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Relay structures in a Lower Permian basement-involved extension system, East Greenland

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Abstract—Extensional relay structures are described as offset listric faults having the same subhorizontal detachment in depth. The extension along one fault is transferred or relayed across a relay ramp defined between the tip-lines of the offset faults. The relay ramp interconnects the hangingwall and the footwall during deformation. An example of a crystalline basement-involved symmetrical relay system is described from the Lower Permian in the Karstryggen area, East Greenland.

INTRODUCTION

SINCE Goguel (1952) described *relais des failles* or relay structures, they have been recognized in several extensional tectonic settings all over the world (e.g. Bristol 1975, Bristol & Treworgy 1979, Rosendahl & Livingstone 1983, Gabrielsen & Robinson 1984, and examples in Lowell 1985, Chadwick 1986). However, the geometrical and tectonic implications of these structures have somehow been neglected in the literature and relay structures were not incorporated into the recent model for the structural development of extensional basins (Gibbs 1984).

In this paper extensional relay structures are considered to form where offset listric fault traces, or two en échelon strands in map view, curve into a single low angle or subhorizontal fault at depth (Fig. 1). The *relay ramp* is situated between the two tip-lines of the offset faults connecting the hangingwall and footwall blocks. In map view relay structures may be arranged in different patterns from random to symmetrical and en échelon (Fig. 2). The relay ramp transfers or relays the displacement from one of the offset faults to the other and the extension measured across an array of symmetrical or en échelon arranged structures is considered constant, as shown in Fig. 2.

During faulting the relay ramp deforms ductily, keeping the hangingwall block interconnected to the footwall block (Figs. 1 and 2). Depending on the strength of the ramp, the strain rate during deformation and the amount of extension, the relay ramp may break down. Instead, a fault develops across the ramp connecting the original offset listric fault traces, and only then is the hangingwall entirely disconnected from the footwall. The cross-cutting fault is an *oblique* or *lateral transfer fault* in the sense of Gibbs (1984).

In a propagating symmetrical relay system the hangingwall block can also be detached from the footwall block by fault migration parallel to the relay ramps (Fig. 3). If two initial faults in their central part have been offset towards the hangingwall block (Fig. 3a), and later during deformation these two faults join up making one major listric fault, the relay system is broken down and left behind in the hangingwall. This structure is here termed a *detached hangingwall relay system*. If the central part of two initial fault traces has been offset towards the footwall block the symmetrical relay system may break down during a propagating deformation by form-

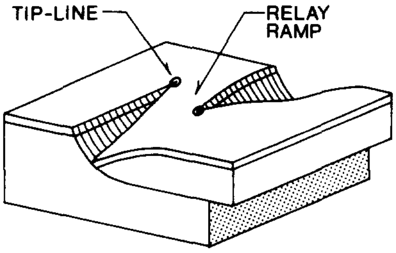

Fig. 1. Block diagram of a relay structure. The relay ramp is situated between the tip-lines of the offset listric faults, which have the same subhorizontal detachment in depth.

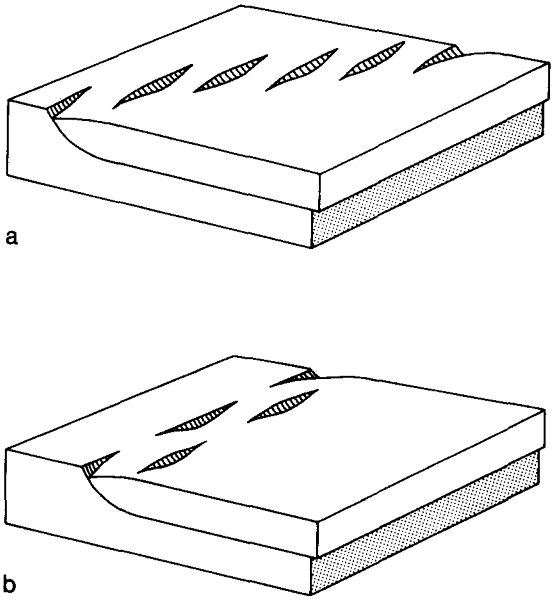

Fig. 2. Block diagrams showing en échelon right-stepping arranged relay structures (a) and symmetrically arranged relay structures (b).

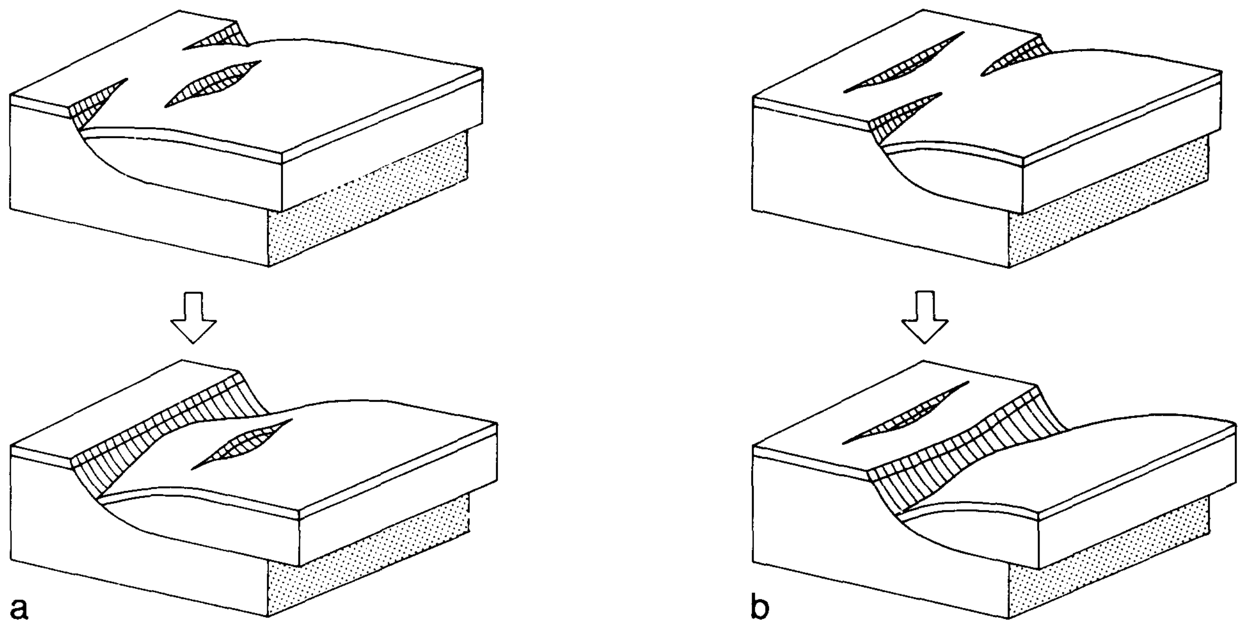

Fig. 3. Development of a detached hangingwall relay system (a) and a detached footwall relay system (b) during propagating extension and break-down of the initially symmetrical relay structures.

ing a *detached footwall relay system* (Fig. 3b). Barr *et al.* (1985) described a structure from the Beatrice oilfield in the Inner Moray Firth Basin, offshore Scotland, which may represent a detached hangingwall relay system. An example of a detached footwall relay system is not known to the author. The symmetrical relay system from the Karstryggen area, described below, could have resulted in the formation of a detached footwall relay system if faulting had continued.

In general, relay structures occur in extensional settings at relatively low strains. High strains and large displacements along offset faults will, and probably must, break down initially formed relay structures, allowing complete detachment of the hangingwall and footwall blocks. The development of a transfer fault *sensu stricto* connecting two initial offset faults may be the most common feature observed at large strains. However, as suggested here, fault propagation parallel to the relay ramps in initial symmetrical systems may also produce fully detached blocks allowing large displacements to occur.

In this paper the geometric aspects of extensional relay structures will be described from the Karstryggen area situated along the western boundary fault of the East Greenland rift basin.

GEOLOGICAL SETTING OF THE KARSTRYGGEN AREA, EAST GREENLAND

In central East Greenland a roughly N–S-trending major fault system separates the Caledonian mountain belt towards the west from the East Greenland rift basin towards the east (Fig. 4). Post-Caledonian strike-slip and extensional tectonics were initiated in the Devonian (Haller 1971, Friend *et al.* 1983), and simple E–W rifting took place in late Carboniferous–early Permian times, followed by a long period of Mesozoic rifting phases which dominated in East Greenland throughout the remaining part of its geological history (Surlyk *et al.* 1981, 1986).

The Karstryggen area is situated along the major bounding fault of the East Greenland rift basin to the south (Fig. 4). Here Lower Permian continental sandstones rest on crystalline Caledonian metamorphic basement (Kempter 1961, Collinson 1972). Syn-sedimentary faulting was active along a roughly N–S-trending fault system, which seems to have controlled the distribution of various alluvial environments and palaeocurrents (Larsen & Stemmerik work in preparation).

In mid-Permian time the Karstryggen area was uplifted relative to the base-level, resulting in a peneplanation of the area (Fig. 5). In the late Permian, the sea for the first time transgressed the area, depositing mainly carbonates and evaporites in various shallow marine environments (Stemmerik 1985, Surlyk *et al.* 1986). The marine Upper Permian sequence is considered to represent the initial phase of basin subsidence caused by thermal contraction following the rifting event (Surlyk *et al.* 1986).

STRUCTURAL DESCRIPTION

The structural analysis is based on the geological map of Kempter (1961) supported by new data obtained from field work and computer assisted stereoscopic studies of aerial photographs (Fig. 5) following the method described by Dueholm (1979) and Pedersen (1981). A series of vertical cross-sections were constructed through the area on the basis of strikes and dips of the early Permian strata, the orientations of the major faults, the exposed basement–sediment contacts and the distribution of the various lithological units (Larsen & Stem-

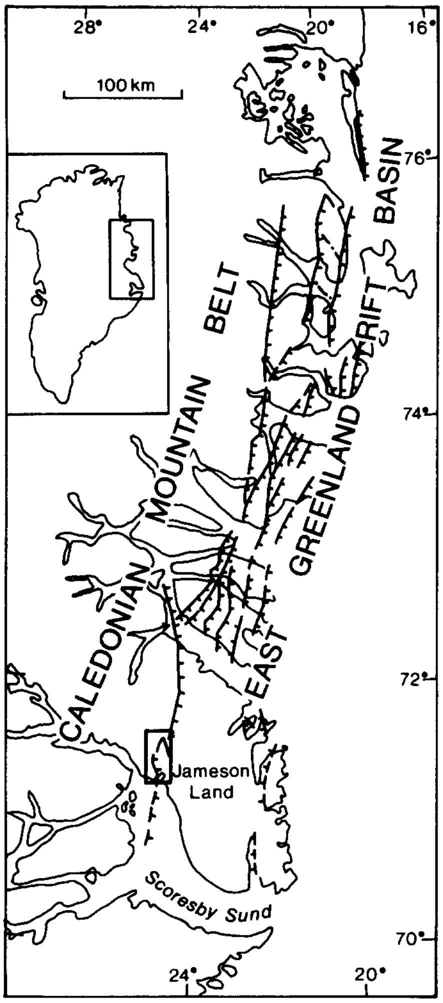

Fig. 4. Tectonic map of East Greenland. The Karstryggen area is indicated (modified from Surlyk *et al.* 1981).

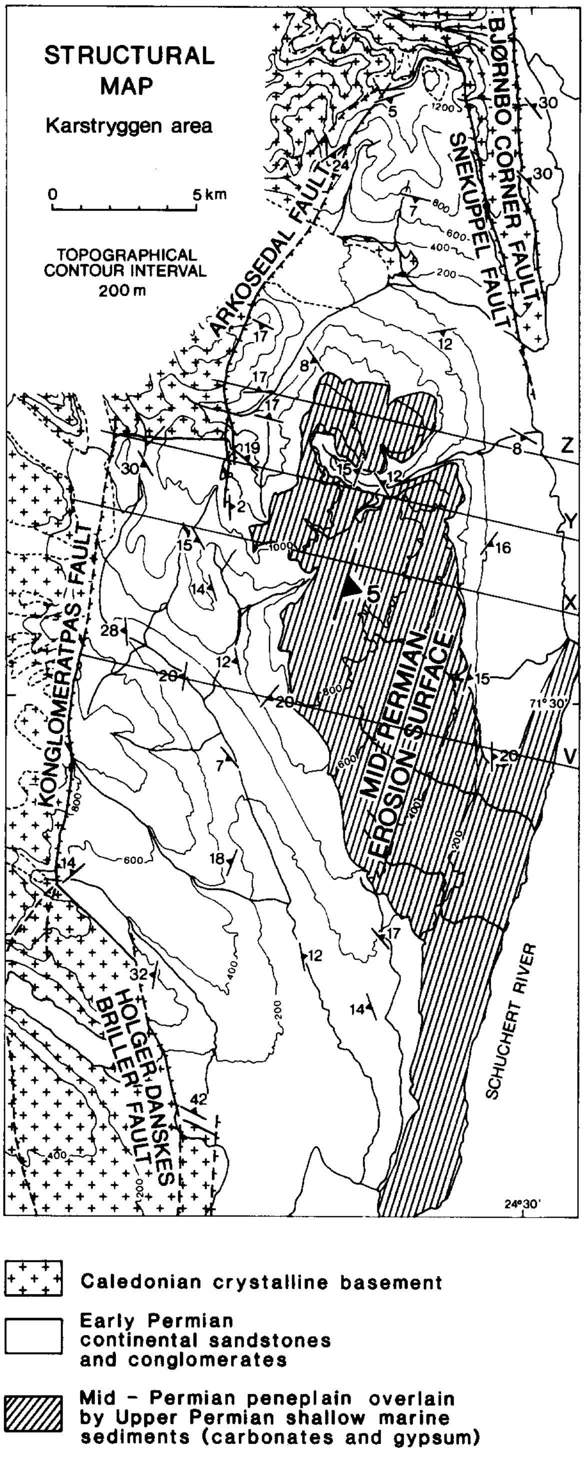

Fig. 5. Structural map of the Karstryggen area, East Greenland. The positions of the cross-sections V, X, Y and Z are shown (based on Kempter 1961, and own observations).

merik work in preparation). A basement contour map and a tectonic model were constructed by combining these cross-sections (Figs. 6 and 7).

The structural map and the basement contour map show that the Arkosedal Fault and the Holger Danske Briller Fault together form an eastward concave fault structure (Figs. 5, 6 and 7). However, in the middle part of this fault the displacement is transferred or relayed westward to the Konglomeratpas Fault. By using the roll-over geometries and balanced cross-section construction techniques of Gibbs (1983) it can be shown that the three faults in map view have the same subhorizontal detachment level within the crystalline basement (Fig. 8). The Arkosedal Fault, the Konglomeratpas Fault and the Holger Danske Briller Fault thus together form a true basement-involved listric fault system, which may be called a symmetrical relay system using the terminology proposed here.

The regional surface to be used in the fault profile construction (Fig. 8) is difficult to define as no sediments are preserved west of the faults on the stable footwall block. However, basement–sediment contacts are preserved on the Marcusdal and Holger Danske relay ramps and in the Snekuppel area to the north. These three points are considered to have moved the least, relative to the regional surface, compared to other parts of the area affected by faulting. Combining the three points with the flat crest of the roll-over structure in section V, a surface can be defined, which is believed to be subparallel to the regional.

The extension or surface heave across the Marcusdal relay structure is approximately 3 km (2.5–3.3 km) when measured on the constructed cross-sections V, X, Y and Z (Fig. 8). Although the exact regional surface cannot be constructed, the fault profile construction suggests

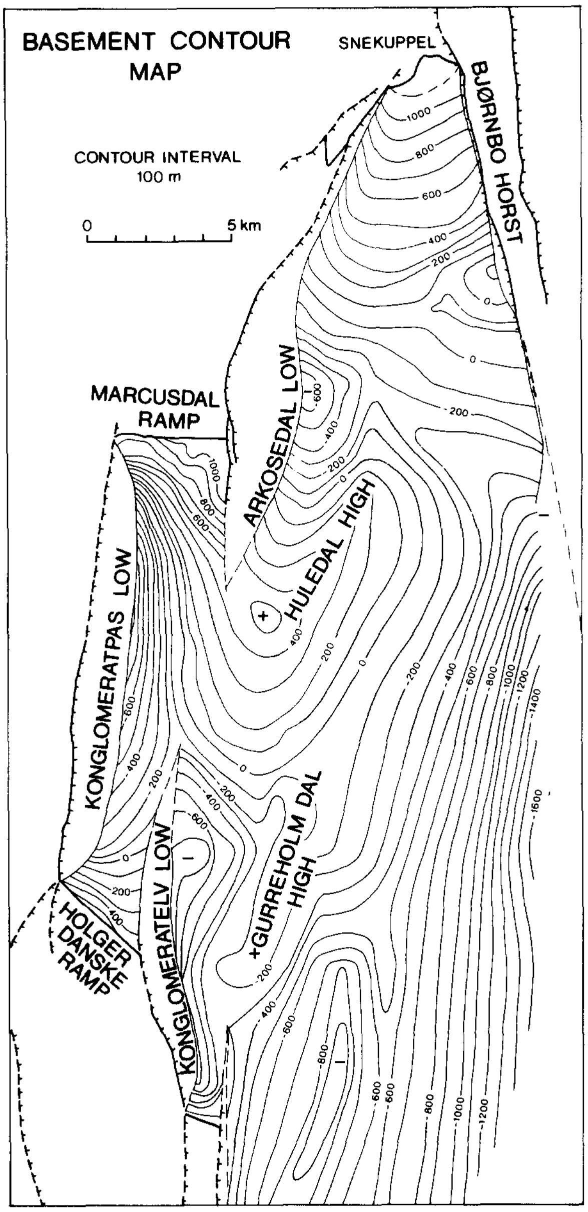

Fig. 6. Basement contour map of the Karstryggen area, East Greenland. The contours show the Caledonian crystalline basement surface in the downfaulted areas in relation to present day sea-level. The fault surfaces in lows are without ornamentation.

that the displacement or heave associated with the Arkosedal Fault is transferred or relayed westward, via the Marcusdal relay ramp, to the Konglomeratpas Fault (Figs. 6, 7 and 8).

The half-graben called the Arkosedal low (Fig. 6) may be characterized as a hangingwall downwarp relative to the footwall uplift of the Markusdal ramp block. Furthermore the Arkosedal low may be referred to as a roll-over downwarp relative to the Huledal high, creating the crest of the continuous roll-over structure associated with the Konglomeratpas Fault (Figs. 6, 7 and 8). To the south the Konglomeratpas–Holger Danske Briller relay structure is a symmetrical analogue to the structure mentioned above. Here the Konglomeratelv low is a hangingwall downwarp relative to the footwall uplift of the Holger Danske ramp block, and likewise a roll-over downwarp relative to the Huledal high.

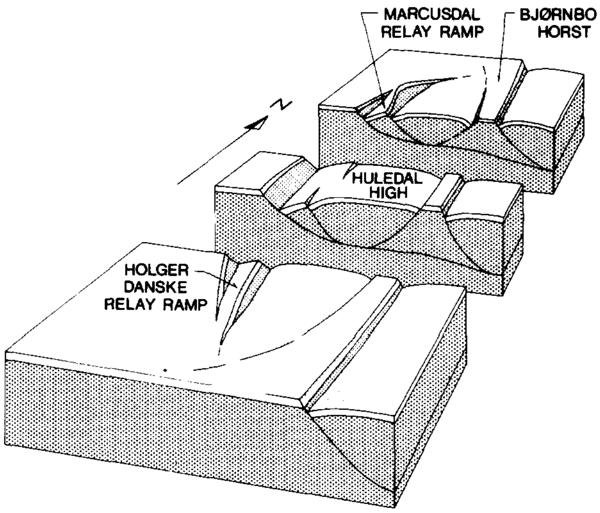

Fig. 7. Tectonic model of the Karstryggen area, East Greenland. The model shows the spatial and geometrical relations of the structural elements discussed in the text. The model is not to scale.

Going northward along the Arkosedal Fault the displacement diminishes, and the fault actually disappears in the Snekuppel area (Fig. 6). Here it joins up with the antithetic Snekuppel Fault, which together with the synthetic Bjørnbo Corner Fault define the Bjørnbo Horst. From offshore seismic studies in the North Sea and on the Norwegian shelf several examples have been published showing the presence of horsts formed in extensional regimes (e.g. Beach 1984, Gibbs 1984). It is believed that the Bjørnbo Horst is rooted in the same subhorizontal detachment surface as the Arkosedal Fault to the west (Figs. 6, 7 and 8).

The interplay of the various structures described above forms the basis for the tectonic model (Fig. 7), which defines an isolated eye-shaped, extensional sub-

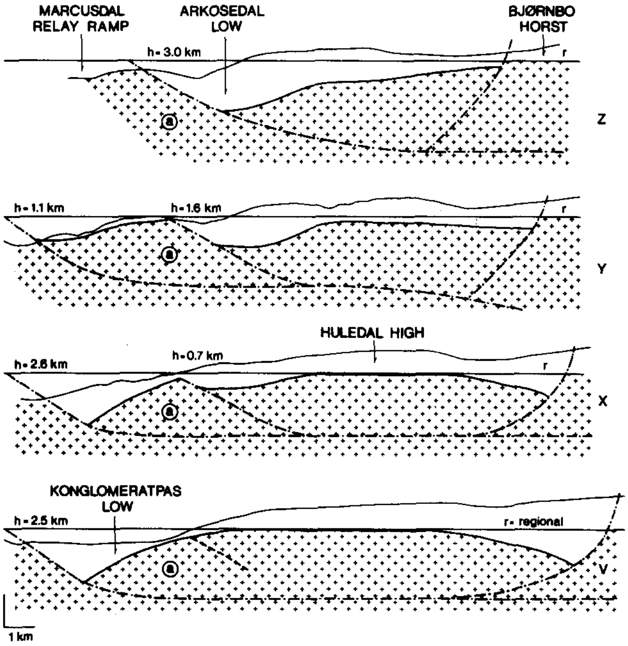

Fig. 8. A series of vertical cross-sections through the Marcusdal relay structure (Figs. 5 and 6). In section Z the Marcusdal relay ramp (a) is part of the footwall block, while in V it is part of the hangingwall block. The extension in each cross-section is indicated as the heave (h).

basin in the Karstryggen area. The southeastern corner of the model is somewhat speculative as no surface data are available from this area. The extrapolation is based on the overall symmetrical arrangement of the other structures (Fig. 7).

DISCUSSION

The recognition of relay structures in extensional dip-slip regimes is important from several points of view. The differential subsidence and half-graben development around a relay structure associated with hangingwall downwarps, footwall uplifts and roll-over downwarps may control the local sedimentary development and facies distribution (Larsen & Stemmerik work in preparation). In hydrocarbon exploration or hydrological evaluation of an area, the fact that relay ramps interconnect the footwall and hangingwall blocks may be of specific interest. The ramp may act as a migration path for fluids from the hangingwall to the footwall block or vice versa.

From the Karstryggen area it has been documented that relay structures and listric normal faults associated with half-grabens and roll-over structures may develop involving crystalline basement rocks (see also Surlyk 1977). In East Greenland the basement is formed of Caledonian metamorphic complexes and syn- to post-kinematic intrusions (Haller 1971, Henriksen & Higgins 1976, Higgins 1976, Henriksen 1978). The main subhorizontal detachment surface is situated within the basement rocks, which also participates in forming roll-overs and relay ramps. The crystalline basement in the Karstryggen area includes amphibolite facies supracrustal rocks and it is likely that the detachment may have developed parallel to marble horizons or along earlier Caledonian thrust surfaces.

Naylor *et al.* (1986) and Woodcock & Fischer (1986) have demonstrated how offset fault traces in strike-slip regimes may reflect two separate faults or two en échelon strands that curve helicoidally into a single fault at depth. Before imbricate strike-slip faults propagate off the lateral tips of the main offset faults and interconnect these, strike-slip relay ramps may be identified between the main offset faults following the concept described in this paper.

In thrust systems relay ramps may be comparable to transfer zones in the sense of Douglas (1958), Dahlstrom (1969, 1970) and Boyer & Elliott (1982). Hossack (1983) compared thrust displacement along a fault terminated by its tip-line to dislocations within crystals. The slipped region is surrounded by the tip-line and a so-called ductile bead. When following the fault plane and crossing the tip-line the slip on the fault has to decrease to zero and is likely to be smeared out across a zone which may extend beyond the tip. By analogy the relay ramps in extensional dip-slip systems form between two such zones of ductile beads as the ramp is situated between the tip-lines of two offset faults (Fig. 9). Depending on whether the extensional offset faults in map view are overlapping or underlapping the relay ramp may represent none or most of this ductile bead, respectively. But in either case the relay ramp will be a strained zone because of shearing and block rotation during slip along the bounding offset faults.

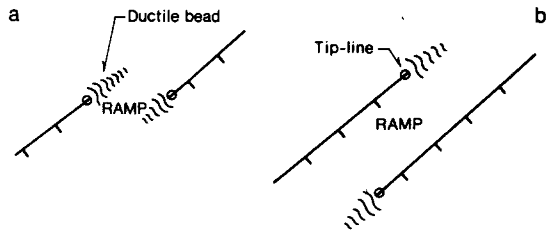

Fig. 9. Underlapping (a) and overlapping (b) offset fault traces in map view terminated by tip-lines and a ductile bead beyond the tips. The relay ramps between the offset faults may represent none of the ductile bead in overlapping systems (b) and most of it in underlapping systems (a).

CONCLUSIONS

Application of simple geometrical models and analogues is of considerable importance in understanding the geometry of extension in dip-slip systems. The thin-skinned extensional model of deformation on low-angle listric faults with ramp and transfer fault geometries, outlined by Gibbs (1984), describes the fully detached system, where the hangingwall block is entirely disconnected from the footwall block. However individual faults may die out along strike and, seen in map view, no direct connection to other faults may be obvious.

This study demonstrates that the extension represented by an individual extensional fault may be transferred by ductile deformation in a relay ramp to another fault having the same subhorizontal detachment surface at depth. The extension transfer takes place without disconnecting the hangingwall and footwall blocks, which may be of importance in the study of fluid migration in extensional settings.

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