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Listric normal faults
Rifting
Subsidence
Stretching

Failles normales listriques
Distension
Subsidence
Étirement

Listric normal faults

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ABSTRACT

The importance of listric normal faults in the formation of sedimentary basins is becoming increasingly more obvious. Based on reflection seismic sections and surface observations, the following genetic types may be differentiated :

— listric normal faults involving the basement that are associated with some crustal attenuation. Such faults occur during the formation of rifts that often precede the formation of passive continental margins (e.g., Gulf of Biscay, Galicia Bank) ;

— superficial soft-sediment listric normal faulting related to deltaic systems and/or to drifting sequences associated with the subsidence of passive continental margins (e.g., Gulf of Mexico) ;

— listric normal faulting associated with the genesis of accretionary wedges of active continental margins (e.g., Colombia) ;

— syn- and post-orogenic faulting associated with the stretching and shearing of orogenic systems and parts of their foreland (e.g., Great Basin).

The role of normal faulting in the evolution of "geosynclines" and folded belts (e.g., the Alps) is better understood in the light of observations on continental margins and late orogenic basins.

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RÉSUMÉ

Les failles normales listriques

L'importance des failles normales listriques dans la formation des bassins sédimentaires est de plus en plus reconnue. A partir des coupes de réflection sismique et des observations de terrain, il est possible de distinguer les types génétiques suivants ;

— les failles normales listriques affectant le substratum associées avec un certain amincissement de la croûte. De telles failles apparaissent lors de la formation des rifts, qui précède souvent celle des marges continentales passives (ex. : Golfe de Gascogne, Bancs de Galice) ;

— les failles normales listriques dans les sédiments mous des systèmes deltaïques et/ou des séquences mobiles associées à la subsidence des marges continentales passives (ex. : Golfe de Mexico) ;

— les failles normales listriques associées à la genèse des prismes d'accrétion des marges continentales actives (ex. : Colombie) ;

— les failles syn- et post-orogéniques associées à l'étirement et au cisaillement des systèmes orogéniques et d'une partie de leur avant-pays (ex. : Great Basin).

Grâce aux observations sur les marges continentales et les bassins post-orogéniques, il est possible de mieux comprendre le rôle des failles normales listriques dans l'évolution des « géosynclinaux » et des chaînes plissées (ex. : les Alpes).

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INTRODUCTION

Eduard Suess, in his "Face of the Earth" (1904-1924, Vol. IV, p. 536, 542 and 582), introduced the concept of listric faults. He described upward concave curved fault surfaces from the coal districts of Northern France, Belgium and Germany, and noted that in a cross-section such faults appear shovel-like (Greek listron, shovel). For many years the term was adopted by German geologists working in coal mining districts, but otherwise gained little acceptance outside Central Europe. Note that Suess was specifically dealing with listric thrust faults, some of which were in fact refolded by later deformation. However, listric normal faults have also been illustrated — although not so named — from the coal districts of Central France (Pruvost, 1960-1963), as well as from Northern France (Bouroz, Stievenard, 1958). Cloos (1936) also preferred to limit his illustrations of the term to thrust faults, although in his clay experiments he showed listric normal fault systems with considerable detail. Kirchmayer and Mohr (1963) gave a detailed review of the terminology of curvilinear and curviplanar structural elements and listed a number of examples of listric faults from coal-bearing sequences, from non-coal-bearing rocks and rock deformation from experiments. These authors also suggested that surface geologic studies do not easily reveal the listric nature of faults, because outcrop conditions often prevent adequate geometric control of fault planes. A number of recent publications, however, illustrate listric normal growth faults from outcrops [e.g., from Spitzbergen, Edwards (1976) ; from Ireland, Rider (1978) ; Crans *et al.* (1980) ; and from Wales, Woodland and Evans (1964)]. See, also, Figure 1 from the Pennine Alps and Figure 2 from Haiti.

Quite independently from all the previously mentioned work, petroleum geologists of the Gulf Coast of the USA during the late 1930's recognized growth faults, that is, faults that display stratigraphic thickening on their downthrown side and have increased throw with depth. Typically, such faults flatten with depth and, therefore, are listric normal growth faults (Ocamb, 1961 ; Bruce, 1973 ; Busch, 1975). Experimental work by H. Cloos (1936) did illustrate listric normal faults in connection with the simulation of graben-like structures, and E. Cloos (1968) made similar experiments to illustrate listric growth faults of the Gulf Coast type.

A number of potential fault surfaces suggested by the theoretical studies of Hubbert (1951) and Hafner (1951) are in fact curved or listric surfaces. A theory of growth faulting in a deltaic environment is offered by Crans *et al.* (1980). Thus, it is surprising to find that most textbooks in structural geology pay little or no attention to the curved nature and the downward flattening tendency of fault surfaces. In recent years, the more widespread use and publication of reflection seismic lines suggests to us that a dominant percentage of all faults are listric or that they were at least initiated as listric faults.

Figure 1

Triassic marbles from Kaltwasser Pass, east of Simplon Pass, Italian-Swiss Alps. Note that dolomitic blocks have been rotated in domino-like fashion, with essentially planar faults separating them. The ductility contrast is such that listric faults are not formed ; instead, the more ductile calcareous material serves as cushion and fills the space between the rotated dolomitic blocks by ductile flow. Extension may be expressed as a function of the dip of the rotated beds.

The seismic documentation of listric thrust faults is rather well known from décollement-controlled fold belts (e.g., Bally *et al.*, 1966 ; Beck, Lehner, 1974 ; 1975 ; Gordy *et al.*, 1975 ; Royse *et al.*, 1975 ; Hamilton, 1977 ; 1979) and is, therefore, not the subject of this paper.

Instead, in this essay we will try to highlight the nature of the evidence favoring listric normal faulting in widely differing settings. This is useful in the context of a discussion of passive continental margins, because the documentation of the listric geometry of normal faults is critical to an understanding of the formation of still intact passive margins, as well as of older passive margins that can now be observed as deformed remnants in ancient folded belts. As McKenzie (1978), Royden *et al.* (1980), Christie and Sclater (1980), and Le Pichon and Sibuet (1980 manuscript) have all pointed out, lithospheric stretching may well be responsible for the initiation of passive margins, and at least the stretching in the brittle crust may be accomplished by listric normal faulting.

Much like listric thrust faults, the shape and complexity of listric normal faults is controlled by ductility contrasts within the rock sequence that is intersected by them. In this context, it is important to differentiate synsedimentary soft

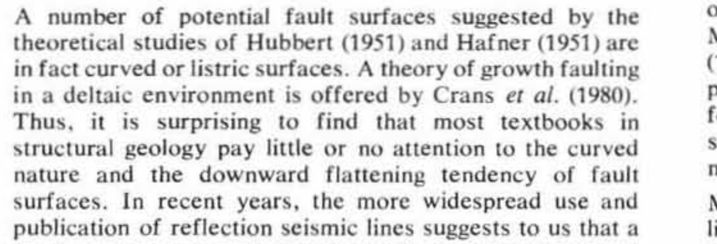


Figure 2

Listric normal faults in calcareous soft sediments from Haiti (late Miocene, NN 11, Jaemel road).

sediment listric normal faulting and other listric faults in consolidated rocks that rise to the surface from listric normal fault structures that involve the underlying basement. Only in the latter case may attenuation of the crust be suggested.

The term listric fault is purely descriptive. We like to differentiate listric thrust faults from listric normal faults, and among them we separate listric growth faults from those that do not show any measurable growth through time. Finally, we note that many faults have been refolded, and thus it may be useful to determine whether the listric nature of a fault is primary, or due to secondary refolding.

LISTRIC NORMAL FAULTS INVOLVING THE BASEMENT OF PASSIVE MARGINS

Passive margins typically display a lower section of rifted structures that often — but by no means always — is separated by a "breakup" unconformity (Falvey, 1974) from overlying less disturbed sequences that subsided during spreading and cooling of the adjacent ocean. These latter, "drifting" sequences are often characterized by soft-sediment gravity type tectonics that do not involve the underlying basement. Let us first discuss basement faulting associated with the rifting phase.

Lowell and Genik (1972) and Lowell *et al.* (1975) postulated crustal attenuation for the Southern Red Sea by listric normal faulting affecting the whole thickness of the crust. These authors correctly point out that in matching conjugate passive margins across oceans, it is important to allow for the amount of extension in the underlying faulted basement. Unfortunately, however, the seismic sections provided by Lowell *et al.* (1975) were not adequate to document the listric nature of the Red Sea faults.

In the nearby Afar triangle, Morton and Black (1974) set up a model that recognizes the tilted fault blocks in the area, but avoids curved faults. Instead, rigid blocks are slipping along inclined straight faults into a ductile substratum, and progressive thinning takes place as new sets of inclined normal faults offset the earlier fault blocks. The authors relate the tilting of the beds to the amount of stretching of the crust. As the paper presents only a model, no documentation of the shape of the fault plane is provided.

The recent studies by de Charpal *et al.* (1978) and montadert *et al.* (1979 *a* and *b*) provide the first direct evidence for listric normal faulting that involves the basement of a passive margin. The basement of the Northern Bay of Biscay is of Variscan age and in part overlain by early Mesozoic basinal sequences that were initiated during an earlier tensional event (Triassic). Major rifting and extension in a marine regime occurred during early Cretaceous times and ceased by Aptian time. Blocks were rotated during the rifting phase by about 20 to 30° along listric normal faults. These faults can be mapped seismically in the Northern Bay of Biscay (Fig. 3 and 4), and Figure 5 shows a subhorizontal reflection (after correction for velocity pull-ups) which appears to be the sole of the listric normal fault system. To show that this situation is not limited to the Gulf of Biscay, similar features are shown on a line west of Galicia Bank (Fig. 6).

Refraction velocities (Avedik, Howard, 1979) indicated on Figure 4 suggest that the sole fault separates an upper faulted brittle crust from a lower crust with velocities exceeding 6.3 km/sec. In other words, as emphasized by Montadert *et al.* (1979 *a*), the base of the sole fault is a mechanical discontinuity within the crust, which, during the rifting period, was about 6-8 km below sea level. The same authors cautioned in an alternate interpretation that the basal flat reflector shown on Figures 5 and 6 may also represent the Moho itself, in which case the Moho would be the main decoupling level for the tilted fault blocks.

Montadert *et al.* used a reconstruction based on migrated seismic profiles. They determined for their preferred interpretation that the upper continental crust was reduced by about 30% from an unusually thin crust of about 6-8 km to a new thickness of about 4-5 km ; thus, the upper brittle crust was, according to the authors, attenuated by listric normal faulting, while it is presumed that the lower crust of about 3 km thickness was attenuated by creep. Le Pichon and Sibuet (1980) tested the stretching model of McKenzie (1978) on the data of the Gulf of Biscay and conclude that "the amount of brittle stretching in the upper 8 km of continental crust reaches a maximum value of about 3 and is equal to the stretching required to thin the continental crust and presumably the lithosphere".

We conclude that listric normal faults involving the basement of passive margins can be mapped by reflection seismic surveys. So far the correlation and identification of

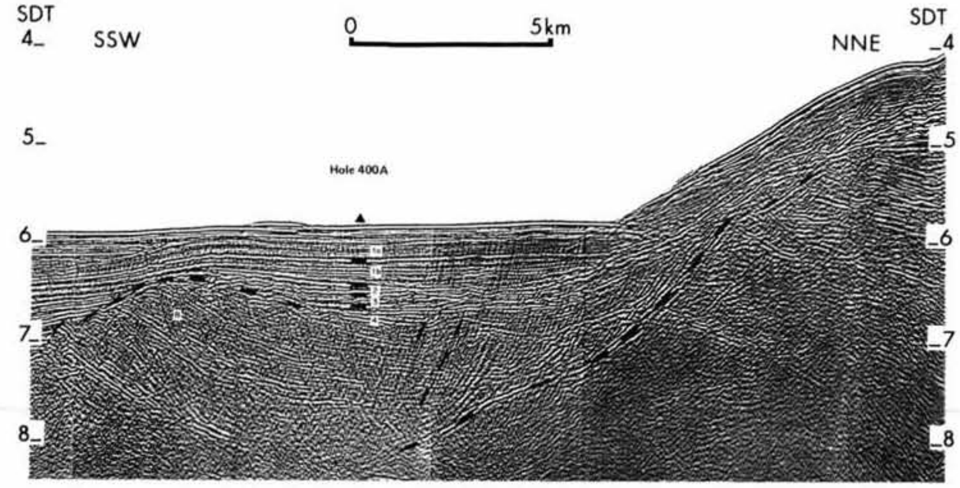


Figure 3

Northern Gulf of Biscay, section across IPOD Hole 400. The acoustic basement (B) consists of layered sedimentary rocks of probable Jurassic and early Mesozoic age. These formerly continuous layers were faulted and tilted during the early Cretaceous rifting phase. Vertical scale in seconds, two-way travel time. Unit. 1-A : Quaternary to late Pliocene ; 1-B : Pliocene to early Miocene, 2 : Miocene to late Paleocene ; 3 : Maastrichtian-Campanian ; 4 : late Albian, late Aptian. After Montadert et al., *1979 a.*

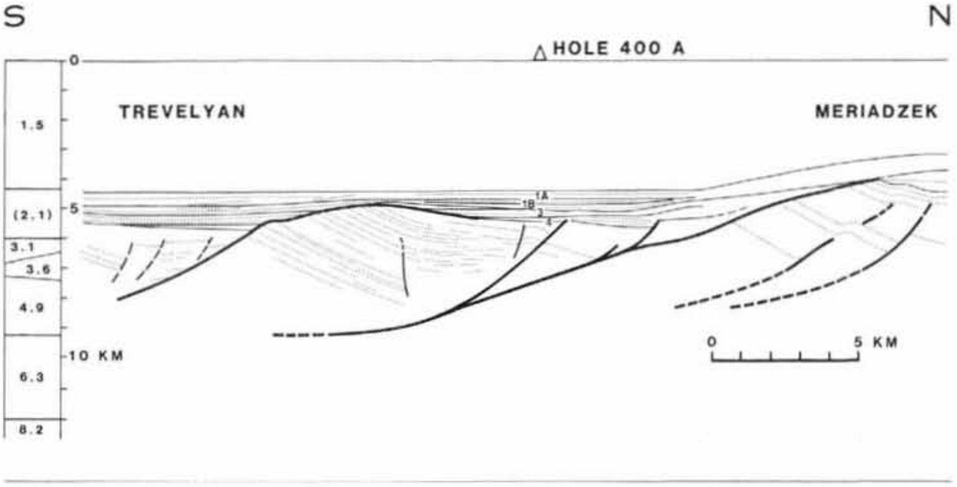


Figure 4

Northern Gulf of Biscay, line drawing of the section of Figure 3 converted to depth and migrated. Horizontal and vertical scale, the same. note listric normal fault bounding the tilted blocks. near the base of the listric faults is a horizontal reflector corresponding to the interface between 4.9 km/sec. and 6.3 km/sec. layers, as defined by seismic refraction (Avedik, Howard, 1979). Moho discontinuity is at 12 km. After Montadert et al., *1979 a.*

reflections between the tilted blocks has been elusive and, consequently, estimates of the amounts of stretching remain crude. It is hoped that in coming years more attempts will be made to regionally map faults within the basement of passive margins and to tie such work with refraction and wide angle reflection studies and calibration wells. Listric normal faults provide an elegant way for extension of the upper brittle crust, but the process which leads to the attenuation of the more ductile underlying lower crust and upper mantle will be more difficult to characterize and to document.

LISTRIC NORMAL FAULTS LIMITED TO DEFORMATION OF SEDIMENTS OF PASSIVE MARGINS

Thick sedimentary sequences overlie the rifted portions of many mature passive margins. These sequences subsided while the passive margin "drifted" away from the mid-ocean ridge. Structural deformation in these sedimentary sequences is often dominated by deformation along listric normal faults and by associated diapiric phenomena. Such deformation is spectacularly dramatized in areas of rapid deltaic deposition such as the Niger Delta (Delteil *et al.*, 1976 ; Weber, Daukoru, 1976 ; Lehner, de Ruiter, 1977) or the Gulf of Mexico, where mobile salt plays an additional role in the genesis of growth faults. In this paper we will limit ourselves to examples from the Gulf of Mexico.

The Gulf Coast Tertiary may be viewed as a thick deltaic clastic wedge prograding on a substratum of high pore pressure shales that in turn is underlain by a Mesozoic carbonate sequence deposited on an unstable basal evaporitic sequence. The crust of the Gulf of Mexico thins rapidly under the Gulf Coast ; where drilled on land — in areas of normal continental crustal thickness — a Paleozoic basement is observed, with evidence of superposed Pennsylvanian and Triassic rifting events. Overlying this basement, a lower set of listric normal faults and "roller" structures is associated with the basal evaporitic sequence, within which the listric faults appear to sole out. Such faults and structures are illustrated on Figures 7 and 8.

Another set of listric faults is associated with the Tertiary wedge. These are the well known Tertiary growth faults which have been illustrated by a number of authors from the Gulf Coast (e.g., Bruce, 1973 ; Busch, 1975 ; Roux, 1977 ; Bally, 1980). A net of more or less slope-parallel anastomosing growth fault systems affects all Cenozoic deposits of the Gulf. The shape of most master faults is listric, and they and their associated fault systems "sole out" or flatten within the overpressured shale section of the Gulf Coast. Hardin and Hardin (1961), Busch (1975), Curtis (1970 ; 1980), Curtis and Picou (1978) among others have described the interaction of sedimentation and growth faulting. The listric normal growth faults of the Gulf of Mexico often interact with diapiric structures that in some cases involve salt and in others, overpressured shales. Clearly, gravity tectonics dominate the scene.

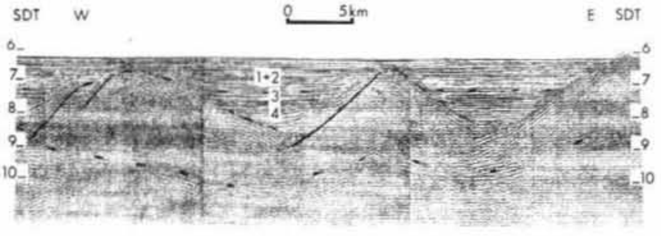


Figure 5

Northern Bay of Biscay, seismic profile south of Goban Spur showing tilted blocks with listric faults. Note the horizontal reflector below the tilted blocks. It is observed on the deepest part of the margin. On Trevelyan, it corresponds to the boundary between a 4.9 km/sec. layer and a 6.3 km/sec. layer only 3 km thick. The Moho is about 12.5 km below sea level. Profile CM 16 processed. After Montadert et al., *1979 a.*

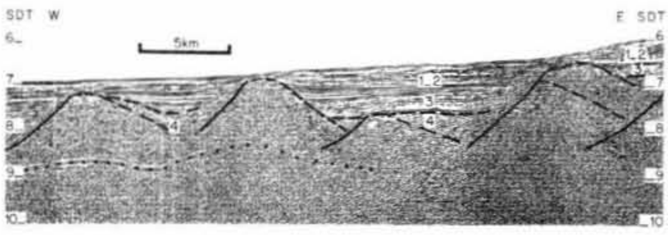


Figure 6

Seismic profile immediately west of Galicia Bank, showing tilted blocks and listric faults and a horizontal reflector below, as on Figure 4 Seismic formations 1-4 are the same as defined in northern Biscay. Profile IFP-CNEXO-CEPM, processed. After Montadert et al., *1979 a.*

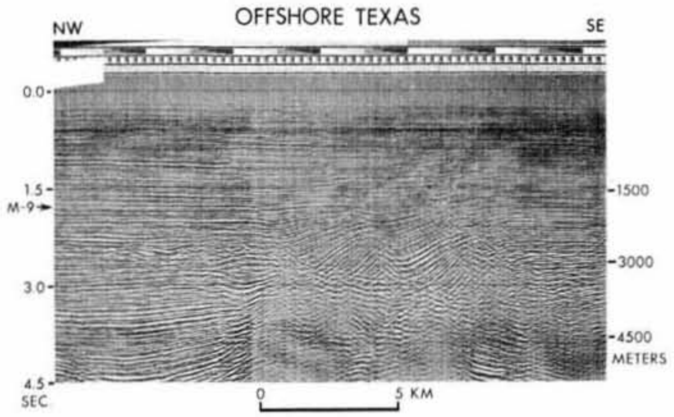


Figure 7
Offshore Texas, reflection seismic section. Note extensive listric normal growth faults in Miocene section. M indicates Miocene marker beds. After Bally, 1980.

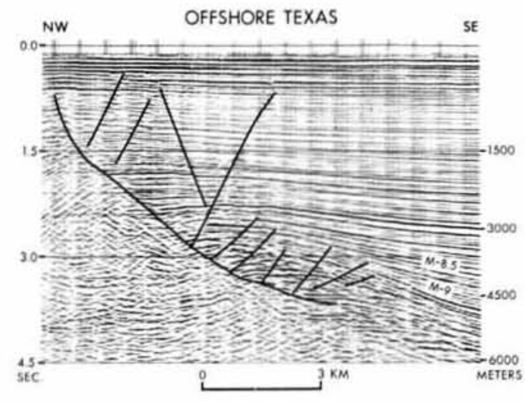


Figure 8
Offshore Texas, reflection seismic profile, showing the interaction of growth faults and diapiric structures. M-9 is a Miocene marker bed. After Bally, 1980.

Soft-sediment growth faults are widespread on many passive margins. Unfortunately, published documentation is less commonly available. While the growth fault systems associated with deltaic sequences always are spectacular, lesser but nevertheless obvious listric growth faults also occur in areas with smaller rates of sedimentation and areas that are not underlain by salt or thick shale sequences. Our undocumented suspicion is that in almost all cases one is looking at gravity tectonics in a shelf-slope setting with overpressured shales. In summary, it may be stated that soft-sediment listric normal growth faults are due to gravity tectonics on passive margins. They appear to be limited to the sedimentary section and do not involve the underlying basement. Such listric normal faults are often also associated with salt or clay diapirs.

Poor quality seismic data commonly do not permit tracing fault systems at depth, and thus the question whether a listric growth fault intercepts the basement or whether the fault is restricted to sediments cannot be answered until high quality reflection data are obtained. If the critical evidence is lacking, it may be tempting to infer basement controlled faulting (often with limited or no mappable growth) for the early rifting phase of a margin. On the other hand, soft-sediment listric growth faulting appears to be preferably associated with the subsidence and slope progradation of the subsiding "drifting" sequence.

The reader is reminded that listric normal growth faulting that also does not involve the basement occurs within the accretionary wedges associated with subduction zones (see example from Colombia by Beck and Lehner, 1975).

LATE SYNOROGENIC AND/OR POSTOROGENIC LISTRIC NORMAL FAULTS ASSOCIATED WITH FOLDED BELTS

Extensional faulting linked by strike-slip fault systems often fragment folded belts late, during, or soon after their tectogenesis. Complex intramontane sedimentary basins form in this manner (i.e., the Vienna basin, Grill *et al.*, 1968 ; Kroell, Wiesender, 1972 ; Kroell, Wessely, 1973 ; and Mahel, 1974 ; the Pannonian basin, Horvath, Stegena, 1977 ; and Sclater *et al.*, 1980 *a* and *b* ; and the wider Cenozoic Basin and Range province of the Western Cordillera of North America).

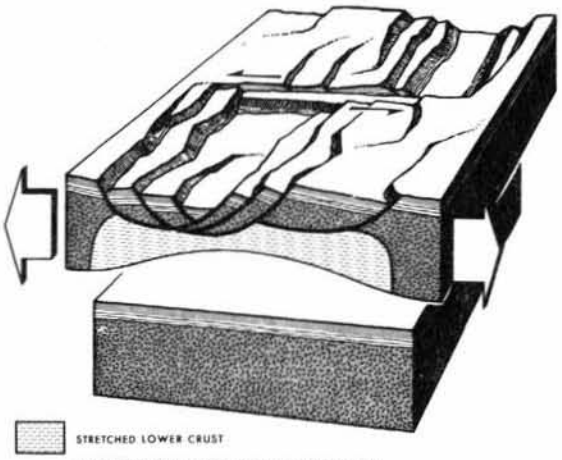
Listric normal faulting associated with the stretching and collapse of folded belts may well represent the rifting event that initiates continental separation and the formation of two opposing conjugate passive margins. Thus, some of the late Paleozoic basins and the widespread Triassic graben systems on both sides of the Central Atlantic appear related to post-collisional extension of the backbone of the late Paleozoic folded belts. Contrast them to the more isolated graben systems of the Red Sea or the African-South American conjugate passive margins, where a propagating crack causes the formation of rift systems that are superposed on a much older and stabilized Precambrian craton.

Here we will only discuss selected aspects of listric normal faulting in the Western Cordillera of North America, because there, although far from being satisfactory, the complex phenomenology of listric normal faulting appears to be somewhat better documented than in other folded belts.

Mid- and young Cenozoic extensional fault and strike-slip fault systems extend from Central British Columbia into the Basin and Range province of the US and Northern Mexico. Hamilton and Myers (1966) have provided an early and unusually farsighted synthesis of the Cenozoic tectonics of the US portion of the Cordillera. Davis and Burchfiel (1973) and Liggett and Ehrenspeck (1974), among others, have shown that normal fault-controlled horst and graben systems may be linked by strike-slip or transform fault zones (Fig. 9).

Extensive summaries of the geology and geophysics of the Basin and Range are given by Thompson and Burke (1974), Newman and Goode (1979), Smith and Eaton (1978), and Armentrout, Cole and Terbest (1979) ; more concise overviews are provided by Eaton (1979 ; 1980), Stewart (1978), Stewart and Carlson (1978), and Davis (1980).

In the western United States normal faults were first described by G. K. Gilbert (1875) as dominating the Cenozoic structure of the Great Basin area. It was not until 70 years later, however, that systematic changes in the dips



MODIFIED AFTER M. LIGGETT & H. EHRENSPECK, 1974

Figure 9
Sketch illustrating strike-slip faulting, listric normal faulting and crustal attenuation, modified after Liggett and Ehrenspeck, 1974.

of some basin and range normal faults with depth were recognized. Chester Longwell (1945) reported that normal faults in the Desert Range and Grand Wash Cliffs areas of southern Nevada had much lower dips (10 to 30°) than might be expected from their occurrence in the Basin and Range province. Furthermore, Longwell stated (1945, p. 111) that he could perceive an "upward-concavity of all fault surfaces that are exposed extensively enough for accurate appraisal of their form". Cautiously extrapolating from his observations in Southern Nevada, Longwell predicted (p. 117) that it would not be surprising to him if it was later found that many of the basin and range faults typically "represented in published sections as plane surfaces, are actually curved in cross-section". Little immediate attention was paid to Longwell's paper, but Moore (1960), Hamilton and Myers (1966), and Armstrong (1972) were among those who later stressed the probable importance to Great Basin geology of both low-angle and listric normal faults.

Confirmation of Longwell's prediction has been slow to come from conventional field studies in the Great Basin, primarily because of the geologist's inability to "see" to depth along the major range-front faults of the region, covered or masked as they are by basinal sedimentary fills. However, recent improvements in seismic reflection technology and increased seismic exploration by the petroleum industry of the Great Basin area have helped to document Longwell's insight into the geometry of basin and range faulting.

Surface geologic evidence for the existence of listric normal faults in the western United States has come from several kinds of observations, as amplified below — among them : 1) direct observations in non-basin areas, e.g., Longwell (1933 ; 1945) ; 2) the geometric interrelations between tilted or rotated hanging-wall strata and normal faults ; 3) subsurface geologic data from wells, boreholes, etc, e.g., Proffett (1977) ; and 4) interpretation of a curviplanar fault geometry at depth based on the arcuate geometry of many range-front faults as seen in plan view (Moore, 1960).

Hamblin (1965) measured a downward decrease in dip along normal faults at the western edge of the Colorado Plateau, where topographic relief is great. He noted that faults such as the Hurricane fault of Utah and Arizona were essentially vertical or dipped very steeply at the top of the plateau, but had average westward dips of 60° along the Colorado River in the Grand Canyon. Proffett (1977) cites rates of flattening at depth for the Hurricane fault of Hamblin (1965), the faults described by Longwell (1945), and faults studied by him in the Yerington area, Nevada, of 1.3-2°/100 m, 0.7-1.3°/100 m, and 0.3-0.7°/100 m, respectively. He concludes from the diverse geologic settings of these three examples that the rate decreases with increasing depth in the crust.

The reverse drag of hanging-wall strata into the Colorado Plateau border faults was explained by Hamblin (1965) as a geometric consequence of the downward decrease in dip of these faults. The tilting of hanging-wall strata into dip orientations opposite to that of bounding normal faults has sometimes been considered as evidence for a listric geometry of faulting, but Thompson (1971) has correctly noted that such rotation can also occur during simultaneous block faulting and tilting on *multiple* and sub-parallel planar faults. However, his mechanism obviously does not apply if footwall strata below the faults in question do not exhibit rotation. Perhaps the most convincing evidence for listric normal faulting, using the geometry of hanging-wall strata, comes from those instances of growth faulting where such strata display a progressive decrease in dip upwards through the stratigraphic section. Relations of this type have been described by Wallace (1979) in the West Humboldt Range and by Proffett (1977) in the Yerington area, both in Nevada, and by Frost (1979) in the Whipple Mountains, southeastern California, and the adjacent Aubrey Hills, Arizona. These authors all interpret dip relationships as indicating continued or intermittent sedimentation during rotational displacement of downthrown blocks along listric normal faults.

Proffett (1977) describes in detail and interprets a complex system of listric growth faults in which earlier, relatively steep listric normal fault planes are intersected by subsequent generations of listric normal faults that rotate the earlier faults into flat positions of much shallower dip. This process leads to an east-west extension of more than 100 percent, with a crustal thinning of the same order supported by seismic refraction data. Dips of tertiary hanging-wall fanglomerate in the West Humboldt Range are as high as 30 to 35° to the east. Overlying basalt caps eroded fanglomerate and dips 8-10° eastward ; still higher basaltic terrace gravels dip only 1 or 2° (Wallace, 1979). Southwestward-dipping strata in the Aubrey Hills, on the east bank of Lake Havasu between California and Arizona, are truncated at depth by the northeast-dipping Havasu Springs fault. E. Frost (pers. comm., 1979) reports that Oligo-Miocene hanging-wall strata dip as steeply as 85°, whereas Mio-Pliocene beds at the top of the progressively shallowing section dip only 15°.

Anderson (1971), Wright and Troxel (1973), and Davis *et al.*, (1979) have mapped the downward flattening of closely spaced normal faults in separate areas of the southern Cordillera (Great Basin, eastern Mohave Desert, Fig. 9), but their faults flatten into structurally shallow and subhorizontal detachment surfaces (or have been inferred to do so) and should not be confused with the major crustal breaks that outline the mountain ranges of the Great Basin. In fact, the relation of these shallow detachment surfaces to major range-front faults is one of the remaining enigmas of basin and range tectonics.

In recent years growing attention has been focused on such low-angle detachment faulting, particularly of the type associated with the metamorphic core complexes of the western United States (see G. H. Davis, Coney, 1979 ; and G. A. Davis, 1980). Metamorphic core complexes are described as domal uplifts of metamorphic rocks that are separated from overlying rocks by *décollement* zones of Tertiary age "marking strikingly sharp thermal and strain gradients" (G. H. Davis, Coney, 1979). The detachment zones appear to be formed in an extensional regime, and they are part of the general phenomenon of "younger over older thrust faults", or "denudational faults", that have been described for many years from Nevada (e.g., Misch, 1960 ; 1971). Armstrong (1972) has determined for the Snake Range of Nevada that these Tertiary extensional faults result from thinning of supracrustal rocks by listric normal faulting (denudational tectonics). An example of this type of faulting from the Whipple Mountains of southeastern California is diagrammatically shown in Figure 10.

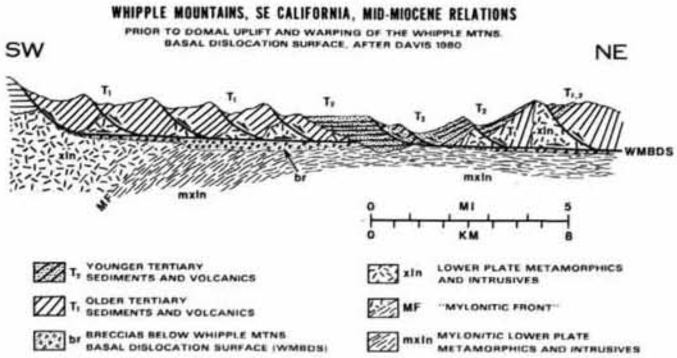


Figure 10

Diagrammatic cross-section across the Whipple Mountains, southeastern California, illustrating Middle Miocene geological relations prior to domal uplift and warping of the Whipple Mountains basal detachment surface (WMBDS). The cross-section illustrates two phases of rotational normal fault displacement along the basal detachment surface. T_1 : older Tertiary sedimentary and volcanic rocks ; T_2 : younger Tertiary sedimentary and volcanic rocks deposited across the detachment surface prior to their involvement in renewed fault displacement ; MF is a "mylonitic front", the abrupt non-fault contact between undifferentiated lower plate metamorphic and intrusive rocks (xln) and their largely mylonitic equivalents (mxln) ; br : breccias developed below the basal detachment surface. From Davis et al., *1979.*

The interpretation of the detachment fault complexes of the Cordillera is highly debated at the present time. G. H. Davis and Coney (1979) view them in the context of the ductile stretching of the basement (megaboudinage), with the layered cover flowing passively during metamorphism and, at higher structural levels, exhibiting brittle detachments and associated normal faulting. G. A. Davis *et al.* (1979) from studies in the lower Colorado River area, rule out the possibility there that detachment faulting occurred synchronously with metamorphic and mylonitic flow in underlying basement rocks. This conclusion is based on geochronologic and geologic evidence that shows that regional mylonization of lower-plate rocks significantly predated the Miocene detachment faults, and that the major detachment surface discordantly overlies underlying tilted, folded and brittley deformed mylonitic gneisses. In fact, these gneisses were locally eroded prior to the Oligocene (?) and Miocene deposition of Tertiary sediments later affected by normal and low-angle faulting. Clasts of what are now lower-plate mylonitic rocks occur throughout the allochthonous Oligocene (?)-Miocene fanglomerates of the area. Profound North-East directed extension within upper-plate rocks was unaccompanied in the Whipple Mountains region by coeval extension in lower-plate rocks. This relation raises the possibility that the Whipple allochthon is an upper crustal landslide sheet moved northeastward under the influence of gravity, or, alternatively, that lower-plate extension commensurate with that observed in the allochthon occurred by unknown mechanisms in areas northeast of those studied to date.

It follows from the previous descriptions that surface geologic observations at best provide only indirect information on the geometry of the normal faults of the Basin and Range province and their possible relation to outcropping "younger over older" *décollement* zones. Proffett (1977) projected surface information into the subsurface using shallow boreholes. Ultimately, however, only reflection seismic studies may help to document the fault configurations controlling the Tertiary basins of the Western Cordillera. The first reflection seismic evidence for postorogenic listric normal faulting in the Western Cordillera was given by Bally *et al.* (1966). The Flathead normal fault of southeastern British Columbia appears to offset the Lewis overthrust by more than 6 km (down to the West). Reflection data do not permit mapping the fault itself ; however, a continuous reflection from the Mesozoic at shallow depths precludes a steep over-all attitude of the fault and demands an interpretation as a listric normal fault that probably merges in — and causes "backslippage" of — the older Lewis overthrust. Based on much poorer reflection seismic data, Bally *et al.* (1966) also postulated that the southern Rocky Mountain trench was part of a system of listric normal faults that separated eastward tilted blocks in Precambrian-Beltian sediments. Similar listric normal fault systems may also be responsible for the Tertiary basins of northern Montana. Note that in all examples from southeastern British Columbia, the listric normal faults are inferred to merge with pre-existing thrust faults and into a major solefault system that presumably overlies the crystalline basement (see also Myers, Hamilton, 1964).

More examples of reflection lines suggesting listric normal faults merging into and controlled by pre-existing thrust faults are offered by Royse *et al.*. (1975) from the Wyoming fold belt. An unusual set of lines (Fig. 11) from the Sevier Desert of Central Utah was published by MacDonald (1976). With the exception of one well, these sections are not calibrated, and the author offers only a limited interpretation of the data. Nevertheless, the sections convincingly show a reflection from a detachment zone, into which the overlying normal faults flatten. Whether the flat *décollement* zone represents an earlier overthrust — as the author suggests — that was used by the late listric fault system, or whether the whole system is only postorogenic in origin cannot be determined from the data.

Effimoff and Pinezich (1980) published reflection seismic sections from northeastern Nevada (e.g., Fig. 12 *a*, *b* and 13 *a*, *b*). Their sections display half-grabens tilted toward the east and bounded on the east by a major listric normal fault system. The flat sole of the listric fault is only rarely displayed by a reflection, but the listric nature of the fault is supported by the rotation of hanging-wall Tertiary beds into the fault plane.

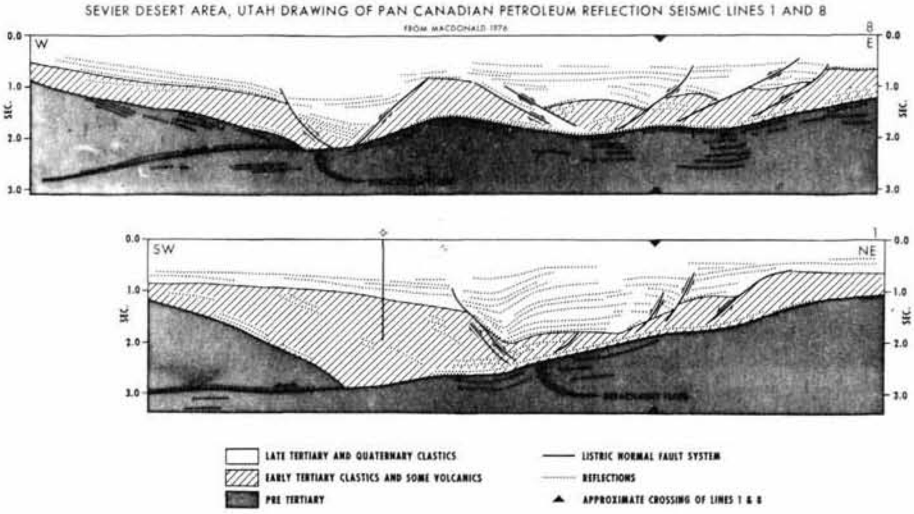


Figure 11
Drawing of seismic line by Pan Canadian Petroleum across the Sevier Desert in Utah, modified after an interpretation published by MacDonald, 1976.

Typically, the lower portions of the sections appear to be more intensely faulted, suggesting an early phase of intensive faulting followed by later tilting into the main fault system. In the mountains adjacent to the seismic lines shown by Effimoff and Pinezich, major low angle *décollement* zones (denudational faults) occur that separate chaotically disturbed Paleozoic strata from underlying less disturbed Paleozoic or Precambrian beds. The seismic lines of Effimoff and Pinezich suggest that the outcropping shallow *décollement* systems of the mountains may merge into the listric normal fault systems that underlie the adjacent basins. The relation may be far from simple, because the shallow surface *décollement* often appears to be offset by the steeper listric boundary fault of the valley. Thus, the surface *décollement* zones may well be the outcropping soles of earlier, originally deeper, listric normal fault systems that were uplifted and later modified by landslide-like gravity tectonics.

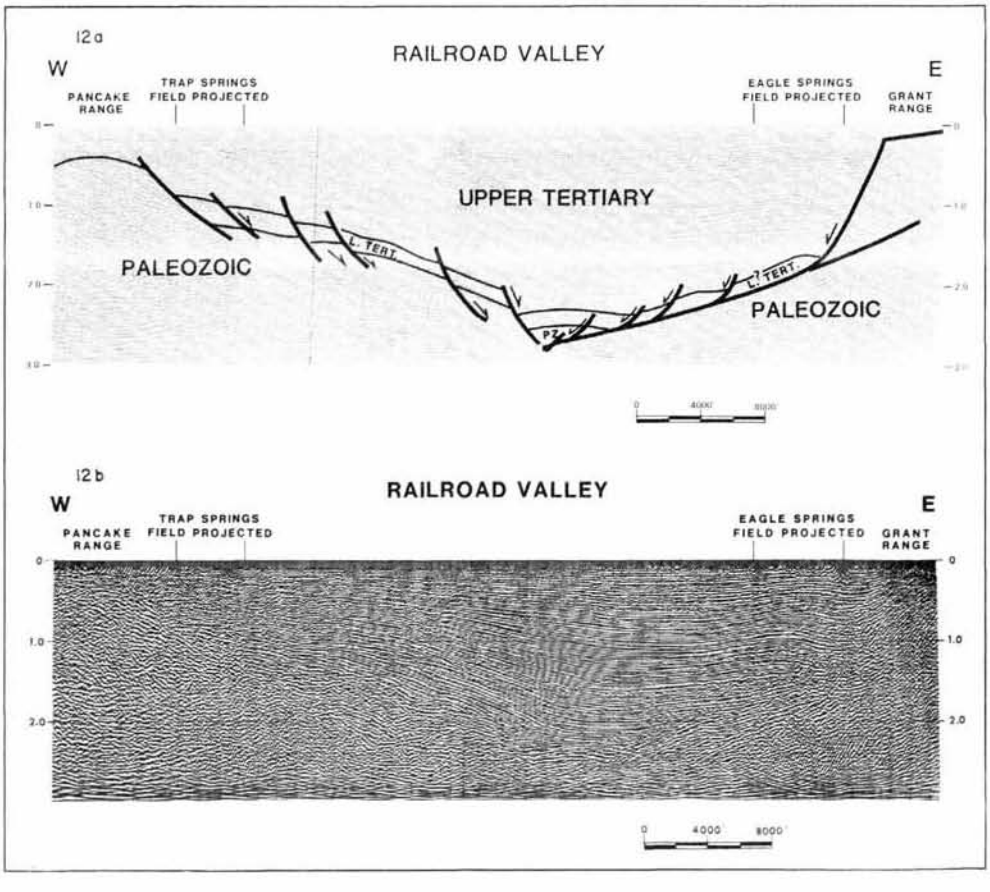


Figure 12
Seismic (migrated) profile across Railroad Valley, Nevada. a : interpreted line ; b : raw data of the same line. Effimoff and Pinezich, 1980.

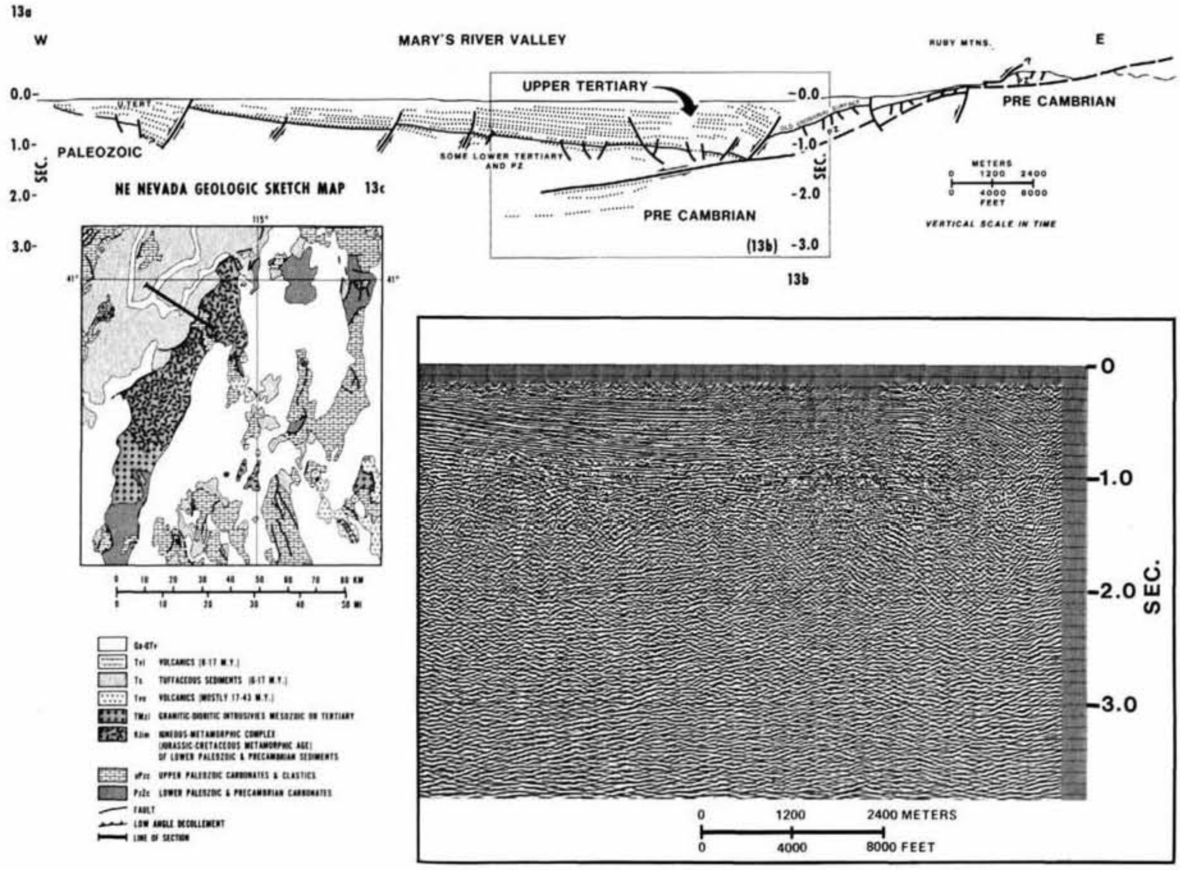


Figure 13
a : drawing of a seismic profile migrated across Mary's River Valley. Published by Effimoff and Pinezich, 1980. b : closeup of eastern segment of seismic line showing presumed continuation at depth of surface décollement *or Ruby Range. After Effimoff and Pinezich, 1980.*

The estimates for extension in the Basin and Range made by different authors range from 10 to 100% (for a review, see Davis, 1980) and are based mainly on judgments derived from surface geology. Although the estimates are probably in the right order, better estimates could be obtained from regional reflection seismic surveys. According to different authors, the depth of normal faulting or their "soling out" occurs in the range of 5-17 km. A preferred interpretation is that extension in the brittle upper crust in taken up by ductile stretching in the lower crust (Thompson, 1959 ; 1966 ; Hamilton, Myers, 1966 ; Stewart, 1971 ; 1978 ; Proffett, 1977). The transition between brittle and ductile crust may well be represented by a crustal low velocity zone which in the eastern Great Basin occurs between 5 and 15 km depth (Smith, 1978 ; and Eaton, 1980).

We conclude that large areas within the Cordillera of North America, from British Columbia to Mexico, have been extended by evolving systems of listric normal faults, linked to each other by strike-slip-transform faults or diffuse zones of transcurrent strain. These fault systems are responsible for the formation of basins initiated in late Paleogene time which, however, ceased to be active at different times in different segments of the Cordillera. The amount of stretching suggested by the normal faults is probably accompanied by corresponding ductile extension in the lower crust.

Most authors have emphasized the stretching aspects of the Basin and Range province. Geomorphological evidence, as well as the uplift of deep-seated metamorphic rocks during the Tertiary, suggest that the crust of the western Cordillera may also have been arched between the Interior Plains and the Sierra Nevada. In other words, it has become important to differentiate the effects of super-regional — possibly thermal — arching from the structural and thermal consequences of simple lithospheric stretching.

LISTRIC NORMAL FAULTS IN REMNANTS OF ANCIENT PASSIVE MARGINS OCCURRING IN DEFORMED FOLD BELTS

Miogeosynclinal sequences in folded belts are today generally recognized as remnants of former passive margins caught in the collisional drama of mountain building. Within this context, it is particularly important to develop criteria that allow differentiation of the following :

— listric normal faulting related to the rifting phase preceding the opening of an ocean. Such normal faults may be postorogenic faults of an earlier cycle, or else directly related to thermal events that affected much older crust ;

— soft-sediment listric normal faulting often related to the drifting phase preceding orogenic deformation : this is suggested by evidence from Atlantic-type passive margins, but has not yet been described from ancient folded belts ;

— late orogenic to postorogenic listric normal faulting imposed on the deformed passive margin sequences after they were deformed and incorporated into the folded belt (i.e., the basin and range faulting previously described).

To illustrate some of the problems, we review examples from the Alps. That the preorogenic Mesozoic evolution of the Alpine "geosyncline" was dominated by tensional block-faulting rather than by "embryonic" (Argand, 1916) compressional movements became clear in the late fifties and early sixties (e.g., Trümpy, 1960 ; 1975 ; Schindler, 1959). Particularly, the importance of normal faulting in the formation of early Jurassic basins was established by a wealth of sedimentological and paleotectonic observations (Wiedenmayer, 1963 ; Bernoulli, 1964) and has since been demonstrated in various regions of the Alpine-Mediterranean belt. The interpretation of ophiolites as remnants of Mesozoic oceanic lithosphere and an understanding of their significance for palinspastic restorations led to the recognition of former continental margins (Laubscher, 1969), and the early Jurassic period of normal faulting was identified with a phase of rifting preceding spreading in the Tethyan ocean (Bernoulli, Jenkyns, 1974).

The occurrence of early faulting in the Alpine belt is often inferred from circumstantial evidence. Where the existence of pre-Alpine faults is firmly established, their original geometry is usually more or less disturbed by later orogenic movements. In most cases the faults were reactivated during Alpine orogeny and *décollement* planes of sedimentary and shallow basement nappes may also have followed pre-existing listric surfaces. Particularly, the most distal areas of continental margins and their passage zone to oceanic crust have been the site of decoupling and most intense deformation, and documentation of the early history is most fragmentary in these areas.

Listric faulting as a mechanism for crustal thinning is inferred, usually in an intuitive manner, in many palinspastic reconstructions of Tethyan continental margins (e.g., Bosellini, 1973 ; Sturani, 1973). Helwig (1976), using Lowell's and Genik's (1972) evolutionary model of the Red Sea as a geotectonic model for the Triassic-Jurassic Alpine Tethys, has also postulated the occurrence of listric faulting to account for preorogenic crustal thinning required to maintain material balance during crustal shortening without subduction of continental crust. Whether or not we admit lithospheric subduction of sometimes already attenuated continental crust (Bally, Snelson, 1980), a mechanism is required to account for the isostatic subsidence of continental margins that formed before their tectogenic involvement in mountain building.

The paleotectonic evolution of many Tethyan margins closely parallels that of the undeformed rifted margins of the Bay of Biscay (de Charpal *et al.*, 1978 ; Montadert *et al.*, 1979 *a* and *b*) and of Iberia (Groupe Galice, 1979 ; Graciansky *et al.*, 1979). In contrast to many rift systems that developed on an ancient subaerial surface (e.g., Basin and Range) rifting occurred in both areas in a pre-existing marine Mesozoic basin — in the case of the central and eastern Tethys discordantly across thick carbonate sequences that were marginal to the earlier, Triassic, Paleotethys ocean (Laubscher, Bernoulli, 1977). As a consequence, there are hardly any siliciclastic sediments associated with the early Jurassic phase of rifting, and evaporite deposits of Jurassic age are conspicuously lacking along the rift zone. Traces of volcanic activity are also extremely scarce along the Jurassic passive margins of the Tethys.

Inside the Alpine belt of the Mediterranean area, the southern Alps of northern Italy probably preserve the most complete and undisturbed record of a Jurassic to early Cretaceous passive continental margin of the Tethyan ocean. The Mesozoic sequences of the area are deformed by folding and some minor thrusts ; however, there are no large-scale nappe structures hampering paleotectonic restorations (Fig. 14 *a*). Particularly, the signature of north-south-trending Jurassic fault scarps is clearly recognizable across the east-west-striking Alpine structural grain.

Rifting in the South Alpine margin began, after precursory movements in the Triassic, during the early Jurassic. The synsedimentary nature of normal faults is clearly established by rapid changes of facies and formational thickness of the syn-rift sediments across the fault zones and by the existence of pronounced fault scarps that were the source areas for gravity flow deposits and carbonate turbidites in

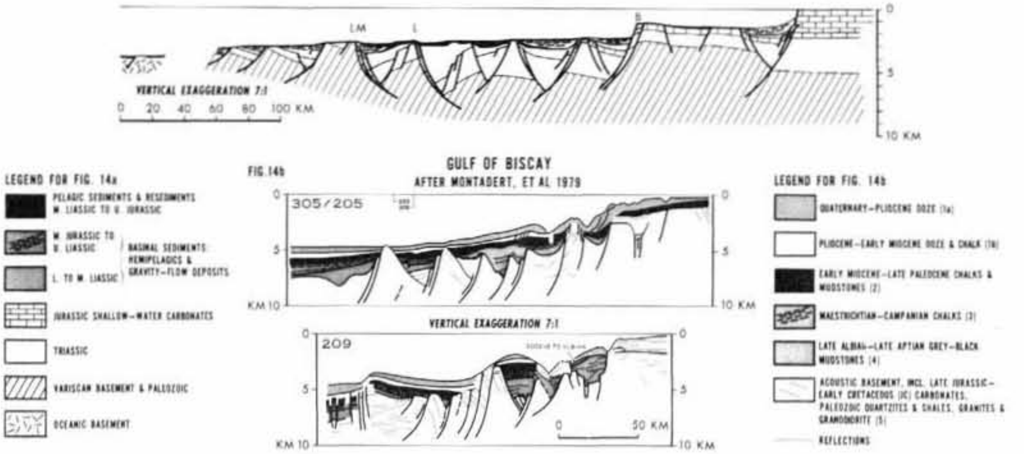


Figure 14

a : Palinspastic cross-section through the southern continental margin of the Tethys in the late Jurassic. After Bernoulli et al., *1979 b, modified. LM : Lago Maggiore fault ; MN : Monte Nudo trough ; L : Lugano fault ; G : Generoso trough ; B : Ballino-Garda escarpment. Vertical exaggeration, approximately 7 times. b : Depth sections across the north Biscay margin, based on seismic reflection sections. For explanation of numbers, see Figure 3. Vertical exaggeration, approximately 7 times.*

the adjacent basins (Bernoulli, 1964 ; Castellarin, 1972). Subsidence rates were highest during this early phase of disintegration of the margin and varied widely between the different fault blocks. Some of the blocks that were submerged only in the course of the late Liassic to early Middle Jurassic became submarine highs and plateaus (e.g., Trento plateau), where only limited amounts of pelagic sediments accumulated. With the onset of spreading and the formation of oceanic crust in the Ligurian-Piemontese ocean in the late early to middle Jurassic, subsidence rates decreased and were more evenly distributed over the margin.

Thus, through time the submerged distal continental margin (Lombardian zone) became increasingly starved, and only pelagic sediments were slowly deposited, their facies being determined mainly by prolonged subsidence, increasing water depth and basin-wide paleoenvironmental changes (Bernoulli *et al.*, 1979 *a* ; Bossellini, 1980).

A fruitful analogy is offered by the examples of the Gulf of Biscay (Fig. 14 *b*).

Evidence for *listric* faulting during the early breakdown of the margin can only be inferred and comes mainly from the sedimentary evolution of the margin. In the Lombardian basin, the syn-rift sediments are essentially composed of well-bedded, current-deposited spongolithic cherty limestones and associated gravity flow deposits (Lombardian siliceous limestones, Medolo group) deposited in fault-bounded troughs. Tilting of fault blocks as a consequence of listric faulting is suggested by the asymmetry of certain troughs reflected by the pattern of formational thicknesses. Deposition rates match approximately the rates of differential subsidence and results in approximately horizontal layering at the end of the rifting phase (compare Fig. 14 *a* from Bernoulli *et al.*, 1979 *b*, with Fig. 14 *b* from Montadert *et al.*, 1979 *a*). There is no unconformity at the base of the basinal syn-rift sequences, but lensing out of packages of strata and local unconformities are ubiquitous within the sequence. Locally, in outcrops, stacks of strata are observed that have been rotated along synsedimentary listric growth faults (Fig. 15). The formation of tilted fault blocks during sedimentation is also suggested by troughs and half-grabens bounded along one side by steep fault scarps, documented by coarse proximal resediments, and by a much smoother topography along the other side (e.g., the middle to late Liassic Monte Nudo basin, Fig. 14 *a*, and Kälin, Trümpy, 1977).

On top of the tilted blocks, particular facies of shallower water are observed in the lower Jurassic (e.g., Broccatello formation of the Lugano swell). These shallow-water areas were restricted in size and characterized by early subaerial and later submarine erosion, and by local angular unconformities (Wiedenmayer, 1963 ; Casati, Gaetani, 1968). Particularly spectacular outcrops of unconformities that may illustrate tilting associated with the rifting phase of the southern Tethys have been exquisitely illustrated by H. Eugster (Fig. 16, and Cadisch *et al.*, 1968) from the Engadine dolomites of Switzerland.

The depositional geometry of the syn-rift sediments of the southern Alps compares well with that of the corresponding formations of the Iberian (Formation 4, Groupe Galice, 1979) and of the Armorican margin (Montadert *et al.*, 1979 *a* and *b*). In the southern Alps, the early Jurassic basins measured some 25 to 40 km across ; this is in accordance with the observations along the Iberian and Armorican margins, where fault blocks from a few to 30 km across are observed. Likewise, the throw of some individual fault zones is on the same order with a maximum of 3 to 4 km ; this corresponds to the throw reconstructed for the early Jurassic Lugano fault (Bernoulli, 1964, Fig. 18, our 14 *a*). In the Iberian and Armorican margins, a polarity of the listric faults towards the axis of the rift zone is observed. In the southern Alps, it appears that rifting started in the central zone of the Lombardian basin with the step-wise foundering of new fault-blocks to the east and west during the Middle to Late Liassic (Fig. 14 *a*). In the Late Liassic to Middle Jurassic, the axis of rifting was finally shifted somewhat, and break-up and spreading occurred a hundred kilometers to the north and west.

In contrast to undeformed passive margins, the geometry of the presumably listric faults cannot be deciphered in the southern Alps. However, the size and aerial extension of the larger fault blocks suggests that the major fault zones

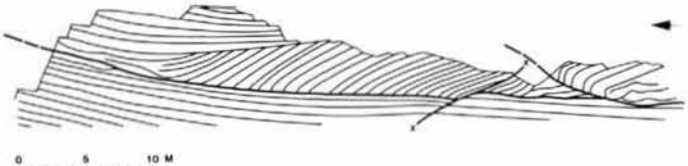
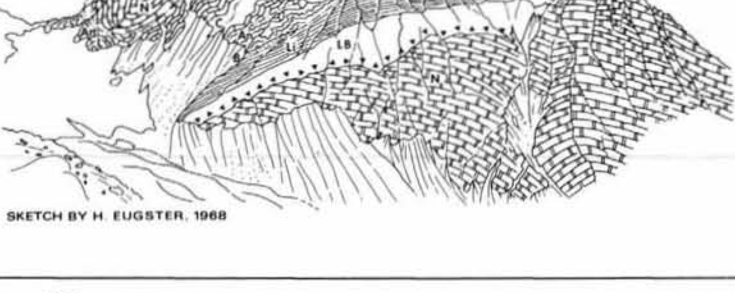


Figure 15

Synsedimentary growth fault in syn-rift sediments, Generoso trough. Lombardian basin. Lombardian siliceous limestones, lower Liassic, road from Caneggio to Bruzella, southern Switzerland. From Bernoulli, 1964.

Figure 16

Piz San Jon (Lower Engadin, Switzerland) seen from the east, as sketched by H. Eugster (see Cadisch et al.*, 1968). Note the pronounced angular unconformity, overlain by Liassic breccias. The dip of the Norian dolomites may be due to rotation of beds along listric faults associated with the rifting phase of the southern margin of the Tethys. Gn : Gneiss of the Oetztal nappe ; Li : Liassic shales ; LB : Liassic breccias overlying angular unconformity ; N : Norian Hauptdolomite ; C : Carnian Raibler schichten ; L : Ladinian dolomites ; An : Anisian Muschelkalk ; B : Permowerfenian Buntsandstein ; x : thrust faults.*



sole within the pre-Triassic basement. In the case of the Lugano fault (Fig. 14 *a*), its present day geometry could indicate a flattening of the fault zone with depth. This north-south-trending fault zone cannot be followed directly into the underlying crystalline basement, but merges with an east-west-trending fault zone that cuts obliquely through Triassic and shallow crystalline basement rocks (see Spicher, 1980).

From middle Liassic to middle Jurassic times, the topography created by rifting in the Lombardian basin was nearly levelled by basinal, hemipelagic and gravity-flow deposits. Only along the platform margin of the Friuli shelf and along the escarpment bounding the Trento platform to the west did important submarine scarps persist throughout the Jurassic and the Cretaceous. In the Lombardian basin, however, local stratigraphic gaps, condensed facies and restricted areas of shallower pelagic facies suggest the persistence of a subdued morphology during post-rift regional subsidence.

The post-rift history of the Tethyan continental margins is characterized by prolonged subsidence probably consistent with exponential thermal decay (Bernoulli *et al.*, 1979 *a* ; Winterer, Bosellini, 1980) as observed in undeformed continental margins (Montadert *et al.*, 1979 *a* and *b*). Water depth at the end of rifting in the Lombardian zone was in the order of 1.000 m or more and about 2.500 m at the end of the Jurassic (Winterer, Bosellini, 1980). During the early Cretaceous the distal continental margin sank to a few kilometers water depth, as shown by the encroachment of deep oceanic facies onto the most oceanward parts of the continental margin. The occurrence of the early Cretaceous black shale formations, believed to be deposited below calcite compensation depth, in tectonic units derived from the most distal parts of the continental margin (Scisti di Levone, Canavese Zone ; Palombini in lowermost Austroalpine nappes ; Trümpy, 1975) suggest water depth in the order of 4 km. Isostatic sinking of the starved distal continental margin to this depth strongly suggests crustal thinning and cooling ; there are, however, so far only limited petrologic data to support this. Perhaps the occurrence of potassium-argon ages of biotite of 170 to 180 Ma in the lower crust of the southern Alps (McDowell, Schmid, 1968) could suggest a phase of crustal thinning and cooling during an early Jurassic phase of rifting. Also, the postulated pre-Alpine high position of the ultramafic rocks of the Ivrea zone and the extreme thinness of some Alpine basement nappes (e.g., Carungas nappe, lower Austroalpine) could possibly be explained in terms of Mesozoic crustal thinning, controlled by listric normal faults.

The paleotectonic evolution outlined for the southern Alps is in no way unique for continental margins of the Tethyan ocean. Although the geological documentation is in most cases very fragmentary, the sedimentary evolution suggests a history of rifting and subsidence (e.g., Bernoulli *et al.*, 1979 *a* ; Graciansky *et al.* ; 1979).

CONCLUSIONS

We have reviewed selected examples of listric normal faults to emphasize the importance of this fault type in the formation of passive margins and orogenic systems.

The documentation of listric normal faults is often elusive. Only reflection seismic data permit either mapping directly or else inferring more or less convincingly the faults themselves. On the other hand, surface data — and in some cases subsurface data based on wells or else from mines — provide a much more detailed perspective of the interaction of sedimentation with the formation of listric normal fault systems. Much work needs to be done to reconcile surface data with reflection seismic data and to come up with satisfactory documentation. It is particularly important to obtain better data on the flat soles of listric normal faults. Only rarely (as in the Bay be Biscay and the Galicia banks) are these displayed on seismic lines. The inference that the *décollement* zones of the metamorphic core complexes of the North American Cordillera may in some way represent the soles of listric normal fault systems that were uplifted to surface is still debated, but is clearly valid in some ranges within the orogen. The problem in the Cordillera is further complicated by the possible reactivation of older thrust fault sole systems by later listric normal faults ("backslippage").

Listric normal fault systems are probably caused by stretching of the upper brittle crust, and they appear to be linked by strike-slip or transform-type faults. The suggestion is that listric normal fault systems tend to bottom out in the middle of an attenuated continental crust (say, 10 km), in a position that may well coincide with some of the low velocity layers that have been reported by seismologists (Mueller, 1977).

The amount of stretching of the upper brittle crust associated with listric normal faulting probably cannot be deduced with any accuracy from extension observed at or near the surface unless regional seismic reflection data and/or drill holes permit linking the surface observation with the deeper subsurface. Rough estimates made in areas such as the Bay of Biscay or the Basin and Range suggest that the stretching of the upper brittle crust had to be accompanied by ductile stretching of the underlying basement to explain the crustal attenuation actually observed on limited refraction data. While it is theoretically appealing to postulate such stretching (or else possible creep) in the lower crust, it is much more difficult to document its occurrence. Such documentation would have to be in the form of geophysical measurements that unambiguously describe the rock properties of the lower crust (and maybe the upper mantle) in an environment that is today under extension. An entirely different type of documentation could come from outcrop studies of the now allochthonous crust originally underlying passive margins that today are involved in folded belts. Such studies would need to date basement fabrics that were generated during the rifting-stretching phase of the former passive margins. Prime candidates for such studies are the Eastern Alpine thrust sheets and the large crystalline thrust sheets of the Himalayas.

In all cases future studies focusing on crustal attenuation and listric normal faulting will have to be based on the integration of geophysical observations with surface and subsurface geological data.

Acknowledgements

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