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Modes of extensional tectonics

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Abstract—Although hundreds of papers have been devoted to the geometric and kinematic analysis of compressional tectonic regimes, surprisingly little has been written about the details of large-scale strain in extended areas. We attempt, by means of quantitative theoretical analysis guided by real geological examples, to establish some ground rules for interpreting extensional phenomena. We have found that large, very low-angle normal faults dominate highly extended terranes, and that both listric and planar normal faults are common components of their hanging walls. The very low-angle normal faults may have displacements from a few kilometres up to several tens of kilometres and we regard their hanging walls as extensional allochthons, analogous (but with opposite sense of movement) to thrust-fault allochthons. Differential tilt between imbricate fault blocks suggests listric geometry at depth, whereas uniformly tilted blocks are more likely to be bounded by planar faults. The tilt direction of imbricate normal-fault blocks within large extensional allochthons is commonly away from the transport direction of these sheets, but in many cases tilts are in the same direction as transport, thus limiting the usefulness of the direction of tilting as a transport indicator. The presence of *chaos* structure, a structural style widely recognised in the Basin and Range Province, implies large scale simple shear on very low-angle normal faults and does not necessarily form as a result of listric faulting.

INTRODUCTION

WORK in extensional terranes has shown that they contain a great variety of faults active during deformation. Extensional faults can be grouped into two broad categories: (1) those which produce extension accompanied by rotation of beds, and in a subgroup are additionally accompanied by rotation of the faults and (2) those which produce extension without rotation of faults or beds. In this paper we present an analysis of the geometric and kinematic properties of these fault types and examples of them from extensional terranes, principally the Basin and Range Province of the western United States. The Basin and Range Province is important in the study of the rifting process because it has not thermally subsided and been covered by post-rift sediments, it is well exposed and locally well mapped, it contains a great variety of extensional fault-types, and finally, because vertical movements and erosion have been substantial, a great variety of structural levels are exposed within the extensional complexes. We believe that the analysis of faults and extensional features in this region can be applied to other extensional terranes, particularly to passive continental margins.

Whereas in most extensional terranes the amount of extension is poorly constrained, there are regions within the Basin and Range Province where a minimum amount of extension can be measured without making any assumptions about cross-sectional fault geometry. Such analyses indicate province-wide extension of 64–100% and local areas which have extended well over 100% (e.g. see Hamilton & Myers 1966, Davis & Burchfiel 1973, Hamilton 1978, Wernicke *et al.* 1981). Extension of this order has been suggested for continental margins, but their fault geometries are less well-known. Our analysis indicates that certain fault types (or combinations of them) can easily produce extension of this magnitude, but these fault types are not the ones commonly assumed to have produced the extension. The conclusion we reach is that widespread imbricate normal-fault blocks (Anderson 1971) and subjacent, large low-angle normal faults provide an explanation for the large magnitudes of extension observed. Listric normal faults function to relieve space problems between families of planar fault blocks, but are not the only contributor to the extension. The geometric and kinematic models we present are testable in the field and by geophysical techniques, especially seismic reflection profiling.

EXTENSIONAL MECHANISMS

We divide extensional structures into two broad classes: rotational and non-rotational (Table 1).

Rotational extension

Rotational extension is defined as a kinematic

Table 1. Types of normal faults

Group	Structures rotated	Fault geometry
Non-rotational	Nothing	Planar
Rotational	Beds	Listric
Rotational	Beds and faults	Planar or listric

mechanism in which extension occurs predominantly by progressive rotation of geological features (hereafter called beds). There are two possible fault geometries in this class: planar and listric.

Planar geometry is depicted in its simplest form in Fig. 1 (all the models presented here are highly simplified and assume no penetrative deformation, pressure solution or bedding-plane slip). As the rock mass is extended, both the faults and the beds rotate (Emmons & Garrey 1910) (Table 1). The simple calculation, the basis of which is presented in Fig. 2 (Thompson 1960), allows us to determine the amount of extension if the attitudes of the faults and beds are known. Figure 3 is a convenient graphical representation of the relationship derived in Fig. 2. Because field examples of rotational extension are invariably more complex than the geometry shown in Fig. 1, it is possible to use Fig. 3 only for approximate determinations. Accurate determination of extension in any given area can be done only by palinspastic restoration of geological maps and cross-sections.

A simple rotational listric fault (Table 1) is shown in Fig. 4. Extension occurs by the separation of two blocks on a curved surface. Because hanging wall strata move down a curved surface convex toward the footwall strata and maintain a constant orientation relative to that surface, listric faults produce differential tilt between hanging wall and footwall, i.e. bedding dips are steeper in the hanging wall than in the footwall. Thus, a series of imbricate listric fault blocks should display successively steeper tilts as one traverses the blocks in the direction of downthrow (Fig. 5), whereas a row of planar fault blocks should all be tilted by the same amount. Another distinction between rotational-planar and listric faults is that planar faults must rotate with bedding, whereas listric faults may remain fixed, rotation occurring only if their footwalls are rotated by structurally-lower faults. Therefore, two groups of rotational faults may be distinguished, one in which both faults and beds rotate, including both listric and planar faults, and a second in which the faults remain fixed while the beds rotate, a situation restricted to listric fault geometry (Table 1).

A geometrically possible situation in which both faults and beds rotate but which is difficult to classify in terms of planar or listric faulting is shown in Fig. 6. The

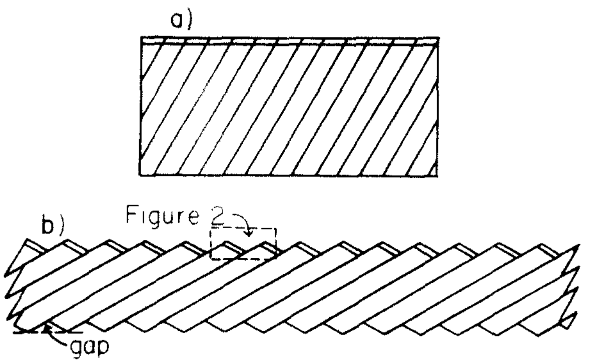
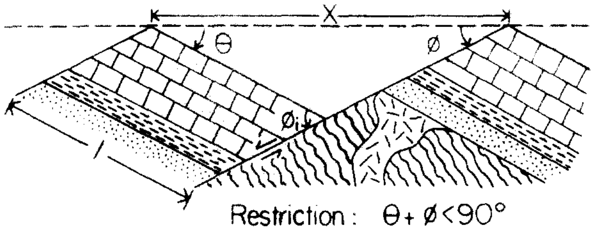


Fig. 1. Extension and attenuation of a rock mass by rotational planar normal faulting.



$$\%\text{ext.} = (X - l)100 = \left[\frac{\sin(\phi+\theta)}{\sin\phi} - 1\right]100$$

$$\text{alternatively, }\%\text{ext.} = \left[\frac{\sin\phi_i}{\sin(\phi_i-\theta)} - 1\right]100$$

Fig. 2. Geometrical derivation of the relationship between fault dip (ϕ) and percentage extension of the rock mass, as proposed by Thompson (1960).

extreme displacement on a series of imbricate listric-fault blocks (fault displacement being about the same as the length of the block) may result in a series of uniformly tilted planar-fault blocks. Even though the faults were initially listric, calculation of extension can be done assuming a planar geometry (Figs. 2 and 3), because the final geometry is that of a series of sub-planar blocks.

Consider a situation, similar to that illustrated in Fig. 5, in which the lowest block is rotated on a listric fault but the remainder of the blocks rotate on planar faults above a basal detachment surface (Fig. 7). It is important to note that even though the planar faults may curve into the detachment surface, rotation and thinning of the mass above it is not a result of listric faulting. Curvature of the faults near the base of the blocks, and the 'gap' (Fig. 1) created by rotation of the planar fault blocks above a detachment surface, are space problems which in real geological situations are accommodated by small-scale faulting, pervasive brecciation and, possibly, plastic flow. The key diagnostic feature of fault geometry is differential tilt between blocks, not necessarily the geometry of the fault near a basal detachment surface.

Syntectonic sedimentary deposits which show increas-

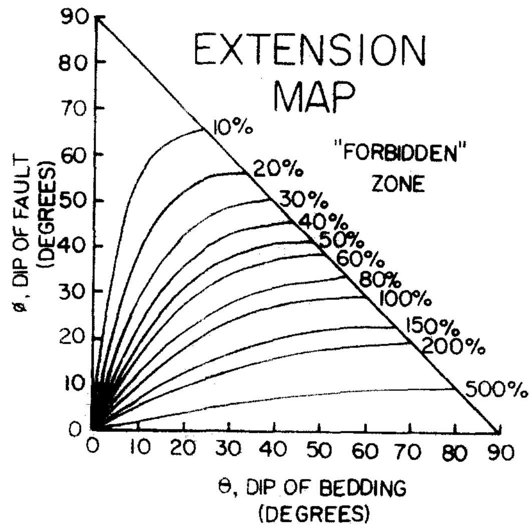


Fig. 3. Graphical representation of relations derived in Fig. 2.

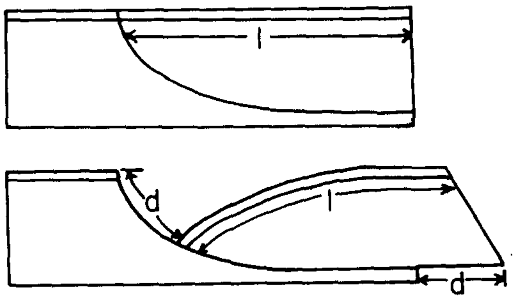


Fig. 4. Listric normal fault with reverse drag (Hamblin 1965).

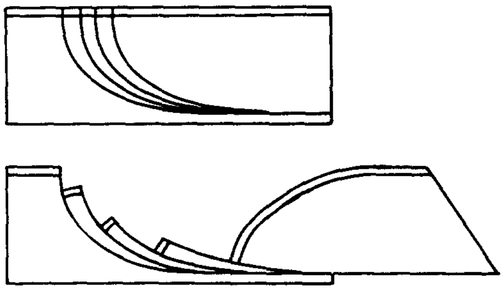


Fig. 5. Imbricate listric normal faults.

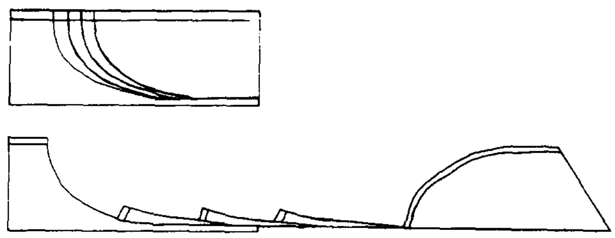


Fig. 6. Thin, imbricate listric fault blocks unflexed by extreme extension, the displacement on each fault being roughly the same as the length of the block.

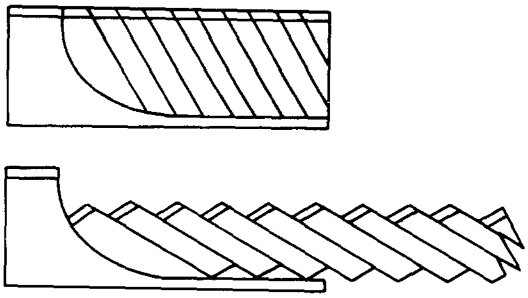


Fig. 7. Listric normal fault bounding a family of planar fault blocks.

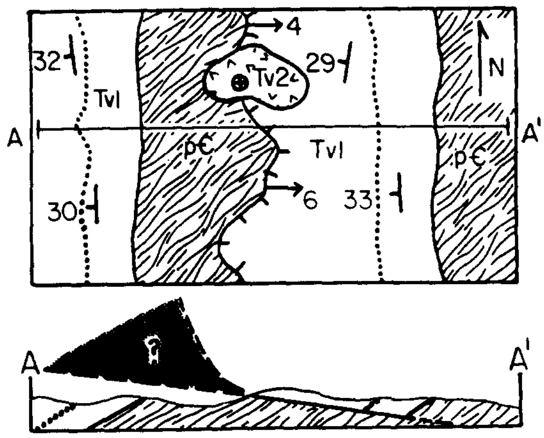


Fig. 8. Hypothetical geological map and section depicting the difference in amount of extension determined palinspastically between planar and listric rotational normal faulting.

ing dip with age, commonly referred to as growth-fault deposits, may develop in any setting involving rotational normal faulting. These deposits always dip toward the fault, except near the fault at the depositional surface where they may dip away from the fault.

A hypothetical situation shown on the geological map and section of Fig. 8 demonstrates the importance of diagnosing fault geometry. A low-angle normal fault dipping about 5° east offsets a section of 41 Ma volcanic rocks (TV1) and is overlain uncomformably by a near-horizontal section of volcanics (TV2) dated at 39 Ma. Because the dip of bedding, and hence net rotation, of the two blocks is equal, the fault is best interpreted as planar, and its projection above the cross-section would be a straight line. However, if one were to assume that the fault was the flat portion of a listric fault and assumed it to steepen above the section, the estimate of extension represented by the fault would be considerably less than that predicted by assuming a planar fault geometry (for an application see Le Pichon & Sibouet 1981). To emphasize this point, we have constructed a geometric model of a listric fault (Fig. 9). The model assumes that the angle between bedding and the fault surface remains constant during deformation, and that curvilinear seg-

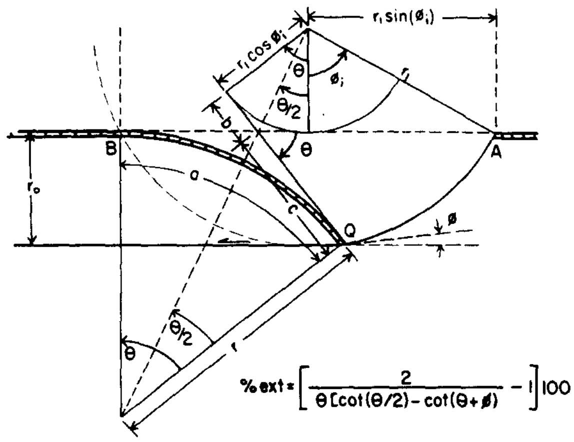


Fig. 9. Listric fault model. See text for explanation.

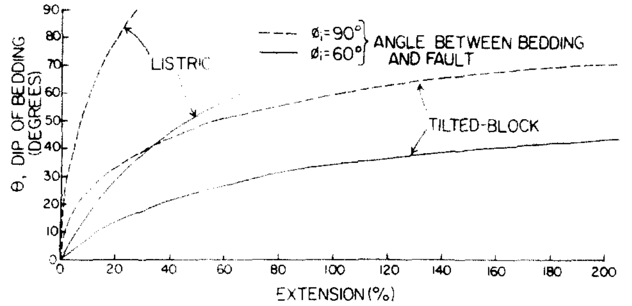


Fig. 10. Comparison of extension for listric and planar rotational normal faults.

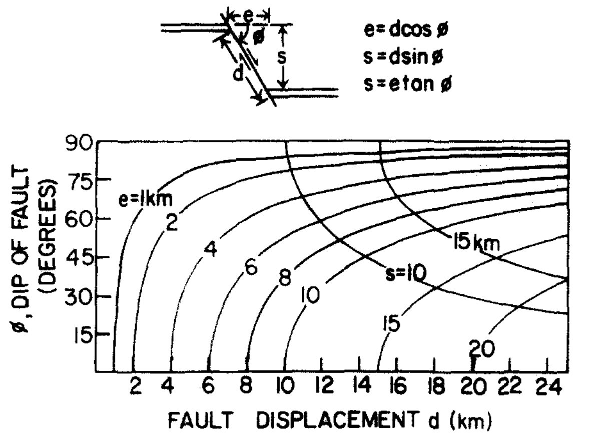


Fig. 11. Non-rotational normal fault, with equations for, and graphical representation of, the relations between displacement (d), extension (e), stratigraphic omission (s) and fault dip (ϕ).

ments of the diagram are arcs of circles. The percentage extension is calculated by comparing the distance between A and B with the length of *a*. By expressing the extension in terms of the dip of the beds next to the fault and the dip of the fault, we may compare the listric model with the planar model derived in Fig. 2. The result, shown in Fig. 10, demonstrates that for a given maximum stratal rotation and fault dip, the listric geometry yields far less extension than the planar geometry.

Non-rotational extension

Non-rotational extension is defined as a kinematic mechanism in which extension takes place without rotation of geological features, for example the high-angle normal fault in Fig. 11 (Table 1). For convenience we have plotted the dip of the fault vs fault displacement for various values of net extension. For non-rotational faults which have a very gentle dip, determination of displacement is difficult in most geological situations. Consider for example an undeformed sequence of strata cut by a very low-angle normal fault. The relationships displayed in Fig. 11 show that displacement and extension on the fault are specified if the dip of the fault and the stratigraphic omission across it are known. Thus, a more convenient representation of the magnitudes of extension possible on these faults is a plot of stratigraphic omission vs fault dip (Fig. 12). In real geological situations, low-angle normal faults, in common with thrust faults, may show a ramp-décollement geometry if developed in sedimentary sequences of variable competence (Fig. 13) (Dahlstrom 1970). The fault dip appropriate for use in Fig. 12 in this situation would be the fault–bed angle averaged along the direction of transport. Introduction of listric faulting by ramps will cause rotation of strata, but the gross picture of one large sheet moving over another is most easily visualized as non-rotational, since there is no net rotation of the hanging wall. The distinguishing characteristic of low-angle normal faults, as opposed to thrust faults, is the juxtaposition of younger rocks on older with omission rather than repetition of strata. Thus, the rules of interpretation are the inverse of thrust faulting.

Large-displacement, very low-angle normal faults may show a number of movement planes, just as large displacement thrusts do. For example, consider the situation depicted in Fig. 14(a) where a large, low-angle normal fault is initiated in an undeformed sedimentary sequence. After an offset of one stratigraphic unit, movement is initiated on a slightly higher plane (Fig. 14b). The thin sheet between the two faults is accreted to the footwall of the first fault, and movement on the second of one more stratigraphic unit creates the configuration shown in Fig. 14(c), an attenuated stratigraphic section. The total displacement on the fault system is the sum of that across the two faults, and thus, no matter how complex the system of faults, the total stratigraphic omission may be used in Fig. 12 to determine how much extension the stack represents, provided the average fault–bed angle is reasonably well-known.

EXAMPLES

We believe that the modes of extension discussed above can be found in the geological record, and present here some examples of each type.

Perhaps the most completely documented type of extensional fault is the simple listric normal fault, shown here in a reflection profile from a continental margin setting (Fig. 15). Although Fig. 15 is a time section only, and thus cannot be regarded as a true geological section,

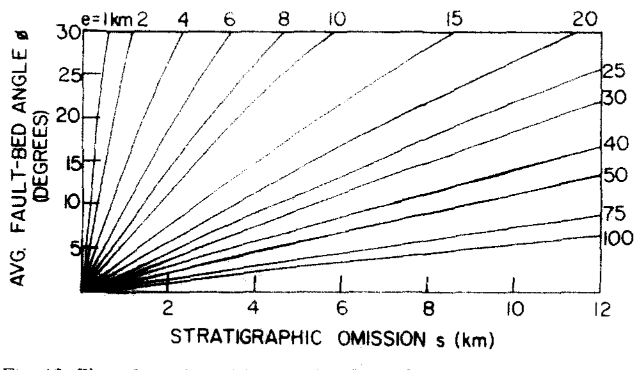


Fig. 12. Plot of stratigraphic omission (s) vs fault dip or average fault–bed angle (ϕ) using non-rotational fault model and equations from Fig. 9.

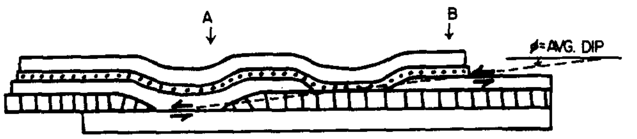


Fig. 13. Ramp-décollement geometry for large normal faults. Introducing a component of listric faulting forces some rotation of bedding (after Dahlstrom 1970).

the differential tilt between hanging wall and footwall, and the growth fault character are clear. We interpret the hanging wall as a series of uniformly tilted fault blocks bounded by planar faults, which serve to extend it without creating differential tilt between the blocks, that is the configuration is analogous to the geometry shown in Fig. 7. It is important to note that in moving downward from the steeply-dipping to the more gently-dipping portions of a listric fault, differential rotation should gradually decrease until the fault has the characteristics of a very low-angle non-rotational fault.

A series of imbricate normal-fault blocks showing successively steeper tilts was mapped by Anderson (1971) (Fig. 16). The configuration requires initially curviplanar fault blocks, although some have apparently been 'straightened out' by the extension (cf. Fig. 6).

Figure 17 shows a small-scale example of rotational planar faulting from the Rawhide Mountains of west-central Arizona, where measured and theoretical determinations of percent extension using Fig. 2 agree at about 25–30%. The first documented planar rotational normal faulting was recognized by Emmons & Garrey (1910) (Fig. 18). They mapped an impressive sequence of evenly-tilted fault blocks in Tertiary volcanic rocks in the Bullfrog Hills of southern Nevada. They interpreted the structures as having formed like a row of tilted dominoes in which both faults and beds rotated simultaneously and concluded that they could be most easily explained by extension of the crust. Fifty years later the relations between fault dip, stratal dip and extension, were derived by Thompson (1960), and were derived again by Morton & Black (1975). Despite three separate conceptualizations of this mechanism, it has been almost completely ignored in the literature on the Basin and Range Province, where beginning with Longwell (1945) virtually all small-scale imbricate normal faults were described as listric (except Thompson 1971), who speculated that some of Anderson's 1971 normal faults may be planar) to the point that low-angle normal fault and listric normal fault came to be used interchangeably by many authors. We believe that true listric normal faults as envisioned by most workers form only a portion of extended terranes, and that much (if not most) extensional strain in the earth's crust is accommodated by both rotational and non-rotational planar normal faults.

Non-rotational, high-angle extensional faults are described abundantly by many geologists (e.g. Stewart 1971), but much less attention has been given to their low-angle counterparts. One of us (Wernicke 1981) has emphasized the potential importance of these faults in accommodating lithospheric extension, and we suspect that structures produced by this type of fault are extremely common in the Basin and Range Province. For example, Dechert (1967) (Fig. 19) mapped a stack of fault slices in Palaeozoic miogeoclinal and Tertiary volcanic strata in the Schell Creek Range of east-central Nevada across which about 5 km of strata are missing. Because the faults are nearly parallel with bedding, the structure is most logically thought of as having been produced by the mechanism shown in Fig. 14. Consideration of Fig. 12 suggests that these sheets record tens of kilometres of extension. Noble (1941) coined the term *chaos* for this type of structure after an example he mapped in the Death Valley region (Amargosa chaos), and attributed its formation to a large, regional thrust sheet. Wright & Troxel (1969) recognised the extensional nature of the Amargosa chaos, and proposed that it developed in a zone of coalescing listric normal faults. Although their interpretation is reasonable for portions of the Amargosa chaos, we would like to emphasize that a comparable structural assemblage may form without rotational faulting simply by peeling sheets off the base of the hanging wall, that is the allochthon, of large displacement, non-rotational normal faults.

Another example of a large-scale extensional allochthon can be seen on a seismic reflection profile from the Sevier Desert area of central Utah (McDonald 1976)

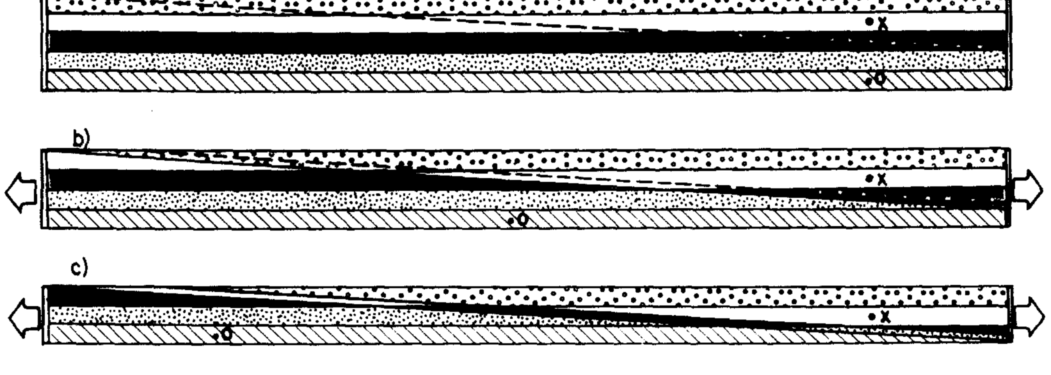


Fig. 14. Formation of *chaos* structure. (a) Unfaulted sedimentary sequence, with reference points marked × and O. (b) Fault displaced one stratigraphic unit. (c) New fault with an additional offset of one stratigraphic unit. See text for discussion.

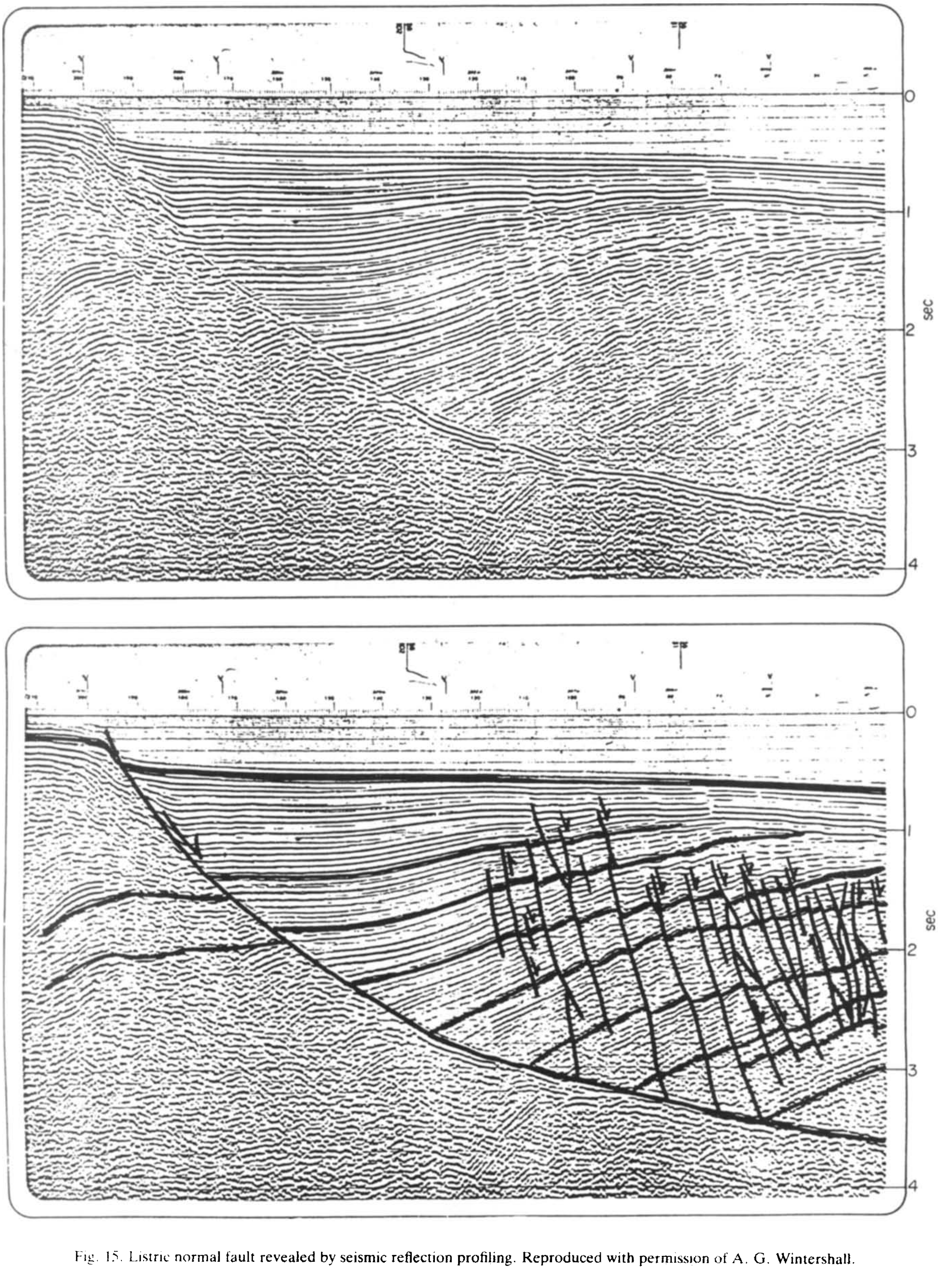


Fig. 15. Listric normal fault revealed by seismic reflection profiling. Reproduced with permission of A. G. Wintershall.

(Fig. 20). The section reproduced convincingly demonstrates that parts of a given hanging wall may remain unrotated while other parts may rotate in opposite directions. We conclude from this that (1) the sense of rotation in a given hanging wall does not indicate its transport direction and (2) the boundaries between tilted and non-tilted parts of extensional allochthons give no information as to the extent of their basal faults beyond those boundaries. In other words, large areas of seemingly intact rock at the surface may be underlain by large, low-angle non-rotational normal faults.

DISCUSSION

The extensional mechanisms described above are not mutually exclusive and can operate contemporaneously within a given extensional system. Listric normal faults, because of their geometry, can separate areas undergoing differential extension and merge at depth with low-angle normal faults. Above a low-angle normal fault further extension can be accommodated by imbricate normal faulting in which both faults and beds rotate (Fig. 21). In areas where large-magnitude extension has occurred, the low-angle normal faults and superjacent imbricate rotational faults may be the main contributors to the overall extension. This simple scheme can be modified and become more complex where differential extension has occurred in the rotated block sequence, in which case listric faults should be present. The low-angle fault or faults at the base of the faulted sequence anastomose leading to the development of *chaos*-type structure. Low-angle faults may also be present at different structural levels, thus dividing the crust into an imbricate stack of allochthonous slices each with both rotational and non-rotational fault blocks in their hanging walls.

One of the important problems is the geometry and character of the low-angle normal fault at the base of a series of faulted blocks. Wernicke (1981) has suggested such faults may involve the entire lithosphere. If this is the situation, the lower crust may be extended simply by divergence of two rigid slabs separated by a gently-dipping shear zone. Brittle shear would occur at shallow levels and grade downward along the low-angle fault to a zone of ductile shear (Fig. 21). The ductile shear would be restricted to the shear zone rather than distributed uniformly throughout the footwall crustal block, as envisioned by Eaton (1979) and Le Pichon & Sibouet (1981). With such a geometry, continental crust could be attenuated to any thickness, and unmetamorphosed sedimentary rocks could be juxtaposed by large-displacement low-angle normal faulting with any part of the crust. In this type of extensional system, rocks which were formerly sheared in a ductile state at deep structual levels along the shear zone early in the history of deformation may be reworked in the brittle regime as shown in Fig. 21.

It is possible, for example, that the prominent reflector at the base of the imbricate normal fault blocks in the Bay of Biscay (reflector '*s*', Fig. 22) is simply a crustal-scale low-angle normal fault, rather than a boundary between brittle extension and penetrative ductile stretching as suggested by de Charpal *et al.* (1978) and Le Pichon & Sibouet (1981). Such an interpretation is consistent with geometrically identical examples in the Basin and Range Province where the rocks below the basal detachments behaved as rigid plates during emplacement of the extensional allochthons (e.g. Misch 1960, Davis *et al.* 1980, Wernicke 1981). Thus, although Le Pichon & Sibouet (1981) demonstrated that the degree of extension by imbricate normal faulting was as large as a factor of two or three, their assumption that the lower crust stretched penetratively by that amount may be incorrect; it is geometrically possible that the crust beneath the basal reflector and mantle lithosphere had not extended at all! This view has rather dramatic implications for geophysical models of passive-margin rifting using subsidence history because it violates their fundamental assumption that the lithosphere stretches like a large elastic band (e.g. McKenzie 1978). It implies that a certain amount of crust which originally lay above reflector '*s*' is now incorporated in the complex southern margin of the Bay of Biscay and in the western Pyrenees. Furthermore, it implies the lower crust can be very heterogeneous.

Large displacement, low-angle normal faults which serve as boundary faults to both rotational and non-rotational extensional fault mosaics have been termed detachment faults by Davis *et al.* (1980) and Dokka (1981), and Davis *et al.* (1981) have followed this usage when describing a number of terranes throughout southern California, Arizona, northern Sonora and Mexico. We believe the overall geometry and kinematics of many extensional terranes have much in common, but because their three-dimensional geometries are

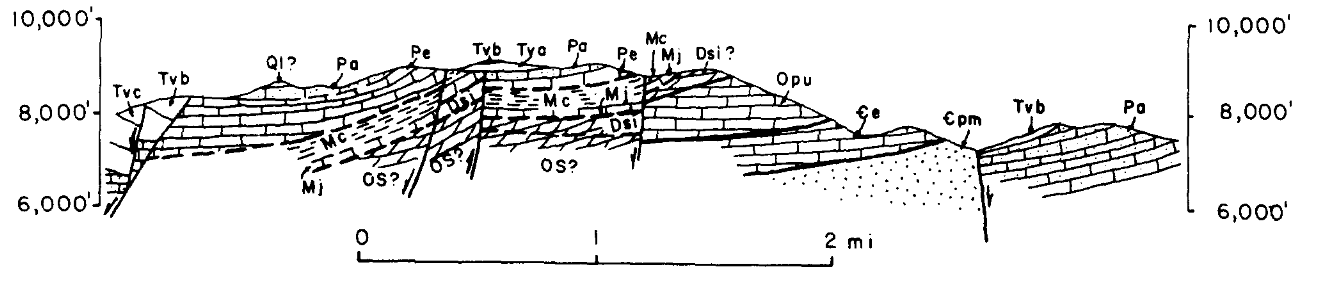


Fig. 19. Cross-section from the Schell Creek Range of east-central Nevada, showing the development of *chaos* structure (after Dechert 1967). Note that the horizontal and vertical scales are in miles and feet, respectively.

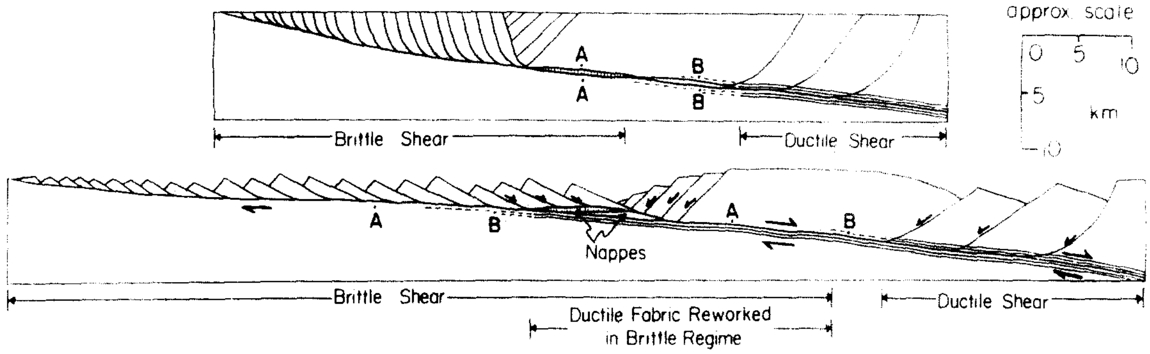


Fig. 21. Large, low-angle normal fault bounding an extensional fault mosaic comprised of listric and planar rotational faults, and an example of how *chaos*-structure might form (two imbricate nappes) beneath an imbricate pile of rotational normal faults. Also shown is a means by which a brittle-fault mosaic may be juxtaposed upon a slightly earlier-formed penetrative ductile fabric (e.g. Snoke 1980). From Wernicke (1981).

poorly known, the use of such terminology should remain informal.

Non-rotational high-angle normal faults are present in extensional terranes, but contribute only a small amount to the overall extension. They may be superimposed on older, large-scale extensional fault systems like those described above (Eberly & Stanley 1978, Zoback *et al.* 1981) and/or be the dominant fault type in areas that have undergone lesser amounts of extension in an inhomogeneously extended terrane.

CONCLUSIONS

The geometry and kinematics of faults in extensional regions can be grouped into two broad categories: (1) those which produce extension accompanied by rotation of layers, and in a subgroup are accompanied by rotation of the faults as well and (2) those which produce extension without rotation of faults or layers (Table 1). Our analysis suggests that large-scale extension is accomplished by large displacements on low-angle faults of the second group and rotated faults and fault blocks (both listric and planar) of the first group. Non-rotated listric normal faults are geometrically important as 'space fillers' but may not be as significant as the other fault types in producing large-scale extension. Several fault types are related and form contemporaneously: listric normal faults, rotated faults and fault blocks, and large-displacement, non-rotational low-angle normal faults may all form a single fault system with the individual fault types unequally developed from place to place.

While many of the examples presented here are from the Basin and Range Province of the United States, the ideas are probably valid for any terrane which has undergone large magnitude extension. Passive continental margins are probably regions of large magnitude extension, and similar complex fault systems may have developed during their formation.

Our ideas are ultimately testable. Greater detailed mapping coupled with geophysics and drill-hole information should provide the necessary three-dimensional control. From such data we should be able to palinspastically reconstruct the extended terrane, just as we do thrust-fault terranes.

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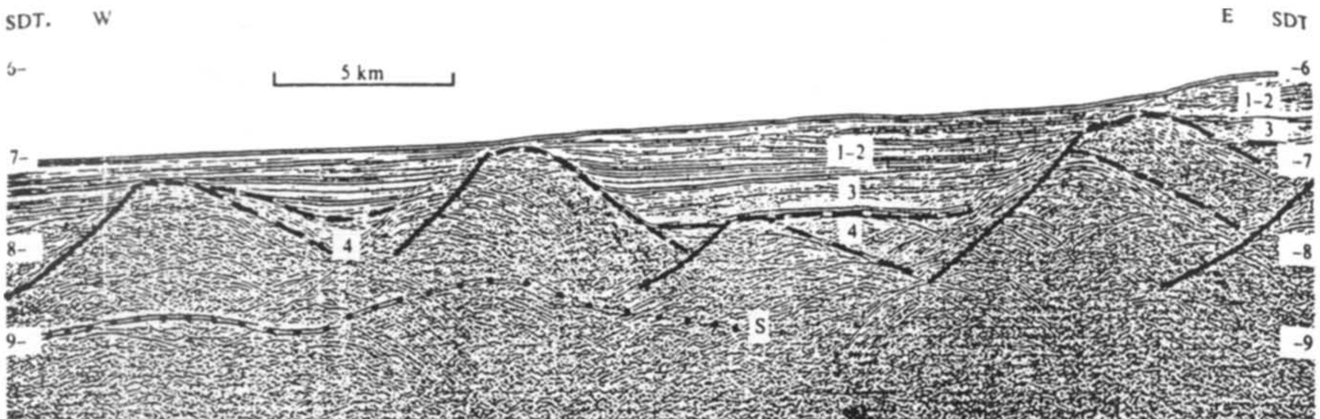
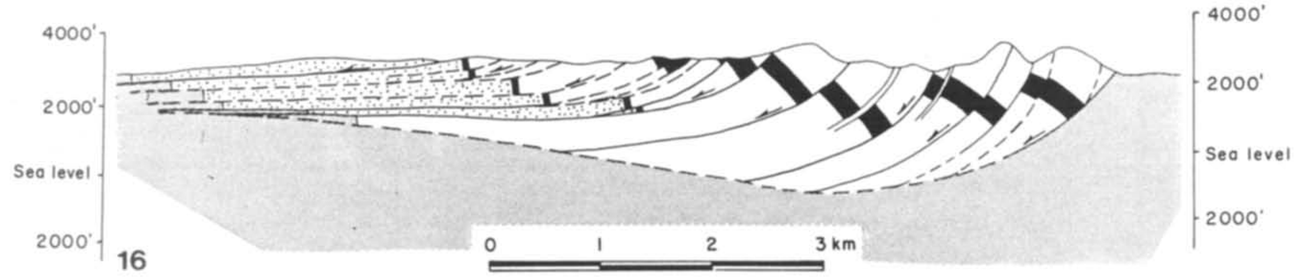
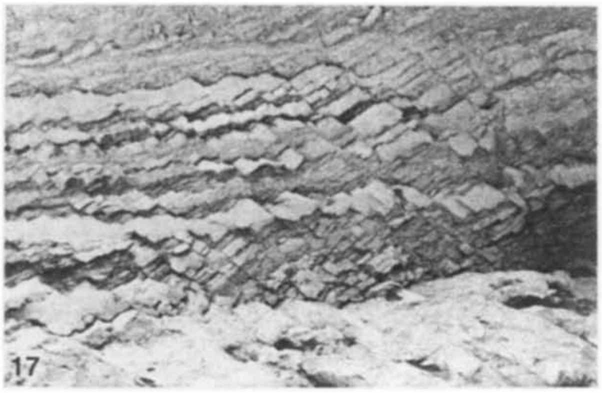


Fig. 22. Seismic reflection profile from the Bay of Biscay (from de Charpal *et al.* 1978).





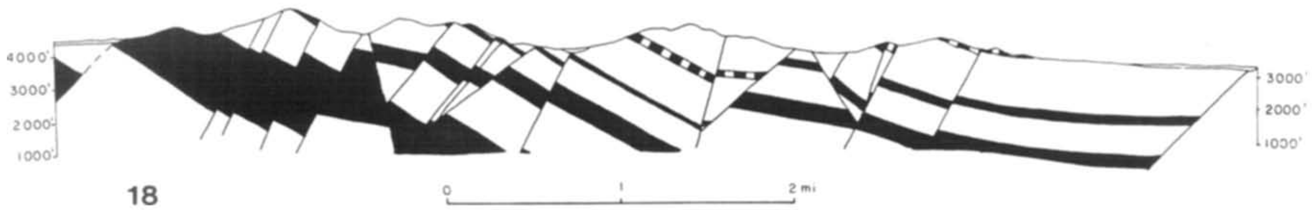


Fig. 16. Cross-section of imbricate listric faults in the Eldorado Mountains of southern Nevada (after Anderson 1971).

Fig. 17. Outcrop-scale example of rotational planar normal faulting from the Rawhide Mountains of west-central Arizona, studied by Shackelford (1980). The area shown is about 2 metres high.

Fig. 18. Cross-section of probable imbricate planar (to the left) and listric (to the right) normal faults in the Bullfrog Hills of southern Nevada (after Emmons & Garrey 1910).

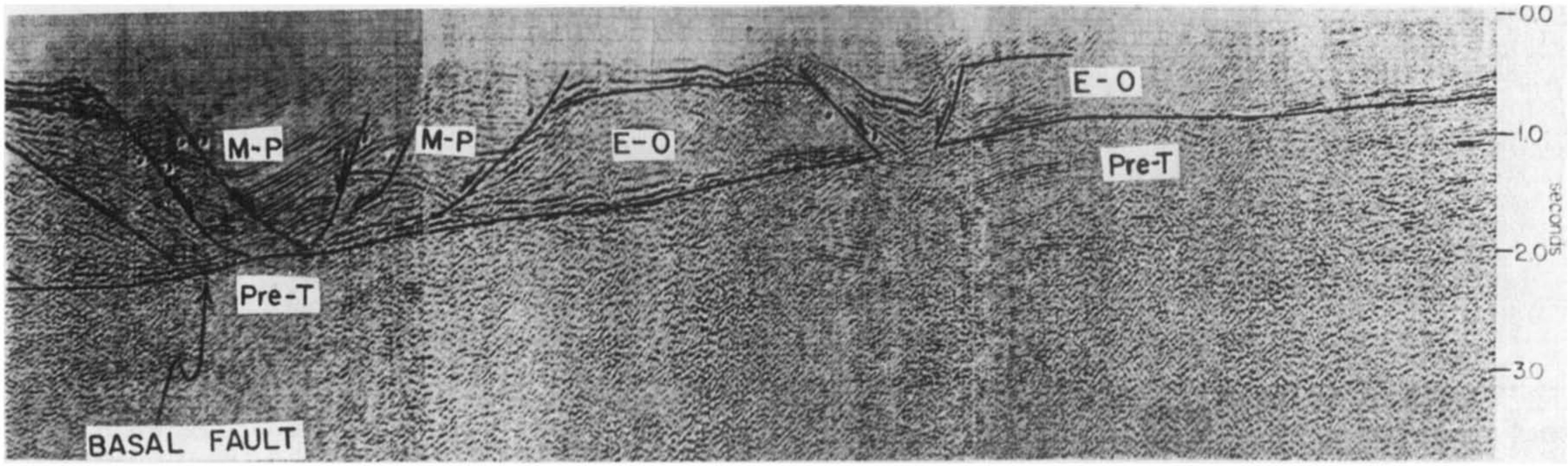


Fig. 20. Two-way time section of the Sevier Desert area, central Utah (after McDonald 1976), section is approximately 40 km long. Reproduced with permission of the Rocky Mountain Association of Geologists.

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