Pakistan Journal of Hydrocarbon Research
Vol. 9, (January 1997). p. 35-47. 15 Figs

Model Geometries of Extensional Faults: Implication on Structures of the Lower Indus Basin in Pakistan

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ABSTRACT

Lower Indus Basin (LIB) in Pakistan is an area of active hydrocarbon exploration related to Mesozoic extension of the Indian plate. Seismic reflection profiles (Ahmed & Ahmad, 1991; Kemal, 1991) show planar, listric normal faults, and horst and graben structures in the lower Indus Basin. Geometry and morphology of normal faults along with physical models of extensional systems are given to provide an insight into the architecture of a passive margin. The model of uniform extension over a non-sloping detachment shows a series of horst and graben structures with planar or listric faults. Uniform extension over a sloping detachments shows dominostyle of faulting. A simple listric detachment produces well developed rollover and a large crestal collapse graben. A listric fault with ramp-flat geometry produces crestal collapse graben and local reverse faults. Model geometries of extensional faults may help to evaluate the structure of the LIB for better hydrocarbon exploration in Pakistan.

INTRODUCTION

The lower Indus Basin (Figure 1) is one of the three petroliferous basins of Pakistan (Raza et al., 1989). Its structure is of a rifted margin related to the Mesozoic extension of the Indian plate. The resultant passive margin is expected to show geometrical elements of an extensional system such as shown in seismic lines by Ahmed & Ahmad (1991) and Kemal (1991). The aim of this paper is to provide an overview of the recent concepts related to the model geometries of an extensional system for regional structural analyses of the lower Indus Basin of Pakistan.

MODELS OF CONTINENTAL EXTENSION

The lower Indus Basin with northwest-southeast oriented extensional structures typifies a divergent plate boundary province, probably superimposed by strike-slip faults (Ahmed & Ali, 1991; Kemal et al., 1991). Divergent plate boundaries result in thinning of the crust along normal faults. Mechanism of extension is not yet fully understood. There are questions about geometry (planar/listric) and depth penetration of the normal faults (Figure 2). However, whatever may be the mechanism it would be influencing the shallow crustal structure of interest to the explorationist.

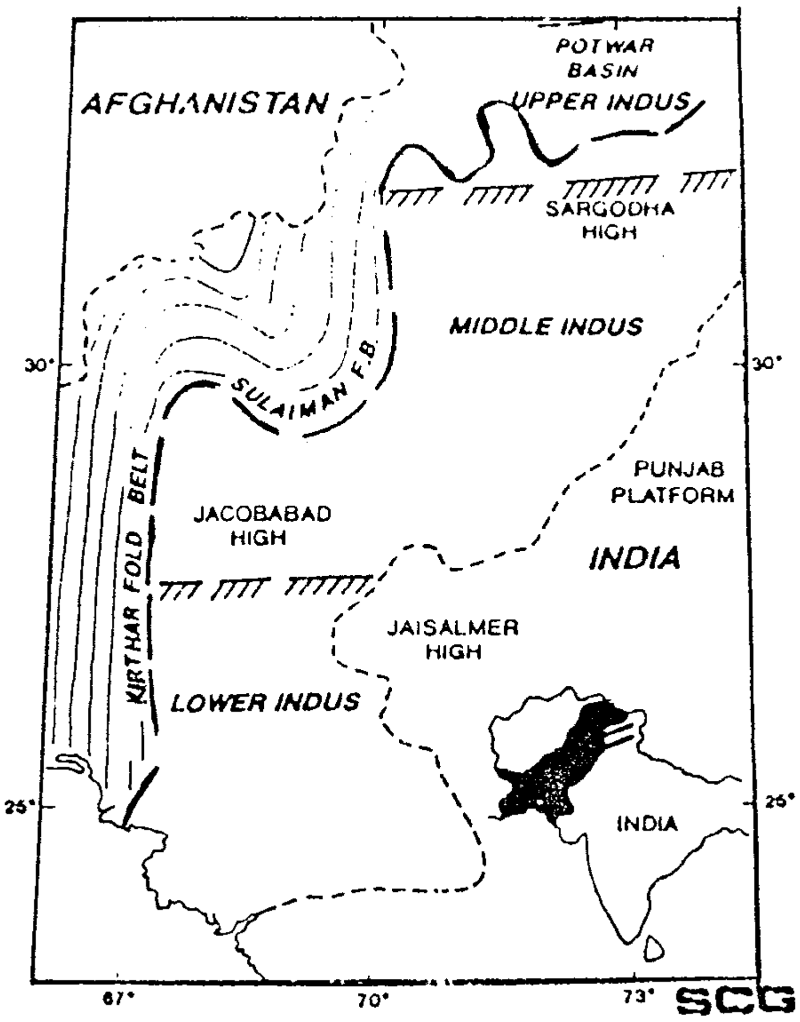

Figure 1- Simplified tectonic map of Pakistan to show the position of the lower Indus Basin (from Kemal, 1991).

Lister et al., (1986) provide an overview of the model geometries of continental extension. These models are recognized as Pure shear model, Werniche model, and Delamination model. Pure shear model suggests uniform extension of the lower crust and brittle deformation in the upper crust being separated from each other by a brittle-ductile transition (Figure 3). This model considers symmetrical structures on both sides of a divergent plate boundary. It may well explain the mechanics of extension in terms of rheological changes from brittle deformation to ductile deformation. However, it does not explain notable absence of symmetrical rift structures in reflection profiles (Bally, 1981, 1982), and identical structures in the opposing margins. Unlike Pure shear model, the simple shear model (Wernicke, 1985) suggests continental extension along a shallow dipping (10°-30°) fault, penetrating the crust and, probably the whole lithosphere. This is followed by the penetrative brittle deformation in the

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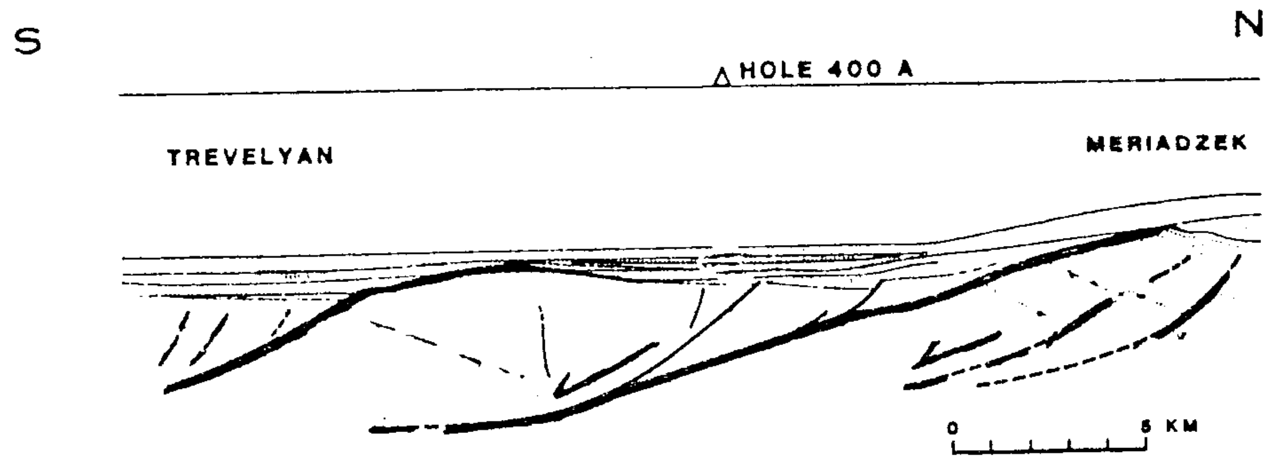

Figure 2- A depth section of northern Gulf of Biscay to show penetrated depth of listric normal faults (from Bally et al., 1981).

sedimentary basin, and its basement with the formation of a normal fault complex, having the internal geometry of a number of highly rotated faults and fault bounded blocks. Continued extension results in the isostatic rebound of the unloaded footwall such that the older rocks are exposed in the form of a metamorphic core complex, as in the Basin and Range structures found in the western USA. In the Basin and Range Province of western USA, large fault bounded blocks are found adjacent to the core complex. The simple shear model can account for the close juxtaposition of brittle and ductile deformation and for the temporal separation of the different types of deformation. This model predicts asymmetry in the opposing margins such that upper plate margin is relatively devoid of structures (Figure 3). It is supported by deep seismic reflection profiles that identify a deep fault extending to a depth of 20 km with a displacement of 30-60 km (Kearey & Vine, 1990). Thus, the model of Wernicke (1985) suggests the lower lithosphere stretching with brittle upper plate overlying ductily deformed igneous and metamorphic rocks. It may well explain sophisticated structures, for example outer rise, continental ribbon, and marginal plateau (Figure 4). The outer rise is produced by a bowed-up lower crust in response to isostatic compensation of the extended crust. The continental ribbons and marginal plateaus are produced by the presence of more than one detachment fault with different trends as shown in figure 4. The model of McKenzie (1978) thins the lower lithosphere homogeneously by ductile extension beneath an upper crust which is thinned by symmetrical faults. Coward (1986) proposed that the Pure shear and simple shear models may represent end members in a range of possible mechanisms. Regardless of the differences in the above models one common feature of the two models is the presence of low angle normal fault called detachment. The detachment separates brittle deformation in the upper plate from relatively undeformed lower plate. In this paper we are concerned with the geometry and morphology of the structures in the upper crust above a detachment surface to provide a framework for hydrocarbon exploration in the lower Indus Basin.

NORMAL FAULTS GEOMETRY AND MORPHOLOGY

Normal faults may occur as single or as sets of conjugate faults (Figure 5). A single fault may have a planar, curved (listric), and a staircase geometry (Figure 6). Listric faults are shovel shaped, steep at the surface and shallower dips at depth. A staircase trajectory follows a ramp and flat geometry. Ramp is a part where fault cuts the section at a steep angle whereas a flat generally remains parallel to bedding or basement.

Displacement along a planar, listric, or a staircase trajectory results in variable structures in an extensional setting. One model for extension along a set of planar faults to produce half grabens is called as domino model or bookshelf model (Figure 7). The model suggests rigid body rotation of each planar fault bounded block as a result of extension. A space problem arises in the triangle above and below each rotating block. This problem is overcome by sedimentary infill as growth strata above and by ductile flow of incompetent rocks intrusion in the lower triangle (Figure 7b). Growth faults develop during deposition, resulting in thicker stratigraphic units in the downthrown block. Clear example of bookshelf model from Pyrenees, France and Death Valley, USA are shown by Ramsay & Huber (1987) (Figure 8).

Displacement along a listric fault may produce a variety of structures (Figure 9). Listric and a staircase geometry may produce an anticline (rollover anticline) and synclines (hanging wall synclines) in the hanging wall (Figures 9a-b). Alternately, a set of secondary faults (antithetic) with dips opposite to the main fault (synthetic) are produced in the hanging wall as a resultant deformation (Figure 9c-d, 10). Secondary faults may develop parallel to synthetic fault to produce a horsetail or a listric fan (Figure 9e). In this structure an individual fault bounded block is called as a rider. A set of synthetic and antithetic listric fan is illustrated in figure 9f. In addition to the above structures, an extensional system is characterized by a series of horst and graben structures (Figure 11), similar to the Jacobabad/Khairpur and Kandkot/Mari horst and Panno Aqil graben in the lower Indus Basin (Ahmed & Ahmad, 1991). Figure 12 summarizes the architecture of a rifted margin in the upper crust. In this figure, sedimentary sequence deposited before, during, and after rifting are called as pre, syn, and post rift sediments respectively. The unconformities separating pre and syn-rift sediments and syn and post-rift sediments may be recognized as breakup and post-rift unconformities. Their recognition allows to constrain timing of rifting in an extended margin.

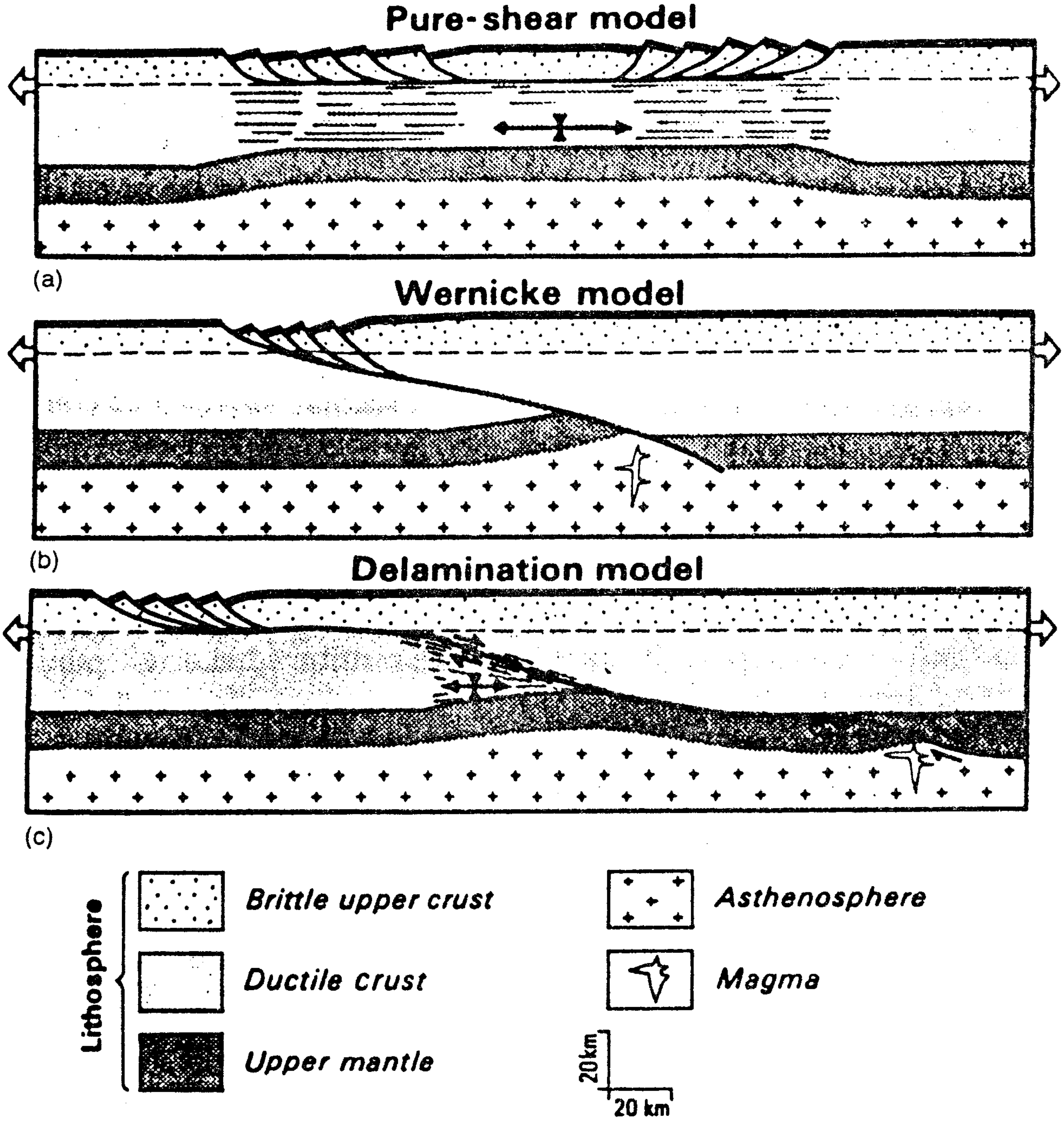

Figure 3- Three models of continental extension (from Lister et al., 1986).

SAND-BOX MODELING AND RESULTS

Experiments were undertaken independently to model the kinematics and mechanics of the extensional systems. Here we discuss three series of sand-box modeling by McClay & Ellis (1987) to investigate the effect in the upper crust.

Uniform Extension

Models of uniform extension compare the effect of homogeneous ductile extension of the lower crust above a horizontal basal detachment and a sloping surface (Figure 13).

Horizontal extension produced a set of horst and graben structures separated by a set of right-dipping extensional faults (Figure 13a). With increased extension new faults nucleate and propagate into the horst and grabens. Faults generally initiated as concave upward (listric) or planar faults and then

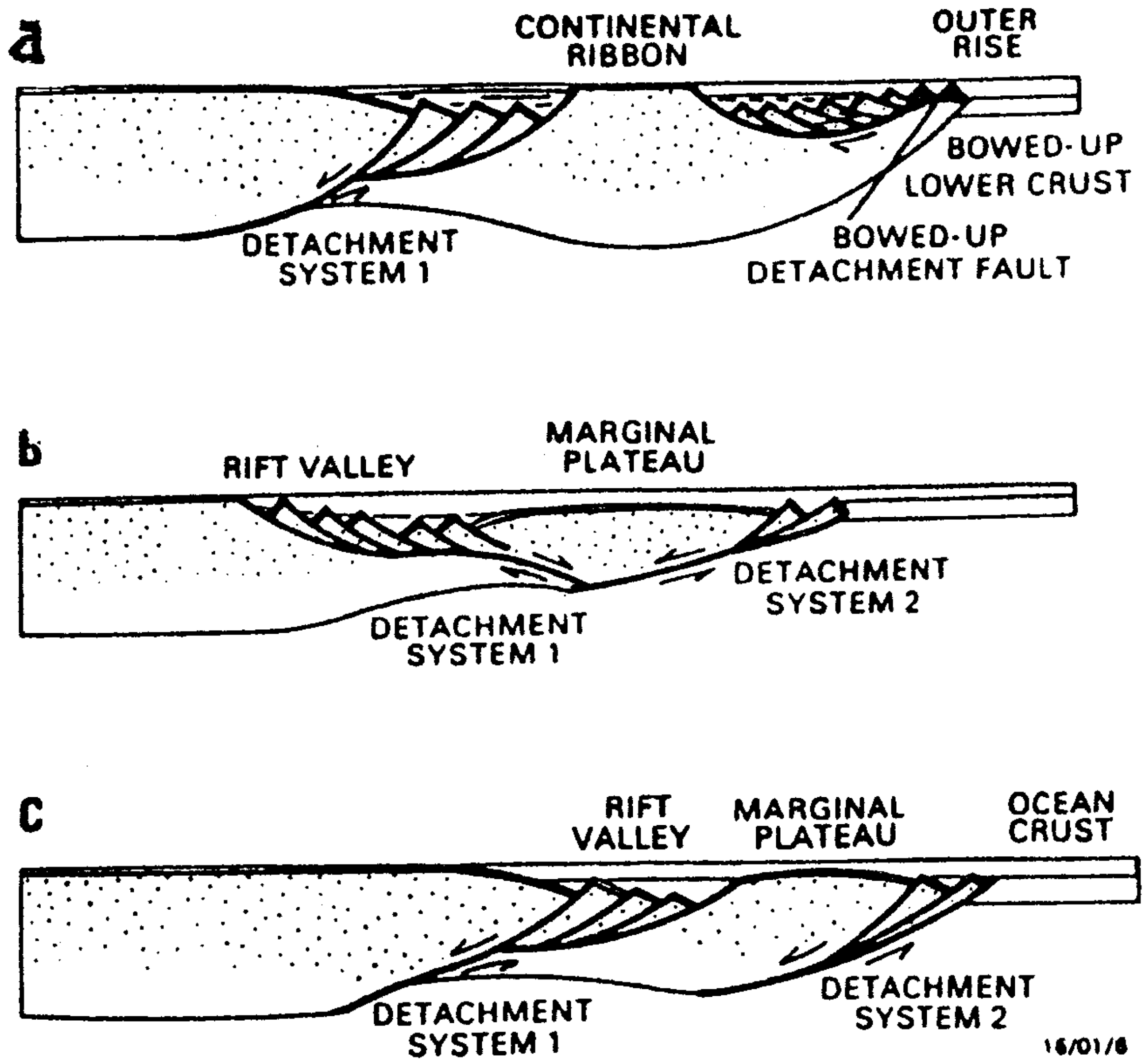

Figure 4- Paired detachment faults and associated isolated ribbon, marginal plateaus, and internal rift valley structure (from Lister et al., 1986).

evolved into convex upward geometry with greater extension and increased rotation (~35%).

Extension above a sloping basement produced a domino-style fault array with all the faults dipping in the dip direction of the detachment. The faults began as planar surfaces and remained predominantly planar with continued extension. However, increased degree of rotation resulted in decrease of dip angle of the planar set of faults down the sloping basement (Figure 13b).

Listric Fault System

Listric fault system produced a well developed rollover structure involving upto 50° rotation of the layering. The fault sequence began with a main set of conjugate faults (1 and 2 in Figure 13c) characterized by a planar set of faults on one margin and a slightly convex-upward fault geometry on the other margin of a crestal collapse graben. This slightly convex upward geometry is observed to be a result of heterogeneous rotation within the rollover anticline.

Listric Fault With a Ramp/Flat Geometry

Listric fault with a ramp/flat geometry produced a pair of crestal collapse graben and a hanging-wall syncline separated by an array of reverse faults (Figure 13d). The fault geometry shows that the graben is bounded by a set of planar faults on the non-rotated margin and convex upward extension faults on the rotated margin. All the reverse faults began above the crest of the detachment fault. The experiments demonstrate progressive evolution of an extension system controlled by the geometry of a detachment surface.

IMPLICATIONS ON THE STRUCTURE OF THE LOWER INDUS BASIN

Exploration for hydrocarbon in the lower Indus Basin, over the years, has produced extensive seismic and well data coverage. Cross-sections constrained with the subsurface data were made to generate prospects for drilling (Ahmed & Ahmad, 1991; Kemal, 1991). A representative depth and a seismic section are shown in figure 14 and 15 to show an array of predominantly normal faults below Paleocene post-rift unconformity. Yet there is much to learn about the architecture of the lower Indus Basin. An in-depth study involving the structural geometries/models is believed to be more helpful in the exploration of hydrocarbon in the region.

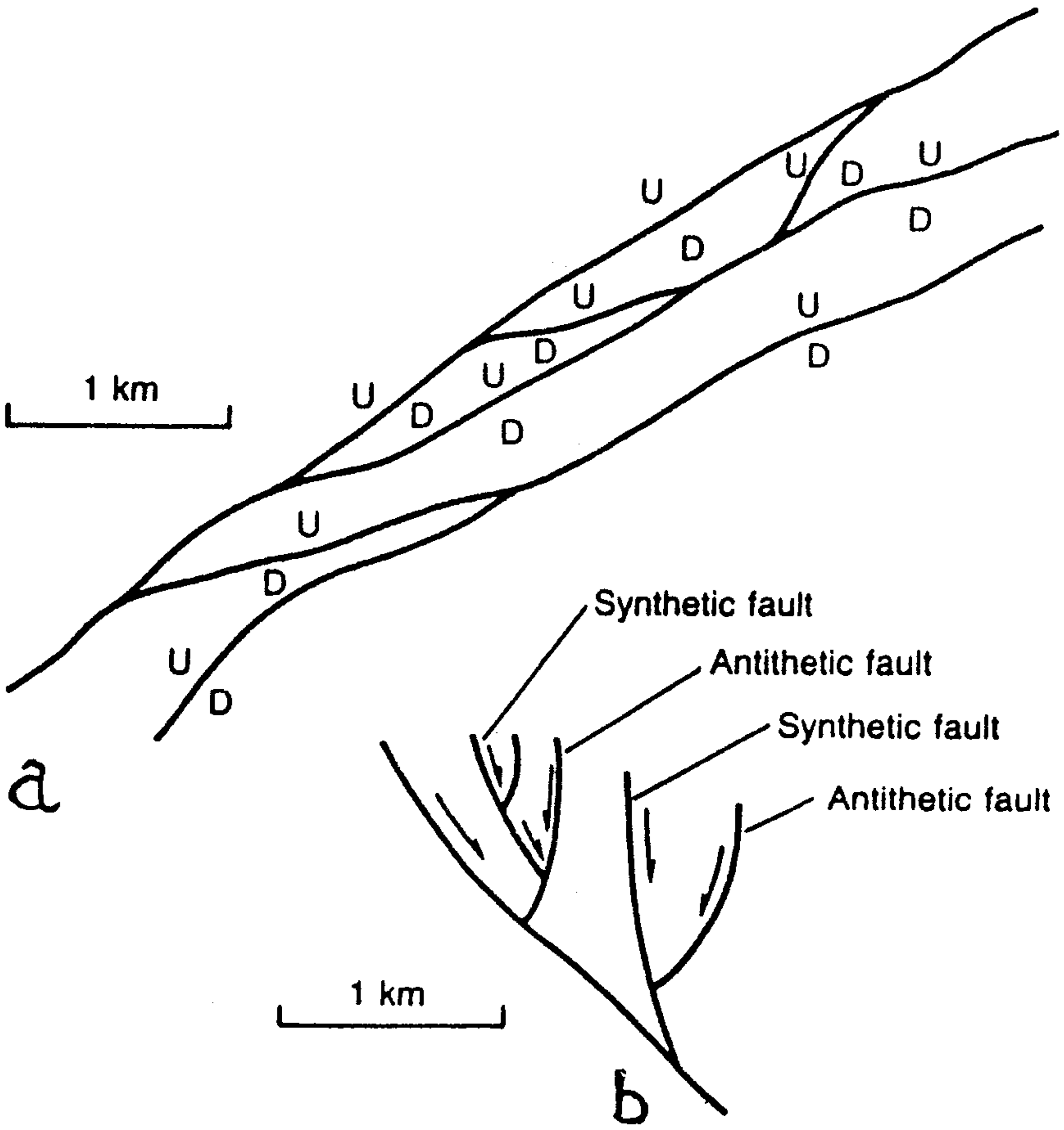

Figure 5- Map and sectional view of a conjugate set of normal faults.

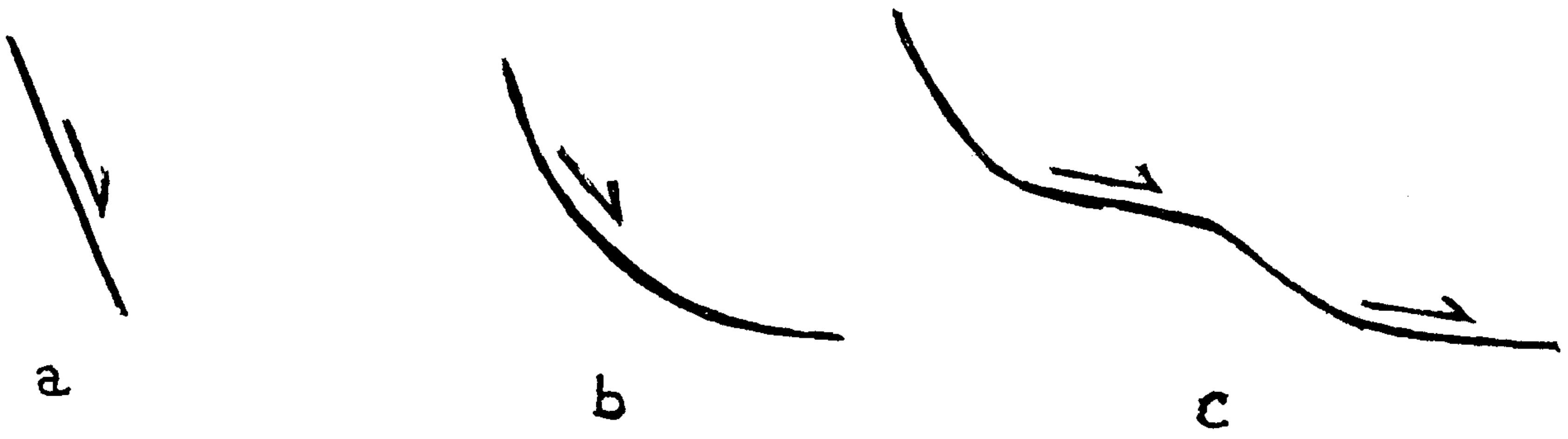

Figure 6- Normal fault geometries. a) Planar, b) Listric, c) Staircase or ramp/flat geometry.

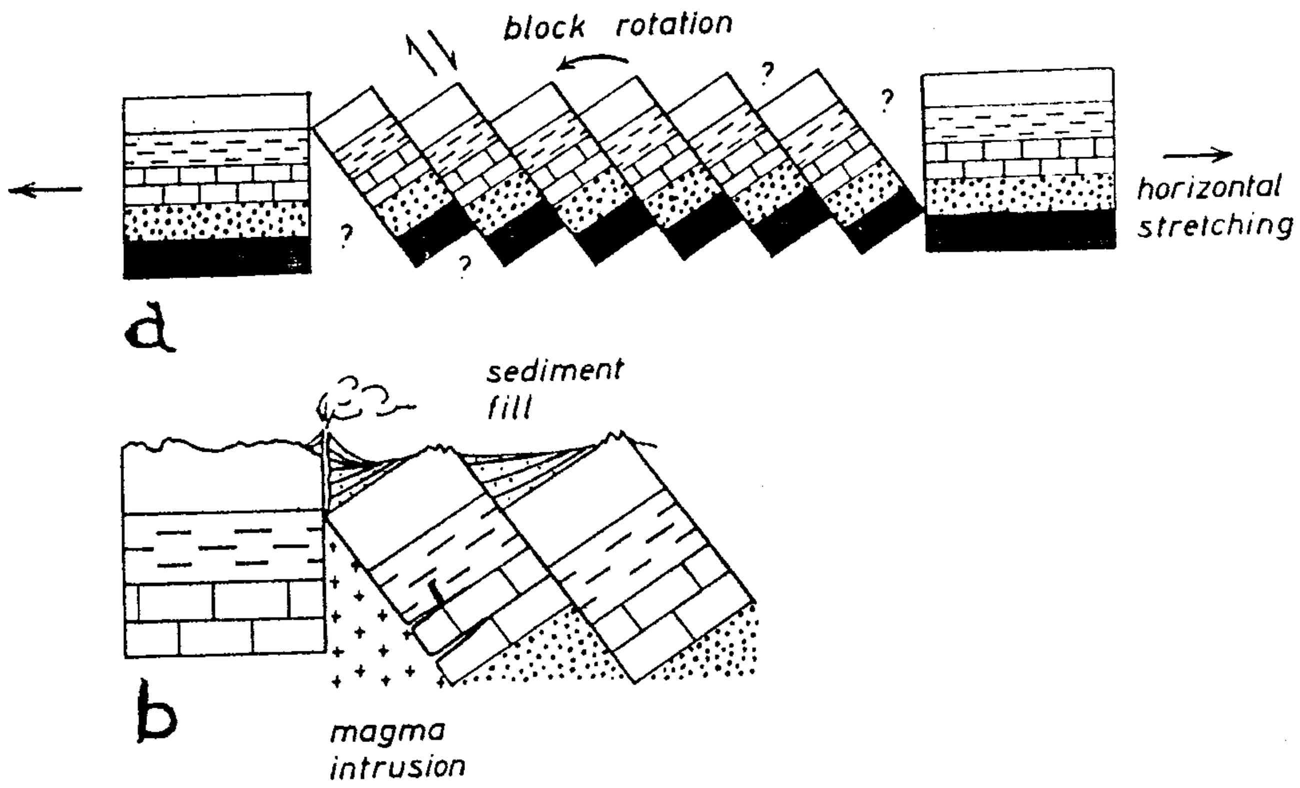

Figure 7- Bookshelf or domino model for planar normal faults and associated half grabens. The space problem in the upper and lower part of the rotated blocks in figure 7a is filled by growth strata/sedimentation and intrusion and/or ductile flow of substratum respectively in figure 7b (from Ramsay & Huber, 1987).

Figure 8- Physical example of planar fault bounded blocks according to the bookshelf model (from Ramsay & Huber, 1987).

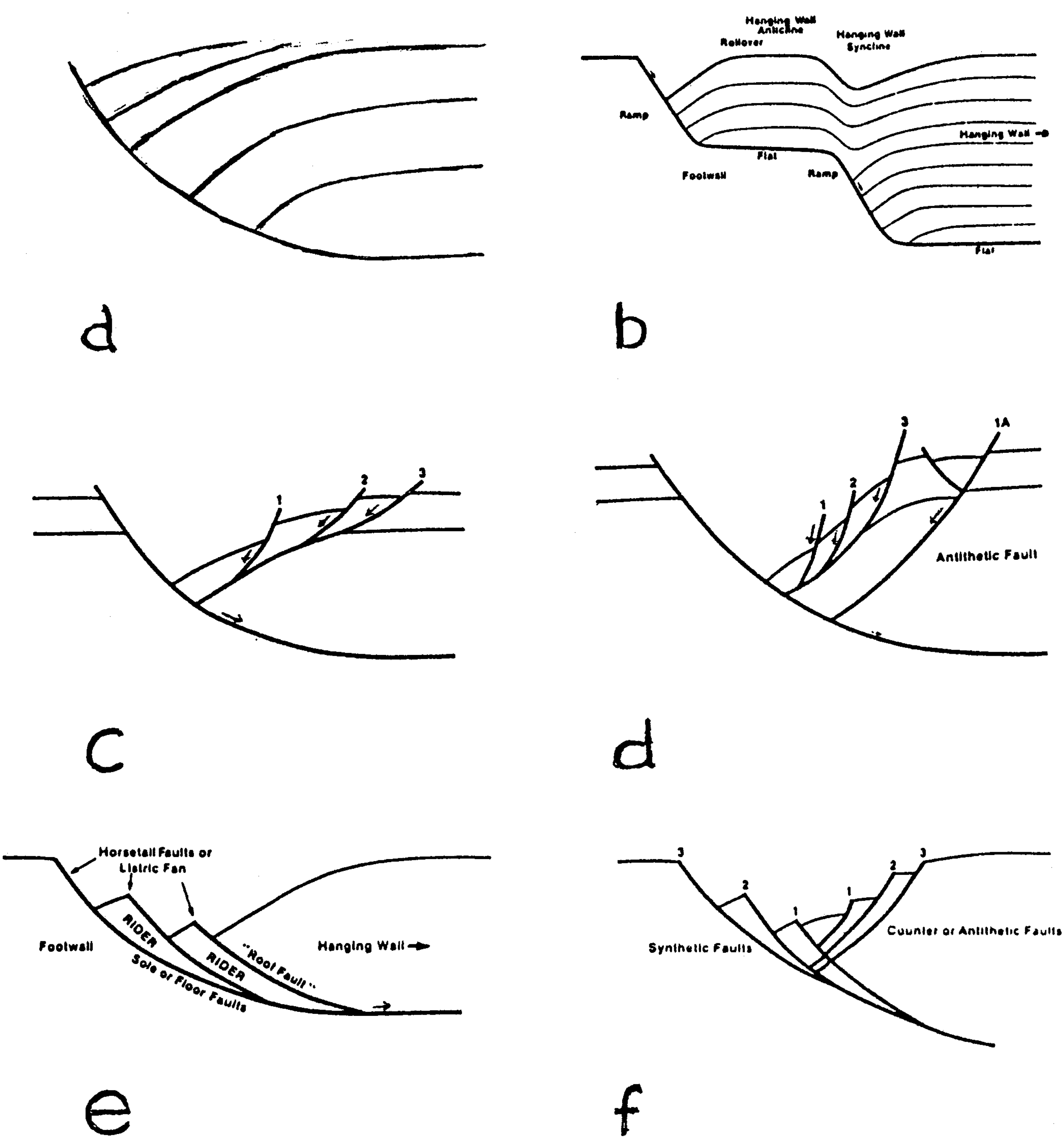

Figure 9- Normal fault geometry and morphology. a) Listric normal fault and a rollover anticline, b) Ramp/flat geometry with a hanging wall anticline and syncline, c) and d) Listric normal fault (synthetic) with a set of counter listric (antithetic) faults, e) Listric normal fault with a set of listric (synthetic) fan, and f) Listric normal fault with a set of synthetic and antithetic listric fan.

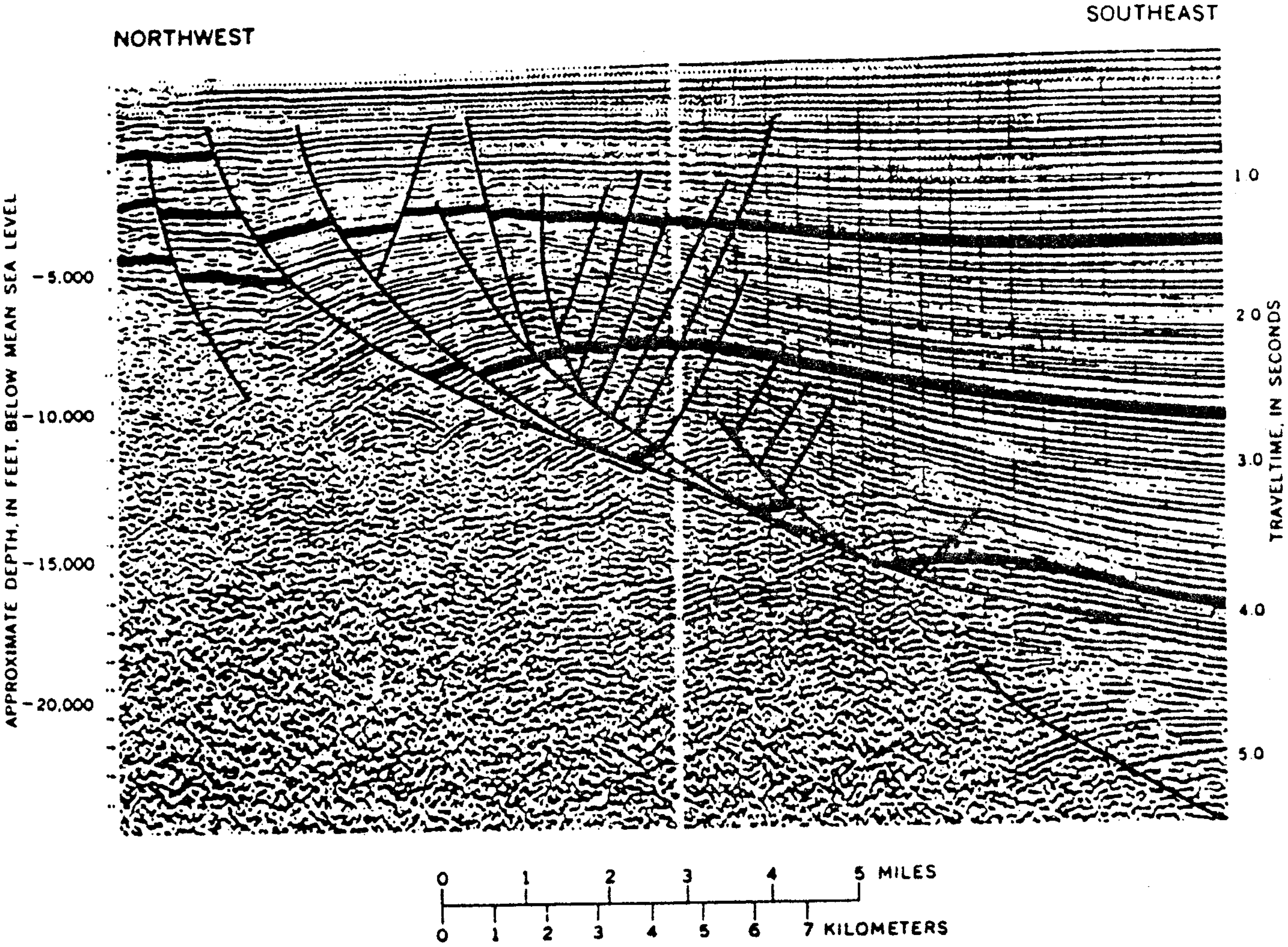

Figure 10- A seismic reflection profile with a synthetic and antithetic listric fans.

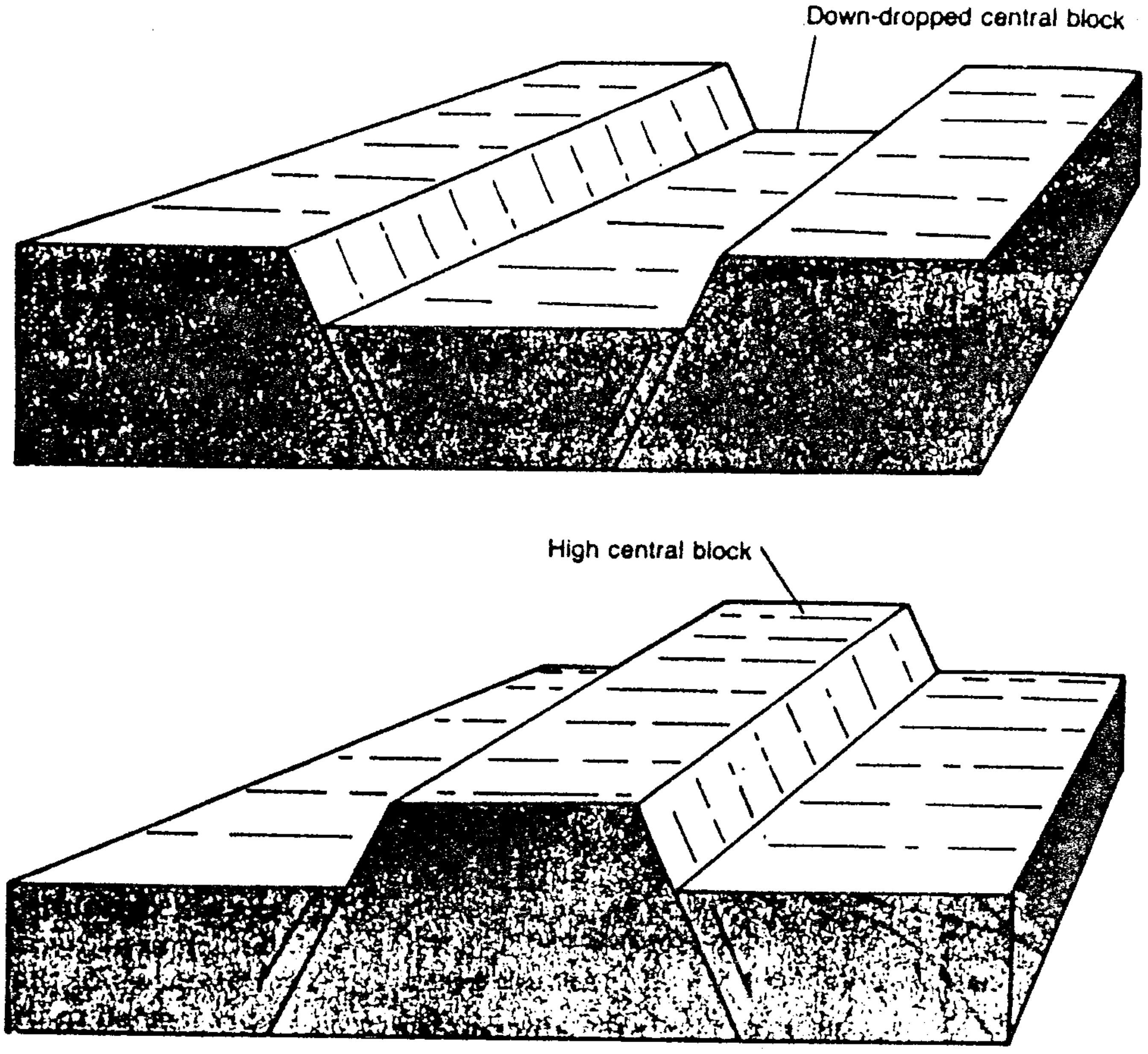

Figure 11- A 3-D diagram of a down dropped central block (graben) and an uplifted central block (horst).

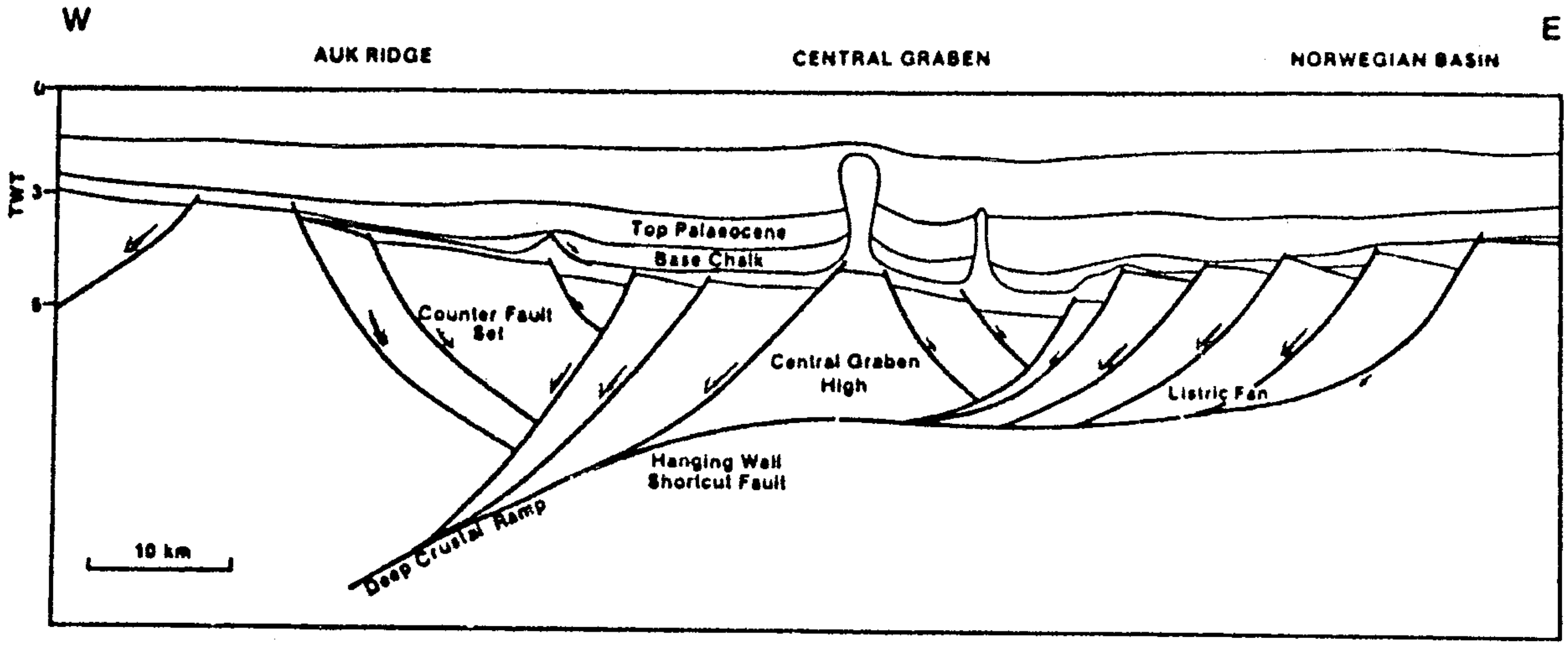

Figure 12- A composite cross-section to show the structures of an extended margin.

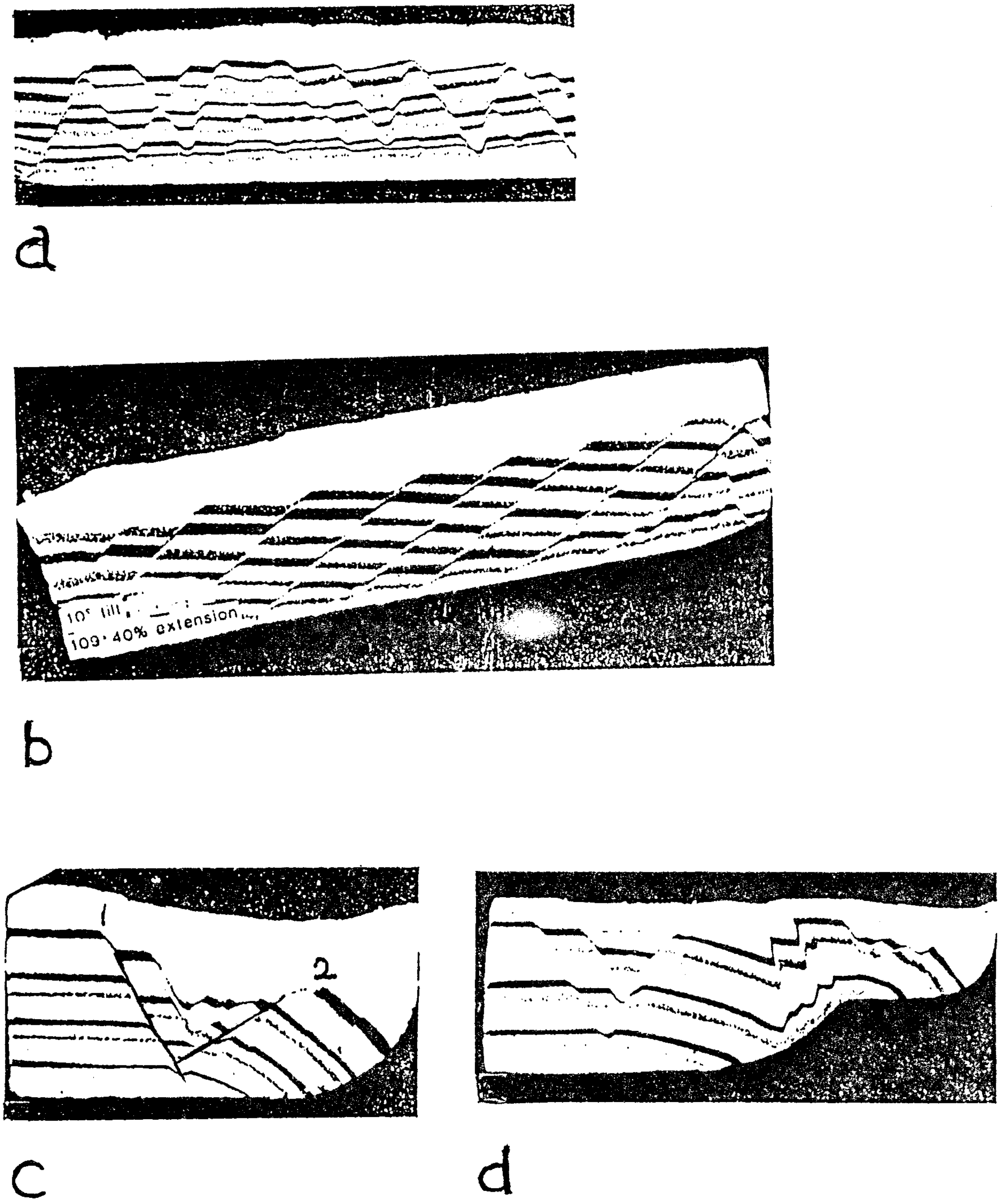

Figure 13- Sand Box models (from McClay & Ellis, 1987). a) Uniform extension with horizontal detachment, b) Uniform extension with dipping detachment, c) Listric extension fault geometry, and d) Ramp/flat listric extension fault geometry.

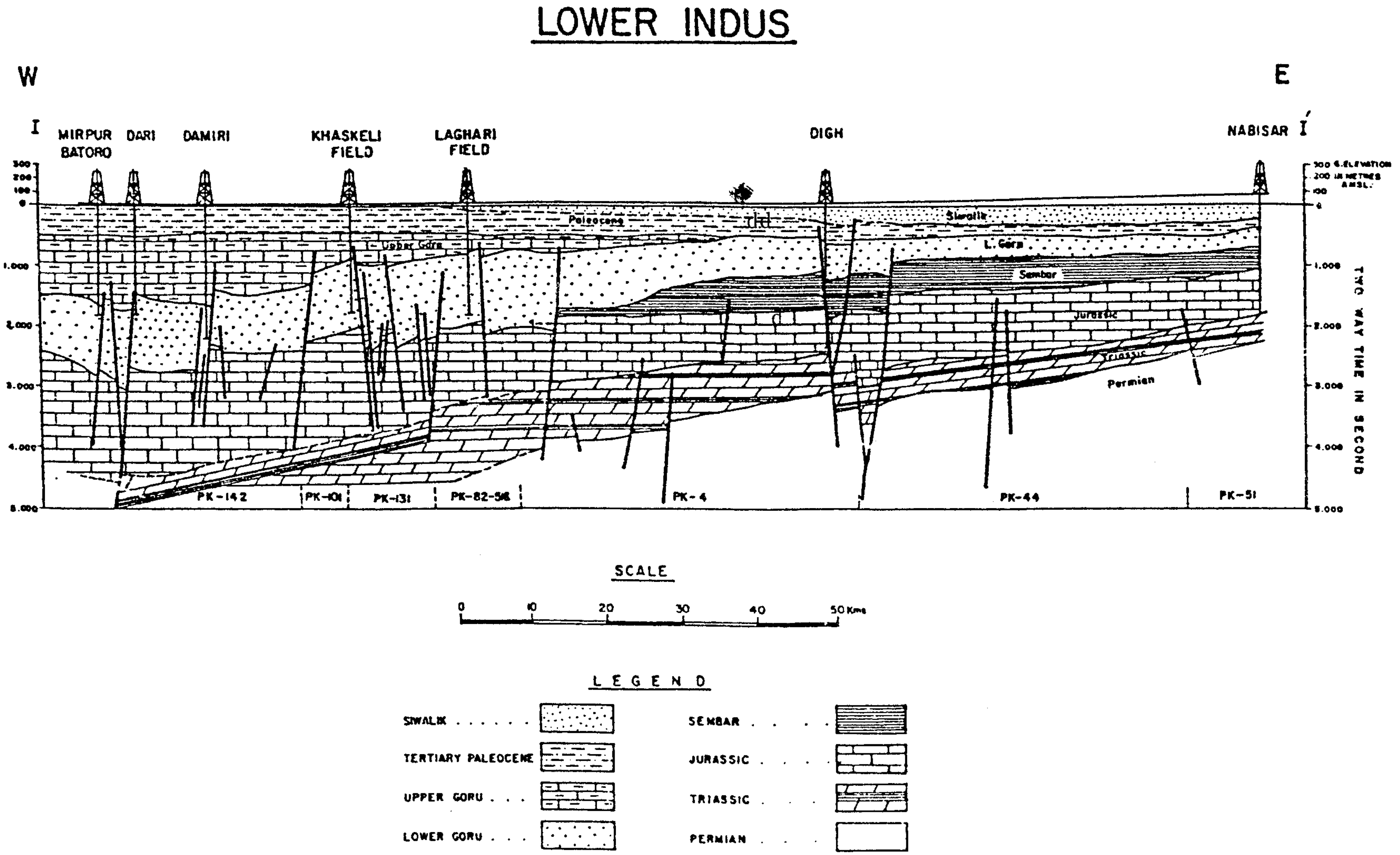

Figure 14- A depth section from lower Indus Basin with predominantly normal faults below Paleocene post-rift unconformity (from Kemal, 1991).

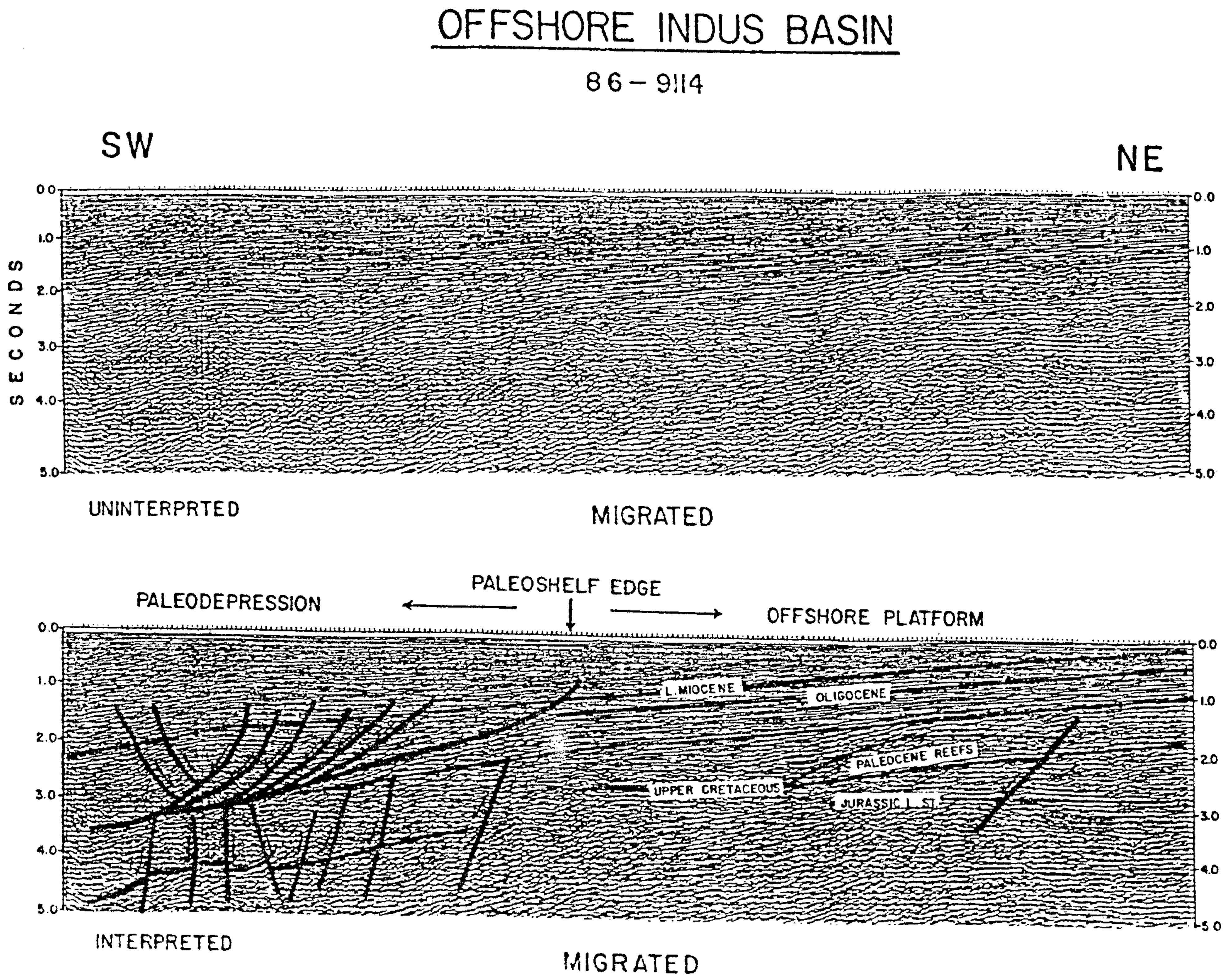

Figure 15- An uninterpreted and interpreted seismic reflection profile from lower Indus Basin (from Kemal, 1991).

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