CHAPTER

6 Thrust Faults

Thrust faults and reverse faults are dip-slip faults on which the hanging wall block has moved up relative to the footwall block (Figure 4.10*A*). Generally, older rocks are emplaced over younger rocks, and in a vertical section through the fault, stratigraphic section is duplicated. These faults accommodate shortening of the Earth's crust. Reverse faults have dips greater than 45°, whereas thrust faults dip less than 45°. We limit our discussion to thrust faults, because they are much more abundant than reverse faults.

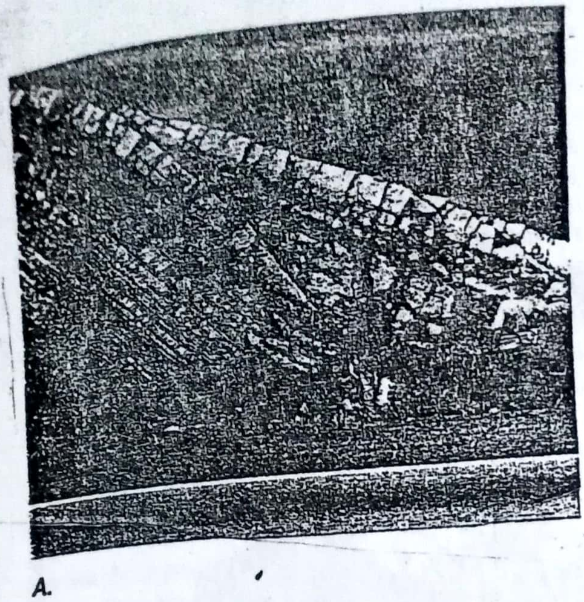
Thrust faults exist at all scales. They range from small ones with extents and displacements on the order of millimeters to meters (Figure 6.1*A*), through major low-angle thrusts at the scale of mountain ranges that show displacements on the order of tens to hundreds of kilometers (Figure 6.1*B*), up to global-scale features such as convergent plate margins. The latter are enormous, complex zones of thrust faults that have total displacements as large as thousands of kilometers.

A hanging wall block above a very low-angle thrust commonly has an areal extent that is large compared with its thickness and therefore is called a thrust sheet or a nappe (the French word *nappe* means "sheet"). A thrust sheet that has moved a large distance and is thus geologically out of place is an allochthon, and the rocks within it are said to be allochthonous (from the two Greek words *allo*, which means "other," and *chthonos*, which means "ground" or "earth"). A large region of rock that has not been moved and is close to its original location, such as the basement rocks in the footwall block of a thrust, is an autochthon, and the rocks within it are autochthonous (the Greek word *auto* means "this"). Figure 6.1*B* is a photo of the Keystone thrust in southern Nevada. The irregular dark/light contact is the trace of the low-angle thrust fault, which dips gently to the west (left) and is cut by irregular topography. The light rocks forming the cliff are autochthonous Jurassic Aztec sandstones, whereas the overlying dark rocks are allochthonous Paleozoic sequence that extends from lower Paleozoic at the fault to upper Paleozoic in the snow-covered peaks in the background. These rocks have moved up to 20 km on the thrust fault.

6.1 Recognition of Thrust Faults

Most thrust fault surfaces exhibit structures formed either by brittle or ductile deformation. The deformation features intrinsic to faults, as well as other features associated with them, are discussed in Section 4.2. In this section, we confine our discussion to stratigraphic characteristics that are unique to thrust faults.

Thrust faults characteristically emplace older rocks on top of younger rocks. On a vertical section through


A.

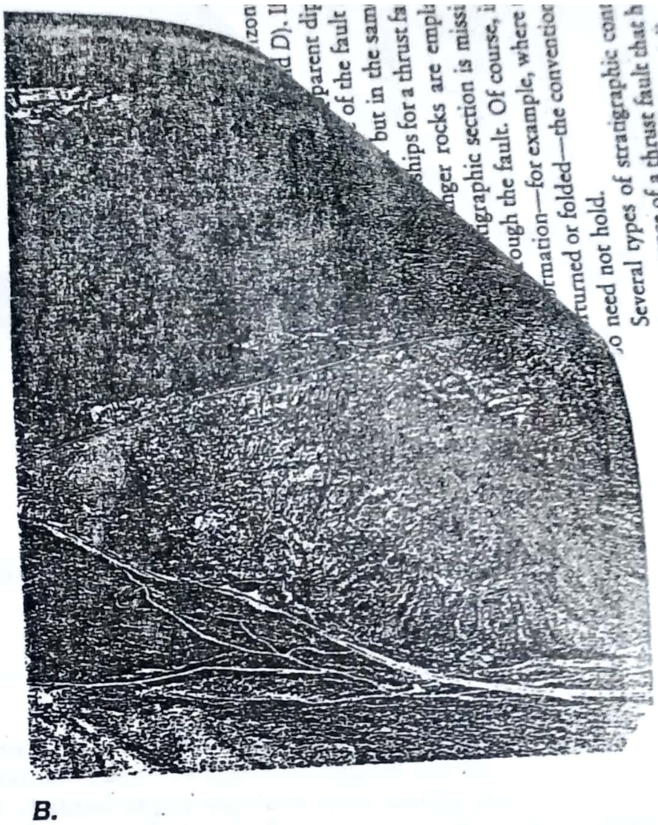

B.

Figure 6.1 The geometry and expression of thrust faults at different scales. *A.* Thrust fault cutting carbonate strata, Valley and Ridge province of the Appalachian Mountains, Tennessee. *B.* The Keystone thrust, southern Nevada.

a thrust fault, stratigraphic section is generally duplicated (Figure 6.2; compare Figures 4.10*A* and 6.1*B*).

The horizontal separation across a thrust fault can be variable, depending on the attitude of the layers before faulting, as illustrated in Figure 6.2. Each pair of block diagrams shows the results of thrust faulting of upright stratified rocks that have a particular orientation relative to the fault. The left of each pair of block diagrams shows the hanging wall block suspended over the footwall block, and the right diagram shows the same structure with the hanging wall block eroded down to the same level as the footwall block. The separations on either the horizontal surface or the vertical section do not define uniquely the displacement on the fault. In all the diagrams, however, a vertical section through the fault shows the duplication of stratigraphy with older rocks resting on top of younger rocks across the fault. Different orientations of the layers with respect

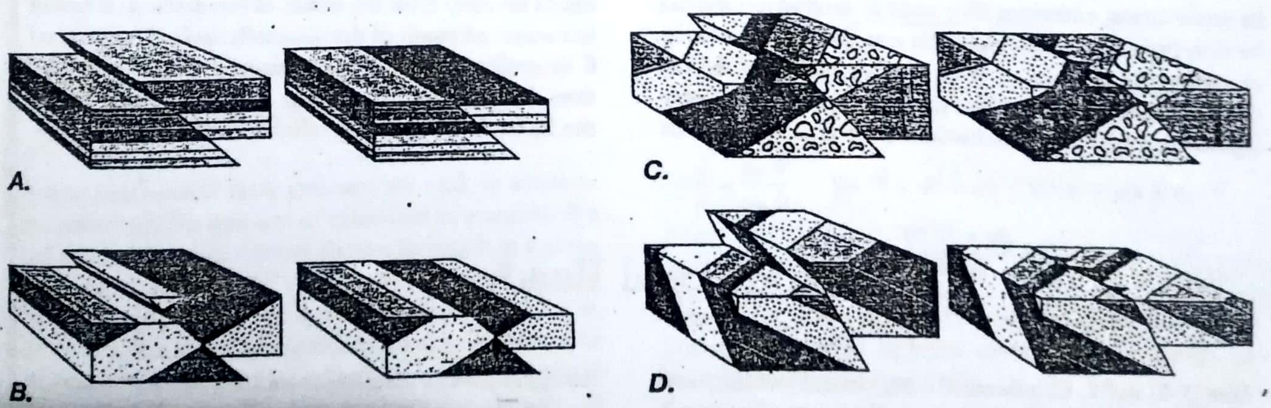


Figure 6.2 The effect of the dip of strata on the separations developed as a result of thrust faulting. The right diagram of each pair shows the hanging wall block eroded down to the same level as the footwall block. On the top surfaces (map views), *A* shows a simple discontinuity, *B* shows the cutting out of strata, and *C* and *D* show left and right lateral separations, respectively.

t horizontal separations
C and *D*). If, however, the
ir apparent dips on a vertical
trike of the fault are larger than
itself but in the same direction, the
tionships for a thrust fault do not hold.
, younger rocks are emplaced on top of
stratigraphic section is missing along a ver-
e through the fault. Of course, in areas of com-
deformation—for example, where the stratigraphy
overturned or folded—the conventional relationships
also need not hold.

Several types of stratigraphic contrasts may indicate the presence of a thrust fault that has displaced the hanging wall block from substantially deeper levels or large horizontal distances from its final location.

Plutonic or high-grade metamorphic rocks are generally associated with deeper structural levels than unmetamorphosed or low-grade rocks. Thus if plutonic or high-grade metamorphic rocks overlie low-grade or unmetamorphosed sedimentary rocks, the normal structural sequence is inverted, suggesting that thrusting has occurred.

Some thrust faults separate stratigraphic sequences of essentially the same age but of markedly different sedimentary facies. Thrust faults of this nature commonly emplace allochthonous rocks of oceanic or deep-water environments, usually shales, cherts, and/or oceanic crustal rocks, on top of autochthonous shallow-water deposits such as limestones and sandstones or even rocks of continental origin. The striking discontinuity in the sedimentary environments suggests that the contact between the two sequences is a thrust fault of large displacement.

In some cases, highly deformed allochthonous rocks overlie slightly deformed or undeformed autochthonous rocks. If, for example, the rocks above and below the fault are the same stratigraphic layers, but those above are deformed by folds and those below are not, a thrust fault probably separates the two sequences.

All these criteria are only general indicators: Each pattern conceivably could form in some other fashion, for example, from a sequence of two or more episodes of deformation. The possibility of such structural complications means that we must pay careful attention to stratigraphic sequence and to evidence for sedimentary environment, conditions of igneous crystallization, and conditions of metamorphism. The geologic literature contains many examples of egregious errors committed by conscientious geologists who, when mapping a region, failed to take adequate account of these factors.

6.2 Shape and Displacement of Thrust Faults

✓ *Shape of Thrust Faults*

Many map traces of thrust faults are highly irregular, a feature that results either from the intersection of a shallow-dipping fault with the irregularities of topography (Figure 6.1*B*) or from folding of the fault surface. In some cases, an irregular fault surface may reflect the original path cut by the fault through the stratigraphy.

At depth, thrust faults generally are listric faults that curve toward shallow or horizontal dips (see Figure 6.12). Some faults continue at a dip of roughly 30° through most of the crust (Figure 6.3). Others become steeper with depth, such as where they accommodate

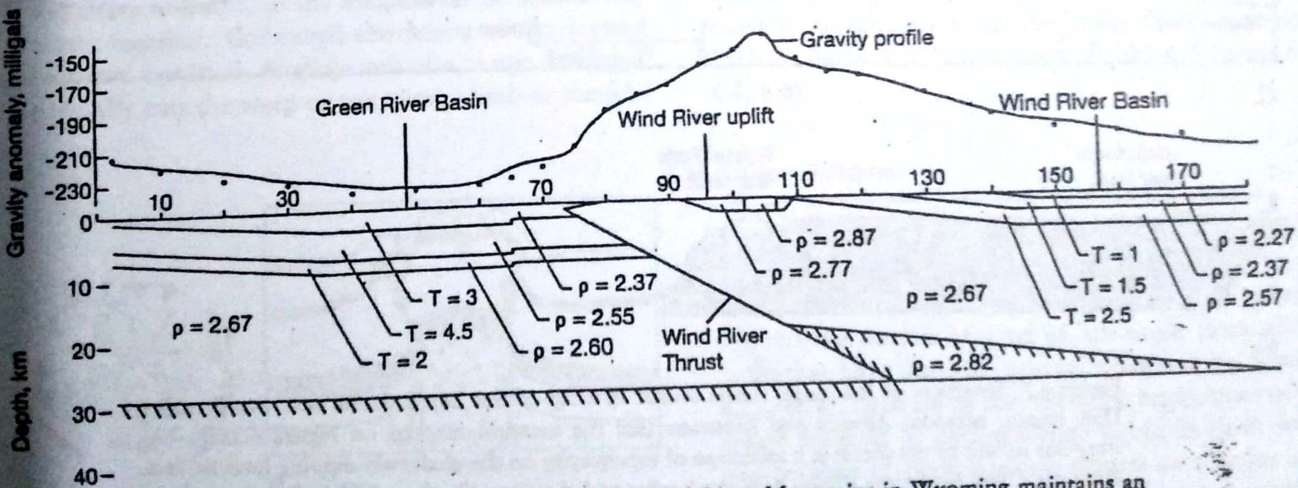


Figure 6.3 The Wind River thrust under the Wind River Mountains in Wyoming maintains an almost constant angle through the entire crust. This gravity model has been constrained by seismic reflection data. Values of T and ρ are, respectively, the thicknesses (in kilometers) and densities (in grams per cubic centimeter) of the different layers. On the gravity profile, dots are measured values of the gravity anomaly, and the solid line is the anomaly computed from the model.

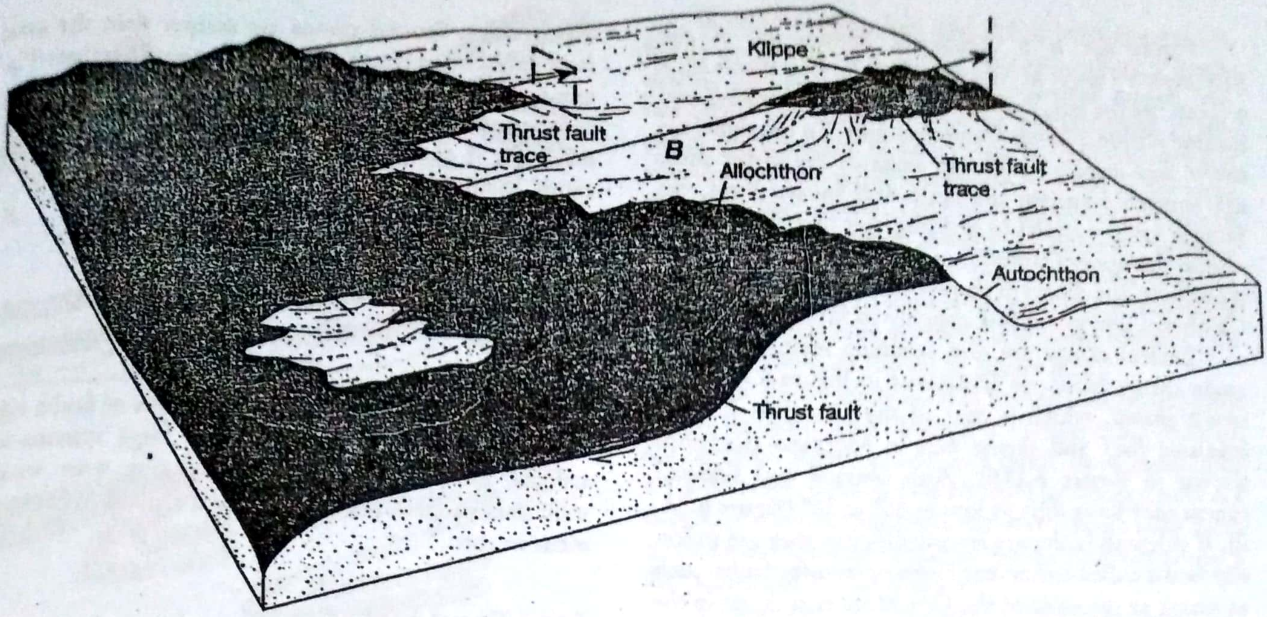


Figure 6.4 Block diagram illustrating a thrust surface, thrust sheet, thrust fault trace, window or fenster, klippe, allochthon, autochthon, and conventional thrust symbol with teeth on the hanging wall side. Minimum constraints on the displacement are given by *A* the sinuosity of the thrust fault trace and *B* the distance from the back of the window to the front of the klippe.

compression at a jog in a strike-slip fault (see Section 7.2; Figures 7.7*C*, 7.8*B*) or where they end against an upward moving intrusion (see Figure 6.9*B*).

Erosion of a thrust sheet that lies above a shallowly dipping fault commonly leaves an isolated remnant of the allochthon, a klippe, resting on the lower plate (Figure 6.4). (*Klippe* comes from a German word that means "cliff," reflecting the fact that most klippen in the Alps are bounded by cliffs.) A klippe indicates a minimum extent of the original thrust sheet. In other cases, erosion can create a hole through the thrust sheet, a window or fenster (*Fenster* is the German word for "window"), and expose an isolated area of the rocks that lie beneath the thrust (Figure 6.4). These rocks may be part of the autochthon or part of another underlying thrust sheet. A window provides a minimum constraint on how far the thrust sheet extends out over the underlying rocks.

A low-angle thrust fault generally does not form a smooth, simple surface. The fault plane characteristically cuts through the stratigraphy in steps, alternately following flat bedding planes or easily deformed layers such as shale or evaporite beds, and then cutting up-section in the direction of displacement to form a frontal ramp (Figure 6.5; compare Figure 4.25 and Section 4.4). The fault surface thereby develops a characteristic ramp–flat geometry. Figure 6.5 also shows that in some places where the fault parallels the bedding, a normal stratigraphic sequence is preserved despite the presence of the fault.

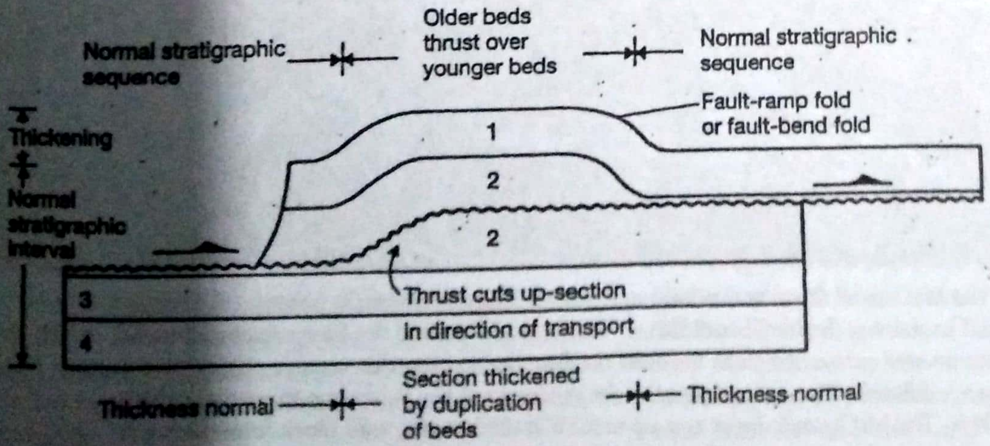


Figure 6.5 Idealized cross section of a low-angle thrust, showing the thrust surface (wavy line) cutting up-section at a frontal ramp from one horizontal glide surface to another. Changes in stratigraphic thickness and duplication of stratigraphic section are localized near the ramp.

Figure 6.6 is a composite photograph of the McConnell Thrust in Alberta, Canada, that shows such a ramp. At the left, the thrust is parallel to bedding and located within a lower Cambrian unit. To the right, the lower and middle Cambrian units of the thrust sheet are truncated against the fault. Still further right, the fault is again parallel to bedding, but here it is located within the upper Cambrian unit. The geometry is comparable to the diagram shown in Figure 6.5, the lower Cambrian corresponding roughly to layer 2.

Lateral ramps are also common features of low-angle thrust faults, as illustrated in Figure 6.7 for the Lewis thrust, which is part of the Canadian Rockies foreland fold and thrust belt in Montana (locations shown in Figure 6.11*B*). Both oblique and sidewall ramps may have dips as low as 15° to 20° (Figure 6.7*A*, *B*). If sidewall faults are steeply dipping, they are strike-slip faults called either tear faults or transfer faults, such as occur at the ends of the Pine Mountain thrust in the Appalachian Valley and Ridge province (Figure 6.7*C*, *D*; location shown in Figure 6.11*A*; see also Figure 6.13).

Displacement on Thrust Faults

Although displacement on thrust faults is typically up the dip of the fault surface, on irregularities in the fault plane such as lateral ramps, the displacement must in general be oblique slip. Ramps in the fault surface also require that the thrust sheet deform as it moves. Movement of a thrust sheet over a ramp causes a fold to develop in the thrust sheet, which is called a fault-ramp fold or a fault-bend fold (Figures 6.5, 6.6). The trend of the fold reflects the trend of the ramp below the thrust sheet. Frontal ramps are steeper than the main fault surface and therefore produce ramp anticlines (Figure 6.5). On lateral ramps, if the displacement has a component up the ramp, then an anticline forms (Figure 6.8*A*, *B*); if displacement has a component down the ramp, then a syncline develops (Figure 6.8*A*, *C*).

6.3 Structural Environments of Thrust Faults

Thrust faults exist as local faults, as sets of faults subsidiary to larger structures, and as large systems involving multiple thrusts and extending over whole mountain ranges. We consider each structural environment in turn.

Local Thrust Faults

Subsidiary thrust faults form wherever the geometry of other structures requires local convergence or shortening and the rocks react brittlely.

Diapiric structures involve less dense rocks that move upward through more dense surroundings. In some cases, the diapir shoves the surrounding rocks upward and outward, and marginal thrust faults develop. One common example of such features is the thrust faults marginal to some salt domes (Figure 6.9). In plan view, the thrust faults mimic the outline of the diapir. Because the cover rocks must also be stretched by this motion, normal faults develop over the top of the dome, as described in Chapter 5.

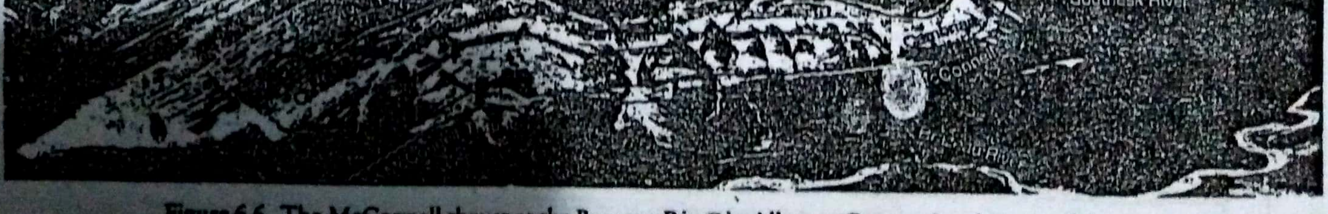


Figure 6.6 The McConnell thrust at the Brazeau River in Alberta. Composite photograph looking north at a cliff containing the McConnell thrust. The background and the foreground to the cliff do not match up well across the joins between the frames, because the vantage points for the photographs are different. The scale is given by the thickness of the Fairholme formation, which is about 1400 ft. The McConnell thrust cuts up-section in the hanging wall block from the lower Cambrian units (center) to the upper Cambrian (right) along the cliff (compare Figure 6.5).

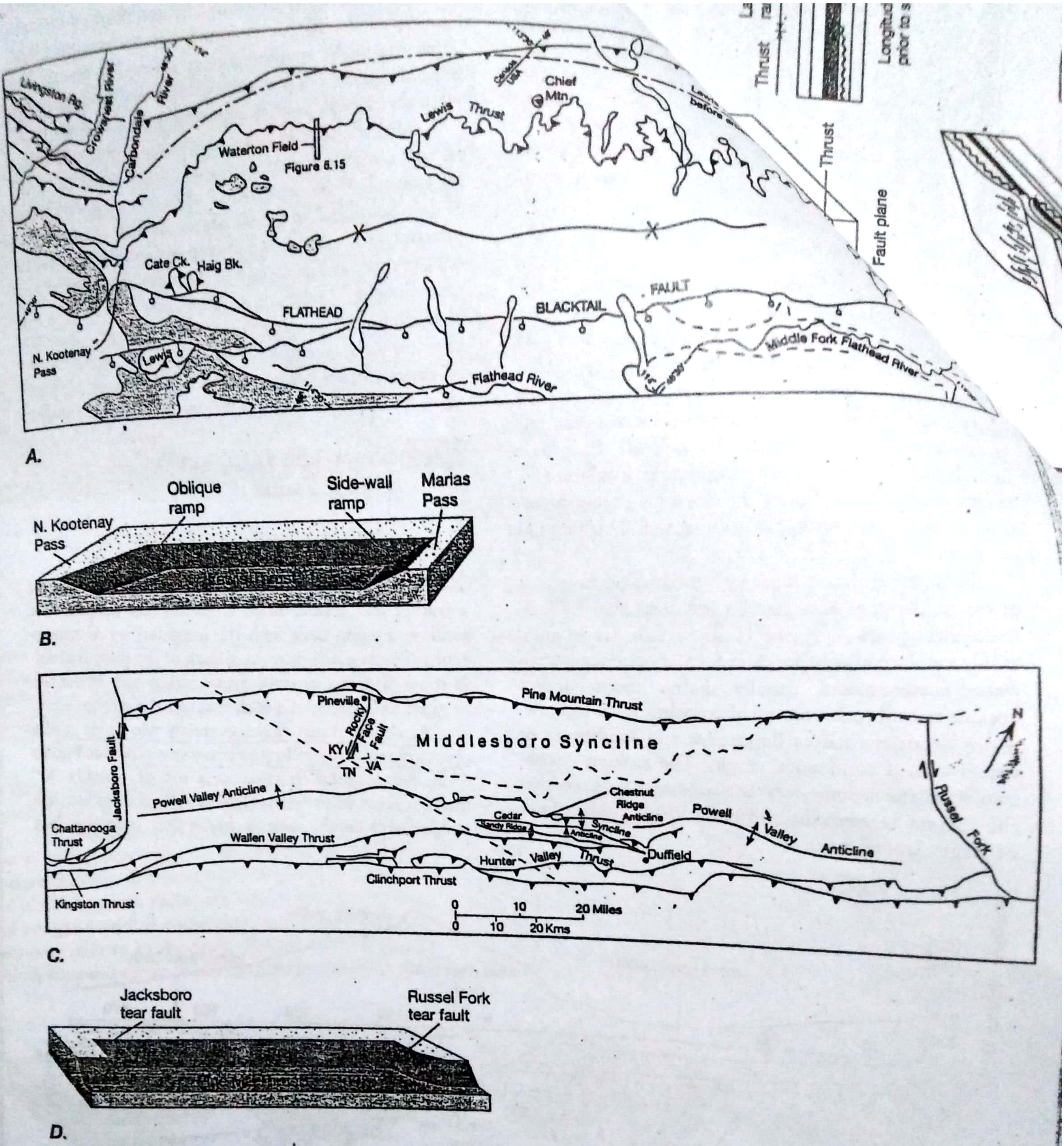


Figure 6.7 Structure of low-angle thrust faults. *A.* Map of the Lewis thrust near the Canada–USA border between Alberta and Montana (see the location marked on Figure 6.11*B*). The irregular nature of the thrust is a reflection of topography on the shallowly dipping fault surface. Note the Chief Mountain klippe near the border and the Cate Creek and Haig Brook windows near North Kootenay Pass. *B.* Schematic block diagram showing the geometry of the Lewis thrust surface. Note in particular the frontal ramp that brings the fault up to the surface, the sidewall ramp near Marias Pass, and the oblique ramp near North Kootenay Pass. *C.* Map of the Pine Mountain thrust in the southern Appalachian Valley and Ridge province (see the location marked on Figure 6.11*A*). Tear faults mark the northeast and southwest ends of the Pine Mountain thrust sheet. *D.* Schematic block diagram showing the geometry of the Pine Mountain thrust surface. The tear faults bound the frontal ramp at either end.

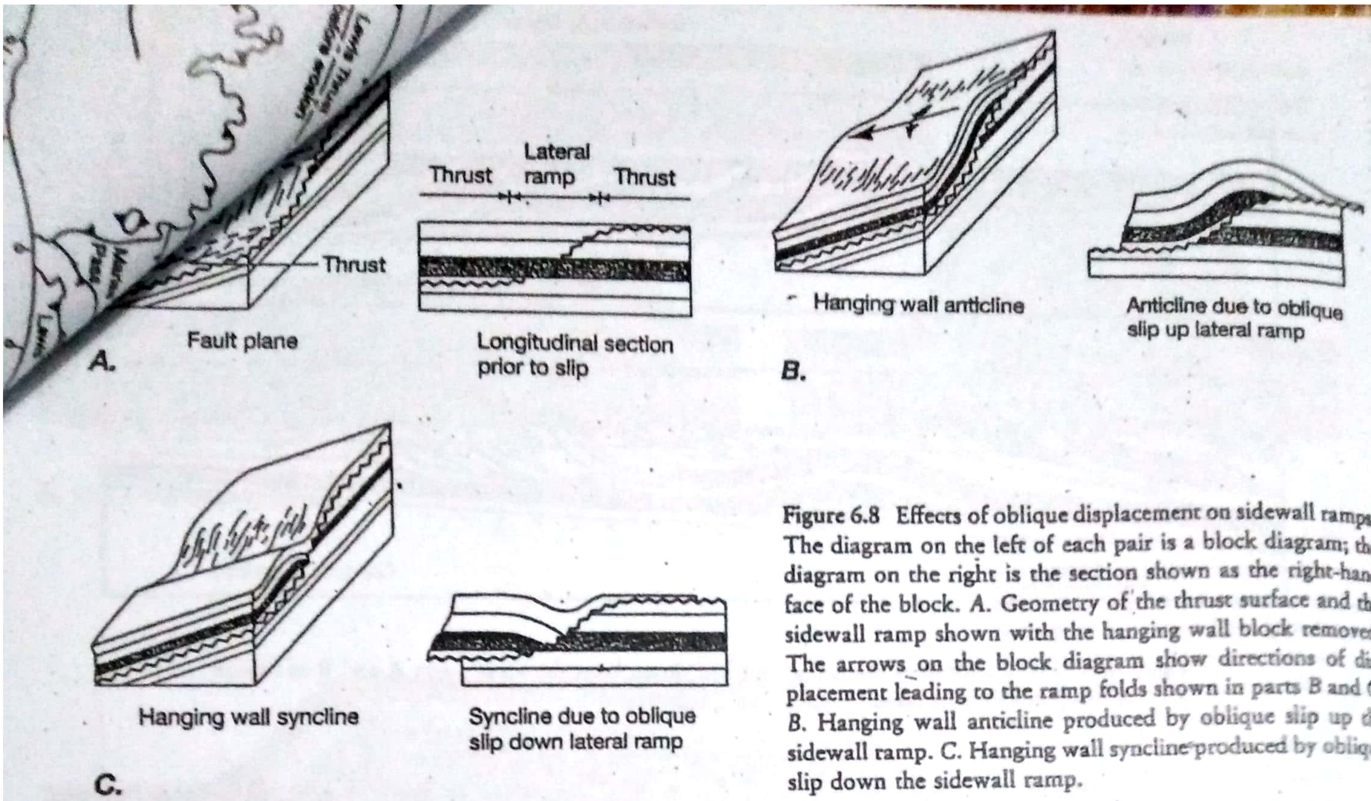


Figure 6.8 Effects of oblique displacement on sidewall ramps. The diagram on the left of each pair is a block diagram; the diagram on the right is the section shown as the right-hand face of the block. *A*. Geometry of the thrust surface and the sidewall ramp shown with the hanging wall block removed. The arrows on the block diagram show directions of displacement leading to the ramp folds shown in parts *B* and *C*. *B*. Hanging wall anticline produced by oblique slip up the sidewall ramp. *C*. Hanging wall syncline produced by oblique slip down the sidewall ramp.

Thrust faults are commonly present where bends in strike-slip faults result in compression of the rocks across the fault. We discuss this structural environment in greater detail in Chapter 7 (see Figures 7.7, 7.14).

Thrust Faults Associated with Folds

Thrust faults are associated with folds in four ways. First, as some folds develop, they reach a stage at which the sides, or limbs, of the fold cannot be rotated any closer together. Continued shortening of the layered sequence results in development of a thrust fault that generally cuts the steep or overturned limb of the fold (Figure 6.10*A*). Second, folds may develop as a result of thrusting to accommodate the deformation above the tip line of the thrust; these are therefore called fault-propagation folds. As the displacement on the thrust increases, the tip line propagates through the layers and cuts the steep limb of the fold (Figures 6.10*B*, 12.27). Third, folds may develop a steep or inverted limb that becomes progressively sheared and thinned until, in effect, it is a ductile thrust fault (Figure 6.10*C*). Fourth, where thrust faults have an alternating ramp–flat geometry, movements along the faults cause fault-bend folds to form in the hanging wall block (Figures 6.5, 6.6, 6.8).

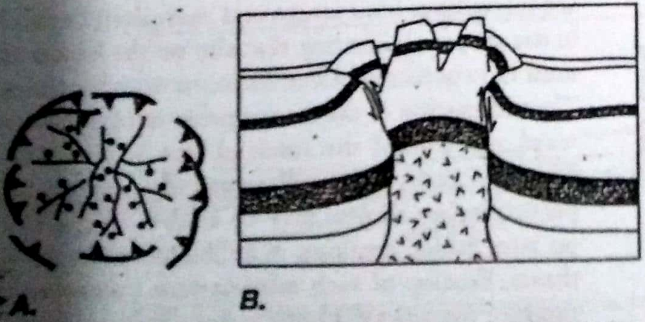


Figure 6.9 Peripheral thrust faults produced by diapiric intrusion. Normal faults in the central area accommodate extension associated with uplift. *A*. Schematic map. *B*. Schematic cross section.

Thrust Systems

Thrust faults in foreland fold and thrust belts, which mark the margins of major orogenic belts, are by far the most common examples of large thrust systems. These belts consist of a set of low-angle listric thrust faults that have the same general strike and dip (Figures 6.11, 6.12). Because of the economic importance of the major reserves of hydrocarbons found in these belts, and because of their intrinsic interest as a major type of tectonic feature of the world, these systems have been the object of an enormous amount of research.

The geometry of such thrust systems is distinctive. In plan view, a foreland fold and thrust belt consists of

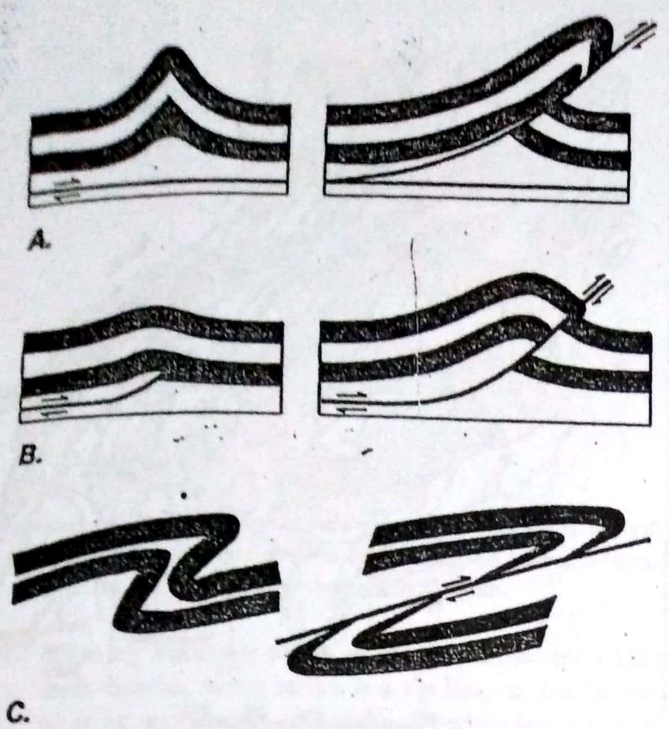


Figure 6.10 Diagrammatic cross sections illustrating relationships between folds and thrust faults (see also Figure 6.9). *A.* Thrust fault cuts up from the décollement through the foreland limb of a fold when the fold becomes too tight to accommodate further shortening. *B.* Fold forms in association with the propagation of a thrust fault. *C.* Formation of a fold by ductile flow can result in the shearing out of one limb to form a ductile thrust fault.

a set of folds and thrusts, more or less parallel, that extends for tens or hundreds of kilometers. The area in front of the thrusts toward which the thrust sheet moved is the foreland, and the region behind the thrusts is the hinterland. Although in some places these systems are nearly straight, they are generally curved, as shown in Figure 6.11.

We describe the curvature in terms of its relationship to the direction of relative motion of the thrust sheet. In a salient or virgation, faults and folds form an arcuate belt convex toward the foreland. In a reentrant or syntaxis, the arcuate belt is concave toward the foreland. Figure 6.11 shows three examples of such thrust systems. As is evident from the figures, there are many faults and folds in these systems, and these particular systems extend for hundreds or even thousands of kilometers.

Thrust systems also display differences in elevation along strike. Relatively high areas, or culminations, are usually present along salients or virgations, and relatively low regions, or depressions, accompany reentrants or syntaxes.

In cross section, fold and thrust belts characteristically overlie an undeformed basement along a gently sloping décollement surface (*décollement* means "detachment" in French), also called a detachment or sole thrust (Figure 6.12). In such cases, the deformation and shortening in the thrust system are confined to the rocks above the décollement. The décollement cuts up through the stratigraphic section toward the foreland, forming a wedge-shaped thrust sheet that is thinnest near the foreland and thickens toward the hinterland. Individual thrust faults generally are listric and asymptotically join the décollement, as shown in Figure 6.12.

Most thrust faults include frontal and lateral fault ramps, as described in Section 6.2 (Figures 6.5 through 6.8; compare Figure 4.25*A*). As a result, fault-ramp folds are a common feature. Not all folds in thrust sheets are necessarily fault-ramp folds, however; some may form to accommodate shortening of the thrust sheet above a flat portion of the décollement.

Thrust sheets are not structurally continuous features. Rather, they are segmented by tear faults, or transfer faults, that accommodate differential displacement of different parts of the sheet or connect noncoplanar parts of the active thrust (Figure 6.13). For example, one part of the thrust sheet may shorten by faulting, and an adjacent part may shorten by folding. The discontinuity in displacement is then taken up by a tear fault (Figure 6.13*A*).

Many thrust systems include an imbricate fan, or schuppen zone (the German word *Schuppe* means "scales"), in which a number of individual listric thrust sheets, all dipping in the same direction, overlap like a series of roofing tiles (Figure 6.12). Faults in such imbricate systems generally are concave upward, decreasing in dip with increasing depth and distance behind the thrust front. These listric faults either cut the topographic surface or are blind and terminate upward at tip lines within the stratigraphic section. At depth, they terminate at branch lines along the basal décollement.

A thrust duplex is a system of imbricate thrust faults that branch off from a floor thrust below and curve upward to join a roof thrust at a branch line above, thereby forming a stack of horses (Figure 6.14; compare Figure 4.26*A*). Unlike an imbricate fan that can break through to the surface, a duplex is necessarily contained within the stratigraphic section. Like an imbricate fan, however, a duplex can develop along a frontal ramp on which the main thrust rises toward the foreland.

Duplexes exhibit a variety of forms, depending on the amount of displacement of the individual horses. Where the displacement of the horses is relatively small, they dip predominantly toward the hinterland (hinterland dipping) and form a zone of roughly constant thickness between the roof and the floor thrusts (Figure

Figure 6.11 Major thrust systems, showing the foreland, hinterland, salient or virgation, and reentrant or syntaxis relative to the direction of movement for each fold and thrust belt. Teeth on the thrust faults are on the side of the hanging wall. *A.* Generalized map of the Appalachians. Plain lines are fold hinges; barbed lines are thrust faults. *B.* Generalized map of the Canadian Cordillera. *C.* Generalized map of the Himalaya.

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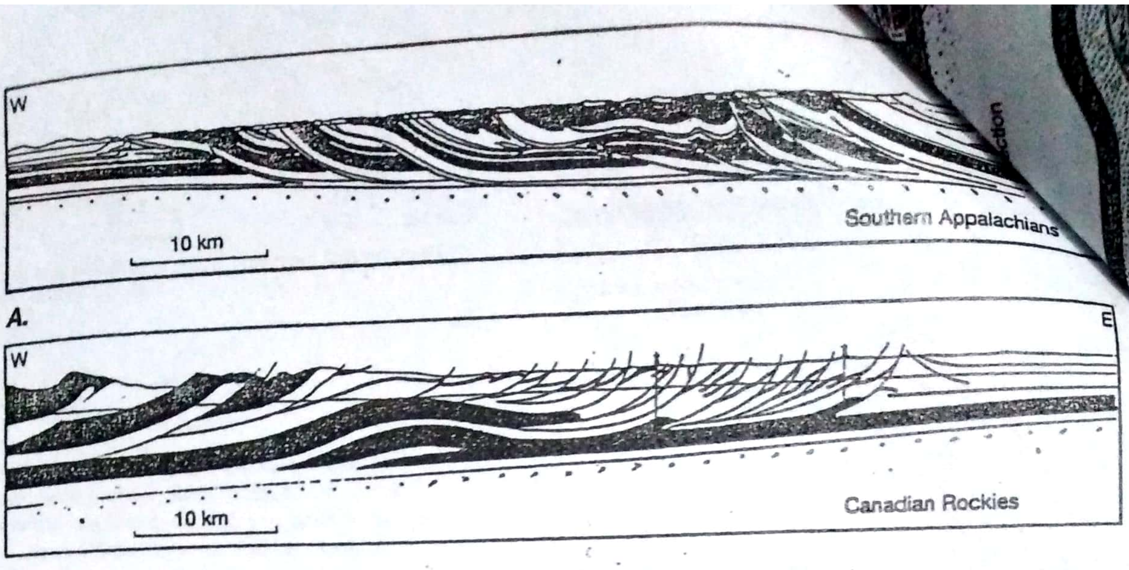

Figure 6.12 Cross sections of the major fold and thrust belts shown in parts *A* and *B* of Figure 6.11. *A.* Southern Appalachians. *B.* Canadian Cordillera.

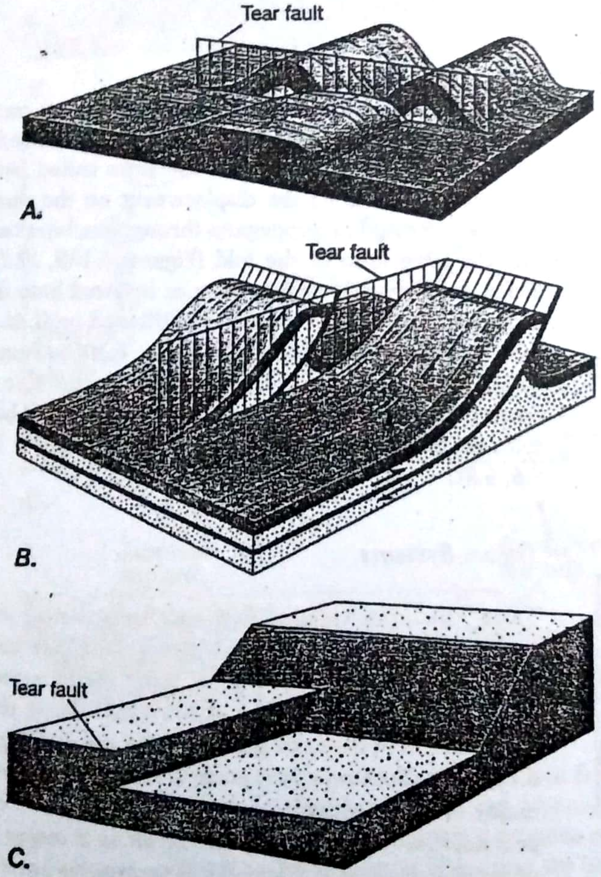

Figure 6.13 Thrust sheets segmented by tear faults. *A.* Shortening is accommodated by thrusting on one side of a tear fault and by folding on the other. *B.* Two noncoplanar imbricate thrusts are connected by a tear fault. *C.* Two segments of a thrust fault surface, each at a different structural level, are connected by a vertical sidewall ramp, or tear fault.

6.14*B*). With greater displacement, they form an antiformal stack over which the roof thrust curves through an antiform (Figure 6.14*C*). With still larger displacement, they dip predominantly toward the foreland (foreland dipping), again defining a zone of roughly constant thickness between the roof and the floor thrusts (Figure 6.14*D*).

Strata within the stack of horses generally display characteristic asymmetric anticline–syncline pairs, as shown in Figure 6.14*B*, *D*. Beds above and below the duplex generally parallel the roof and floor faults.

The Lewis thrust in the Waterton Field (Figure 6.7*A*) displays a more complex duplex structure (Figure 6.15*A*). There the Lewis thrust appears as the floor thrust, and the Mount Crandell thrust is the roof thrust. The duplex geometry combines elements of a hinterland-dipping duplex and an antiformal stack. Higher thrust faults in the duplex, and the horses between them, are folded over fault ramps and associated horses lower in the section, indicating that slip on the higher thrusts must have occurred before the lower ones became active. Thus formation of the thrusts progressed in time downward and toward the foreland (see Section 6.4). The Waterton Field duplex illustrates the fact that in duplexes, earlier thrusts may be folded by displacement on later faults, resulting in culminations in the earlier thrust. Erosion of such culminations subsequently can produce windows exposing lower structural levels. Restoration of this cross section (Figure 6.15*B*) is discussed in detail in Section 6.5.

Individual thrust faults, like any other structure, are not of indefinite extent; generally they are considerably shorter than the fold and thrust belt as a whole. If the shortening normal to a fold and thrust belt is

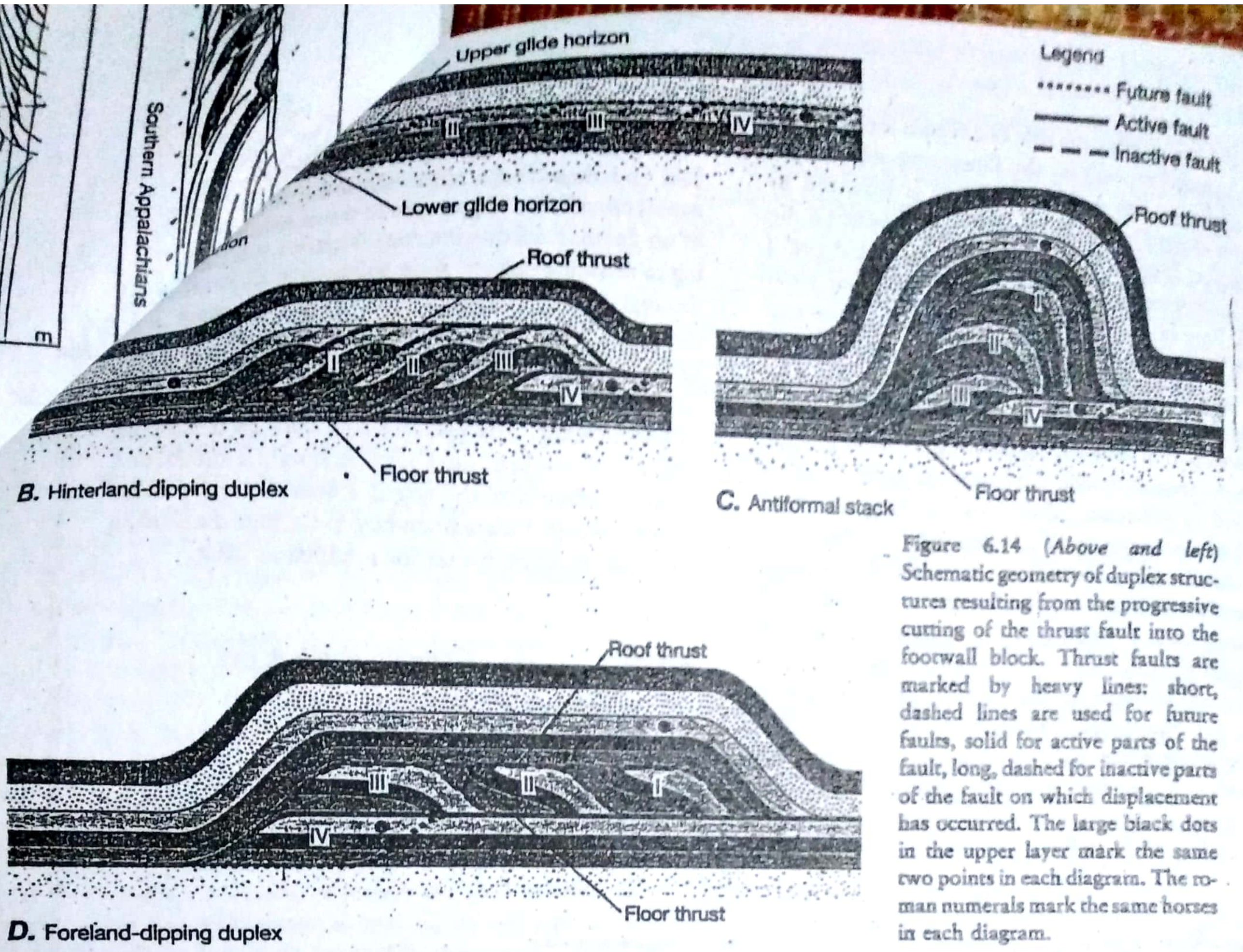

Figure 6.14 *(Above and left)* Schematic geometry of duplex structures resulting from the progressive cutting of the thrust fault into the footwall block. Thrust faults are marked by heavy lines: short, dashed lines are used for future faults, solid for active parts of the fault, long, dashed for inactive parts of the fault on which displacement has occurred. The large black dots in the upper layer mark the same two points in each diagram. The roman numerals mark the same horses in each diagram.

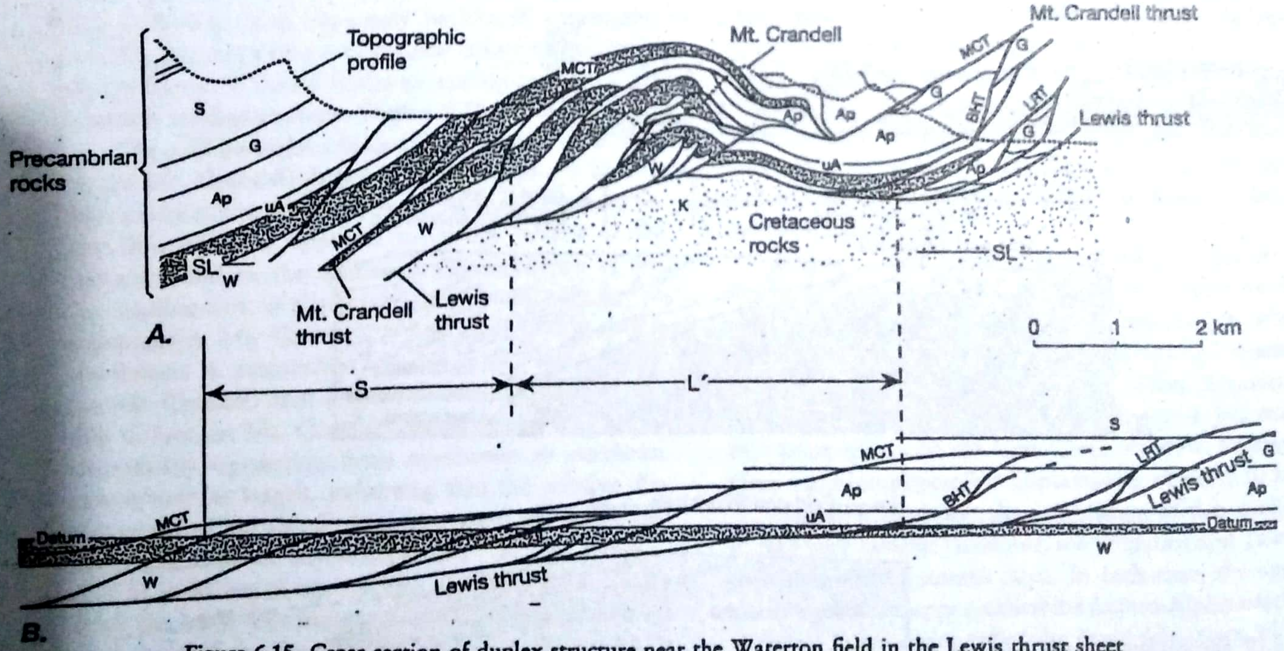

Figure 6.15 Cross section of duplex structure near the Waterton field in the Lewis thrust sheet near the Canada–USA border (compare Figure 6.7*A*). *A.* Generalized cross section showing that the Lewis thrust is the floor of the duplex where Precambrian rocks are thrust over Cretaceous siliciclastics. The Mount Crandell thrust is the roof thrust. *B.* Palinspastic balanced cross section restoring the duplex in part *A* to its inferred original configuration.

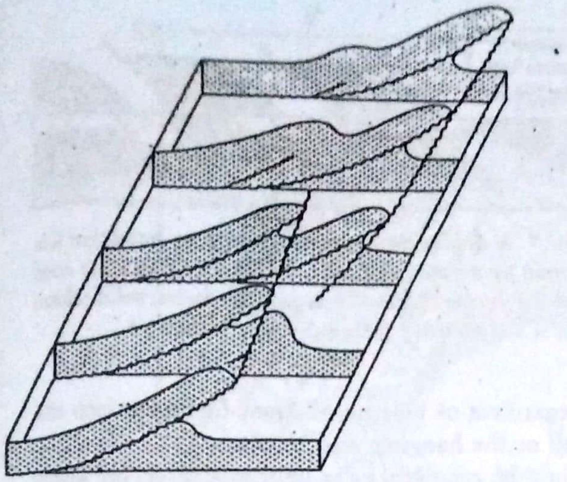

Figure 6.16 A simple transfer zone where one thrust fault dies out and the displacement is transferred through the transfer zone by folds to an *en echelon* thrust fault.

relatively constant along the belt, then where a thrust fault dies out along strike at a tip line, its displacement must be transferred to another overlapping, or *en echelon*, thrust. Figure 6.16 shows an example of the transfer zone between two *en echelon* thrusts that merge into the same basal décollement. As the displacement on the upper thrust decreases, shortening is taken up first by a fold in its footwall block and then by a new thrust that cuts the fold (compare Figure 6.10*A* or *B*). Finally, the upper thrust decays into a fold in the hanging wall of the lower thrust, and the displacement is progressively transferred to the lower thrust.

6.4 Kinematic Models of Thrust Fault Systems

To understand how thrust systems form, we need to know the sequence of development of the faults in duplexes and imbricate fans, that is, whether new faults develop in front of the older faults (toward the foreland) or behind (toward the hinterland).

The structure of duplexes is diagnostic of the sequence and indicates the progressive extension of the fault system toward the foreland. For example, the duplex structure illustrated in Figure 6.14*C* indicates that the youngest thrusts are those that branch from the sole fault closest to the foreland. A thrust must exist before it can be folded. If folding is a result of movement along ramps that splay off the sole fault, then displacement on the folded thrust must predate that on the underlying ramps. Moreover, a highly folded surface is not a surface of easy slip, and we expect the active part of the fault to have a simpler geometry. These relationships imply that the duplex formed as a result of the stepwise advance of the sole fault into the footwall and the progressive incorporation of the resulting horses into the hanging wall. We examine the consequences of this mechanism by looking at four idealized models for the formation of duplexes.

In Figure 6.14*A*, the sole fault in the lower glide horizon at the base of the section first cuts up across the strata on the frontal ramp to the left of block I and continues along the upper glide horizon. After the front edge of the thrust sheet has advanced part way across the top of block I, the sole fault in the lower glide horizon branches and extends into the footwall block under block I to a frontal ramp between blocks I and II. Block I becomes a horse, and the ramp and flat overlying block I cease to be active (heavy dashed line, Figure 6.14*B*, *C*, *D*). Block I is incorporated into the hanging wall, rides up over the new frontal ramp, and advances part way across the top of block II. In the process, block I and its overlying inactive thrust segment become folded. The sequence repeats itself, the sole fault branching in the lower glide horizon and advancing under block II, and the same process occurs twice more to form the final duplex.

In this model the active part of the thrust fault cuts progressively deeper into the footwall block as the horses become incorporated into the thrust sheet (the hanging wall block). The roof thrust above the duplex structure is never active as a distinct fault. It consists of segments of the upper glide horizon that are inactive by the time they become parts of the roof fault. For example, when block IV in Figure 6.14*B* is cut from the footwall block and advances up the ramp, a segment of the inactive fault above block III becomes part of the roof thrust, but by this time the segment is no longer active. Activity ceases at different times on the various segments of the roof thrust, and the segments above the youngest horses have the longest history of thrusting. In this model, the folds that develop in the horse immediately above an active ramp are slightly unfolded when the fault branches and the next horse slips up its frontal ramp.

The models in Figure 6.14*B* and *D* are constructed such that the roof thrust appears as a smooth, horizontal fault. This appearance depends entirely on how far the overriding horse advances beyond its frontal ramp; in Figure 6.14*B*, for example, it advances only a distance equal to the ramp's up-dip length. If its displacement is less or more than this amount, the roof thrust is an uneven structure. If the displacement carries the front tip of each horse just beyond the point where the next frontal ramp will emerge, the duplex develops an antiformal stack (Figure 6.14*C*). If the displacement is still greater, so that only the rear end of the youngest horse overlaps the front end of the incipient horse, a foreland dipping duplex develops (Figure 6.14*D*). This model

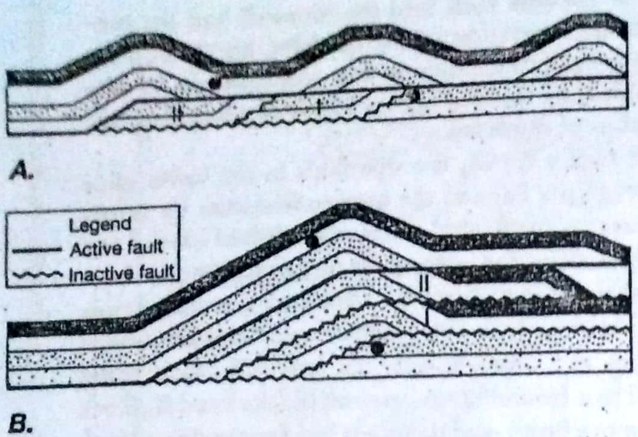

Figure 6.17 Two kinematic models for the formation of duplex structure in which the duplex developed by the stepwise retreat as the thrust fault frontal ramp steps back into the hanging wall block leaving horses in the footwall block. Thrust faults are marked by heavy lines: solid for active segments of the thrust system, and wavy for inactive segments of the thrust system. *A.* The upper glide horizon remains the same with each stepwise retreat of the frontal ramp. *B.* The upper glide horizon steps up in the structure with each stepwise retreat of the frontal ramp.

therefore seems able to account for the geometry of duplexes found in nature. Hinterland-dipping, antiformal, and foreland-dipping duplexes constitute a continuum of structures resulting from the progressively larger displacement of each horse in the structure.

Duplexes could also develop if ramps in the thrust fault cut progressively into the hanging wall block and therefore toward the hinterland. Figure 6.17 shows the geometric consequences for two models of this mode of thrusting. With each stepwise retreat of the frontal ramp, the upper glide horizon in Figure 6.17*A* remains at the same structural level, and in Figure 6.17*B* it steps up in the structure, increasing the length of the ramp with each step. Evidence for such structures is unusual, indicating that these models do not represent common geologic processes.

In a fourth model, a duplex forms if a younger thrust fault truncates a preexisting imbricate thrust fan, thereby becoming the roof fault to the duplex in its footwall block (Figure 6.18). The major characteristics of this model are that the roof thrust is the youngest fault in the system; it is a single fault, active at the same time over its entire length; and the anticlinal parts of the horses are offset, resulting in a truncated imbricate fan in the hanging wall block.

For imbricate thrust fans, it is difficult in many cases to determine the sequence of formation of the splay faults. The kinematic models are similar to those for duplexes shown in Figures 6.14 and 6.17, but because the splay faults eventually break the surface, no roof fault forms, and a stack of imbricate thrust slices would form regardless of whether the new faults cut into the footwall or the hanging wall block.

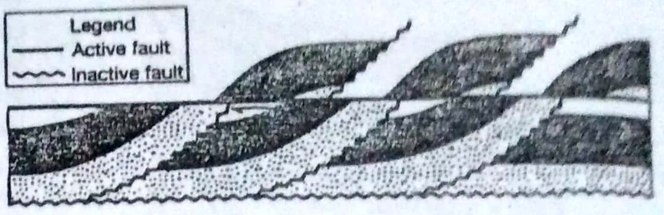

Figure 6.18 A duplex structure develops if an imbricate fan is truncated by a younger thrust, which then forms the roof thrust of the duplex. Heavy lines indicate faults: solid where the fault is active, wavy where the fault is inactive.

Thus the geometry of an imbricate thrust fan alone does not indicate whether the development of a given imbricate system progressed toward the foreland or the hinterland. Stratigraphic information, however, can provide additional evidence. In some regions where sedimentation is active, progressively younger sediments are found involved in the thrust wedges closer to the foreland. Inactive faults may be covered over by undisturbed sediments, but the same sediments in other places are cut by faults which therefore must be younger. Distinctive sediments such as conglomerates deposited toward the foreland from an active thrust sheet may subsequently be cut by the next listric fault that propagates into the footwall block. In the Idaho–Wyoming fold and thrust belt, for example, which is a southern continuation of the Canadian Rockies fold and thrust belt, such data demonstrate that the development of the imbricate fan progressed toward the foreland.

Most large fold and thrust systems appear to be dominated by the progressive cutting of fault ramps and fault splays into the footwall block and therefore toward the foreland (Figure 6.14), although examples of a progression toward the hinterland also occur at least locally, in which case they are referred to as out-of-sequence thrusts.

6.5 Geometry and Kinematics of Thrust Systems in the Hinterland

None of the thrust system models discussed so far deals with a complete cross section containing all fault termination lines (Section 4.4). Because thrust systems accommodate substantial shortening of the crust, and because these systems are composed of shallowly dipping faults, we must consider what happens to the continental crust below the sole fault. Moreover, to complete the model we must consider what becomes of the sole fault beneath the hinterland. We examine three models that provide a geometrically complete system.

In the first model, the sole fault could return to the surface somewhere so that the shortening along listric thrust faults in one area of the crust is balanced by extension along a system of listric normal faults in another region (Figure 6.19*A*). The implied pairing of a belt of shortening with a belt of lengthening may occur with shallow fault systems, such as in the sediments of the Gulf Coast (Figure 5.14*C*). The scale of displacement there, however, is probably much less than that observed in typical foreland fold and thrust belts, which have never been paired with an area of comparable extension.

In the second model, the basement rocks could be shortened by processes other than thrusting. The hinterland of an orogenic belt is characterized by high-grade metamorphic rocks that show abundant ductile deformation. Perhaps sole faults of the foreland fold and thrust belts terminate in a so-called root zone of ductile deformation within the metamorphic core. The gravitational collapse of the topographic high created by the shortening and thickening of the metamorphic core would be responsible for compression in the shallow wedge-shaped fold and thrust belt on the margin of the orogenic belt (Figure 6.19*B*; compare model experiment Figure 20.16*B*).

Still a third possible model—a one—is that the large displacements and fold and thrust belts reflect the involvemen nental crust in the largest type of thrust system we of on Earth, a subduction zone (Figure 6.19*C*). Accor ing to seismic evidence, some subduction zones are continuous down to depths of 1200 km or more and therefore have at least this much displacement on them. Where continental crust is on a down-going plate, it can be carried into a subduction zone and subducted to some extent. The ultimate sole fault to a foreland fold and thrust belt, then, may be simply a subduction zone, in which case the belt is a series of splay faults off a convergent plate boundary fault, and the driving force for thrusting is that for subduction itself.

6.6 Analysis of Displacement on Thrust Faults

On large thrust faults, the existence of piercing points (Section 4.3) on both sides of the fault is rare, and it is necessary to resort to other methods to obtain an in-

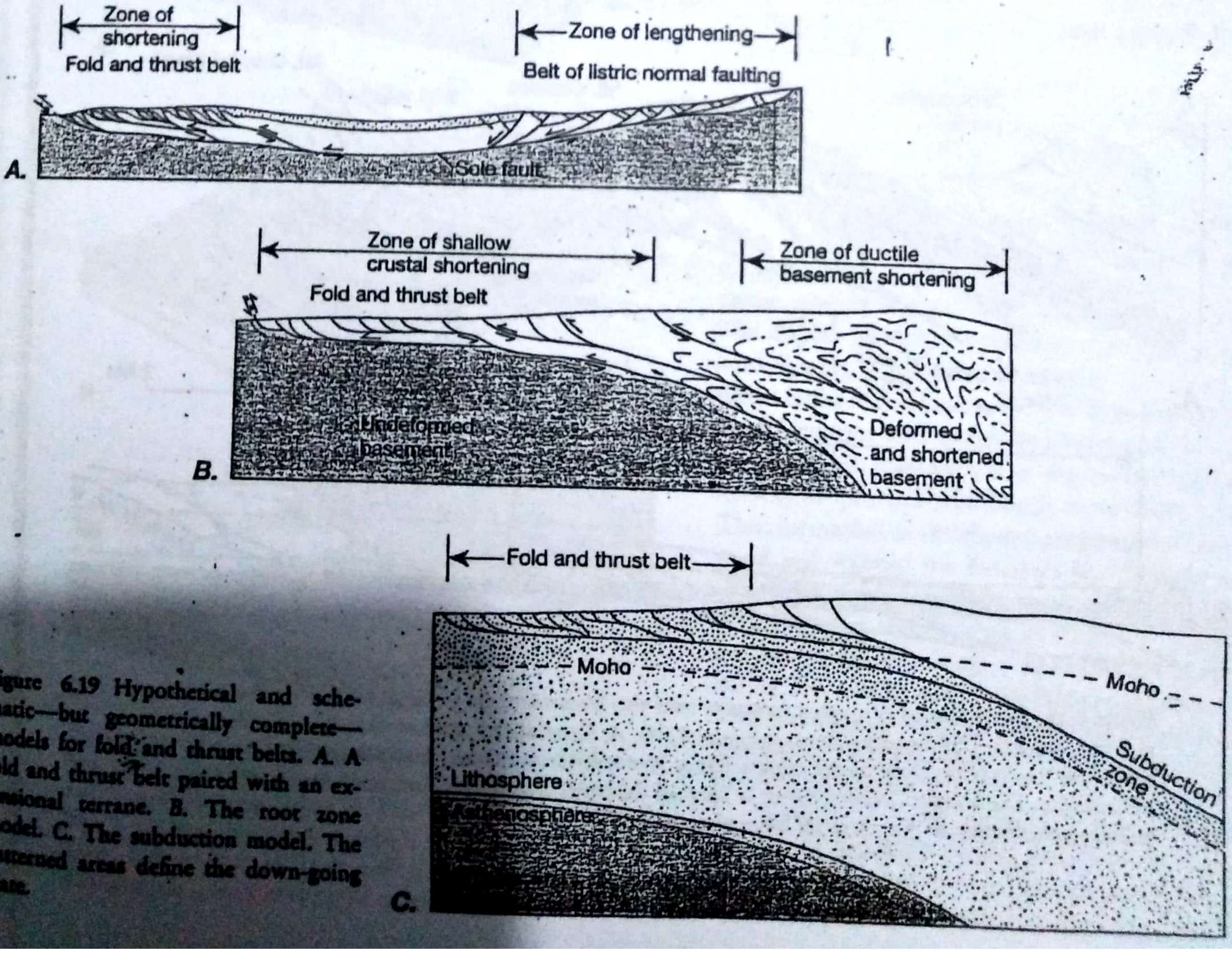

Figure 6.19 Hypothetical and schematic—but geometrically complete—models for fold and thrust belts. *A.* A fold and thrust belt paired with an extensional terrane. *B.* The root zone model. *C.* The subduction model. The patterned areas define the down-going plate.

with other faults, the mine are the displacement and the amount of the dis-

and Sense of Displacement

dition to general features of faults that indicate ear sense and relative displacement direction (Sections 4.3 and 6.1), some structures within the thrust sheet as well as the geometry of the thrust system itself can be used to constrain the thrust motion.

If, on a regional scale, the total amount of displacement on a thrust is generally the same along its length, and if erosion has not worn the sheet back unevenly, then the displacement is commonly taken to be approximately normal to the regional strike of the thrust fault or thrust system. Using this criterion, we find that the thrust sheets in the southern Appalachian Mountains (Figure 6.11*A*) moved to the northwest, and those in the Canadian Rockies (Figure 6.11*B*) moved to the northeast.

On many thrust faults, it may not be obvious in which direction the thrust sheet moved on the fault, especially on a local scale, and we must then rely on stratigraphic evidence. Although we tend to think of the hanging wall block as moving up the dip of the thrust fault, this is an unreliable assumption, because after thrusting, fault dips may be altered by folding. The slip direction of a thrust sheet is best indicated by the tendency of thrust faults to cut up-section in the direction of displacement (Figure 6.12 and 6.15).

The problem with a folded thrust fault is illustrated by the Mt. Crandell thrust shown in Figure 6.15*A*. In the vicinity of Mt. Crandell, the folded fault has a northeast dip, which is opposite to its dip further to the northeast and to the southwest. An inference of updip displacement of the thrust sheet, based only on the exposures in Mt. Crandell, would indicate top to the southwest. A restoration of the initial structure of the Mt. Crandell area (Figure 6.15*B*), however, shows that in fact the Mt. Crandell thrust cuts gradually but consistently up-section from southwest to northeast throughout its length, indicating that the relative displacement of the thrust sheet is toward the northeast, consistent with the regional picture.

In imbricate thrust systems, the thrusts branch up from the basal décollement in the direction of relative movement of the thrust sheet (Figures 6.12 and 6.15). In a complexly deformed region, therefore, identification of thrusts branching off the sole fault and determination of the direction in which they cut up-section provide other indications of their relative displacement.

The use of any of these criteria requires accurate data on the overall attitude of the faults, the nature of their intersections, and their relationships with the surrounding stratigraphy.

In many thrust sheets, asymmetric folds develop during thrusting. Such folds have one longer side, or limb, that dips at a relatively shallow angle and one shorter limb that dips steeply or is overturned (see Figure 6.10C, for instance). The tops of the folds can be thought of as leaning in the direction of the steep or overturned limb. This direction of leaning, the vergence of the fold, indicates the direction of relative motion of the thrust sheet. We discuss the geometry of folds in more detail in Chapter 12.

Determining the Amount of Displacement from Maps

In order to gain a better understanding of large-scale tectonic processes, as well as to predict possible sites for accumulation of economic deposits such as oil, we need to determine the amount of displacement along a thrust fault or system. Unfortunately, a map cannot provide unequivocal determinations of displacement, and it is therefore advisable to employ more than one method in order to obtain a more comprehensive understanding of the thrusting.

In some cases, the irregularities in the thrust trace, including windows and klippes, provide a minimum estimate of displacement. The desired measurement is the distance between the exposures closest to, and those farthest from, the hinterland in the movement direction. Figure 6.4 illustrates the technique. Figure 6.4*A* shows the displacement determinable from irregularities in the trace of the thrust fault. Using the exposure of a window and a klippe (Figure 6.4*B*) provides a larger lower bound for the displacement.

For the Lewis thrust (Figure 6.7*A*), we assume a displacement direction of N55E perpendicular to the average trend of the fault trace. The minimum possible displacement determined from the fault trace irregularities (Figure 6.4*A*) is approximately 12 km. Measuring parallel to the same displacement direction but using the thrust trace and the Cate Creek window, however, gives a minimum possible displacement of about 40 km.

Figure 6.20 shows the application of this analysis to two very famous windows, the Engadine and Tauern windows of the eastern Alps. In each case, the upper thrust sheets or nappes, called the Austro-Alpine nappes, overlie a lower series called the Penninic nappes, which are exposed in the windows. The distance from the rear of these windows roughly northward to the front of the main thrust trace indicates a minimum displacement of as much as 100 km for the Austro-Alpine nappes.

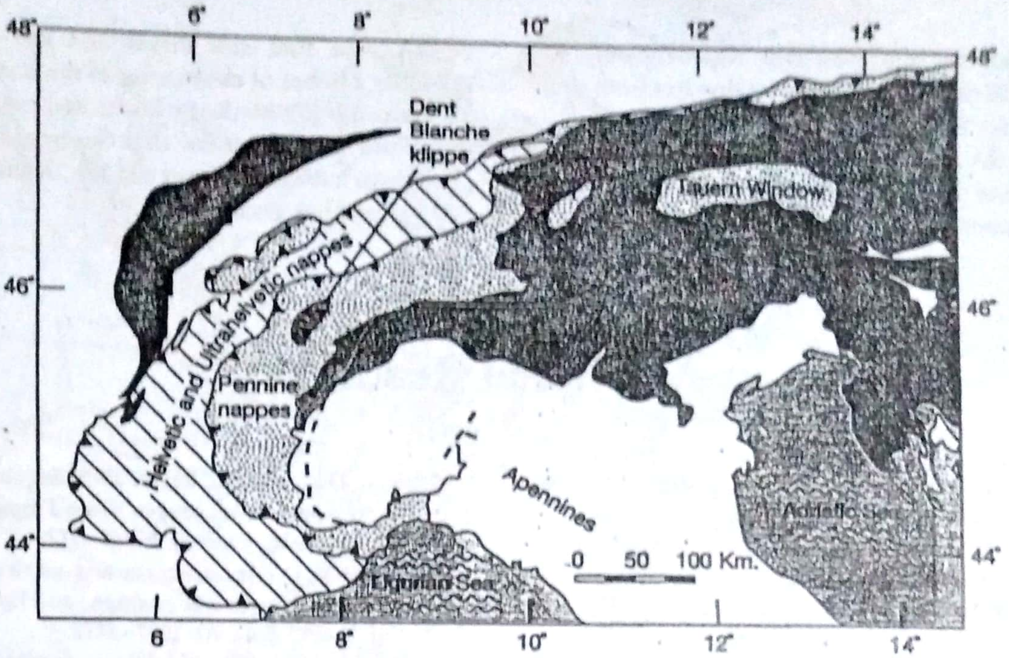

Figure 6.20 Generalized map of the Alpine region, Europe, showing three principal thrust complexes: the Helvetic (diagonal ruling), Penninic (stipple pattern), and Austro-Alpine systems (medium grey). Two windows, the Tauern and the Engadin, show the Penninic nappes underneath the Austro-Alpine nappes. The Dent Blanche klippe is an erosional outlier of the Austro-Alpine nappes on top of the Penninic nappes. To the northwest is another klippe of the Penninic nappes on top of the Helvetic nappes.

Determining the Amount of Displacement from Cross Sections

Cross sections of thrust faults can be used to determine the magnitude of the displacement if the section is parallel to the displacement direction on the fault. Figure 6.21 shows the simplest example of this situation, in which the displacement and shortening are related by the dip angle (ϕ) of the fault, and the displacement (d) is determined with a simple linear measurement.

For more complicated structures, determination of the total amount of displacement and shortening is more difficult. The cross section through the Lewis thrust system in Figure 6.15, for example, consists of a combination of imbricate and duplex faults, some of which have been folded above the younger thrusts. The original continous stratigraphic sequence appears intact at the left side of the cross section.

In such cases, we construct a balanced cross section (see Section 4.5), concentrating for this example on the area between the Lewis thrust and the Mt. Crandell thrust. The lower Altyn formation, shown as the shaded layer, is used as the reference layer because it is contained in most of the thrust wedges and horses of the thrust system. The pinning points must be to the northeast (right) of where the Lewis thrust cuts up through the stratigraphic section that is being balanced, and to the southwest (left) of the duplex between the Mt. Crandell and Lewis thrust.

Figure 6.15B is the balanced palinspastic cross section, showing the undeformed stratigraphic sequence with the paths of the various thrust faults through the sequence. Two reference points at the top of the shaded lower Altyn unit in both the deformed and the palinspastic balanced cross sections show that the amount of shortening (S) caused by the thrusting amounts to

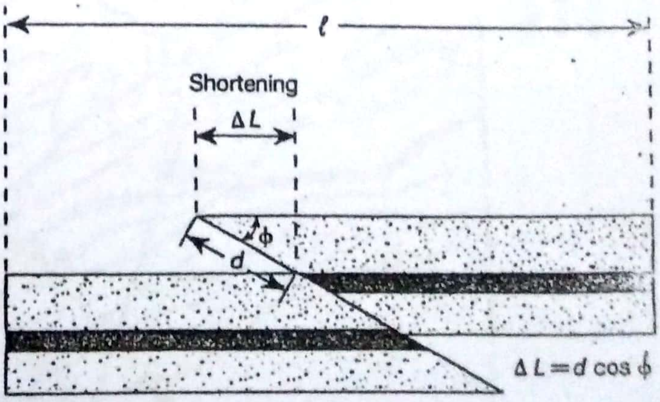

Figure 6.21 Shortening associated with thrust faulting, showing how the change in length ΔL is related to the displacement d and the dip angle of the fault ϕ for simple faults.

almost 3.5 km for a section that was originally only 8 km long. Thus this part of the section has been shortened by about 43 percent.

Across the Appalachian Valley and Ridge province from the Pine Mountain thrust to the Brevard fault (between points A and B on Figure 6.11*A*; see Figure 6.12*A*), the fold and thrust belt has accommodated roughly 280 km of shortening of the Earth's crust. "Retrodeforming" the thrust faults and taking eroded section into account reveal that the original width of the belt must have been about 435 km. A shortening of over 60 percent has occurred!

Additional Readings

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faults develop in regions of
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