Properties of Faults

7.1
Introduction

This chapter focuses on the recognition of faults, their geometrical properties, displacement distributions, and the correlation of multiple fault cuts into continuous fault surfaces. Unconformities are treated here because, by truncating units at the map scale, they share characteristics with faults and need to be distinguished from faults.

7.2
Recognition of Faults

Faults are recognized where they cause discontinuities in the traces of marker horizons on maps and cross sections, discontinuities in the stratigraphic sequence, and anomalies in the thicknesses. Faults may also be recognized from the diagnostic shape of drag folds adjacent to the fault and by the distinctive rock types caused by faulting.

7.2.1
Discontinuities in Geological Map Pattern

At the map scale, a fault is inferred where it causes a break in the continuity of the units on a geologic map. A time slice through a 3-D seismic-reflection volume is similar to a geologic map in a region of low topographic relief and will also show faults as discontinuities. As an example, the coal seams in the north half of Fig. 7.1 are abruptly truncated along strike where they intersect faults (points A). Fault dips and hence fault separations (Sect. 7.4.2) cannot be determined from the near-horizontal map surface, but these are known to be normal-separation faults. The truncation of units by a contact (B, Fig. 7.1) indicates that the contact is a fault or that the beds are cut by an unconformity. The base of the continuous bed that crosses the truncated beds (C, Fig. 7.1) is either a fault contact or an unconformity. The contact indicated by B and C in Fig. 7.1 is a fault because the truncated beds to the north (bc, ml) are younger than the cross-cutting unit to the south (by) and so should be above the unconformity, not below it. At D, E, and F, the contacts are parallel and so provide no direct evidence of faulting, although the absence of stratigraphic units at the contacts suggests the presence of faults. The contact at D can be traced into a location (C) where it is faulted; hence it is probably a fault. The contact at F is a reverse fault because the dips of bedding on both sides of the contact show that the older units to the south lie on top of the younger units to the north. The contact indicated by E places upright lower Cambrian rocks adjacent to overturned younger units to the north, suggesting re-

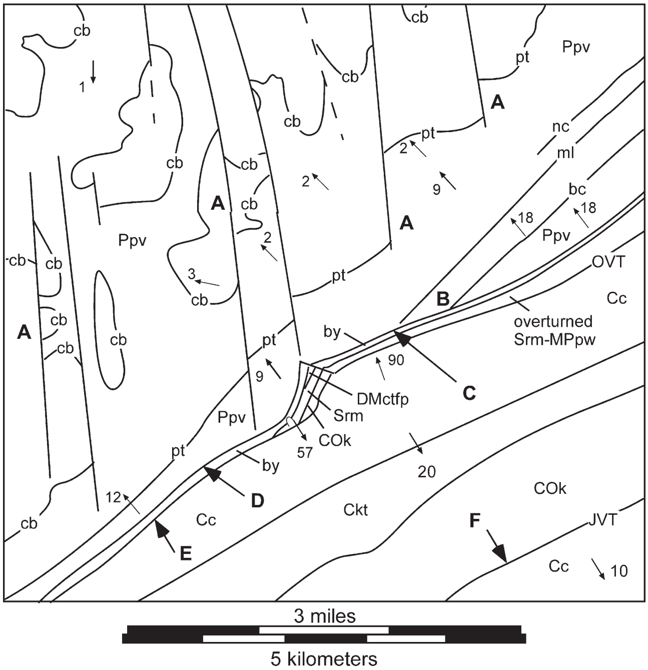

Fig. 7.1. Geologic map of the Ensley area, Alabama. The topography is nearly flat, making the map close to a horizontal section. Units (oldest to youngest): Cambrian: *Cc:* Conasauga Ls., *Ckt:* Ketona dolomite; Cambro-Ordovician: *COk:* Knox dolomite; Silurian: *Srm:* Red Mountain Formation; Devonian-Mississippian: *DMctfp:* Chattanooga Shale, Tuscumbia Limestone, Fort Payne Chert; Mississippian-Pennsylvanian: *MPpw:* Parkwood Formation; Pennsylvanian: *Ppv:* Pottsville, containing the following marker units (oldest to youngest): *by:* Boyles sandstone, *bc:* Black Creek coal, *ml:* Mary Lee coal, *nc:* Newcastle (upper Mary Lee) coal, *pt:* Pratt (American) coal, *cb:* Cobb coal. *OVT:* Opossum Valley thrust, *JVT:* Jones Valley thrust. Contact relationships: *A:* offset of strike traces, *B:* truncation of units at contact, *C:* unit crosses contacts, *D:* missing section, *E:* missing section, *F:* older over younger. (After Butts 1910 and Kidd 1979)

verse fault drag (Sect. 7.2.7). The contact indicated by C and D is a reverse fault. Once a contact has been identified as a fault, it is usually shown as a heavier line on the map.

The juxtaposition of different units across a fault favors some form of topographic expression for the fault because of the likelihood that the two units will not weather and erode identically. The boundary between the juxtaposed units is likely to form a topographic lineament. The fault-zone material (Sect. 7.2.6) may erode differently from any of the surrounding country rocks and thus cause a topographic valley or ridge along the fault.

7.2.2 Discontinuities on Reflection Profile

The primary criterion for recognizing a fault on a seismic- or radar-reflection profile is as a break in the lateral continuity of a reflector or a group of reflectors (Fig. 7.2a, arrows A). Picking faults can be difficult because sometimes the reflectors hang over the actual fault

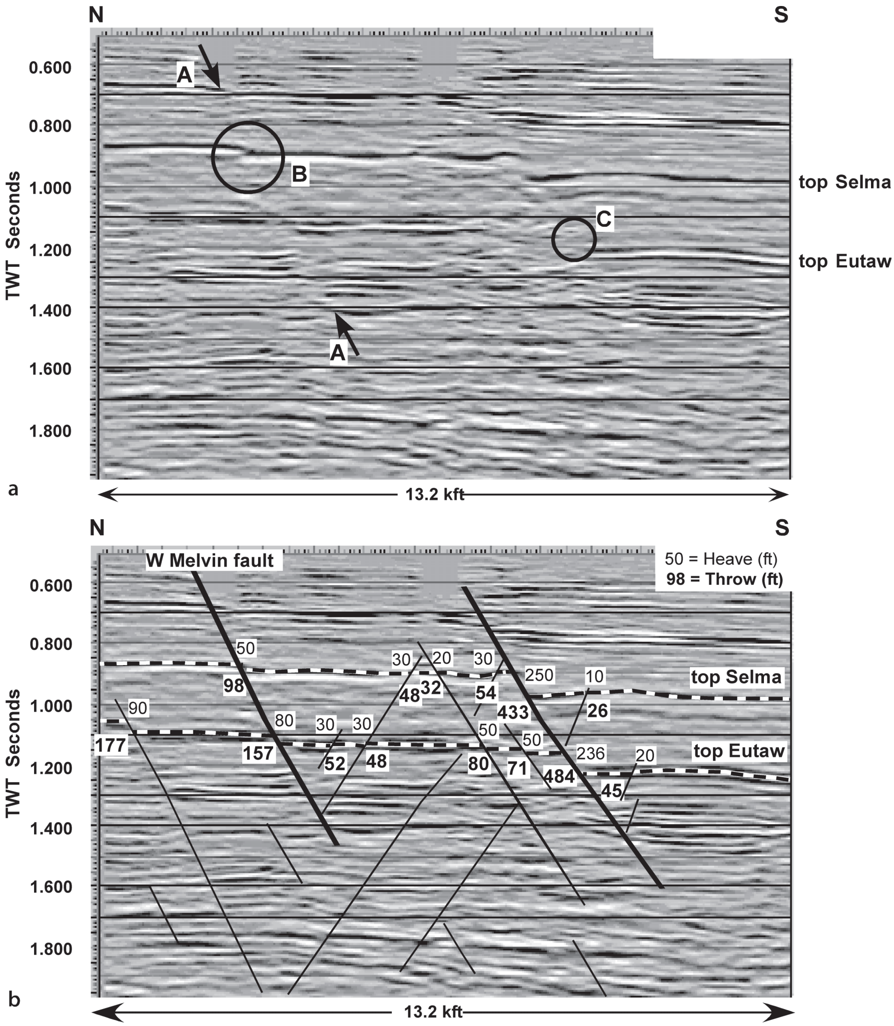

Fig. 7.2. Normal faults on a vertical profile from a time-migrated 3-D seismic reflection volume. V.E. about 1 : 1. The profile is from the Gilbertown graben system, southern Alabama (modified from Groshong et al. 2003a). **a** Uninterpreted. *A:* fault trace between arrows; *B:* reflectors hang over fault trace; *C:* disturbed zone along fault trace. **b** Interpreted. The faults indicated with *heavier lines* have been identified in nearby wells. *Numbers* next to the faults are heave (regular type) and throw (bold). Throws are determined from the heaves using Throw = Heave times tan (fault dip). Only the most obvious faults are interpreted below the top of the Eutaw

trace (Fig. 7.2a, location B), obscuring the exact location of the fault and its separation. At location B (Fig. 7.2a) the overhang makes the fault look like it is reverse, although it is actually a normal fault (c.f., Fig. 7.2b). Local disruption of reflectors or lack of reflectors in the fault zone may also make the location uncertain (C, Fig. 7.2a). The termination of multiple reflectors along a straight line or a smooth curve, together with a consistent sense of separation, provide the most convincing evidence of a fault.

In some areas the faults produce reflections as, for example, along the large normal fault in the Gulf of Mexico (Fig. 7.3). Fault reflections are favored along low-angle faults and where the impedance contrast (difference in physical properties) is large across the fault. Steeply dipping reflectors, whether originating from beds or faults, are difficult to image on conventional seismic lines because the reflections return to the surface beyond the farthest receiver.

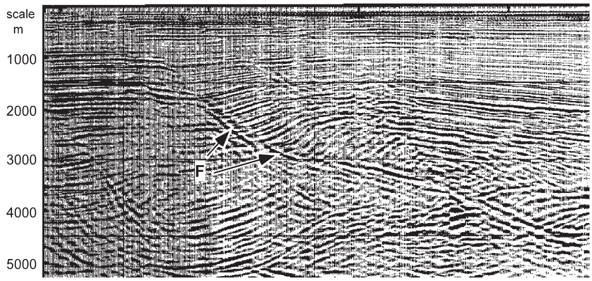

Fig. 7.3.
Corsair fault, a thin skinned growth fault on the Texas continental shelf. 48-fold, depth-converted seismic line. *F:* fault reflectors. (After Christensen 1983)

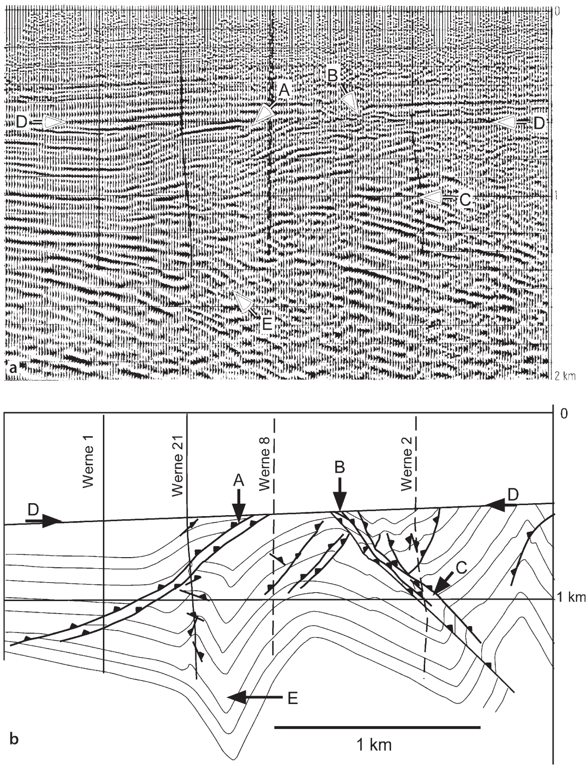

Fig. 7.4.
Faults in a portion of the Ruhr coal district, Germany. **a** Seismic reflection profile: dynamite source, 12-fold common-depth-point stack, time migrated. *A:* reflector discontinuity at a large thrust fault; *B:* reflector discontinuity at a small, complex, reverse fault zone; *C:* crossing reflectors in a fault zone; *D:* reflector discontinuity at an angular unconformity; *E:* zone of disturbed reflectors on the steep limb of a fold. **b** Geological cross section based on the seismic profile and the wells shown. *Letters* designate the same features as in **a**. (Adapted from Drozdzewski 1983)

The abrupt termination of a reflecting horizon at a fault provides a point source of diffractions, arcuate reflectors that emanate from the fault and cross other reflectors. Time migration of the seismic profile is designed to restore the reflectors to their correct relative locations and dips and to remove the diffractions. Nevertheless, some diffractions may remain in time-migrated profiles, as seen in the region between B and C in Fig. 7.4a.

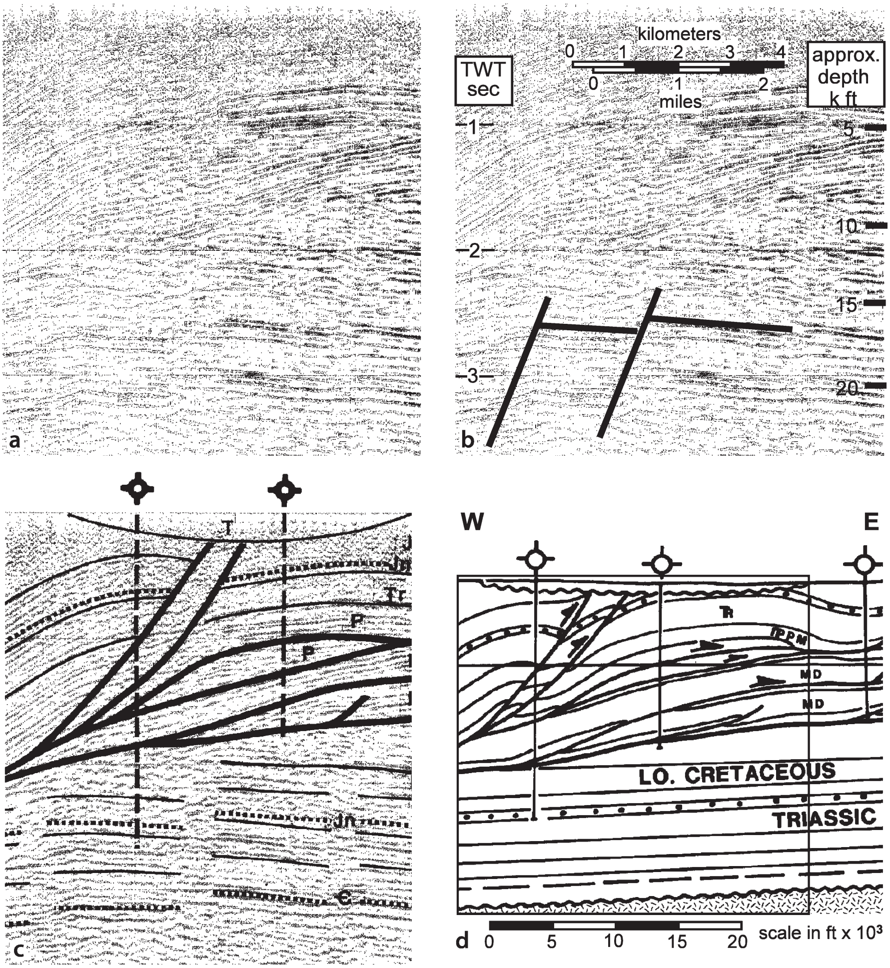

Fig. 7.5. Velocity discontinuities create features that look like faults on seismic profiles. **a** Segment of a seismic line across Wyoming thrust belt (dynamite source, eight-fold common-depth-point stack, migrated time section, approximate vertical exaggeration 1.3 at 2.7 s; Williams and Dixon 1985). **b** Discontinuities in seismic reflectors that might be normal faults. **c** Interpretation by Williams and Dixon (1985). **d** Geological cross section using well control and the seismic line; no vertical exaggeration (Williams and Dixon 1985). The *box* outlines the area of the seismic line. No normal faults are present. *TWY:* two-way traveltime (s); *C:* Cambrian; *MD:* Mississippian-Devonian; *IPPM:* Pennsylvanian, Permian, Mississippian undifferentiated; *P:* Permian; *Tr, TR:* Triassic; *J:* Jurassic undifferentiated; *Jn:* Jurassic Nugget sandstone; *T:* Tertiary

Features other than faults may resemble faults. Reflectors are also truncated at an unconformity (Fig. 7.4a, between the arrows labeled D). The presence of parallel reflectors above the unconformity supports the interpretation that the truncation is indeed an unconformity, not a fault. Reflections from steeply dipping beds may fail to be recorded or may not be correctly migrated, leading to zones of disturbed reflectors that can easily be mistaken for fault zones. The lack of reflector continuity around and above location E (Fig. 7.4a) is due to the steep limb of a fold (Fig. 7.4b), not to a fault.

Regions of complex structure are commonly associated with faults and may have steep dips and large lateral velocity changes, either of which can create discontinuities at deeper levels on the seismic profile (Fig. 7.5). Discontinuities in the otherwise continuous reflectors below 2-s two-way travel time (Fig. 7.5a) might easily be interpreted as being normal faults (Fig. 7.5b), although the interpreters of the line correctly did not do so (Fig. 7.5c). This region is below a major thrust fault that places rocks as old as Devonian on top of Cretaceous units. The older rocks have significantly higher seismic velocities than the Cretaceous rocks. The geological interpretation (Fig. 7.5d), based on well control and the seismic profile, indicates no offset of the Cretaceous and older units below the thrust, but rather a continuous westward regional dip of the subthrust units. The apparent eastward dip of the subthrust units is a velocity pull up caused by the high velocities of the rocks in the thrust sheet. The apparent normal faults in the subthrust sequence are probably caused by the rapid lateral velocity gradients associated with fault slices within the thrust sheet.

Reflection profiles can be one of the most powerful tools for structural interpretation. Because the profile itself is an interpretation based on the inferred velocity structure of the region, the geological interpretations must be tested with all of the same techniques that are applied to geological data.

7.2.3
Discontinuities on Structure Contour Map

A linear trend of closely spaced structure contours that form a monoclinal fold may represent an unrecognized fault (F, Fig. 7.6). The monocline could be replaced by a fault. Linear fold trends are, of course, perfectly reasonable and so independent evi-

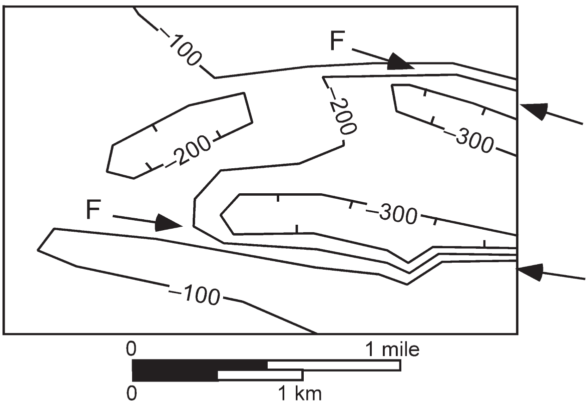

Fig. 7.6. Structure contour map showing the possible locations of faults (*F*) between the *arrows*. Contours are in feet

dence for faulting is desirable before the fold is reinterpreted as a fault as, for example, a direct observation of the fault somewhere along the trend. In some areas, especially in extensional terrains, folds with steep limb dips are rare or do not occur at all and so the closely spaced contours could be replaced by a fault on the basis of consistency with the local structural style.

7.2.4
Stratigraphic Thickness Anomaly

A linear thickness anomaly in a generally uniform stratigraphic unit may be caused by a fault. The anomaly can be caused by the stratigraphic section missing or repeated by an unrecognized fault. A fault appearing as a thickness anomaly is a very likely occurrence where the stratigraphic separation on the fault is less than the stratigraphic resolution. A unit penetrated by three wells (Fig. 7.7a) might be interpreted as having a stratigraphic thin spot in the middle well. The thin spot might also represent a normal fault cut (Fig. 7.7b). Where a thickness anomaly is recognized as a possible fault, the data should be re-examined for other types of evidence of a fault cut. A cross section involving multiple units, rather than just one unit as in Fig. 7.7, should be constructed. Thickness anomalies that line up on a cross section with a dip appropriate for a fault probably represents a fault.

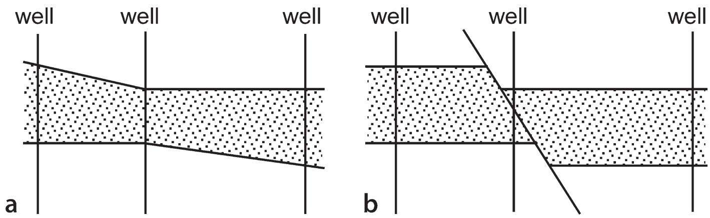

Fig. 7.7. Cross sections showing alternative interpretations of a stratigraphic thickness anomaly in the *shaded* unit of the center well. **a** Thinning interpreted as due to stratigraphic change. **b** Thinning interpreted as due to a normal fault

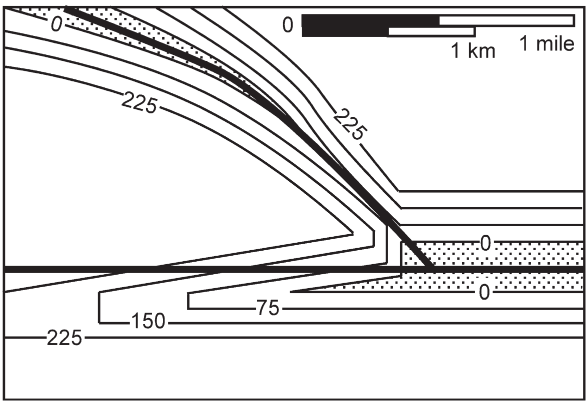

Fig. 7.8. Isopach map showing the effect of two intersecting normal faults on the thickness of a formation that is regionally 225 or more units thick. Contours are of thickness, the formation is *absent* in the *shaded areas*. *Heavy lines* mark the fault trends; because the faults are dipping planes, the lines do not represent the exact map traces of the faults

On an isopach map a thickness anomaly will follow the trace of the fault (Fig. 7.8). A fault with normal separation will cause the unit to be thinner and a reverse separation will cause the unit to be thicker. The greater the stratigraphic separation of the fault, the greater the thickness change from the regional value. The maximum thinning is to zero thickness but the maximum thickening can be any amount, depending on the number of repetitions that occur within the boundaries of the formation. The example shows an east–west trending fault that is losing displacement to the west while an intersecting fault to the north increases in displacement to the west. See Sect. 8.5 for the quantitative interpretation of fault separation from isopach maps.

7.2.5 Discontinuity in Stratigraphic Sequence

The recognition of a fault at a point such as in an outcrop or a well log is commonly based on a break in the continuity of the normal stratigraphic sequence (Fig. 7.9). Except for the special case of fault slip exactly parallel to the stratigraphic boundaries (Redmond 1972), some amount of the stratigraphic section is always missing or repeated at the fault contact. The measure of the fault magnitude that can be obtained from the information available at a point on a fault is the stratigraphic separation, equal to the thickness of the missing or repeated section (Bates and Jackson 1987). Only the stratigraphic separation can be determined at a point on the fault, not the slip. Determination of the slip requires additional information. The true slip on the faults in Fig. 7.9 could be oblique or even strike slip if the dip of bedding is oblique to the dip of the fault.

The method for determining the position of the fault cut and the amount of the stratigraphic separation is the same in the field as in the subsurface. A well log is the same as a section measured across a fault. The faulted section must be correlated to a reference section. Correlate upward in the footwall (Fig. 7.10) until the sections no longer match. Then correlate downward in the hangingwall until the sections no longer match. The mismatch will occur at the same place in the faulted section if a single fault is present. A mismatch in upward and downward correlation that fails to occur at the same place in the faulted section could be caused by the presence of more than one fault or by a fault zone of finite thickness. In the former situation, the process should be repeated on a finer scale until all the faults are located.

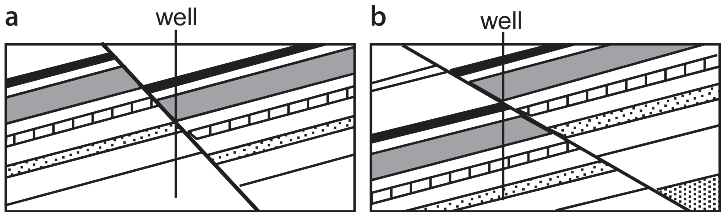

Fig. 7.9. Cross sections of faults recognized from a stratigraphic discontinuity where the well cuts a fault. **a** Normal separation. Part of the normal stratigraphic sequence is missing in a vertical well. **b** Reverse separation. Part of the normal stratigraphic sequence is repeated in a vertical well

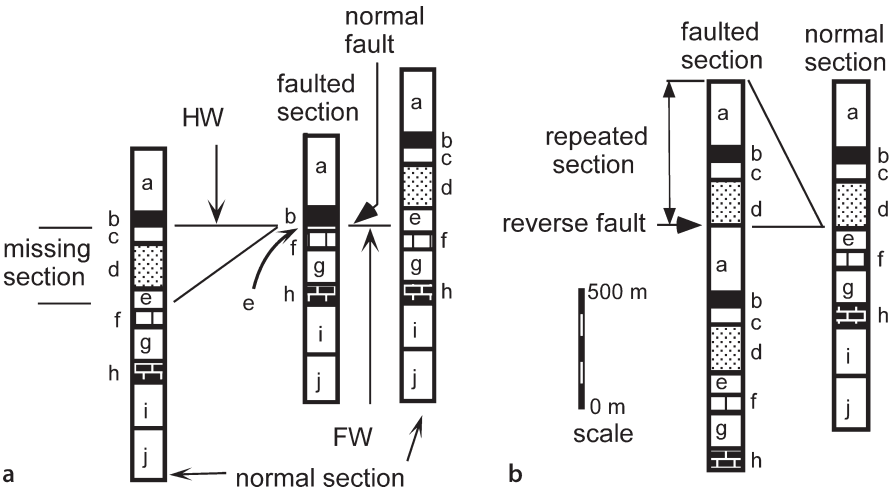

Fig. 7.10. Location and amount of stratigraphic separation determined from the missing or repeated section across the fault. **a** About 300 m of section is missing across a normal fault. **b** About 600 m of section is repeated across a reverse fault

An overturned fold limb can easily be mistaken for a fault zone. The upward and downward correlations will break down at the axial surfaces that bound the overturned limb. The overturned sequence will appear to be an unfamiliar unit and so is easily interpreted as being a fault zone. Try correlating an upside-down stratigraphic column to the possible fault zone to see if an overturned section is present. Beds near the fault may be steeply dipping, causing a great exaggeration of the bed thicknesses in a vertical well, representing another factor to consider when correlating to the type section.

The precision of the determination of stratigraphic separation depends on the level of detail to which the stratigraphy is known. For example, if the fault cut in Fig. 7.10a was at the top of unit e rather than near the base, the missing section would be significantly (50–75 m) greater. The error in the amount of missing section is the sum of the stratigraphic uncertainties in the units on both sides of the fault. Lack of stratigraphic resolution means that small faults may not be detectable by correlation of sections.

The *fault cut* refers to the position of the fault in a well and the to the amount of the missing or repeated section compared to the reference section (Tearpock and Bischke 2003). The location of the fault cut, the amount of the fault cut and the reference section should be recorded for each fault cut. It is not unusual to find that after preliminary mapping has been completed, the original stratigraphic thicknesses were inappropriate. For example, the units in a reference well may be shown by mapping to have a significant dip and their thicknesses therefore will have been exaggerated. Mapping may also reveal that the reference section is faulted. Any change in thickness in the reference section requires changes in the magnitudes of all the fault cuts determined from it.

7.2.6 Rock Type

Rock types diagnostic of faulting (Fig. 7.11) include the cataclasite suite, produced primarily by fragmentation, and the mylonite suite, produced by large crystal-plastic strains and/or recrystallization (Sibson 1977; Ramsay and Huber 1987). A cataclastic fault surface, or slickenside, is usually grooved, scratched, or streaked by mineral fibers or may be highly polished. The parallel striations or mineral elongation directions are slickenlines which indicate the slip direction at some stage in the movement history. A mylonite typically has a thinly laminated compositional foliation and a strong penetrative mineral lineation which is elongated in the displacement direction. Soft-sediment fault zones typically have macroscopic textures similar to those of mylonite zones, although no metamorphism has occurred. At the microscopic scale, the grains in a soft-sediment fault zone are usually undeformed.

A fault zone may be recognizable in well logs. An uncemented cataclastic fault zone is mechanically weak and very friable. This is the reason why an outcropping fault zone may erode to a valley. Where a well encounters a mechanically weak unit, such as an uncemented fault zone, an enlargement of the well-bore diameter occurs. A caliper log is produced by a tool that measures the size of the well bore and a fault may be recorded as an expansion in the size of the borehole, generally short in length. Well enlargement may occur in any mechanically weak unit such as coal, uncemented clay or sand, salt, etc. If the normal stratigraphic reasons for well enlargement can be eliminated, however, then the presence of a fault zone is a good possibility. A high-resolution dipmeter provides a log that resembles a photograph of the wall of the borehole. A fault zone may be inferred from the same observational criteria that would apply to

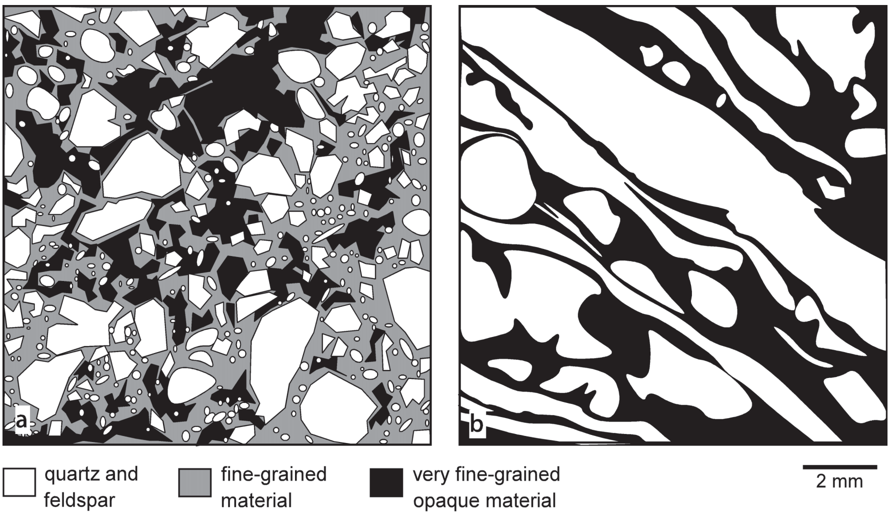

Fig. 7.11. Representative fault-rock textures. The scale is approximate. **a** Cataclasite. **b** Mylonite. Drawn from thin section photographs in Ramsay and Huber (1987)

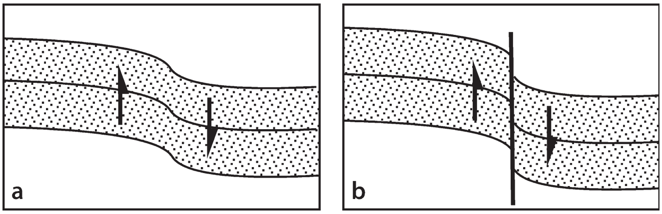

Fig. 7.12. Drag folds caused by permanent bending strain before faulting. **a** Fold before the units reach their ductile limit. **b** A fault forms after the ductile limit is exceeded, and the permanent strain remains as a drag fold

an outcrop, in particular, a high concentration of fractures or an abrupt change in lithology not part of the normal stratigraphic sequence.

7.2.7 Fault Drag

The systematic variation of the dip of bedding adjacent to the fault shown in Fig. 7.12b is known as "normal" drag, or simply *drag*, as the term will be used here. A drag fold gives the sense of slip on the fault. This geometry is probably best interpreted as being the result of the permanent strain that occurs prior to faulting (Fig. 7.12a), a sequence of formation well known from experimental rock mechanics. The term "drag" is thus a misnomer because the fold forms prior to faulting, not as the result of frictional drag along a pre-existing fault. In fact, the strain associated with slip on a pre-existing fault tends to produce bending in the opposite direction relative to the sense of slip (Reches and Eidelman 1995) called "reverse" drag. The reverse drag described by Reches and Eidelman (1995) is significantly smaller in magnitude than the normal drag produced before faulting and might not be noticeable at the map scale. Map-scale reverse drag is also well known as a consequence of slip on a downward-flattening normal fault (Hamblin 1965). Because the term drag is long established for the fold close to a fault and because the curvature of drag folds gives the correct interpretation of the sense of shear, use of the term is continued here. The drag-fold geometry usually extends no more than a few to tens of meters away from the fault zone. Although the drag geometry is common, not all faults have associated drag folds.

7.3 Unconformities

Unconformities are important surfaces for structural and stratigraphic interpretation. They provide evidence for structural and sea-level events, and mineral deposits, including hydrocarbons, are commonly trapped below unconformities. An unconformity truncates older geological features and so shares a geometric characteristic with a fault which also truncates older features (Figs. 7.4 and 7.13). Sometimes the two can be difficult to distinguish. The flat portion of a fault may cut bedding at a very low angle, just like the typical unconformity.

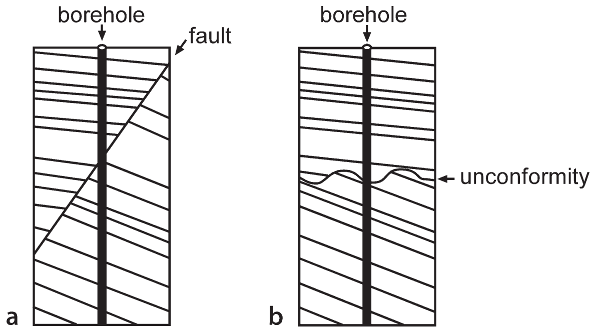

Fig. 7.13.
A dip change across a stratigraphic discontinuity may be either a fault or an unconformity. **a** Fault. **b** Unconformity. (After Hurley 1994)

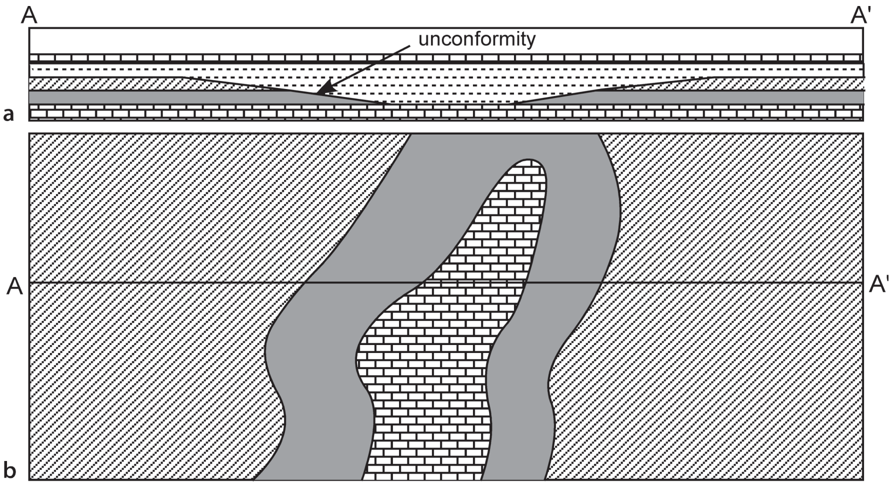

Fig. 7.14. The geometry of a low-angle unconformity. **a** Cross section showing a filled paleo-valley. Vertical exaggeration is about two to three times. **b** Subcrop map of units below the unconformity. (After Calvert 1974)

An unconformity can be mapped like a stratigraphic horizon, but it is significantly different because the units both above and below the unconformity can change over the map area (Fig. 7.14). An unconformity surface should be mapped separately from the units that it cuts or that terminate against it. The stratigraphic separation across an unconformity can be mapped and the separation can be expected to die out laterally into a continuous stratigraphic sequence (the correlative conformity) or at another unconformity. A subcrop map shows the units present immediately below an unconformity (Fig. 7.14b). This type of map has several important uses. It provides a guide to the paleogeology, can indicate the trends of important units, for example hydrocarbon reservoirs, and can suggest the paleostructure. An analogous map type is a subcrop map of the units below a thrust fault.

The dip change across an unconformity can be very small, a few degrees or less. A plot of the cumulative dip versus depth (Hurley 1994) is very sensitive to such small

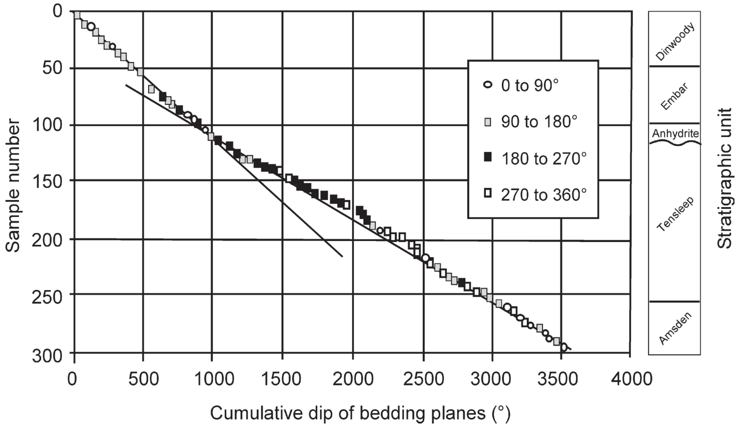

Fig. 7.15. Cumulative dip versus sample number from a well in the Bighorn basin, western U.S. Samples are *numbered* from the top of the well. Bedding planes are derived from a high-resolution dipmeter log. Points falling into different quadrants of the compass are coded with different *symbols*. (After Hurley 1994)

changes (Fig. 7.15). The vertical axis can be either depth or the sample number. Equal spacing of points on the vertical axis gives a more interpretable result and so if the bedding planes are sampled at irregular intervals, it is better to plot sample number rather than true depth or distance (Hurley 1994). The dips of the bedding planes are added together in the direction of the traverse to obtain the cumulative dip. In the example (Fig. 7.15), the change in average slope of the line through the data points indicates the position of an unconformity at the top of the Tensleep sandstone. The dip change in Fig. 7.15 is only 1.3° across the unconformity, yet it is clearly visible.

An additional analysis technique for the cumulative dip data is a first derivative plot (Hurley 1994). The first derivative (slope) between each two data points is plotted as the vertical axis and the cumulative dip of bedding planes as the horizontal axis. The slope between two successive dip points is the difference in depth or the sample-number increment (1) divided by the difference in cumulative dip between adjacent samples. Abrupt dip changes, even small ones, appear as large departures from the overall trend on this type of plot.

7.4 Displacement

Displacement is the general term for the relative movement of the two sides of a fault, measured in any direction (Bates and Jackson 1987). The components of displacement depend on five measurable attributes: the attitude of the fault, the magnitude of the stratigraphic separation, the attitudes of the beds on both sides of the fault, and direction of the slip vector in the fault plane. Different sets of these attributes are used to define the displacement components of slip or separation as will be discussed next. Throw and heave are the separation components most useful in structure-contour map construction because they appear on the map.

7.4.1 Slip

Slip (or net slip) is the relative displacement of formerly adjacent points on opposite sides of the fault, measured along the fault surface (Bates and Jackson 1987). Slip is commonly described in terms of its components in the plane of the fault, dip slip and strike slip (Fig. 7.16a). Dip slip components are normal or reverse and strike slip components are right lateral or left lateral. The offset of a marker horizon, as recorded on a map, can be produced by slip in a variety of directions. The geometry of the fault and the offset horizon are identical in Figs. 7.16a,b but the fault in 7.16a is oblique slip and in 7.16b is pure dip slip.

There are two traditional approaches for finding the net slip on a fault. The most direct is to find the offset of a geological line that can be correlated across the fault. A geological line may be a geographic or a paleogeographic feature such as a stream channel or a facies boundary. The alternative is based on the distance in the slip direction between correlative planar surfaces. In this method the slip direction must be known, for example, from the slickenline direction. The orientation of the slip vector may be recorded as the bearing and plunge of the lineation, or as the rake, which is the angle from horizontal in the plane of the fault.

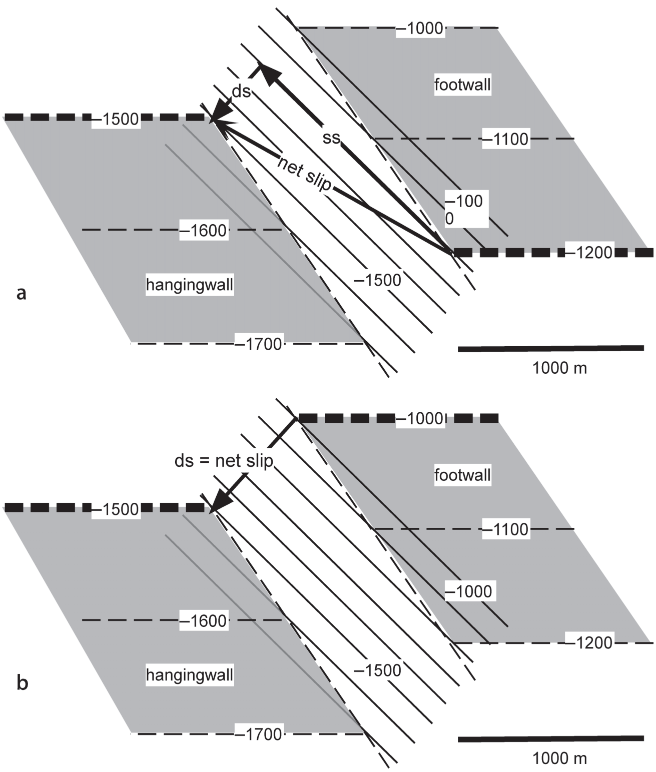

Fig. 7.16. Displacement of a marker horizon (*shaded*, with *dashed contours*) across a fault (*unshaded*, with *solid contours*). The final geometries of **a** and **b** are identical although the slip is different. *Wide contour lines* represent correlative linear features displaced by the fault. *ds:* dip slip; *ss:* strike slip. **a** Right-lateral, normal oblique slip. **b** Normal dip slip

The best features for determining true displacements are the offsets of pre-existing linear stratigraphic trends or the intersection lines produced by cross-cutting features, for example, a dike-bedding plane intersection line. Offset structural lines may be used in some circumstances. Fold hinge lines on identical marker horizons are potentially correlative marker lines. The offsets of the hinge lines in Fig. 7.17 give the true displacement for both the dip slip and strike slip examples. Offset hinge lines are good markers of displacement if the folds developed prior to faulting. Tear faults present at the beginning of folding may divide a region into separate blocks in which the folds can develop independently. The folds in adjacent blocks may have never been connected and so the separation of their hinge lines is not a measure of the displacement. If more than one fold hinge line can be matched across the fault and more than one hinge line gives approximately the same displacement, the probability is higher that the fault displaces pre-existing folds and the displacement determination is valid. The most complete method for the determination of the slip from the offset of geological features that intersect the fault is based on Allan maps of cutoff lines in the fault surface (see Sect. 8.4.3).

Fault slip can be obtained if marker beds can be matched across the fault in the slip direction. The slip direction may be given by the direction of grooves or slickenlines observed on the fault surface or by the trend of the lineation in the fault-zone rock.

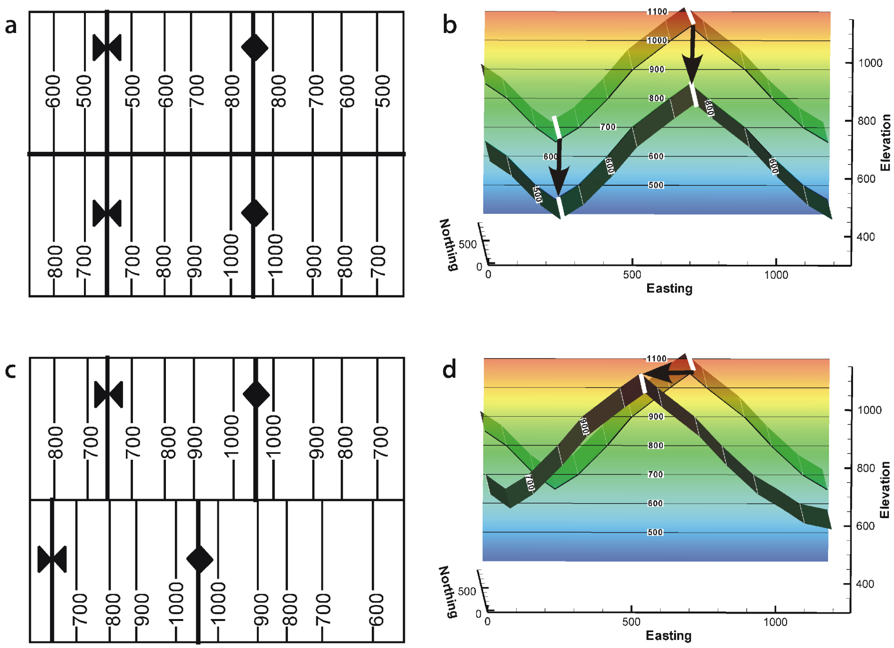

Fig. 7.17. Folds offset by a later fault. **a** Structure contour map of vertical slip on vertical fault. **b** Oblique view to N of 3-D version of **a**. **c** Structure contour map of strike-slip on a vertical fault. **d** Oblique view to N of 3-D version of **c**. North-south lines on **a** and **c** are structure contours labeled with elevations. *White lines* on **b** and **d** are fold hinge lines, *black arrows* are slip vectors, fault is shaded with contours labeled

The slip direction is usually perpendicular to the axis of the drag fold at the border of the fault zone, which can be observed in outcrop or be inferred by dip sequence (SCAT) analysis (Chap. 9, see also Becker 1995). The axes of folds contained within a fault zone are approximately normal to the slip direction, but may be arcuate, in which case the slip direction bisects the arc (Hansen 1971). Slip vector determination contains inherent ambiguities that must be considered, however. Different slip directions may be overprinted with only the last increment being observed or the slip trajectories may be curved.

To determine the fault slip, draw the slip vector on the structure contour map of the fault so that it connects the correlated points on the hangingwall and the footwall as in Fig. 7.16. If the end points of the slip vector are specified by their *xyz* coordinates, the length of the slip vector in the plane of the fault is (from Eq. 2.4)

$$L = [(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2]^{1/2} \quad , \qquad (7.1)$$

where L = the slip and the subscripts "1" and "2" = the coordinates of the opposite ends of the slip vector. If the end points are specified by the horizontal and vertical distance between them (from Eq. 4.7)

$$L = (v^2 + h^2)^{1/2} \quad , \qquad (7.2)$$

where L = the slip, v = vertical distance between end points, and h = the horizontal distance between end points.

Without the information provided by the correlation of formerly adjacent points across the fault or knowledge of the slip vector, it is impossible to determine whether a fault is caused by strike slip, dip slip, or oblique slip. Map interpretation must frequently be done without knowledge of the slip amount or direction, a situation for which the fault separation, given next, provides the framework for the interpretation.

7.4.2 Separation

Separation is the distance between any two index planes disrupted by a fault (Dennis 1967; Bates and Jackson 1987). Several different separation components are commonly used to describe the magnitude of the fault offset. Strike and dip separations are, respectively, the separations measured between correlative surfaces along the strike and directly down the dip of the fault (Billings 1972). The stratigraphic separation (Fig. 7.18) is the stratigraphic thickness of the beds missing or repeated across a fault (after Bates and Jackson 1987). Stratigraphic separation is a thickness, and therefore represents a measurement direction perpendicular to bedding. The stratigraphic separation is equal to the fault cut, that is, the amount of section missing or repeated across a fault at a point. It is possible for a fault to have a large displacement and yet show no stratigraphic separation. For example, strike-slip displacement of horizontal beds produces no stratigraphic separation. Other combinations of slip direction and dip of marker beds can also result in zero separation (Redmond 1972).

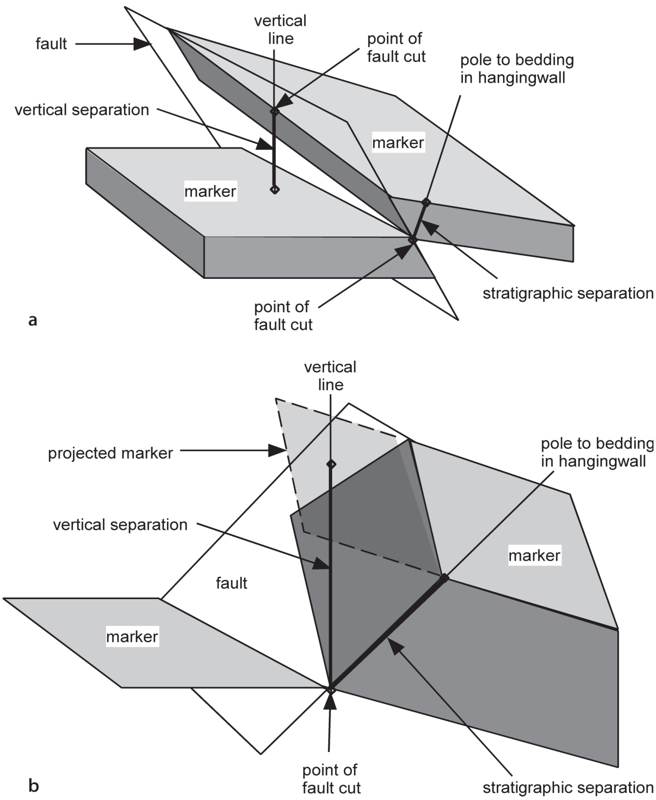

Fig. 7.18.
Vertical and stratigraphic fault separation. **a** Reverse fault. **b** Normal fault: the marker horizon must be projected across the fault in order to measure the vertical separation

Vertical separation is the distance, measured vertically, between the two parts of a displaced surface (Fig. 7.18; Dennis 1967). In the case of a normal-separation fault, one of the surfaces must be projected across the fault to make the measurement. The vertical separation of an offset marker horizon is shown in a vertical cross section in the direction of dip of the bedding across the fault from the fault cut (Fig. 7.19). The separation is measured from the marker horizon at the point of the fault cut to the position of the same marker horizon across the fault (reverse separation; Fig. 7.19a) or from the marker horizon at the fault cut to the *projection* of the marker horizon from its location across the fault (normal separation, Fig. 7.19b). The amount of the vertical separation is

$$v = t / \cos\delta \quad , \tag{7.3}$$

where v = vertical separation, t = stratigraphic separation = amount of the fault cut, and δ = cross-fault bedding dip. The cross-fault bedding dip is the dip of bedding across the fault from the marker horizon at the fault cut. The vertical separation of a vertical bed is undefined.

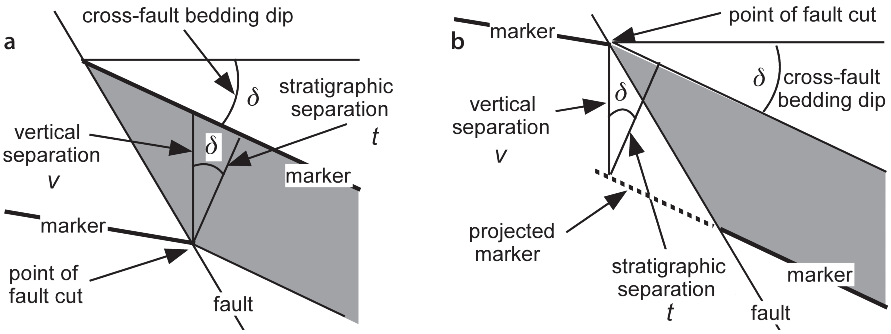

Fig. 7.19. Vertical separation calculated in a vertical cross section in the direction of the cross-fault bedding dip. **a** Reverse separation fault. **b** Normal separation fault

7.4.3 Heave and Throw from Stratigraphic Separation

Heave and throw have a special significance because they are the separation components visible on the structure contour map of a faulted horizon. Throw is the vertical component of the dip separation and heave is the horizontal component of the dip separation, both being measured in a vertical cross section in the dip direction of the fault (Dennis 1967; Billings 1972). Throw and heave can be found directly from the stratigraphic separation. The following discussion refers to the geometry shown in Fig. 7.20. Let point P_1 be the location of the fault cut in a well or exposed in outcrop. The marker horizon is shaded. P_2 is the location of the marker horizon in a vertical plane oriented in the direction of fault dip. The calculation of throw and heave is a projection across the fault from the control location (P_1) to a predicted location (P_2). The stratigraphic separation at the point of the fault cut is the thickness of the missing or repeated section, *t*. The dip separation, S_d, is equal to the apparent thickness of the missing or repeated section in the direction of the fault dip (dip vector) between points P_1 and P_2. The dip separation can be found from Eq. 4.1 as

$$S_d = t / \cos \rho \quad , \tag{7.4}$$

where t = the stratigraphic separation and ρ = the angle between the pole to the cross-fault bedding attitude and the dip vector of the fault. The dip of bedding used is always that belonging the side of the fault to which the projection is being made (P_2), that is, across the fault from the fault cut on the marker horizon. The value of ρ can be found with a stereogram (Sect. 4.1.1.1) or from any of the analytical methods in Sect. 4.1.1.2.

The heave and throw are determined by taking the horizontal (H) and vertical (T) components (Fig. 7.20) of S_d from Eq. 7.4:

$$H = t \cos \phi / \cos \rho \quad , \tag{7.5}$$

$$T = t \sin \phi / \cos \rho \quad , \tag{7.6}$$

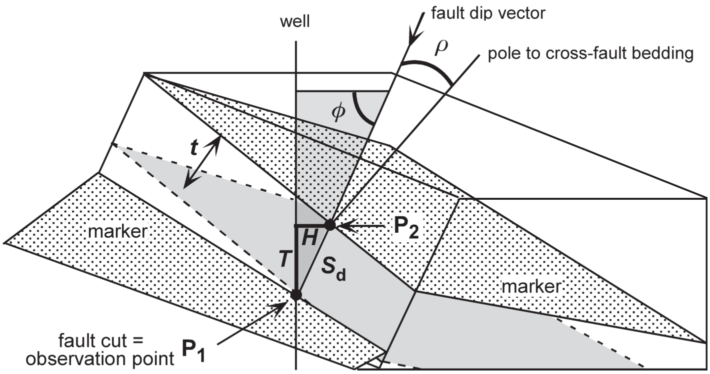

Fig. 7.20. Fault heave (H) and throw (T) at a fault cut (point P_1). S_d = dip separation; $H = L \cos \phi$; $T = L \sin \phi$; t stratigraphic separation = fault cut; ϕ dip of the fault; ρ angle between the fault dip and the pole to the cross-fault bedding attitude at P_2. The marker horizon is *shaded*

where H = heave, T = throw, t = stratigraphic separation, ϕ = the dip of the fault, and ρ = the angle between the cross-fault bedding attitude and the dip vector of the fault. If bedding is horizontal, its pole is vertical, causing ρ to be equal to 90 – ϕ, and Eqs. 7.5 and 7.6 reduce to

$$H = t / \tan \phi \quad , \tag{7.7}$$

$$T = t \quad . \tag{7.8}$$

In the case of zero dip of bedding, and only in the case of zero dip of bedding, the stratigraphic separation is equal to the fault throw and equal to the vertical separation.

As an example of the calculation, consider a fault having a stratigraphic separation of 406 m, the cross-fault bedding attitude is δ = 10, 180, and the fault dip is ϕ = 37, 220. The pole to bedding is found to be 80, 360 and the angle between the pole to bedding and the fault dip is ρ = 60°. From Eq. 7.5, H = 648 m, and from Eq. 7.6, T = 489 m. These values are derived for the fault in Fig. 7.16 and could have been caused by any number of different combinations of net slip magnitudes and directions.

Neither the stratigraphic thickness nor the attitude of bedding are necessarily the same on both sides of a fault, which is important when the throw and heave are calculated from Eqs. 7.5 and 7.6. The appropriate dip and thickness values are always the cross-fault magnitudes found in the block across the fault from the marker horizon at the fault cut. In subsurface mapping based only on formation tops and fault cuts, it is likely that none of the required dips will be known at the early stage of mapping. This means that throw and heave cannot be calculated accurately at this stage. Throw and heave can be estimated for preliminary mapping purposes by estimating the dip of the fault and the dip of cross-fault bedding. If no other information is available, normal-separation faults can be estimated to dip 60°, reverse separation faults to dip 30°, and bedding can be assumed to be horizontal. As the required dips are determined by mapping, the throw and heave magnitudes can be corrected.

7.5 Geometric Properties of Faults

In this section the typical characteristics of an individual fault surface and its displacement distribution are described.

7.5.1 Surface Shape

A fault surface is usually planar to smoothly curved or gently undulating (Fig. 7.21). The structure contour map of a fault surface should usually be smooth. Viewed over their entire surface, many faults are smoothly curved into a spoon-like shape. Primary surface undulations, if present, are typically aligned in the slip direction and provide a good criterion for the slip direction (Thibaut et al. 1996).

7.5.2 Displacement Distribution

The displacement on a fault dies out at a tip line which is the trace in space of the terminations of a fault (Boyer and Elliott 1982). If the displacement dies out in all directions (Barnett et al. 1987), the fault is surrounded by a tip line (Fig. 7.22) like a dislocation in the theory of crystal plasticity (Nicolas and Poirier 1976). Faults are typically significantly longer in the strike direction than in the dip direction. Faults always

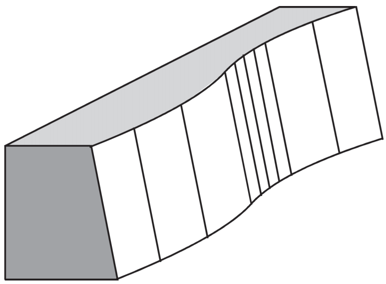

Fig. 7.21.
Perspective block diagram of a curved fault surface

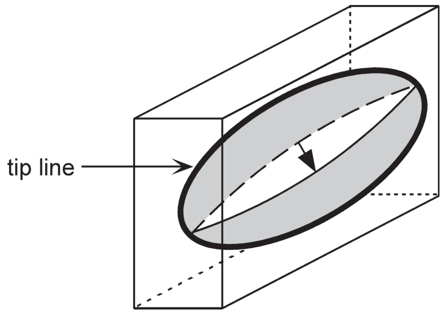

Fig. 7.22.
Dislocation-like fault for which the displacement (*arrow*) dies out to zero in all directions at the tip line. The trace of the displaced marker horizon is *dashed* on the footwall of the fault and *solid* on the hanging-wall

die out along strike (Figs. 7.22, 7.23a) or transfer displacement to some other fault or to a fold. Displacement in the dip direction may or may not go to zero. A fault may flatten into a detachment without losing displacement (Fig. 7.23b; Gibbs 1989). The variation in displacement in the dip direction is a function of the structural style and a variety of relationships are possible.

An accurately mapped example from the Westphalian coal measures in the United Kingdom (Fig. 7.24a) has a displacement distribution nearly as simple as that in Fig. 7.22. The fault-displacement maps are derived from mapping at five different levels in underground coal mines and so require little inference. Another example from the same area (Fig. 7.24b) is more complex but the displacement is still seen to die out along strike. For this area, a representative aspect ratio is 2.15 (strike length/dip length) for a group of isolated normal faults that die out in all directions for over a length range of 10 m to 10 km, and is in the range of 0.5 to 8.4 for normal faults that intersect other faults or reach the surface (Nicol et al. 1996).

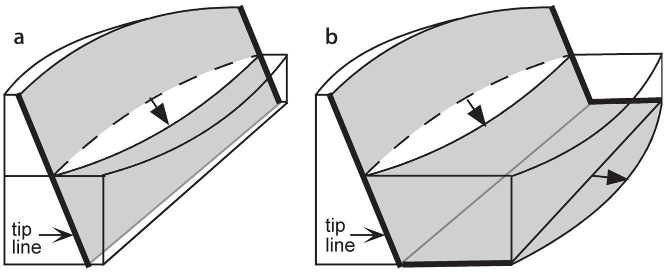

Fig. 7.23. Faults for which the displacement does not die out in the dip direction. The displacement (*arrow*) dies out along strike at the tip lines marked by *heavy lines*. The trace of the displaced marker horizon is *dashed* on the footwall of the fault and *solid* on the hangingwall. **a** Fault of unspecified extent in the dip direction. **b** Fault that bends into a planar lower detachment without losing displacement

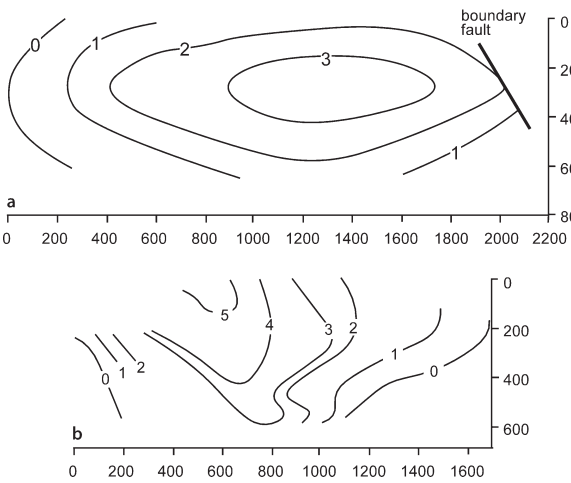

Fig. 7.24. Two examples of contours of fault throw on normal faults dipping about 65°. Contours are projected onto a vertical plane that has the strike of the fault. Scales in meters. **a** Elliptical heave distribution. The fault ends to the right against the boundary fault. **b** Complex heave distribution. (After Rippon 1985)

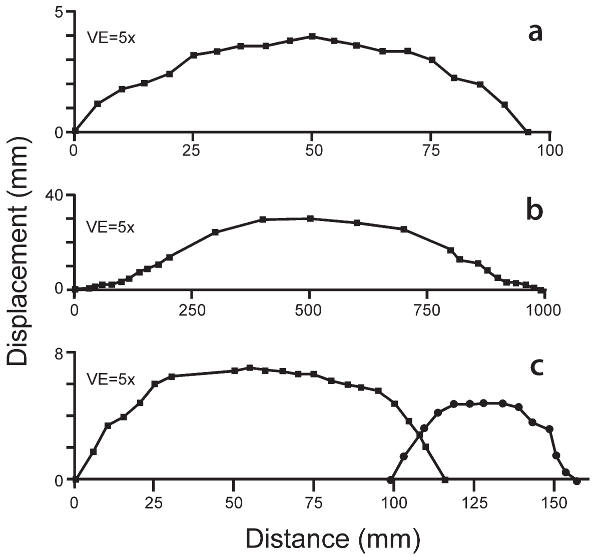

Fig. 7.25.
Displacement versus distance plots for completely exposed small normal faults. **a** Approximately circular-arc distribution. **b** Approximately sinusoidal distribution. **c** Two overlapping faults with D-shaped distributions. *VE:* vertical exaggeration. (Schlische et al. 1996)

The change in displacement along the strike of a fault can be illustrated with a displacement-distance graph. The displacement-distance curve typically ranges from a circular arc (Fig. 7.25a) to sinusoidal (Fig. 7.25b) to D-shaped (Fig. 7.25c). All three distributions in Fig. 7.25 come from one small area in a quarry and are completely exposed. More complex displacement distributions (Fig. 7.24b) may be the result of the coalescence of multiple faults, like the two faults in Fig. 7.25c.

The smooth variation of displacement along a fault in the style of Figs. 7.24a and 7.25 has been described as the bow and arrow rule (Elliott 1976). The trace of a faulted horizon on one side of the fault (fault cutoff line) forms the bow and a straight line joining the tips of the fault is the bow string. A line perpendicular to the bow string at its center is the arrow. The distance along the arrow between the bow and the bow string is an estimate of the displacement amount and the direction of the arrow is an estimate of the displacement direction. These are reasonable first approximations for dip slip faults although they should be used with caution. If the displacement distribution on the fault resembles that in Fig. 7.22, then the displacement with respect to the correlative horizon across the fault is twice that given by the bow and arrow rule because both hangingwall and footwall are displaced from their original positions (the position of the bow string). The rule does not apply to strike-slip faults.

The length of a fault in the strike direction is usually much greater than its maximum displacement. A comparison between the maximum displacement on a fault and its length, down dip or along strike, shows that ratios of 1 : 8 to 1 : 33 are common, regardless of location, size, or fault type (Table 7.1). The maximum displacement is expected to occur near the center of the fault as in Fig. 7.24a and 7.25. Fault displacements measured from maps or cross sections may not go through the point of maxi-

Table 7.1. Ratio of maximum displacement to length for a variety of faults that die out in tip lines in the direction of the measurement. The first two measurements from Rippon (1985) are from Fig. 7.24a, the third is from Fig. 7.24b

Max. displ./ length	Direction measured	Size range	Fault type	Location	Reference
1/10 to 1/20	Dip	40 – 450 cm	Normal	Japan	Muraoka and Kamata (1983)
1/10 to 1/20	Strike	10 – 400 km	Thrust	Canadian Rocky Mts.	Elliott (1976)
1/8	Strike	1.5 – 21 km	Strike slip	Iran	Freund (1970)
1/82	Strike	2.5 km	Normal	Alabama	Chap. 7, Fig. 7.46
1/700	Strike	2 km	Normal	Derbyshire, UK	Rippon (1985)
1/450	Dip	1 km	Normal	Derbyshire, UK	Rippon (1985)
1/340	Strike	1.5 km	Normal	Derbyshire, UK	Rippon (1985)
1/90	Strike	10 – 200 m	Normal	Western USA	Dawers et al. (1993)
1/125	Strike	0.2 – 10 km	Normal	Western USA	Dawers et al. (1993)
1/30 to 1/50	Strike	0.2 – 10 km	Normal	Timor Sea	Nicol et al. (1996)
1/33	Strike	1 – 123 cm	Normal	Eastern USA	Schlische et al. (1996)

mum displacement and so the displacement/length ratios could be smaller than the values recorded in Table 7.1. The examples of Rippon (1985), however, are well exposed in three dimensions and the ratios are very large. In summary, long faults usually have large displacements but may have small displacements; short faults do not have large displacements.

The relationship between the maximum displacement and the fault length is generally considered to have the form

$$D = \gamma L^C \quad , \tag{7.9}$$

where D = maximum displacement, γ = a constant of proportionality, L = fault length, and C is between 1 and 2 (Watterson 1986; Marrett and Allmendinger 1991; Dawers et al. 1993). The exact relationship appears to depend on many factors including the mechanical stratigraphy and the nature of interactions between overlapping faults (for example, Cowie and Scholz 1992). For the practical estimation of the displacement-length relationship in map interpretation, it appears satisfactory to let $C = 1$ and recognize that the value of γ may change when the size of the fault changes by an order of magnitude and will be different in different locations (Cowie and Scholz 1992; Dawers et al. 1993; Schlische et al. 1996). With $C = 1$, the value of γ is the D/L ratio given in Table 7.1. This relationship can be used to estimate the length of a fault from its maximum displacement or estimate the maximum displacement from the length.

7.6 Growth Faults

A growth fault moves during deposition and controls the thickness of the deposits on both sides if the fault. The classic Gulf of Mexico thin-skinned extensional growth fault, from the region where the concept was developed (Fig. 7.26), is depositional on both sides and the sediments thicken across the fault. A growth fault in a rifted environment may show footwall uplift and erosion concurrent with deposition on the hangingwall. Growth faults can be normal (Fig. 7.26) or reverse (Fig. 7.27); in fact, any type of fault can record growth, including strike-slip faults.

7.6.1 Effect on Heave and Throw

Because the stratigraphic thicknesses are different on opposite sides of a growth fault, the heave and throw determined from the fault cut depend on whether the marker being mapped is in the hangingwall or footwall of the fault. The appropriate thickness is that belonging to the section across the fault from the fault cut in the marker horizon. For a marker on the hangingwall of a normal fault (Fig. 7.26a), the appropriate fault-cut thickness is that of the footwall stratigraphic section. To map a footwall marker in the same well (Fig. 7.26b), the appropriate thickness is that of the hangingwall strati-

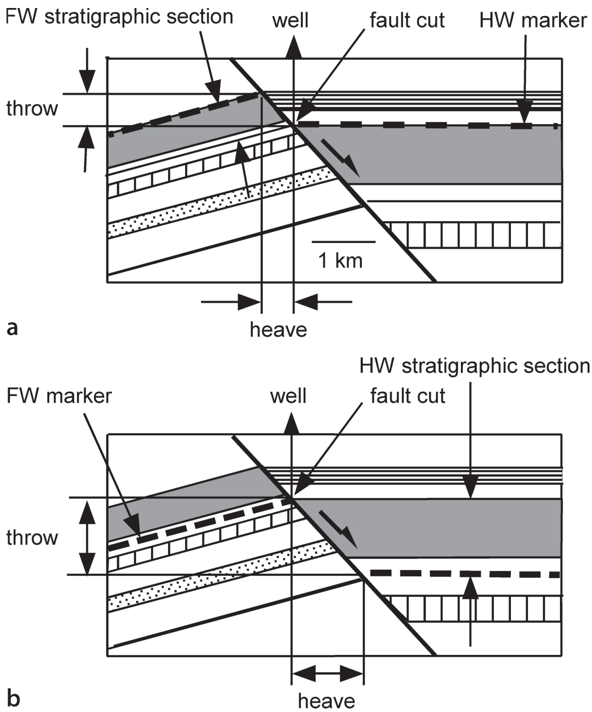

Fig. 7.26. Identical cross sections across a growth normal fault showing effect of growth on throw and heave. The section is vertical and in the direction of fault dip. The fault cut is at the same point in both sections. **a** The fault cutoff of a hangingwall marker (*dashed*) is extrapolated to the footwall cutoff of the same marker using dip and thickness values from the footwall. **b** The fault cutoff of a footwall marker (*dashed*) is extrapolated to the hangingwall cutoff of the same marker using dip and thickness values from the hangingwall

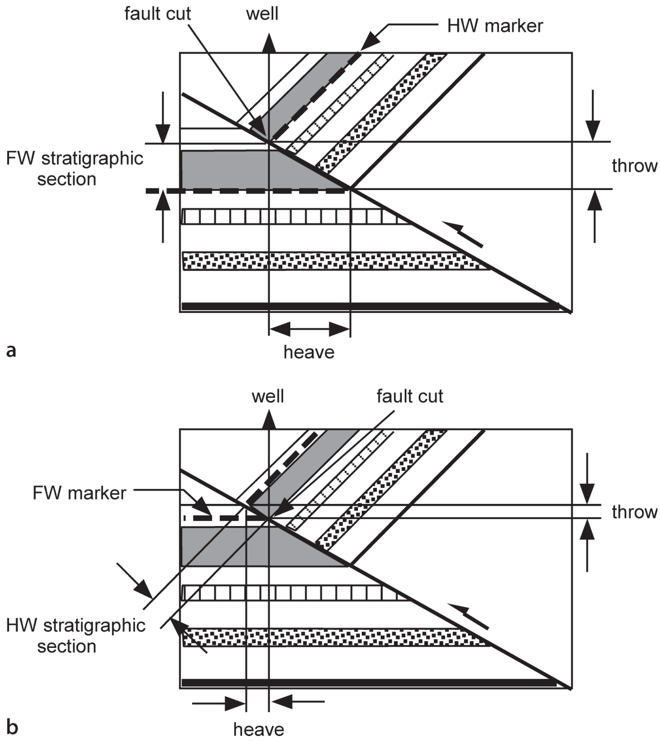

Fig. 7.27. Identical cross sections of a growth reverse fault showing effect of growth on throw and heave. The section is vertical and in the direction of fault dip. The fault cut is at the same point in both sections. **a** The fault cutoff of a hangingwall marker (*dashed*) is extrapolated to the footwall cutoff of the same marker using dip and thickness values from the footwall. **b** The fault cutoff of a footwall marker (*dashed*) is extrapolated to the hangingwall cutoff of the same marker using dip and thickness values from the hangingwall

graphic section. The same considerations apply to the correct choice of thickness for growth reverse faults (Fig. 7.27).

7.6.2 Expansion Index

The growth history of a fault can be illustrated quantitatively with the expansion index (E) of Thorsen (Fig. 7.28):

$$E = t_d / t_u \quad , \tag{7.10}$$

where t_d = the downthrown thickness (hangingwall) and t_u = the upthrown thickness (footwall). The thicknesses should be measured perpendicular to bedding so as not to confuse dip changes with thickness changes, and as close to the fault as possible because that is where the maximum thickness changes occur.

The simplest possible growth fault is one that starts, increases in growth rate, then slows and stops (Fig. 7.28). In the pre-growth interval, $E = 1.0$ (unit j); as the growth rate increases, so does the expansion index, to a maximum of 2.1 in Fig. 7.28. The growth of the fault slows and eventually stops and E returns to 1.0 (unit a). The plot of stratigraphic interval versus expansion index gives a visual picture of the growth his-

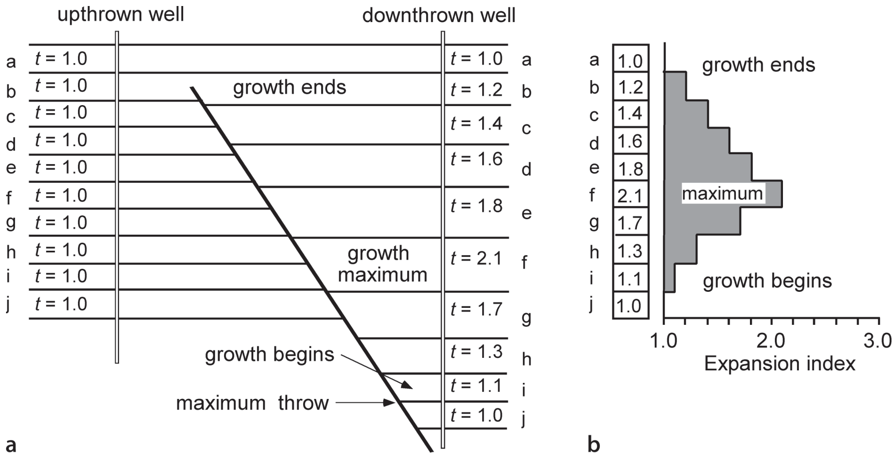

Fig. 7.28. Expansion index for a fault that begins to move, reaches a growth maximum and then stops. **a** Cross section. **b** Expansion index vs. stratigraphic interval graph. (After Thorsen 1963)

tory. If the relative offset is large and if shale units are being compared at less than 3 000 ft of burial, it might be important to correct *E* for compaction. At greater depths, the relative change in thickness will be small and have little effect on *E*.

The expansion index plot characterizes the growth history of a fault and might be correlated to other time-dependent features such as the sand/shale ratio or the time of hydrocarbon migration. The use of *E* eliminates the effect of absolute interval thickness, allowing the growth rates of a generally thin interval to be directly compared to that of a generally thick interval. The use of the similarity between expansion index plots at different fault cuts as an aid to fault correlation will be illustrated in Sect. 7.7.4.

7.7 Fault-Cut Correlation Criteria

Faults are commonly mapped on the basis of observations made at a number of separate locations, called fault cuts. If more than one fault may be present, a very significant problem is to establish which observations belong to the same fault (Fig. 7.29). This problem arises in surface mapping where the outcrop is discontinuous, in sub-

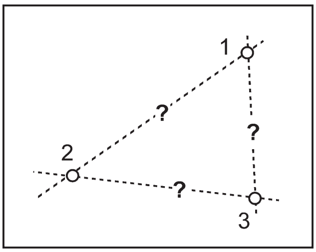

Fig. 7.29. Map showing three locations where faults have been observed. Which, if any, points are on the same fault? *Numbered circles* are observation points, *dashed lines* are some possible fault correlations

surface mapping based on wells, and in constructing maps from two-dimensional seismic data. Correlating faults in an area of multiple faults is one of the most challenging problems in structural interpretation. A number of fault properties can be used to establish the correlation between fault cuts. Correlation criteria include the fault trend, the sense of throw across the fault, the smoothness of the fault surface, the amount of separation, and the growth history. The rules for correlation that are presented below may have exceptions and should be used in combination to obtain the best result.

7.7.1 Trend and Sense of Throw

The consistency of the fault trend and the consistency of the sense of throw are usually the first two criteria applied in the correlation of fault cuts. The fault trend can sometimes be established at the observation points by direct measurement in outcrop, by physically tracing the fault, or by SCAT analysis of outcrop traverses or dipmeter logs (Chap. 9). If, for example, the fault trend in the map area of Fig. 7.29 can be shown to be east–west, then observation points 2 and 3 are more likely to be on the same fault than are points 1 and 3 or 1 and 2 (Fig. 7.30a), and the fault through point 1 is also likely to trend east–west. A preliminary structure contour map on a horizon for which there is good control may give a clear indication of the fault trends (Fig. 7.30b). Faults that are directly related to the formation of the map-scale folds are commonly parallel to the strike of bedding, especially in regions where the contours are unusually closely spaced. Such zones may represent unrecognized faults.

The high and low areas on a structure contour map of a marker horizon should be explained by the proposed faults. The upthrown and downthrown sides of a fault will commonly be the same along strike. For example, the proposed fault linking observation points 2 and 3 in Fig. 7.30b is downthrown on the north at both locations. A constant sense of vertical separation is a common and reasonable pattern, but not the only possibility on a correctly interpreted fault.

Faults that offset folds may produce complex patterns of horizontal and vertical separations. Vertical displacement on a fault that strikes at a high angle to fold axes

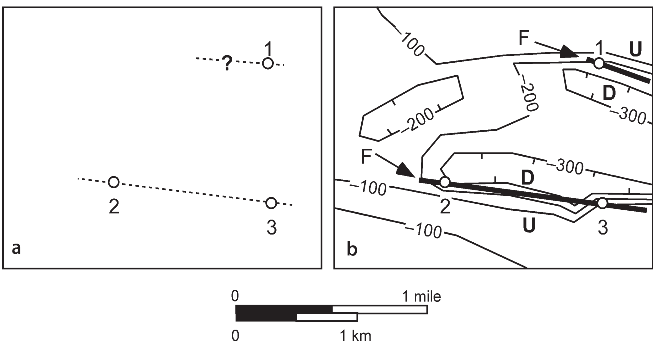

Fig. 7.30. Maps showing possible correlations between fault cuts at points 1–3. **a** Correlations (*dashed lines*) along an east-west trend. **b** Preliminary structure contour map on a marker horizon. Fault correlations (*heavy solid lines* marked F) along structure contour trends are supported by the consistent sense of throw across the faults

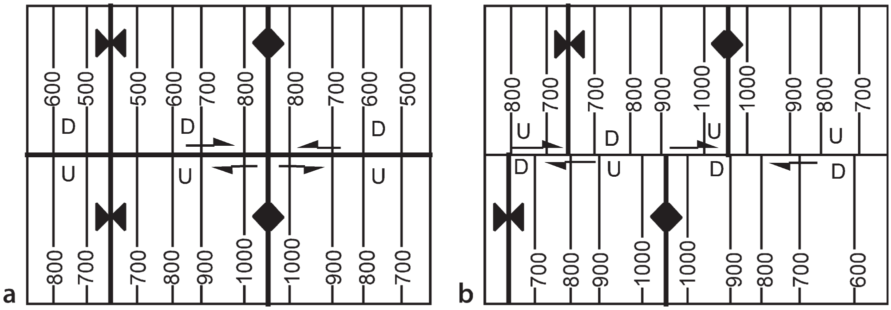

Fig. 7.31. Displacement along faults oblique to the fold trend. North-south lines are structure contours labeled with elevations. **a** Pure vertical slip. The implied strike slip on the fold limbs (*arrows*) is incorrect. **b** Pure strike-slip displacement. The implied vertical slip (*U*, *D*) is incorrect. For 3-D views of these maps see Fig. 7.17

produces apparent strike-slip displacements of the fold limbs for which the sense of slip reverses at the fold hinge line (Fig. 7.31a) although the sense of throw is constant across the fault. Strike-slip displacement of the folds produces throw that changes sense along the fault (Fig. 7.31b) but the sense of strike separation is constant. Faults for which the sense of throw reverses along the trend of the fault are called scissors faults. Such faults may form by rotation around the points of zero separation or, as in Fig. 7.31b, may be caused by the strike-slip displacement of folds.

7.7.2 Shape

The inferred shape of a fault is an important criterion in correlating fault cuts and in validating fault interpretations. A valid fault surface is usually planar or smoothly curved and has an attitude that is reasonable for the local structural style. Contours on fault surfaces follow the same rules as contours on bed surfaces (Sect. 3.2) with the exception that the fault contours can end in the map area where displacement on the fault ends (Bishop 1960). The dip of the fault is obtained from a structure contour map (Sect. 3.6.1).

Smooth contours on the fault surface demonstrate that the correlations between the fault cuts are acceptable (Fig. 7.32). Because faults are typically planar or gently curved, it is reasonable to assume that both the strike and dip of the fault are approximately constant. Surface undulations, if present, are most likely to be aligned in the slip direction. Unfaulted points or unfaulted wells near an inferred fault provide additional constraints on the geometry because they must lie entirely within the hangingwall or footwall. Negative evidence, e.g., the absence of a fault cut in a well the penetrates an inferred fault plane, requires remapping the fault or faults. The dips implied by the contours must be reasonable for the structural style. Very irregular contours on a fault surface suggest an incorrect correlation of the control points. Folded faults are possible, especially thrusts, but must be consistent with the folds in the hangingwall and footwall.

The process of correlation of fault cuts and bed offsets into individual fault planes based on shape can be made easier and faster with a fault template. A fault template is

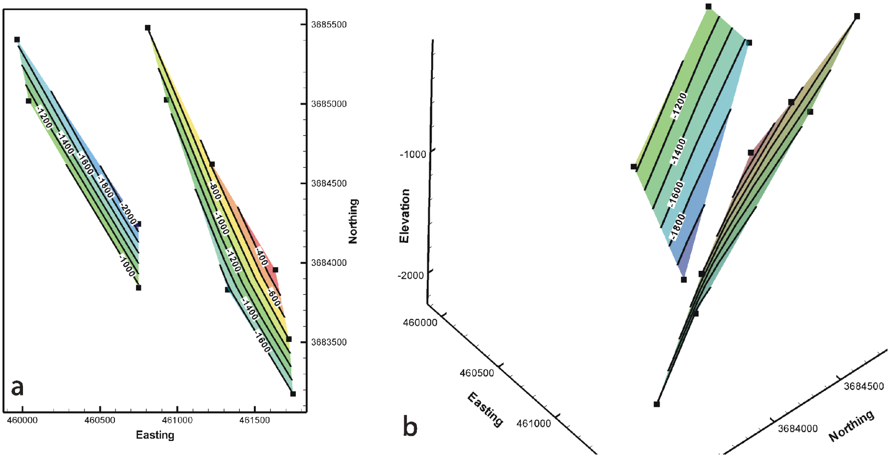

Fig. 7.32. Maps of two normal faults mapped from wells in Deerlick Creek coalbed methane field (modified from Groshong et al. 2003b). *Squares* are the positions of fault cuts, *contours* are on the fault surfaces. **a** Structure contour map. **b** 3-D view to the NW of the two faults

a structure contour map of the expected fault plane at the scale of the map. If mapping on paper, construct a template by picking a suitable contour interval for the fault along with a reasonable dip, then use Eq. 2.21 to find the horizontal spacing between contours on the template. 3-D software will probably allow a plane of a given orientation to be specified. If not, use the equations of a plane (Sect. 2.4.2) to place a plane in an appropriate location. The template can be moved around the map and rotated until a set of fault cut elevations and/or bed offsets are reasonably correlated. Then the real fault plane is constructed directly from the data with the template as a guide. If a representative fault dip for the area is known, then it should be used for the template. If a representative dip is unknown, it is reasonable to begin with 60° for normal faults, 10–30° for low-angle reverse faults, 50–80° for high-angle reverse faults, and 70–90° for strike-slip faults, based on stress theory (Sect. 1.6.4) and common experience.

7.7.3
Stratigraphic Separation

The stratigraphic separation along a fault surface is normally a smoothly varying function, with a maximum near the center of the fault and decreasing to zero at the tip line (Sect. 7.5.2). This simple pattern can be perturbed if the fault grew by linking separate faults (Sect. 8.6), but the variation is nevertheless likely to remain smooth. The stratigraphic separation on the fault is the component usually known, and can be used as a proxy for the displacement as long as the bed geometry adjacent to the fault is not too complex. The distribution of the separation can be displayed by posting the separations on a map of the fault surface (Fig. 7.33a). A point on a fault for which the location of the fault cut and the stratigraphic separation do not agree with the points around it (Fig. 7.33b) is likely to be miscorrelated with the fault.

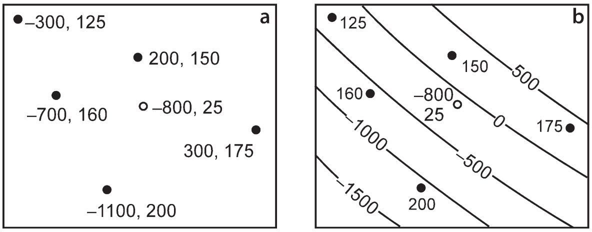

Fig. 7.33. Fault-cut maps with stratigraphic separations. **a** Data: elevation of fault cut, amount of stratigraphic separation (fault cut). **b** Structure contour map on the fault surface; amount of fault cut is posted. The contour interval is 500 units, and negative contours are below sea level. The fault cut (*open circle*) does not correlate with the contoured fault

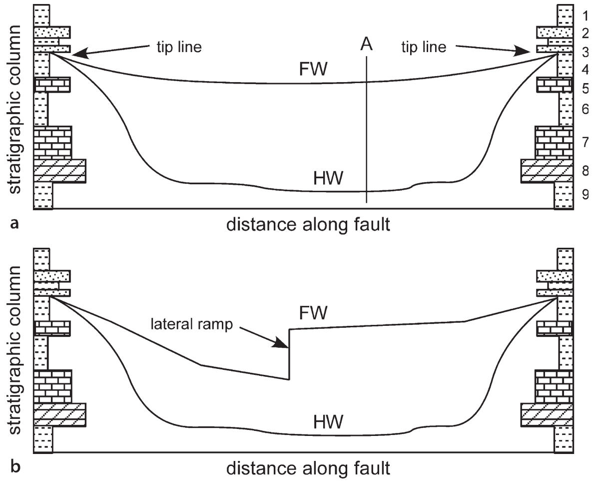

Fig. 7.34. Stratigraphic separation diagram representative of relationships seen along the strike direction of a thrust fault. *FW curve:* Stratigraphic position of the thrust in the footwall; *HW curve:* stratigraphic position of the fault in the hangingwall. **a** Single unbroken thrust sheet. **b** Thrust sheet broken by a lateral ramp

Another method for displaying the variation of the stratigraphic separation along a fault is by means of a stratigraphic separation diagram (Fig. 7.35; Elliott and Johnson 1980; Woodward 1987). The vertical axis of the diagram is the scaled stratigraphic column and the horizontal axis is the distance along the fault. The curves on the diagram show the stratigraphic unit that the fault is in at any particular point. A thrust fault usually places older over younger units and so the footwall block should be the upper curve (Fig. 7.35). The opposite is true for a normal fault. For example, line A (Fig. 7.35a) represents a particular geographic point on the fault, one at which the footwall is at the base of unit 4 and the hangingwall is in unit 9. If the complete fault has been observed, the hangingwall and footwall curves will join at the fault tips. Both hangingwall and footwall curves will be smooth if they are not broken by oblique faults. An oblique structure will produce a rapid change in the stratigraphic level of the curve of the block that contains the feature (Fig. 7.35b). If the rapid change is in the footwall, it is likely to have been caused by a lateral ramp. If the oblique structure is in the hangingwall, it is likely to be a tear fault that subdivides only the hangingwall. If the feature is present

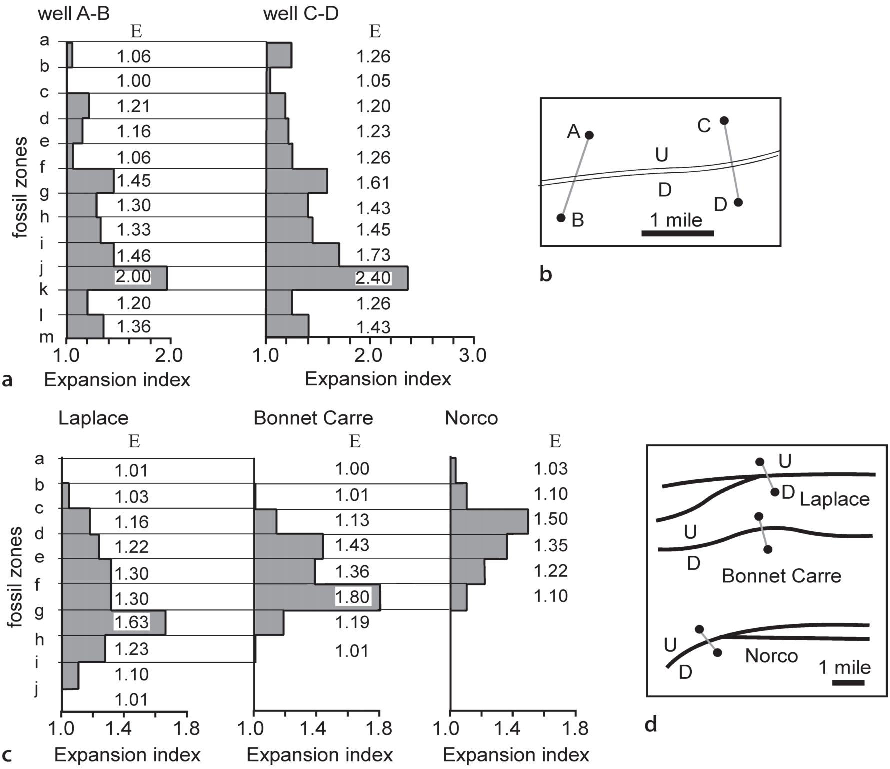

Fig. 7.35. Expansion index (*E*) diagrams across Louisiana growth faults. **a** Expansion indices from two crossings of the same fault. **b** Locations of wells used to determine the expansion indices in **a**. **c** Expansion indices across three adjacent faults. **d** Locations of the wells used to determine the expansion indices in **c** (after Thorsen 1963)

to about the same degree in both the hangingwall and the footwall curves, it may have been caused by a later fault that cuts and displaces the fault in question.

Stratigraphic separation diagrams are most widely used for data derived from the outcrop traces of thrust faults. If the distance coordinate follows the sinuous erosional trace of a low-angle thrust, some of the stratigraphic variation in thrust levels will be caused by the changing depths of erosion and reentrants on the fault. To eliminate this source of variability, it is better to make the diagram follow a straight line or smooth curve that is either parallel to or perpendicular to the transport direction of the fault (Woodward 1987).

7.7.4 Growth History

The stratigraphic evolution of a growth fault provides another criterion for correlating fault cuts. A single fault can be expected to have a similar stratigraphic growth history along its trend. Expansion index diagrams (Sect. 7.6.2) clearly illustrate the details of the growth history and are valuable in fault correlation. In an example from Louisiana, the expansion index diagrams have the same form across the same fault at an interval about 2.5 miles apart (Fig. 7.35a,b). The values of *E* for the same units are not the same, but the forms of the expansion index curves are the same. Both crossings of the same fault show the maximum growth interval to be of the same age. Three different faults in the same area give three different expansion index diagrams over similar distances (Fig. 7.35c,d). The maximum growth interval becomes younger to the south. Thus, similar growth-history relationships can indicate that the same fault has been crossed and different relationships can indicate that different faults have been crossed.

7.8 Exercises

7.8.1 Fault Recognition on a Map

Use the partially complete geologic map of Fig. 7.36, to do the following: Mark all the faults. Explain the reason for each fault. Indicate the sense of displacement on each fault.

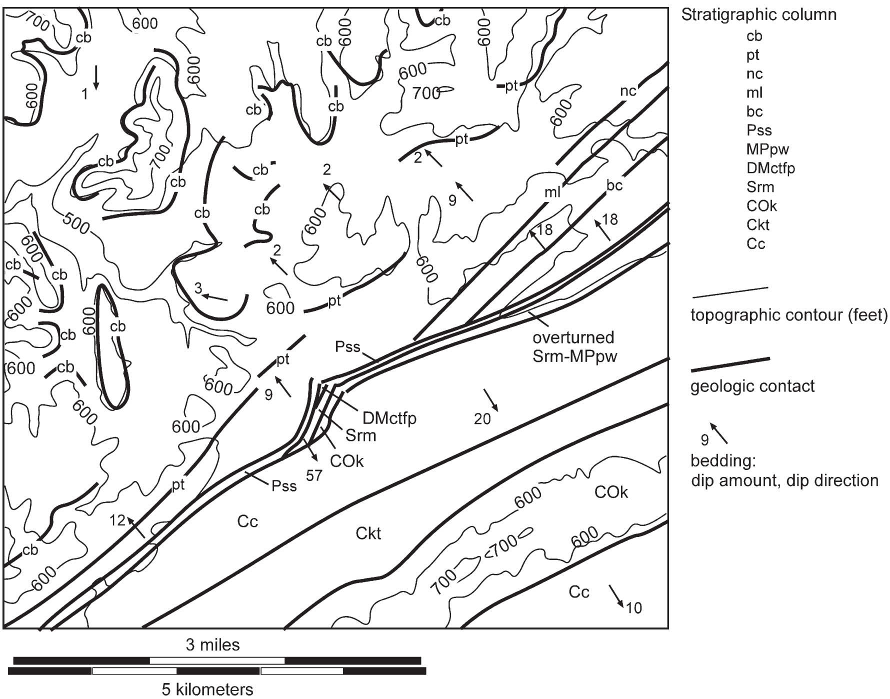

Fig. 7.36. Geologic map of the Ensley area, Alabama, with fault contacts not marked. (After Butts 1910; Kidd 1979)

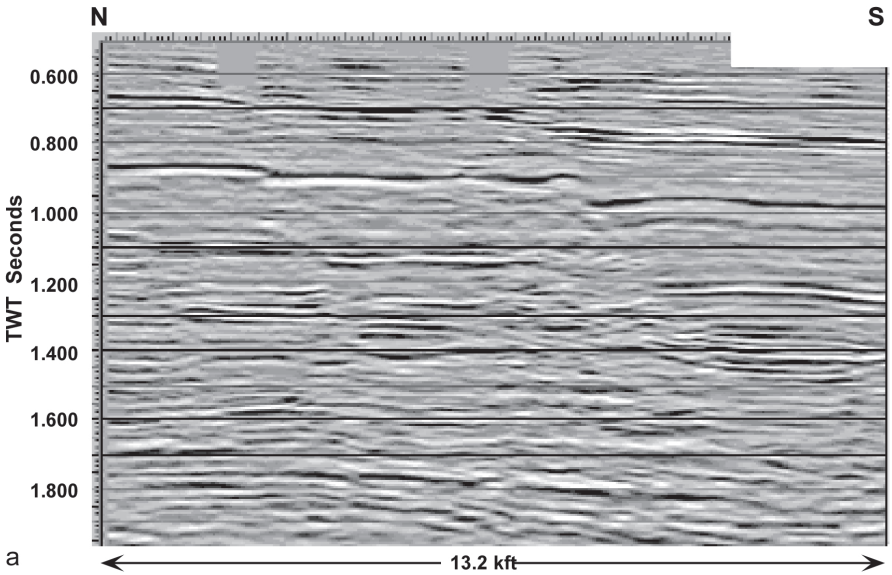

Fig. 7.37. Seismic line across part of Gilbertown graben system, Alabama (modified from Groshong et al. 2003a). V.E. approximately 1 : 1

7.8.2 Fault Recognition on a Seismic Line 1

Interpret the faults in Fig. 7.37.

7.8.3 Fault Recognition on a Seismic Line 2

Interpret the faults and unconformity in Fig. 7.38.

7.8.4 Finding Fault Cuts

Locate the position of the faults and the amounts of the fault cuts on the logs from the northern Gulf of Mexico (Fig. 7.40) based on the type log in Fig. 7.39. Example courtesy of Jack Pashin (Pashin et al. 2000).

7.8.5 Correlating Fault Cuts

Contour a fault (Fig. 7.41) that includes all four wells that cut faults. Is the fault surface obtained reasonable? What is the attitude of the fault plane given by the three

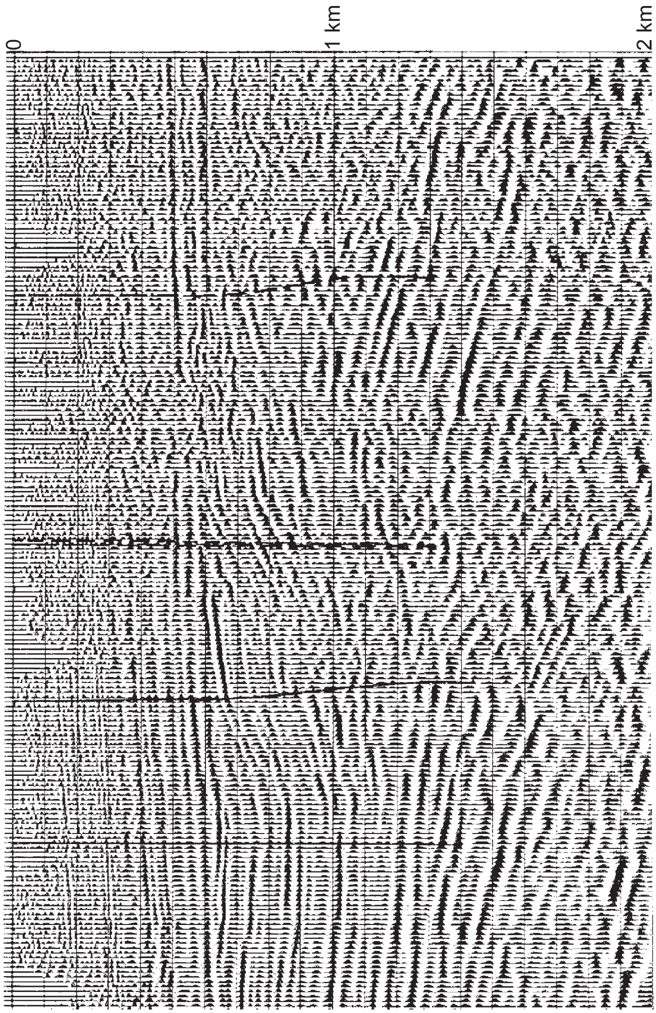

Fig. 7.38.
Seismic reflection profile from the Ruhr district, Germany. (Drozdzewski 1983)

points 1, 4, 2? What is the attitude of the fault plane given by the three points 2, 3, 4? What is the attitude of a fault plane through wells 1, 2, and 3? Is this a possible fault plane? Why or why not?

7.8.6
Estimating Fault Offset

Use Table 7.1 to answer the following questions. A fault in the Black Warrior basin of Alabama has a maximum displacement of 100 m. How long is it? What is the length range if the fault is a thrust in the Canadian Rocky Mountains? A fault in the Black

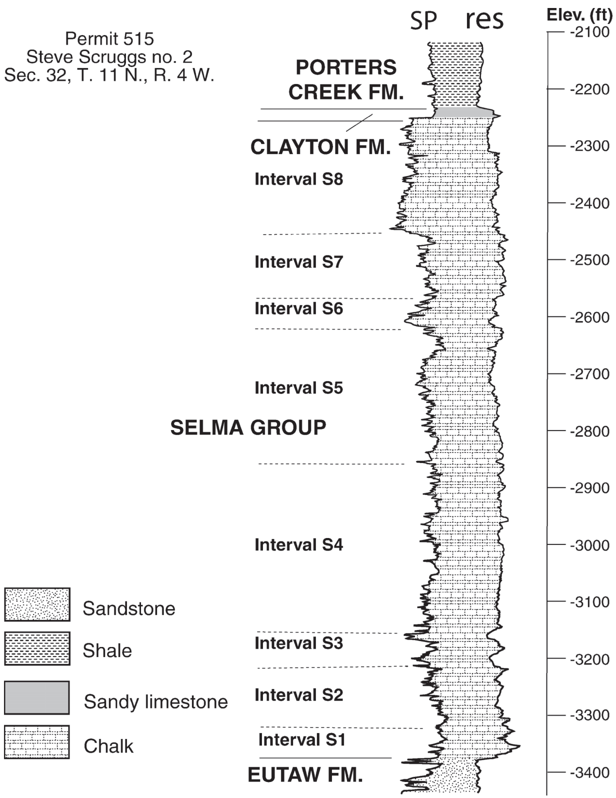

Fig. 7.39. Unfaulted type log of Selma Chalk, Gilbertown oil field

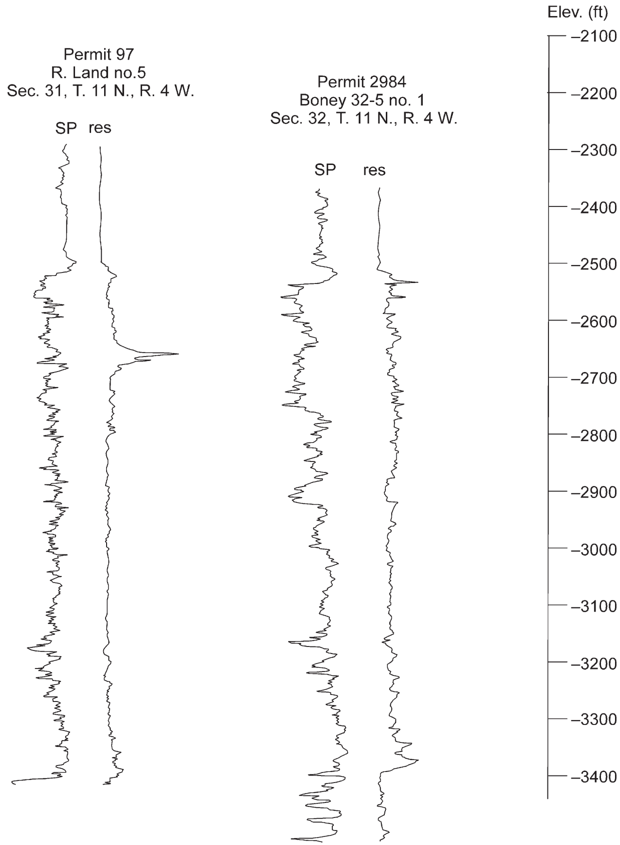

Fig. 7.40. Logs of two faulted wells in Selma Chalk, Gilbertown oil field

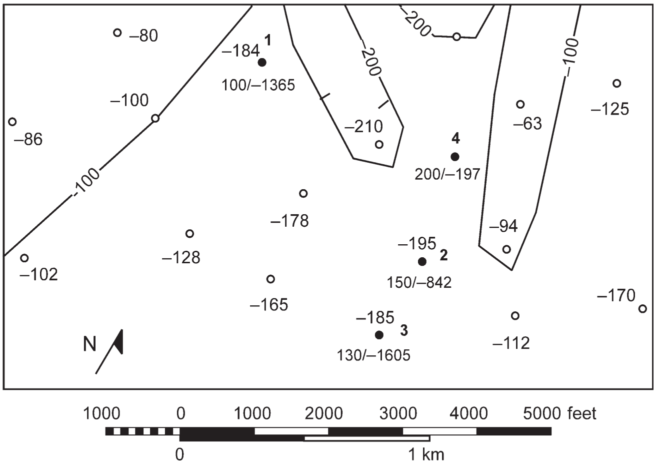

Fig. 7.41.
Map of the southern portion of the Deerlick Creek coalbed methane field. *Open circles* are wells with the elevation of the top of the Gwin coal cycle (ft). *Solid circles* are wells with fault cuts; single number is top of Gwin if present, number pair is stratigraphic separation/elevation of fault cut. Structure contours shown on the top of the Gwin are tentative. Elevations below sea level are negative

Table 7.2. Fault attitude and separation data

Fault attitude	Stratigraphic separation	HW attitude	FW attitude	Fault cut in	ρ	Heave	Throw	Vertical separation
60, 270	100	0	0					
60, 270	100	20, 070	30, 200	HW				
				FW				
30, 200	100	0	0					
30, 200	100	20, 070	30, 070	HW				
				FW				

Warrior basin is 5 kft long. What is its probable maximum displacement? What is the displacement range if the fault is a normal fault in the western United States?

7.8.7
Fault Offset

Find the heave, throw, and vertical separation for the faults listed in Table 7.2.

7.8.8
Growth Faults

Determine the expansion indices across both faults in Fig. 7.42. Discuss the growth of the faults and the relationship of growth to the hydrocarbon occurrence.

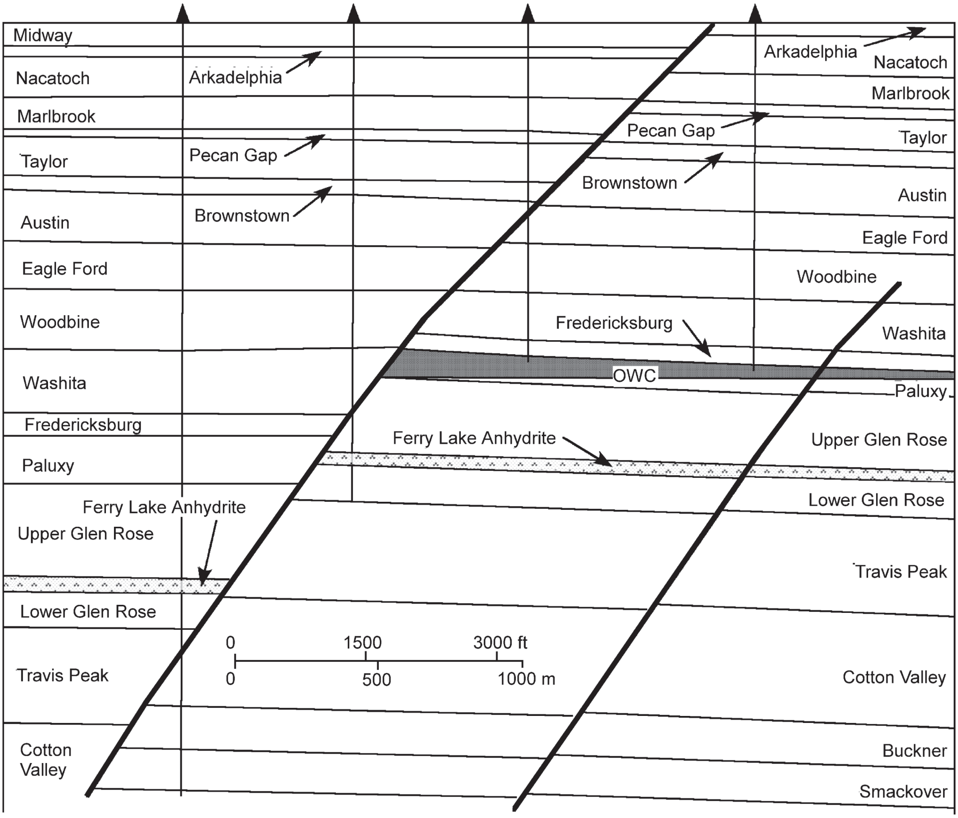

Fig. 7.42. Cross section of the Talco field, northern Gulf of Mexico, Texas. Oil field *shaded; OWC:* oil-water contact. (After Galloway et al. 1983)