CHAPTER

5

Normal Faults

Normal faults[1] (Figure 5.1) are inclined dip-slip faults along which the hanging wall block has moved down with respect to the footwall block. Generally, they emplace younger rocks on top of older rocks, and in a vertical section through the fault, stratigraphic section is missing. Most normal faults have steep dips of about 60°, but many have lower dips, some approaching horizontal. As a result of the hanging-wall-down motion, normal faults accommodate a lengthening, or extension, of the Earth's crust.

5.1 Characteristics of Normal Faulting

Separation and Normal Faulting

Strike and dip separations produced by normal faulting depend on the relative orientations of the fault and the stratigraphic layering. As we noted in Section 4.3, separation can be quite misleading as an indication of the nature of a fault. For example, Figure 5.2 shows a series of block diagrams of a normal fault cutting various orientations of bedding, none of which are overturned. In all the diagrams on the left, pure dip-slip motion on the fault displaces the stratigraphy and produces a scarp on the footwall block. Each diagram on the right shows the same geometry as the diagram to its left, except that the fault scarp has been eroded away, leaving a horizontal planar surface.

In Figure 5.2A, the fault cuts horizontal beds, leaving a simple stratigraphic discontinuity. In Figure 5.2B–D, the bedding is inclined at various angles to the fault, resulting in some potentially confusing separations. In Figure 5.2B, for example, the horizontal plane shows a repetition of the stratigraphy across the fault, although stratigraphy is missing on the vertical section. This example emphasizes the fact that for a normal fault, the characteristic of *missing* stratigraphic section applies only to a vertical section through the fault. If, however, on a vertical section normal to the fault, the apparent dip of the beds is in the same direction as, but steeper than, the fault, a vertical hole through the fault reveals *repeated* stratigraphy. Moreover, if the beds are not overturned, then such a fault places older beds on top of younger.

In Figure 5.2C and D, the stratigraphic pattern is characterized by strike separation on the horizontal plane and dip separation on a vertical section. In C, the

---

[1] *The terms* normal *and* reverse *applied to faults stem from eighteenth- and nineteenth-century mining. The "normal" situation in the coal mines of Britain was that the coal seams in the hanging wall block moved down on the fault relative to the same seam in the footwall block. If the hanging wall block had moved up, the "reverse" of the normal situation existed.*

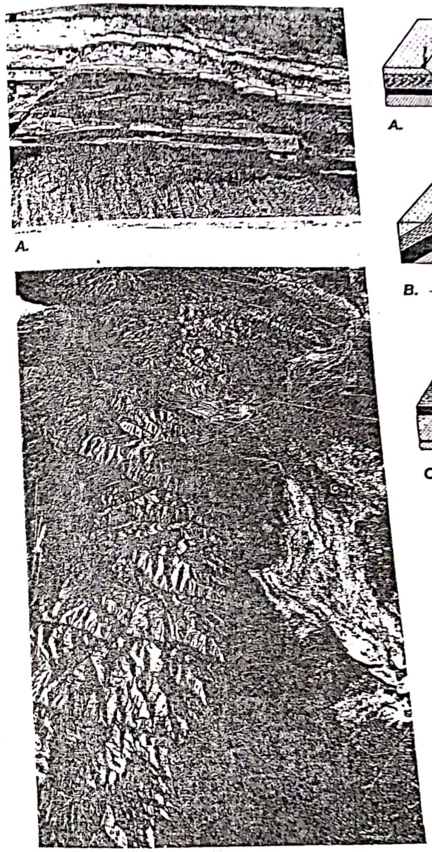


Figure 5.1 Normal faults. A. Small-scale normal faults including examples with opposite directions of dip in beds of volcanic ash exposed in a road cut approximately 5 m high near Klamath Falls, Oregon. B. A normal fault bounds the east side of the Stillwater Range in Nevada, separating the rugged topography of the range from the flat valley floor. Note the sinuous trace of the fault and the flatirons, or faceted ridges, along the length of the fault.

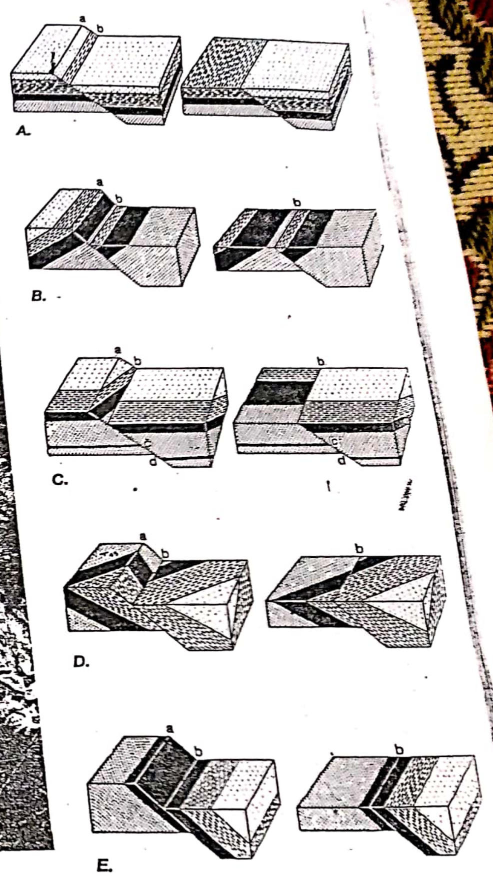


Figure 5.2 Separations of stratigraphy created by dip-slip normal faults cutting different attitudes of bedding. In the diagrams on the left, the fault blocks have been displaced, leaving scarps on the footwall block. In the diagrams on the right, the scarp has been eroded down to a level even with the hanging wall block.

strike separation is right-lateral, and in *D* it is left-lateral, even though both faults have identical, pure dip-slip displacement.

In Figure 5.2*E*, the fault and the displacement are both parallel to the bedding, leaving no separation visible on any bedding plane. In fact, for any situation, including all those shown in Figure 5.2, any component of displacement parallel to the cutoff line of the bedding on the fault surface produces no effect on the separation in any section through the fault. Thus, because of the indeterminate magnitude of this component of displacement, none of the patterns of separation in Figure 5.2 is unique to normal dip-slip motion on the fault.

A surface across which the metamorphic grade of the rocks changes abruptly from high-grade rocks below to lower-grade or unmetamorphosed rocks above may be a normal fault. The cutting out of metamorphic grades is comparable geometrically to the cutting out of stratigraphy.

Folds Associated with Normal Faults

In areas where flat-lying beds are deformed by normal faults, rollover folds in the hanging wall block are common, illustrated by the deeper strata in Figure 5.3 (compare Figure 4.11*D*). In these folds, the beds in the hanging wall block tilt down into the fault, which is opposite to the direction of tilt on drag folds (compare Figure 4.11*B*). They form on listric normal faults, which are concave-upward faults—that is, faults whose dip decreases with increasing depth (the Greek word *listron* means "shovel") (see Section 5.2). As the hanging wall block slips on the fault, it deforms to maintain contact with the footwall block across the fault, thereby producing a bend in the layering (see Figure 5.17).

Drag folds tend to be smaller-scale features on normal faults than rollover folds and may be less common. In these folds, the beds in the hanging wall block tilt up against the fault, and those in the footwall block tilt down into the fault, as shown by the shallow strata in Figure 5.3, and the small-scale folds against the eastern fault of Railroad Valley in Figure 5.6. Where they can be definitely recognized, they indicate the sense of relative displacement across the fault.

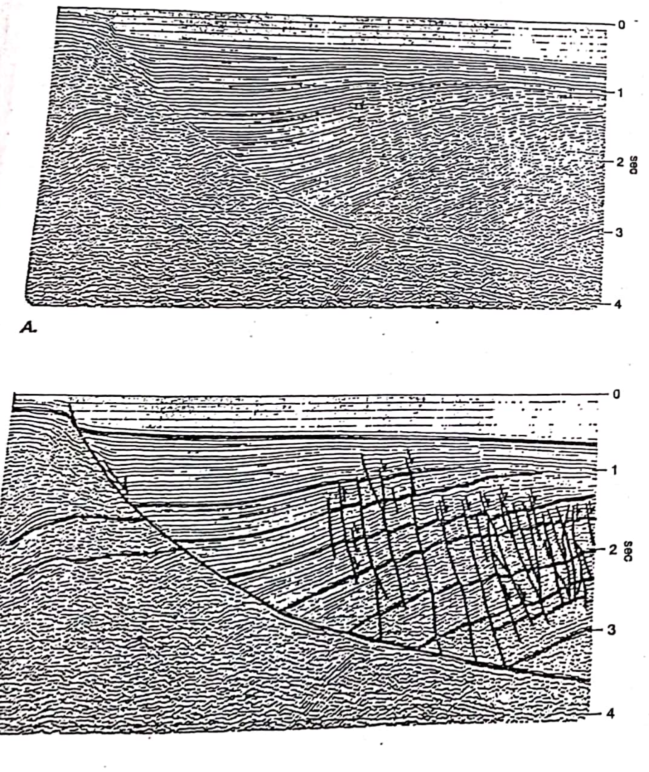


Figure 5.3 Seismic reflection profile of a listric normal fault. The hanging wall block is cut by a set of subsidiary "synthetic" normal faults, which are faults having the same dip direction and sense of shear as the major fault. Note the small scale drag of the layers in both blocks along the steep part of the fault and the larger-scale rollover fold in the layers of the hanging wall block along the shallowly dipping parts. *A.* Seismic reflection profile. *B.* Interpretation of beds and faults on the seismic section.

Features of Fault Surfaces

Like all faults, normal faults exist at all levels in the crust. The surface features of faults vary with the shape of the fault, the depth at which movement on the fault occurred, and whether faulting was accommodated by brittle fracture with frictional sliding, or by ductile deformation.

Like all faults at shallow levels (Section 4.2), normal faults develop cataclastic rocks (see Figures 4.5 and 4.6), slickensides, and slickenside lineations (Figure 4.8) along their surfaces. Some gently dipping normal faults in regions such as the Basin and Range province of the United States are characterized by large thicknesses of breccia and megabreccia (see Figure 4.5). In many cases, such breccias develop in hanging wall blocks from the pervasive fracturing and internal faulting that accommodate brittle, layer-parallel extension above shallow normal faults. In other cases, they may be associated with large, low-angle landslides.

At deeper structural levels, normal faults develop features associated with ductile deformation, including mylonitic textures (see Figure 4.7) which may be present in shear zones tens to hundreds of meters in thickness.

5.2 Shape and Displacement of Normal Faults

Shape of the Surface Trace

The sharp planar discontinuities that we commonly use to represent normal faults, such as those in Figure 5.2, are idealized representations of the structures we actually observe in nature. The surface trace of a normal fault is generally not a straight line but instead may be a sinuous curve or a series of connected, roughly straight line segments (Figure 5.1*B*; see also Section 4.4 and Figure 5.10). Although surface trace irregularities may result in part from the intersection of inclined faults with irregular topography, in many places the faults themselves must be nonplanar surfaces.

Shape at Depth

Normal faults need not maintain a constant dip with increasing depth as is shown in Figure 5.3, for example. Some listric normal faults join or turn into a detachment fault at depth (Figure 5.4). A detachment fault is a low-angle fault that marks a major boundary between unfaulted rocks below and a hanging wall block above that is commonly deformed and faulted. Normal faults in the hanging wall block may form a set of imbricate faults, which are closely spaced parallel faults of the same type that either terminate against (left end of Figure 5.4) or merge with (right end of Figure 5.4) the detachment fault.

Lateral ramps on the fault show up at the surface as an irregular fault trace (Figure 5.1*B*), and frontal ramps may also occur (Figures 4.25*A* and 5.5). Thus a map or cross section alone does not provide a complete picture of the geometry of a normal fault at depth, and we must keep in mind the potential complications of the third dimension when interpreting a simple two-dimensional view.

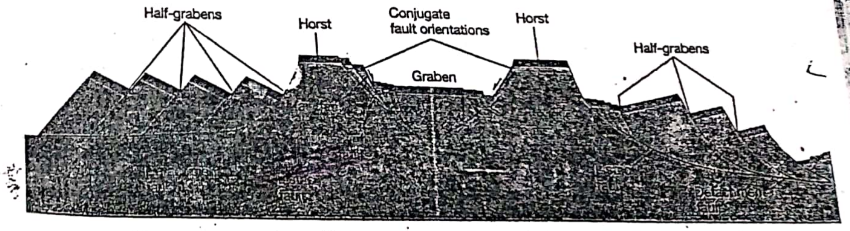


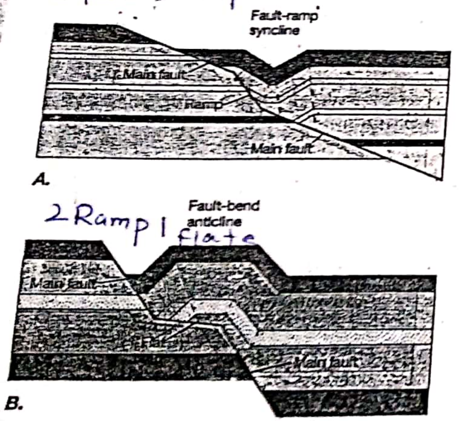
Figure 5.4 Systems of normal faults commonly are characterized by a main fault with associated subsidiary faults and by low-angle detachment faults with imbricate fault blocks in the hanging wall block.

Displacement on Normal Faults

By definition, displacement on ideal normal faults is parallel to the dip of the fault surface. If the strike of the fault varies, however, rigid movement of the hanging wall block relative to the footwall block cannot everywhere be down the dip of the fault. This fact is illustrated in Figure 4.30, where the displacement on the fault varies from pure normal dip slip to oblique slip as the fault trace curves. Thus the complex shape of real faults requires that they depart from our idealized models.

Movement on normal faults can be either nonrotational or rotational, depending on whether the orientations of the fault blocks remain constant or change as a result of the faulting. Both conditions exist in nature. If the apparent dip of the fault, measured in the direction of the displacement, does not change with depth (for example, Figures 5.2 and 4.30), and if the fault itself is not rotated during faulting, then the orientations of the fault blocks do not change during slip. Horizontal beds in the blocks remain horizontal; inclined beds maintain the same strike and dip. If, however, the dip changes with depth, then slip must result in rotation or deformation of the hanging wall block. On listric normal faults, the rotation takes place ideally about an axis parallel to the strike of the fault plane, and originally horizontal bedding ends up dipping toward the fault on which the fault block rotates. The angle between the bedding and the fault remains constant (see left and right ends of Figure 5.4).

2 flate 1 Ramp



2 Ramp 1 flate

Figure 5.5 Displacement on normal faults with a ramp-flat geometry showing characteristic deformation of the hanging wall block. A. A fault-ramp syncline. B. A fault-bend anticline.

A hanging wall block moving over a fault with ramp-flat geometry must in general deform internally. If a ramp connects two more shallowly dipping segments of the fault, slip on the fault produces a fault-ramp syncline (Figure 5.5A). If a flat connects two more steeply dipping segments of the fault, slip produces a fault-bend anticline (Figure 5.5B), which is comparable in part to a rollover anticline. These folds must parallel the associated ramp or flat, whether it intersects the main fault surface in a line perpendicular or oblique to the displacement direction. Deformation in the hanging wall block may take place by ductile bending (Figure 5.5), distributed faulting (see Figure 5.17D), or a combination of both.

5.3 Structural Associations of Normal Faults

Normal faults generally are present as systems of many associated faults. In many cases, the orientations of the faults fall into two groups, which are referred to as conjugate orientations; they have comparable dip angles but opposite dip directions and opposite senses of shear (Figure 5.4).

Commonly in such systems, some of the faults have a major amount of displacement along them and accommodate the major deformation, whereas other faults have a relatively small amount of displacement and provide the minor adjustments required for the large-scale displacements. If the smaller-scale faults are parallel to the major fault and have the same sense of shear, they are synthetic faults; if they are in the conjugate orientation, they are antithetic faults.

A graben is a down-dropped block bounded on both sides by conjugate normal faults (Figure 5.4) (the German *grabe* means "ditch"). A half-graben is a down-dropped tilted block bounded on only one side by a major normal fault. A horst is a relatively uplifted block bounded by two conjugate normal faults (the German *horst* means "a retreat" or "eyrie"—the nest of a bird of prey, typically built on a high cliff). These terms may refer either to the topographic feature formed by the faulting or to the structural feature of relatively down-dropped or uplifted fault blocks (Figure 5.1A). Alternating uplifted and down-dropped fault blocks are called a horst and graben structure. In some cases a series of half-grabens results in tilted fault blocks that also form alternating topographic highs and lows (Figure 5.4).

In regions of active normal faulting, horsts and the higher ends of tilted fault blocks provide the sediments that accumulate in the basins formed by the grabens and the lower ends of tilted blocks. As faulting continues during deposition of the basin sediments, the sediments themselves often become involved in the faulting. Study of these faults and of the age, composition, thickness, and distribution of the sediments can reveal when the major periods of uplift occurred, as well as the sequence and the time of exposure of the different rock types in the uplifted fault blocks.

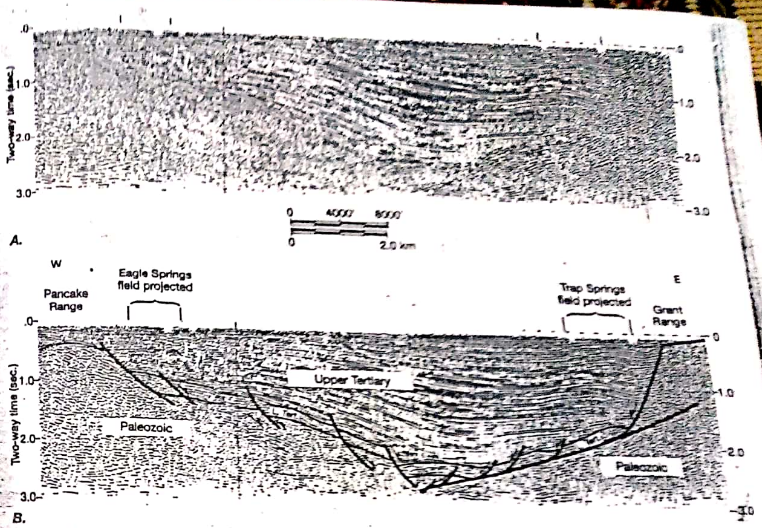


Figure 5.6 Seismic reflection profile of Railroad Valley, east central Nevada, showing typical asymmetric graben form. A. Seismic reflection profile. B. Interpretation of the faults on the seismic section.

Railroad Valley (Figure 5.6) in east-central Nevada illustrates the nature of an individual graben. This structure clearly is down-dropped on both sides, though more so on the east. It had a valley fill of late Tertiary and Quarternary sediments approximately 6 km thick that includes coarse to very coarse alluvial deposits shed from the surrounding ranges, playa lake sediments, and landslide deposits. These sediments record the interplay between faulting and concurrent sedimentation.

Systems of normal faults exist either on a local scale, subsidiary to other structures, or on a regional scale, where they dominate the structure. We briefly consider each scale of structure in turn.

Local Normal Faults Associated with Other Structures

Normal faults of local extent are generally associated with other structures whose geometry requires extension of crustal layers. Examples include domes, folds, cavities, and pull-apart structures on strike-slip faults.

Structural domes cut by a system of normal faults commonly result from the intrusion of bodies of salt or magma. The faults radiate from the center of the dome and may include a single major fault, one or two grabens (Figure 5.7A), or a Y-shaped set of grabens. The displacement on the faults is greatest at the center and dies out at tip lines near the margin of the dome. At depth, the faults terminate at or near the intrusive margin (Figure 5.7B). Elongate domes, described as doubly plunging anticlinal folds, often exhibit a comparable pattern of normal faults.

If a cavity forms at depth, surficial rocks commonly collapse into it along a set of concentric normal faults, forming a system of ring faults. Examples of such struc-

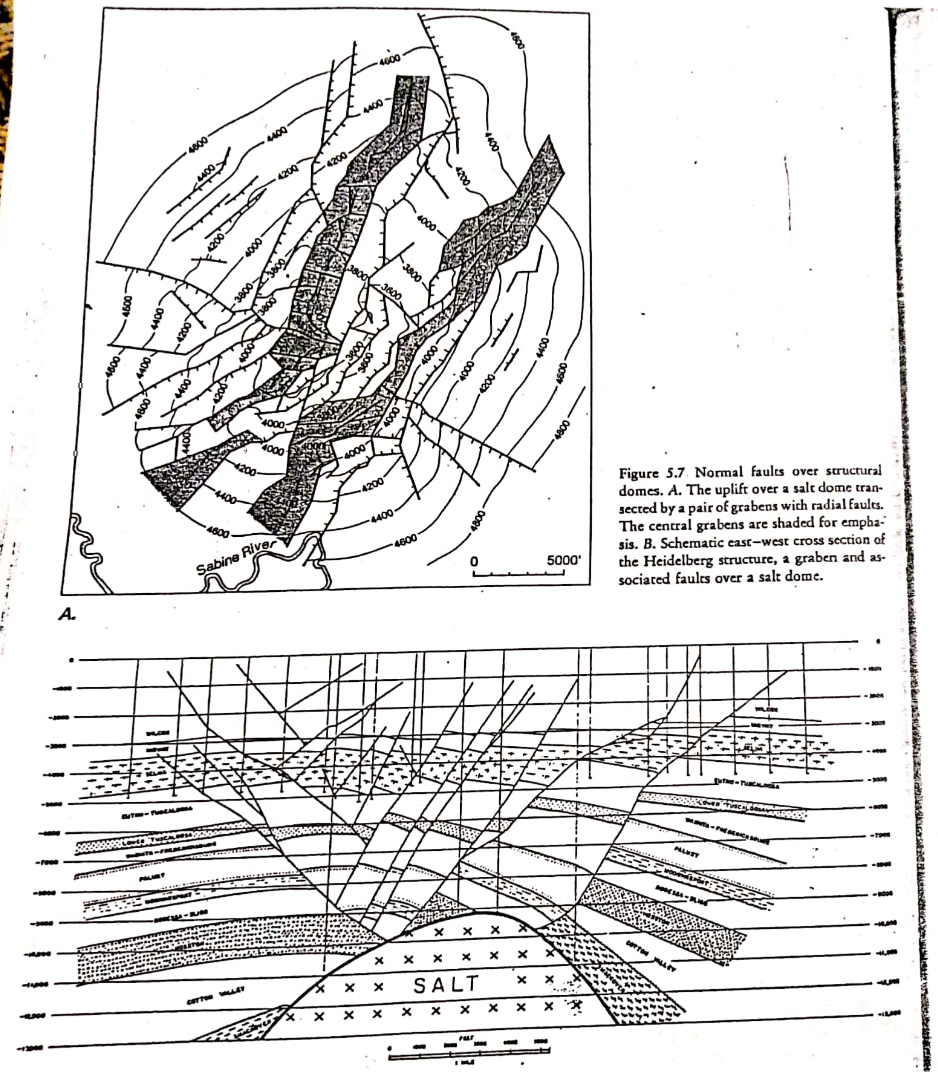


Figure 5.7 Normal faults over structural domes. *A.* The uplift over a salt dome transected by a pair of grabens with radial faults. The central grabens are shaded for emphasis. *B.* Schematic east–west cross section of the Heidelberg structure, a graben and associated faults over a salt dome.

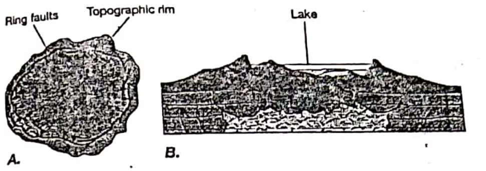


Figure 5.8 Normal faults associated with a caldera, a volcanic collapse structure. *A.* Schematic map of ring faults around a caldera. *B.* Schematic cross section of the caldera structure at Crater Lake, Oregon.

tures include calderas, which form by the collapse of surficial rocks into a magma chamber emptied during an explosive eruption (Figure 5.8); diatremes, which are volcanic pipes explosively blasted through crustal rocks; and collapse structures, which result from the dissolution of limestone, salt, or gypsum at depth. Individual faults are not continuous around the circumference of such structures. Where one fault dies out, however, the displacement associated with the collapse is taken up by adjacent or overlapping faults, thereby forming concentric rings of discontinuous normal faults (Figure 5.8*A*). At depth, the major faults must terminate at the cavity boundary (Figure 5.8*B*).

Regional Systems of Normal Faults

Regional systems of normal faults define large, distinct structural provinces in many parts of the world (Figure 5.9). In the oceanic crust, the midoceanic ridge system constitutes an active, world-encircling extensional province characterized by normal faulting. Continental examples of such provinces include the Basin and Range province in western North America, the East African Rift region, the western Turkey–Aegean Sea region, and the Shansi graben in China, all of which are currently active. Inactive continental provinces of normal faulting include the Triassic–Jurassic–age graben system of the

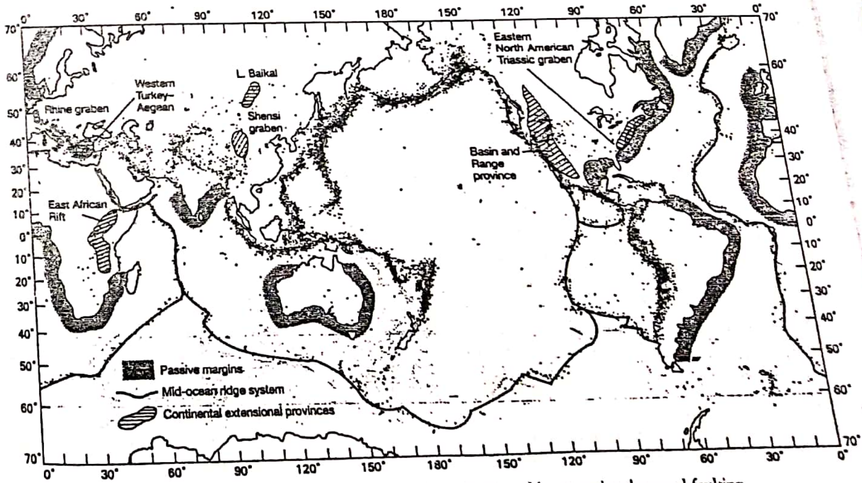


Figure 5.9 Map of the world, showing regions dominated by extensional normal faulting.

eastern United States and the Tertiary Rhine graben system in western Europe, as well as systems of normal faults in basement rocks of rifted continental margins, such as along eastern North America, western Europe, western Africa, eastern South America, southern India, and western and southern Australia. The sedimentary cover rocks of many such margins also contain systems of active normal faults not necessarily associated with the underlying basement systems. We concentrate our discussion on the Basin and Range province of North America (Figure 5.10), which provides a good example [illegible], and on the Gulf Coast province, which exemplifies the structures in the sedimentary cover rocks of an extended continental margin (see Figure 5.14).

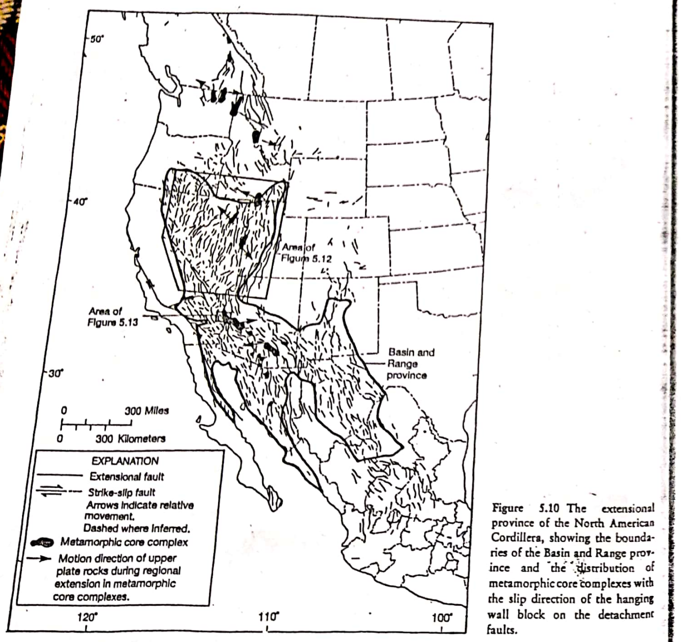


Figure 5.10 The extensional province of the North American Cordillera, showing the boundaries of the Basin and Range province and the distribution of metamorphic core complexes with the slip direction of the hanging wall block on the detachment faults.

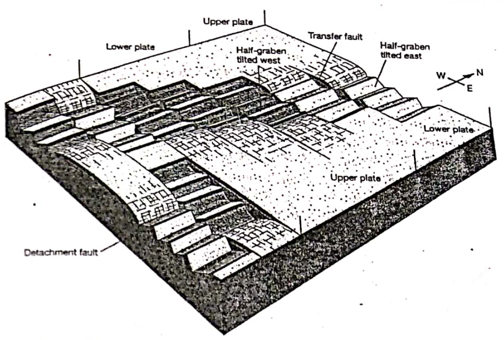


Figure 5.11 Model of the fault geometry in basement rocks of a continental extensional province. Different domains of normal faulting are separated by transfer faults. Some domains, such as the two on the left, may contain sets of oppositely dipping normal faults separated by an unfaulted block.

In all of these regions, normal faults form in conjugate sets, with approximately the same strike and with dips of varying magnitude in both directions (Figures 5.6 and 5.14). The faults are always of limited length (Figure 5.10). Where one fault dies out at a tip line, regional extension is taken up by displacement on adjacent faults. Between these faults there is commonly a transfer zone within which deformation is accommodated by folding, faulting, and fracturing. In some cases, these transfer zones may be distinct strike-slip transfer faults. Transfer zones or faults may divide an extensional province into domains distinguished by different amounts of extension, different predominant orientations of faults, or different predominant directions of tilting. A schematic model of the geometry is shown in Figure 5.11.

Many rifted passive continental margins in the world originated as extensional terranes during the plate tectonic breakup of continental masses. Beneath layers of younger sediments, these margins are characterized by systems of normal faults with geometries similar to that shown in Figure 5.11.

In the Great Basin area of the Basin and Range province, several strike-slip faults have been recognized, some in part by the mapping of paleontologic associations (Figure 5.12). Both dextral and sinistral faults occur. These faults may be transfer faults of the type shown in Figure 5.11. The direction of tilting of fault blocks tends to be consistent over large areas, which suggests a structural association at depth and requires some discontinuity between major domains. The boundaries of these tilt domains therefore may be other transfer zones or faults.

In cases of extreme extension, normal faulting effectively strips off the shallower layers of rock to expose rocks that originally were deeper in the crust. This process enables us to examine rocks that were deep enough to undergo ductile faulting. There are, in the Basin and Range province, numerous regions called metamorphic core complexes (Figure 5.10) where the crust has been extended in a roughly east–west direction on major detachment faults by amounts on the order of 100 percent to 400 percent. These faults are characterized by extensive development of mylonite (see Section 4.2). As a result, the metamorphic and plutonic rocks that lie beneath the detachment faults have been brought up to the surface from depths as great as 20 km. In the Whipple Mountains of southeastern California, for example (Figure 5.13), the rocks beneath the detachment fault are extensively mylonitized and have a gently dipping foliation. The detachment fault itself contains mylonitic rocks, which in turn have been deformed by cataclasis, reflecting the change from ductile to brittle deformation as normal faulting brought the deeper rocks up toward the surface and the temperature and pressure decreased.

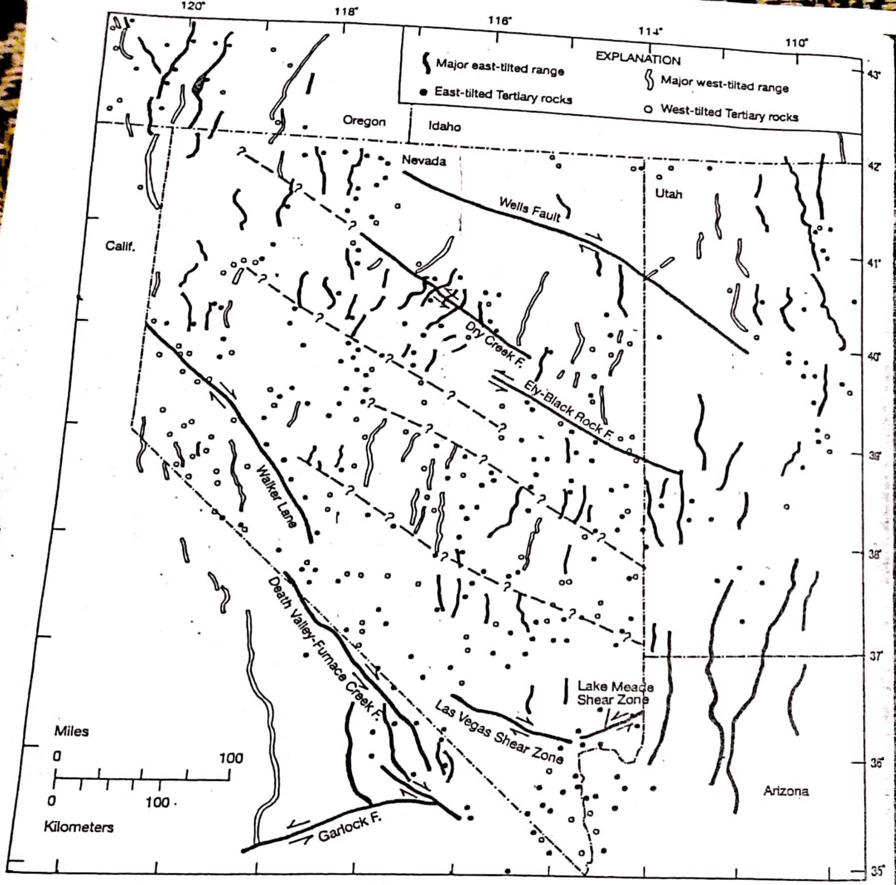


Figure 5.12 Structure of the Great Basin in the Basin and Range province of Nevada and neighboring regions, showing the tilt direction of major ranges and of Tertiary rocks. Strike-slip faults in northeastern Nevada have been identified by the offset of stratigraphic and structural trends. Hypothetical transfer faults, indicated by question marks, are suggested by the possible boundaries of tilt domains and domains of major normal faulting (cf. Figure 5.11).

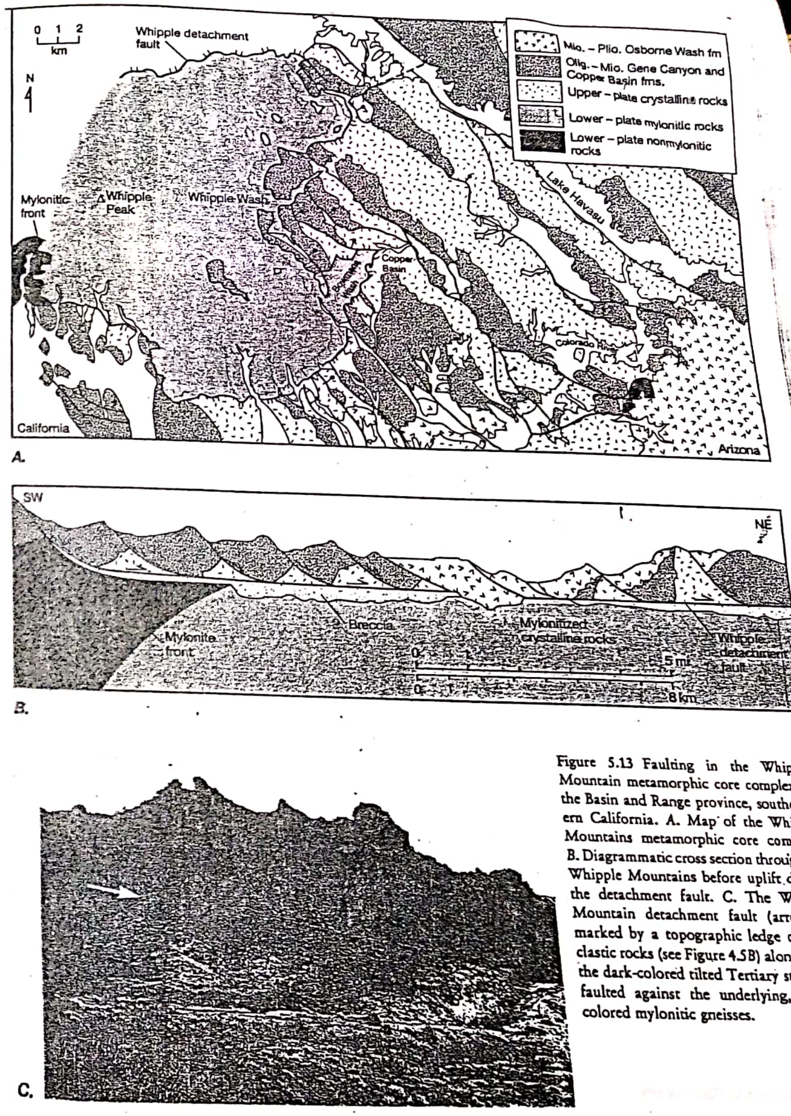
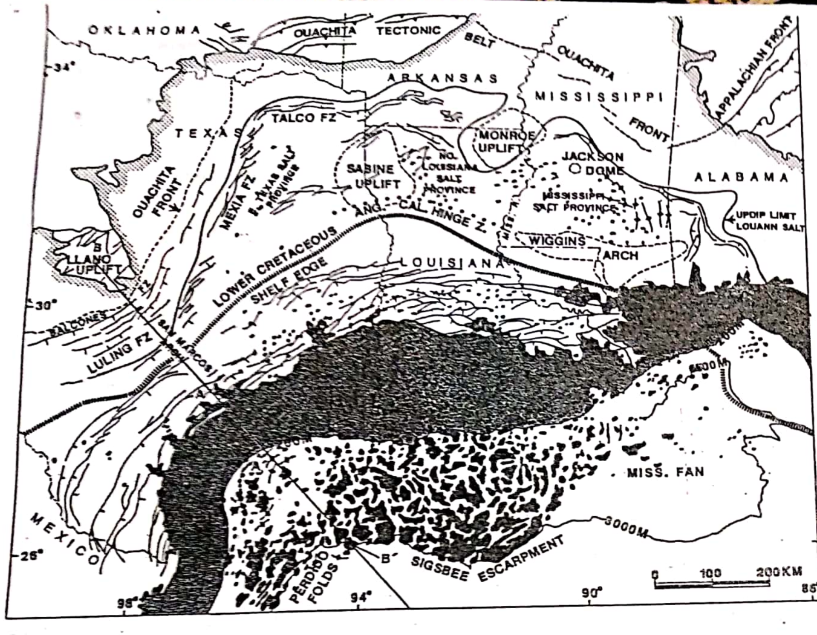


Figure 5.13 Faulting in the Whipple Mountain metamorphic core complex of the Basin and Range province, southeastern California. A. Map of the Whipple Mountains metamorphic core complex. B. Diagrammatic cross section through the Whipple Mountains before uplift domed the detachment fault. C. The Whipple Mountain detachment fault (arrow) is marked by a topographic ledge of cataclastic rocks (see Figure 4.5B) along which the dark-colored tilted Tertiary strata are faulted against the underlying, lighter-colored mylonitic gneisses.



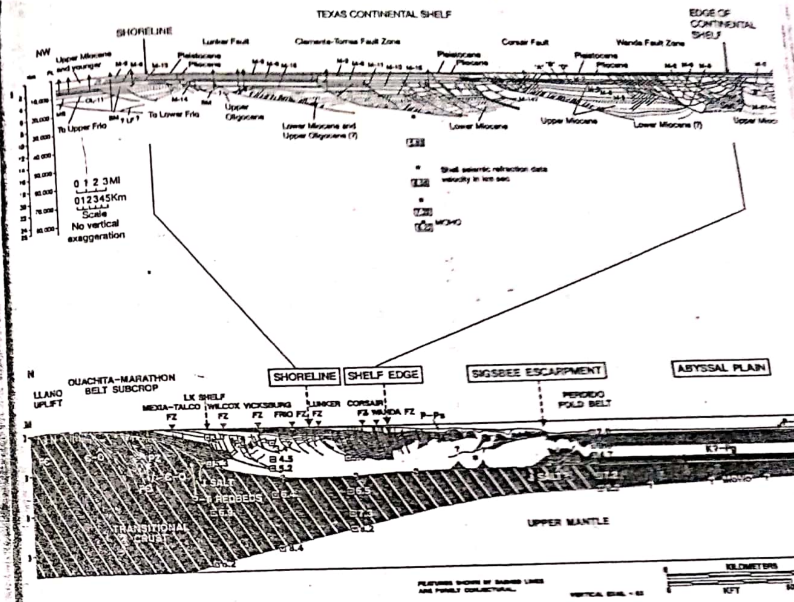
A.

Figure 5.14 Normal fault province in the Gulf Coast area. A. Map of the Gulf Coast region, showing major normal faults and salt structures (black). Major salt deposits occur south of the line marking the updip limit of the Louann salt, and this area which is closely associated with the province of normal faulting. The area shaded grey marks the continental shelf to a depth of 200 m. B. (*Facing page*) Cross section *A–A′* in part *A* across the continental shelf of southwest Texas. Much of the area is believed to be underlain by salt deposits, which are not shown because of a lack of seismic resolution. Note the growth faults and salt structure on the right. There is no vertical exaggeration. C. Interpretive cross section of the Gulf Coast from the Llano Uplift in the northwest to the Gulf abyssal plain in the southeast *B–B′* in part *A*. Jurassic salt is believed to underlie much of the shallow structure and to form the major detachment zone, although the structure is not known. Note the salt nappe behind the Sigsbee escarpment and the underlying Perdido fold belt. Vertical exaggeration 5×.

The "upper plate" rocks above the detachment fault are unmetamorphosed and have been strongly rotated on a set of imbricate listric normal faults that merge at depth with the detachment fault (Figure 5.13*B*, *C*).

The widespread development of core complexes in the Basin and Range province and the large amount of extension associated with them indicate that they are of major tectonic significance. Moreover, reports of similar features from the Aegean Sea and Papua–New Guinea suggest that core complexes have worldwide importance.

The northern Gulf Coast region of the United States from Texas to Alabama is an example of normal faulting along a modern continental margin. The area is characterized by thick accumulations of sediment, rapid subsidence, and an arcuate system of normal faults whose extent is closely associated with the extent of major Jurassic salt deposits. Most faults dip southward (Figure 5.14*A*, *B*, *C*), although north-dipping faults also exist. Southward-dipping faults commonly show rollover anticlines, indicating that the faults are listric, with gentler dips at depth (Figure 5.14*B*).



Many normal faults along the Gulf Coast are growth faults, also referred to as regional contemporaneous faults, which are active during sedimentation. These faults characteristically have stratigraphic sequences that are thicker on the hanging wall block than the equivalent sequences on the footwall block (Figure 5.15; compare Figure 5.14*B*). This disparity in thickness develops because as faulting continues, sediments accumulate most rapidly in the deepest parts of the basin, thereby keeping the surface of deposition approximately flat and horizontal. The down-faulted block thus accumulates a greater thickness of any particular unit. Older units show greater amounts of displacement and large tilts than younger units, because they have experienced a longer history of faulting.

Growth faults apparently form in two ways: by differential compaction of shale layers in a sandstone–shale sequence and by gravity sliding toward the basin. Coarser sands are generally deposited closer to shore than muds, but they undergo less compaction during consolidation and lithification. The greater compaction of the shale can initiate a growth fault near the boundary

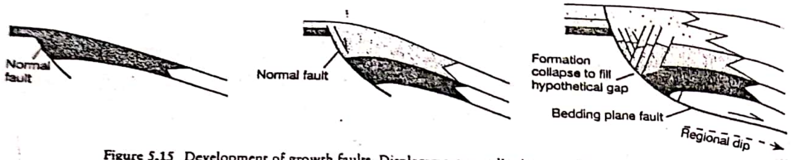


Figure 5.15 Development of growth faults. Displacement on a listric normal fault occurs during sedimentation, resulting in equivalent beds being thicker in the hanging wall block than in the footwall block. The fault passes into a bedding-plane fault at depth.

with the less compactable sands. Growth faults can also develop by formation of a detachment at the base of a sequence, usually in easily deformed shale or salt deposits. In the Gulf Coast, accumulation of large thicknesses of sediment on the continental shelf has caused the thick underlying salt deposits (originally up to 1500 to 2100 m thick) to flow toward the basin. This has created listric growth faults along the continental margin that have a detachment in the salt layers. Associated compressional structures developed in the basin, such as the huge salt nappe behind the Sigsbee escarpment and the Perdido fold belt (Figure 5.14*A*, *C*).

Similar faults are present along many rifted continental margins, such as the Atlantic Ocean margins of North America, Europe, and Africa and the Indian Ocean margins of Africa, India, and Australia. In all these regions, the fault systems are important traps for hydrocarbons and thus are of great interest to the petroleum industry.

A single set of parallel normal faults can accommodate extension in only one direction approximately perpendicular to the strike of the faults. In regions where extension occurs in two perpendicular horizontal directions, more than one orientation of normal fault is required, and a rhombic pattern of fault traces commonly develops. The angle between the faults depends on the relative magnitude of the extension in the two directions.

5.4 Kinematic Models of Normal Fault Systems

A kinematic model of any fault system is a description of the motions that have occurred on the faults in the system. A fundamental constraint on basic models of faulting is that the volume of the blocks of rock involved in the faulting must be conserved. If the deformation is two-dimensional, the cross-sectional area of each unit must remain constant, and appropriate kinematic models and associated cross sections must be balanced.[2] Thus running the inferred fault motions backward from the present configuration must not produce overlaps of different fault blocks or large gaps between them. The model must also account for horizontal extension in the footwall block of major detachment faults.

We generally use cross sections of normal faults to display the geometry of faulting at depth. Any cross section inevitably implies some kinematic model of faulting, whether intended or not. Cross sections, however, are usually incomplete in that they do not include all fault termination lines. This incompleteness may reflect a lack of data, which makes it impossible to determine how apparent geometric problems are accommodated at depth, or it may be required by the scale of the section needed to portray important details of structure or stratigraphy. In any case, such cross sections make it easy to ignore the necessity to conserve volume. The result may be unbalanced cross sections that are geometrically impossible, that leave unresolved fundamental problems about the tectonics of an area, or that contain unintended implications about the kinematics of faulting.

Figure 5.16*A*, for example, shows an unbalanced cross section of a graben that is geometrically impossible. There is no way in which the motion on the two faults can be reversed to produce an originally continuous layer without large gaps (Figure 5.16*B*) or overlaps (Figure 5.16*C*). Nor does this cross section specify what happens to the fault at depth. This type of inconsistency is difficult to recognize in a cross section showing multiple intersecting faults. We note other examples of incomplete cross sections in the following discussion.

Normal fault provinces typically show tilted fault blocks (Figure 5.13*B*), and in some cases the rotations may approach 90°. Horizontal bedding typically is rotated about an axis roughly parallel to the strike of the fault so that the beds dip toward the fault. On geometric grounds, this type of block rotation must imply either that the fault surfaces curve toward shallower dips with increasing depth or that planar faults rotated with the fault blocks during faulting. We shall discuss three kinematic models for normal faulting that result in tilted fault blocks.

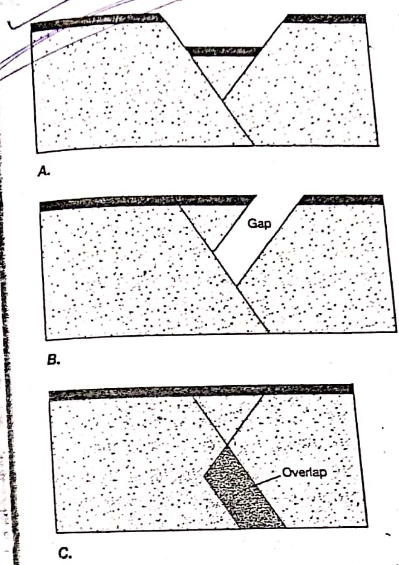


Figure 5.16 Geometrical constraints on cross sections. A. A geometrically impossible cross section of a graben. Attempted reversal of the fault motion leads to B. major gaps or C. major overlap of fault blocks.

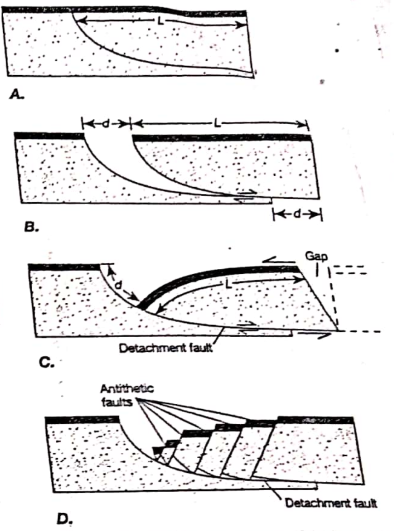


Figure 5.17 Model for the geometry of displacement on a listric normal fault accompanied by rollover folding or antithetic normal faulting. A. Crustal block with the incipient fault. The length *L* of the hanging wall block is kept constant. B. Rigid displacement of the hanging wall block a distance *d* parallel to the horizontal part of the listric normal fault results in the opening of a geologically ridiculous gap. C. Deformation distributed through the hanging wall block allows contact to be maintained along the fault and results in rollover folding of the layers. The length *L* remains constant, resulting in the development of another gap problem in the hanging wall block. D. Distributed faulting on antithetic faults in the hanging wall block reduces the gap problem along the normal fault to small misfits along the listric fault.

Figure 5.17 illustrates some geometric problems inherent in accommodating extension on a listric normal fault. Horizontal extension of the block on a listric normal fault by an amount *d* opens a large gap between the hanging wall and footwall blocks (Figure 5.17*A*, *B*). If the bottom edge of the hanging wall block must conform to the shape of the listric fault, while at the same time keeping constant the length *L* of the surface layer and the total area of the block (Figure 5.17*C*), then the process requires internal deformation of the hanging wall block. The resulting geometry is a rollover anticline similar to those commonly associated with listric normal faults.

One problem introduced by this model is that if there is no extension of the layers in the hanging wall block, a shearing must be distributed throughout the block, as indicated by the large arrows in Figure 5.17C. If the entire hanging wall block does not shear, a triangular gap must open up between the sheared and unsheared portions of the block. Neither shearing of

---

[2] Any component of motion out of the plane of the cross section, or volume loss due to solution, however, makes the balancing exercise unreliable (see Section 4.5).

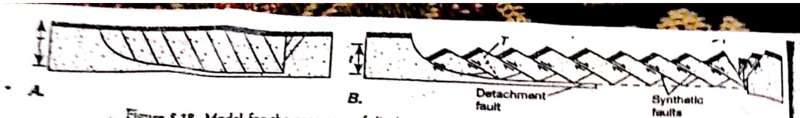


Figure 5.18 Model for the geometry of displacement on a listric normal fault accompanied by synthetic normal faulting. *A.* Rotation on the listric fault can be accommodated by forming a set of synthetic faults. *L* and *T* are the original length and thickness, respectively, of the hanging wall block. *B.* After extension of the crust, the fault blocks have slipped and rotated on the system of normal faults synthetic to the listric normal fault. Here *ℓ* and *t* are the final length and average thickness, respectively, of the hanging wall block. The original thickness *T*, measured normal to the bedding, is shown in the second fault block from the left.

the entire hanging wall block nor the triangular gap is geologically reasonable.

The problem illustrated in Figure 5.17C can be alleviated by allowing extension parallel to the layer in the hanging wall block. A set of antithetic faults cutting the hanging wall block (Figure 5.17*D*) permits the block to conform fairly well to the listric fault and effectively extends the block above the curved part of the detachment. As a result, the right edge of the block remains perpendicular to the base. Greater continuity and smaller gaps under the antithetic fault blocks can be obtained if the spacing of the faults is smaller. The residual gaps are easily accommodated by local fracturing of the blocks.

A second model for slip on a listric fault requires the hanging wall block to maintain contact along the curved part of the listric fault by rotating as it slides. This mechanism can work only if the hanging wall block breaks up into a set of dominolike blocks along synthetic faults dipping in the same direction as the main fault (Figure 5.18*A, B*). Rotation of the fault blocks requires the synthetic fault planes to rotate as well, and the result is comparable to the collapse of a row of standing dominos. The triangular gap that opens at the right where the set of synthetic faults ends could be closed by a set of antithetic faults, as shown in Figure 5.18*B*. Again, the small gaps that occur below the synthetic fault blocks can be accommodated by closer spacing of the faults and by localized fracturing near the base of the fault blocks.

A third model of slip on listric normal faults requires slip of tapered fault blocks on a set of imbricate listric normal faults. As the fault blocks slip down the faults (Figure 5.19*A, B*), they must deform to conform to the shape of the fault. At large amounts of extension, the imbricate blocks are almost completely flattened out on the listric detachment fault, and bedding in the fault blocks is rotated to very steep dips. Rotation of the surface layer approaches a value equal to the initial dip of the fault where it cut the layer (Figure 5.19*A*). The unfaulted part of the hanging wall block, however, encounters the same geometric problems in Figure 5.17.

In principle, the latter two models might be distinguishable in the field. For the "domino block" model of planar rotating normal faults (Figure 5.18*B*), the dip of the bedding is constant across the entire hanging wall block above the detachment fault. For the imbricate listric fault model, however, if extension has not been too great (Figure 5.19*B*), the dip of the bedding should increase with distance in the direction of displacement on the detachment fault.

The models we have discussed are, of course, simplified idealizations of the natural world. The presence of triangular gaps in the models, for example, results from our implicit assumption that the fault blocks behave rigidly. Although this assumption is in accordance with our intuitive experience with rock on a relatively small scale over short periods of time, on the scale of tens of kilometers and millions of years, the mechanical behavior of rocks is quite different. When the natural behavior is scaled down to models we might make in the laboratory, the mechanical properties of rock are closer to those of sand or clay (see Sections 20.5 and 20.7). Thus the deformation in the hanging wall block required by the model in Figure 5.17C and the flattening of the imbricate fault blocks shown in Figure 5.19*B* are not outrageous propositions, and the small gaps that open up along the detachment fault in models such as Figures 5.17*D* and 5.18*B* could readily be accommodated by local deformation (see Figure 20.18).

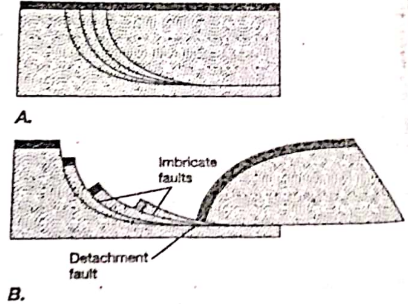


Figure 5.19 Model for the geometry of displacement on a set of imbricate listric normal faults. *A.* Geometry of incipient imbricate listric normal faults. *B.* As the imbricate fault blocks slip down the faults, they rotate and straighten out.

The geometry of normal fault systems is generally more complex than our model cross sections imply. It is common, for example, for listric normal faults to have a ramp–flat geometry and to cut progressively into either the hanging wall block or the footwall block as faulting proceeds. In some cases, later normal faults may cross-cut earlier systems of normal faults in the same episode of extension. Figure 5.20, for example, illustrates the structure resulting from the progressive cutting of the active fault back into the footwall block, as indicated by the number sequence. An imbricate listric fan of faults develops at the surface, and with an adjacent set of conjugate faults, it defines a graben. At depth, an extensional duplex develops, characterized by a stack of horses that are progressively cut from the footwall block and added to the hanging wall block. The floor fault, which defines the bottom of the duplex, is the active fault, whereas the roof fault, which bounds the top of the duplex, is never active at one time as a single fault.

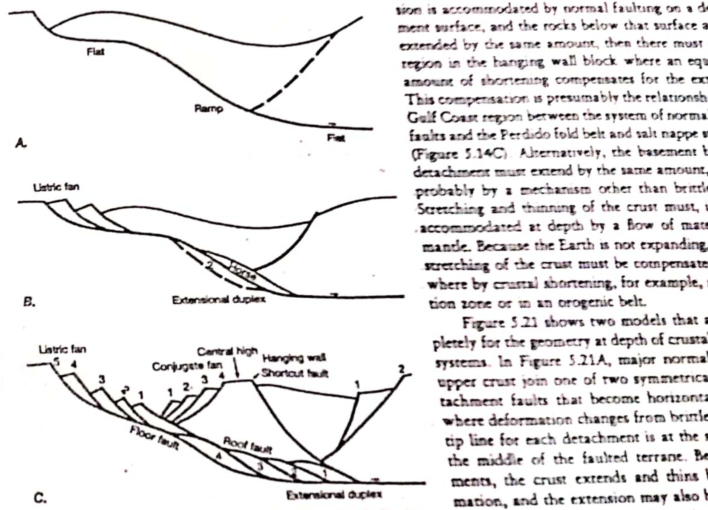


Figure 5.20 Model for the progressive development of a listric fan and an extensional duplex associated with a ramp and flat in a normal fault. A. Listric normal fault with a ramp-flat geometry. A rollover anticline and a ramp syncline are developed in the hanging wall block. B and C. Progressive propagation of the fault into the footwall block produces a listric fan near the surface and an extensional duplex at depth. Eventually other faults, including the conjugate fan, develop to accommodate the deformation of the hanging wall block.

Although all three models in Figures 5.17 through 5.19 can account for the rotation of fault blocks, all of them ignore a major tectonic problem implied by a horizontal or low-angle detachment fault. Normal faulting inherently increases the distance between two points on opposite sides of the fault and, on the average, must thin the faulted block if cross-sectional area is conserved (compare parts A and B of Figure 5.18). Thus if extension is accommodated by normal faulting on a detachment surface, and the rocks below that surface are not extended by the same amount, then there must exist a region in the hanging wall block where an equivalent amount of shortening compensates for the extension. This compensation is presumably the relationship in the Gulf Coast region between the system of normal growth faults and the Perdido fold belt and salt nappe structures (Figure 5.14C). Alternatively, the basement below the detachment must extend by the same amount, although probably by a mechanism other than brittle faulting. Stretching and thinning of the crust must, in turn, be accommodated at depth by a flow of material in the mantle. Because the Earth is not expanding, horizontal stretching of the crust must be compensated for somewhere by crustal shortening, for example, at a subduction zone or in an orogenic belt.

Figure 5.21 shows two models that account completely for the geometry at depth of crustal normal fault systems. In Figure 5.21A, major normal faults in the upper crust join one of two symmetrically located detachment faults that become horizontal at the depth where deformation changes from brittle to ductile. The tip line for each detachment is at the same location in the middle of the faulted terrane. Below the detachments, the crust extends and thins by ductile deformation, and the extension may also be accommodated to some extent by magmatic intrusion. Below the crust, the mantle accommodates the crustal extension by ductile inflow of rock.

In Figure 5.21B, a major detachment fault extends completely through the lithosphere, changing from a brittle to a ductile fault at a depth of roughly 15 km to 20 km. Predominantly synthetic imbricate normal faulting in the hanging wall block produces an asymmetric

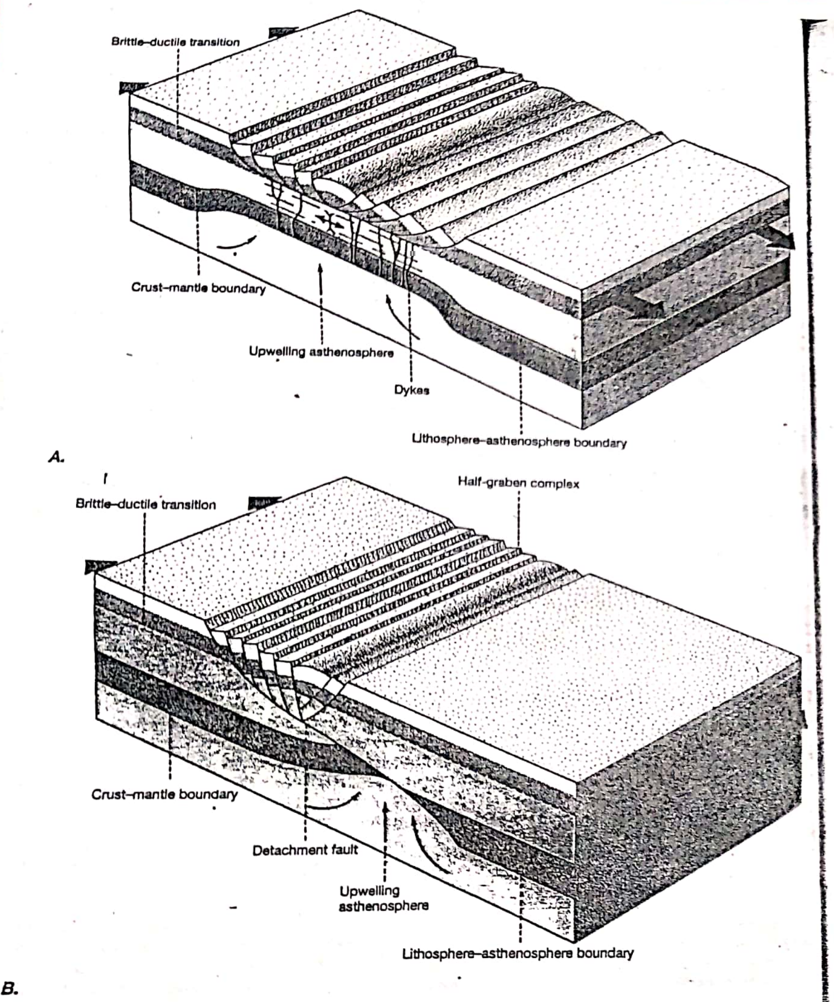


Figure 5.21 (*Left*) Complete cross sections accounting for the extension in provinces of normal faulting. *A*. The shallower crust extends by brittle normal faulting. The deeper crust extends and thins by ductile deformation. The extension is accommodated in the mantle by ductile inflow of material. Dip directions of normal faults are symmetrical about the center of the province. *B*. Extension occurs by displacement along a normal detachment fault that extends completely through the lithosphere. The brittle shallow crust extends by brittle imbricate listric normal faulting. Faulting on the detachment at depth is by ductile shear. The extension is accommodated in the mantle by ductile inflow of material. The dips of normal faults are predominantly in a direction synthetic to the detachment.

normal fault province. Thinning of the crust by faulting on the detachment fault is accommodated in the mantle by ductile inflow of material. The termination of the fault is at the base of the lithosphere, where it and the asthenosphere are both moving to the right at approximately the same rate. A large amount of extension would emplace the deep crustal mylonites of the footwall block against the brittlely faulted blocks of the hanging wall block. Pervasive ductile extension of the crust in the footwall block is not required.

Both models include all termination lines of all the faults and account for all the required tectonic motions. The actual driving force for the extension could be the same in both cases. Structural aspects of each model that could in principle be tested include the predicted symmetry or asymmetry of normal faulting across the structural province, the extent of ductile extension of the crust below the detachment, and the geometry of the Moho. The tests are not easy to make, however, and which model is better remains to be determined through field and geophysical investigations.

5.5 Determining Extension Associated with Normal Faults

In studying normal fault systems, we wish to estimate quantitatively the amount of extension in a region. We define the extension e as the change in length in a given direction caused by the deformation, divided by the original length. Thus in Figure 5.18, for example, $e = (\ell - L)/L$. Estimates of the extension can constrain our reconstructions of an area and help us better understand its tectonic history. We can estimate the amount of extension by examining fault geometry and by using map relationships to restore the stratigraphy to its original state.

Estimating Extension on the Basis of Fault Geometry

To evaluate the extension across a region by using fault geometry, we must make a few simplifying assumptions. We assume that the fault strike is uniform and that the change in length of the region is the sum of the horizontal extensions on all the faults (Figure 5.22A). The extension is then this change in length divided by the original distance across the region, which must be measured normal to the strike of the faults.

For example, let us take a simple cross-sectional model of planar nonrotating normal faults producing a horst and graben structure (Figure 5.22A)[3]. The segments of a particular stratigraphic layer labeled L_i meaning (L_1, L_2, L_3, and so on) when summed together equal the original length of the cross section. The segments labeled ΔL_i when summed together give the total change in length. The extension e is calculated for N segments by the formula

$$e = \frac{\sum_{i=1}^{N} \Delta L_i}{\sum_{i=1}^{N} L_i}$$

For an individual fault, the change in length ΔL is related to the dip-slip displacement d and the dip angle of the fault ϕ by

$$\Delta L = d \cos \phi$$

For a model of rotating planar normal faults (Figure 5.18*A*, *B*), if we assume that bedding is initially horizontal and that, on the average, the faults have the same orientation, spacing, and slip, we can easily derive a relationship among the extension e, the dip of the rotated bedding θ, and the dip of the rotated fault planes ϕ (Figure 5.22B).

$$e \equiv \frac{\overline{AB}_{\text{final}} - \overline{AB}_{\text{initial}}}{\overline{AB}_{\text{initial}}}$$

$$e = \frac{d}{L} \cos \phi + \cos \theta - 1$$

$$\frac{d}{L} = \frac{\sin \theta}{\sin \phi} \qquad \sin(\theta + \phi) = \sin \theta \cos \phi + \sin \phi \cos \theta$$

$$e = \frac{\sin(\theta + \phi)}{\sin \phi} - 1$$

The assumptions limit the applicability of the model, but it can be used in some cases to give a rough approximation of the extension.

---

[3] Note that this model ignores the obvious problem of the fault geometry at depth.

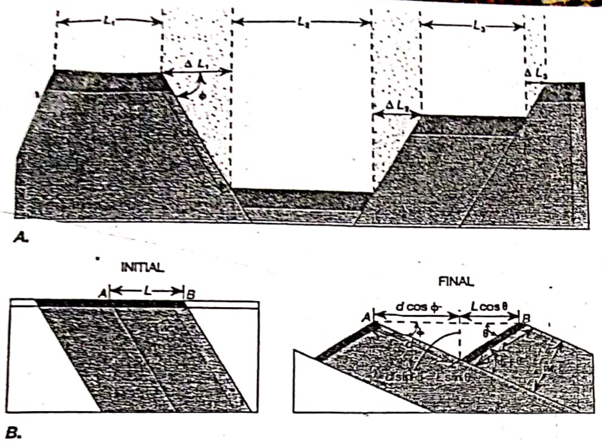


Figure 5.22 Determination of extension in a terrane faulted by planar normal faults. A. On nonrotating faults, the overall extension is the ratio of the sum of the extensions on each fault ΔL_i, divided by the sum of the original lengths L_i of the strata in each fault block. B. Geometric relationship—for equally spaced, planar, rotating normal faults above a detachment fault (Figure 5.18B)—among the dip of the faults ϕ, the dip of the beds θ, and the extension e.

For the models of listric normal fault slip shown in Figures 5.17C and 5.19B, which involve deformation of the fault blocks above the detachment, there is no simple geometric relationship between fault dip, bedding dip, and displacement.

Determining Extension from Map Relationships

In some cases, extension in a normal-faulted terrane can be determined by a palinspastic restoration—that is, by constructing a balanced cross section parallel to the slip direction and restoring the geology to its original configuration prior to deformation. (The term *palinspastic* is derived from two Greek words: *palin*, which means "again," and *spasmos*, which means "contraction" or "breaking.") Comparison of the restored cross-sectional length with the length after faulting, as measured in the field, makes it possible to calculate the extension. Reliable application of the method requires good data from the subsurface as well as from the surface, including firm constraints on the slip direction. These requirements severely limit the utility of the method. If erosion has removed much of the originally faulted terrane, and if large-displacement listric normal faults are prevalent, then the difficulty in knowing the original curvature of the faults also limits the reliability of the restoration.

Additional Readings

Brun, J.-P., and P. Choukroune. 1983. Normal faulting, block tilting, and décollement in a stretched crust. *Tectonics* 2: 345–356.

Coney, P. J. 1980. Cordilleran metamorphic core complexes: An overview, in M. D. Crittenden, Jr., P. J. Coney, and G. H. Davis (eds.), *Cordilleran metamorphic core complexes*. *Geol. Soc. Am. Memoir* 153: 7–31.

Lister, G. S., and G. A. Davis. 1989. The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A. *J. Struct. Geol.* 11 (1/2): 65–94.

Gibbs, A. D. 1984. Structural evolution of extensional basin margins. *J. Geol. Soc. Lond.* 141: 609–620.

Lister, G. S., M. A. Etheridge, and P. A. Symonds. 1986. Detachment faulting and the evolution of passive continental margins. *Geology* 14: 246–250.

Wernicke, B., and B. C. Burchfiel. 1982. Modes of extensional tectonics. *J. Struct. Geol.* 4: 104–115.

Worrall, D. M., and S. Snelson. 1989. Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt, in A. W. Bally and A. R. Palmer (eds.), *The geology of North America: An overview*, DNAG. The geology of North America, Vol. 4. Boulder, Col.: Geological Society of America, pp. 97–138.

Zoback, M. L., R. E. Anderson, and G. A. Thompson. 1981. Cainozoic evolution of the state of stress and style of tectonism of the Basin-Range province of the western United States. *Phil. Trans. Roy. Soc. Lond.* A-300: 407–434.