Chapter 8

Faulted Surfaces

8.1 Introduction

This chapter covers how to construct maps containing faults, the integration of fault maps with horizon maps, interpreting faults from isopach maps, mapping overlapping and intersecting faults, and mapping cross-cutting faults.

8.2 Geometry of a Faulted Surface

Faults cause discontinuities in the map of a marker horizon and result either in gaps, overlaps, or vertical offsets of the marker surface. Normal faults produce gaps (Fig. 8.1a,b), reverse faults cause overlaps (Fig. 8.1c,d), and vertical faults produce line discontinuities on the map of a marker horizon (Fig. 7.17). Structure contours on the fault plane intersect the offset marker where the contours on the marker and the fault are at the same elevation. It is best practice to show the fault contours on the map, scale permitting. Structure contours on a fault surface are easily constructed by connecting the points of equal elevation where the marker horizon intersects the fault surface on opposite sides of the fault. This is called the implied fault surface (Tearpock and Bischke 2003). A fault intersects the marker surface along lines known as hangingwall and footwall cutoff lines. If the fault ends within the map, then the contours on the marker surface are continuous at the ends of the fault.

Heave and throw are the components of fault separation directly visible on the structure contour map of a faulted marker horizon. Throw is the vertical component of the dip separation; heave is the horizontal component of the dip separation (Fig. 8.2; also Sect. 7.4.3), both components being defined in the dip direction of the fault. The throw is the change in vertical elevation between the hangingwall and footwall cutoff lines in the direction of the fault dip. The throw and heave are related to the stratigraphic separation by Eqs. 7.5–7.8.

8.2.1 Heave and Throw on a Structure Contour Map

On a structure contour map the heave is the map distance between the hangingwall and footwall cutoff lines, measured in the direction of the fault dip (Figs. 8.3, 8.4). The fault gap (or overlap) is the horizontal distance between the hangingwall and

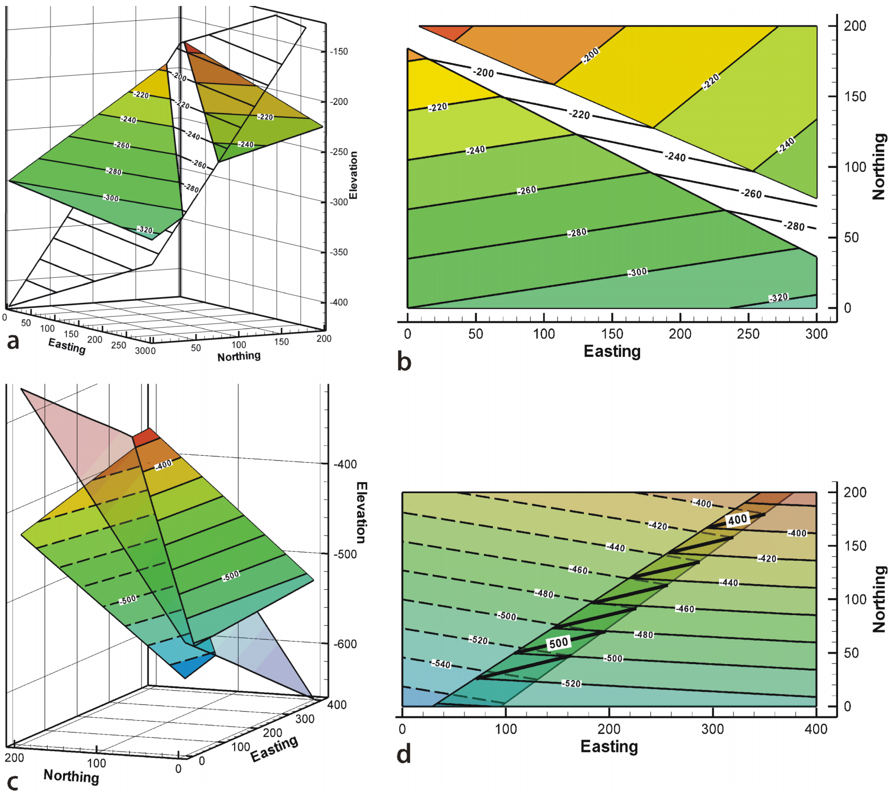
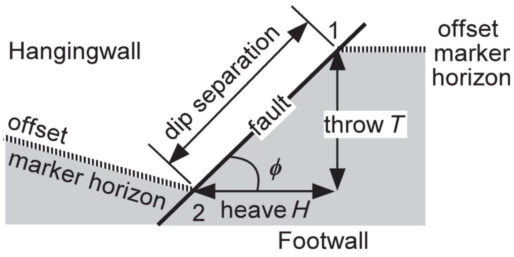


Fig. 8.1. 3-D and map views of faulted surfaces (*shaded*), fault surfaces are *unshaded*, structure contours shown on all surfaces. **a** Normal fault, oblique view. **b** Normal fault map. **c** Reverse fault, oblique view, FW contours *dashed*. **d** Reverse fault map. FW contours *dashed*, fault contours *heavy lines*

Fig. 8.2.
Vertical cross section in the dip direction of a fault showing throw and heave as components of the dip separation of an offset marker horizon



footwall cutoffs, measured perpendicular to the trace of the fault on the map. Although both are measured in the horizontal plane, the fault heave is not the same as the fault gap (or overlap) because, as seen in Figs. 8.3 and 8.4, the perpendicular distance between the hangingwall and footwall cutoff lines is not necessarily in the direction of the fault dip.

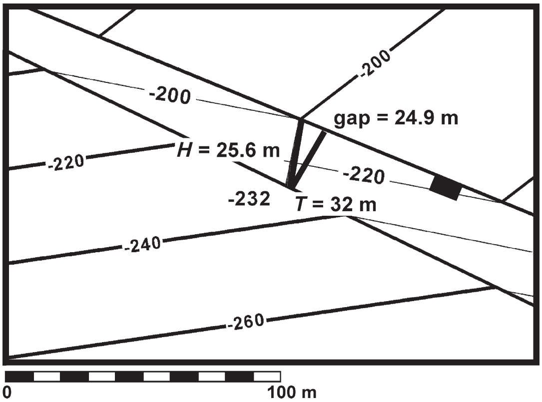


Fig. 8.3.
Marker surface offset by a normal fault. Contours on the fault are *thin lines* and contours on the marker surface are *heavier lines*. Throw on the fault is 32 m, heave is 25.6 m, and the gap is 24.9 m

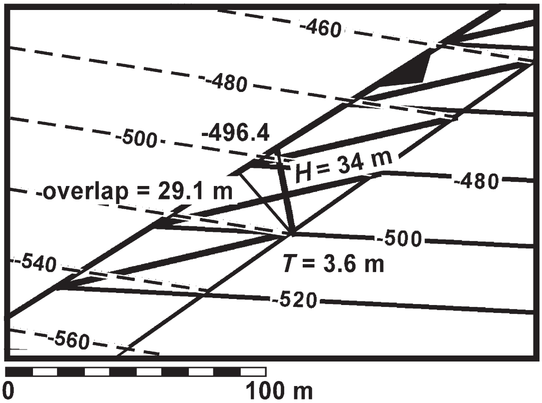


Fig. 8.4.
Marker surface offset by a reverse fault. Contours on the fault, *heavy lines*; on the hangingwall, *solid lines*; on the footwall, *dotted lines*. The throw is 3.6 m, heave 34 m, and overlap 29.1 m

8.2.2 Stratigraphic Separation from a Structure Contour Map

Stratigraphic separation is found from the heave or throw by solving Eqs. 7.5 and 7.6 for t, giving

$$t = H \cos\rho / \cos\phi \quad , \tag{8.1}$$

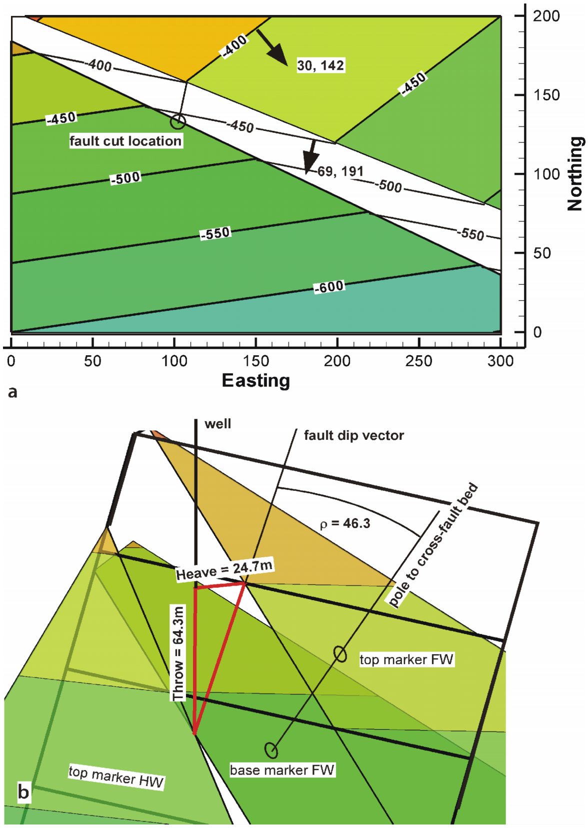
$$t = T \cos\rho / \sin\phi \quad , \tag{8.2}$$

where t = stratigraphic separation, ρ = the angle between the fault dip vector and the cross-fault bedding pole, ϕ = amount of fault dip, H = heave, and T = Throw. If bedding is horizontal then the stratigraphic separation = Throw. The angle ρ is found by one of the methods in Sect. 4.1.1.1 or 4.1.1.2. The dip of the fault can be determined from the heave and throw as

$$\phi = \arctan(T/H) \quad , \tag{8.3}$$

where ϕ = fault dip, T = throw, and H = heave.

Fig. 8.5. Stratigraphic separation from heave or throw. **a** Structure contour map of offset marker and fault. **b** 3-D oblique view to NW, including base of marker at fault cut in FW (*dark shading*)



As an example, find the stratigraphic separation predicted for a fault cut at the location indicated on Fig. 8.5a. At this point the heave is 24.6 m and the throw is 64.5 m, measured as indicated in Sect. 8.2.1. The cross-fault bedding dip and the fault dip magnitudes are found from the contour spacings using Eq. 2.22. The dip directions are perpendicular to the structure contours, giving for the fault, $\phi = 69, 191$, and for the bed, $\delta = 30, 142$, and the angle $\rho = 46.3°$ from Eq. 4.3. Applying either Eqs. 8.1 or 8.2, the stratigraphic separation is $t = 47.6$ m. This result is shown in a 3-D model (Fig. 8.5b) in which all the parameters can be measured directly to illustrate and validate the relationships in Eqs. 7.5–7.6 and 8.1–8.2.

8.3 Constructing a Faulted Marker Horizon

Placing the trace of faults on the structure contour map of a marker surface generally begins with a preliminary map of the marker horizon without faults (Fig. 8.6a), then the faults are mapped and the traces of the faults are found (Sect. 2.7) on the preliminary marker surface (Fig. 8.6b). The marker surface is separated into hangingwall and

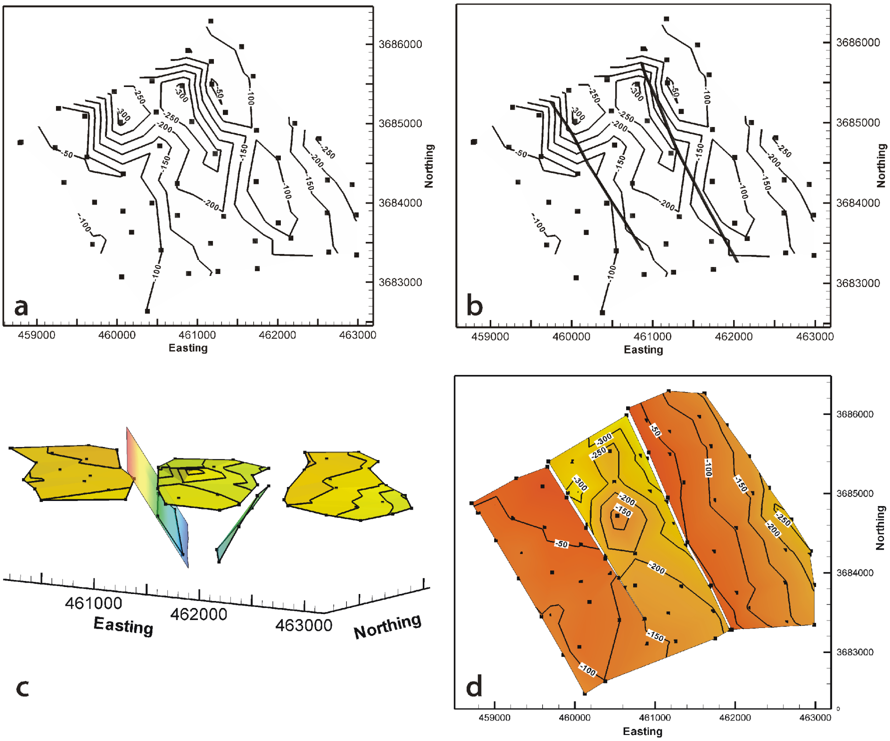


Fig. 8.6. Example of procedure for fault interpretation applied to top of Gwin coal cycle, Deerlick Creek coalbed methane field, Alabama (based on data in Groshong et al. 2003b). Contour interval is 50 ft, *squares* show well locations. **a** Top of the Gwin contoured without faults. **b** Top of the Gwin showing approximate fault traces. **c** 3-D oblique view of top Gwin broken into separate blocks at fault traces and re-contoured. **d** Top of Gwin re-mapped to fit the faults. Additional *squares* are points defining HW and FW cutoff lines

footwall blocks (Fig. 8.6c) and finally re-mapped to join the marker surface to the fault planes (Fig. 8.6d). The final re-mapping requires contouring up to and across the fault planes and must honor the known fault separations. Locating the faults, projecting beds to the fault surface, and contouring up to and across a fault will be discussed next.

8.3.1 Locating the Fault

In mapping a single marker surface with data from wells, the exact location of a fault is usually uncertain. Closely spaced, parallel contours on the marker surface provide a clue to the presence of a fault but do not necessarily give an accurate location. For example, the traces of the faults in Fig. 8.6b are in regions of closely spaced contours but do not follow the contours. Furthermore, it is rare for a well to cut a fault exactly at the marker horizon being mapped and so direct evidence of the fault location in the marker horizon is usually absent. All fault cuts at any stratigraphic level that can be correlated should be mapped, as discussed in Sect. 7.7.2. The right-hand fault in Fig. 8.6c is a typical result: the directly mappable fault usually does not extend laterally or vertically across the entire region of interest. The ambiguity of fault location in any single horizon can be greatly reduced by mapping multiple horizons in the vicinity of the fault.

Mapping multiple beds on both sides of a proposed fault will help to confirm its existence and location. As an example, the fault trace in Fig. 8.6c is not accurately located on any single horizon. Once multiple horizons have been mapped the location of the fault is much better defined (Fig. 8.7). An oblique view down the fault trace in 3-D (Fig. 8.7a) shows a narrow but clear path for the fault plane. The edge views (Fig. 8.7b,c) show that the units maintain nearly constant thickness and that they have been correctly separated into hangingwall and footwall blocks. Now it can be seen that the best-fit fault trace (Fig. 8.8) is much smoother and straighter than that suggested by the closely spaced structure contours mapped without a fault (Fig. 8.6a). If 3-D software is not available, serial cross sections across the fault provide nearly the same information about the hangingwall, footwall and fault trace.

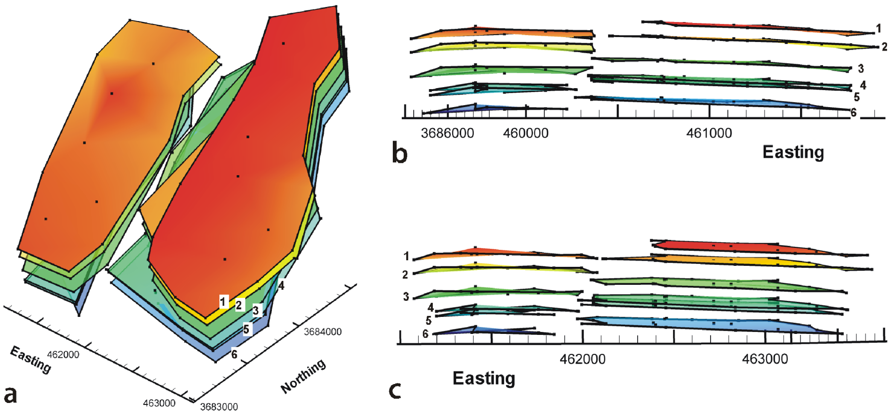


Fig. 8.7. Marker surfaces on both sides of the eastern fault in Fig. 8.6c (Deerlick Creek coalbed methane field). The markers are numbered; *1:* top Gwin, the same surface mapped in Fig. 8.6. *Small squares* are control points from wells. **a** Oblique view to NW down the fault trace. **b** View NW, parallel to bedding in footwall. **c** View NW, parallel to bedding in hangingwall block

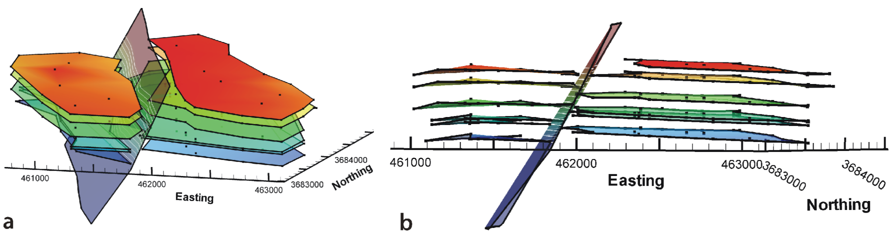


Fig. 8.8. Interpreted fault surface between hangingwall and footwall blocks of Fig. 8.7. **a** Oblique view to NW. **b** View to NW, approximately parallel to fault strike and bed dip

Faults may die out laterally or vertically into folds. During interpretation of the fault location, wells should be examined for evidence of continuity across the proposed fault trace. An unfaulted well (or outcrop) at an intermediate elevation and between the upthrown and downthrown blocks would be evidence for a fold. No such evidence is found for the fault in Figs. 8.7or 8.8, hence it is mapped as extending across the entire stratigraphic section, e.g., across the top of the upper map horizon (Fig. 8.8) originally mapped as being continuous (Fig. 8.6a).

8.3.2
Joining Offset Marker Surfaces to a Fault

The final step in constructing a complete structure contour map of a faulted surface is to extend the marker surfaces until they join the fault. The basic principle is that the offset marker must join the fault along cutoff lines where the elevations exactly match those of the fault as exemplified by the faulted surfaces in Fig. 8.1. Rarely are there enough data close to the fault plane to eliminate the need for interpretation (Fig. 8.9). The data gaps adjacent to the faults in Fig. 8.6c are typical.

The marker-surface geometries on opposite sides of the fault may or may not be directly related, depending on the nature of the fault. If the fault is curved or if the structures on opposite sides of the fault developed independently using the fault as a displacement discontinuity, then the marker surfaces may be completely unrelated on opposite sides of the fault (Fig. 8.10a,b) and the two sides should be contoured

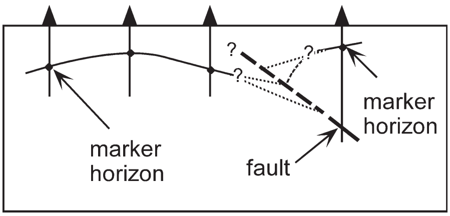


Fig. 8.9. Cross section showing typical subsurface data available for contouring a marker horizon across a fault. *Thin dotted lines* show area of uncertain marker bed location. *Thick dashed line* shows area of uncertain fault location

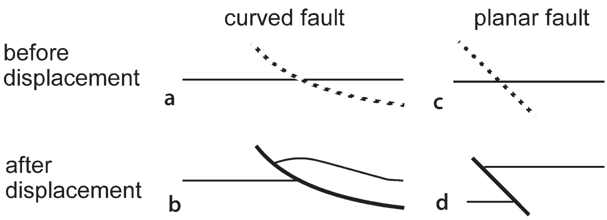


Fig. 8.10. Effect of fault curvature on the relationship between hangingwall and footwall bed geometry. **a** Listric fault before displacement. **b** Listric fault after displacement: the hangingwall shape is changed. **c** Planar fault before displacement. **d** Planar fault after displacement: the hangingwall shape is unchanged

independently. Folds produced by displacement on faults are discussed in Chap. 11. If a planar fault displaces a pre-existing structure, then the shape of the marker horizon will be unaffected by the fault (Fig. 8.10c,d) and the two sides should be contoured so that the hangingwall and footwall bed geometries are related to one another across the fault. The fault separation, if known, should be used to control the size of the fault. The next sections describe interpolation techniques designed to complete the faulted surface based on the different types of information commonly available.

8.3.2.1
Extrapolation of Marker Surface to the Fault

The following method is appropriate where there are enough data to define reasonable marker geometries in the vicinity of the fault. The marker on one side of the fault is contoured to define its shape (Fig. 8.11a). The marker surface is projected into the fault to find the line of intersection, known as the cutoff line. In 3-D software the model can be rotated until the view is along the marker trend and the cutoff line traced directly onto the fault. If a fold is present, see Sect. 5.2 for defining the fold trend and Sect. 6.6 for projection techniques. Once the cutoff line has been found it is added to the marker-horizon data set and contoured (Fig. 8.11b). If comparable information is available, the same procedure is followed on the opposite side of the fault to produce the finished map (Fig. 8.12).

Where no information is available about the dip of the fault and the fault separation is unknown, the structure contours on the fault surface can be generated from the fault geometry most reasonable for the local structural style, for example, a 60° dip for a normal fault. The marker beds are extrapolated from both the hangingwall and footwall until they intersect the fault. The structure contours on the hypothetical fault and the extrapolated marker horizon are intersected to produce the fault trace on the map. The resulting map will be internally consistent but is, of course, hypothetical.

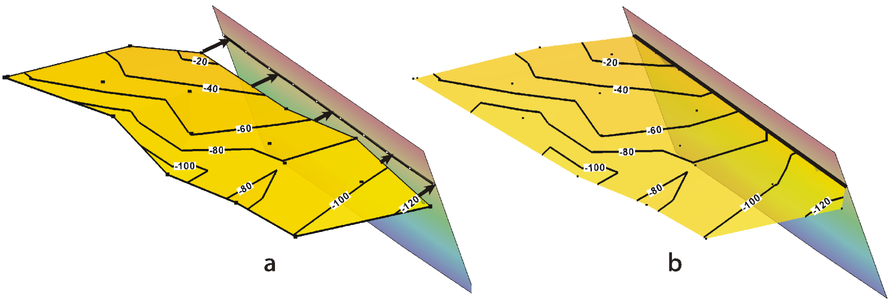


Fig. 8.11. Projection of a marker surface to a fault plane. The example is the top Gwin of the footwall on the western fault in Fig. 8.6c. **a** Faulted marker surface is projected along trend (*arrows*) to its intersection with the fault. **b** Points along the resulting footwall cutoff line are contoured with the original marker data to produce a surface that accurately meets the fault

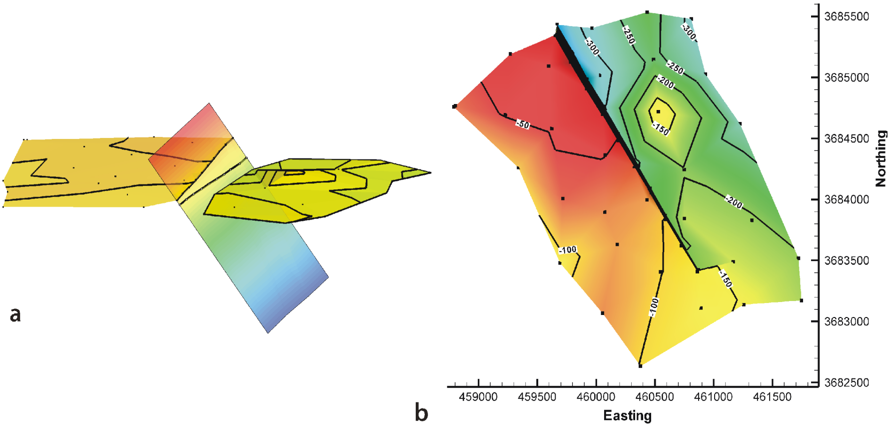


Fig. 8.12. Completed projection of a marker surface to a fault plane. The example is the top Gwin of the fault in Fig. 8.11. **a** Faulted marker surface showing projected hangingwall cutoff line on the fault surface. **b** Final structure contour map of the top Gwin including the fault cutoff lines. Fault gap is *black*

8.3.2.2 Honoring Stratigraphic Separation

If the stratigraphic separation on a fault is known, it provides an important constraint on the interpretation and provides a critical check on the size of a mapped fault. Heave and throw are calculated from the stratigraphic separation (Sect. 7.4.3) and the map is constructed to accurately include these values.

Structure contours on the best-known marker horizon are extrapolated to join the structure contours on the fault surface, defining the trace of the "known" cutoff line (Fig. 8.13). Either the heave or the throw can then be used to control the position of the other cutoff line. To use the throw (Fig. 8.13), move directly up the fault dip (or down the dip, as appropriate) to the point where the elevation is equal to the original elevation plus (or minus) the throw. This represents one point on the inferred cutoff line. The heave and throw are likely to change along the trace of the fault, thus the values closest to the points being inferred should be used. A smooth line through the inferred points is the trace of the inferred cutoff line. The elevations along the inferred cutoff line provide control points for the marker surface on that side of the fault.

The strength of this method is that it works where the marker horizon shapes are different across the fault. When fault blocks are contoured independently, use of this method will ensure that the fault separation between the blocks is correct. The weakness in the method is that the location of the fault cutoff and the cross-fault dip must be known or inferred before the cutoff can be projected across the fault. Developing the best interpretation is commonly an iterative process. The map may be used to provide the dips and then the heave and throw used to improve the map in the vicinity of the fault. Changes in the map may give different values for the fault dips, requiring another revision of the heave and throw calculations, and so on.

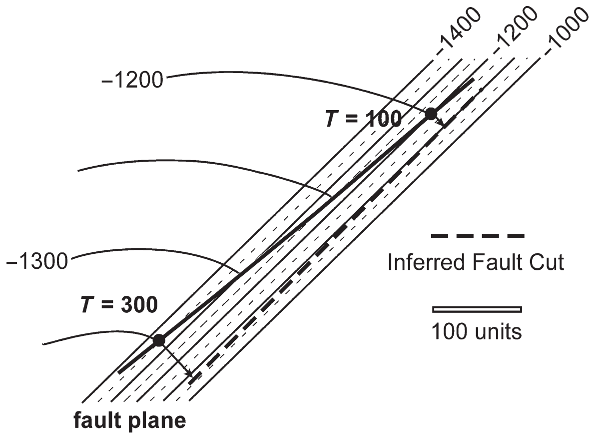


Fig. 8.13.
Structure contour map illustrating fault cutoff line inferred from throw. *Heavy solid line:* known cutoff line; *heavy dashed line:* inferred cutoff line on opposite side of fault; *T:* throw at known points, *arrows* point directly up the fault dip

8.3.2.3
Restored Vertical Separation

Contouring based on restored vertical separation (restored tops) is appropriate where the geometry of the hangingwall and footwall beds is unchanged by faulting except for the vertical separation on the fault (Jones et al. 1986; Tearpock and Bischke 2003). This method is used to find the shape of a surface before faulting and its configuration after a displacement amount equal to the vertical separation of the fault (Fig. 8.14). Begin the interpretation by finding the vertical separation from the stratigraphic separation at a fault cut (well 4, Fig. 8.14a). To calculate the vertical separation (Eq. 7.3) it is necessary to know or assume the dip of bedding at the fault cut. For dips below about 25°, the stratigraphic separation is similar in magnitude to the vertical separation and can be used as an approximation. The stratigraphic separation is always less than the vertical separation, but below a marker dip of 25° the difference is under about 10%. Next, remove the vertical separation by adding it to all marker elevations on the downthrown side of the fault (wells 1–3, Fig. 8.14a). Then contour the marker horizon as if no fault were present to obtain the restored top (Fig. 8.14a). Then, subtract the vertical separation from all contour elevations on the downthrown side of the fault (Fig. 8.14b). Recontour the data while maintaining the shapes of the structure contours from the restored-top map. Break the map at the fault by intersecting the contoured fault surface with the marker horizon on both the upthrown and downthrown sides of the fault. This method ensures that the vertical separation on the fault is included on the final map and that the marker geometry is related across the fault.

The strength of this method is that it guarantees that the marker horizon shape is related across the fault. The weakness in the method is that in many structural styles the hangingwall and footwall geometries should not have the same shape (Fig. 8.10a,b). If there is any strike-slip component to the fault displacement, it must be removed before the points are contoured in order to correctly relate the hangingwall and footwall geometry.

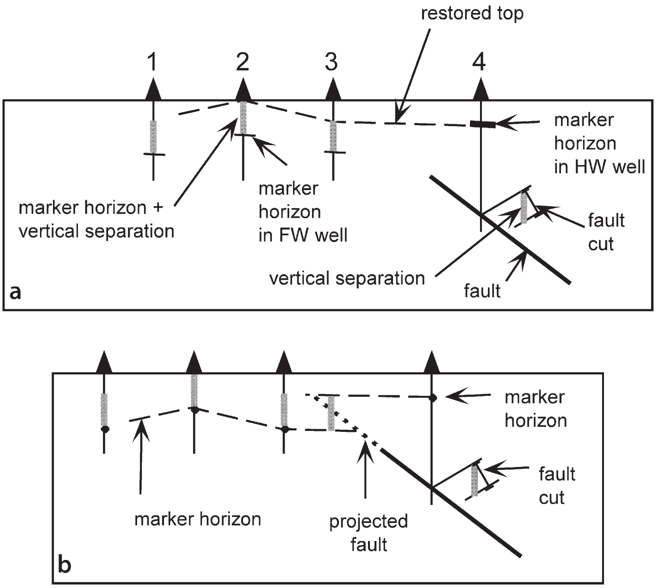


Fig. 8.14.
Cross sections in the fault dip direction, showing the method of restored vertical separation to control position of the marker horizon. The dip shown at the fault cutoff is used to determine the vertical separation. **a** Fault separation is added to all marker elevations on the downthrown side of the fault and elevations are contoured to give the restored top. **b** Vertical separation is subtracted from the downthrown side and the marker horizon re-contoured to give the inferred geometry

8.4 Fault Cutoff Maps and Allan Diagrams

A fault cutoff map is a map of the traces of beds where they are truncated against a fault (Fig. 8.15). Maps can be made of either or both hangingwall and footwall cutoffs. Superimposed hangingwall and footwall cutoff maps are known as Allan diagrams from their use by Allan (1989) in the prediction of fluid migration pathways and traps for hydrocarbons migrating in the vicinity of a fault zone. The cutoff lines are also termed Allan lines. Fault cutoff maps provide quality control on the bed geometries at the fault, are useful in predicting traps and spill points of hydrocarbon reservoirs formed against faults, and potentially provide a relatively unambiguous method for determining the slip on a fault without piercing points.

8.4.1 Construction

The first step in producing a fault cutoff map is to project the faulted horizons to the fault surface and find the lines of intersection between the horizons and the fault, as has been discussed in Sect. 8.3.2.1. Projections of the fault cutoffs onto either vertical or horizontal planes are convenient when the section is made directly from a completed structure contour map. A vertical map plane is suitable where the fault is steeply dipping (Fig. 8.16) and will show the throw on the fault. If the fault is curved in plan view, a vertical projection foreshortens the length of the fault. A horizontal map plane is suitable where the fault is gently dipping and will show the heave on the fault

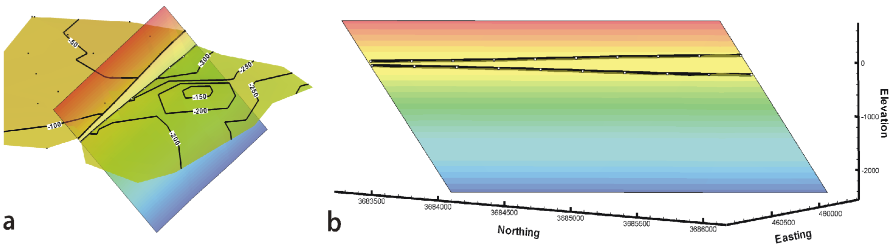
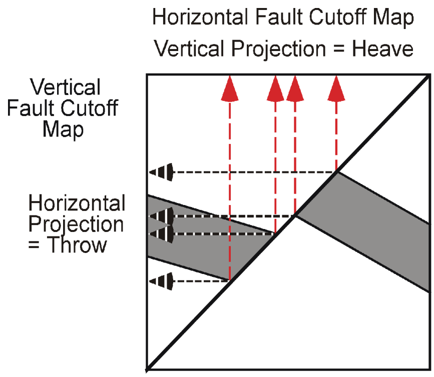


Fig. 8.15. Fault cutoff map of fault from Deerlick Creek coalbed methane field (data from Groshong et al. 2003b). **a** 3-D oblique view of marker surface truncated at fault. **b** 3-D oblique view of fault surface showing hangingwall and footwall cutoff lines (*heavy lines*)

Fig. 8.16. Cross section in the dip direction of the fault, showing projection of fault cutoffs onto horizontal and vertical fault cutoff map planes



(Fig. 8.16). If the fault is curved in cross section, a horizontal projection foreshortens the width of the fault. Three-dimensional computer graphics techniques allow maps to be made directly on the fault surface (Fig. 8.15b).

The construction of a fault cutoff map is illustrated for a fault seen in an underground mine along two coal seams in the Black Warrior basin of Alabama. The fault dips about 60° to the northeast and forms one side of a full graben (Fig. 8.17). To the southeast it dies out by transferring its displacement to a parallel fault. To the northwest the fault zone continues along multiple parallel branches. The first step in constructing the cutoff map is to choose the plane of the map. In this example the fault dips steeply and so projection onto a vertical plane is suitable. The trace of the map plane is taken parallel to the trend of the fault and with a view direction to the southwest, from the hangingwall to the footwall (Fig. 8.18). The vertical scale is exaggerated by a factor of three because the maximum displacement on the fault is so small relative to its length. The elevations of the cutoffs of the top of both coal seams against the fault are transferred to the cutoff map along lines perpendicular to the trace of the map, which is the method of illustrative section construction (Sect. 6.3). The splays at the northwest end of the fault necessitate a choice of which elevations to map. The entire zone is included here so that the cutoff map (Fig. 8.18) shows the total displacement across the fault zone.

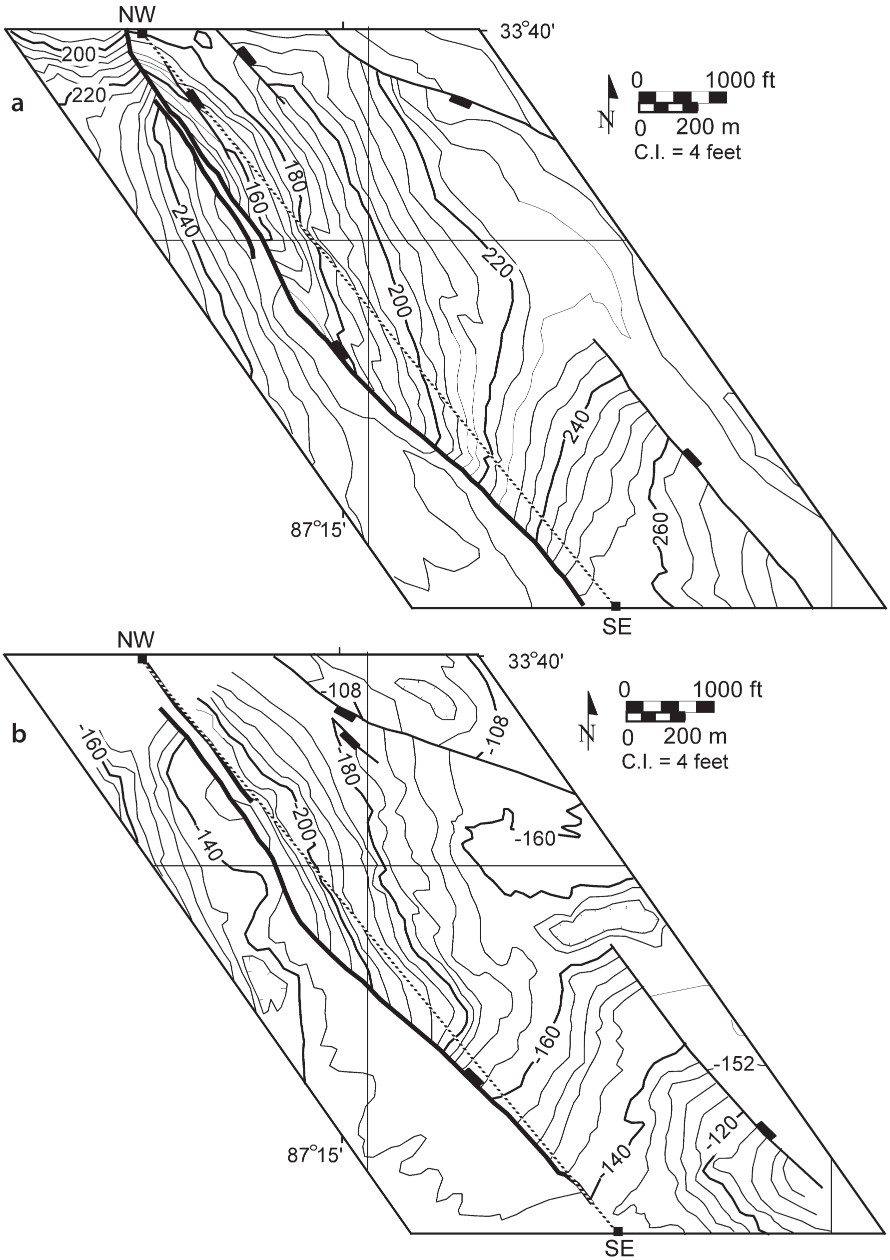


Fig. 8.17. Structure contour maps on the tops of two coal seams in the Drummond Goodsprings No. 1 Mine, central Alabama. The line of the fault cutoff map is the NW-SE *dotted line*. The fault zone represented on the cutoff map is indicated by *heavy solid lines*. **a** Top of America coal seam. Elevations are in feet above sea level. **b** Top of Mary Lee coal seam. Elevations are in feet below sea level. *C.I.* Contour interval. (After Hawkins 1996)

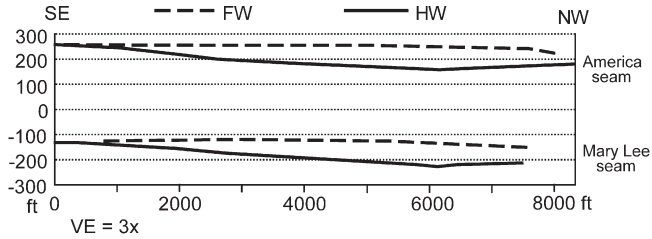


Fig. 8.18. Fault cutoff map (horizontal projection) of throw on the coal seams for the fault zone indicated by the *heavy solid lines* in Fig. 8.17. The section is along azimuth 321°. *Dashed* cutoff lines belong to the footwall (*FW*) and *solid* cutoff lines belong to the hanging-wall (*HW*)

The cutoff map (Fig. 8.18) shows that the fault separation dies out to the southeast and has a maximum at about 6 000 ft on the profile. Both seams have similar throws, with the maximum decreasing downward from 90 ft in the America seam to 80 ft in the Mary Lee seam. The dip separation on the 60° dipping fault is 104 ft in the America seam and 92 ft in the Mary Lee seam (obtained from $L = T / \sin \phi$, where L = dip separation, T = throw, and ϕ = fault dip). Assuming that the point of maximum dip separation is close to the center of the fault, the length/displacement ratio is about 8 000 / 98 or 82 to 1.

8.4.2 Determination of Fluid Migration Pathways

Fault cutoff maps are extremely useful in determining the possible routes of fluid migration in fault zones where the fault plane itself is not a barrier to the migration (Allan 1989). A fault trap is a closure in a permeable bed that is sealed by impermeable units across the fault. Multiple porous beds in the section can lead to very complex migration paths (Fig. 8.19) in which the migrating fluid crosses back and forth across the fault. Figure 8.19 shows eight fold closures against the fault, only three of which are sealed for the up-dip migration of a light fluid like oil or gas. The spill point at the base of each closure is located where permeable beds are in contact across the fault. Fluids that are heavier than water, such as man-made contaminants, may spiral downward across a fault into synclinal closures at some distance from the original contamination site.

The sequential migration of hydrocarbons through multiple traps like those in Fig. 8.19 can lead to a reversal in the expected positions of the oil and gas. The expected sequence in the filling of a trap in place is illustrated in Fig. 8.20. Thermal maturation of the hydrocarbon source leads first to the formation of oil (Fig. 8.20a) which is less dense than water and displaces the water in the trap. Gas forms later in the source bed or in the trap itself and, being less dense than the oil, displaces the oil to form a gas cap on the reservoir (Fig. 8.20b). The formation of a large volume of hydrocarbons can fill the trap to the spill point where the closure is no longer complete and allow displaced hydrocarbons to be forced out at the base of the accumulation to continue migrating up dip. The process of spilling from the base of the reservoir causes the most dense hydrocarbons to continue migrating up dip into new traps (Gussow

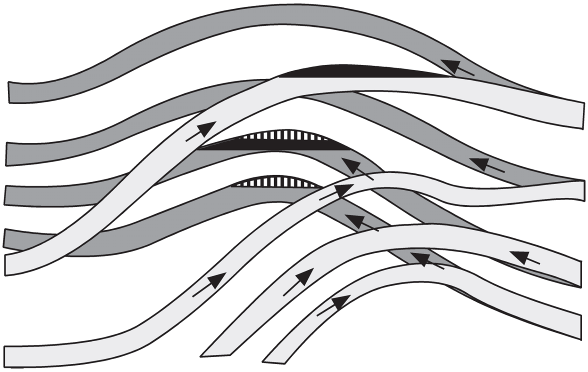


Fig. 8.19.
Allan diagram showing fluid migration pathways through permeable beds separated by impermeable beds; footwall *shaded*. *Arrows* give migration routes of fluids that are lighter than water. Oil accumulations are *solid black*; gas accumulation is indicated by *vertical lines*. (After Allan 1989)

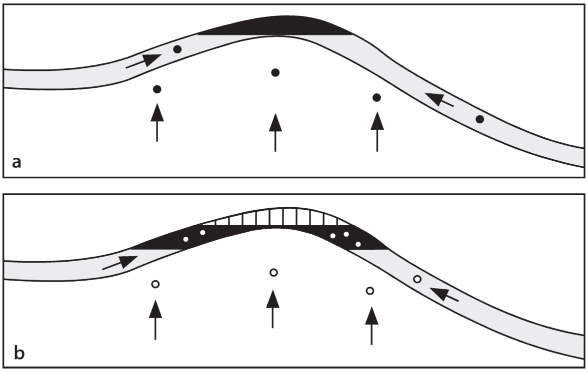


Fig. 8.20.
Sequential formation of oil (*black*) and gas (*vertical lines* and *open circles*) and filling of a trap. **a** Burial to the temperature of the formation of oil. **b** Additional burial to the temperature of the formation of thermal gas. The gas displaces oil in the trap

1954; Allan 1989). The lightest hydrocarbons, mainly gas, remain in the deeper traps. Thus the presence of deep gas-filled traps and shallow oil-filled traps as shown in Fig. 8.19 can be caused by the upward migration of hydrocarbons across multiple spill points (assuming that oil and gas are both thermally stable at the trap depths).

8.4.3
Determination of Fault Slip

The slip on a fault is normally determined by the offset of geological lines that pierce the plane of the fault. Geological lines may be formed by original stratigraphic features, such as linear sand bodies or paleo-shorelines; intersection lines, such as a vein-bed intersection or a vein-vein intersection; or a structural feature like a fold hinge line. An Allan diagram provides an excellent format for the display of the cutoff information.

An anticline-syncline pair offset by a normal fault (Fig. 8.21a) appears at first glance to have both right-lateral and left-lateral slip, a common map pattern where faults cut folded beds (see also Fig. 7.17). The Allan diagram (Fig. 8.21b) makes it clear that the fault is dip slip and shows the amount of the slip from the offset of the fold hinge lines.

Structures may develop independently across some fault zones and so may not directly correlate across the fault. That the fold geometry is the same on both sides of the fault in Fig. 8.21 supports the concept that a pre-existing fold has been cut by a later fault and that the arrows connecting hinge lines (Fig. 8.21b) represent the slip.

If croscutting features are present at the fault surface, an Allan diagram will make both the slip and rotational components obvious and readily measurable. Both vein-bed and vein-vein intersections can be correlated across the fault in Fig. 8.22. As a result of the rotational displacement on the fault, each correlated point has a different net slip.

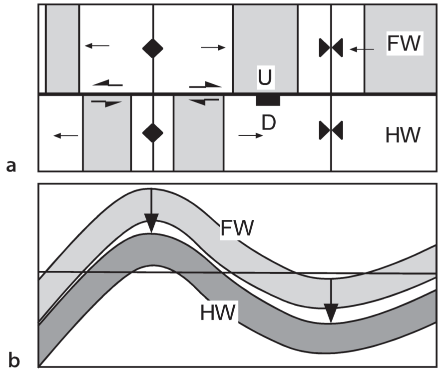


Fig. 8.21. Anticline-syncline pair cut by a normal fault. **a** Map. The *shaded* bed is the same on both sides of the fault. *Full arrows* show bedding dips, *half arrows* show strike separations, not slip. **b** Fault cutoff map of hangingwall (*darker shading*) and footwall cutoffs. The *horizontal line* is the line of intersection of the outcrop map and cutoff map. *Arrows* show the hangingwall slip vectors of the anticlinal and synclinal hinge lines and indicate pure dip slip

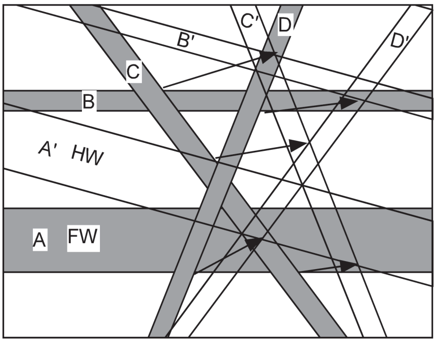


Fig. 8.22. Rotational fault displacement on a fault cutoff map. Superimposed fault-surface sections of hangingwall (*unshaded*) and footwall (*shaded*). Horizontal footwall beds labeled *A* and *B* rotate to *A′* and *B′*; veins *C* and *D* rotate to *C′* and *D′*. *Arrows* show hangingwall slip of correlated bed-vein intersection points. Fault slip is a left-lateral reverse translation produced by a 15° clockwise rotation of the hangingwall relative to the footwall

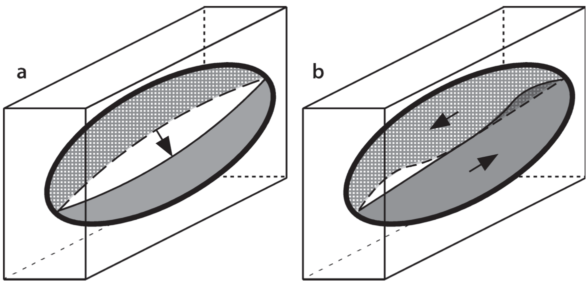


Fig. 8.23. Allan diagrams for **a** dip-slip and **b** strike-slip dislocation-model faults

The Allan diagram of a complete fault may, by itself, provide all the information needed for a reasonable estimate of total slip. It is well established that the Allan diagram of a single bed cut by a dip-slip fault resembles that shown in Fig. 8.23a, with the arrow giving the slip. Displacement-distance graphs and the bow-and-arrow rule for fault displacement are comparable concepts (c.f., Sect. 7.5.2). Strike-slip and oblique-slip faults will doubtless show more complex geometries. Figure 8.23b is a hypothetical strike-slip bed geometry that approximately preserves bed length parallel to the fault strike between the fault tips. The maximum strike-slip displacement would be at the center and equal to the sum of the difference between the straight-line length and the curved-bed length between the fault tips for both sides of the fault.

8.5 Faults on Isopach Maps

Faults cause characteristic thickness variations on isopach maps (Hintze 1971). If unrecognized, these variations could be misinterpreted as being stratigraphic in origin. Recognized as fault related, they provide a useful tool for fault interpretation. A normal fault thins the stratigraphic unit (Fig. 8.24) and a reverse fault thickens the unit. A single fault produces two parallel bands of thickness change (Figs. 8.24, 8.25), one associated with the cutoff of the top of the unit and one with the cutoff of the base of the unit. The affected width on the isopach map is appreciably wider than the fault gap or overlap on the struc-

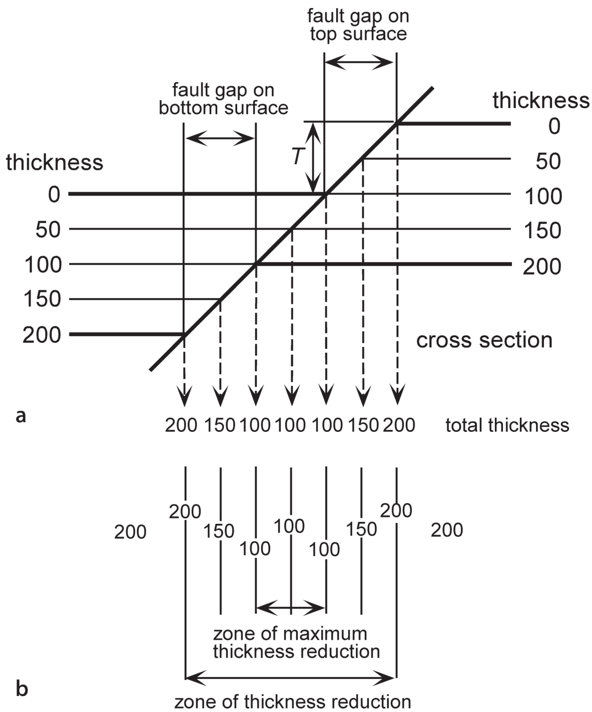


Fig. 8.24. Effect of normal-fault displacement on the thickness of a unit. **a** Cross section. *T* throw on the fault. **b** Isopach map. (After Hintze 1971)

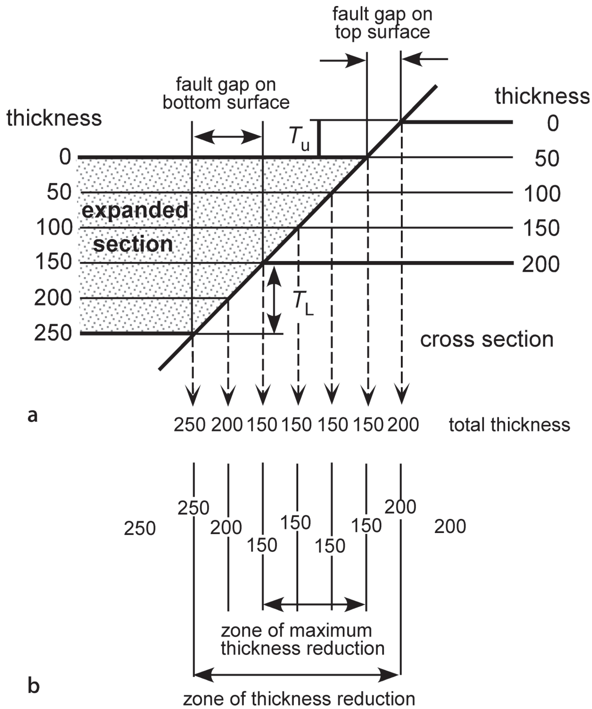


Fig. 8.25.
Effect of normal-fault displacement on the thickness of a growth unit. **a** Cross section, T_u = fault throw at upper surface, T_l = fault throw at the lower surface of the unit. **b** Isopach map

ture contour map of the top or base of the unit. The affected zone extends from the fault cutoff of the upper surface of the affected bed on one side of the fault to the fault cutoff on the lower surface of the affected bed on the other side of the fault (Fig. 8.24). The zone of thinning (normal fault) or thickening (reverse fault) is centered on the trace of the fault through the middle of the unit. Such elongate zones of thinning or thickening can indicate the presence of faults having displacements that are too small to completely separate the map unit and that might otherwise go unrecognized.

The throw on the hangingwall or the footwall of a fault that does not completely separate the unit can be determined from the maximum and minimum thicknesses of the unit as

$$T = t_{max} - t_{min} \quad , \tag{8.4}$$

where T = fault throw, t_{max} = maximum thickness inside (reverse fault) or outside (normal fault) the zone of thickness change, and t_{min} = minimum thickness inside (normal fault) or outside (reverse fault) the zone of thickness change.

For a growth unit (Fig. 8.25) the thickness change is different on opposite sides of the fault. Less thickness change occurs on the upthrown side of the fault because the displacement is partly erased by sedimentation. The asymmetry can be used to infer the dip direction of the fault. A normal fault dips toward the thicker side and a reverse fault dips away from the thicker side.

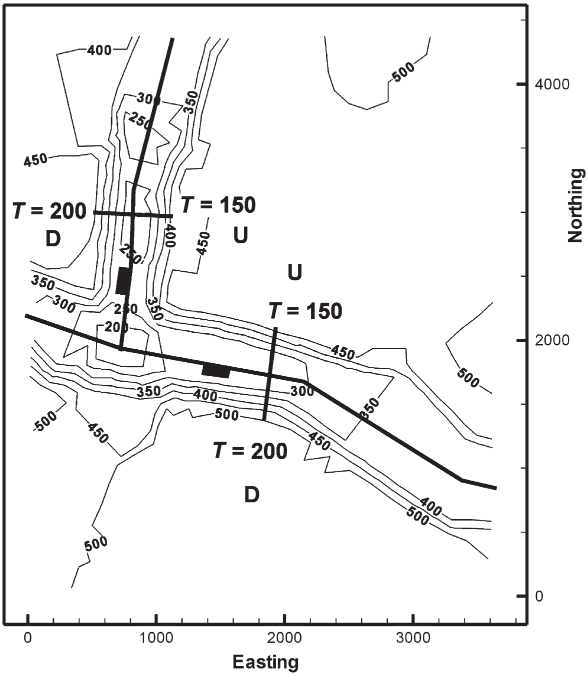


Fig. 8.26.
Interpreted isopach map of the top of the lower Taylor Formation on part of the Hawkins salt dome, Texas. The contour interval is 50 ft. *D* Downthrown block, *U* upthrown block. (Isopach map after Hintze 1971)

A map on a portion of a salt dome provides an example of the effect of normal faults on an isopach map. Elongate zones of isopach thinning are developed along faults (Fig. 8.26). On a traverse across the north-south fault, the throw is 150 ft on the east (Eq. 8.4: 400–250) and 200 ft (Eq. 8.4: 450–250) on the west. The thicker section on the west of the normal fault indicates that it dips to the west. A similar analysis indicates that the east-west fault is a growth fault, down to the south with 150 ft of throw at the top of the unit and 200 ft at its base.

8.6 Displacement Transfer

This section describes the geometry of linked faults. As a fault dies out it usually transfers its displacement to another fault (Fig. 8.27). Displacement transfer between nearby faults is an important process in both map and cross section (Crowell 1974; Childs et al. 1995; Walsh et al. 1999). Faults that transfer displacement but do not intersect are termed soft linked and are separated by a continuous bed segment called a relay ramp (Kelly 1979). Faults that intersect are said to be hard linked (Walsh and Watterson 1991; Childs et al. 1993) and join along a branch line (Boyer and Elliott 1982). Conjugate faults (Sect. 1.6.4) that overlap will form convergent or divergent links (Fig. 8.27). Bends or overlaps that trend oblique to the slip direction are either restraining or releasing (Crowell 1974; Mansfield and Cartwright 1996) depending on their overlap direction relative to the slip direction (Fig. 8.28).

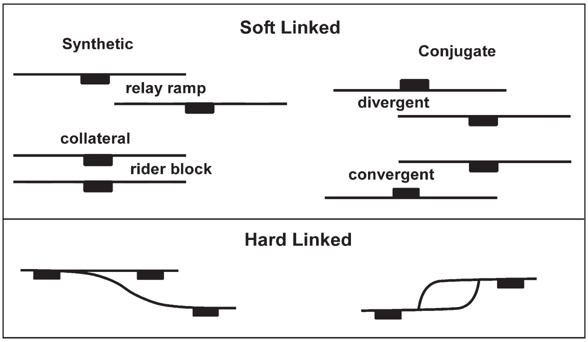


Fig. 8.27.
Displacement-transfer geometries on normal faults in map view. (After Morley et al. 1990)

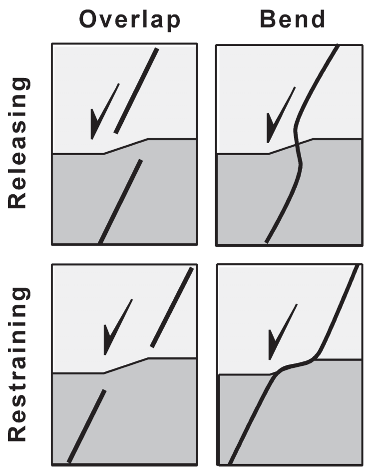


Fig. 8.28.
Displacement-transfer geometries on normal faults in cross section

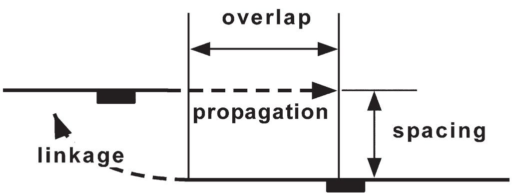


Fig. 8.29.
Possible evolution of a relay zone into a hard link. *Dashed arrows* indicate fault propagation directions

Soft links may evolve into hard links as displacement increases and the faults grow longer. Faults may propagate in their own plane or curve to intersect (Fig. 8.29). In general, a wide spacing between the propagating faults favors overlap and a small spacing favors linkage.

In the following sections the basic patterns of fault-to-fault displacement transfer are examined. All types of faults show the same forms of displacement transfer. The examples given will mainly be normal faults because they are easy to visualize, but the same principles and terminology can be applied to reverse and strike-slip faults.

8.6.1 Relay Overlap

Faults that transfer displacement from one to the other without intersecting constitute a relay pattern (Fig. 8.27). The displacement is said to be relayed from one fault to the other. The displaced horizon in the zone of fault overlap forms a ramp that joins the hangingwall to the footwall (Figs. 8.30, 8.31a). The ramp may be unfaulted or may itself be broken by faults. An unbroken ramp provides an opportunity for pore fluids to migrate across the main fault zone. Second-order faults within a ramp typically trend at a low angle to the strike of the ramp and are therefore at a high angle to the relay faults. Faults exhibiting a relay pattern may appear to be unrelated on a map because a single fault will have the displacement pattern of an isolated fault that dies out along strike (Figs. 7.22, 7.25). The covariation of displacement on the two faults reveals their relationship to be that of displacement transfer (for example, Fig. 7.25c). Detailed examination of large fault zones may reveal that the main fault consists of multiple segments with relay overlaps between the segments.

On the structure contour map of a horizon displaced in a relay zone, the ramp is the region between the two faults where the contours on the marker horizon are at a high

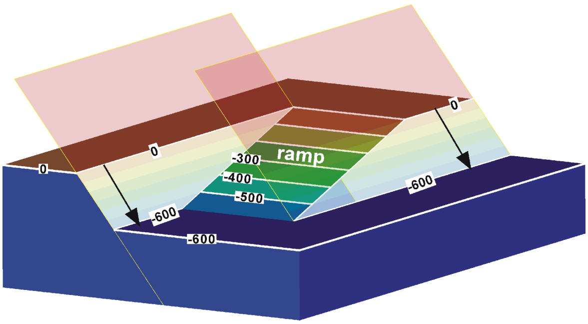


Fig. 8.30. Displacement transfer at a relay overlap. *Arrows* indicate amount of dip separation on the relay faults

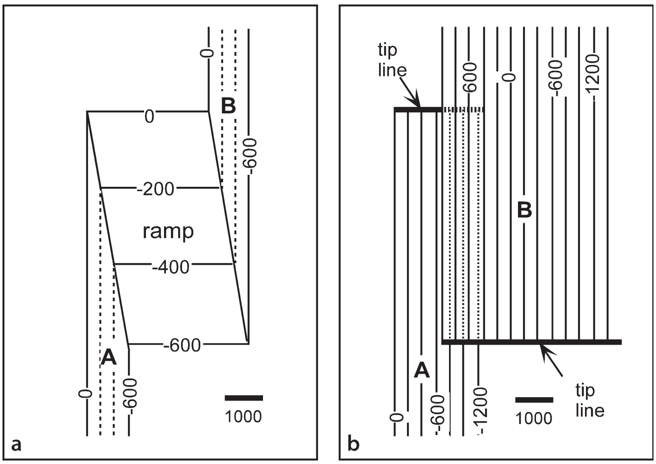


Fig. 8.31. Structure contour maps based on the relay overlap geometry in Fig. 8.30. Both maps are at the same scale. **a** Displaced stratigraphic horizon. *Solid contours* are on the offset marker, *dashed contours* are on faults *A* and *B*. **b** Portions of the two fault planes; contours on fault *A* are *dashed* where they lie below fault *B*

angle to the trend of the faults (Fig. 8.31a). Structure contour maps on the faults show them to overlap in the relay zone (Fig. 8.31b). Both faults end at tip lines that define the ends of the relay zone. The extent of the faults may be large, both updip and downdip, and the tip lines may be straight or curved.

8.6.2 Branching Fault

The intersection of two faults (Fig. 8.32) occurs along a branch line (Boyer and Elliott 1982). Some of the displacement is transferred from the main fault to the branch fault at the intersection. Displacement is conserved at the branch line (Ocamb 1961). As can be seen from Fig. 8.32, at the branch line, the throw of the largest fault will be equal to the sum of the throws on the two smaller faults. All the faults may change throw independently away from the branch line.

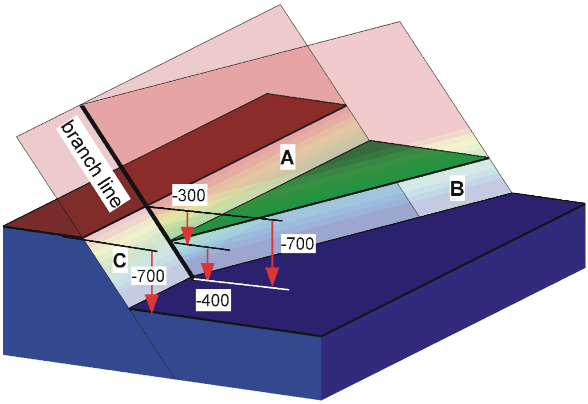


Fig. 8.32. Displacement transfer at a branch line on a normal fault. Fault surfaces are *shaded*. The total throw is constant at the branch line. In this example faults *A* and *C* are a single plane; fault *B* is the branch

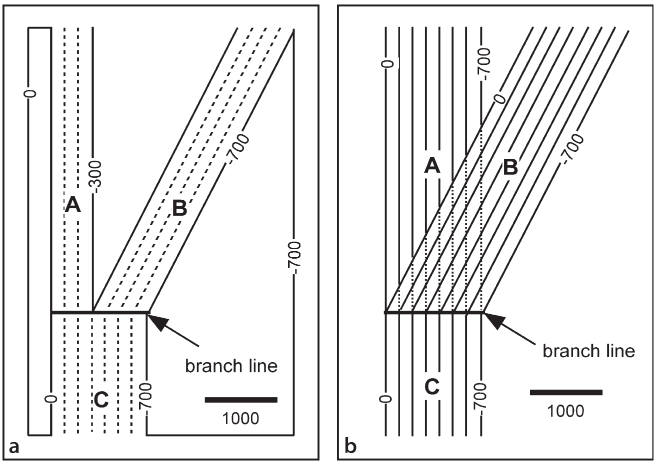


Fig. 8.33. Structure contour maps of a branching normal fault, based on the geometry of the structure in Fig. 8.32. Both maps are at the same scale. **a** Structure contours on the displaced marker horizon (*solid lines*) and on the faults (*dashed lines*). **b** Structure contours on portions of the three fault planes; contours on fault *A* are *dashed* where the plane lies below fault *B*. Fault planes *A* and *C* are the same

The structure contour map of a marker horizon displaced by a branching fault (Fig. 8.33a) shows two intersecting faults and an abrupt change in throw at the intersection. The throw of fault A plus that of fault B is equal to that of C at the branch line. In this example, the fault plane of A is continuous with the plane of fault C. Contours on the faults (Fig. 8.33b) show a straight branch line and a region of fault overlap. All three faults at the branch line could have different strikes.

A good test of the fault interpretation on a map is to measure the throws in the vicinity of all branch lines and show that the throws of the two smaller faults are equal to that of the larger fault. If this is not true, the map is wrong. An abrupt change in the throw of a fault is probably caused by an undetected fault branch (Ocamb 1961) or relay fault that carries the missing throw.

8.6.3
Splay Fault

Splay faults are minor faults at the extremities of a major fault (Bates and Jackson 1987). The master fault splits at one or more branch lines to form the splay faults (Figs. 8.34, 8.35). The splays then die out along strike at tip lines. Splay faults distribute the total

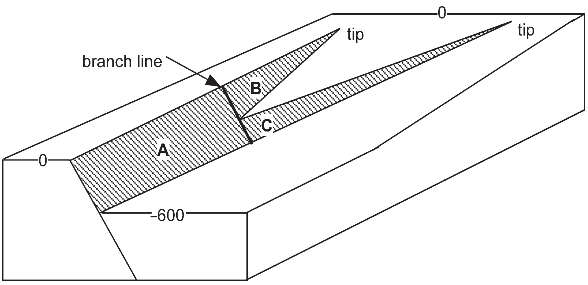


Fig. 8.34. Splay faults (*B* and *C*) at the end of a master normal fault (*A*)

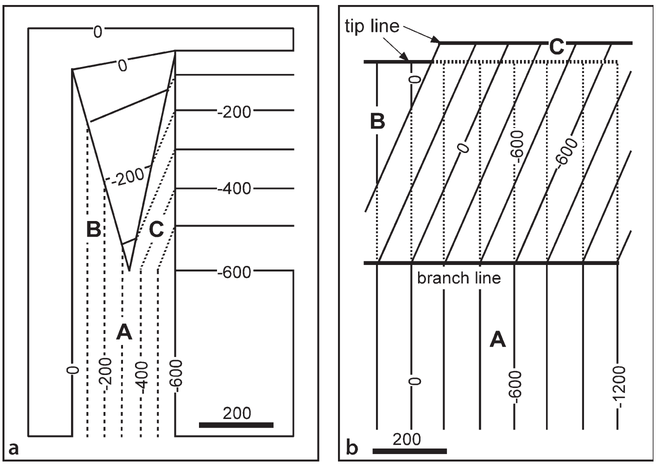


Fig. 8.35. Structure contour maps of a splaying normal fault based on geometry of the structure in Fig. 8.34. The master fault is *A*, its continuation into the region of splay faulting is *B*, and the other splay fault is *C*. Both maps are at the same scale. **a** Offset marker horizon. *Solid contours* are on the marker horizon and *dashed contours* are on the faults. **b** Portions of the faults. Contours are *dotted* where they lie below another fault

offset over a wider area, which makes it possible for more of the displacement to be accommodated by folding rather than faulting. This helps a large fault die out into a fold. The master fault may continue straight in the region of fault splays (Fig. 8.34), or all the splays may have different orientations from that of the master fault.

Splay faults are ultimately bounded in all directions by branch lines and tip lines. The leading edge of a structure is its termination in the transport direction, and the trailing edge is in the opposite direction (after Elliott and Johnson 1980). For a thrust fault, the leading edge of a splay is a tip line and the trailing edge is a branch line (Fig. 8.36a). The leading hangingwall and footwall cutoff lines of a unit carried on a splay join and end at the tip line of the leading fault (Fig. 8.36b). The trailing bed cutoff line continues along the trailing thrust beyond the tip of the splay.

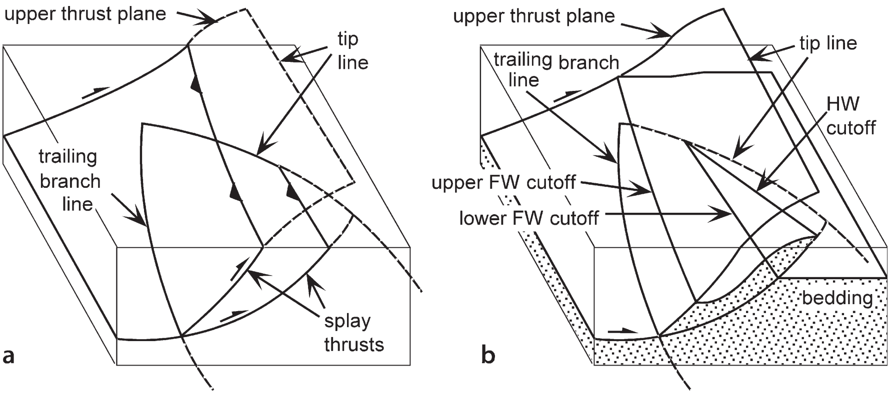


Fig. 8.36. Splay faults at the leading edge of a thrust fault. **a** Fault surfaces in three dimensions. **b** Bedding cutoff lines of a unit transported on the lower splay. (After Diegel 1986)

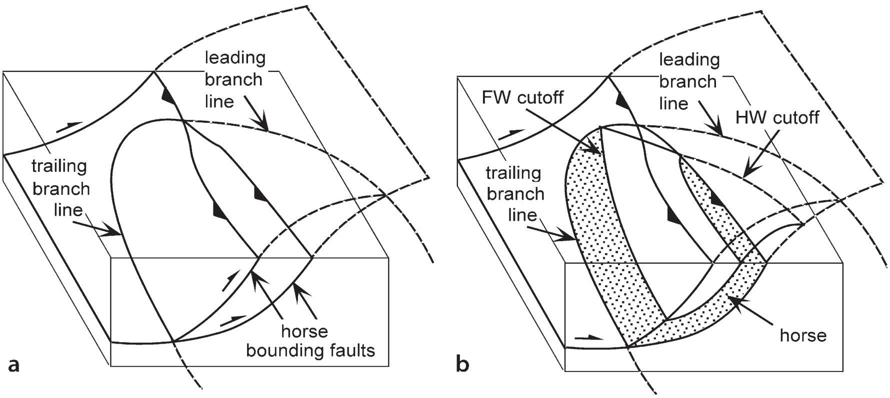


Fig. 8.37. Fault horse bounded on all sides by fault surfaces that end in all directions at a closed branch-line loop. **a** Main fault and branch lines. **b** Bedding cutoff lines for a stratigraphic unit within the fault horse. (After Diegel 1986)

8.6.4
Fault Horse

A fault horse (Fig. 8.37) is a body of rock completely surrounded by fault surfaces (Dennis 1967; Boyer and Elliott 1982). The geometry can be thought of as a splay fault that rejoins the main fault. A horse is completely bounded by a branch-line loop along which the two fault surfaces join (Fig. 8.37a). A stratigraphic unit within a horse will have leading and trailing cutoff lines at the two bounding fault surfaces (Fig. 8.37b). Multiple fault horses form a duplex (Boyer and Elliott 1982).

8.7
Crossing Faults

Two intersecting faults may both continue past their line of intersection, a relationship here termed crossing faults. Where one fault offsets the other, the line of intersection between the two faults is a cutoff line of one fault by the other, not a branch line. Crossing faults may be sequential or contemporaneous. Sequential faulting means that an older fault is cut and displaced along a younger fault. Contemporaneous faulting means that the faults form at approximately the same time and as part of the same movement picture.

8.7.1
Sequential Faults

Crossing dip-slip normal faults are illustrated in Fig. 8.38. Both faults have constant (but different) displacement, but the shaded marker horizon is displaced to four different elevations, reflecting the four different combinations of displacement from the original elevation (no displacement, fault 1 alone, fault 2 alone, fault 1 + 2). At first glance the structure contour map (Fig. 8.39a) appears to imply that fault 1 is younger and is a strike-slip fault because its trend is straight whereas the trend of fault 2 appears to be offset. Comparison with Fig. 8.38 shows that fault 2 is the through-going plane. It is the different elevations of the marker horizon along fault 2 that make this fault appear to bend at the intersection. The fault-plane map (Fig. 8.39b) shows fault 2 to be unbroken and fault 1 to be displaced. In the area near the intersection of the two faults, both faults would be penetrated by a vertical well (Fig. 8.39b).

The footwall cutoff line formed by the intersection of fault 1 with the marker horizon forms a geological line that can be used to determine the net slip on fault 2. In the example in Fig. 8.38, the slip on fault 2 is 300 units of pure dip slip, as indicated by the arrow on the fault surface. No geological line is present that predates the displacement of fault 1; hence the displacement can only be constrained as having a dip separation of 400 units.

Where fault 2 displaces fault 1, fault 2 carries the combined stratigraphic separation of both faults (Figs. 8.38, 8.39), making this area have a much larger separation fault than either fault 1 or 2 alone. The zone of combined separation for a particular horizon is restricted to a small region (Fig. 8.39a) where the second fault crosses the first fault. In three dimensions, the zone of combined separation (Dickinson 1954)

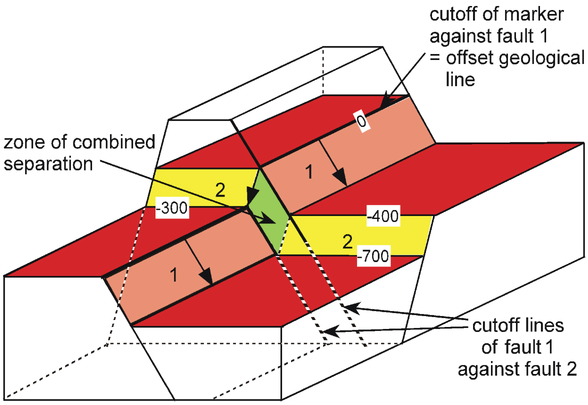


Fig. 8.38. A young normal fault (*2*) cuts and displaces an old normal fault (*1*). An offset marker surface is *shaded*. Displacement on each fault is dip slip of a constant amount. The displacement of the offset geological line is the slip on fault 2

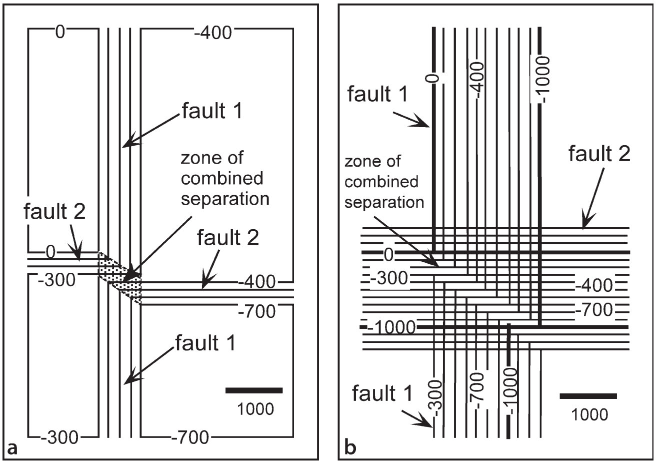


Fig. 8.39. Structure contour maps based on the geometry of the structure in Fig. 8.38. Both maps are at the same scale. Fault 2 is through-going and displaces fault 1 down dip 300 units to the south. **a** The marker horizon. **b** Portions of both faults in the vicinity of the offset marker horizon

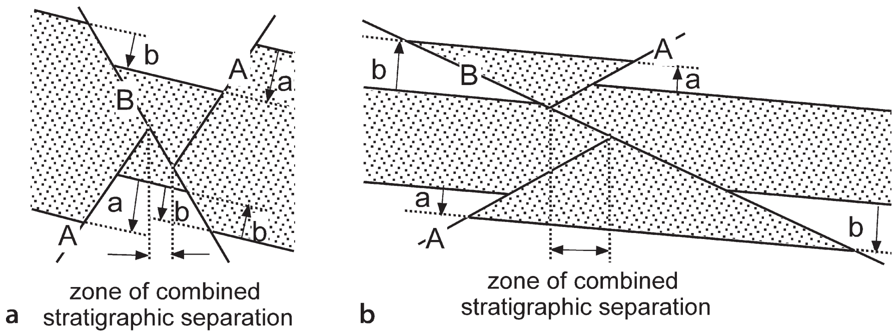


Fig. 8.40. Zone of combined stratigraphic separation on younger fault *B*. Fault *A* is displaced by fault *B*. **a** Two normal faults. **b** Two reverse faults

continues along the plane of the younger fault, between the traces of the cutoff lines of the older fault against the younger fault (Figs. 8.39b, 8.40). Other horizons will have their zones of combined separation along the same trend, but offset from one another. Given low bedding dips, a vertical well drilled into the zone of combined separation for two normal faults will cut one fault that carries the combined separation (Fig. 8.40a). A vertical well drilled into the zone of combined separation for two reverse faults will have three fault cuts (Fig. 8.40b), the middle one of which will carry the combined separation.

The amount of the combined separation is given by a relationship from Dickinson (1954). If the younger fault (B, Fig. 8.40a) is normal,

$$t = -b + (\pm a) \quad , \tag{8.5}$$

and if the younger fault (B, Fig. 8.40b) is reverse,

$$t = +b - (\pm a) \quad , \tag{8.6}$$

where t = combined stratigraphic separation, a = stratigraphic separation on the older fault, b = stratigraphic separation on the younger fault, the "+" sign indicates reverse separation = thickening, and the "–" sign indicates normal separation = thinning. The simplicity of this result is due to the fact that all the beds have the same dip. If dip changes occur across the faults but are small, then Eqs. 8.5 and 8.6 will still provide good estimates.

The map pattern produced by crossing normal faults depends on the angle of intersection of the faults, the dip of the faults and the marker horizon, and the magnitude and sense of slip of the faults. The trace of the fault on the marker horizon depends on the dip of the marker as well as on the attitude of the fault surface. The following examples illustrate some of the possibilities. In the three parts of Fig. 8.41, the orientation of the older fault (A) is changed while the orientation of the younger fault (B) and the attitude of the marker horizon remain constant. The structure changes from a geometry that could be described as tilted steps (Figs. 8.41a,c) to a horst that changes into a graben along a northwest-southeast trend (Fig. 8.41b). Note that the direction of the fault-bedding intersection is not parallel to the fault strike in any of the examples because the strike of bedding is not parallel to the strike of the faults.

The width of the zone of combined stratigraphic separation is reduced to a line for certain combinations of the displacement directions (Fig. 8.42a,b). An apparent strike separation on the older fault will be caused by slip on the younger fault that is in the strike direction of the younger fault. In Fig. 8.42c the later, through-going fault (B) appears to be offset by left-lateral strike-slip on fault A, although it is, in fact, fault B that displaces fault A.

The development of the map pattern of cross-cutting reverse faults is illustrated with a forward model (Fig. 8.43). The first fault (A) trends obliquely across the northwesterly regional dip of the marker (Fig. 8.43a). The trace of the second fault (B) is found by intersecting the contours of the fault with the displaced marker surface

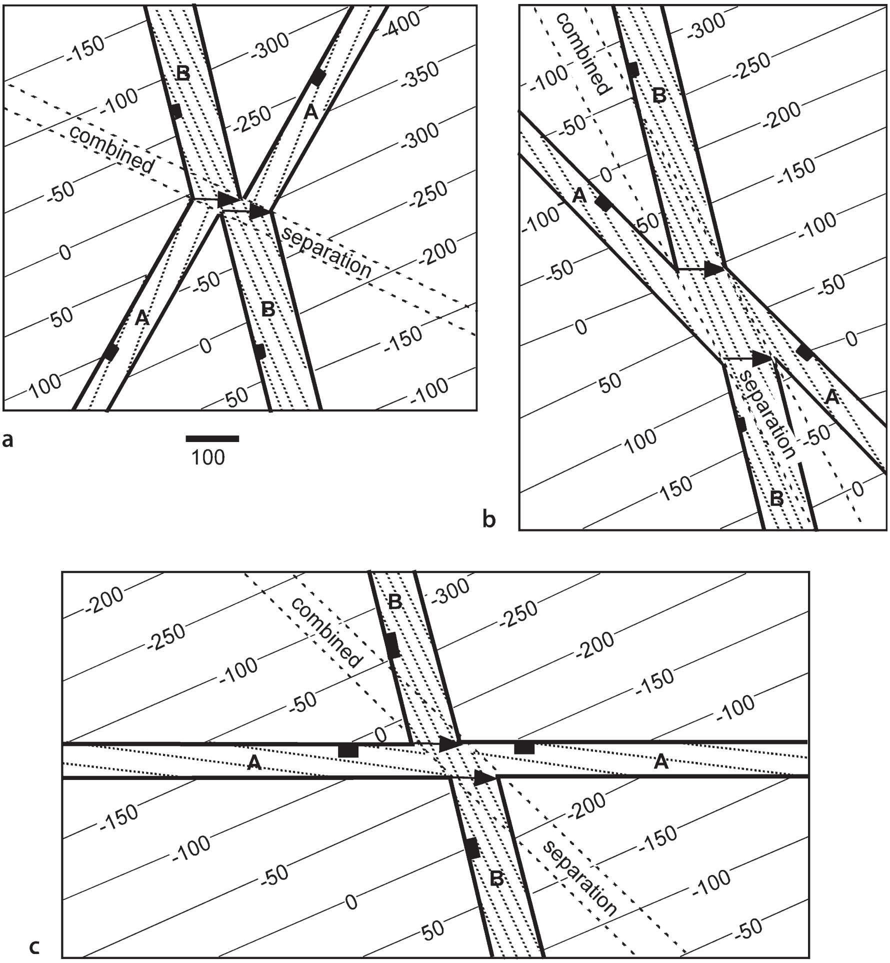


Fig. 8.41. Structure contour maps showing the effect of the angle of fault intersection on the geometry of sequential dip-slip normal faults. Fault *A* is older and has a pure dip-slip of 100 units; fault *B* is younger, strikes 335°, and has a slip of 200 units down to the east. *Arrows* give the slip direction of fault *B*. Structure contours on the displaced marker horizon are *thin solid lines*; contour interval is 50 units. *Dotted contours* are on the fault planes. Note that the strikes of the faults, as shown by the structure contours, are not the same as the trend of the fault cutoff lines of the marker horizon. **a** Fault *A* strikes 020°. **b** Fault *A* strikes 326°. **c** Fault *A* strikes 276°

(Fig. 8.43b). In the final step, the hangingwall of fault B is displaced up to the west and the location of the hangingwall cutoff and the contours are drawn as an overlay on the footwall (Fig. 8.43c). Three fault cuts are present in the vertical zone of combined stratigraphic separation where the older fault is repeated by the younger fault (Dickinson 1954).

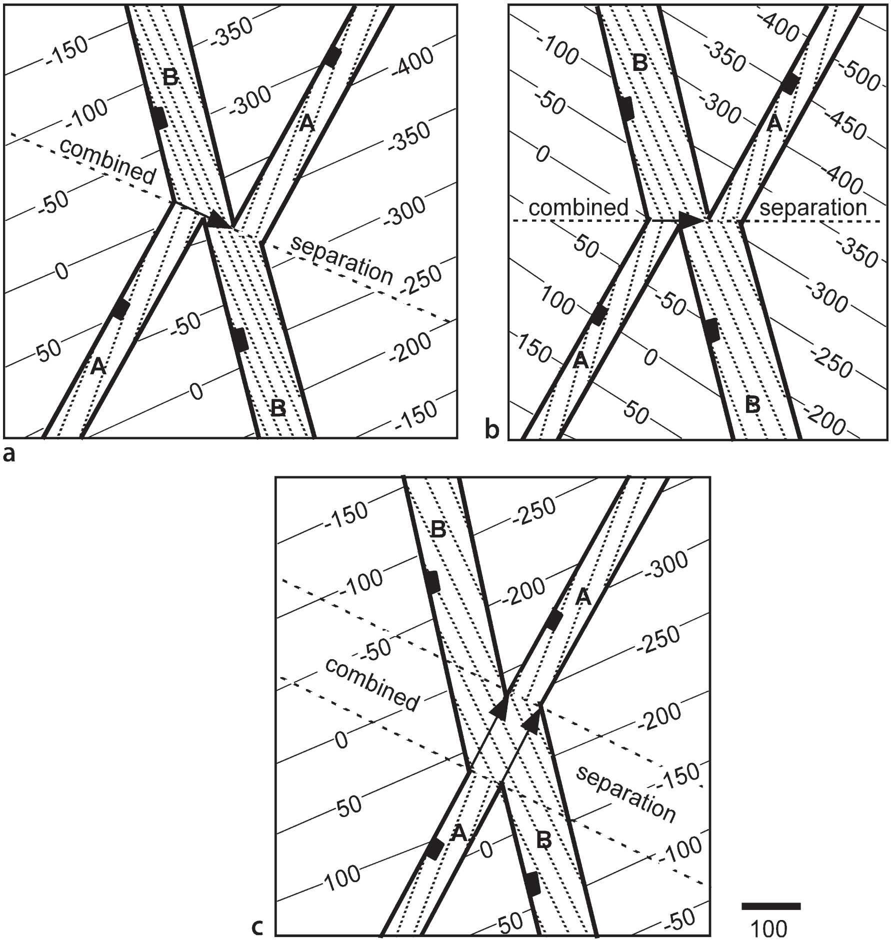


Fig. 8.42. Structure contour maps showing effect of the slip direction of the later fault (*B*) on the intersection geometry between normal-separation faults. *Thin solid contours* are on the marker horizon, *dotted contours* are on the faults. Fault *A* strikes 020°, is older, and has a throw of 100 units. Fault *B* strikes 335° and has a throw of 200 units. The slip is downthrown in the direction of the *arrows*. Note that the strikes of the faults, as shown by the structure contours, are not the same as the trend of the fault cutoff lines. **a** The slip direction of fault *B* is obliquely down to the southeast, in the dip direction of *A*. The attitude of the marker horizon is the same as in Fig. 8.41. **b** The slip direction of fault *B* is obliquely down to the east. **c** The slip direction of fault *B* is obliquely down to the northeast, in the strike direction of *A*. The attitude of the marker horizon is the same as in Fig. 8.41

A cross section (Fig. 8.44) shows the evolution of two reverse faults having the same dip direction, like those in the previous map (Fig. 8.43c). In the zone of combined stratigraphic separation between the dashed lines, a vertical well would cut three faults, but the top of the shaded unit would be penetrated only twice. Inside this zone the throw on the top of the shaded unit is the combined value for both thrusts.

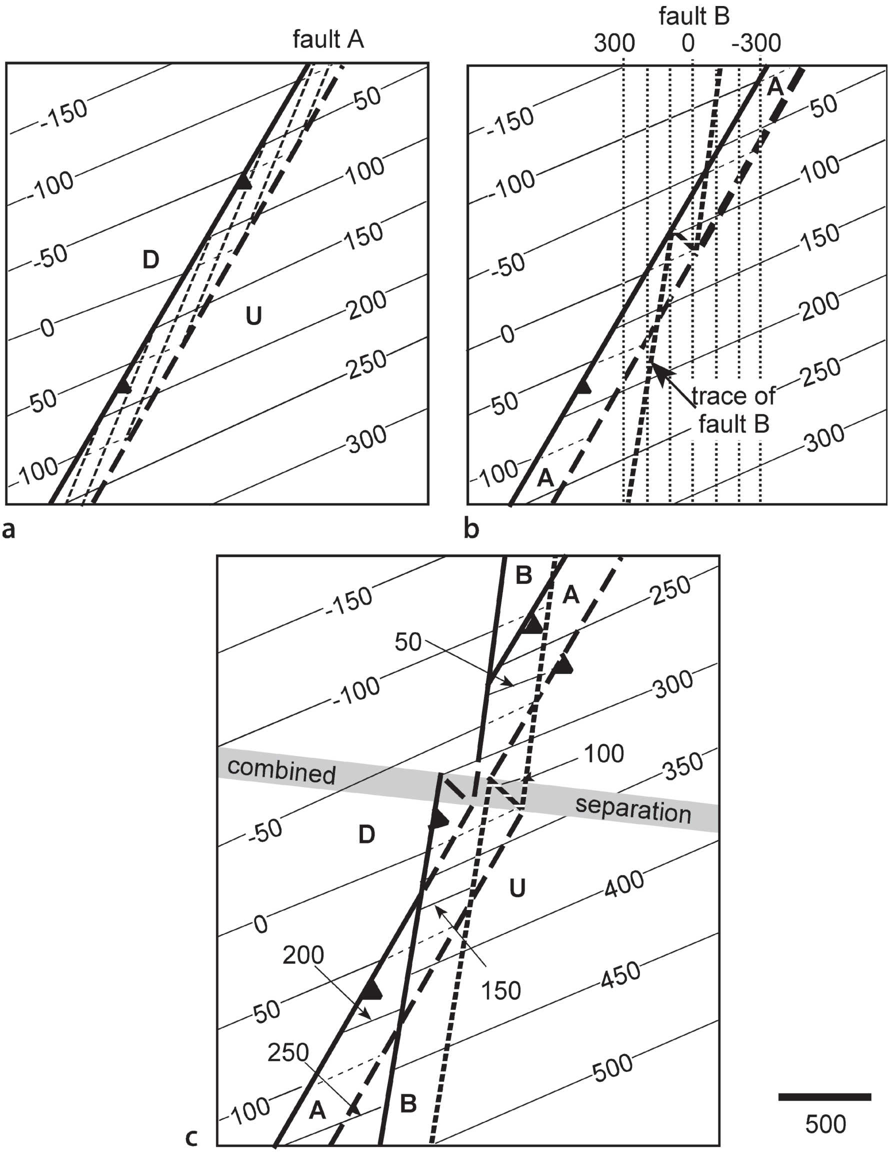


Fig. 8.43. Structure contour maps showing evolution of intersecting reverse faults having similar dip directions and sense of displacement. Contours on the fault planes are *dotted*. Contours on hidden surfaces are *dashed*. *Thin solid lines* are contours on the marker horizon. *D:* Downthrown block, *U:* upthrown block. **a** First displacement. The northeast striking thrust (*A*) has a displacement of 100 units up on the southeast. The hangingwall cutoff is a *thick solid line* and the footwall cutoff is a *thick dashed line*. **b** Structure contours on incipient fault *B* are added. The trace of thrust *B* on the marker surface is *dotted*. **c** Second displacement, enlarged to show detail. Thrust *B* displacement is 200 units up on the east. *Dotted bed contours* are in the footwall of fault *A*; contours indicated by *arrows* are in the footwall of fault *B*

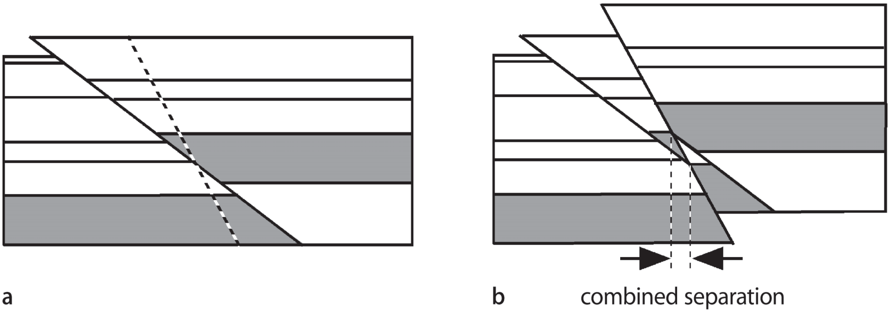
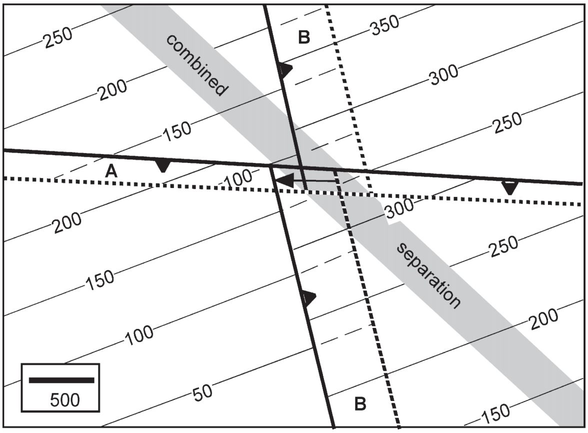


Fig. 8.44. Evolution of crossing reverse faults having the same dip direction. The cross sections approximate the evolution along an east-west cross section through the center of Fig. 8.43c. **a** First fault displacement showing the *dashed* trace of the second fault. **b** Displacement on the second fault. *Dotted lines* bound the zone of combined stratigraphic separation for the *shaded* horizon

Fig. 8.45.
Structure contour map of crossing reverse faults. Fault *A* is older, strikes 273°, and has a heave of 100 units, up on the south; fault *B* has a heave of 200 units, strikes 347° and is up on the east with displacement parallel to the trace of fault *A* (*arrow*). *Thin solid lines* are contours on the marker horizon. The intersection lines of faults with the contoured horizon are *wide lines*. *Dashed contours* are hidden below faults. (After Dickinson 1954)



Just as for normal faults, a variety of different geometries are produced by the intersection of reverse faults of varying attitudes, amounts and directions of slip, and that cut marker horizons of differing attitudes. The map of Fig. 8.45 is the result of displacement of a southeast dipping bed by two orthogonal reverse faults, fault A being the older. Figure 8.46 shows the evolution of two parallel thrusts having opposite dips. The evolution of an east-west cross section of a structure approximately like that of Fig. 8.46c is shown in Fig. 8.47. A vertical well in the zone of combined separation would have three fault cuts and penetrate the top of the shaded unit twice. Even though the two faults thicken the section, a unit within the zone of combined separation can be reduced in thickness by the second fault. In the region labeled “T” (Fig. 8.47b) the shaded unit is thinned by the crosscutting reverse faults and the middle fault cut could be mistaken for a normal fault downthrown to the west.

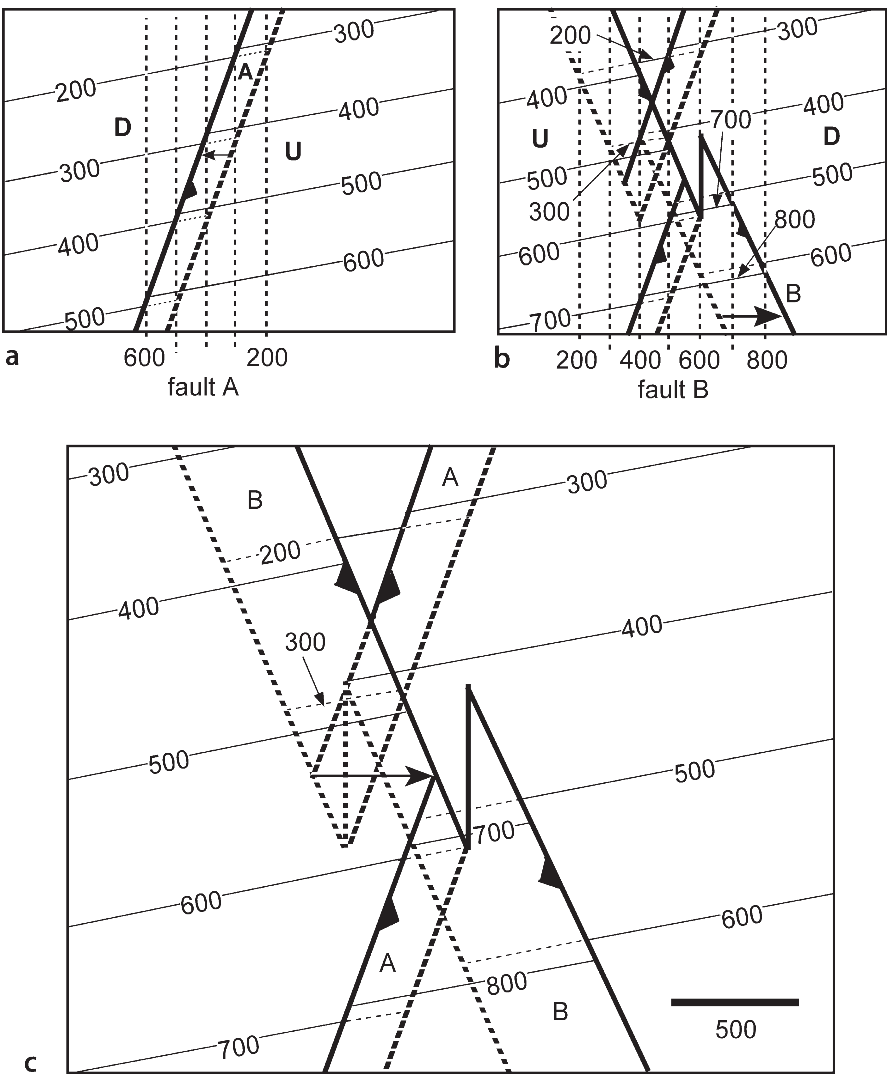


Fig. 8.46. Evolution of the structure contour map of reverse faults having equal and opposite dips. North-south *dashed contours* are on faults *A* and *B*. *Thin solid lines* are contours on the marker horizon. *Wide lines* are fault traces. Contours are *dotted* where hidden. **a** Fault *A* strikes north–south and is displaced 100 units up due west. **b** Fault *B* strikes north–south and is displaced 200 units up due east. **c** Final map, enlarged to show detail. *Arrow* shows the displacement direction of fault *B*

It should be noted that all the previous examples of crosscutting faults are based on the simplest possible fault geometries. The faults are planar and so the attitude of the marker horizon is not changed by displacement on the faults. The displace-

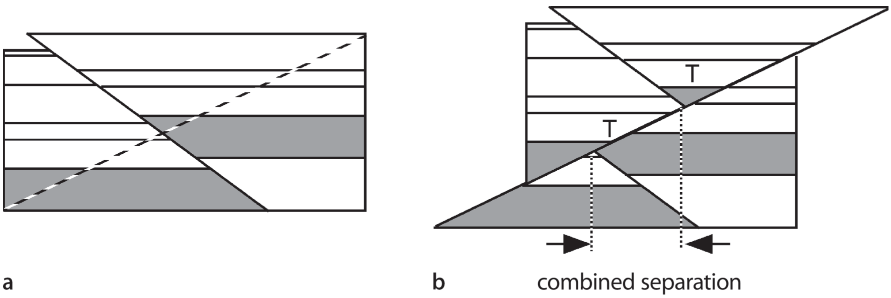


Fig. 8.47. Evolution of crossing reverse faults having opposed dips, similar to those in Fig. 8.46c. **a** Displacement on the first fault, with location of the second fault *dashed*. **b** Displacement on the second fault. *Dotted lines* bound the zone of combined stratigraphic separation for the *shaded* horizon. *T* indicates regions of local structural thinning of the shaded unit

ment on each fault has been assumed to be constant, a reasonable assumption over a small portion of a fault, but not likely to hold over a long distance along the fault surface.

8.7.2 Contemporaneous Faults

Intersecting faults may be of the same age, that is, contemporaneous. (The term contemporaneous faulting has also been used for faults in which the displacement is contemporaneous with deposition (Hardin and Hardin 1961) but the term growth fault is now widely used for that concept.) According to the Andersonian theory of faulting (Sect. 1.6.4) a biaxial state of stress is expected to produce two conjugate fault trends of the same age that intersect with a dihedral angle of 40–65°. A triaxial stress state may cause three or four fault trends (Oertel faults) to form simultaneously.

The fault pattern in the zone of intersection of contemporaneous faults tends to be more complex than the patterns for sequential faults discussed in the previous section. Multiple small faults may occur in the zone of intersection (Fig. 8.48). In the experimental studies of normal faults by Horsfield (1980), two crossing conjugate faults formed initially and with continuing extension the initial horst and graben were segmented by smaller conjugate faults. Many of the crosscutting relationships described above are probably the result of contemporaneous conjugate faults that cut one another as their displacement increases and they grow along strike and down dip.

As yet there is little published on the geometry of crossing contemporaneous faults. This style of structure may have been overlooked because of the incorrect assumption that crossing faults cannot be contemporaneous or because the geometric relationships are complex. Where timing information, such as growth strata, is available, the time relationships of the fault sets can be determined and used to substantiate the interpretation of fault contemporaneity.

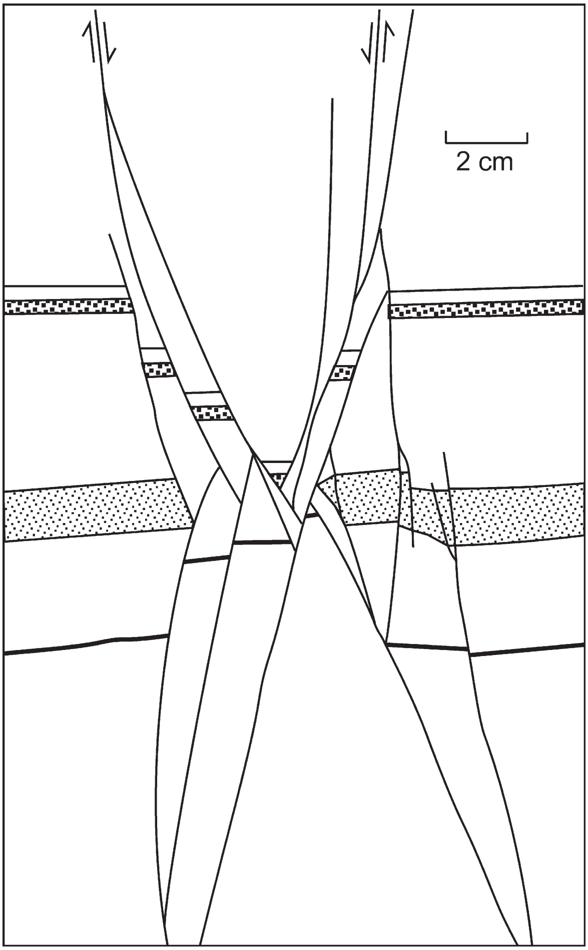


Fig. 8.48.
Crossing conjugate normal faults from a naturally deformed outcrop of Pleistocene sand. (After Walsh et al. 1996, from a photo by Dietmar Meier)

8.8 Exercises

8.8.1 Heave and Throw from a Map

Find the heave and throw on the fault at the point shown on the map in Fig. 8.49.

8.8.2 Construct the Fault Trace

Construct the hangingwall and footwall cutoff lines on both maps in Fig. 8.50. What is the heave, throw, and gap for a point near the middle of each map?

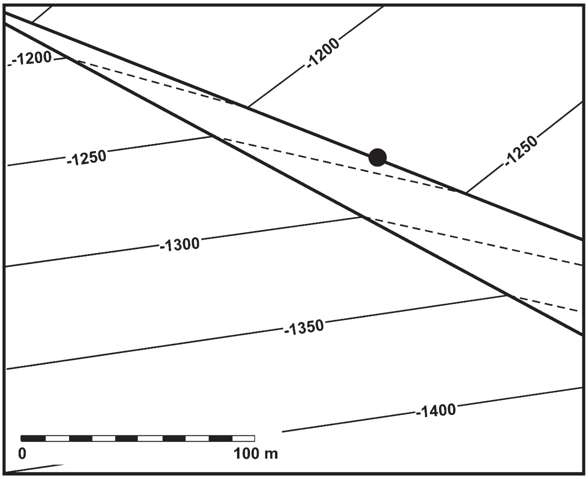


Fig. 8.49.
Structure contour map of faulted surface

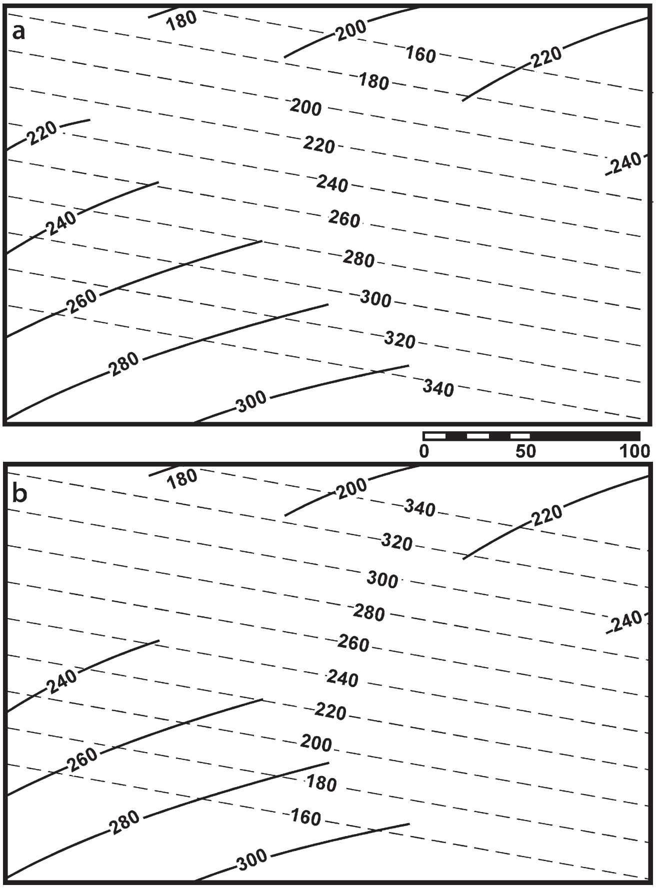


Fig. 8.50.
Unfinished structure contour maps of a fault (*dashed lines*) and a marker surface on both sides (*solid lines*). **a** Fault dips north. **b** Fault dips south

8.8.3
Construct the Fault Trace

Construct the missing fault trace and missing marker horizon on both maps in Fig. 8.51 for a fault throw of 40. Does the marker surface on the map belong to the hangingwall or footwall? Construct one map to show one to be a normal fault and the other to be reverse. What is the heave and gap for a point near the middle of each map?

8.8.4
Reservoir Structure

Use the subsurface information in Fig. 8.52 to make a structure contour map of the top of the Hamner Sandstone reservoir. What type of fault or faults are present? Are there any faults in the reservoir? What is the dip of the fault or faults? What is the calculated heave and throw at each fault cut? Do the fault map and fault separation data agree with the map?

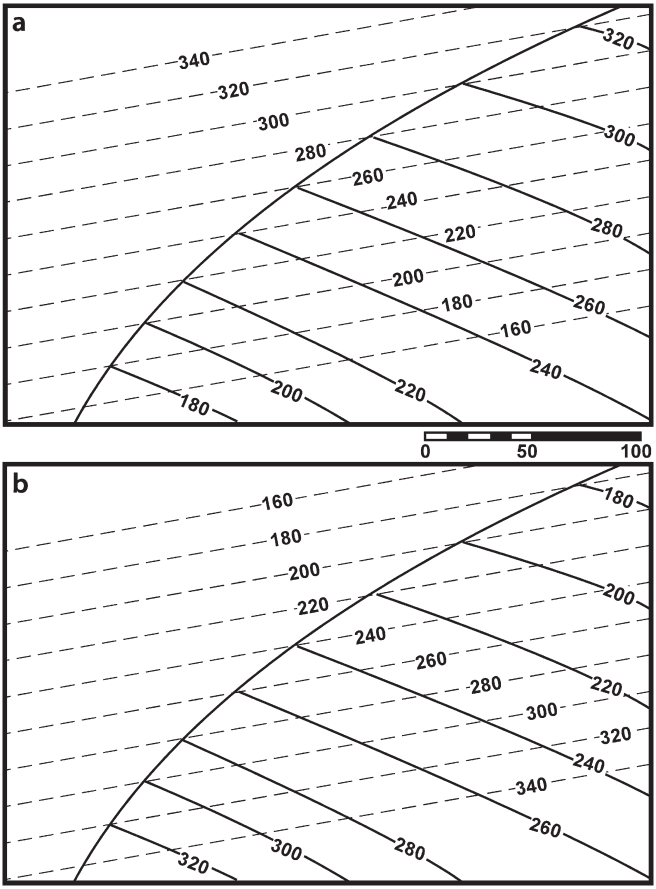


Fig. 8.51. Structure contour maps of a fault (*dashed lines*) and a marker surface on one side (*solid lines*). **a** Fault dips south. **b** Fault dips north

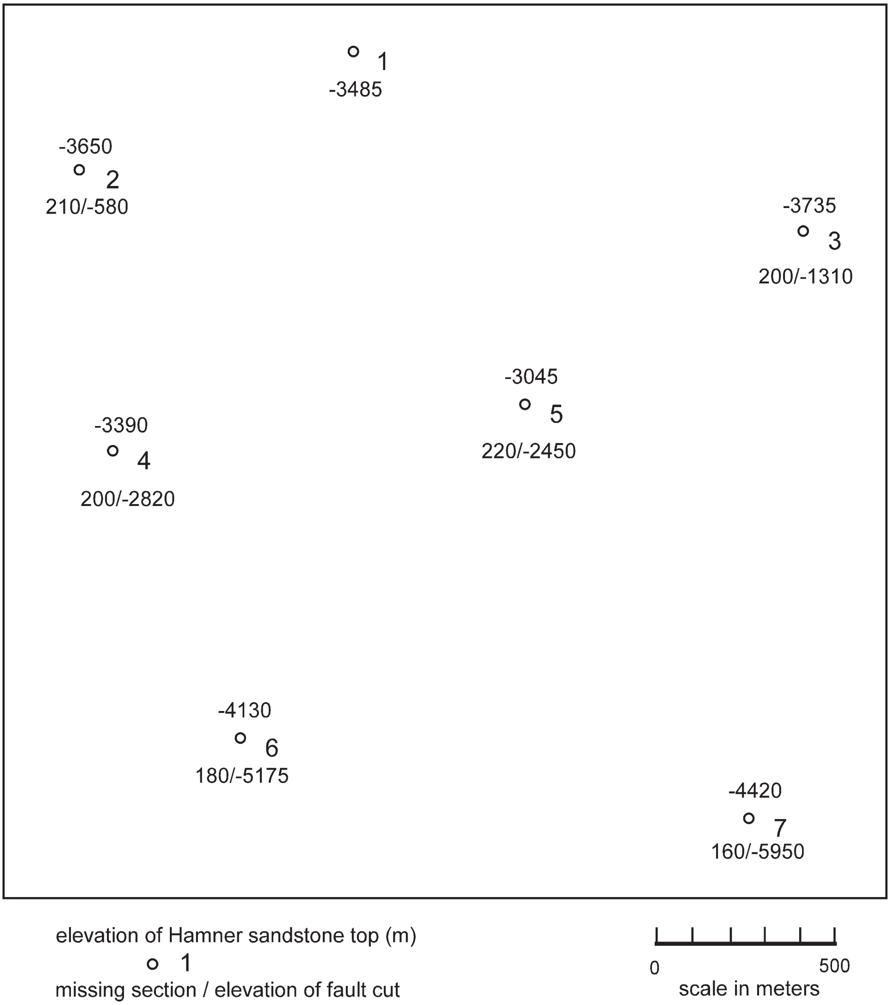


Fig. 8.52. Well data on the Hamner Sandstone reservoir. Wells (*numbered*) penetrate the Hamner Sandstone (*single number* is the elevation of the top contact). Fault cuts are indicated by a *pair of numbers* (amount/elevation). Elevations are in meters, negative below sea level

8.8.5 Normal Fault

Determine the structure of the faulted Oil City Sandstone in Fig. 8.53. Is a single fault present? What kind? What is the evidence? What is the attitude of the fault? of bedding in the hangingwall? of bedding in the footwall? What is the heave and throw on the fault? Does the map agree with the attitude information? Explain the reason for the hydrocarbon trap.

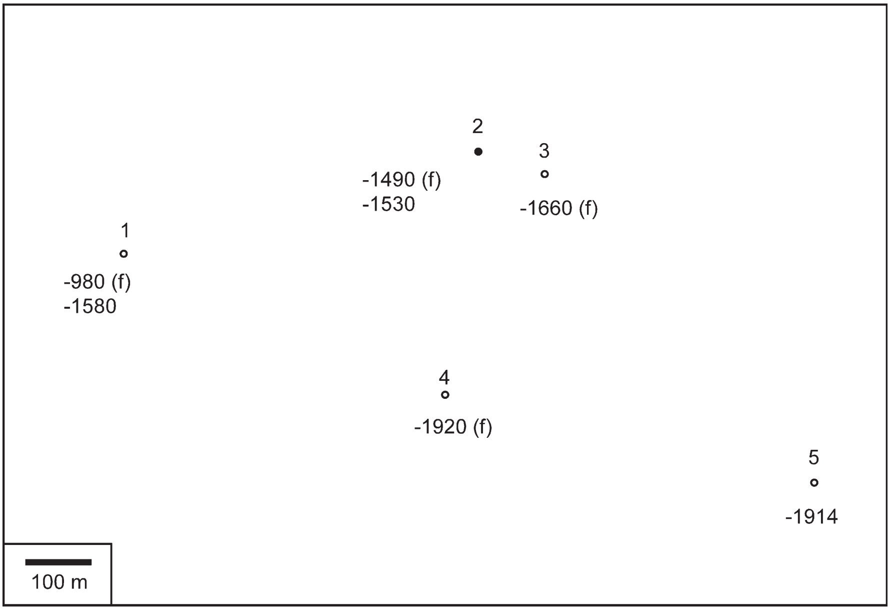


Fig. 8.53. Map of information for the Oil City Sandstone. Posted on the map are the elevations of fault cuts (*f*) and the top of the sandstone. Well *2* is an oil well. Dipmeters in well *1* indicate a bedding attitude of 10, 315 and a fault strike of 045; in well *5* the bedding attitude is 8, 315. Elevations are in meters

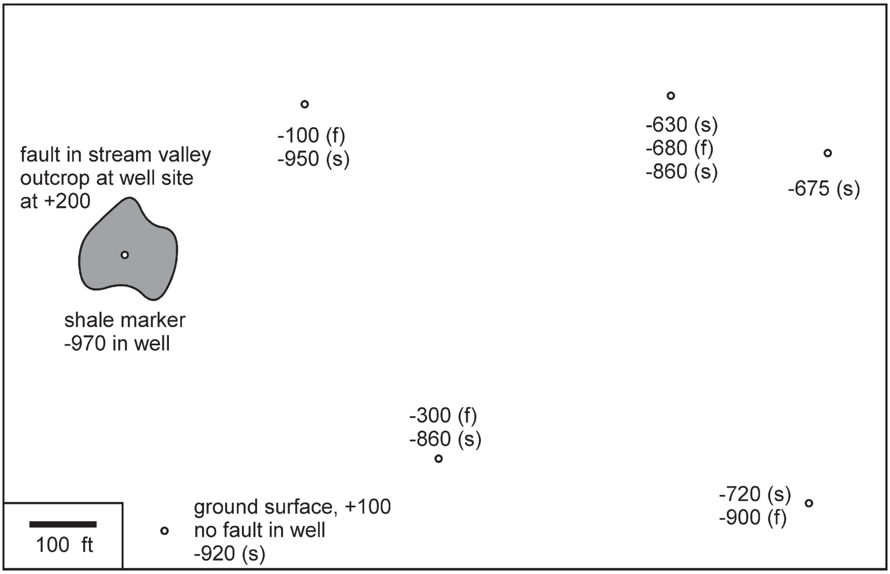


Fig. 8.54. A shale marker and fault cuts in a groundwater basin. Posted on the map are the elevations of fault cuts (*f*) and of the shale tops (*s*) in each well where present. Elevations are in feet, negative below sea level

8.8.6 Reverse Fault

Map the fault (f) and the shale marker horizon (s) using the data in Fig. 8.54. Is a single fault present? What kind? What is the evidence? What is the attitude of the fault? of bedding in the hangingwall? of bedding in the footwall? What is the heave and throw on the fault? If

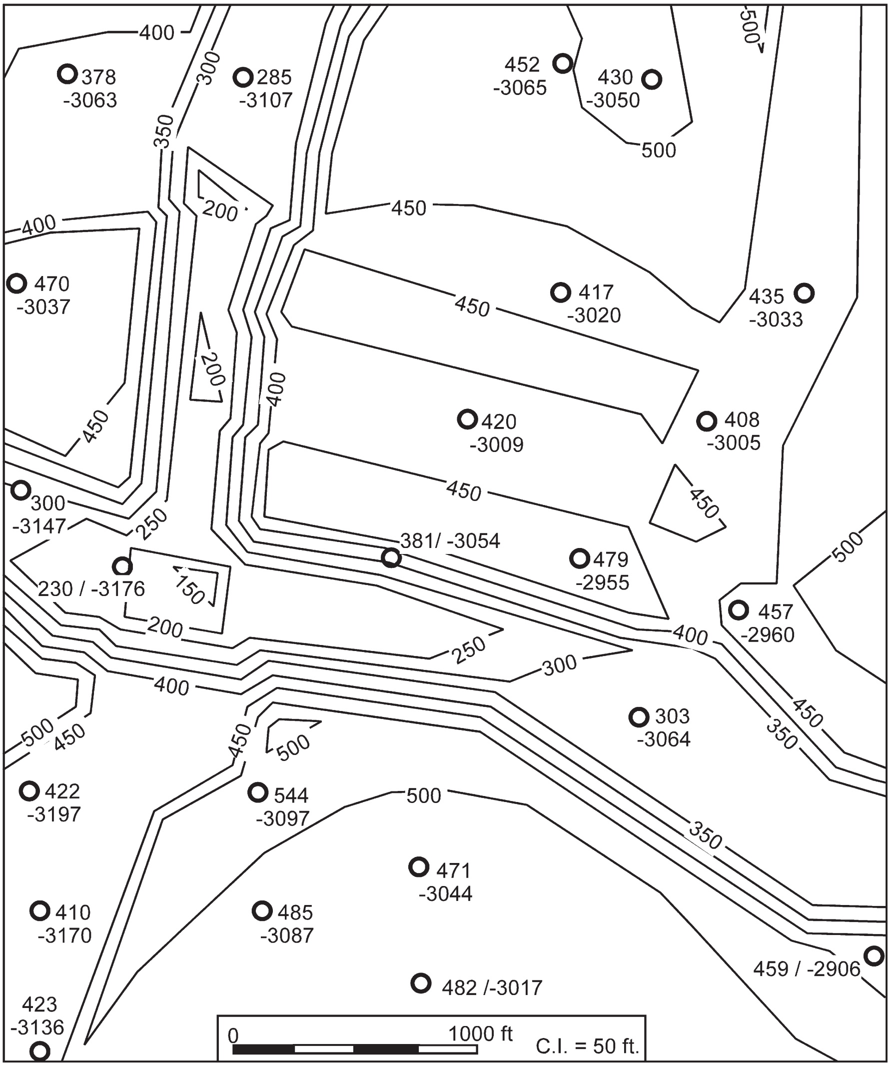


Fig. 8.55. Isopach map of the lower Taylor Formation above the Hawkins salt dome, Texas. Posted next to the wells (*circles*) are the thickness (upper or left-hand *number*) and the elevation of the formation top, in feet below sea level. (After Hintze 1971)

a heavy liquid is spilled in the stream valley in the shaded area, could the fault provide a barrier to the fluid movement in porous units above the shale marker? Explain the reason behind your answer. Where would a fault trap for fluids lighter than water be located?

8.8.7
Faults on an Isopach Map

Figure 8.55 is an isopach map. Locate the faults that explain the thickness changes. Indicate the upthrown and downthrown sides of each fault. Determine the throw on each fault. Make a structure contour map of the faults.

8.8.8
Cutoff Map of Normal Fault

Construct a fault cutoff map for the northern fault on the structure contour map in Fig. 8.56. Project the cutoff lines to the blank profile below the map.

8.8.9
Cutoff Map of Reverse Fault

Construct a fault cutoff map for fault A across the structure contour map in Fig. 8.57.

8.8.10
Fluid Migration across a Fault

Suppose a toxic liquid that is heavier than water is spilled onto the surface in the center of the structure illustrated by the Allan diagram in Fig. 8.58. Where will the liquid go? Will the liquid be trapped at a location on the cross section? If liquid is trapped, will it all be in the same location?

8.8.11
Thrust-Faulted Fold

Based on the map in Fig. 3.29, answer the following questions. What is the 3-point dip of the fault at the surface? Construct a structure contour map of the fault from its surface dip. Intersect the previously-constructed structure contour map of the top Fairholme (Exercise 7.7.4) with the map of the fault. Does the projected structure contour map agree with the drilled depths to the top of the Fairholme?

8.8.12
Relay Zone

Map the faults and the top of the Northriver Sandstone on the map of Fig. 8.59. Where is the relay zone? What is the attitude of the sandstone away from the faults? What is the attitude of the sandstone between the faults? What are the attitudes of the faults? What is the maximum throw and heave on the faults?

Fig. 8.56. Structure contour map with faults and blank cross-section template

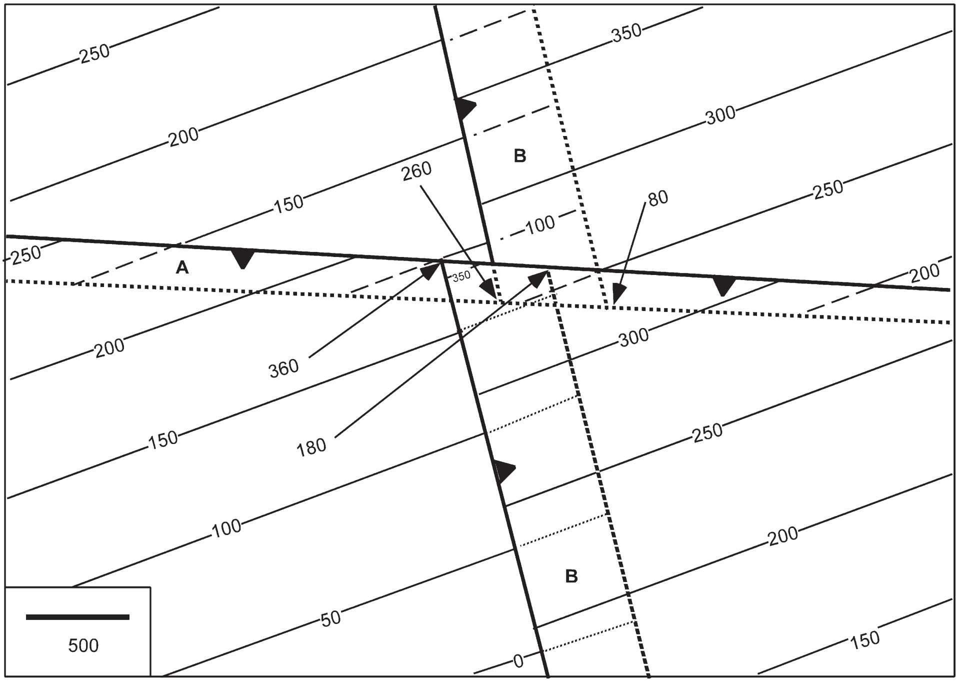


Fig. 8.57. Structure contour map of reverse-faulted marker horizon (*thin lines*). Faults are *thick lines*, hidden contours are *dashed*

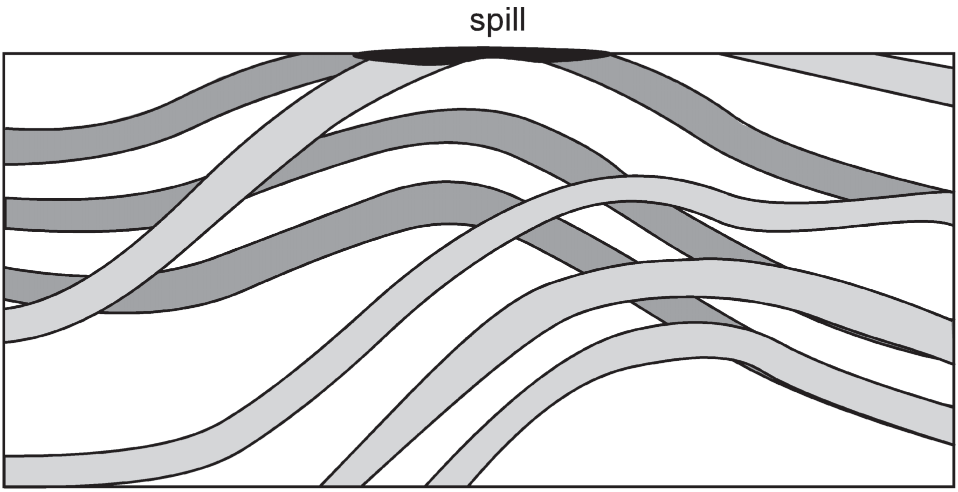


Fig. 8.58. Fault cutoff map, viewed from the hangingwall toward the footwall. The footwall beds have *darker shading* than the hangingwall beds. *Shaded* units are porous and permeable; *unshaded* units are impermeable

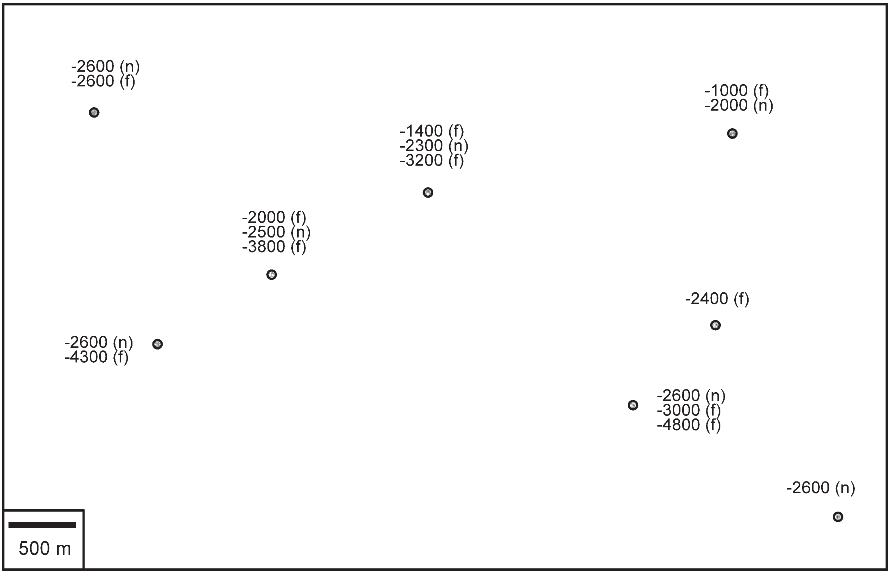


Fig. 8.59. Top of the Northriver Sandstone (*n*) and fault-cut elevations (*f*) in wells. Elevations are in meters, negative below sea level

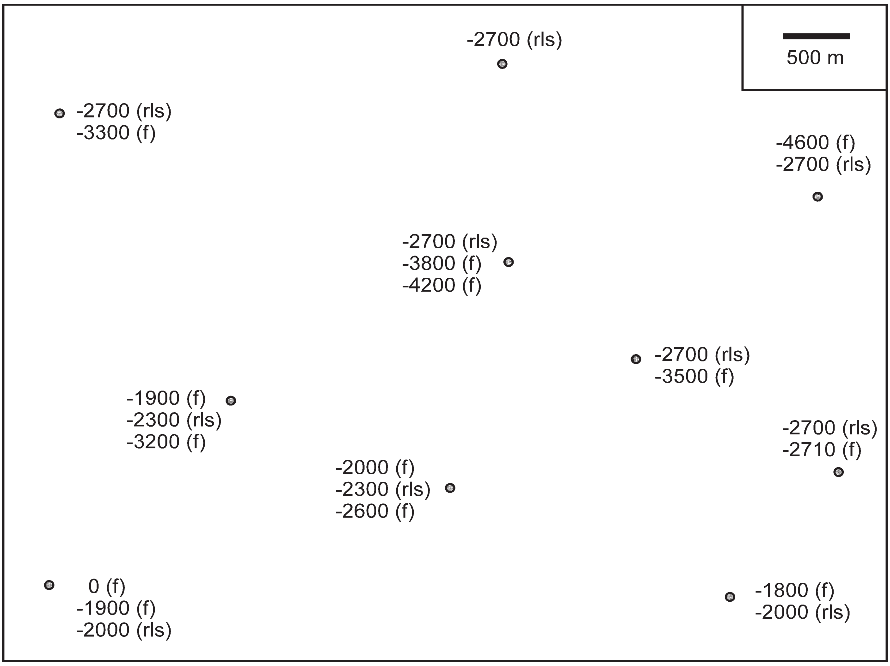


Fig. 8.60. Map giving the top of the Reef Limestone (*rls*) and faults (*f*) in wells. Elevations are in meters, negative below sea level

8.8.13
Branching Fault

Map the faults and the top of the Reef Limestone on the map of Fig. 8.60. Where is the branch line? What is the attitude of the limestone away from the faults? What is the attitude of the limestone between the faults? What are the attitudes of the faults?

8.8.14
Splay Faults

The water-well map of Fig. 8.61 shows a distinctive clay seam to be absent in some wells due to faulting. Map the faults and the top of the clay seam. Where is the branch line? What are the attitudes of the faults? What is the maximum throw and heave on the clay seam? If the clay seam is a barrier to ground water flow from the surface, where is this barrier absent? Is a spill of toxic heavy liquid in the southwest corner of the map area likely to sink below the clay seam? Why or why not? In which direction will a spill of heavy liquid in the southeast corner of the map migrate?

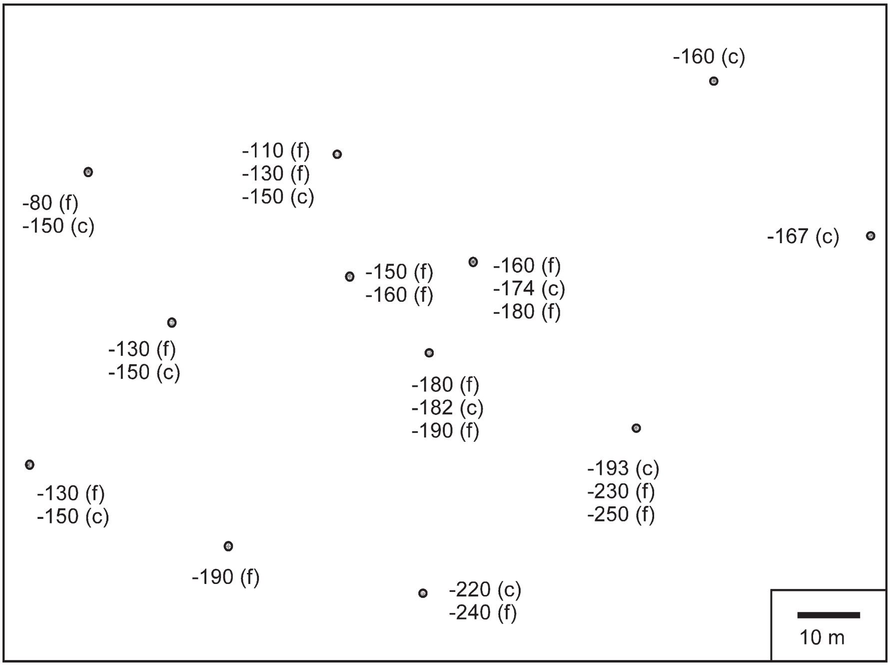


Fig. 8.61. Map of the top of a clay seam in water wells drilled into an alluvial aquifer. Elevations below sea level are negative

8.8.15
Sequential Faults 1

Two different fault trends occur in the area of Fig. 8.62. Map the faults and the A sand. What is the reason for the hydrocarbon trap in the A sand? What are the attitudes of the faults? What is the throw and heave on each fault? Which fault is older? If the hydrocarbons migrated before the formation of the younger fault, would the trapping potential of the structures be the same?

8.8.16
Sequential Faults 2

Contour the Northport Dolomite in the map of Fig. 8.63, being careful to explain the fault cuts and the oil trap(s). Is there one oil field or two? What are the attitudes of the faults? What is the throw and heave on each fault? Which fault is older? If the hydrocarbons migrated before the formation of the younger fault, would the trapping potential of the structures be the same? Are there any additional hydrocarbon prospects?

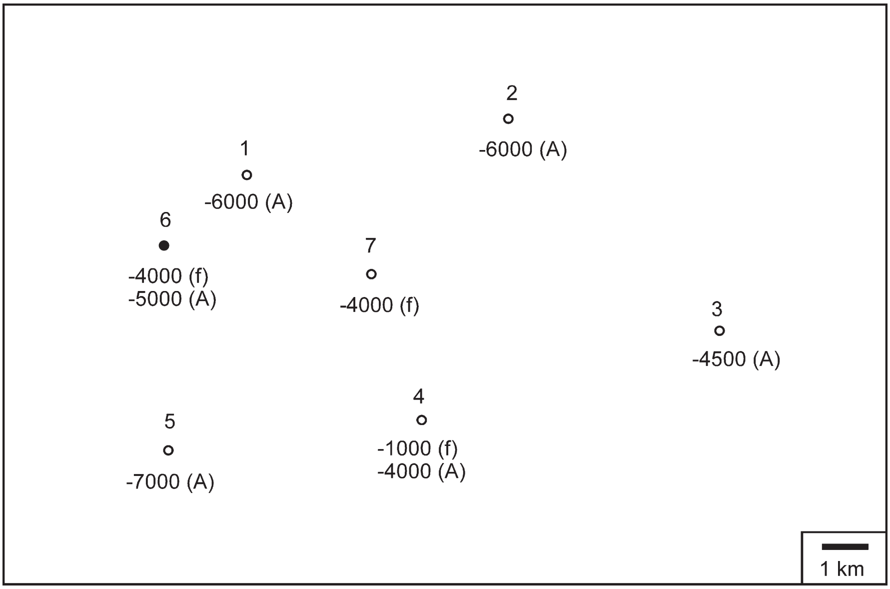


Fig. 8.62. Map of the top of the *A* sand (*A*) and faults (*f*) in wells drilled for oil. The *solid circle* is an oil well, *open circles* are dry holes. Everywhere away from the faults clear bedding dips are recorded on the dipmeter; they are about 27, 334. Close to the fault in well *4* the bedding dip is at azimuth 062. In well *6* the bedding dip close to the fault is at azimuth 189. In well *7* the dips of bedding are in all directions near the fault. Elevations are in meters, negative below sea level

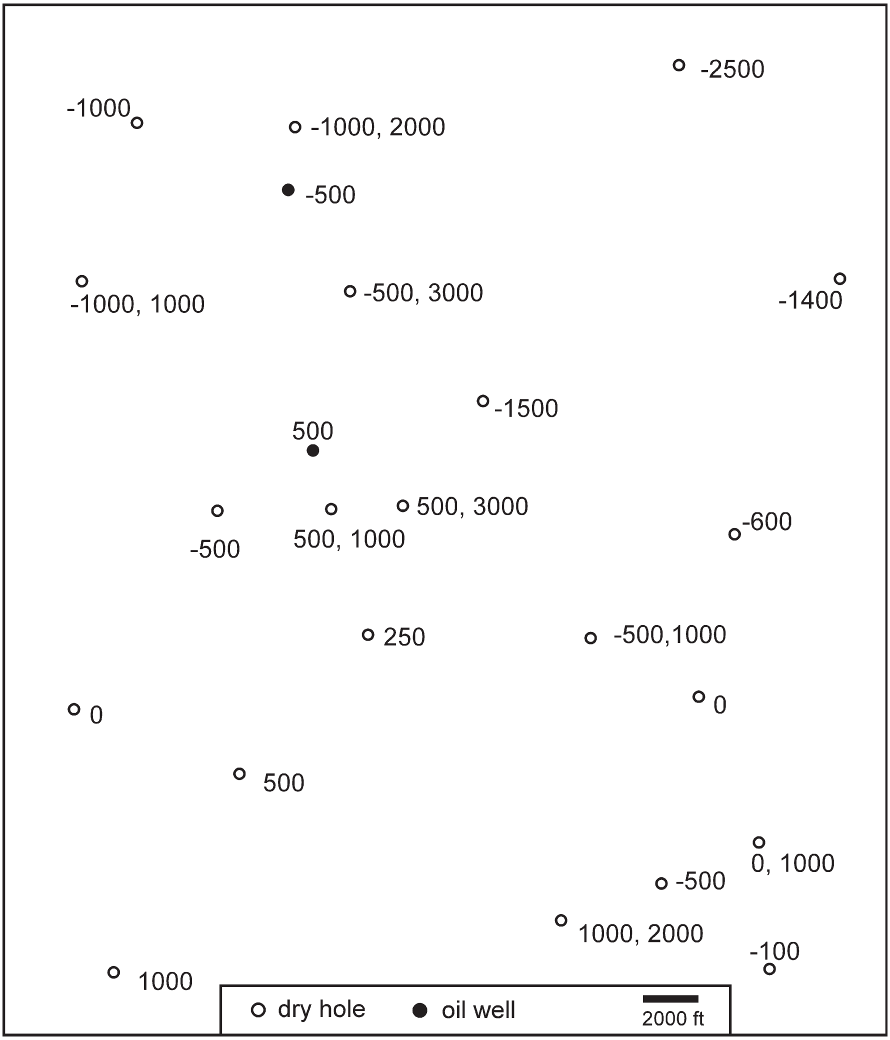


Fig. 8.63. Map of well information from the Northport Dolomite. *Two numbers* together next to a well give fault cut information: 500, 100: depth of fault cut, amount of fault cut. A *single number* by the well is the top of the dolomite. Where only fault-cut information is given, the dolomite is faulted out. The fault trends are generally northwest–southeast. Elevations are in feet, negative below sea level