General comments on listric normal faults with particular reference to growth faults and their role in hydrocarbon trapping

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General Comments on Listric Normal Faults with particular reference to Growth Faults and their role in Hydrocarbon Trapping[1]

with 8 figures

by P.E. GRETENER[2]

Abstract

Three habitats have been identified for listric normal faults:

1. The growth faults in the thick sedimentary wedges on continental margins.
2. The late normal faults in thrust belts such as the Flathead fault and the Rocky Mountain Trench in the Southern Canadian Rockies or the Hoback Normal Fault and the Grand Valley Fault of the Wyoming-Idaho-Utah thrust belt.
3. The normal faults of the intracontinental rift zones where differential tilting between adjacent basement blocks demands curved faults.

The point is made that a single growth-fault-scoop on uniform regional dip does not produce a hydrocarbon trap.

A comparison is made between thrust faults and listric normal faults (Table 1).

Zusammenfassung

Drei geologische Provinzen wurden identifiziert, in denen sogenannte listrische Normalverwerfungen auftreten:

1. Die synsedimentären «Growth Faults» in den mächtigen Sedimentkeilen an Kontinentalrändern.
2. Die späten Normalverwerfungen in Überschiebungsgürteln, wie die Flathead Verwerfung und der Rocky Mountain Trench im südlichen kanadischen Felsengebirge oder die Grand Valley Verwerfung im Wyoming-Idaho-Utah Überschiebungsgürtel.
3. Die saxonische oder germanische Tektonik, wo die gegenseitige Rotation der Krustenblöcke gekrümmte Verwerfungen verlangt.

Es wird gezeigt, dass im Gegensatz zur landläufigen Auffassung, eine einfache Growth Fault Sackung an einem Kontinentalrand keine Oelfalle produziert.

Überschiebungen und listrische Normalverwerfungen werden anhand einer Tabelle vergleichenderweise analysiert.

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1 Based on an address to the scientific session of the Swiss Assoc. of Petroleum Geologists and Engineers, June 15 1984 at Bad Bubendorf, Liestal, Switzerland

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1. General Remarks on Listric Faults

The term «listric» refers to surfaces that are concave upwards. Faults of this type are spoon or shovel shaped. Best konwn, and economically most important, are the growth faults of the continental margins where fault movement is normal. Thrust faults refracting upwards through the sedimentary sequence in a series of ramps and flats contain listric segments where they rise over a ramp. Both types of faults flatten at depth into a sole fault.

Thrust faults in general have a series of ramps and thus a number of listric segments. Listric normal faults in contrast seem to usually have only a single ramp and thus are purely listric.

In either case the sole fault restricts the depth of faulting and both are examples of what is commonly referred to as «thin-skinned» tectonics. Also in both types of faults the variable dip of the fault in the direction of transport leads to a deformation of the allochthonous sequence.

An early paper on the subject appeared in 1965. In the Grand Canyon aera HAMBLIN observed the actual flattening (elevation difference 1500+/5000+ m/ft) of a normal fault. He noticed the associated tilting or roll-over (DAHLSTROM, 1970, Fig. 56, p. 387) which he termed «reverse drag». He also recognized this as a necessary deformation in order to avoid producing an open, half-moon shaped crack, clearly an impossibility in view of our knowledge about rock strength. He further speculated that antithetic faults could be expected. His analysis is a sound piece of structural evaluation. Only the word «reverse drag» remains an unfortunate choice of terminology. The roll-over or dip-reversal on the down-thrown side of listric normal faults is simply dictated by the curvature of the fault and entirely unrelated to the concept of drag.

Recognition now dawns that listric normal faults are an important and universal structural element of the outer skin of the earth. While thrust faults have fascinated geologists for well over one hundred years, papers on listric normal faults have only emerged over the past twenty years. It is, however, comforting to note that the rate at which the topic is gaining attention is accelerating (HAMBLIN, 1965; PRUCHA et al., 1965; DAHLSTROM, 1970; BRUCE, 1973; GRETENER, 1977, 1979; CRANS et al., 1980; CRANS & MANDL, 1980/81; BALLY et al., 1981; MANDL & CRANS, 1981; WERNICKE & BURCHFIEL, 1982; JACKSON & MCKENZIE, 1983; GIBBS, 1983, 1984; ERSLEV & ROBBINS, 1984; JACKSON & GALLOWAY, 1984). At the same time it is deplorable that the coverage of those structures in recent textbooks generally can only be termed inadequate (DENNIS, 1972; HOBBS et al., 1976; SPENCER, 1977; PARK, 1983; SUPPE, 1985) with the notable exception of MATTAUER (1980).

2. Habitats of Listric Normal Faults

Normal faults form under conditions of extension. This is the common denominator of the faults described in this paper. The fact that these faults flatten at depth indicates the extension to be a shallow phenomenon. The term «shallow» may refer to a few metres in the case of landslides, or to tens of kilometres in the case of faults developing during intracontinental rifting.

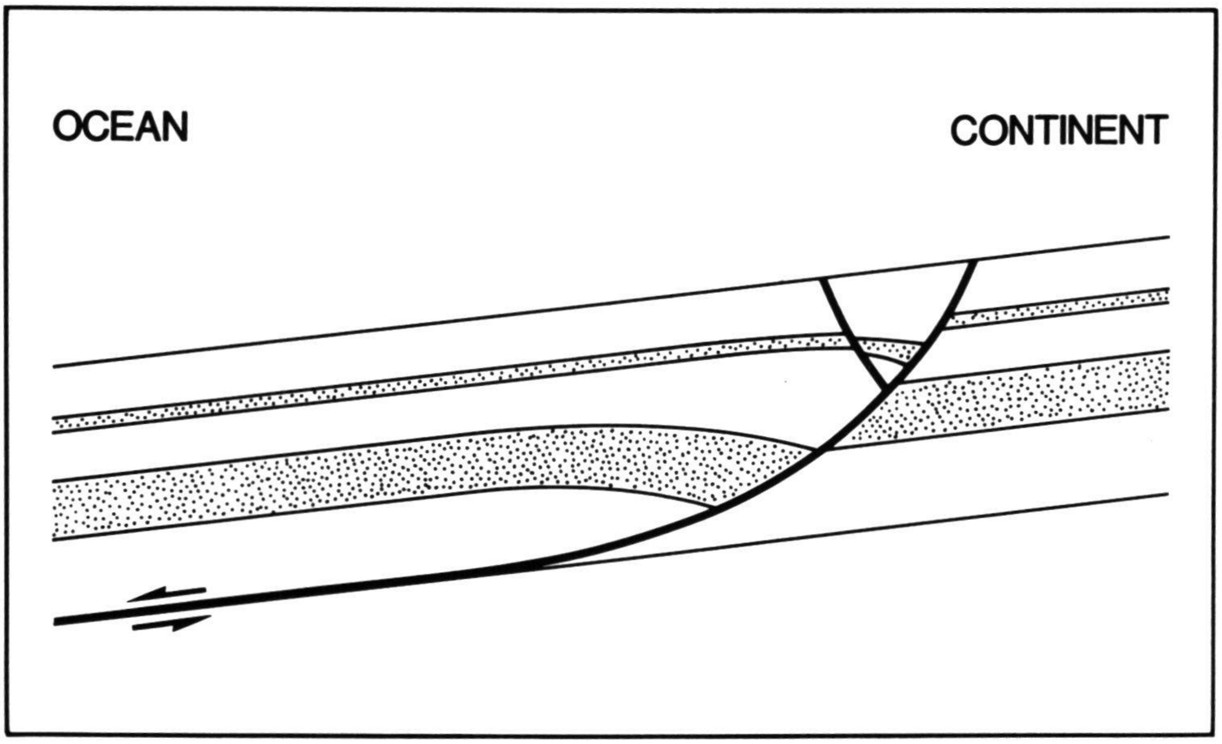

Figure 1: Schematic down-dip cross section of a growth fault showing antithetic faulting and thickening of equivalent units due to synorogenic sedimentation.

2a. The Growth Faults in Young Sediments of Continental Margins

Figure 1 shows the down-dip section of a typical growth fault. Faulting and sedimentation proceed simultaneously producing a distinct thickening of individual stratigraphic units on the down-thrown side, i.e. as the fault moves it creates a sediment trap. Continuous loading of the down-thrown side tends to perpetuate the fault movement.

Such faults have been reported from all continental margins where a strong sediment supply creates a thick sedimentary wedge. Reports include the Mississippi-, the Niger-, the Mackenzie-, and the Amazon-deltas. The reversal of dip or roll-over on the down-thrown side is directly related to the curvature of the fault and thus is an integral part of such structures.

2b. The Late Listric Faults of Thrust Belts

Classic cases of such faults have been reported from the Southern Canadian Rocky Mountains by BALLY et al. (1966) and from the Wyoming-Idaho-Utah thrust belt by ROYSE et al. (1975). In the Southern Canadian Rockies latest thrust movements are Paleocene in age while the normal fault in-fill wedge is of Oligocene age. In the Wyoming-Idaho-Utah belt latest thrust movements are dated as early Eocene while the in-fill wedges range in age from Eocene to Recent. The normal faults merge into previous thrust faults which have preserved their character as «planes of weakness». Extension is both «thin-skinned», and minor compared to the preceding thrust movement. Recognition of these late faults in a basically compressive regime calls for a subsequent and superficial stress reversal. Dating of the in-fill sediments attests to the swiftness of this process.

The negative structures (half grabens) created by this process are immediately filled with sediments. This continuous loading of the downward moving side tends to promote further movement and perpetuate the fault. One is thus tempted to classify these faults as growth faults in a broader sense. However, the accumulating sedimentary wedge is limited to the down-thrown side and is clearly younger than any strata on either side of the fault. The typical thickening of equivalent units across the fault is lacking and fault displacement, typically increasing with depth for real growth faults, is fixed for all strata predating the in-fill wedge. To use the term «growth faults» for these structures could easily lead to pointless, semantic arguments and it should be avoided. In addition, the well known contemporaneous diapirism of true growth fault provinces is absent and the sole fault, a pre-existing thrust fault, is a well defined, planar feature.

2c. The Listric Normal Faults of Continental Rift Zones

In places of intra-continental spreading a typical crustal block fault tectonics develops. The fact that adjacent crustal blocks show differential tilt is a clear indication that the separating normal faults are not straight, since a purely linear translation cannot produce a rotation (PRUCHA et al., 1965). These structures involve the basement and it follows that detachment planes must be located within or below the crust. Prime candidates are the intracrustal low velocity layers as well as the upper asthenosphere (GUTENBERG, 1955; MÜLLER & LANDISMAN, 1966; GRETENER, 1977, 1979).

3. Further Comments on Block Faulted Basement Terranes

Structural provinces of this type have a global distribution and occur wherever the crust is being extended. In earlier days this structural style was often referred to as Germano-type or Saxonic tectonics. Older sections as well as the general sections presented in textbooks show no differential tilting between adjacent basement blocks.

This ideal horst-and-graben tectonics preserves the original horizontality of marker beds and merely translates them in the vertical direction. The separating normal faults are straight and show a dip near the theoretical value of 60°. However, in reality most block faulted basement terranes exhibit differential tilt betweem blocks (MAXSON, 1961; WISE, 1963; BECK & LEHNER, 1974; ALBRIGHT et al., 1980; HALLER, 1982). Such conditions can only exist when faults are curved as shown by PRUCHA et al. (1965). Straight normal faults between basement blocks that are differentially tilted violate the concept of the balanced cross section (DAHLSTROM, 1969). DAHLSTROM (1969) applied the concept strictly to the realm of thrust faulting but this should in no way obscure its general validity. Geometric balancing is a must for any cross section. Fault displacements cannot vary at random and volumes must be preserved (GIBBS, 1983; ERSLEV & ROBBINS, 1984). WRIGHT & TROXEL (1973) in an early publication accepted the fact that tilted basement blocks demand curved fault blocks and show cross sections which are drawn accordingly.

Listric normal faults call for decollement planes. For faulted terranes involving the basement it thus becomes necessary to look for such detachment planes within and below the crust. GRETENER (1977, 1979) has suggested as strong possibilities the low velocity layers within the crust and below the lithosphere. Deep reflection work provides increasing evidence that die idea has merits by demonstrating the presence of intra- and sub-crustal detachment planes (BREWER & SMYTHE, 1983; ALLMENDINGER et al., 1983). The message is clear: MECHANICAL LAYERING DOES NOT STOP AT THE BASE OF THE SEDIMENTARY SEQUENCE.

The question remains why it has taken so long to discover the obvious. The answer may well be found in the way we present our data. Much of our erroneous understanding of listric normal faults in faulted basement terranes may result from our preference for vertically exaggerated cross sections. Vertical exaggeration, an occasionally necessary, but always bad practice, tends to emphasize the roll-over or tilt while straightening the curvature of the fault *(Figure 2)*. In such sections differential tilts are greatly enhanced while the blocks are separated by seemingly linear faults

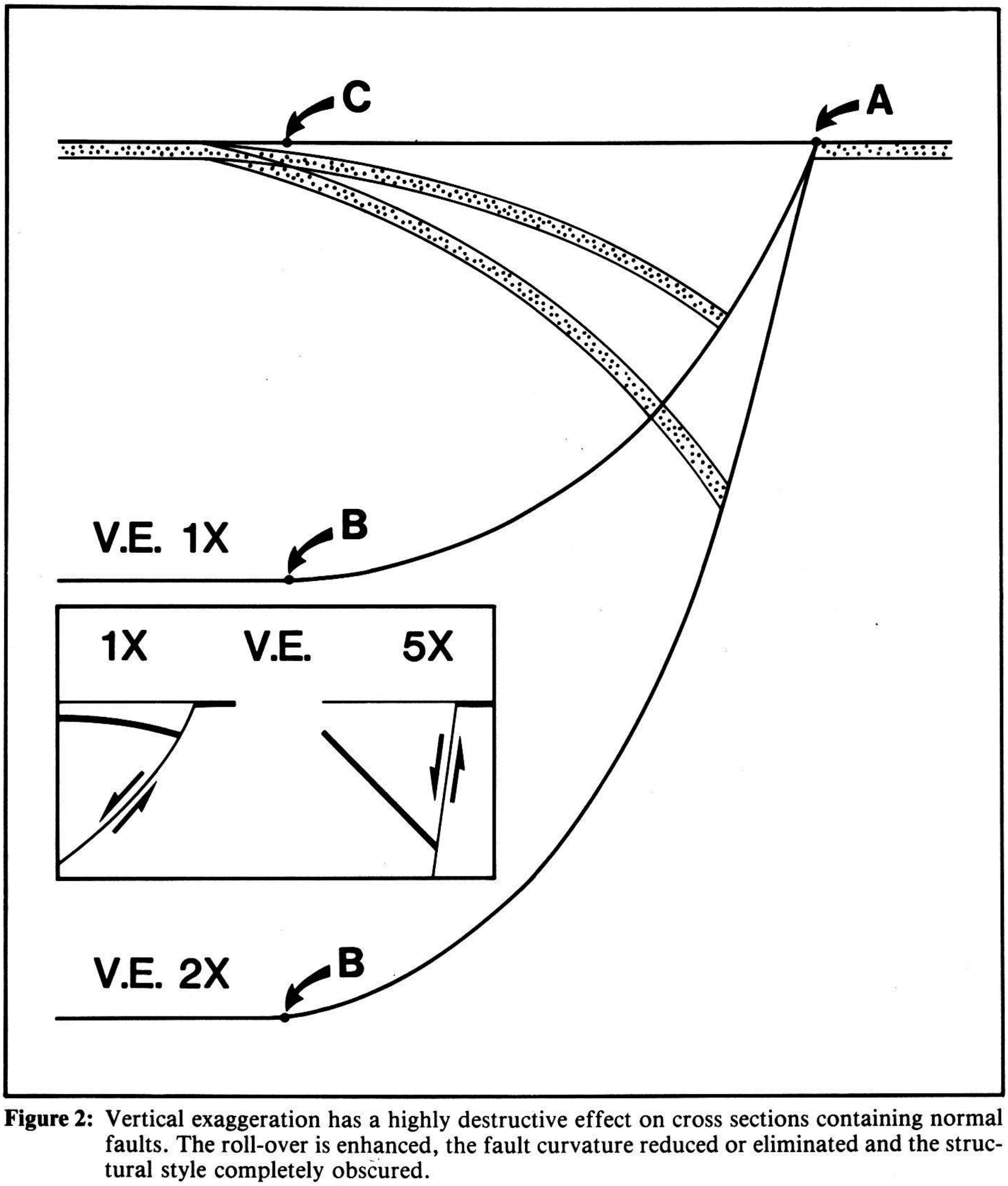

Figure 2: Vertical exaggeration has a highly destructive effect on cross sections containing normal faults. The roll-over is enhanced, the fault curvature reduced or eliminated and the structural style completely obscured.

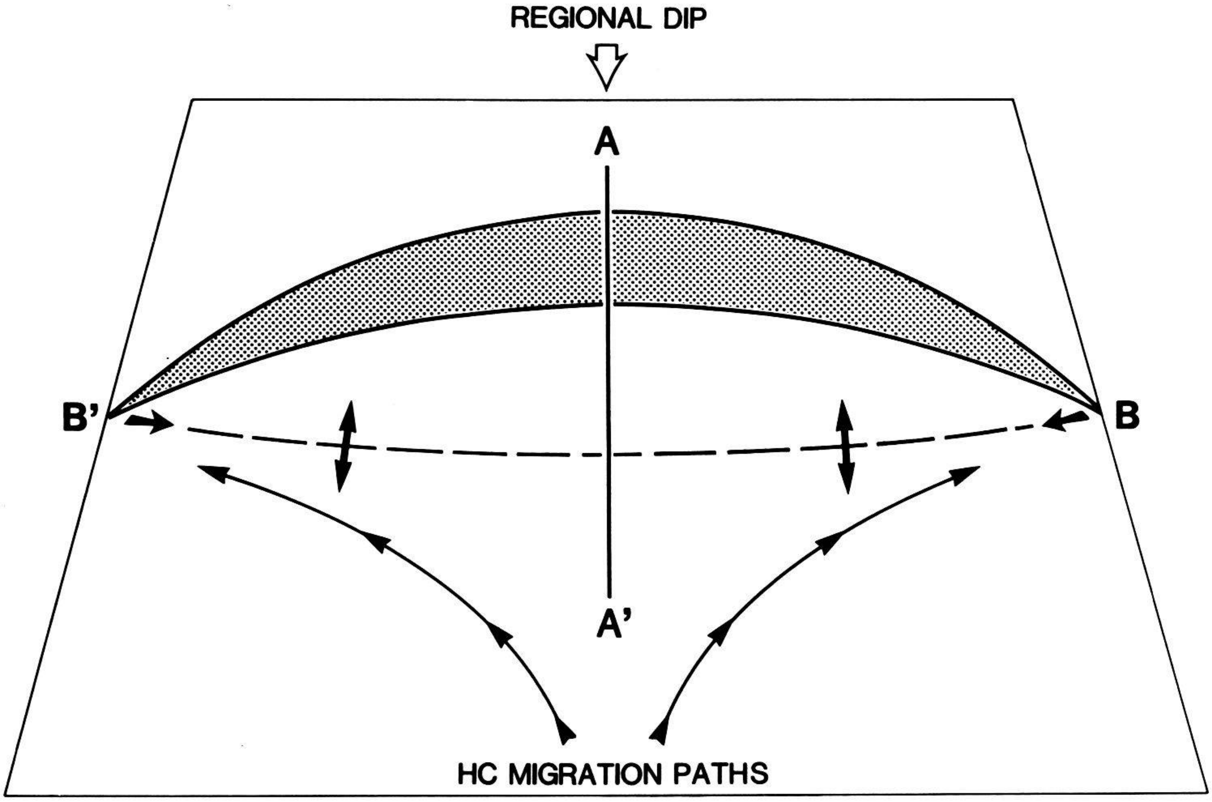

Figure 3: A simple growth-fault-scoop superimposed on regional dip in map view. Contrary to the thrust-fault-sliver the negative displacement on the growth fault produces an axial depression and not a culmination.

(ALBRIGHT et al., 1980, Fig. 5, p. 180). Thus it is the preferred presentation that promotes the misunderstanding of the structural style rather than the facts.

In passing we may note that listric normal faults are not the only victim of vertical exaggeration. Patch reefs become pinnacle reefs when grossly vertically exaggerated stratigraphic sections are used for structural purposes. How such a misnomer as «pinnacle reef» can survive in the face of all that «on location research» in the Bahamas is difficult to understand.

4. A Detailed Look at Growth Faults

Figure 1 shows the commonly published cross section of a growth fault. It seems to produce a hydrocarbon trap by the simple combination of regional dip and dip-reversal or roll-over caused by movement along the curved fault path. A recent paper by SHELTON (1984) contains a total of 32 figures, 29 of which are dip sections as shown in *Figure 1.* The paper does not include a single strike section. *Figure 3* presents a simple growth-fault-scoop in plan view and *Figures 4a and 4b* give the respective dip and strike sections. Obviously the movement on such a fault, which is negative rather than positive as is the case for thrust faults, produces a depression and as such not a hydrocarbon trap. The strike section on the crest of the roll-over is saddle shaped and up-dip migration of hydrocarbons will simply circumnavigate such a structure as indicated in Figure 3. In a nutshell: «a 3-D concept (closure)

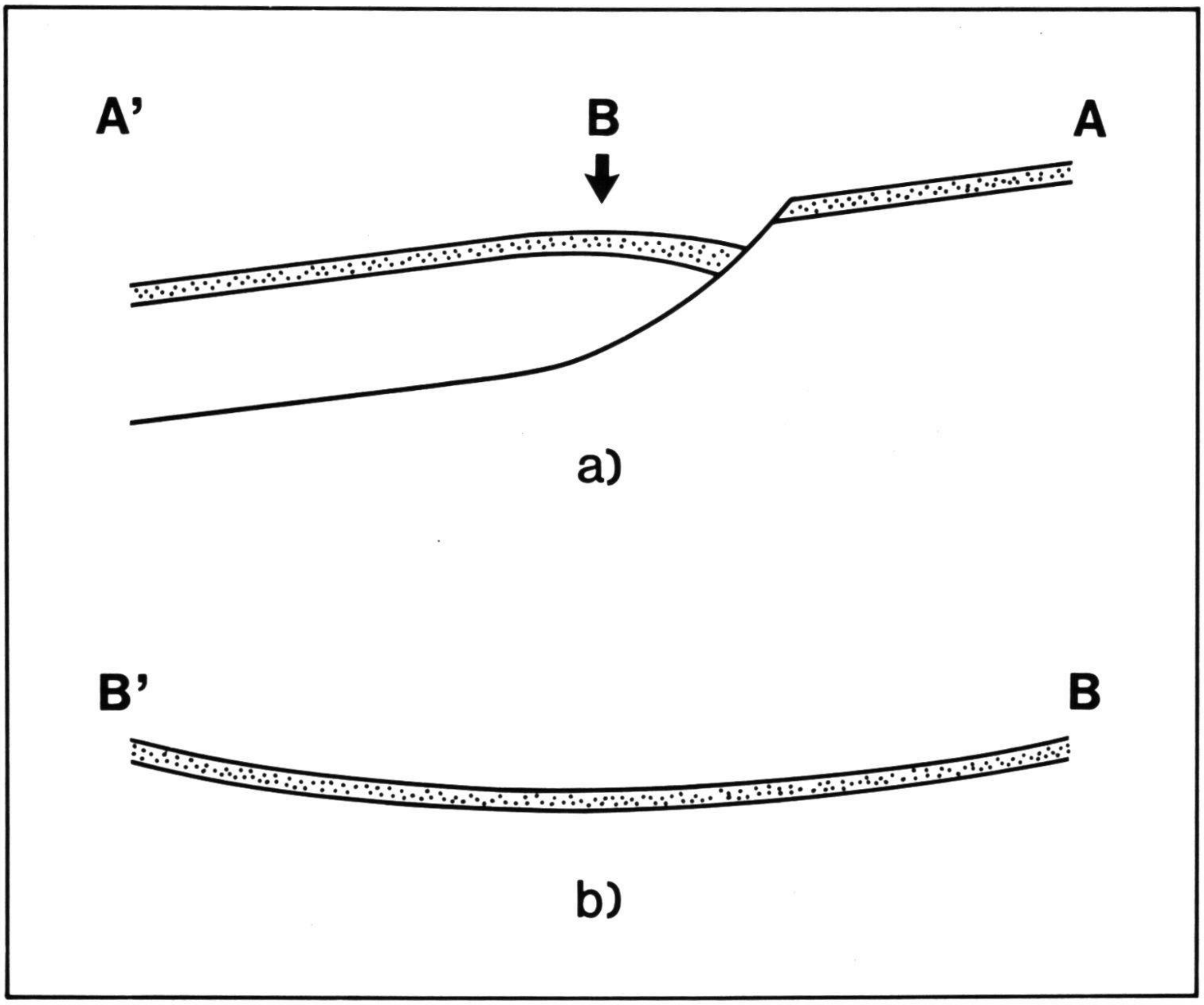

Figure 4: The down-dip (4a) and the strike (4b) cross sections for *Figure 3*. There is no closure in the strike direction and hydrocarbons will not be trapped as shown by their up-dip migration paths in *Figure 3*.

cannot be investigated by a 2-D technique» as pointed out by BILLINGSLEY (1983). Figure 6.4-9 in GRETENER (1979, p. 111) and Figure 2 in JACKSON & GALLOWAY (1984, p. 57) are wrong and stand to be corrected.

In this context it is interesting to note that the early papers of OCAMB (1961) and PERKINS (1961) fully confirm this view. Only where growth faults superimpose themselves on a pre-existing structure (such as a nose on regional dip) can they be a crucial element in the closure forming process.

Growth faults can be very extensive and reach lenghts in excess of 50 km (30 mi) as shown by WEBER &DAUKORU (1975) and EVAMY et al. (1978). Under such conditions differential movement along such a fault may be the sole cause for hydrocarbon traps. Axial depressions and culminations will alternate as shown in *Figure 5*. In contrast to thrust faulted terranes, axial culminations will correspond to places of minimum fault displacement.

In reality the trap forming mechanism in most cases is quite different and not related to growth faulting. The growth faults of the continental margins usually have as a decollement horizon a thick zone of either salt or overpressured shale. These materials are prone to flowage. Both have low density, high mobility, and occur in thick

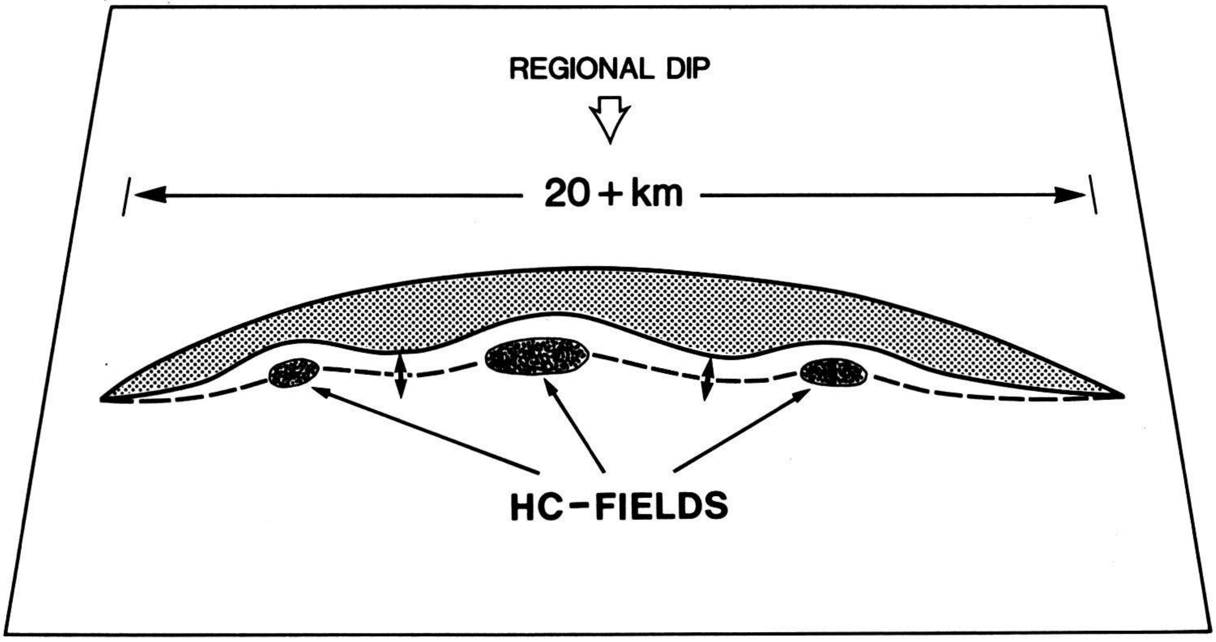

Figure 5: A giant regional growth fault superimposed on regional dip. Variable fault displacement may be sufficient to produce closed structures. In contrast to thrust faulting, axial culminations occur at locations of minimum fault displacement.

layers, all the necessary requirements for diapirism. Thus the primary structure producing process is one of diapirism with the associated growth faults acting as a modifying element. This has already been shown quite clearly by BRUCE (1973) in his classic paper on the subject. Unfortunately it has been forgotten by many subsequent writers. A glance at structure contour maps of fields in such areas demonstrates the point beyond a shadow of a doubt. As examples one may check the: Baronia field, East Malaysia (SCHERER, 1980); Membe field, Nigeria (NELSON, 1980); Bomu and Okan fields, Nigeria (FRAENKL & CORDRY, 1967); Eugene Island Block 330 field, Louisiana (HOLLAND et al., 1980); Hibernia field, East-Coast Canada (ARTHUR et al., 1982); Ninian field, North Sea (ALBRIGHT et al., 1980).

For listric normal faults to be balanced the curvature of the roll-over and the fault plane must match. A very sharp roll-over is incompatible with a normal fault flattening at great depth (DAHLSTROM, 1970, Fig. 56, p. 387; GRETENER, 1979, Fig. 6.4-8, p. 110). *Figure 6* illustrates the point in a schematic manner. In the gliding section only the area ABC experiences deformation. To the left of the line BC movement is restricted to bedding parallel translation (gliding block). Stretching is maximal for the line AC and dimishing to zero as point B on the sole fault is approached. Once the total displacement (TD) exceeds the ramp lenght (RL) no further deformation occurs. The definite relationship between fault curvature, roll-over and total displacemente permits the reconstruction of the fault plane from the roll-over (which is most often better defined on seismic sections) as shown by GIBBS (1983). For the case of growth faults the process is complicated by synorogenic sedimentation keeping fault displacement at the surface near zero.

Antithetic faults seem to be a common feature of growth faults (Figure 1). They are completely compatible with the above observation that deformation increases in the area ABC with distance from the sole fault plane. In order for any high angle antithetic fault to be balanced it is mandatory that its displacement be zero at the junction with the main fault. Such faults must show increasing displacement away

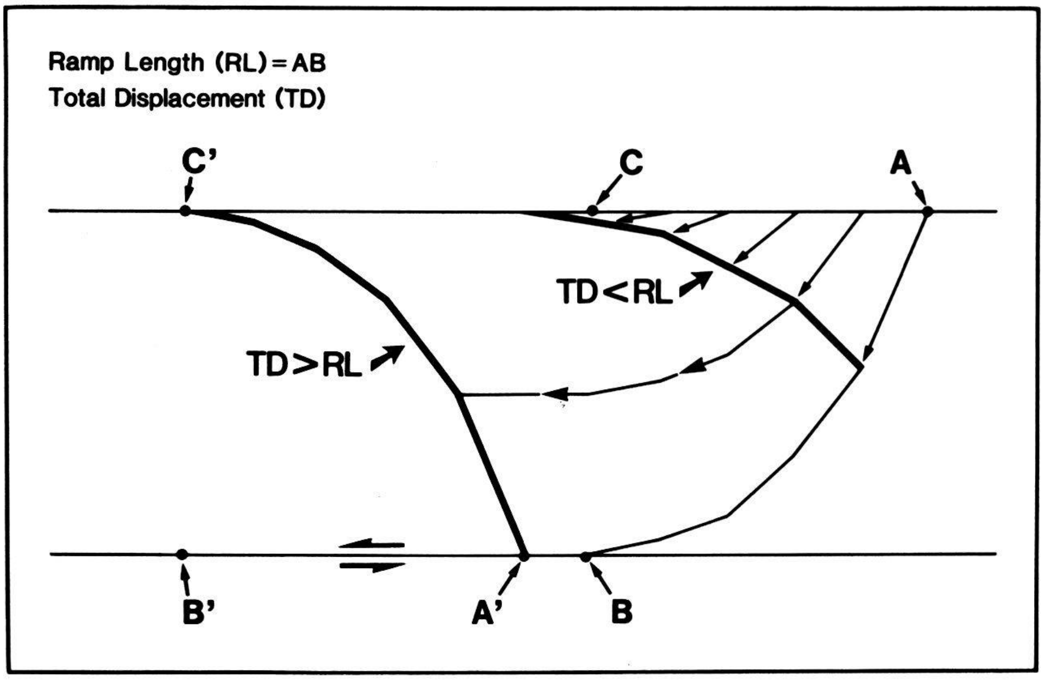

Figure 6: Deformation for the allochthonous sequence above a listric normal fault is restricted to the area ABC. For a total displacement (TD) exceeding the ramp lenght (RL) no further deformation occurs since behind line BC only layer parallel gliding occurs. Roll-over and fault curvature are related and line A'C' is the displaced mirror image of line AB. Curvatures are approximated by straight line segments and no allowance is made for contemporaneous sedimentation.

from the main fault which in turn demands increasing extension in that direction *(Figure 7)*. Antithetic faults are thus the perfect mechanism by which to alleviate the extension experienced by area ABC.

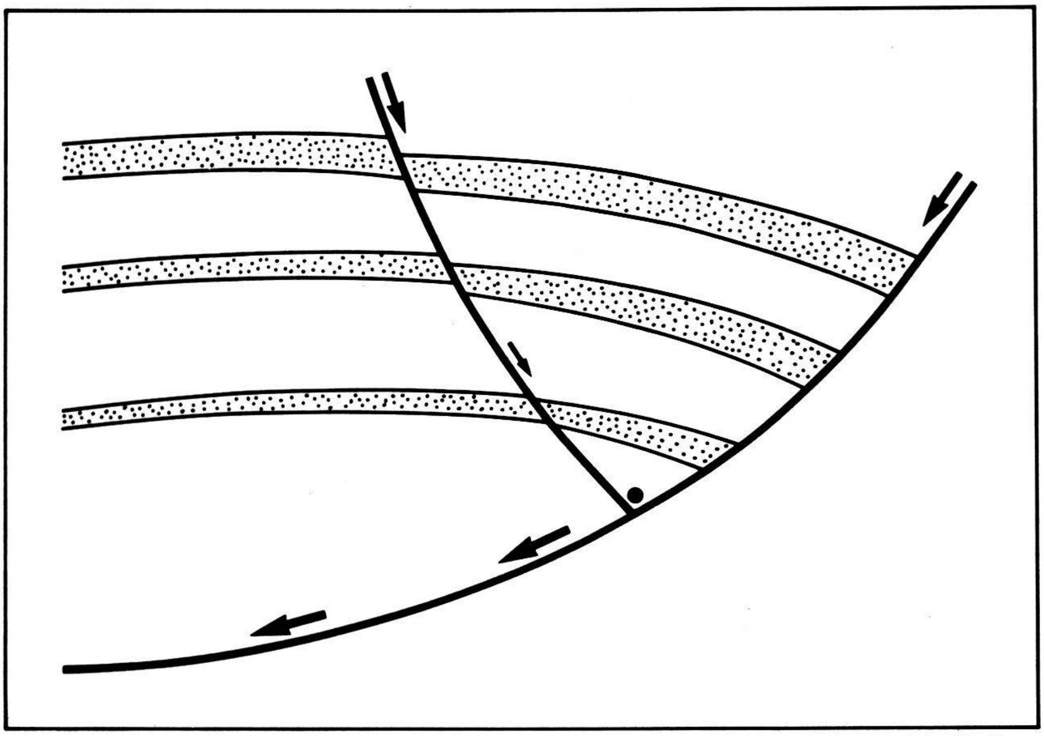

Figure 7: Extension is maximum at the surface (line AC in *Figure 6*). Antithetic faults, with displacement that is zero at the main fault and increases with distance from the sole fault, are the ideal mechanism to alleviate the variable extension experienced by the area ABC of *Figure 6.*

5. Comparing Listric Normal Faults and Thrust Faults

A comparison between listric normal faults seems to be in order since these two types of faults share a number of common features. Such a task is most effectively accomplished with the help of a table *(Table 1).* Besides some similarities, of which the most important is the thin-skinned nature, many discrepancies are apparent.

Economically the most glaring discrepancy is the fact that an individual thrust-sliver with its positive displacement will produce a viable hydrocarbon trap in the form of a «half turtle shell» (HALL, 1969) whereas a single growth-fault-scoop will not result in a closed structure.

Published information indicates that listric normal faults generally have only a single ramp that gradually merges into the detachment plane. While little or no evidence exists at this time for listric normal faults with multiple ramps it is nonetheless interesting to speculate about the associated structures. General configurations are given by DAHLSTROM (1970) and GIBBS (1984). *Figures 8a and 8b* show the effect of multiple ramps. As in the case of thrust faults, it is important to distinguish between a total displacement (TD) that is larger than the ramps spacing (RS) and one that is smaller (GRETENER, 1972). Since the total displacement on listric normal faults is minor when compared to that of large thrust plates, the case of *Figure 8a,* producing «odd» structures, seems more realistic. Whether structures of this type will be mapped in the future remains to be seen. The existence of multiple weak layers both within the sediments and the crust leads us to anticipate such structures.

It should be noted that concept of the balanced cross section as advanced by DAHLSTROM (1969) is applicable to any type of structure. While the concept has seen intense application in the realm of thrust faulting, this has not been the case for listric normal faulting. Until very recently listric normal faulting received in fact little attention in the literature. The proof of this sad state of affairs can be found in modern textbooks which still provide little space for the discussion of listric normal faults. The treatment provided is often either vague, contradictory, outright erroneous, or at the very least inadequate.

At first it seems strange that a structural realm which economically is far more important than the thrust belt tectonics should suffer such neglect. However, the reason is immediately apparent when one considers that thrust faults are well exposed in mountain belts and provide spectacular fieldtrips whereas the evidence for listric normal faults is almost exclusively geophysical. In that sense it is ironical that one of the early, classic papers on the subject (HAMBLIN, 1965) is based on field observations. However, the great hole, the Grand Canyon, has always been an exceptional area providing immense vertical relief in a region of non-compressional tectonics.

6. Summary and Conclusions

Listric normal faults occur in three different tectonic habitats, all of which are characterized by «surficial» extension:

Tab. 1 COMPARISON BETWEEN THRUST FAULTS AND LISTRIC NORMAL FAULTS

THRUST FAULTS	LISTRIC NORMAL FAULTS
a) Similarities	
a case of thin-skinned tectonics (sole fault)	do
basic cause: mechanical heterogeneity of a layered sequence	do
variable dip of fault plane produces deformation in transported rock package	do
b) Discrepancies	
tectonic regime: compressional	tectonic regime: extensional
multiple ramps	single ramp
multiple listric segments	single listric scoop
for TD_{max}: get axial culmination	for TD_{max}: get axial depression
synorogenic erosion	synorogenic deposition
detachment plane: well defined / commonly thin / shale and/or evaporite	detachment plane: thick layer of overpressured shale or salt / alternately old thrustplane
primary structures	1. successory structures: a) growth faults related to contemporaneous diapirism; b) late listric normal faults post-dating thrust faults. 2. primary structures: c) intracontinental rifting.
theoretical ramp dip: $\sim 30°$	theoretical ramp dip: $\sim 60°$
ramp-flat transition: abrupt	ramp-flat transition: gradual
resulting structure: positive	resulting structure: negative
minor structures: secondary thrusts, folds	minor structures: antithetic normal faults
single sliver with central maximum total displacement produces HC trap with closure	single scoop with central maximum total displacement does NOT produce HC trap (no closure in strike direction)
axis of fold developed over ramp remains fixed with depth	axis of fold developed over ramp migrates down dip with depth

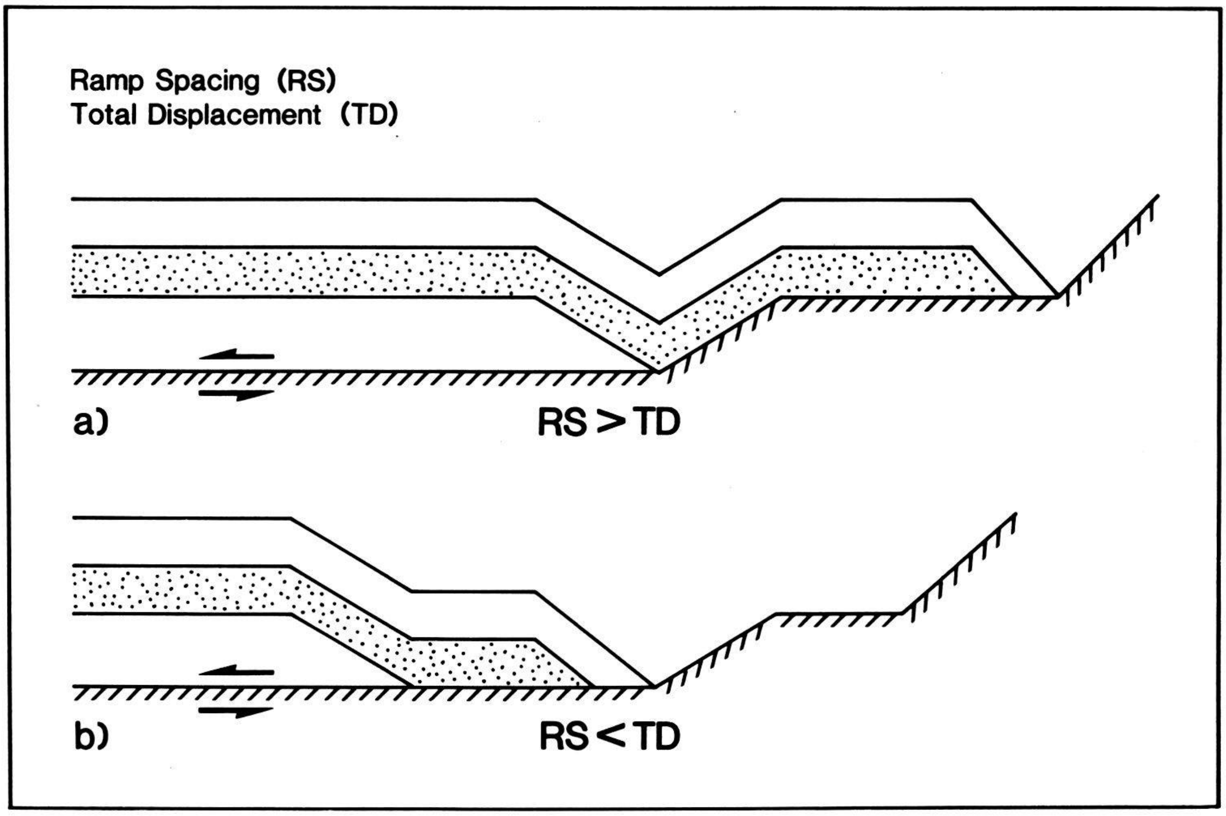

Figure 8: Schematic cross sections of structures formed above a listric fault containing multiple ramps. The resulting deformation is a function of the ramp spacing (RS) and the total displacement (TD).

1. The growth faults of the continental margins. Originally described from the U.S. Gulf Coast but now recognized as a common feature of all such continental edges. Stretching is confined to the near surface and caused by continued subsidence producing a seaward dip conducive to down slope sliding. Invariably the detachment surface is a thick layer of salt and/or overpressured shale. Since these materials tend to form diapirs the structures are mixed with much, and essential parts, of the deformation attributable to diapirism. A simple growth-fault-scoop superimposed on a uniform regional dip does not produce a hydrocarbon trap.

2. The late normal faults of thrust belts. The observations in the Southern Canadian Rocky Mountains and in the Wyoming-Idaho-Utah thrust belt tend to show that a late phase of surficial, and in comparison to the preceding thrusting minor, stretching is an integral part of such structural provinces. Detachment planes are old thrust planes. This constitutes confirmation of the concept of the plane of weakness, the thurst faults being reactivated at a later date with an opposite sense of movement.

3. Rifting at intracontinental plate margins (Germano type tectonics). These faults involve part or all of the crust. Candidates for decollement planes are the intracrustal low velocity layers as well as the top of the asthenosphere. The relative

tilting of adjacent basement blocks demands non-linear faults. Many cross sections published for such areas will have to be redrawn in order to conform to the concept of balancing.

Listric normal faulted terranes share with thrust belts the nature of thin-skinned tectonics. A sole fault is the essential feature of both compressional and extensional tectonics. In view of our acceptance of plate tectonics, one wonders whether in the final analysis not all tectonics is thin-skinned, making the term obsolete.

Acknowledgments

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