15

Construction of Balanced Cross Sections

Objectives

- **Determine the relationship between the shapes of folds exposed at the earth's surface and the types of faults in the subsurface that produced these folds.**
- **Evaluate existing cross sections for balance.**
- **Construct retrodeformable, balanced cross sections in fold-thrust belts.**

A geologic cross section depicts subsurface geology along a vertical profile. Cross sections are constructed from geologic maps, well data, seismic lines, and other geophysical data. Typically, a geologist can draw different cross sections that satisfy the available, and usually limited, data. This chapter introduces you to the construction of balanced, or restorable, cross sections. These techniques will help you draw cross sections that are geologically reasonable, and they will also help you evaluate published cross sections. Our discussion is limited to thrust belts, where the concepts of balanced cross sections were first developed and where the structural style is well understood. A different set of techniques is needed to balance cross sections in regions of extension.

Thrust-belt "rules"

Research in many thrust belts has revealed several recurring characteristics that can be synthesized into the following set of "rules" regarding the geometry and orientation of thrust faults. As with most rules in geology, there are notable exceptions and variations; hence, these "rules" should be treated as guidelines only.

Rule 1 Thrust faults follow a staircase trajectory marked by *flats* and *ramps*. Flats occur where a fault lies at a specific stratigraphic horizon for a great distance. Ramps occur where a fault cuts across stratigraphic contacts over a short distance (Fig. 15.1a); they usually dip at angles of less than 30°.

Rule 2 Thrusts cut up section, most commonly in the direction of tectonic transport (left to right in Fig. 15.1b).

Rule 3 The conditions that promote thrust faulting often result in the creation of multiple thrusts. The thrust system commonly propagates in the direction of slip; that is, new thrusts tend to form "in front of" or toward the *foreland* of existing thrusts. For this reason, thrusts tend to be progressively younger in the direction of tectonic transport (toward the foreland). However, "out-of-sequence" thrusts (younger faults that developed behind earlier

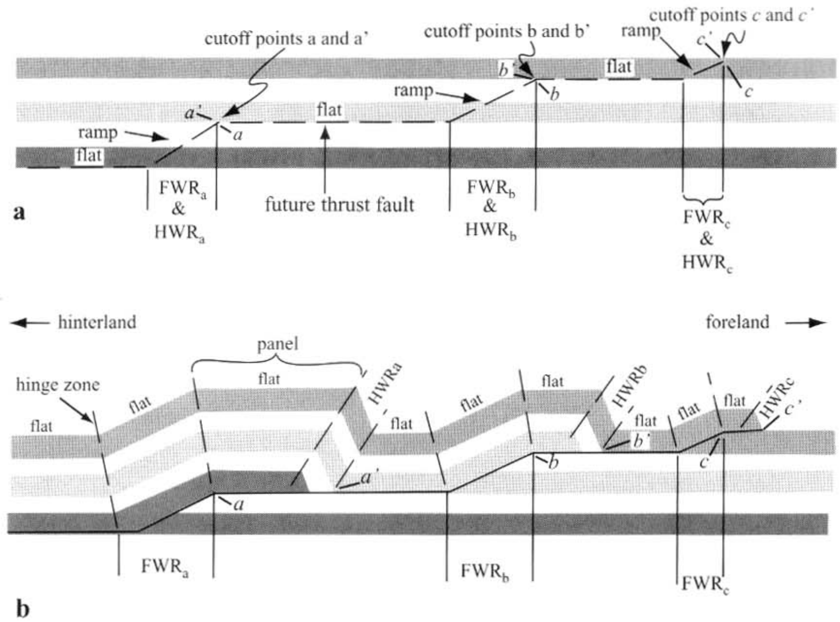

Fig. 15.1 Schematic cross section showing typical elements of thrust terranes. (a) Pre-deformation cross section showing ramp-and-flat geometry of future thrust fault (dashed line). Letters *a*, *b*, and *c* show the positions of future footwall cutoffs at the tops of footwall ramps; *a'*, *b'*, and *c'* show the positions of future hanging-wall cutoffs at the tops of hanging-wall ramps. (b) Deformed-state cross section showing the relation of folds to thrust ramps and the new positions of hanging-wall cutoffs. Dashed lines are fold axial traces; FWR, footwall ramp; HWR, hanging-wall ramp. Notice that for each hanging-wall cutoff there is a corresponding footwall cutoff.

formed thrusts) have been recognized in many thrust belts and often play an important role in the evolution and movement history of thrust belts.

Rule 4 Net slip along a thrust cannot increase upward. But it can decrease upward, provided that shortening is accommodated by folding or imbricate faulting.

Rule 5 Thrusts may terminate upward, without reaching the earth's surface. Such faults are called *blind thrusts*, and they terminate in asymmetric folds. Thrusts that reach the surface are referred to as *emergent thrusts*.

Recognizing ramps and flats

Thrust sheets are typically characterized by kink folds, which consist of "panels" and "hinges." A panel is a portion of the hanging wall in which the bedding attitude is more or less constant over a large area. A hinge, or hinge zone, is the narrow zone between adjacent panels (Fig. 15.1b).

Carefully examine Fig. 15.1a and b; note the geometry of the thrust, paying particular attention to the geometry of the folds in the upper plate (hanging wall). Find point *a* on both diagrams. It is the point in the footwall where the upper surface of the lower white bed has been cut by the thrust. Such a point is called a *cutoff point*. In three dimensions a cutoff point is a line, called a *cutoff line*.

Now find point *a'* on Fig. 15.1a and b. Prior to faulting, cutoff points a and *a'* lay adjacent to one another. Cutoff points *a*, *b*, and *c* all lie in the footwall, and each has a corresponding displaced point, *a'*, *b'*, and *c'*, in the hanging wall.

Notice in Fig. 15.1 that this thrust has three footwall ramps, labeled FWR$_a$, FWR$_b$, and FWR$_c$. Footwall ramps are recognizable as portions of the lower plate (footwall) containing strata that have been diagonally truncated. Each footwall ramp must have a corresponding ramp in the hanging wall of the thrust.

Hanging-wall ramps and flats are defined by their positions *relative to bedding*. Ramps occur where the thrust fault cuts across bedding; flats are present where the thrust is parallel to bedding. For example, hanging-wall ramp HWR$_a$, which corresponds to FWR$_a$, is recognizable as the panel in the hanging wall in which the same strata that are diagonally truncated in FWR$_a$ are truncated in the direction of tectonic transport. Strata in hanging-wall-ramp panels typically dip in the direction of tectonic transport (toward the *foreland*). Examine

Fig. 15.1b, and be sure you understand why HWR_a is identifiable as the portion of the hanging wall that lay adjacent to FWR_a prior to faulting.

Flats are the panels between ramp panels. They do not contain truncated strata, either in the hanging wall or in the footwall. Displacement along the thrust fault may result in a hanging-wall flat coming to lie either parallel to bedding in the footwall or at an angle to bedding in the footwall. In the latter case, the bedding in the hanging wall typically dips in the direction opposite to the direction of tectonic transport (toward the *hinterland*) (Fig. 15.1b). It is important to remember that hanging-wall flats do not have to be horizontal, but they do not contain truncated strata. In Fig. 15.1b, all of the panels in the hanging wall that lie between hanging-wall-ramp panels are flats.

For each footwall flat there must be a corresponding hanging-wall flat, and both flats must be the same length. However, due to deformation of the hanging wall, a particular footwall segment may correspond to two or more adjacent panels in the hanging wall. Similarly, each hanging-wall ramp must have a corresponding footwall ramp of equal length. This is known as the "template" constraint.

The most important feature is the relationship between the fault and stratigraphy. If the fault stays at the same stratigraphic horizon in either the footwall or the hanging wall, then that portion of the footwall or hanging wall is a flat. If the fault cuts stratigraphically upward, then that portion of the hanging wall or footwall in which this occurs is a ramp.

Relations between folds and thrusts

Research in thrust belts has shown that most folds are ultimately generated by fault movement at depth. There is a systematic and predictable geometric relation between a fold and the thrust that generated it. Thus, we can use the geometry of an exposed fold to infer the position and geometry of a fault at depth. The kink-like character of folds in thrust belts can be generalized in cross-section construction by use of the "kink-fold" method, which is described below. This method, developed in the early 1980s by John Suppe of Princeton University, assumes that the folds are produced by a flexure-slip mechanism so that bed thickness does not change. This assumption of constant bed thickness will be taken for granted throughout this chapter, but it must be established for each individual geologic situation.

Another assumption of the kink-fold method is that the footwall remains undeformed during the formation of folds in the hanging wall. This assumption is a necessary simplification of the real world; the relatively common occurrence of footwall synclines in thrust belts indicates that it is not exactly correct. If footwall folds are present in an area, they must be shown on the cross section, but they can be added after the kink-fold method has been applied.

Many folds in thrust belts are associated with underlying thrust ramps. Two types of ramp-related folds are the most common. These are *fault-bend folds* and *fault-propagation folds*, each of which is described below.

Fault-bend folds

Fault-bend folds occur where a thrust fault steps up from a structurally lower flat to a higher flat. The folds in the hanging wall of Fig. 15.1b are all fault-bend folds. Figure G-44 (Appendix G) contains a series of drawings that can be cut up and compiled into a flipbook, permitting you to observe the evolution of a fault-bend fold and compare it with a fault-propagation fold.

Figure 15.2 shows the evolution of a fault-bend fold. Initially, two kink bands form in the hanging wall, one above the base of the ramp, and the other above the top of the ramp (Fig. 15.2a). With continued slip on the fault, these two kink bands grow in width (Fig. 15.2b). As the truncated hanging wall moves up the ramp, and the two kink bands widen, an anticline forms at the top of the ramp. This anticline terminates downward into the upper flat (Fig. 15.2c). The ramp anticline grows in amplitude as the kink bands grow in width. Meanwhile, one syncline develops at the base of the ramp, and another develops on the foreland-side of the anticline (Fig. 15.2c). Note that the ramp height determines the amplitude of the fold, which, in turn, determines the structural relief.

Notice that throughout the development of a fault-bend fold, axial traces A and B coincide with the top and bottom of the ramp, respectively, and the hanging wall "rolls" through these hinges as it traverses the ramp. The other two axial traces (A′ and B′) migrate along the fault, but they are fixed with respect to the rocks in the hanging wall.

When the cutoff point of the lowest stratigraphic unit in the upper plate reaches the upper flat (Fig. 15.2c), the fold ceases to grow in amplitude, but the distance between the axial traces of the ramp anticline (A and B′ in Fig. 15.2c) increases with increasing displacement. In a fully developed fault-bend fold, axial traces A and A′

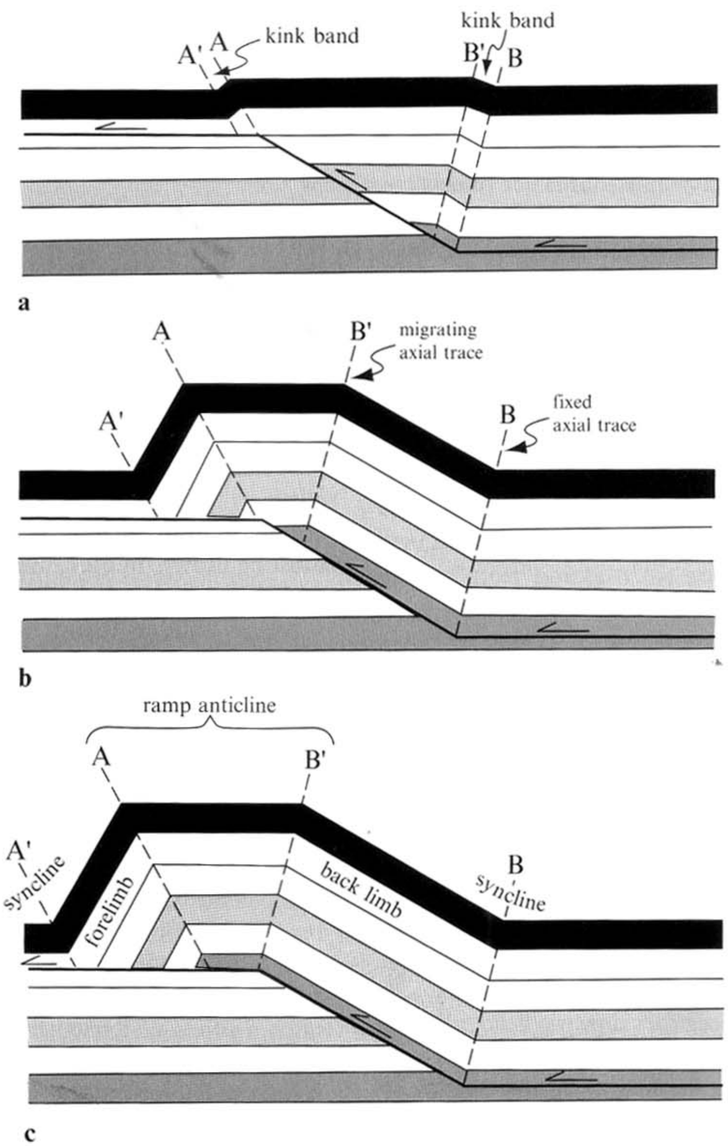

Fig. 15.2 Progressive development of a fault-bend fold as the thrust sheet moves over a ramp in a decollement (after Suppe, 1983). Letters A, A′, B, and B′ denote the axial traces.

are fixed with respect to the hanging-wall rocks, and they move along the flat with movement on the fault. Note that all fold axial traces bisect the interlimb angle of the fold, i.e., the angle between adjacent panels. Use the flipbook (Fig. G-44) to confirm these features of fault-bend folds.

Look at Fig. 15.2c again and note the following important relations between an exposed fault-bend fold and the associated thrust. These relations allow us to infer subsurface fault geometry from known fold shape.

1 In originally horizontal or gently dipping strata, the backlimb of the hanging-wall anticline always dips more gently than the forelimb.
2 The dip of the backlimb is equal to the dip of the ramp in all stages of fold growth.
3 The axial trace of the hanging-wall syncline (axial trace B) terminates at the base of the ramp.
4 In a fully developed fault-bend fold, the axial trace that separates the backlimb from the upper flat (axial trace B′) terminates at the top of the ramp.
5 For every hanging-wall cutoff there must be a corresponding footwall cutoff of equal stratigraphic thickness. This is the template constraint, discussed above.
6 For every hanging-wall flat there must be a corresponding footwall flat of equal length.

Fault-propagation folds

In a fault-propagation fold, rather than stepping from one flat to another, the fault simply dies out upward, into the axial surface of a syncline (Fig. 15.3). A fault-propagation fold is the surface expression of a blind thrust. Shortening above the fault terminus, or *fault tip*, is accommodated by folding. Use your flipbook (Fig. G-44) to compare the development of a fault-propagation fold with that of a fault-bend fold.

As is the case with fault-bend folds, there are several important relations between the exposed fault-propagation folds and the associated thrusts that allow us to infer fault geometry at depth. Note that in both types of folds the axial trace bisects the interlimb angle of the fold. This is the geometry required to preserve constant bed thickness.

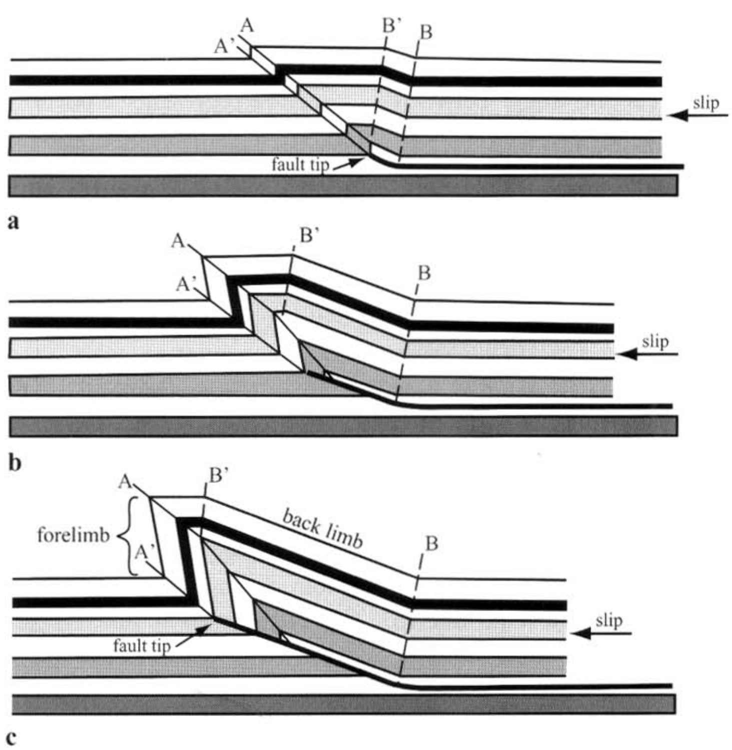

Fig. 15.3 Progressive development of a fault-propagation fold at the tip of a thrust, as the thrust sheet moves over a ramp in a decollement (from Suppe, 1983). Letters A, A′, B, and B′ denote the axial surfaces. Note that the fault tip coincides with the hinge of an asymmetric syncline.

1 In cases where the fault cuts originally horizontal (or gently dipping) strata (as in Fig. 15.3), the backlimb dips more gently than the forelimb. In general, fault-propagation folds are more strongly asymmetric than are fault-bend folds, and the forelimb of a fault-propagation fold is typically very steep to overturned (Fig. 15.3c). This characteristic alone is an important clue about the type of fold you are dealing with, especially in the absence of other information.
2 The dip of the backlimb is equal to the ramp angle.
3 The axial trace of the syncline that forms on the hinterland-side of the fold (axial trace B in Fig. 15.3) terminates at the base of the ramp.
4 The thrust terminates in an asymmetric syncline that forms on the foreland side of the structure. The fault tip lies at the intersection of the synclinal axial surface and the thrust ramp (Fig. 15.3c).
5 The fault-propagation model of fold formation explains why box folds commonly reduce to simple chevron folds in their cores. The two axial traces of a box-like fold (A and B′ of Fig. 15.3c) bound a flat panel that separates the backlimb from the forelimb of the anticline. The stratigraphic horizon at which the fault terminates is the same stratigraphic horizon at which the two axial traces merge to form a single axial trace (Fig. 15.3c). This single axial trace bisects the angle between the fold forelimb and fold backlimb (Fig. 15.3c). Cool, isn't it!

Requirements of a balanced cross section

For a cross section to be valid, certain assumptions inherent in its construction must be valid. A fundamental assumption is that rock *volume* (displayed as area in a two-dimensional cross section) is conserved during deformation; that is, deformation approximates *plane strain* and simply redistributes rock volume in the two-dimensional cross-section profile. This assumption will not be justified if volume loss has occurred (e.g., due to pressure solution accompanying cleavage development) or if there is movement of material in or out of the cross section. This latter situation can occur if oblique slip occurs along the thrust faults, if strike-slip faults intersect the cross-section line, or if the line of section is oblique to the principal movement direction. In order for the techniques described in this chapter to be applicable in a particular situation, the validity of the conservation-of-volume assumption must be demonstrated. The methodologies for testing this assumption are beyond the scope of this book; references are provided at the end of the book.

Within any given region, specific types of structures, and associations of structures, are characteristic. A geologically reasonable cross section must honor the structural style of the region. For example, uniformly verging asymmetric folds are characteristic of thrust belts. A cross section that honors this constraint is said to be *admissible* (Elliott, 1983). In addition, the cross section must be restorable, or *retrodeformable*. This means that if all of the shortening represented by the faults and folds is removed, the layers should restore to a reasonable predeformational configuration, without large gaps or overlaps in strata. A cross section that can be restored to a reasonable predeformational configuration is said to be *viable*. A *balanced cross section* must be both admissible and viable. Note that there may be several viable solutions to a given data set. Just because a cross section is balanced does not mean it is correct. However, if it is not balanced, it cannot be correct, assuming plane strain and no volume change.

Examine Fig. 15.4a, which is a simple example of a cross section that is *not* balanced. If this cross section represents a portion of a thrust belt, with tectonic transport from left to right, it is an admissible cross section. But is it restorable (and therefore viable)? To test this, imagine sliding the hanging wall back down the thrust fault until layer 1 in the hanging wall connects with layer 1 in the footwall. As shown in Fig. 15.4b, when we do that, there is an overlap of layer 2. If the hanging wall is slid back to the point at which layer 2 in the hanging wall connects with layer 2 in the footwall, there is a gap in layer 1 (Fig. 15.4c). Therefore, this is not a viable cross section; it is not balanced.

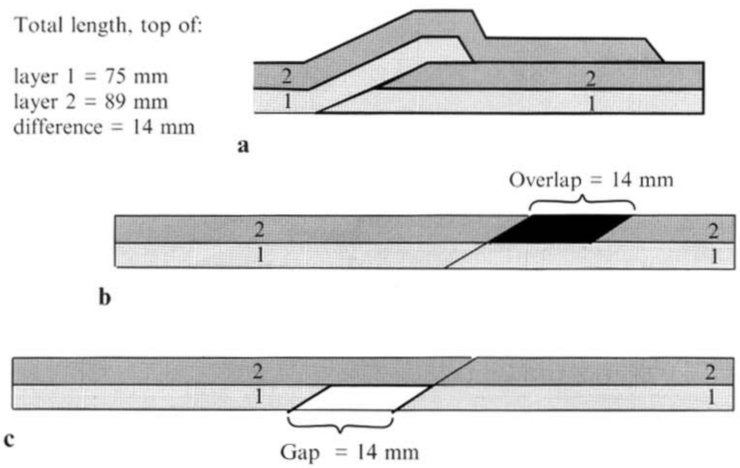

Fig. 15.4 Unbalanced cross section. (a) Deformed-state cross section. (b) The removal of the slip along a thrust to restore bed 1 to its predeformational configuration does not produce a reasonable predeformational restoration of bed 2, but results in an "excess" or overlap of bed 2. (c) The restoration of bed 2 to a reasonable configuration results in a "deficiency" of bed 1, creating a gap. Thus, the deformed-state cross section is not viable.

Constructing a restored cross section

If the assumptions discussed above are valid, then a deformed cross section should restore to an undeformed section of equivalent area. A cross section can be tested for balance by measuring areas in both the deformed and restored states. Where map units show consistent thicknesses over the distance of the cross section, the *bed length* will be proportional to the area (i.e., area = bed length × thickness; if thickness is constant, area is proportional to bed length). Therefore, in regions of constant unit thickness we can simply measure bed lengths in deformed and restored (undeformed) cross sections. If the cross section is balanced, the bed lengths will be equal, or nearly so. We will focus exclusively on bed-length balancing in this chapter.

Here are the steps for evaluating whether a cross section is balanced:

1 Draw a regional *pin line* on the deformed cross section (Fig. 15.5a). This is a vertical line drawn on the foreland side of the cross section that will serve as a reference marker from which the bed lengths will be measured. Typically, a regional pin line is chosen in an area of no interbed slip such as a point beyond the limits of thrusting or in a fixed fold hinge. In Fig. 15.5a the pin line is drawn to the left of the leftmost thrust.
2 Draw another line, called the *loose line*, perpendicular to bedding on the hinterland side of the deformed cross section (Fig. 15.5a).
3 Begin the construction of the restored cross section by drawing a series of horizontal, parallel lines representing the regional stratigraphic sequence, as in Fig. 15.5b. The spacing between the lines must be proportional to the thicknesses of the units. This regional stratigraphic sequence will serve as the template for the restored cross section.
4 On the deformed cross section (Fig. 15.5a), measure the length of each stratigraphic unit, from the pin line to the loose line. Measure the top and bottom (or center) of each unit, and record the length within each panel. Determine the total length of each bed, and also the distance from the pin line to each cutoff point, where a bed has been truncated by the fault.
5 Transfer the bed-length measurements from the deformed section to the restored section. Use the bed lengths from the pin line to each cutoff point to determine where to draw the fault on the restored section.
6 On the restored section, connect the cutoff points with a dashed line to indicate the prethrusting configuration of the fault (Fig. 15.5b).

If the cross section is balanced, all of the bed lengths in the restored sections will be equal within 5–10% of each other, depending upon the complexities of geology and the validity of the assumptions discussed above for that particular cross section. Figure 15.5c is an example of a restored cross section in which the bed lengths

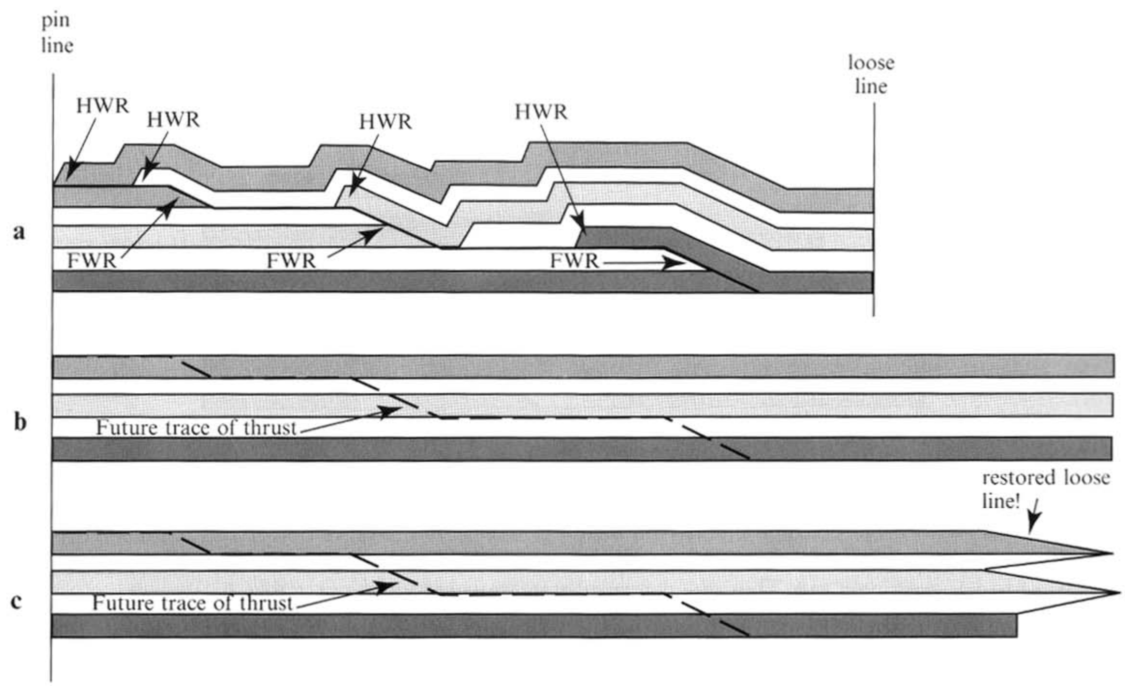

Fig. 15.5 (a) Deformed-state cross section. (b) Stratigraphic "template." (c) Undeformed-state cross section restored by measuring the bed lengths at the top and bottom of each unit. Note that the bed lengths are not consistent, hence the section does not balance. Notice also that the section does not obey the template constraint. FWR, footwall ramp; HWR, hanging-wall ramp.

are not equal; the corresponding deformed cross section, therefore, is not balanced.

Several features can also be used to inspect a cross section for problems without actually measuring each bed length. For example, the cross section shown in Fig. 15.5a contains several serious errors that indicate, at a glance, that it cannot be balanced. Specifically, there are four hanging-wall ramps (labeled HWR), but only three footwall ramps (FWR). Thus, the section violates the template constraint. Another problem is that the hanging-wall flats are not the same length as the footwall flats. Recall that each hanging-wall ramp or flat must have a corresponding footwall ramp or flat. Although application of these principles may seem overwhelming at first, a bit of practice will train your eye to recognize inconsistencies such as those just described; they occur in many published cross sections.

Once a restored cross section is constructed, the amount of net shortening can be determined by the equation:

$$[(l_d - l_u)/l_u] \times 100\%$$

where l_u is the bed length in the undeformed state, and l_d is the bed length in the deformed state. For thrust belts, this equation will yield a negative number, which indicates percent shortening.

Constructing a balanced cross section

Having learned to critique cross sections drawn by others, you are now ready to draw your own. When deciding the best place on a geologic map to draw a cross section, remember that it must be drawn parallel to the tectonic transport direction. Cross-section lines that are oriented more than 5–10° from parallel to the tectonic transport direction may not restore to a reasonable predeformational configuration. In thrust belts, one should choose a line of section that is perpendicular to the regional strike of the major thrust faults and also perpendicular to the trend of the major fold axes. Avoid lateral ramps (those that are approximately parallel to the transport direction) or areas near tear faults.

After you have: (1) constructed the topographic profile along the line of section, (2) transferred the strikes and dips from the geological maps, and (3) incorporated any well-log data onto the cross section, the chances are you will still be confronted with a lot of "blank space" on your cross-section diagram where you have no data to guide you. It is your task to infer the structure at depth to fill up the blank paper. This is where you earn the big bucks that the oil company is paying you. Fortunately, a few simple rules and techniques can help you in this effort. Recall that in thrust belts, folds bear systematic and predictable geometric relations to the thrusts that generate them. Therefore, you can use the shapes of folds to infer fault position and orientation at depth, as indicated in the following procedure.

1 Define panels of constant dip. Project all contacts into the "air" and into the subsurface. But do not project faults to depth just yet!
2 Determine the orientations of axial traces of folds. This is done by constructing bisectors of adjacent dip panels. The axial surface of a concentric fold bisects the interlimb angle. For example, if the interlimb angle of a fold is 150°, in a cross-section diagram the axial trace would be shown as a dashed line that lies at 75° to each fold limb or panel.
3 Project folds to depth, or into the "air" where eroded. Where two axial traces merge downward, as in a box fold, the result is a single hinge that bisects the chevron fold (recall that box folds reduce to chevron folds in their cores, as in Fig. 15.3). Construct a new axial trace that bisects the limbs of the chevron fold.
4 Determine which of the two types of ramp-related folds is probably present (fault bend or fault propagation). If there is evidence that the fault ramps up from a lower to an upper flat, then the fold is a fault-bend fold. If the evidence suggests that the fault dies out into an asymmetric syncline, a fault-propagation fold is indicated. The presence of an overturned limb is evidence of a fault-propagation fold. If data are insufficient to choose between the two possibilities, you may have to construct both fold types and select the solution that best honors the available geologic data.
5 When you are working on the exercises at the end of this chapter, refer freely to Figs 15.2 and 15.3 and the discussions of fold characteristics that accompany those figures.