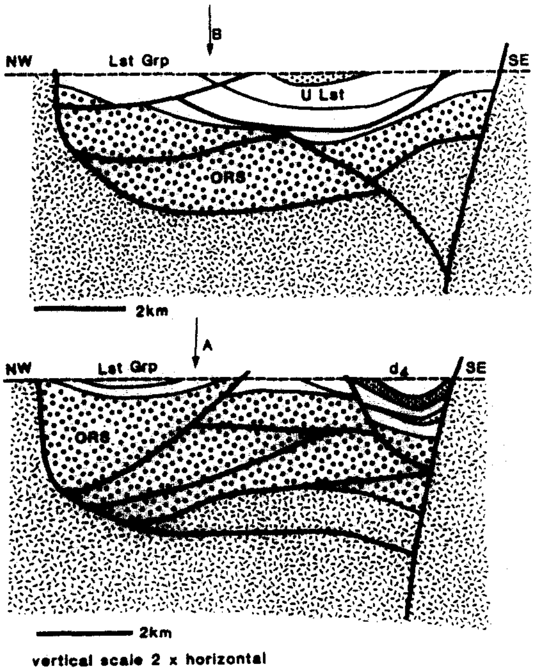

Fig. 19. Two representative sections across the Douglas Basin. See text for details. Note that the basin-forming extension faults dip towards the reader and appear as a set of sub-horizontal detachments.

In the field, a simple linked system will generate microstructures on the fault planes which may individually be interpreted in terms of different relative and absolute displacements. in appropriate circumstances it may be possible to use kinematic indicators such as slickencrysts on the fault surfaces to choose an appropriate geometric model for hangingwall deformation, that is to have a geological basis for selecting the appropriate geometric construction (Fig. 10) for the hangingwall deformation.

## CONCLUSIONS

The structures that form basins are susceptible to analysis at all scales using simple models of linked fault and shear zone systems. Linkage may be through displacement transfer on discrete slip surfaces, through compatible ductile zones, or both. Within the limitations imposed by the technique, analysis can be made using

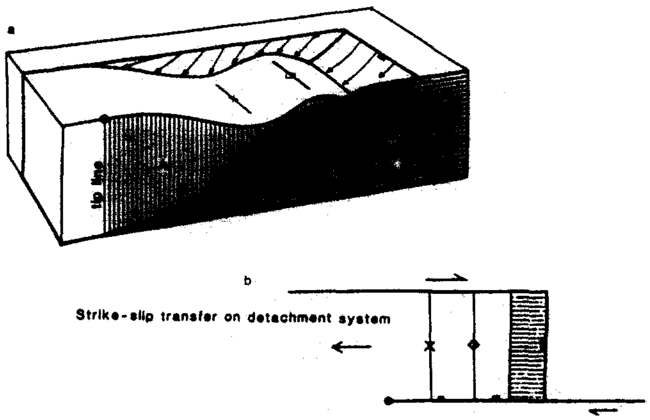

Fig. 20. Linked transfer and detachment system for strike-slip pull-apart or local element of an extensional basin. Front surface of the block diagram (a) represents the lower fault on the map (b). A—hangingwall drops down on transfer fault giving normal displacement, C—strike-slip displacement on fault surface and B—strike-slip displacement followed by normal-slip. Arrows on block diagram represent finite displacement vectors for hangingwall block.

geometric models and balanced section constructions. In all cases the only satisfactory interpretation is one which is balanced or balanceable in three dimensions. In the first place the geometric components of the balanced linked system can be deduced from general considerations of hangingwall geometry by use of qualitative models such as those shown in the cartoons accompanying this paper. Rigorous balance is then possible by choosing an appropriate technique to refine the relationship between the structural elements. This will involve both the use of simplified models and formal restoration and iterative modification of the interpreted sections and maps.

In some cases map and field control will clearly dictate the appropriate restoration technique but generally the problem will not be well enough constrained by unequivocal data to allow a choice between techniques to be made on geological grounds. In these cases the simplest possible technique should be used and its predictions tested against future data acquisition. The major differences will not be between a section constructed using inclined shear or vertical shear, etc., but between such sections and those which are unconstrained with reference to a workable geometric model. A balanced interpretation should never be regarded as the final 'truth' but as a starting point for further work and a model against which future observations can be tested.

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