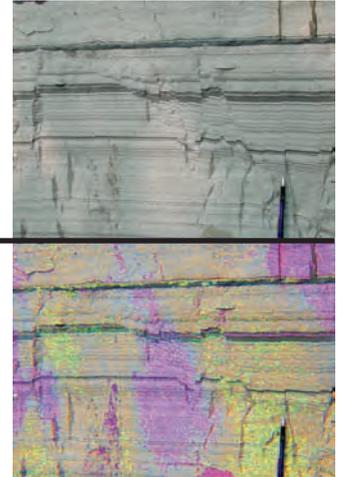


4. Normal faults and rift zones



Crustal-scale extensional fault systems develop in the following tectonic regimes:

- Intracontinental rift systems (East African Rift)
 - Passive continental margins (North America and Europe passive margins)
 - Mid ocean Ridge systems (Mid Atlantic - Iceland ridge)
 - Back-Arc basin (Lau basin-Tyrrhenian Sea)
 - Extensional collapse Basins (West Norway, Basin and Range)
 - Strike-slip pull apart basins (Dead sea Basin)
- Shallow detached extensional fault systems (i.e., limited to sedimentary cover above a detachment level, normally located in evaporites and shales) are found in the following tectonic regimes:
- Progradational delta systems (Niger Delta)
 - Passive continental margins (West Africa, Brazil and Gulf of Messico)
 - Submarine Scarps Collapse (East Coast USA).

Normal faults are of three kinds (fig. 89): 1) planar non-rotational (fig. 90), 2) planar with rotation of beds and faults (domino faults) (figs. 91 - 93) and 3) curvilinear with rotation

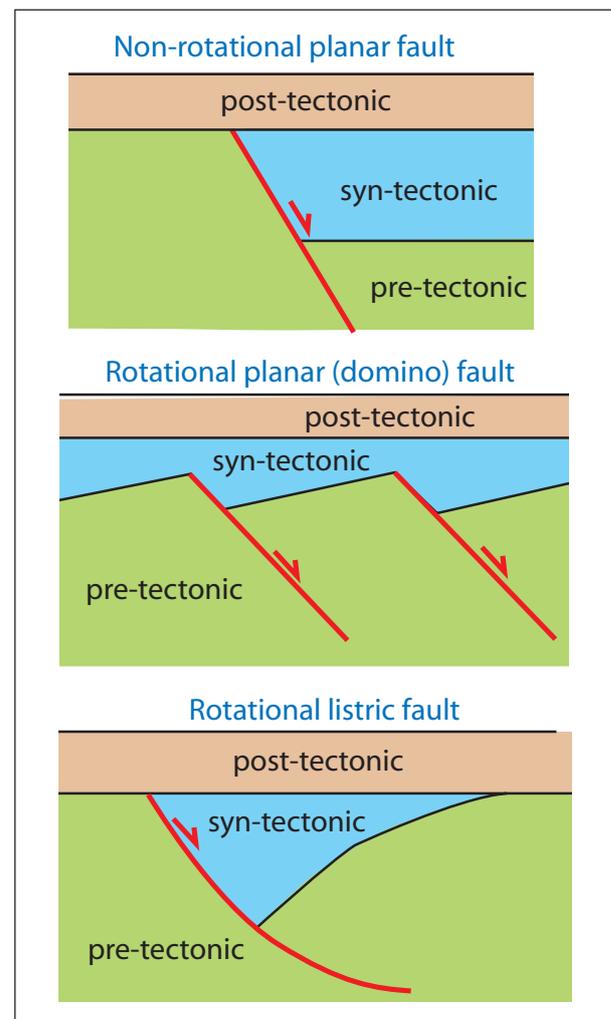


Fig. 89 - 2D geometric classification of normal faults. The classification is based on the effects that faults have on beds and on other faults.

of the beds (listric faults) (figs. 94 - 96).

Types 1 and 2 are found in intercontinental rifts, passive continental margins, mid-oceanic ridges, back-arc basins and pull apart basins. Type 3 occurs in delta systems, passive continental margins, areas characterised by salt detachments and diapirs, areas characterised by collapses of submarine scarps and extensional collapse (mostly post-orogenic) basins.

When investigated in 2D, normal faults are classified as rotational or non-rotational and their fault plane may be planar, listric or kinked. Planar faults can be non-rotational or rotational (fomino faults). In this latter case both beds and fault planes rotate. Both domino and listric faults necessitate of a detachment level. Curved or kinked normal fault planes pose severe space accommodation problems that are eliminated either by folding of the hangingwall with the formation of synforms and antiforms or by tectonic erosion of the fault walls.

Listric faults are associated to rotations of the hangingwall beds. Such rotation generates roll-over anticlines that may be characterised by crestal collapse normal faults delimiting a graben (figs. 97 - 99).

Syn-sedimentary or growth faults (figs. 100 - 106) are characterised by differences in sedi-

ment thicknesses between hangingwall and footwall. Rotational growth faults (either listric or planar) are characterised by the development of a wedge geometry of hangingwall syn-rift sediments that thicken towards the fault plane.

As also discussed for thrust faults, normal faults may be associated to folding (normal fault propagation folds) (figs. 107, 108). Folding occurs during the vertical and lateral propagation of a normal fault involving a rigid basement and a ductile sedimentary cover. Fault tips are associated with the development of a monoclinial fold above the blind, upward and laterally propagating normal fault.

When normal fault systems are discussed in 3D, it is to be emphasized that normal faults are laterally segmented and connected by transfer zones (figs. 109 - 114). In transfer zones displacement is transferred from one fault to the adjacent fault either by strike-slip transfer faults (hard linkage) or by relay ramps (soft linkage). Rift systems (figs. 115, 116) are markedly asymmetric with dominant half-graben structures. In intracontinental rift systems and in passive margins extensional fault systems (i.e., semi-grabens) change frequently polarity along strike. The different semi-grabens are connected by accommodation zones.

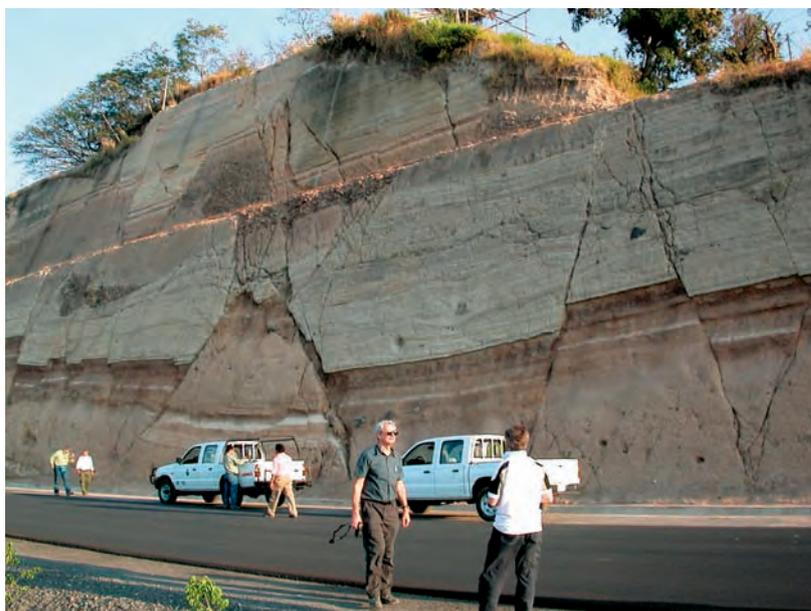


Fig. 90 - Planar non-rotational conjugate extensional faults affecting volcanic deposits along the Panamerican Road in El Salvador. Fabrizio Innocenti for scale.

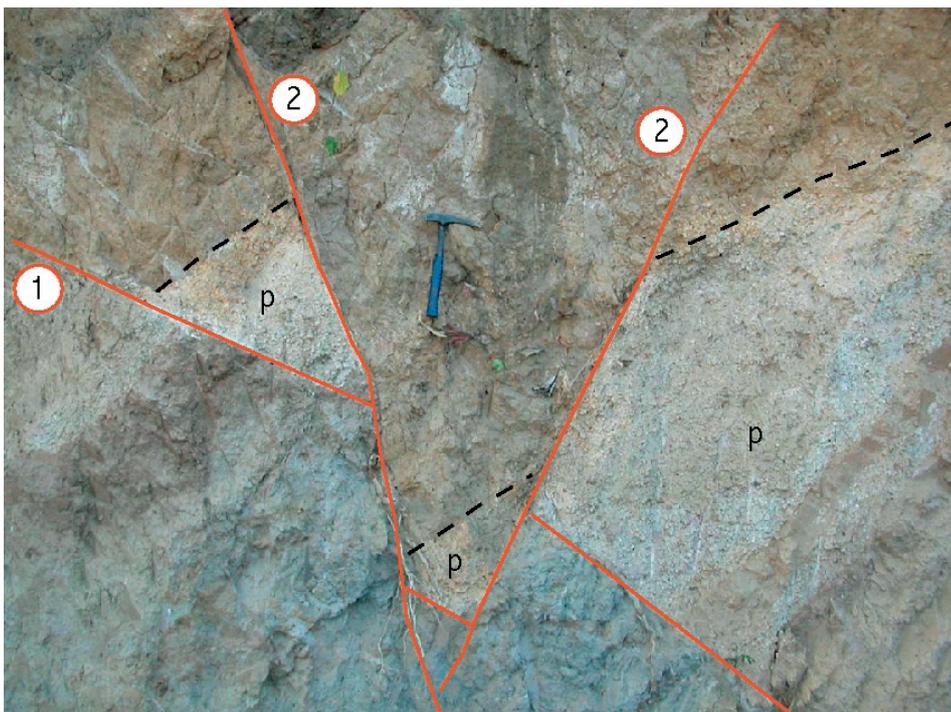


Fig. 91 - Domino normal faults in Pleistocene-Holocene volcanic deposits near the Laguna de Llano, western El Salvador. Notice that a first generation of normal faults (labelled 1 in the close up) were characterised by strong rotations that lowered considerably the fault dip. This produced a severe misorientation of the faults with respect to the direction of active extension. The first fault generation was therefore unsuitable to accommodate further stretching and a new generation of steeply dipping normal faults (labelled 2 in the close up) developed. A sketch of the structural evolution of the area is shown in figure 93. Courtesy of Giacomo Corti and Samuele Agostini.



Fig. 92 - Domino set of planar rotational normal faults, Liassic Medolo Fm, Lake Maggiore, Lombardy. The faults are decoupled along the marly intrabed layers. Courtesy of Daniel Bernoulli.

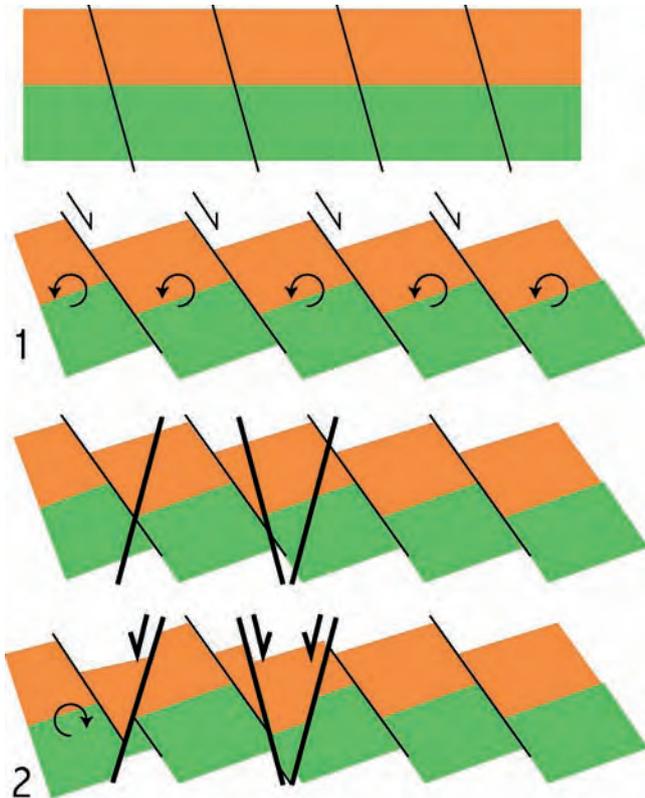


Fig. 93 - Sketch of the structural evolution of the area portrayed in figure 91. Four evolutionary stages are represented. The faults labelled 1 and 2 refer to the two generations of normal faults that developed in the Laguna de Llano (El Salvador) area. The faults of the first generation were rotated and entered the field of extreme misorientation with respect to the active extensional stress field and were therefore abandoned. The faults of second generation nucleated at high angle, compatibly with the predictions of the Anderson's faulting model. Courtesy of Giacomo Corti and Samuele Agostini.

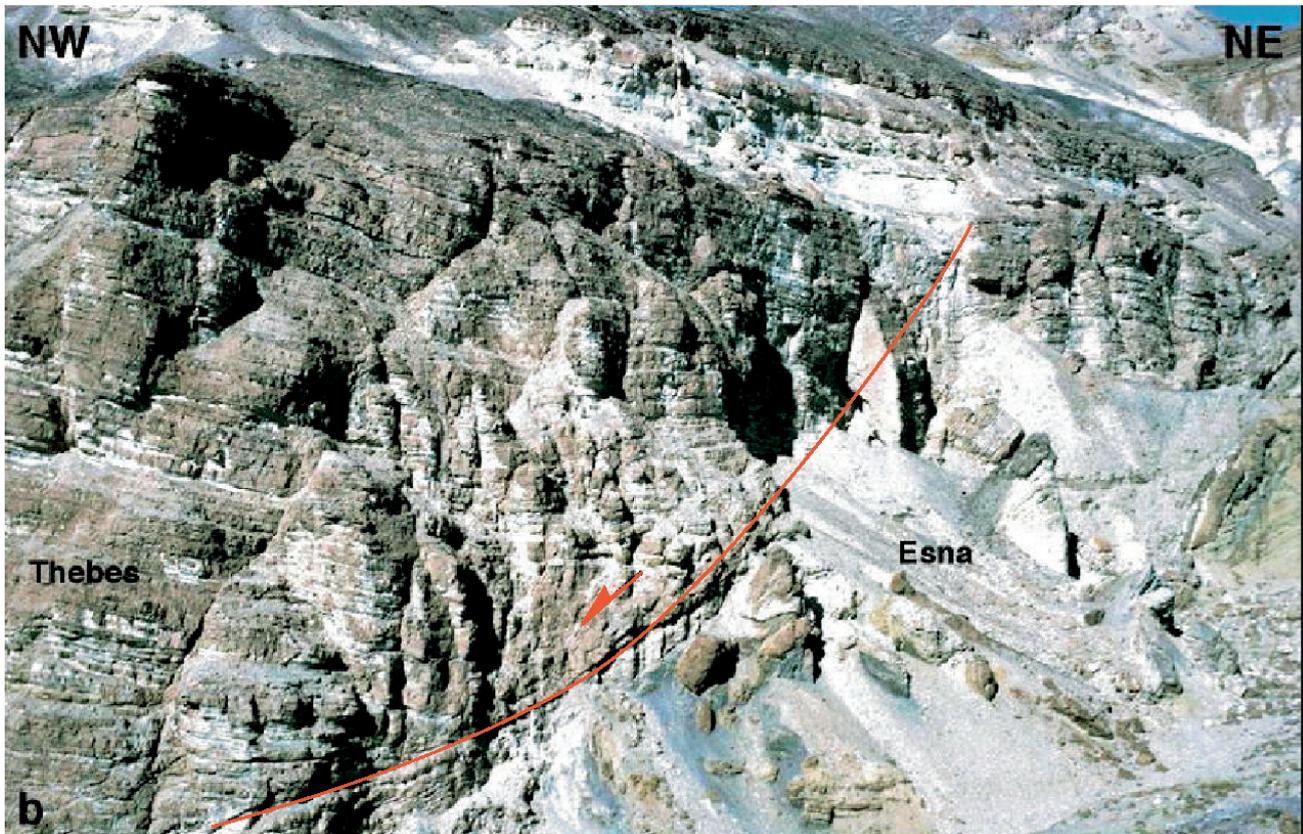


Fig. 94 - Listric fault cropping out in the Sinai Peninsula, Egypt (after KHALIL, 1998).



Fig. 95 - Seismic line showing a rotational, mainly planar domino set of extensional faults. Gulf of Mexico.

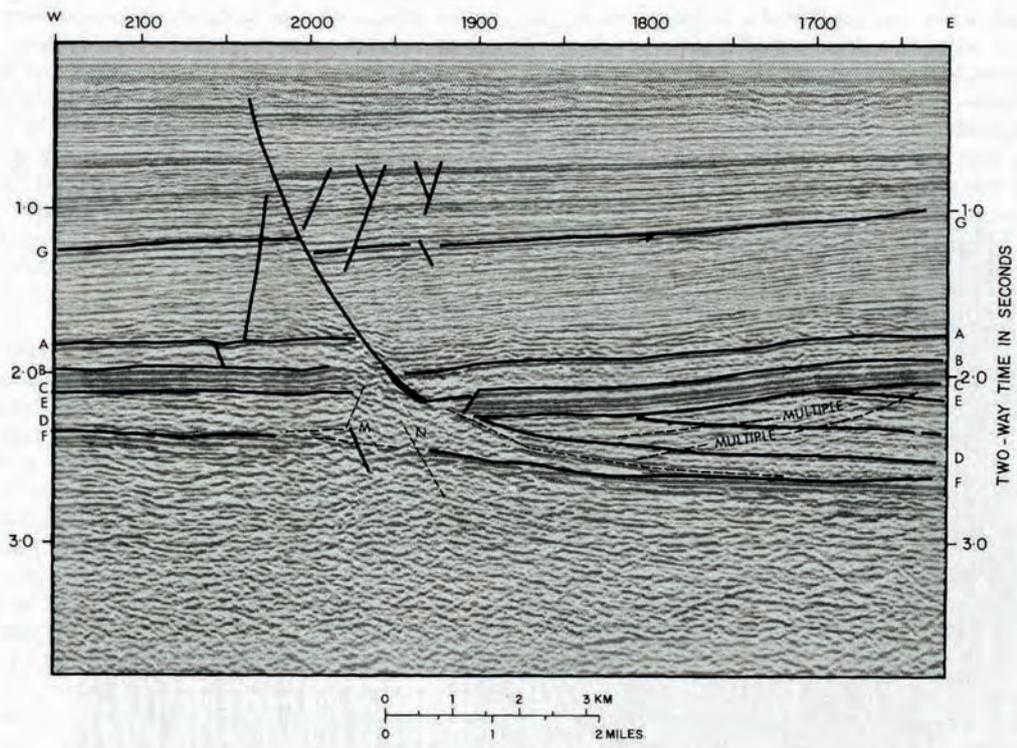
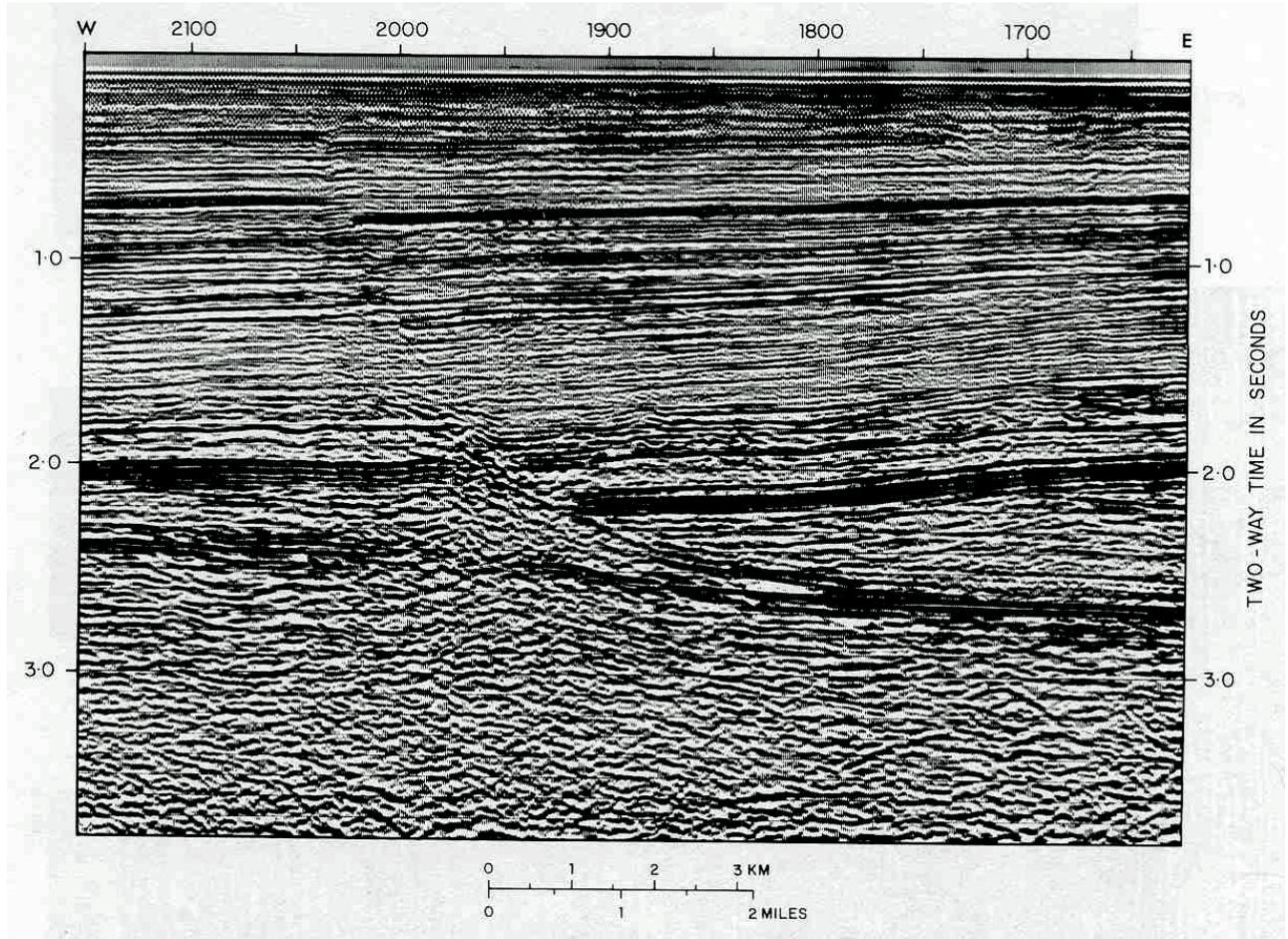


Fig. 96 - Seismic line and interpretation showing a listric normal fault. Notice that the upper half of the figure shows, in the hanging-wall, sedimentary wedges that thicken toward the fault, indicating that they were deposited when the fault was active (after BADLEY, 1985).

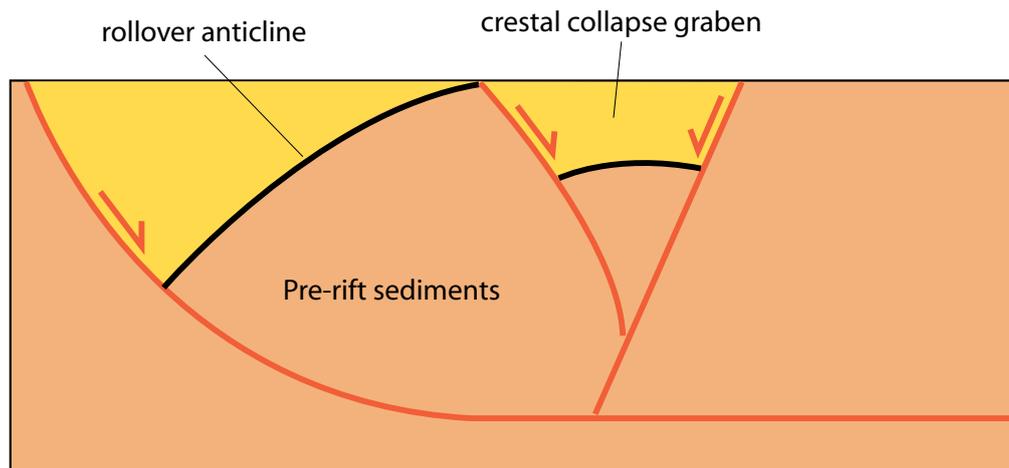


Fig. 97 - Listric faults are characterised, in the hangingwall, by the occurrence of rollover anticlines. Such structures accommodate the slip along the curved fault plane and are possibly characterised at their top by a crestal collapse, with the development of graben like structures.

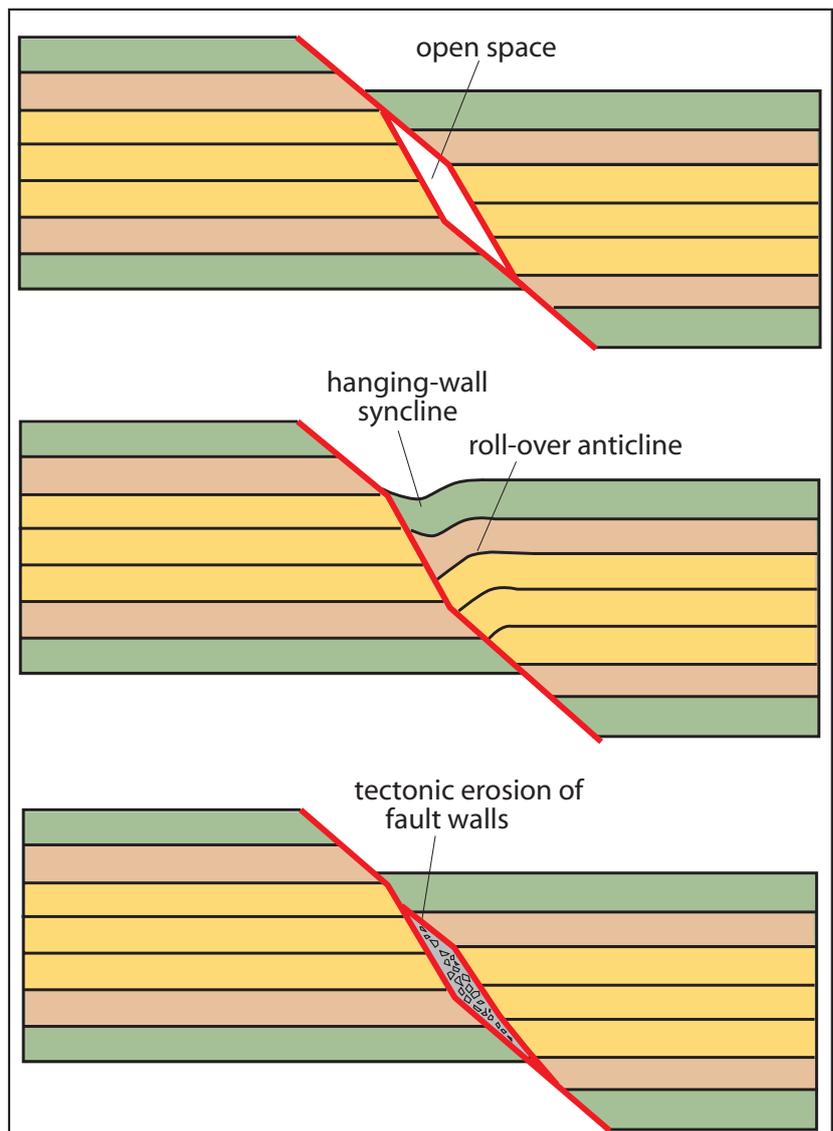


Fig. 98 - Curved or kinked normal fault planes pose severe space accommodation problems (opening of voids) when the fault kinematics are investigated. In nature, the voids may be eliminated either by folding of the hangingwall with the formation of synforms and antiforms or by tectonic erosion of the fault walls (after RAMSAY & HUBER, 1987).

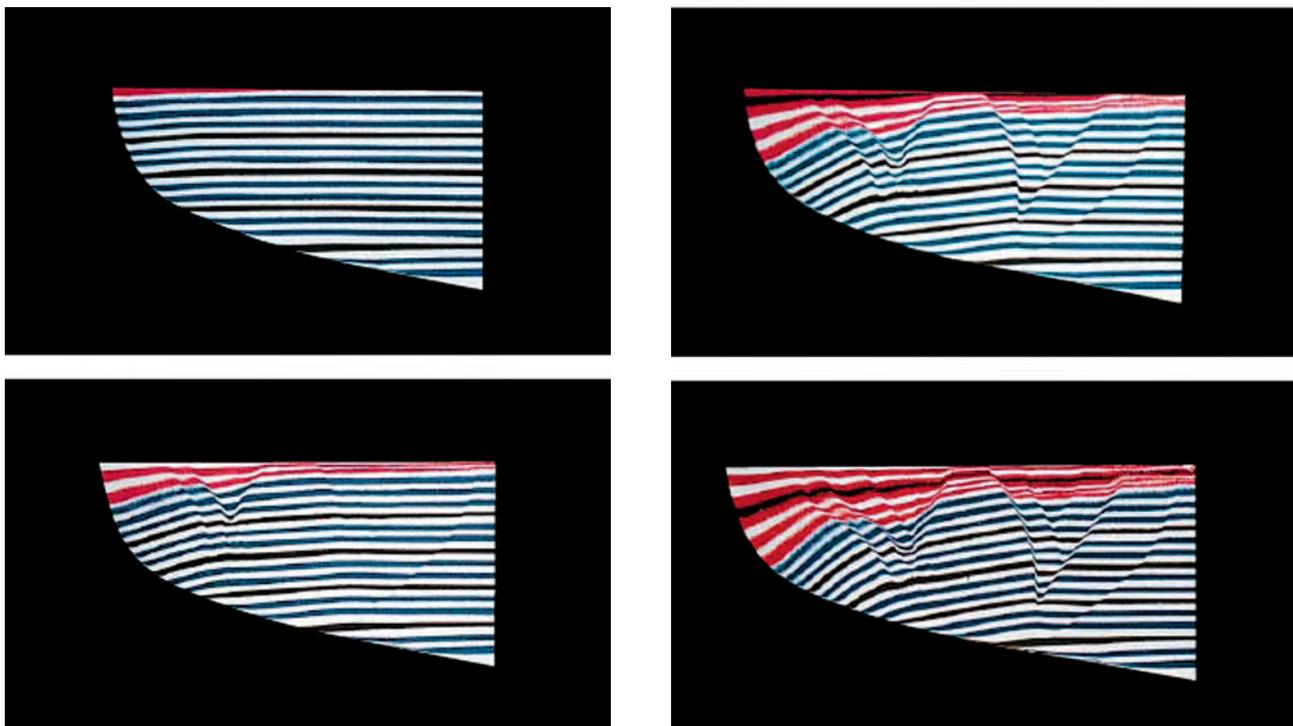


Fig. 99 - Analogue modeling showing the development of a rollover anticline and of the associated crestal collapse graben (after PLATT *et alii*, 1993).

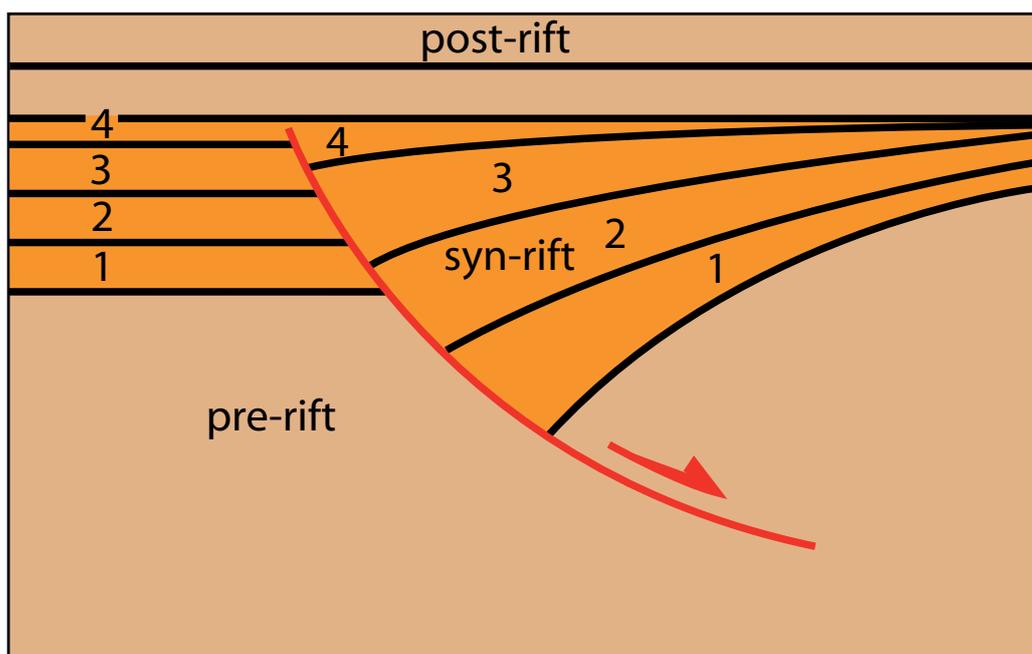


Fig. 100 - Synsedimentary listric fault. The syn-rift strata show in the hangingwall a wedge-like thickening towards the fault.

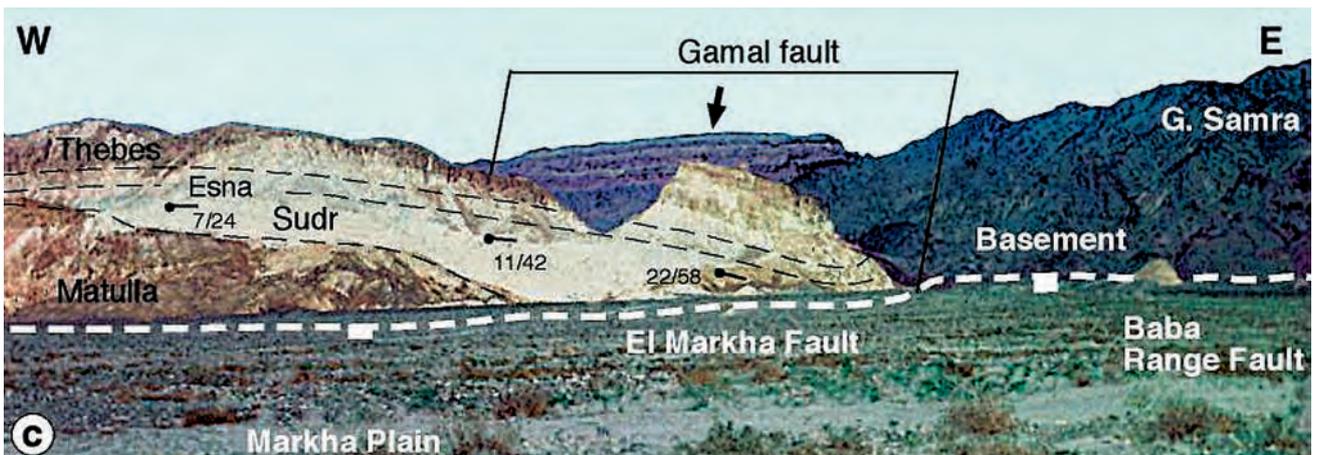
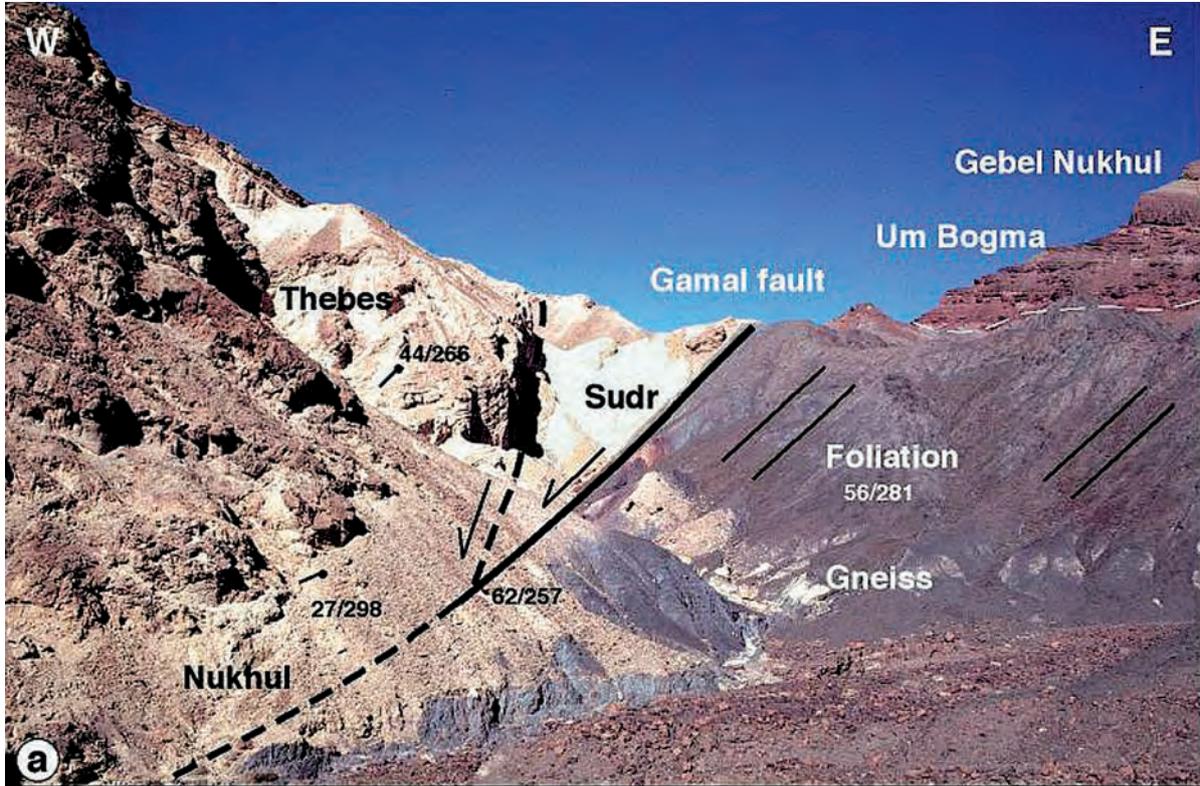


Fig. 101 - An example of rollover anticline cropping out in the Sinai Peninsula. The Gamal fault has a listric geometry (upper panel). In the lower panel it is shown that the Paleozoic sediments overlying the basement are horizontal (just below the black arrow), whereas the hangingwall sediments of the Thebes, Esna and Sudr Fms. progressively bend producing a rollover anticline geometry (after KHALIL, 1998).

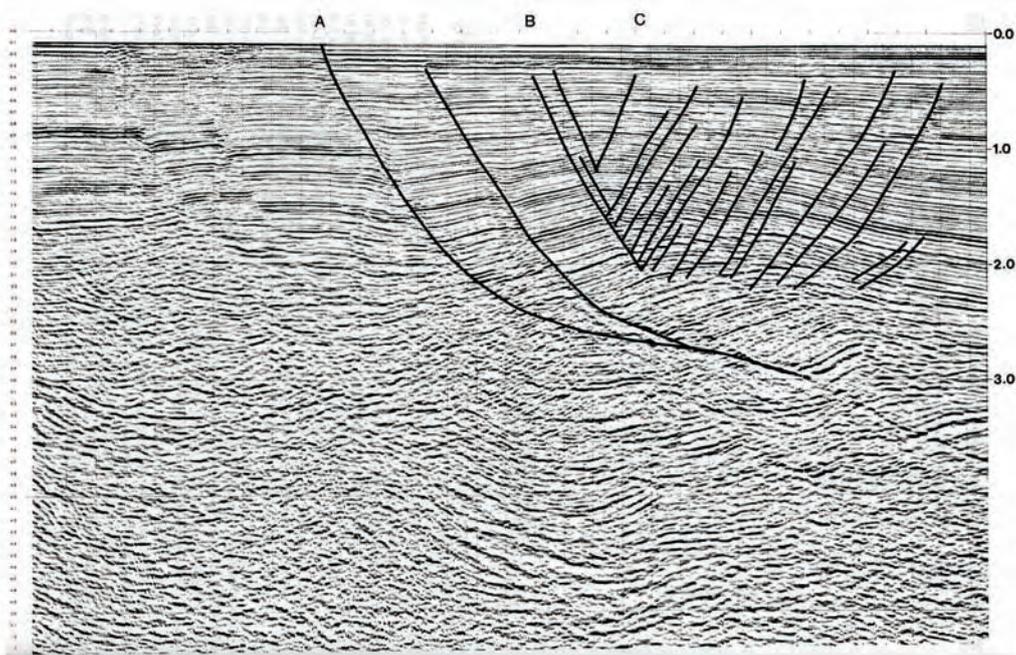


Fig. 102 - Seismic section showing a listric fault associated with a rollover anticline characterised by crestal collapse (after XIAO & SUPPE, 1992).

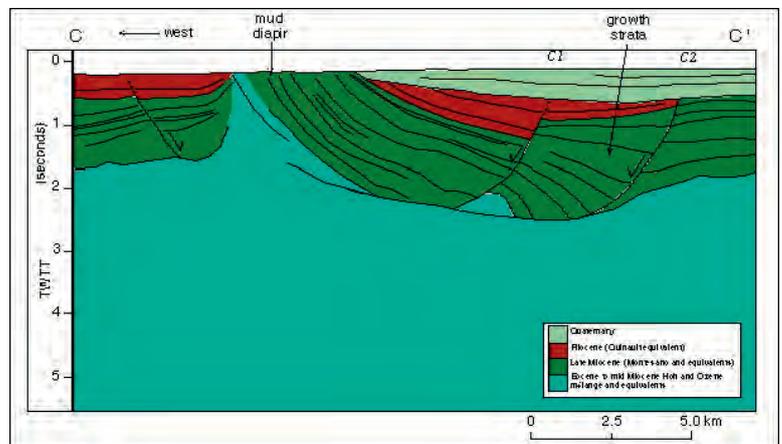
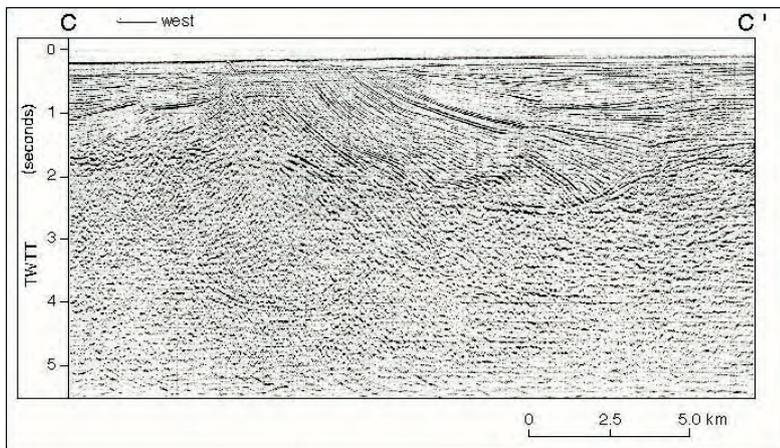


Fig. 103 - Seismic line and interpretation showing syn-sedimentary listric faults from the Cascadia subduction zone (after McNEILL *et alii*, 1997).

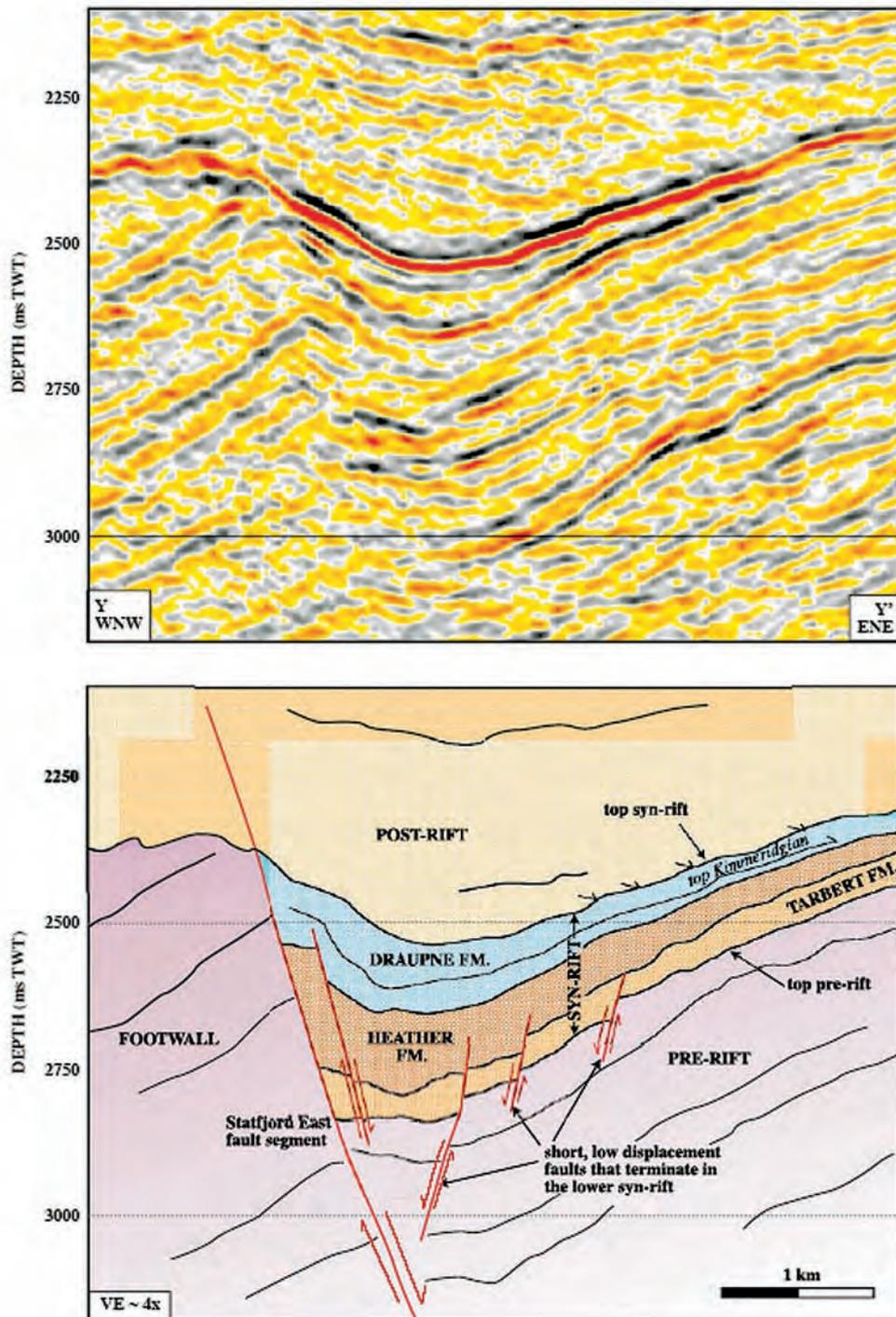


Fig. 104 - Seismic section and interpretation of a growth fault from the North Sea. Notice that the master listric fault is associated to synthetic and antithetic normal faults (after DAVIES *et alii*, 2000).

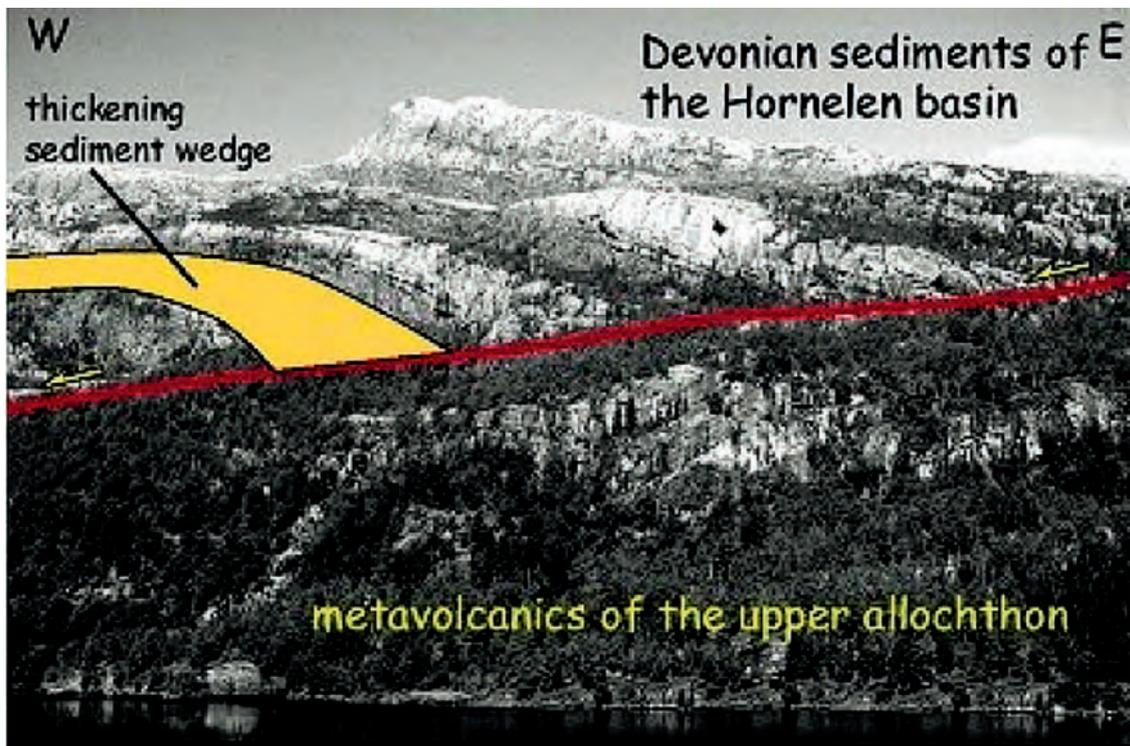


Fig. 105 - Growth normal fault in the Devonian Hornelen Basin, Norway (after DAVIES & REYNOLDS, 1996).

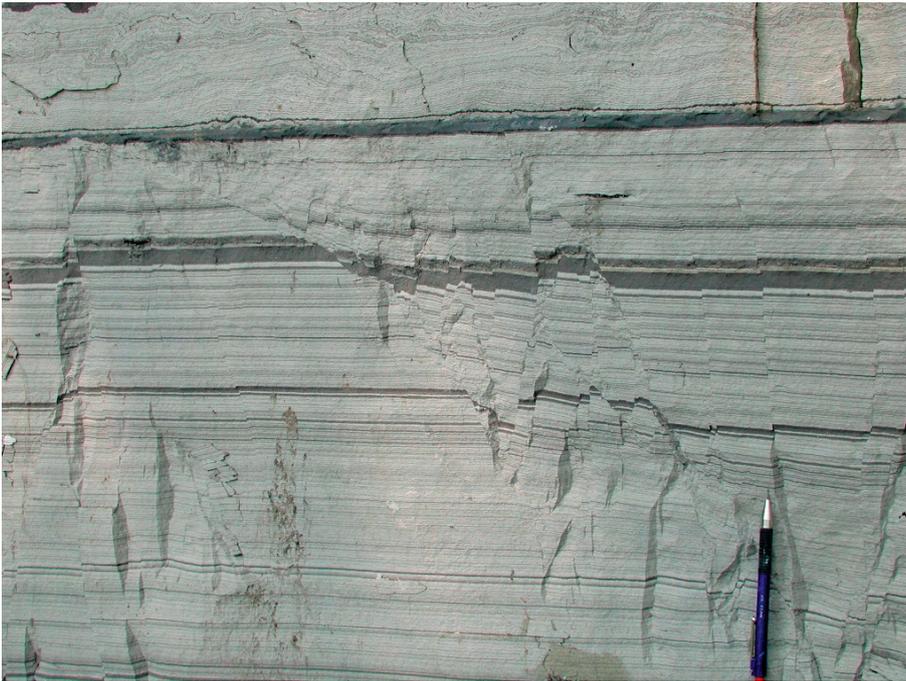


Fig. 106 - Syn-sedimentary normal faults in lacustrine sediments of the Pianico Basin, Lombardy. Courtesy of Fabrizio Berra.

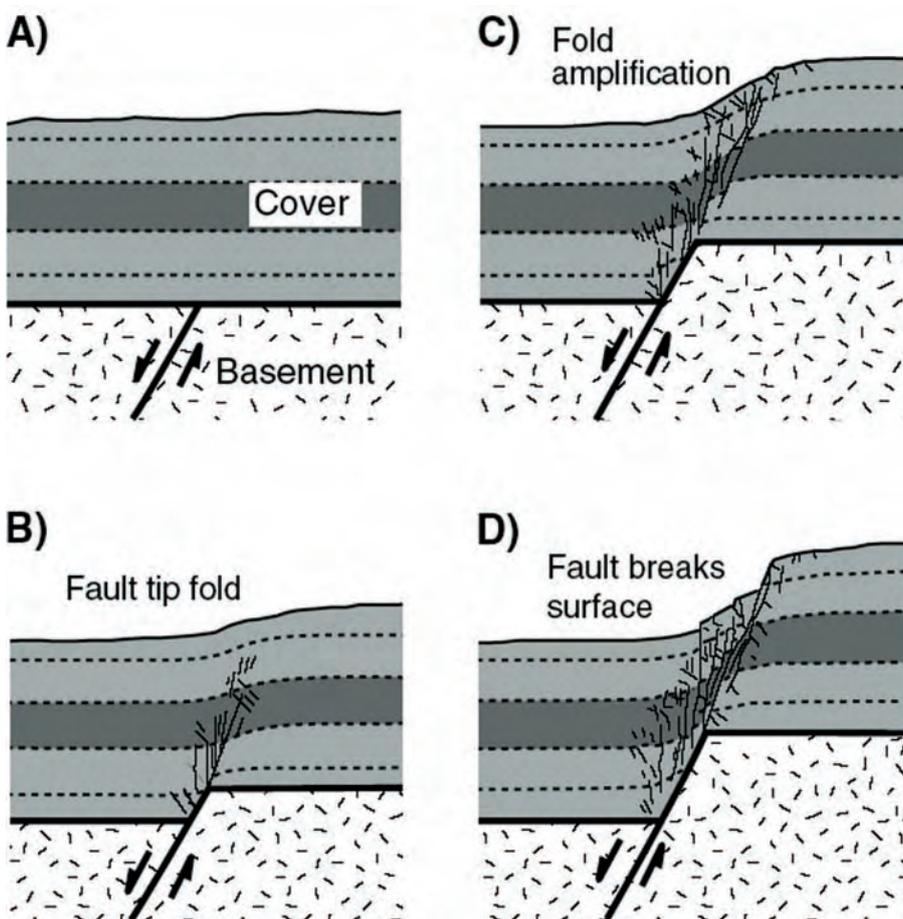


Fig. 107 - Forced folds may develop above blind normal faults. Extensional fault-propagation folds form above steeply dipping normal faults typically, though not exclusively, where there is a distinct mechanical contrast between basement and sedimentary cover or a ductile unit overlies the basement and acts to decouple the basement and the overlying sediments (after GAWTHORPE & LEEDER, 2000).

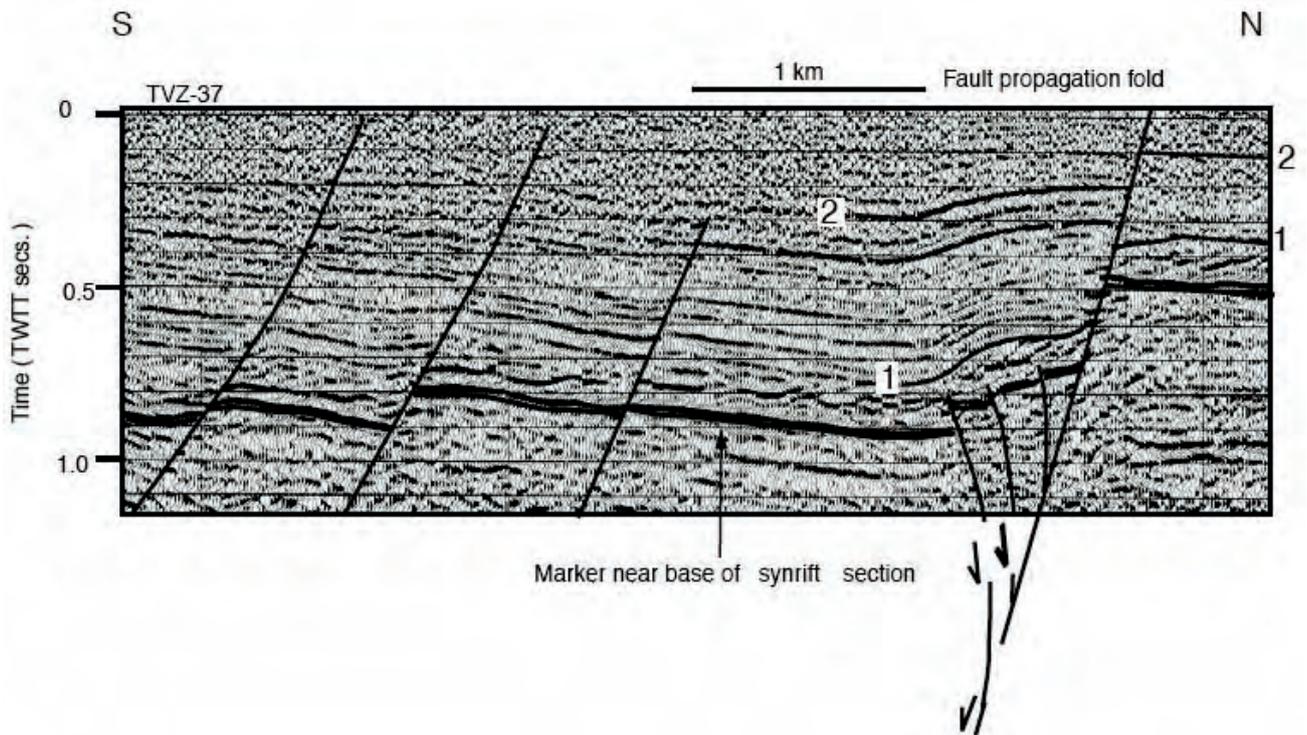


Fig. 108 - Seismic section showing a normal fault-propagation fold developed in the Usungu Flats, Tanzania (after MORLEY, 2002).

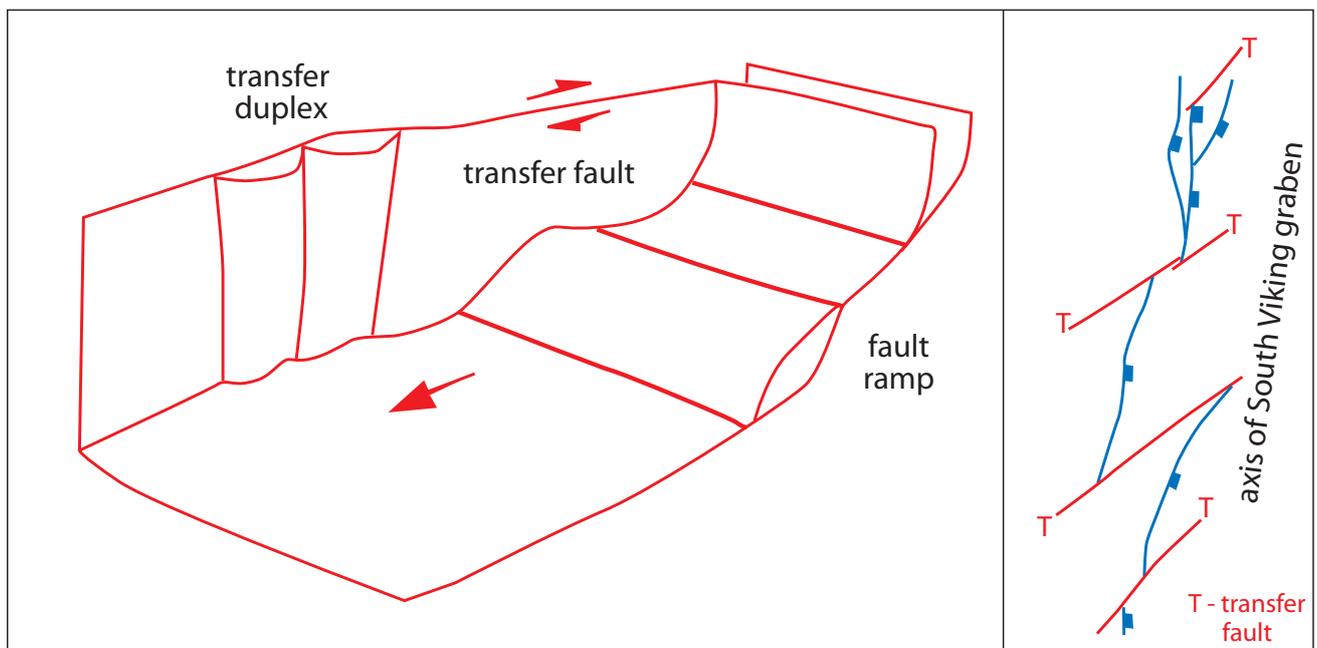


Fig. 109 - The development of mainly strike-slip (transfer) faults may accommodate normal fault segmentation. In this case the displacement between two normal faults is transmitted by hard linkage. The panel to the right shows a tectonic map from the Viking graben showing extensional faults offset by transfer faults (after GIBBS, 1984 and 1990).

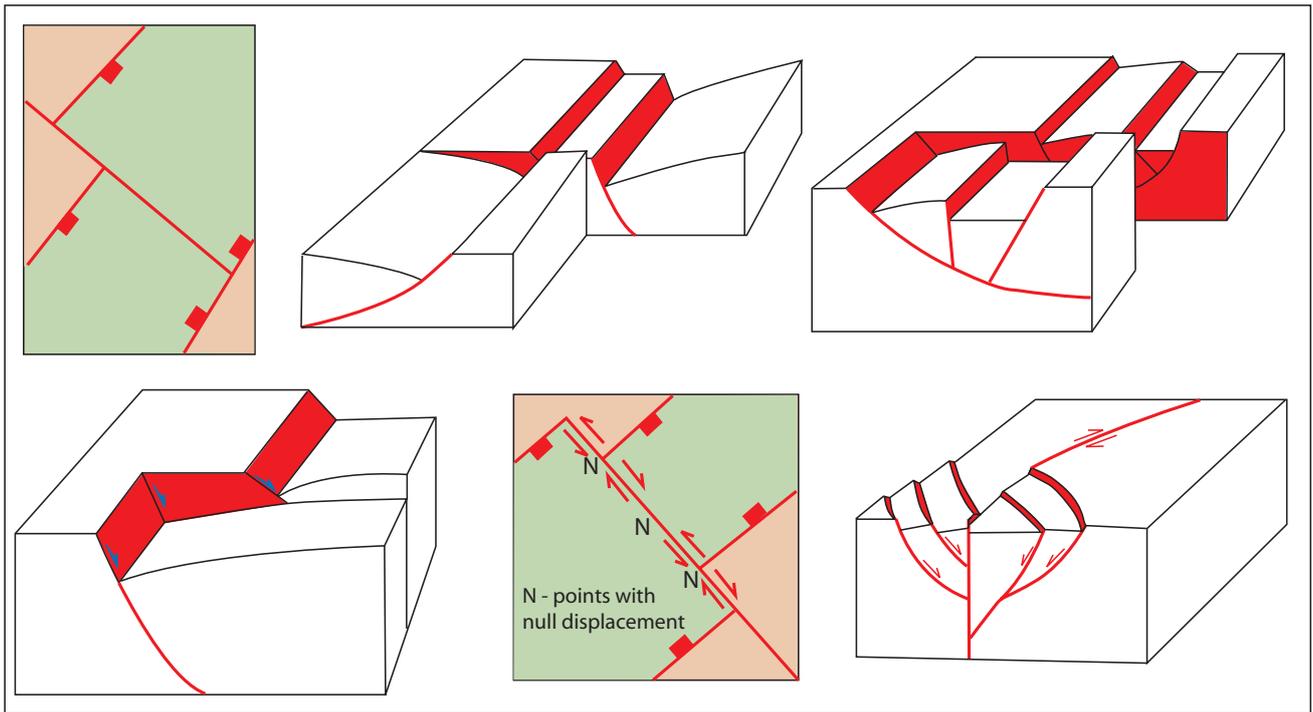


Fig. 110 - Hard linkage structures may link normal faults or semi-grabens with opposing or common dips. After MILANI & DAVISON (1988).

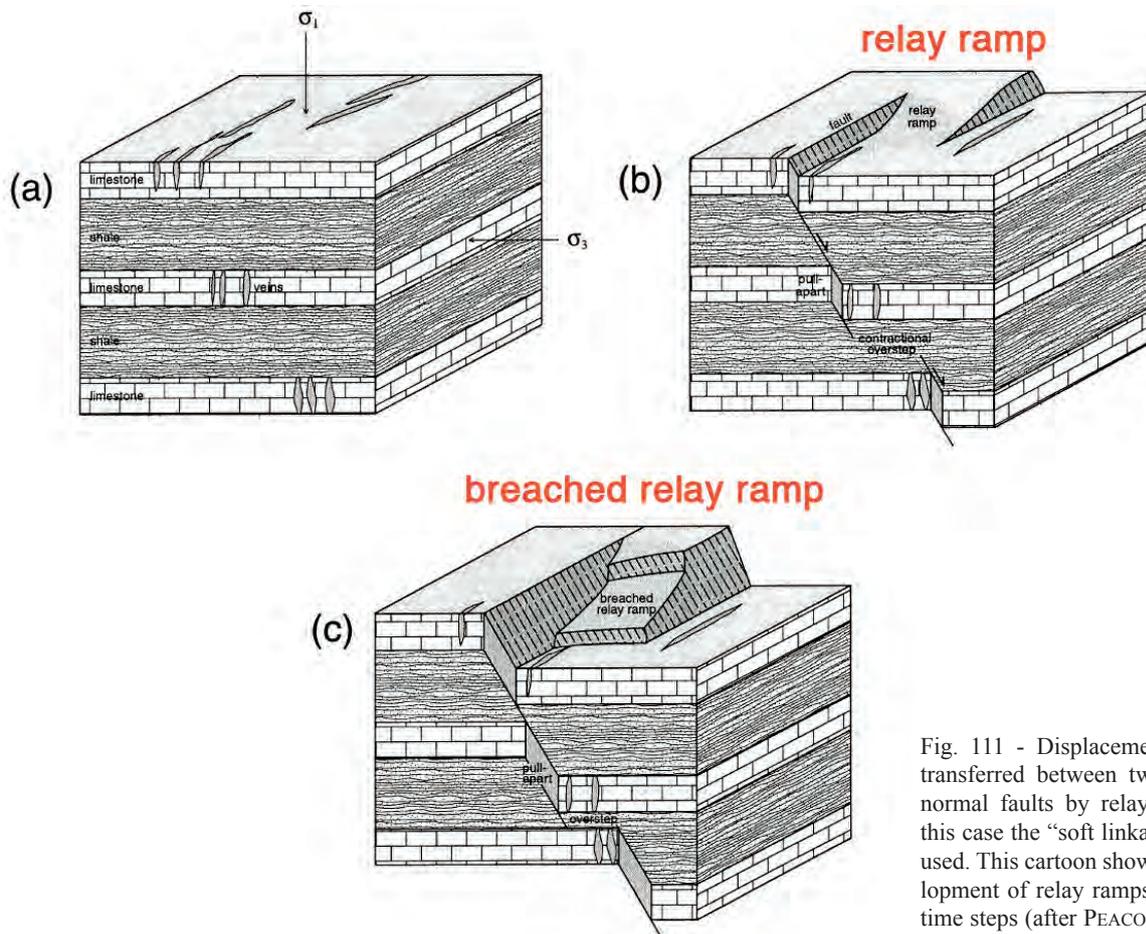


Fig. 111 - Displacement may be transferred between two adjacent normal faults by relay ramps. In this case the “soft linkage” term is used. This cartoon shows the development of relay ramps in various time steps (after PEACOCK, 2002).



Fig. 112 - Relay ramps develop at very different scales. In this case decimeter-scale relay ramps are exposed in limestones, East Quantoxhead, Somerset, UK (after PEACOCK & SANDERSON, 1994).

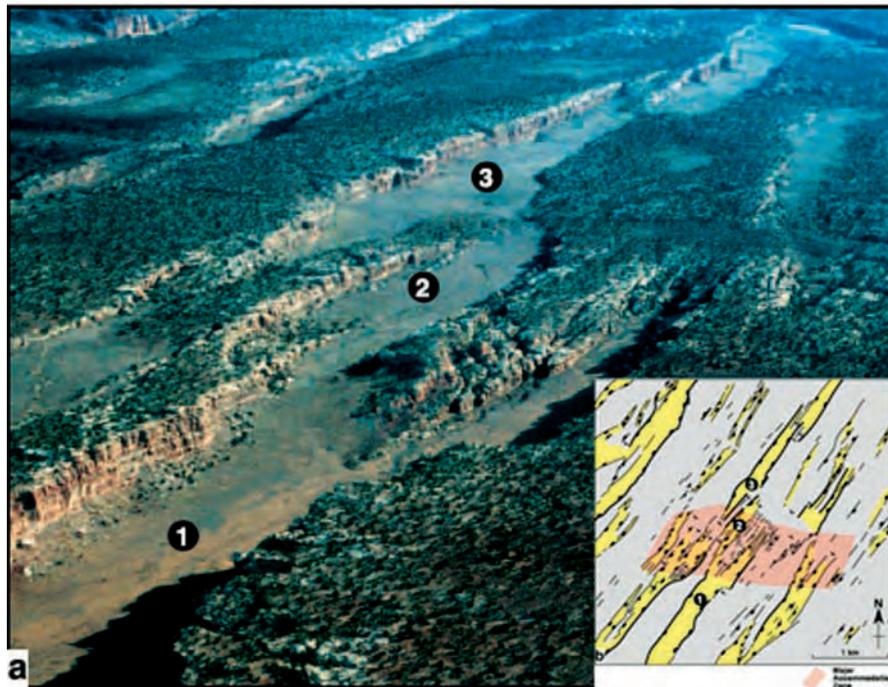


Fig. 113 - Relay ramps develop at very different scales. In this case kilometre-scale relay ramps are imaged by an aerial photograph (the inset is the interpretation) taken in the Canyonlands National Park, Utah, USA. At the terminations of individual grabens, the main faults branch into a series of splays that form relay ramps between overlapping, like-dipping faults (after MCCLAY *et alii* 2002).

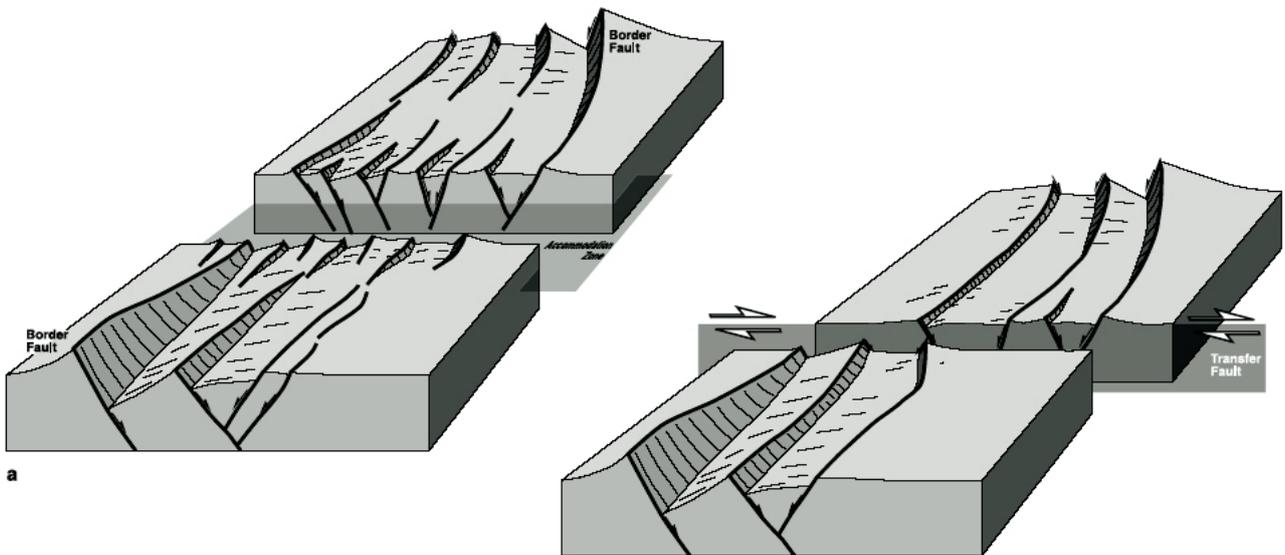


Fig. 114 - Conceptual models of displacement transfer in rift systems. (a) Synoptic model of a low-strain intracontinental rift with along-axis segmentation. Individual half grabens are separated by soft-linked accommodation zones formed by overlapping fault segments. (b) Synoptic model of hardlinked, strike-slip, rift transfer fault system (after McCLAY *et alii*, 2002).

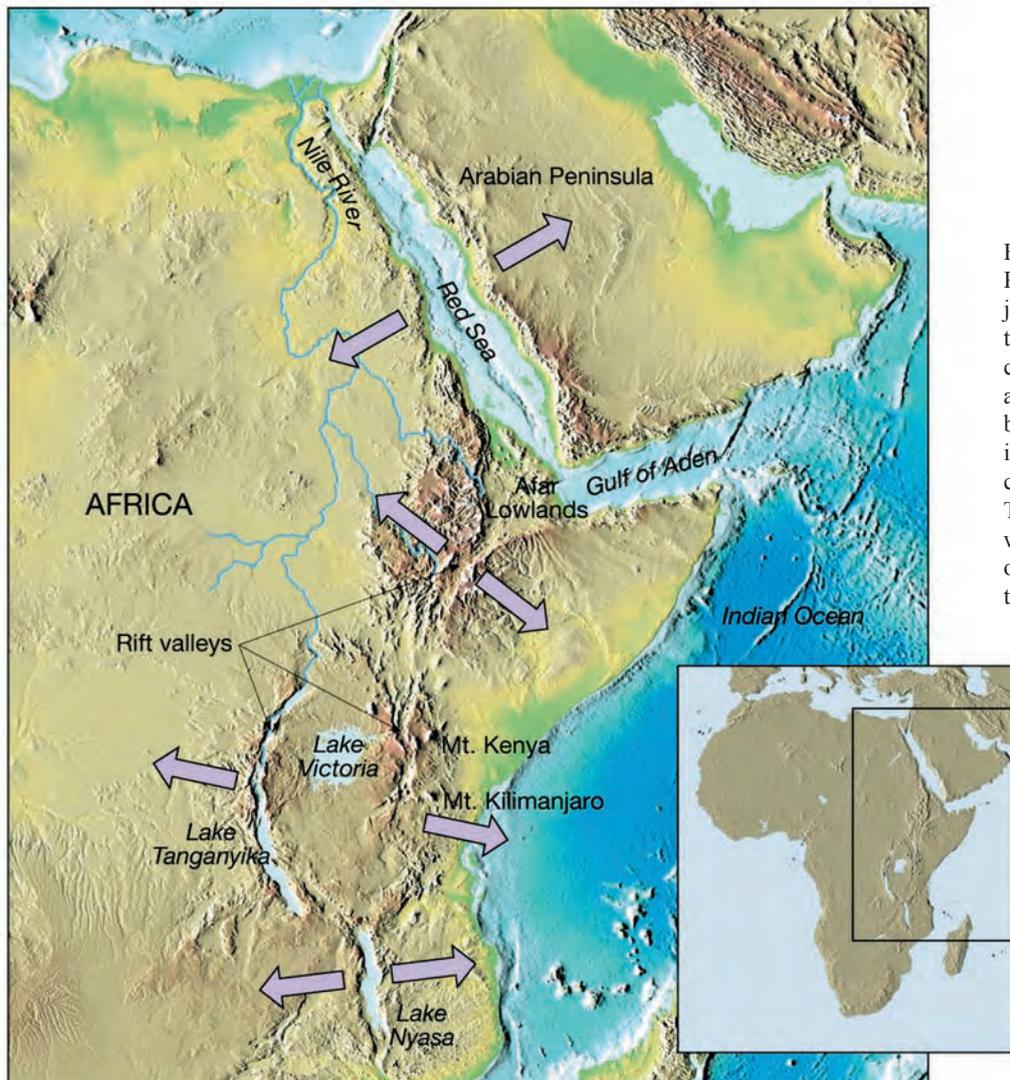


Fig. 115 - The East African Rift system and the Afar triple junction. Notice the organization of the rift system in branches (west and east branches, around the Lake Victoria block) and zones. Each zone is laterally segmented and constituted by semi-grabens. The transfer of extension between adjacent semigrabens occurs through accommodation zones. See next picture.

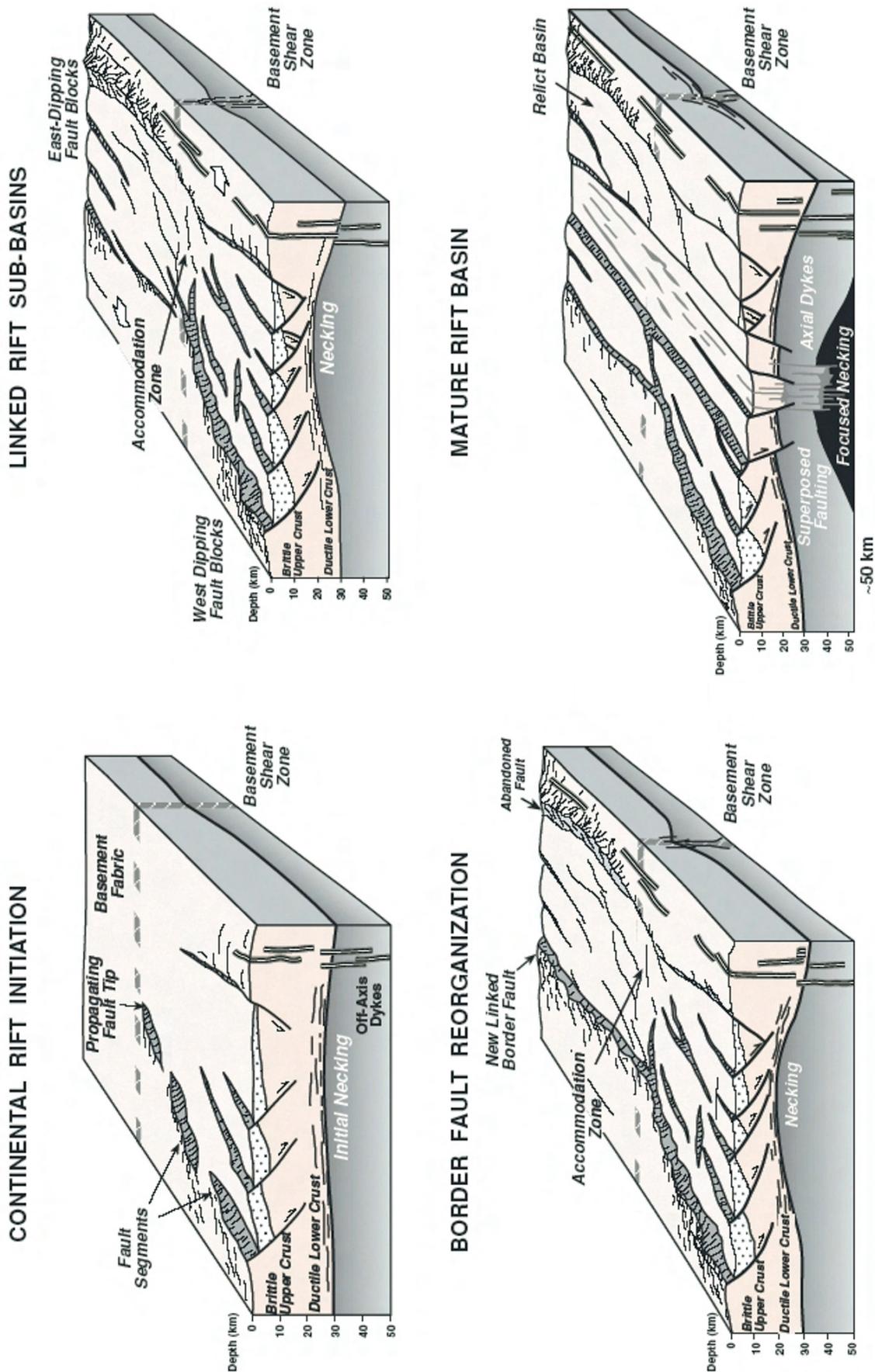


Fig. 116 - Evolutionary model of the Gulf of Suez and the Northern Red Sea system. The various stages of the transition from rifting to drifting are portrayed. Notice the marked asymmetric nature of semi-grabens and the development of accommodation zones in the early stages of rift development (after KHALIL & MCCLAY, 2001).