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Thrust Systems[1]

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ABSTRACT

A general geometric framework underlies the structure, evolution, and mechanical processes associated with thrust faulting. The main purpose of this paper is to review and extend this geometric framework. A certain family of lines must exist where thrust surfaces join along branch lines or end at tip lines. Starting from a description of these lines and individual thrust faults, we examine how they join into thrust systems, either as imbricate fans or duplexes. These thrust systems have distinctive map patterns commonly observed near culminations and windows. Many of the culminations have origins tied in with a particular thrust system. The order in which the fault slices form has a marked effect on the geometry of the thrust system. These systems must be identified to understand the provenance of the synorogenic sediments.

Part of a thrust belt may be dominated by one particularly large thrust sheet. In front and beneath these dominant sheets, there is a characteristic sequence of thrust systems with a regular pattern to the involvement of basement.

This overall geometric framework provides new insight into some classic areas, illustrated by a balanced cross section through the Mountain City and Grandfather Mountain windows, in the southern Appalachians and another from the Jura to the Pennines (in the western Alps).

INTRODUCTION

For almost any work in thrust belts, it is essential to establish the three-dimensional relations between faults. These geometric relations between thrusts arise, for example, in the following typical questions. Does my interpretation change if this thrust fault joins that one? Is it possible to establish the time sequence of faulting from the geometry? Is the thrust pattern associated in some way with the origin of my culmination? What does this map pattern of thrusts imply for the cross section?

In this paper we try to draw together part of the geometric principles that we find useful in deciphering three-dimensional thrust structures. This framework has reasonably wide application, and our examples come from the North American Cordillera, the Appalachians, the Caledonides, and the Alps. Although some of these geometric concepts are fairly old, they have seldom been reviewed; we have tried to establish their origin and say something about how the ideas evolved.

There are two general categories of tools useful in thrust belt analysis. The first is balanced cross sections, or cross sections that are both restorable to the undeformed state and conform to certain specified standards of admissibility (Dahlstrom, 1969; Elliott, in prep.). The same set of data may have several different solutions, all of which allow restoration and are otherwise admissible.

The second main category, and the subject of this paper, is concerned with the interconnections or relationships among faults. We shall see that the solutions of thrust belt problems fall into certain categories or types. Choice of the correct type of solution is commonly the most important single step in the interpretation. When we specify how the various parts connect to each other we may refer to the "logic" of the fault network, in the same way we speak of the logic of an electronic device. We will use a building-block approach, starting with the geometric elements and a very few thrusts, and then look at some characteristic patterns of larger numbers of thrusts.

GEOMETRIC ELEMENTS

A thrust sheet is a volume of rock bound below by a thrust fault. A useful convention is to name the thrust sheet after this underlying or leading thrust fault. This name usually continues to the trailing thrust, which joins the leading thrust along a branch line (Fig. 1). A sheet may have a distinctive stratigraphy, state of strain, or metamorphic grade, and on this basis individual sheets are often correlated long distances. There is a long tradition in the European Alps of focusing attention on the thrust sheet volumes (nappes), and we shall discuss this later in the paper.

The intersection of a thrust surface with a stratigraphic horizon is a cutoff line (Douglass, 1958, p. 132). A cutoff line could also be called an "edge" because it indicates the intersection of two surfaces. Dahlstrom's (1970, p. 352) terms "leading edge" and "trailing edge" thrust surfaces are in this sense self-contradictory, so we have shortened them to "leading and trailing thrust surfaces." J. K. Arbenz remarked (1981, personal commun.), "In

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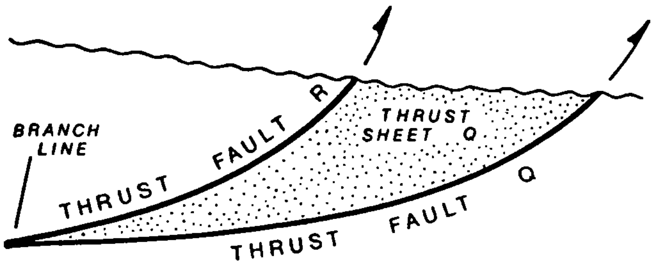

FIG. 1—Cross section through thrust sheet (Q), which is volume of rock above leading fault (Q) and below trailing fault (R).

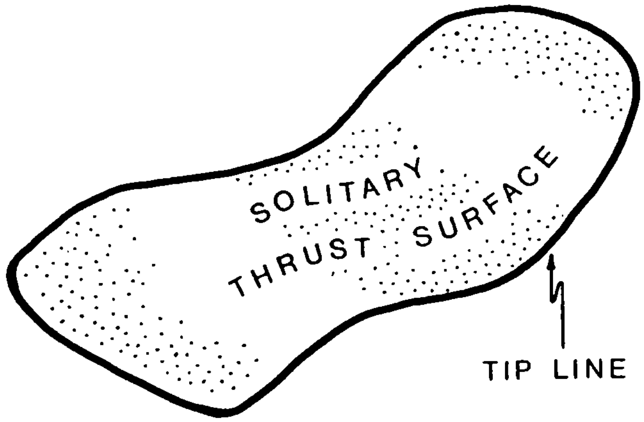

FIG. 2—Three-dimensional view of solitary thrust surface. This is buried, or blind, and its perimeter is everywhere a tip line.

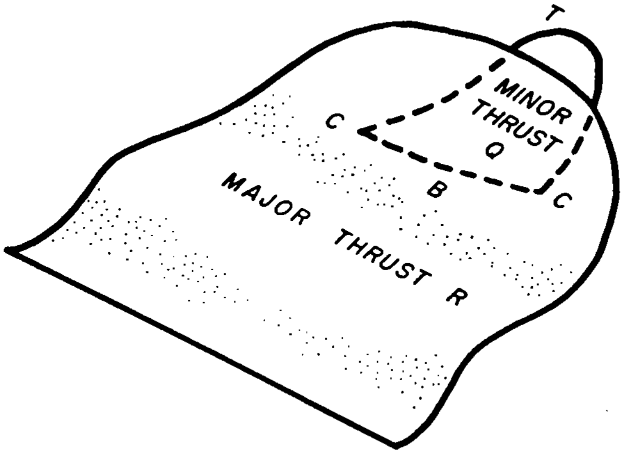

FIG. 3—Minor thrust surface (Q) branches off major thrust (R). Both thrusts meeting along branch line (B). Blind minor thrust (Q) has tip line (T) which meets branch line (B) at two corners (C).

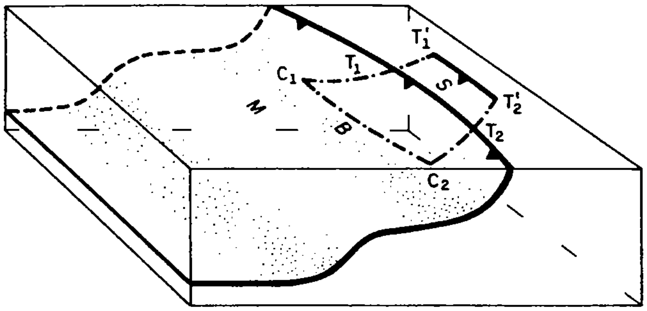

FIG. 4—Erosion cuts branching pair of thrust surfaces which might have once resembled Figure 3. Map pattern is main thrust (M) with isolated splay (S), which has one branch (B), two tip lines (T_1, T_2) that outcrop (T_1, T_2) at termination on map of fault trace.

industry usage, the term 'leading edge' refers to the line of intersection of a thrust surface with a specific stratigraphic horizon of that particular thrust sheet (e.g., the leading edge of the Madison). In fault closures the leading edge becomes the line along which the stratigraphic top seal passes to the fault seal."

So far we have concentrated on blind thrusts,[4] or those in which the tip line does not reach the ground surface (Fig. 2). These thrusts are particularly common near the frontal margin of the thrust belt. Many thrusts start blind and later turn upward to meet the synorogenic erosion surface.

Erosion through a tip or branch line produces the tip or branch points shown on maps. These are particularly important because near these special points we may observe many of the physical processes that produce thrusts (Elliott, 1976, p. 299). There are several examples illustrating the use of branch lines in the Moine thrust belt in Elliott and Johnson (1980, Fig. 17).

A splay rejoins the main fault once. Splays can crop out at the synorogenic erosion surface or arise by later erosion through an originally blind branching thrust (see Fig. 3). We can have an isolated splay (Fig. 4), where erosion cuts the tip line into two, and a diverging splay where erosion cuts the branch and tip lines once (Fig. 5). Maps show that on approaching their lateral termination, major thrusts often turn into a network of diverging splays. In a rejoining splay the tip line is fully removed and the map surface cuts the branch line twice (Fig. 6). Slightly more complex is a connecting splay, where the branch line is strung together along two different fault intersections (Fig. 7).

It is possible for an individual thrust surface to be completely surrounded by branch lines (Fig. 8), because a pair of fault surfaces may diverge after branching and then, farther up, converge to meet again at the branch line. Usually, but not necessarily, the thrust rejoins along strike as well as updip, so that the tip line is eliminated. A horse is a pod of rock completely bound by two or more such fault surfaces. This is an old and useful term (Dennis, 1967, p. 89) which we here extend beyond its original usage for pods bound by normal faults. Horses, unlike the other kinds of branching thrusts, are unlikely to meet a synorogenic erosion surface. Horses can be cut from either the hanging wall or the footwall of major thrusts and may consist entirely of inverted rocks (Fig. 9). They frequently decorate the edges of major thrusts and are particularly helpful in the field to identify thrusts that put shale upon shale. They may also provide stratigraphic information from beneath a major thrust, infor-

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[4] Blind thrusts were used and described in Calgary lectures in 1977 by Elliott. We feel earlier usage exists; but were unable to locate the references.

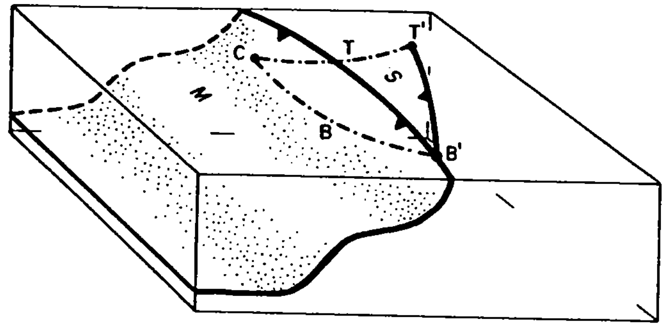


FIG. 5—Block diagram showing diverging splay (S), which has only one tip line (T) with a map termination (T′) and one branch line (B) that intersects erosion surface at B′. There is one corner C.

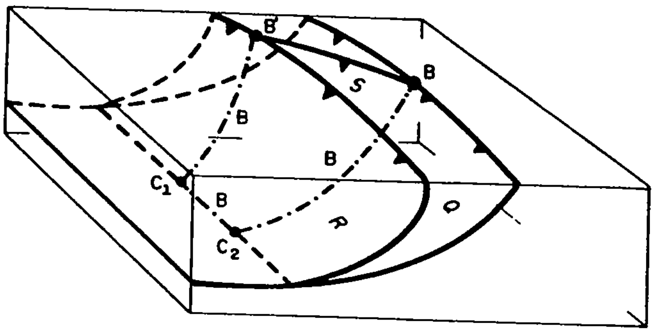


FIG. 7—Two major faults (Q, R) with connecting splay (S). Two branch lines (B) have surface terminations (B, B′) and one branch line at depth has two corners (C_1, C_2).

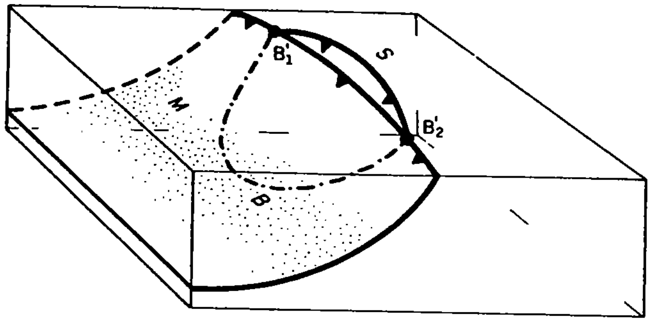


FIG. 6—Rejoining splay with one branch line (B) which intersects map at two branch points (B_1, B_2).

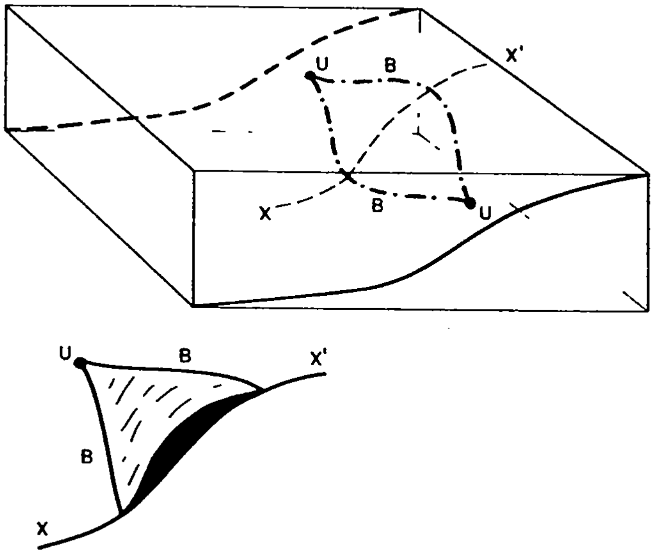


FIG. 8—Above: Horse in volume of rock surrounded by fault surfaces. Two fault surfaces meet at single closed branch line (B) with two cusps (U). Below: diagram illustrates half of horse, cut along line of section XX′.

mation which may not be obtainable otherwise.

One must try to describe the three-dimensional geometry relative to the synorogenic erosion surface, not the current one and this can be difficult. For example, how do we distinguish a rejoining splay from an eroded horse on a map? If a rejoining splay has roughly parallel and gently plunging branch lines then cross sections can show two-dimensional pods that resemble horses (Fig. 10), how do we tell them apart?

Transfer Zones and Connectivity

A stratigraphic formation could be cut into interlocking pieces in such a way that if it were fully excavated and you started at one side of the map, you could walk around the ends of the faults on a tortuous path to the other side without having to jump across any faults (Douglas, 1958, p. 131). In this case each thrust sheet is related to its neighbor by an unfaulted envelope that acts as a transfer zone (Dahlstrom, 1970, p. 358). This description of interlocking thrust sheets is correct only for isolated and diverging splays, each of which has at least one tip line. It is not the case within rejoining and connecting splays or horses where each faulted part of the formation is surrounded by fault surfaces.

The extent to which thrust sheets are connected to each other depends on the relative length of tip and branch lines. Because all thrust surfaces are generated by tip lines (Elliott, 1976, p. 298) the degree of connectivity depends on the duration and intensity of activity in that part of the thrust belt. Other things being equal, horses are more common in the more internal, older, and deeper parts of thrust belts, whereas blind thrusts and isolated and diverging splays are more common in the younger, external, and shallower portions.

IMBRICATE THRUST SYSTEMS

So far we have concentrated on the geometric relations between two or three connected faults. Several nearby faults may join up in closely related branching array known as a thrust *system* or family (Rodgers, 1953, p. 130). Now we shall look at patterns that arise at thrust systems where a substantial number of faults are the same general shape and size.

If each thrust in a system repeats the size and shape of the neighboring thrust so that the thrust sheets overlap like roof tiles, all dipping in the same general direction, we have an imbricate system. This important special type of thrust system was recognized in 1883, when Suess defined schuppen structure as the repetition of strata by a

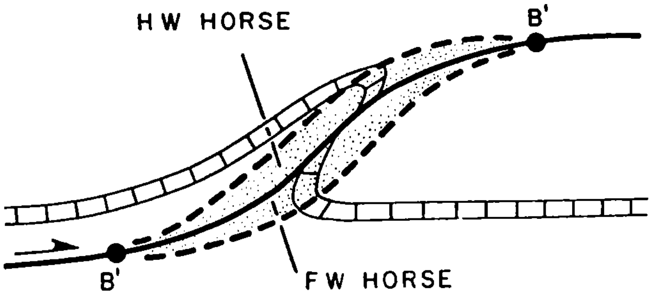


FIG. 9—Cross section through incipient horses. New fractures (dashed) may cut horses from either footwall (FW) or hanging wall (HW) of major thrust surface. Note that horses in this figure would consist entirely of inverted rocks.

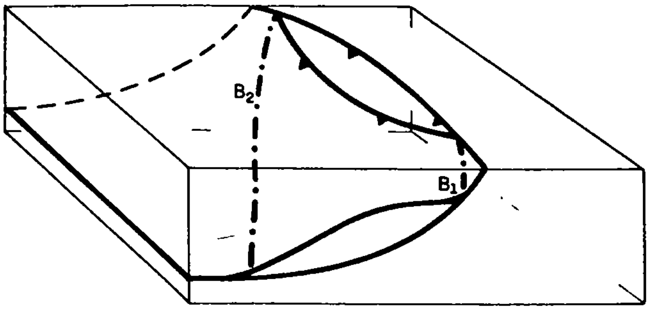


FIG. 10—Two fault surfaces meeting along two branch lines (B_1, B_2), whose map pattern resembles diverging splay and whose cross section resembles horse.

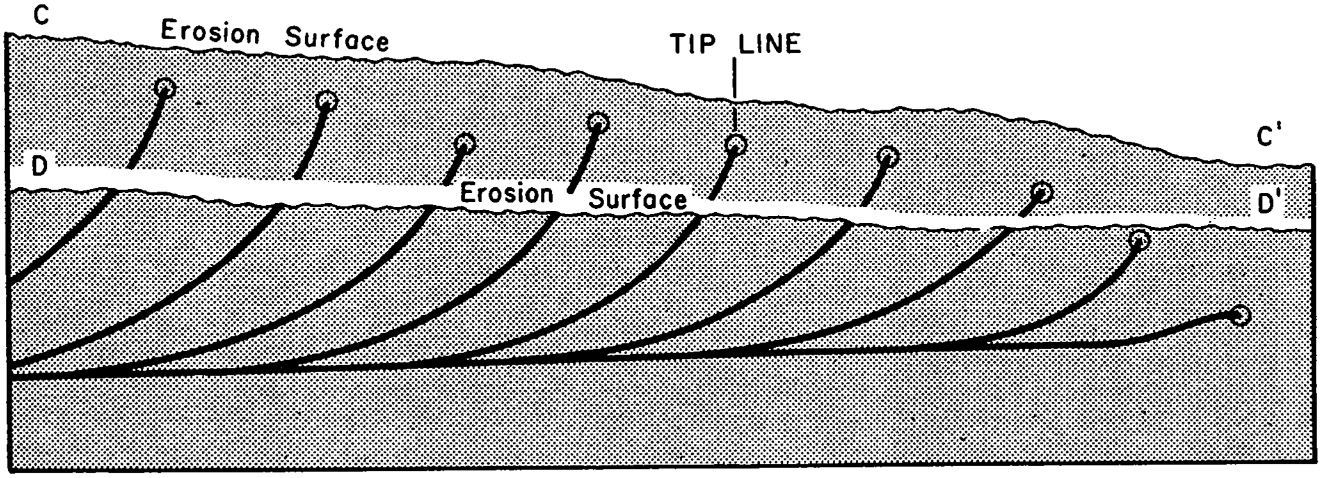


FIG. 11—Cross section of imbricate fan at two different levels of erosion. Each thrust sheet is an upward-opening crescentic slice, and all curve asymptotically downward to a common basal sole thrust. If most faults cut synorogenic erosion surface DD′ we have an emergent imbricate fan. Alternatively, it is possible that tip lines do not reach synorogenic erosion surface CC′, producing blind imbricate fan. Note that subsequent erosion (CC′ down to DD′) may obliterate any means of distinguishing two kinds of imbricate fans.

series of parallel and evenly spaced overlapping faults (see Suess, 1904, p. 112). As the concept evolved, several other terms came into use. The literal French equivalent is "structure ecailleuse" (Gosselet, 1885). Both the French and German expressions mean a scaly or flaky structure. However, de Margerie and Heim (1888) used "structure imbriquee" as the French equivalent of Suess's term. Hobbs in 1893 introduced "weatherboard structure," but later (1894) accepted a suggestion by Bernard Hobson to use imbricate structure as the English equivalent. In modern usage, schuppen zone is synonymous with imbricate zone but is less frequently employed.

Imbricate structures are an efficient means to shorten and thicken a sequence. Relative movement ". . . is trivial, as concerns adjacent members, but may in the aggregate lead to impressive telescoping of the affected zone" (Bailey, 1938, p. 607).

A sole thrust is the lower common thrust in an imbricate system (Dennis, 1967, p. 139). In an imbricate fan, a swarm of curved triangular thrust slices are asymptotically shaped downward to the sole thrust and spread out upward like an open fan (Fig. 11). Emergent imbricate fans where the faults reach the erosion surface are most common, but blind faults could produce blind imbricate fans. On approaching the synorogenic erosion surface the thrusts often increase their dip, and our impression is that they can meet the ground surface at about 60°. Imbricate fans dominate this near surface level.

An imbricate fan in which a thrust with maximum slip is at the front is a leading imbricate fan. If the thrust with maximum slip is at the back, it is a trailing imbricate fan (Fig. 12). These two terms were modified from Dahlstrom (1970, p. 352).

It is also possible to construct a thrust system with an imbricate family of subsidiary contraction faults asymptotically curving downward to a sole or floor thrust and upward to a roof thrust. This thrust system is known as a duplex (Fig. 12).

DUPLEXES

The term "duplex" first appeared in a paper by Dahlstrom (1970, p. 352), but he does not take credit for originating the duplex concept or coining the term, maintaining that these ideas were already present in the

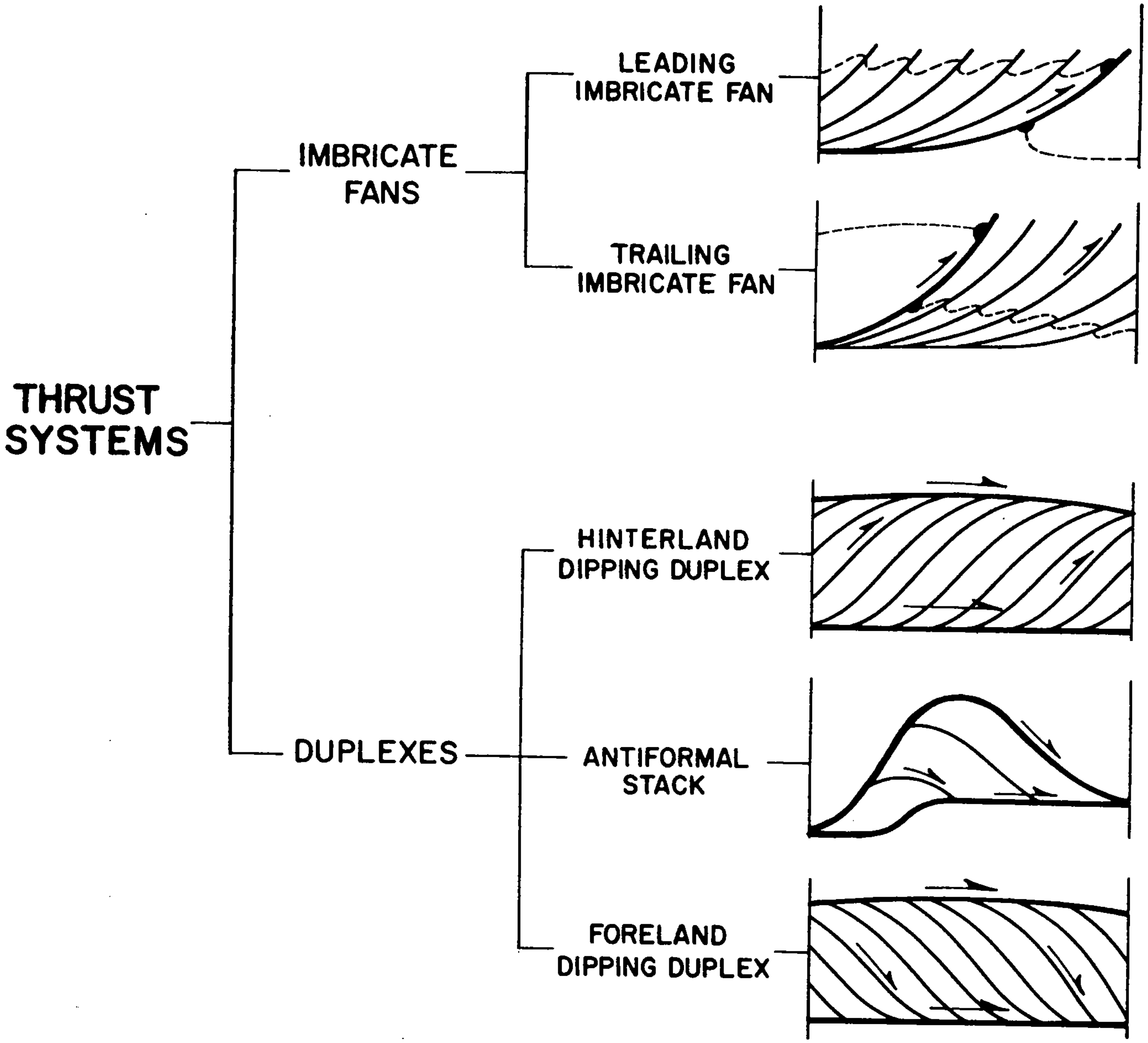


FIG. 12—Classification of different systems of thrusts; most are imbricate.

minds and writing of several people in Calgary (D. A. Dahlstrom, 1978, personal commun.). The evolution of the concept is best appreciated by studying some historically important examples.

Moine Thrust System

A 50-year controversy over the existence of the Moine thrust resulted in geologic mapping at about 1:10,000 scale, which was completed between 1883 and 1896 (Fig. 13). Early in this project, B. N. Peach interpreted the exposures on the east shore of Loch Eriboll as a duplex (McIntyre, 1954, p. 206). Shortly afterward, in an exceptionally exposed area with 0.6 mi (1 km) of local relief, a spectacular duplex zone (Foinaven duplex; Table 1) repeating a distinctive Lower Cambrian quartzite was discovered by Cadell (Peach et al, 1907, p. 491, Fig. 25) (Fig. 14). Throughout this early Scottish work the usage of "schuppen" and "imbricate zone" corresponded to what we would now call a duplex.

Lewis Thrust System

The Lewis thrust is one of the largest in the North American Cordillera (Table 2; Fig. 15). The Precambrian Belt sequence within the thrust sheet, spectacularly exposed in Glacier and Waterton Parks, shows remarkably little internal deformation, but going down through the sheet one may suddenly enter a duplex, a few hundred meters thick, whose floor is the Lewis thrust surface. This is particularly clear in the Willis (1902) illustration of the Chief Mountain klippe (Fig. 16). Douglas (1952) mapped a duplex near Mount Crandell (Fig. 17), which was cited by Dahlstrom (1970, p. 354) as his type exam-

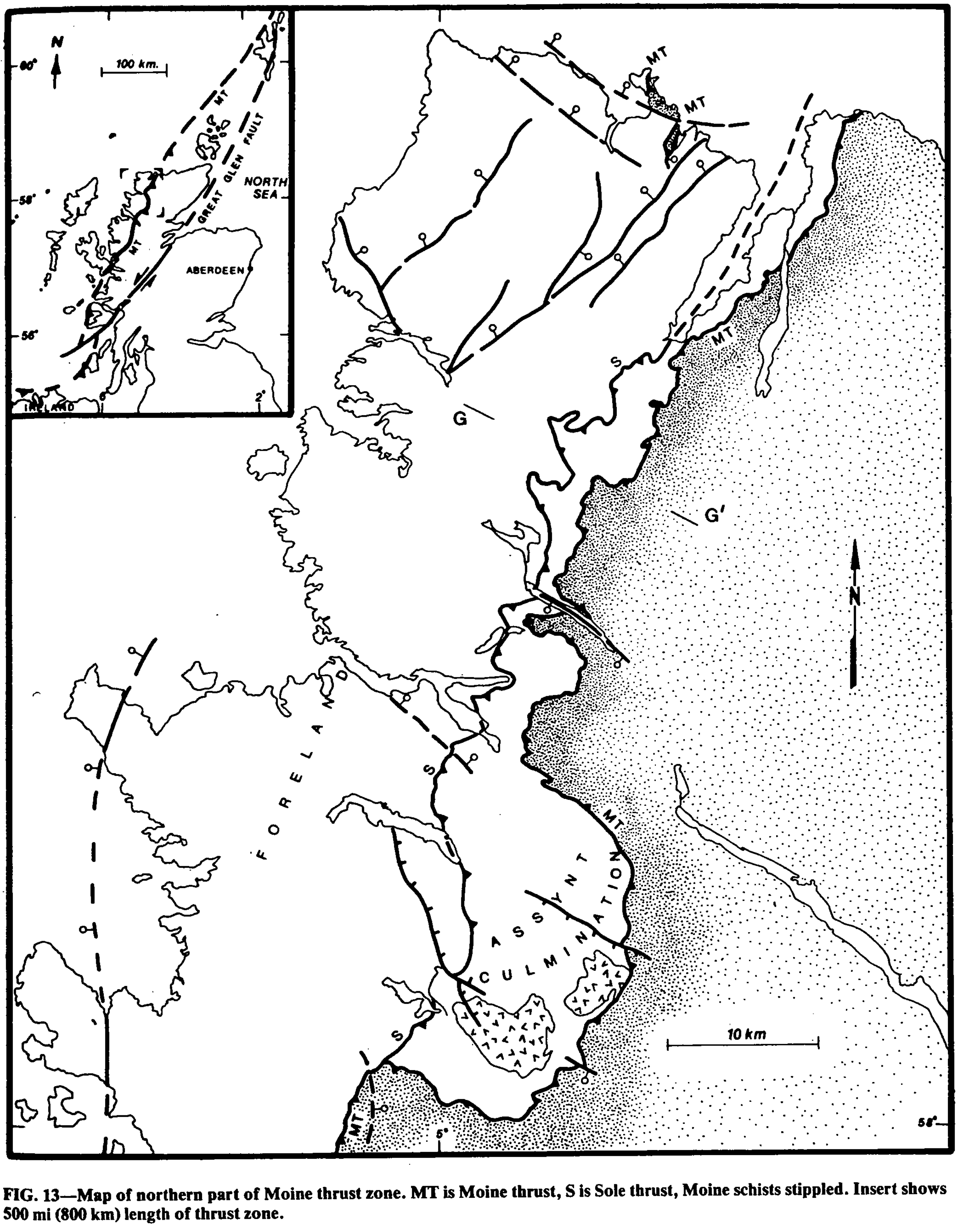


FIG. 13—Map of northern part of Moine thrust zone. MT is Moine thrust, S is Sole thrust, Moine schists stippled. Insert shows 500 mi (800 km) length of thrust zone.

ple. The Cate Creek and Haig Brook windows (Fig. 15) through the Lewis thrust sheet are particularly spectacular examples of duplexes (Dahlstrom, 1970, Fig. 24; Fermor and Price, 1976). It appears that substantial portions of the Lewis thrust are the floor of a duplex.

Klippen and reentrants demonstrate that the Lewis thrust once extended northeast of its present outcrop, possibly as much as 6 to 12 mi (10 to 20 km) (Fig. 15). Consequently, many thrusts that crop out in Cretaceous rocks, such as near the headwaters of the Carbondale River and Marias Pass, are part of a duplex whose roof was the Lewis thrust. Possibly, however, the Paleozoic rocks of the Livingstone and Sawtooth Ranges were brought up on emergent imbricate fans. Along strike, these Paleozoic rocks plunge beneath the Lewis thrust and might become part of the duplex containing the Waterton field (Gordy et al, 1977, Fig. 11b), but this is not clear, for other sections show the Waterton field as an imbricate fan (Gordy et al, 1977, Fig. 14).

A duplex is an imbricate family of horses—a "herd of horses"—but in the same way that a horse can change along strike into a splay (Fig. 10), it is possible for a duplex to change along strike into an imbricate fan.

The subject of along-strike variations in duplexes is discussed later, but it is important to emphasize here the lateral changes in the horses that make up a duplex. This change in shape of a horse, such as shown in Figure 8, is a result of oblique and lateral ramping giving the distinctive scoop shape of roof, subsidiary, or floor thrusts. The huge horses of Paleozoic carbonate rock underlying the Alberta foothills show just this sort of behavior, and are responsible for the doubly plunging culminations that affect the higher sheets. This is outstandingly illustrated by the longitudinal cross sections based on seismic and drill-hole data in Bally et al (1966, Plate 8). The Moine thrust belt also shows along-strike variation of a major duplex. In this case it is exposed at the surface for direct observation because of a regional dip of 10 to 15° which was imposed after thrusting (Elliott and Johnson, 1980, Fig. 6).

Dimensions and Internal Geometry

Duplexes have characteristic internal features (Fig. 18). Beds within a horse often trace out an elongate anticline-syncline fold pair, and bedding near the central inflection point roughly parallels the subsidiary faults. Above and below the duplex the bedding may be rela-

Table 1. Dimensions of Duplexes

Duplex	Contraction Ratio (L'/L_o)	Number of Horses (N)	Approx. Angle Subsidiary to Floor Thrust	Reference
Foinaven duplex in Moine thrust zone	0.29	34	40°	Fig. 14
Windows duplex, southern Appalachians	0.36	21	30-45°	Fig. 29
Lewis thrust (floor of duplex), North American Cordillera				
Chief Mtn.	—	2	23°	Fig. 16
Mt. Crandell	0.57	6	33°	Fig. 17
Cate Creek	0.58	2	31°	Dahlstrom (1970)
Haig Brook	0.6	12	27°	Fermor and Price (1976)
Central Appalachian Valley and Ridge	0.54	4	33°	Fig. 26
Idealized model				
Duplex constructed with kink folds	0.50	—	30°	Fig. 18

Table 2. Some Dominant Thrust Sheets

Dominant Thrust Sheet (Location)	Approximate Width Downdip (km)	Lithology
Moine (Northwest Scotland)	100	Precambrian and Cambrian siliciclastics refolded and metamorphosed to medium and high grades (Figs. 13, 14).
Semail Ophiolite (Oman)	100	Oceanic crust and upper mantle thrust over Arabian continental margin.
Austro-Alpine (European Alps)	150	Mesozoic continental margin unconformable on folded Paleozoic nonmarine sediments and quartzo-feldspathic crystalline complex of medium and high grade (Figs. 31, 34).
Lewis (North American Cordillera of U.S. and Canada)	100 to 200	Paleozoic shelf carbonates unconformable over late Precambrian shelf and slope sequence (Figs. 15, 17).
Jotun (Southwest Norway)	180	Crystalline Precambrian basement of two pyroxene granulites (Hossack et al, 1982).

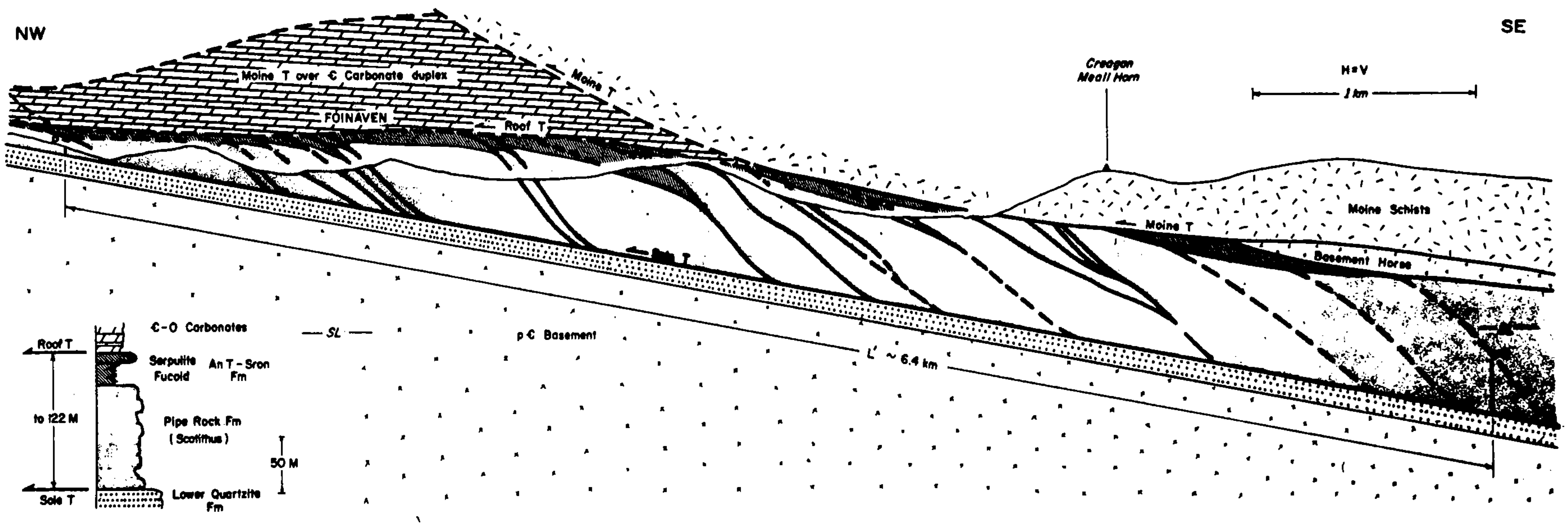


FIG. 14—Cross section of the Foinaven duplex from Moine thrust zone, line of section GG′ on Figure 13. Duplex has area PQ of 2.65 km² and is made up almost entirely of Cambrian Pipe Rock with a little An t-Sron. After Elliott and Johnson (1980, Fig. 4).

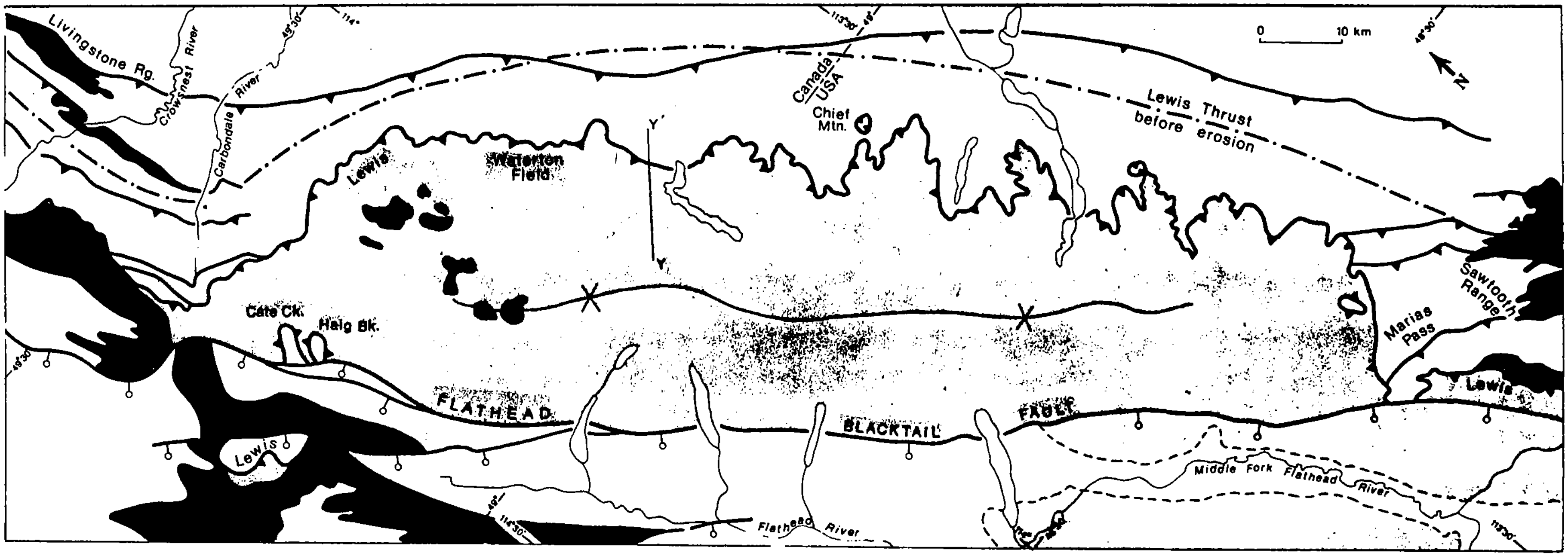


FIG. 15—Map of central portion of Lewis thrust sheet. Proterozoic is light pattern area, Paleozoic is dark area.

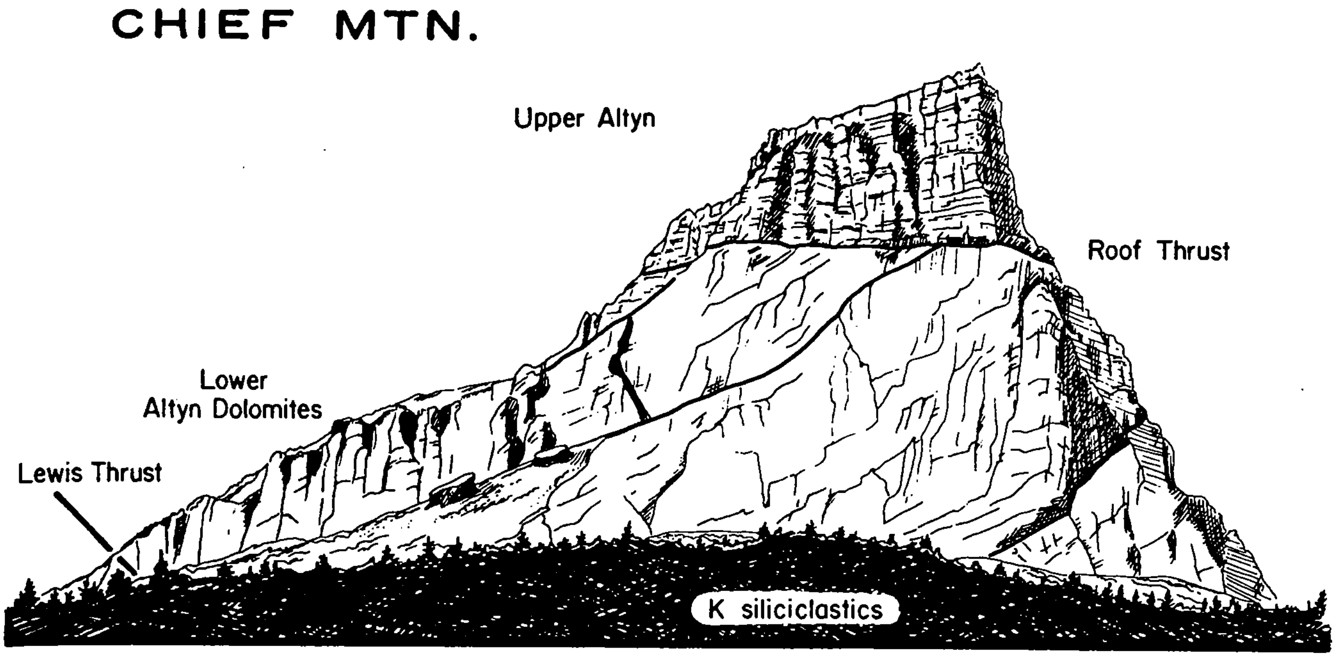


FIG. 16—Chief Mountain klippe, looking north, is eroded fragment of duplex in Precambrian Belt Supergroup whose floor is Lewis thrust. All lie on Upper Cretaceous siliciclastics. After Willis (1902, Fig. 5) and Dyson (*in* Nevin, 1949, Fig. 101).

tively undisturbed, and for long distances a particular stratigraphic unit may compose the hanging wall of the roof or the footwall of the floor.

The fold pairs within any one duplex have a somewhat similar shape and size, and it is often possible to draw enveloping surfaces through the whole sequence of horses. These enveloping surfaces are at very low angles to the floor thrust, seldom exceeding 15°.

While constructing current and restored cross sections through duplexes we repeatedly make a number of simple calculations (equations 1 to 7). Capitals indicate measurements over the complete thickness or length of a duplex, and small letters refer to one horse. The easiest measurements are the current duplex length (L'), structural thickness (H'), cross-section area (A), initial stratigraphic thickness of the formations making up the horses (t), and the current angle (β')between floor thrust and the central portion of the subsiding faults (Fig. 18).

We assume plane strain, with the cross-section area

$$A = H'L' = tL_o, \qquad (1)$$

where L_o is the initial length of the duplex. The overall shortening distance (S), accomplished by formation of the duplex, is

$$S = L_o - L', \qquad (2)$$

and from equation 1

$$S = A/t - L'. \qquad (3)$$

If the bed length (ℓ) within each horse is unaltered by deformation, then the total initial bed length within the duplex is

$$L_o = \Sigma\ell = N\ell_a, \qquad (4)$$

where N is the number of horses with an average bedding length of ℓ_a.

The perpendicular distance (h) between subsidiary faults bounding a horse may approximate the initial stratigraphic thickness (Fig. 18), $h = t$, so that the spacing between subsidiary faults, measured parallel with the floor thrust, is

$$p' = t/\sin\beta'. \qquad (5)$$

Now the total number of horses in the duplex is

$$N = L'/p', \qquad (6)$$

and the number of faults per unit length

$$N/L' = \ell/p'. \qquad (7)$$

A duplex beneath the Moine thrust provides an example of these calculations (Fig. 14). The duplex has a cross-section area (A) of 2.65 $10^6 m^2$ and a current length (L') of 6.38 km. The average structural thickness (H') is 415 m, although in the central and southeast part the duplex is thicker (H' is 510 m). The duplex consists almost entirely of quartzite, although some shale is present toward the top, and the initial stratigraphic thickness (t) of the formations making up the duplex is 122 m. The initial length (L_o) is equivalent to 21.7 km from equation 1, and from equation 3 the shortening (S) is 15.3 km.

Only 20 faults, clearly observed on cliffs, were plotted

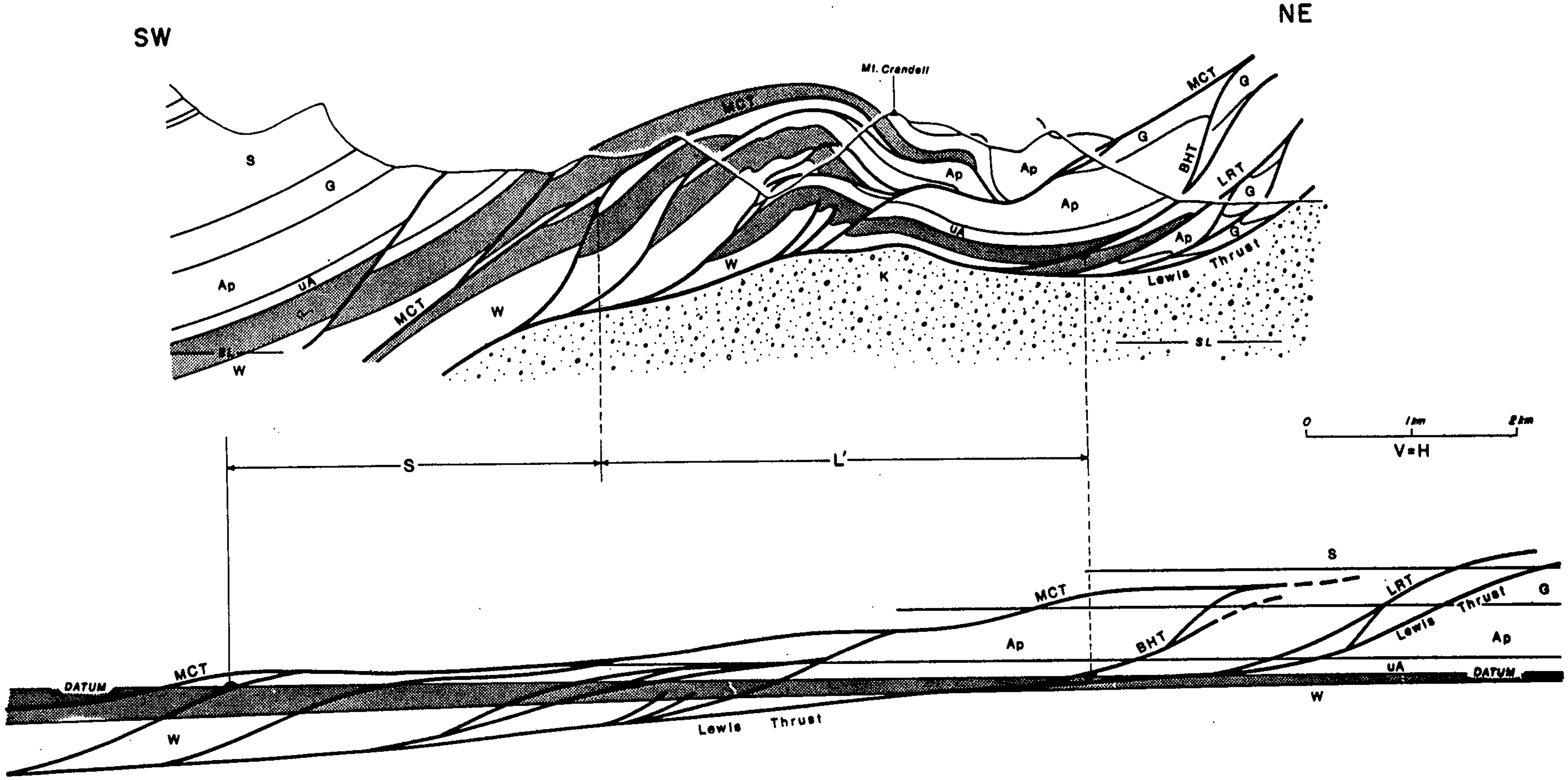


FIG. 17—Precambrian Belt Supergroup, comprising Waterton (W), lower Altyn (fine stipple), mid and upper Altyn (uA), Appekunny (Ap), Grinnell (G), and Siyeh (S), is thrust over Cretaceous siliciclastics (K, with pebble pattern) by Lewis thrust. Mount Crandell thrust (MCT) is roof and Lewis thrust is floor to duplex, and folded horse just northwest of Mount Crandell suggests that duplex developed toward foreland. Cross section is balanced (with current distance L′ between points recording a shortening of S), and is based on excellent control provided by over 2 km of local relief. Modified from Douglas (1952).

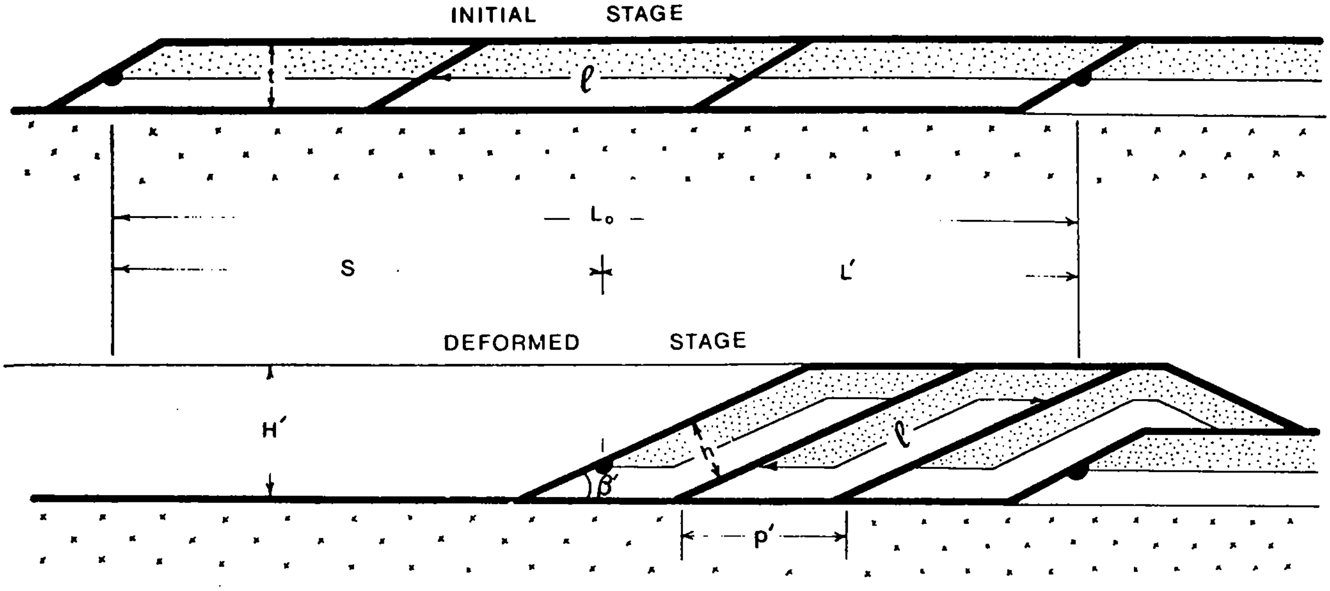


FIG. 18—Initial and deformed stages in formation of duplex, showing quantities L_o, L', S, t, H', ℓ, h, p', β' used in equations 1 through 8. Note elongate "S" folds in horses. Modified from Boyer (1978).

on the section. Many more subsidiary faults must be present, but how can this number be estimated? The angle β' between subsidiary faults and floor averages around 40°, but ranges between 25 and 55° and is smallest at the northwest end of the section.

The spacing between subsidiary faults must also vary (from equation 5) between 290 and 150 m, with a mean spacing (p') equal to 190 m. Consequently, the total number of faults (using equation 6) varies between 22 and 45, with the mean (N) being 34.

The shortening and structural thickening can vary from place to place. If the duplex involves a similar stratigraphic thickness and uniform mean bedding length (ℓ_n) in the horses, it follows from equations 4, 5, and 6 that

$$\left\{\frac{L'}{L_o}\right\} = \frac{p'}{\ell_n} = \left\{\frac{t}{\ell_n}\right\} \frac{1}{\sin \beta}. \tag{8}$$

Therefore, as the shortening and thickening decrease, the ratio (L'/L_o) increases, and the angle β' must decrease.

As the Foinaven duplex gets thinner, the angle β' becomes smaller and the local shortening must diminish. By comparing different duplexes (as in Table 1), we see that β' varies inversely with the contraction ratio (L'/L_o).

Sequence of Development

There are two sides to any thrust belt. On one side is the internal zone or hinterland, and on the other, beyond the external zone and the margin of the thrust belt, is the foreland. When we require a sense of direction toward the hinterland or foreland, we use the terms "hindward" or "forward."

In this section, we review several different geometric arguments for the successive development toward the foreland, or a forward progression, of the subsidiary faults in duplexes. The oldest argument is best illustrated by an example, the Mount Crandell duplex (Fig. 17), where a higher horse is folded over a lower one proving the forward development (Dahlstrom, 1970, p. 352). Independently, Perry (1971, p. 195) deduced the same time sequence in a central Appalachian duplex.

The next arguments are based on a series of simple graphic experiments developed by Boyer (1978). First, we construct an idealized model based on typical dimensions and angles of observed duplexes (Table 1) assuming plane strain, constant bed lengths, and kink folds (Fig. 19). In the initial stage a major thrust with slip S_o has climbed upward in the section from a lower to an upper glide horizon, cutting rather steeply through a more competent sequence and making a footwall ramp. A new crack propagates from the base of the ramp, continues in the lower glide zone for some distance, and then cuts upsection to the higher glide horizon where it rejoins the preexisting major thrust. During the next time interval (Fig. 19, stage 1), this new fracture (S_1) slips, the overlying fault segment remains fixed, yet behind and in front of the new horse the major thrust slips by $S_o + S_1$. In other words, as slip is transferred to the new and lower fault a portion of the major thrust is deactivated and rides passively within the growing thrust sheet. The new horse, the inactive portion of the major thrust, and the rest of the overlying thrust sheet are folded, possibly in kinklike fashion, over the footwall ramp. Movement is again transferred to a new branch fault and the process is repeated (Fig. 19, stages 2, 3).

After the development of several subsidiary faults the duplex achieves its characteristic features: elongate folds within the individual imbricate horses with bedding locally parallel with the subsidiary faults, relatively undisturbed bedding above the roof thrust, and the same stratigraphic unit in the hanging wall along the roof thrust for a great distance. Compare the features in Figure 19 with those in the Mount Crandell duplex (Fig. 17).

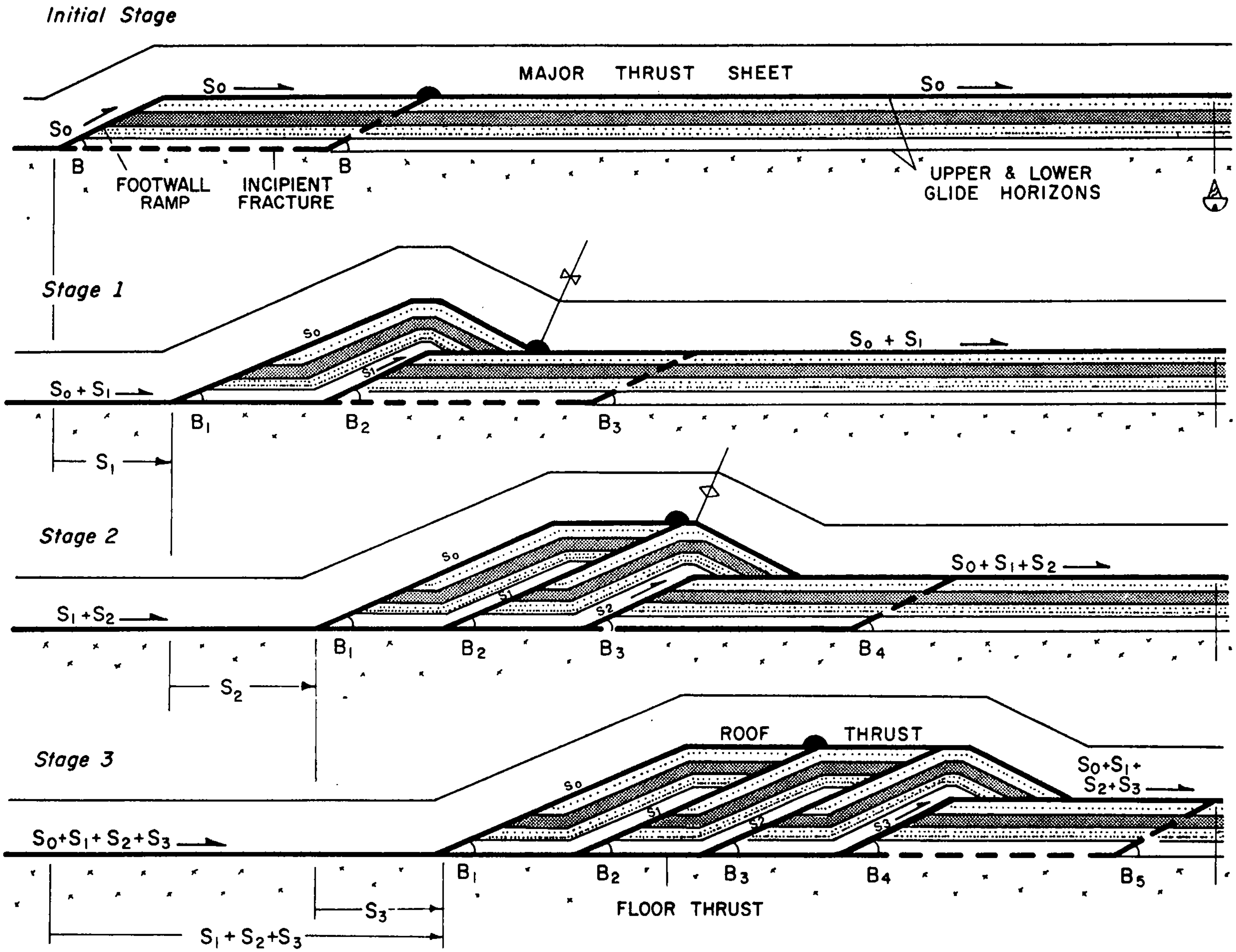


FIG. 19—Progressive collapse of footwall ramp builds up duplex. This is measured graphical experiment, assuming plane strain and kink folding, with angles and ratios of dimensions typical of natural examples (Table 1). Roof thrust sheet undergoes complex sequence of folding and unfolding, seen by following black half dot. Modified from Boyer (1978).

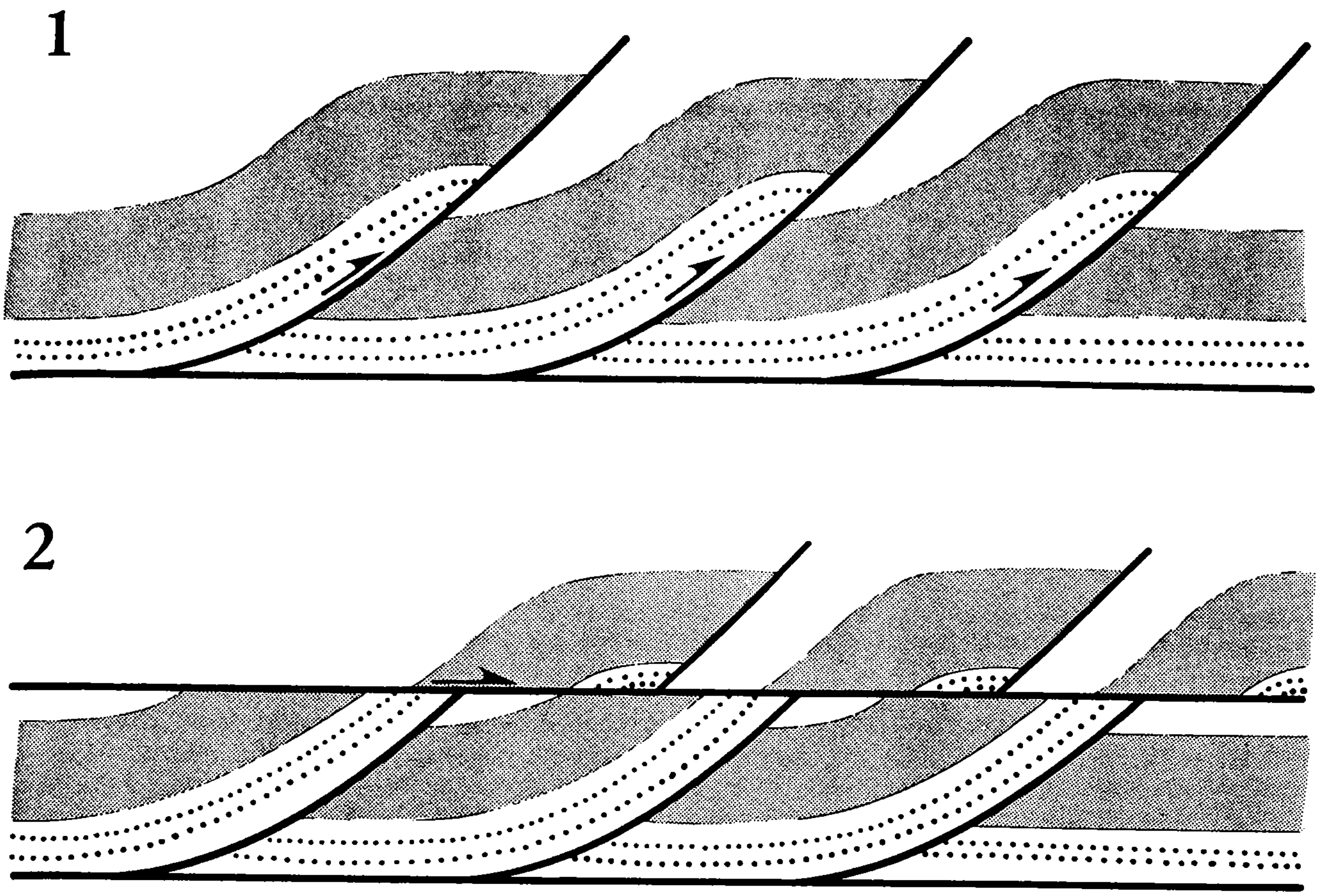


FIG. 20—Alternative method for developing duplexes. Earlier formed imbricate faults in stage 1 (above) are truncated by younger and higher thrust in stage 2 (below) (Boyer, 1978).

The faulted stratigraphic section is doubled in the area of each footwall ramp. As the thickened section enters the next ramp, the leading limb of the anticline is returned to the horizontal, and the fold is partially opened (solid half-dot in Fig. 19). At this point a new branch fault forms in this idealized model.

Duplexes are a mechanism for slip transfer from one glide horizon at depth to another at shallower levels. In the direction of movement, slip decreases along the floor and increases along the roof, and total slip at any point along the floor or roof thrust is dependent on the number of horses that lie between that point and the head of the duplex. Slip transfer and the creation of new horses causes structural thickening, duplex growth, and addition of mass to the moving thrust complex.

Let us now try some graphic experiments using alternative sequences of development. Because hanging-wall rocks of the roof thrust are often flat-lying or only gently folded, one might suggest that the high-angle subsidiary faults formed first by branching upward from the floor thrusts, then were truncated by the roof thrust. The resulting stratigraphic relations, however, are unlike those of any duplexes described to date (Fig. 20).

Could a duplex form by sequential branches that become younger toward the hinterland, a hindward progression? Here also the geometric features are not found in natural duplexes, although the imbricate fan is a possible structure (Fig. 21).

If the roof thrust were partially removed by erosion, one might be able to see the layout of the entire internal structure in the eroded duplex. For example, a number of southern Appalachian imbricate thrusts converge upward to the Rome thrust (Rodgers, 1970, p. 57), and the map pattern is probably an oblique section through a duplex. A map would show the roof thrust running across the subsidiary thrusts and appearing to "truncate" them (Fig. 22). This appearance of "truncation" or "overlap" in the Moine thrust belt led numerous authors to the erroneous belief that the higher Moine thrust was the last to form (Elliott and Johnson, 1980, p. 90). Repeated examples of this typical geometric pattern of apparent truncation in the southern Appalachians are interpreted, we think incorrectly, as a hindward sequence of imbrication (Rodgers, 1970, p. 178; Milici, 1975; Harris and Milici, 1977, p. 14). In Montana, precisely similar relations exist along the Lewis thrust and are misinterpreted as a hindward thrust sequence (e.g., Mudge and Earhart, 1980, p. 14).

But the problem is not trivial. We see that as each subsidiary thrust in turn joins the roof a steadily increasing portion of the roof is immobilized. Thus, there is an apparent paradox: a major roof thrust moved at different times along its map trace, yet everywhere it may bear the same name.

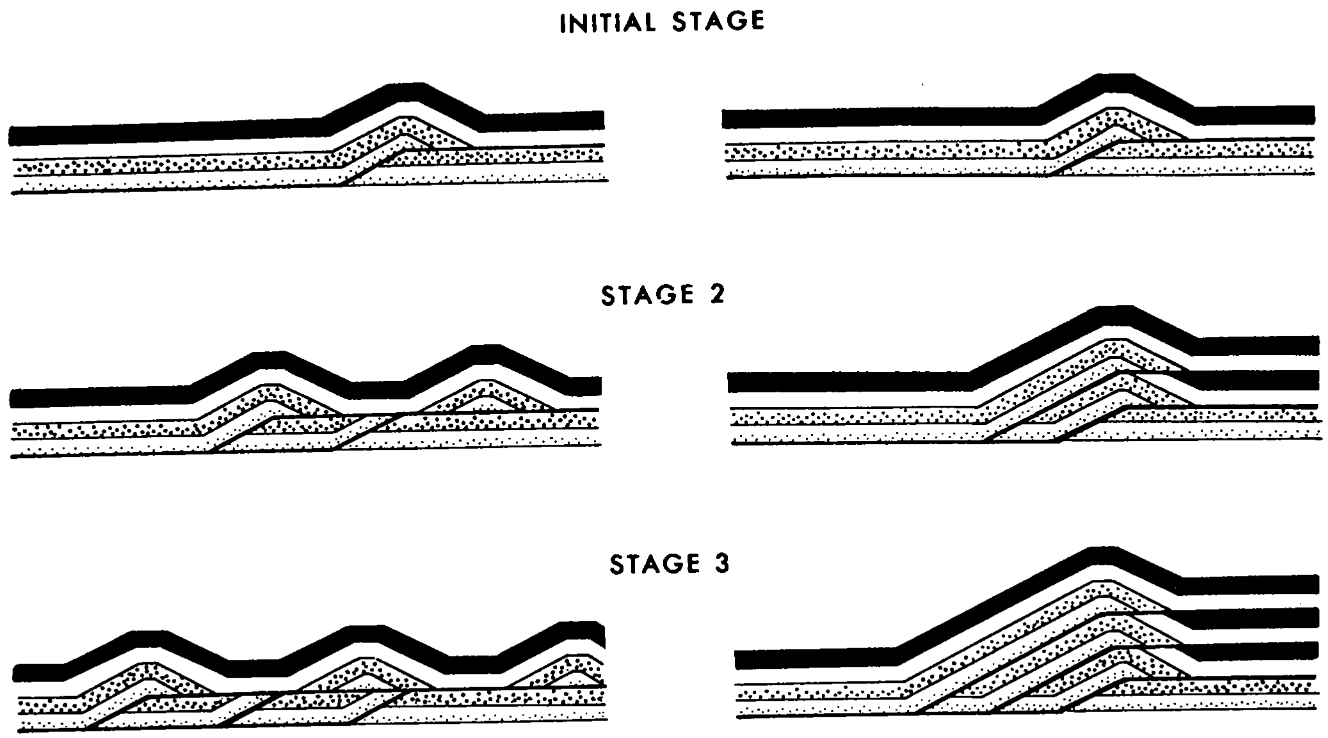


FIG. 21—Two alternative methods of hindward imbrication shown by measured graphical experiments (Boyer, 1978).

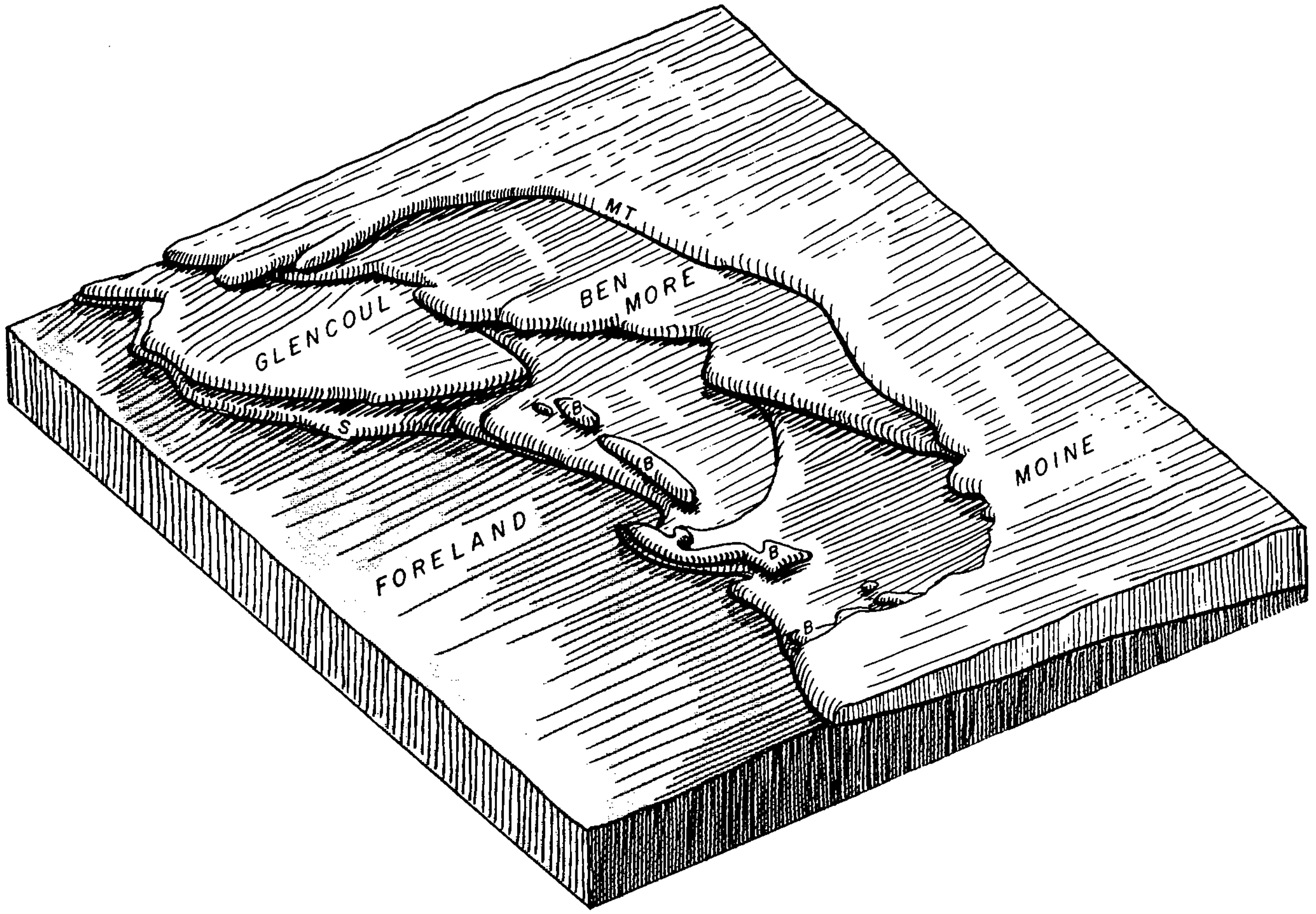


FIG. 22—Block diagram of Assynt culmination in Moine thrust zone (Fig. 13). This is oblique section through duplex. Diagram follows geologic interpretation of Elliott and Johnson (1980) and was inspired by plaster model on display at University of Edinburgh, and drawing by H. Cloos (1936, Fig. 290).

Antiformal Stacks and Forward-Dipping Duplexes

In a hindward-dipping duplex—the only kind discussed o far (Fig. 19)—the effect of shortening is to move the ranch lines somewhat closer together. If the slip on the ubsidiary faults is roughly equal to the length of the orse, then adjacent branch lines will bunch up and the orses will lie on top of one another. This occurs from me to time in an otherwise normal duplex, like the pper horses in the Mount Crandall duplex (Fig. 17). If e bunching of branch lines is widespread, the shinglelike imbricate pattern is destroyed. Instead, we have an ntiformal stack of horses where each higher horse is olded about the lower ones. This folding dies out downard and provides unambiguous evidence of the equence in which the horses were accumulated into the ack, as we see in the Dundonnell antiformal stack (Fig. 3). This small structure in the Moine thrust belt is historally important, for it was here that field geologists first orked out the piggyback or forward sequence of thrustng (Cadell and Horne, in Peach et al, 1907). However, ault "truncation" (discussed in the previous section) ave exactly the opposite time sequence, and this view revailed until recently (Elliot and Johnson, 1980, p. 90-3).

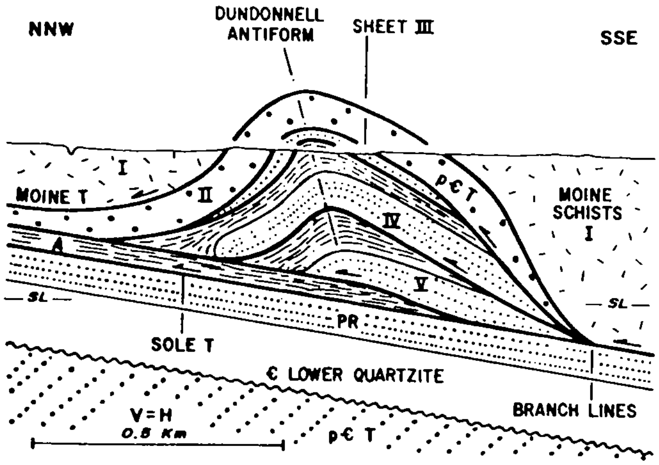
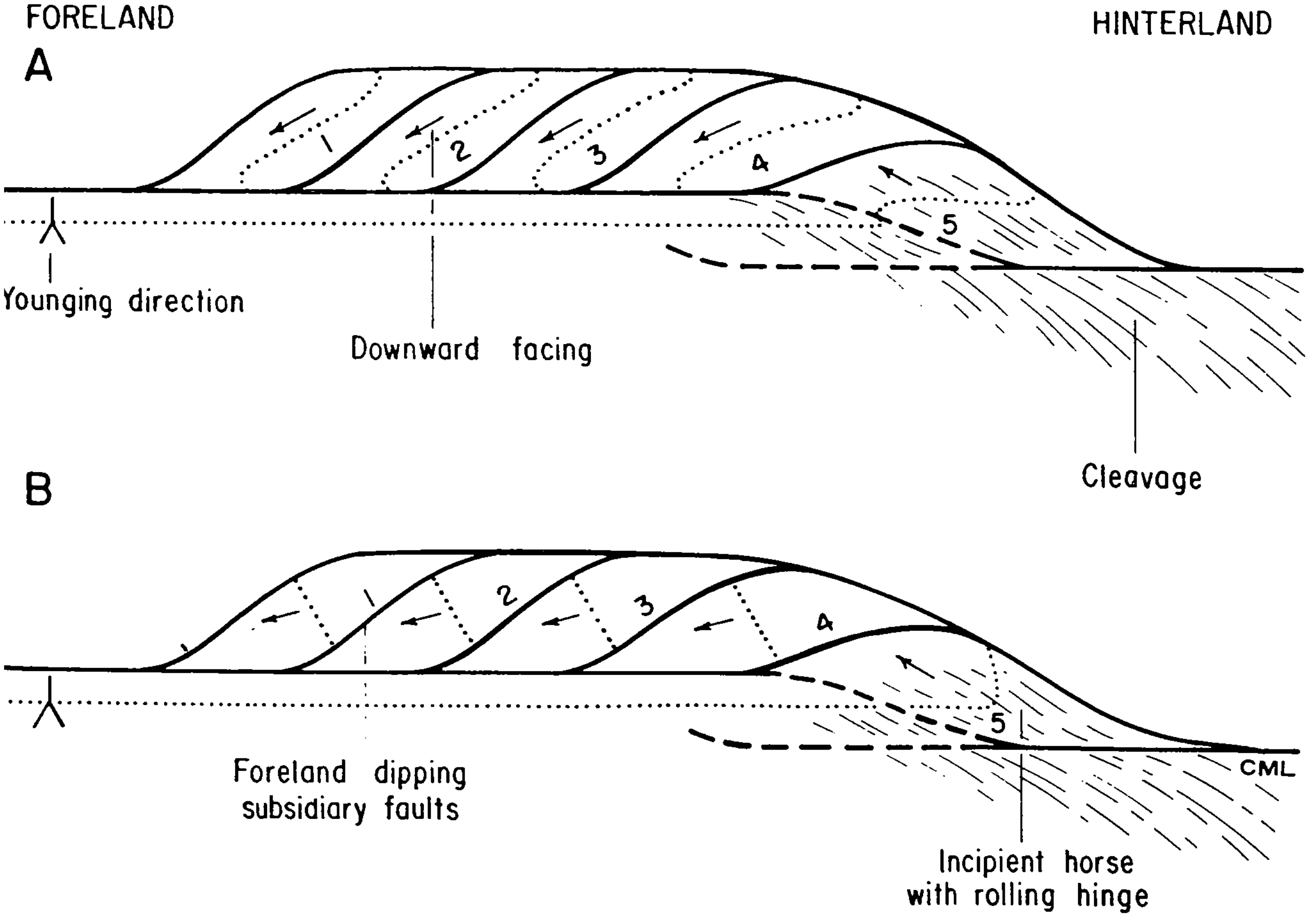


FIG. 23—Balanced cross section constructed normal to fold axis of Dundonnell antiformal stack, but at high angle to movement direction (see Elliott and Johnson, 1980, p. 90). Pebble pattern (pЄT) is Torridon group fluvial sandstones and conglomerates. Stippled pattern (PR) is Cambrian Pipe Rock formation, a quartzite. Dashed pattern A, is Cambrian An t-Sron formation, with an important shale. The sheets are numbered I to V in their order of formation.



IG. 24—Formation of forward-dipping duplexes. Horses numbered in order of formation; youngest horses (5) are not yet comletely developed. Formations within horses may be predominantly right-way up (A) or upside-down (B), structures are often ownward facing, but always forward facing.

In the Dundonnell structure, several of the higher and originally more internal branch lines are now over and forward of the underlying ones. This process can develop further when each branch line passes over and beyond the underlying one. We now recover once more the imbricate pattern (Fig. 24). The dip of the subsidiary faults suggests the term, forward-dipping duplexes, and the roof now contains the branch lines that started on the floor thrust. Forward-dipping duplexes were first proposed by N. Woodward (personal commun., 1981) for the southern part of the Mountain City Window.

Consider a horse just in the process of being plucked from a ramp and with cleavage developing in the surrounding rocks (Fig. 24). Stratigraphy, cross-bedding, or other primary features will usually provide the way-up or younging direction, and the cleavage/younging orientation within each horse fixes the structural facing of the horse from Shackleton's rule (Shackleton, 1958). Forward-dipping duplexes will usually consist of downward-facing horses (Fig. 24), even when the beds are upside down and originated at a footwall syncline with a rolling hinge (Fig. 24). In a similar fashion, hindward-dipping duplexes are usually composed of upward-facing horses, but both hindward and forward-dipping duplexes always have a forward structural facing. We have assumed here a particularly simple relation

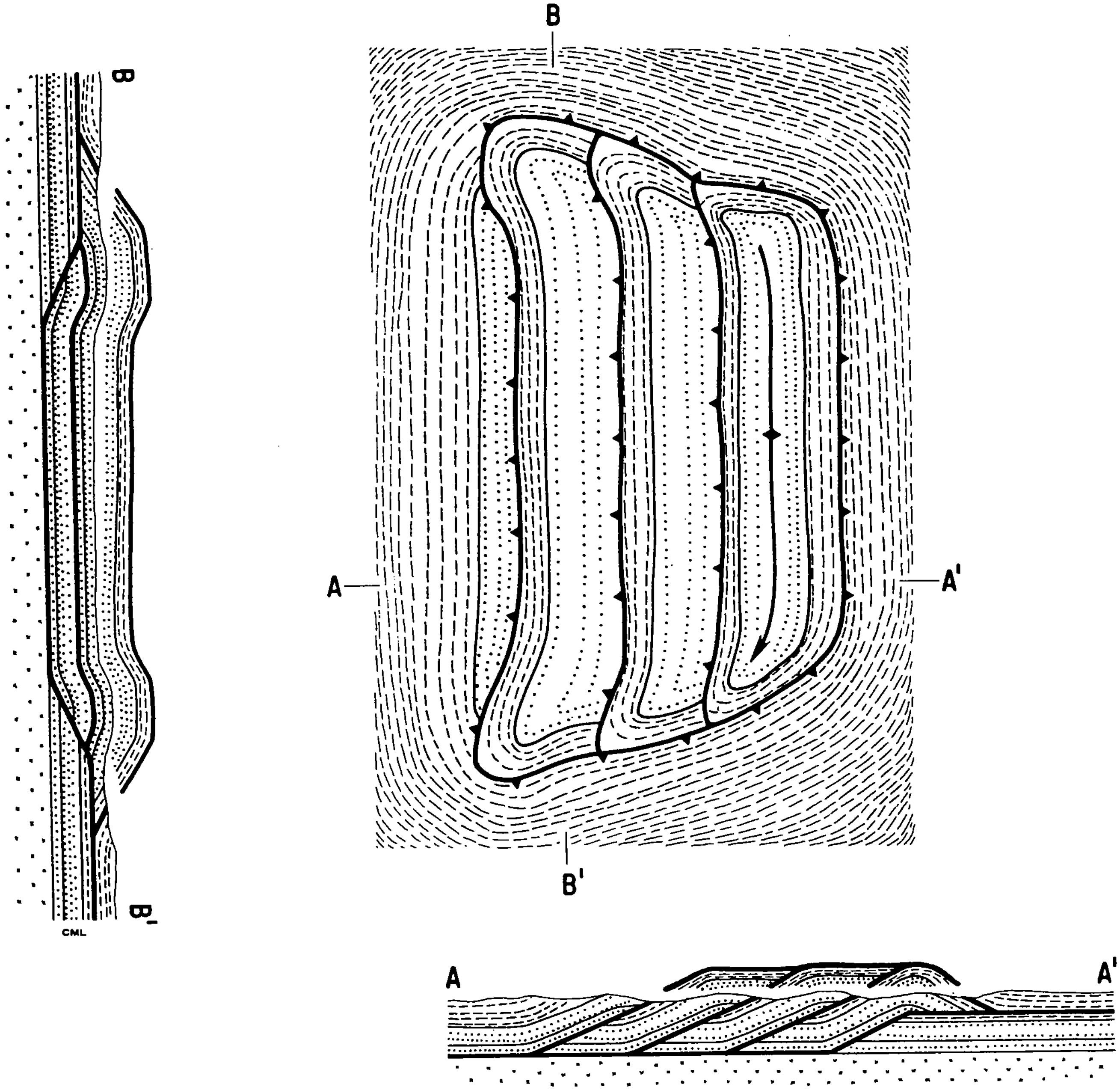
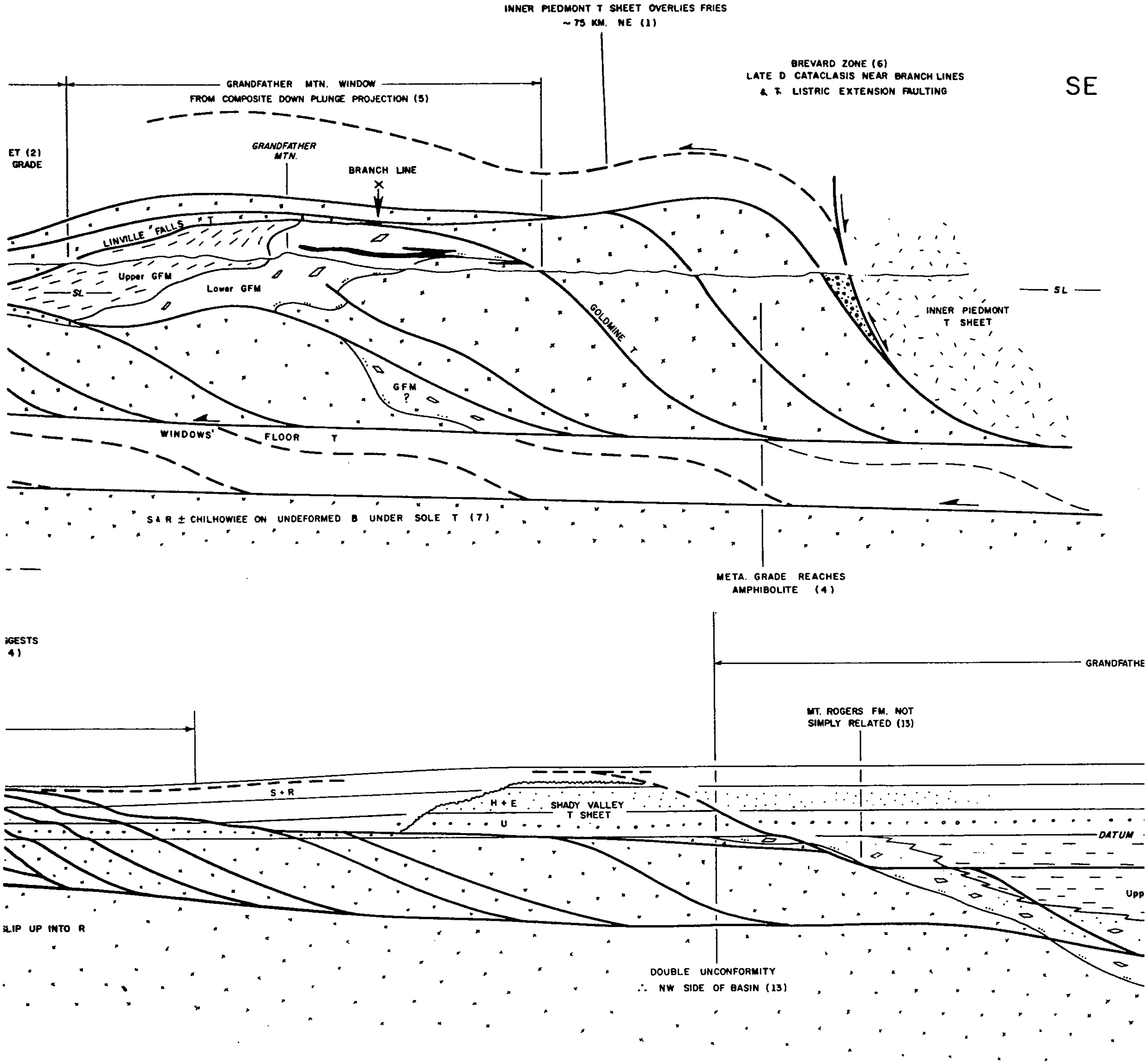
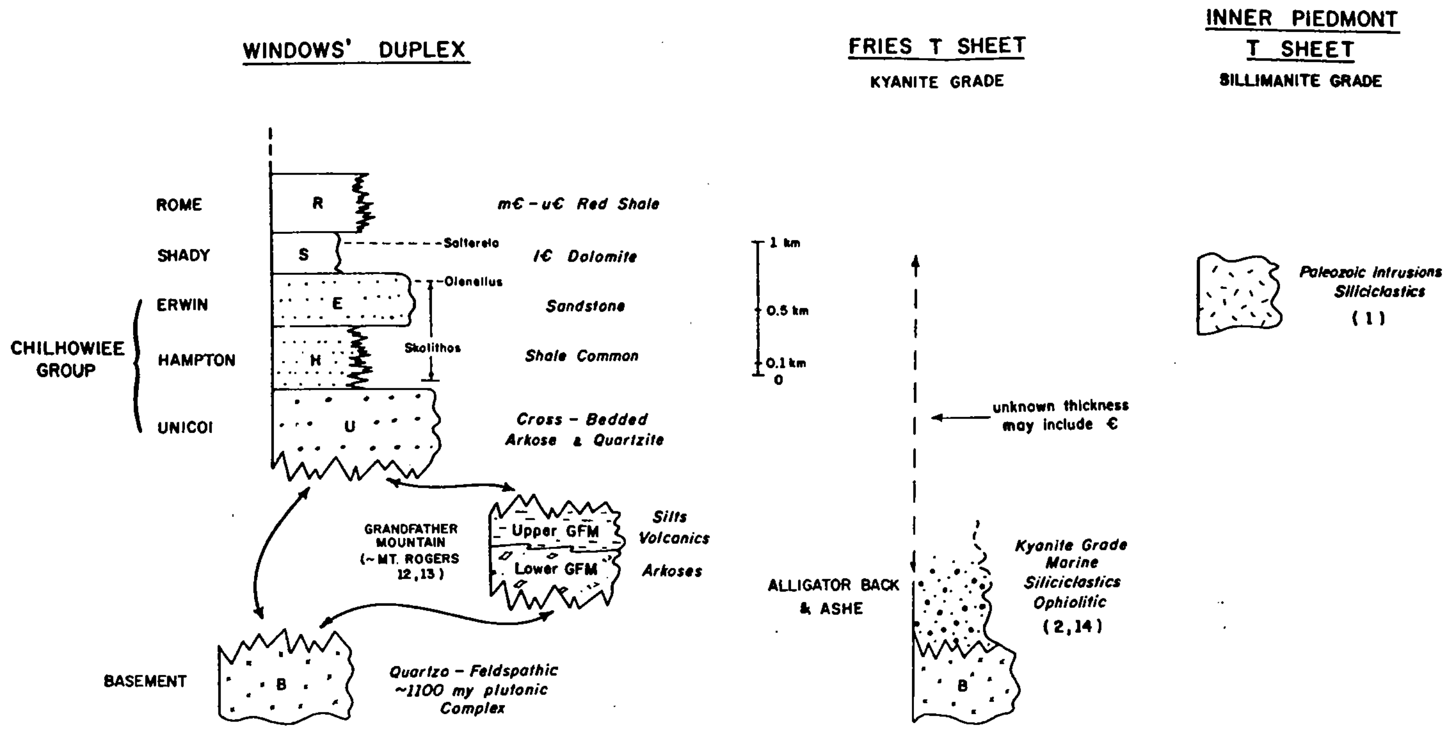


FIG. 25—One type of window into duplex. Anticline occurs at foreland side of window and overlies ramp in floor thrust. Othe anticlines occur within each horse. Lateral termination of window may be lateral ramp in sole or floor thrust, with roof and flo thrusts rejoining along strike as well as across strike (Boyer, 1978).



The section is balanced below the Fries thrust.



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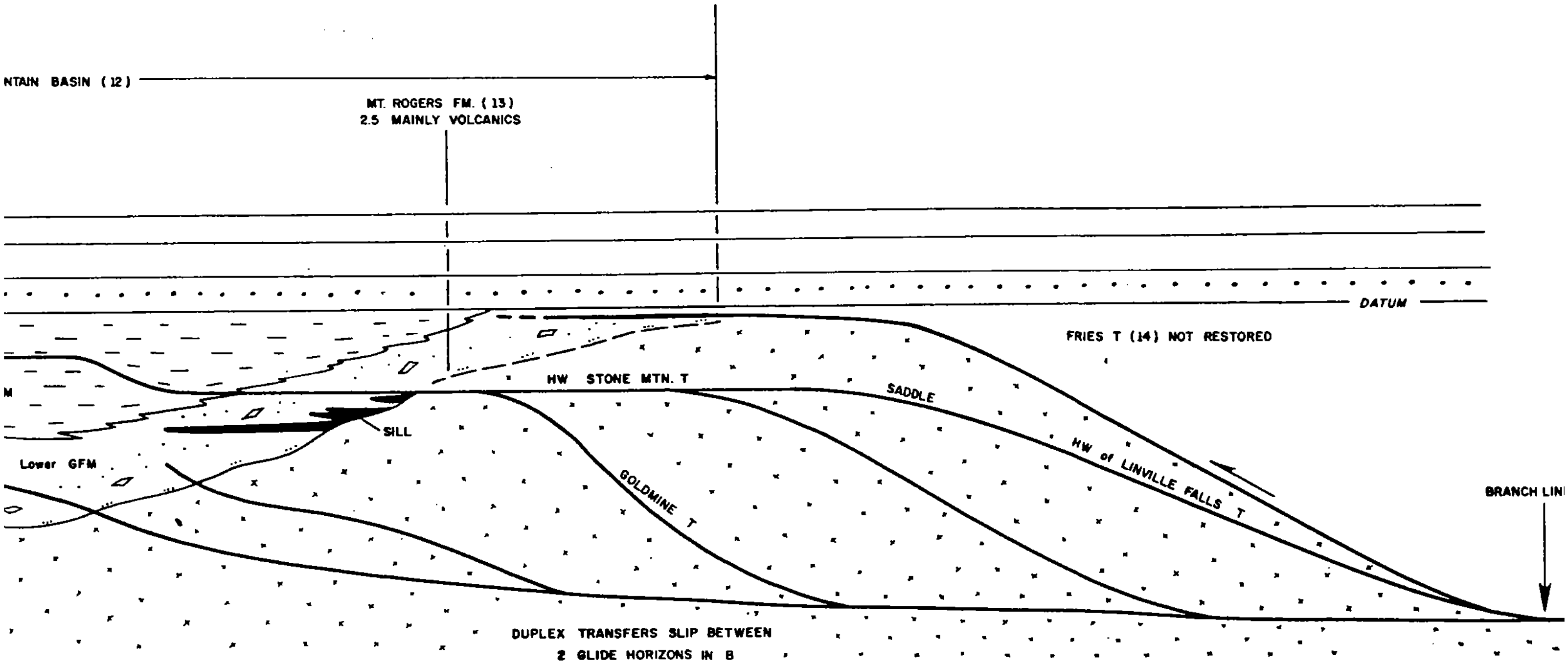


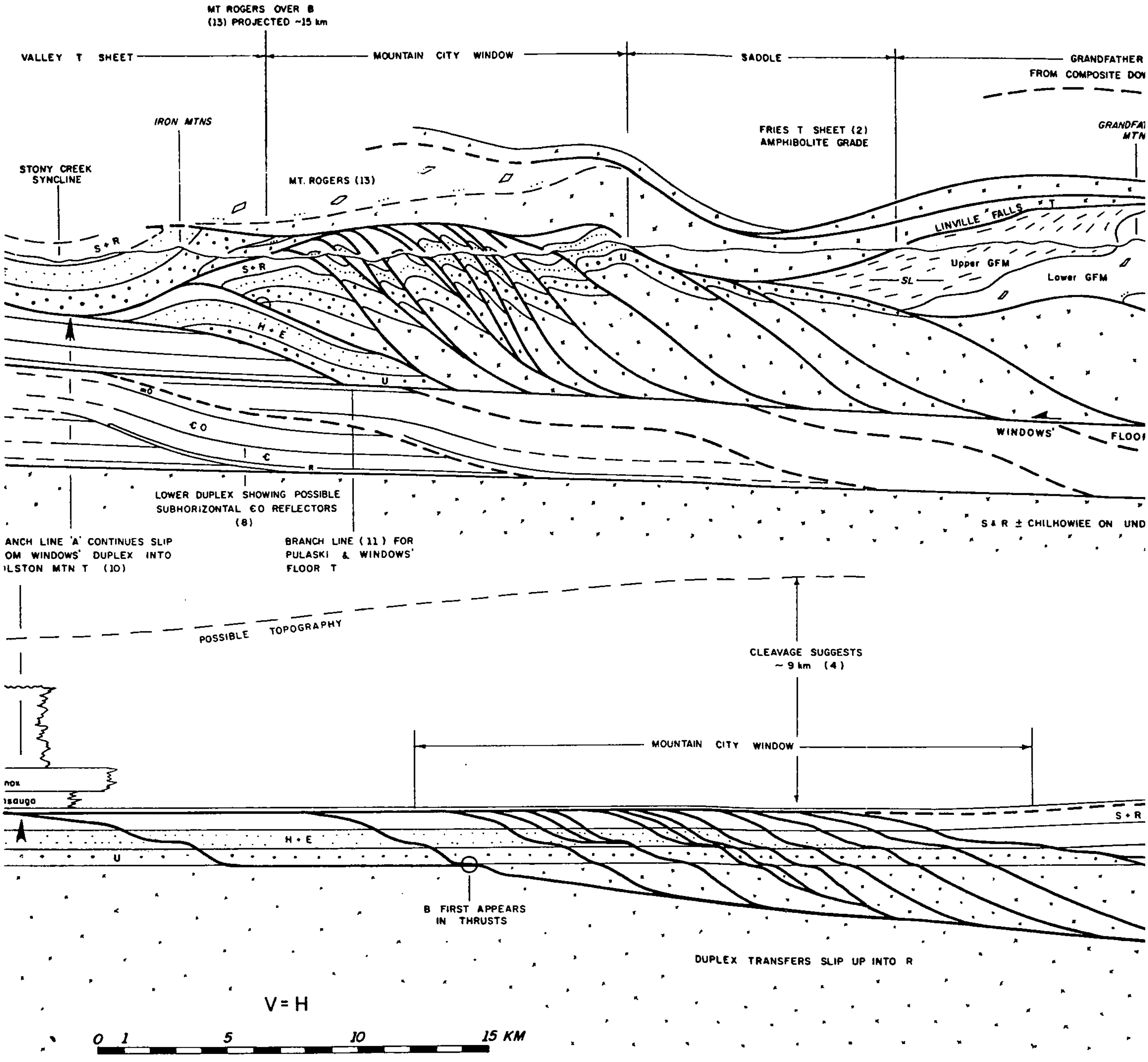
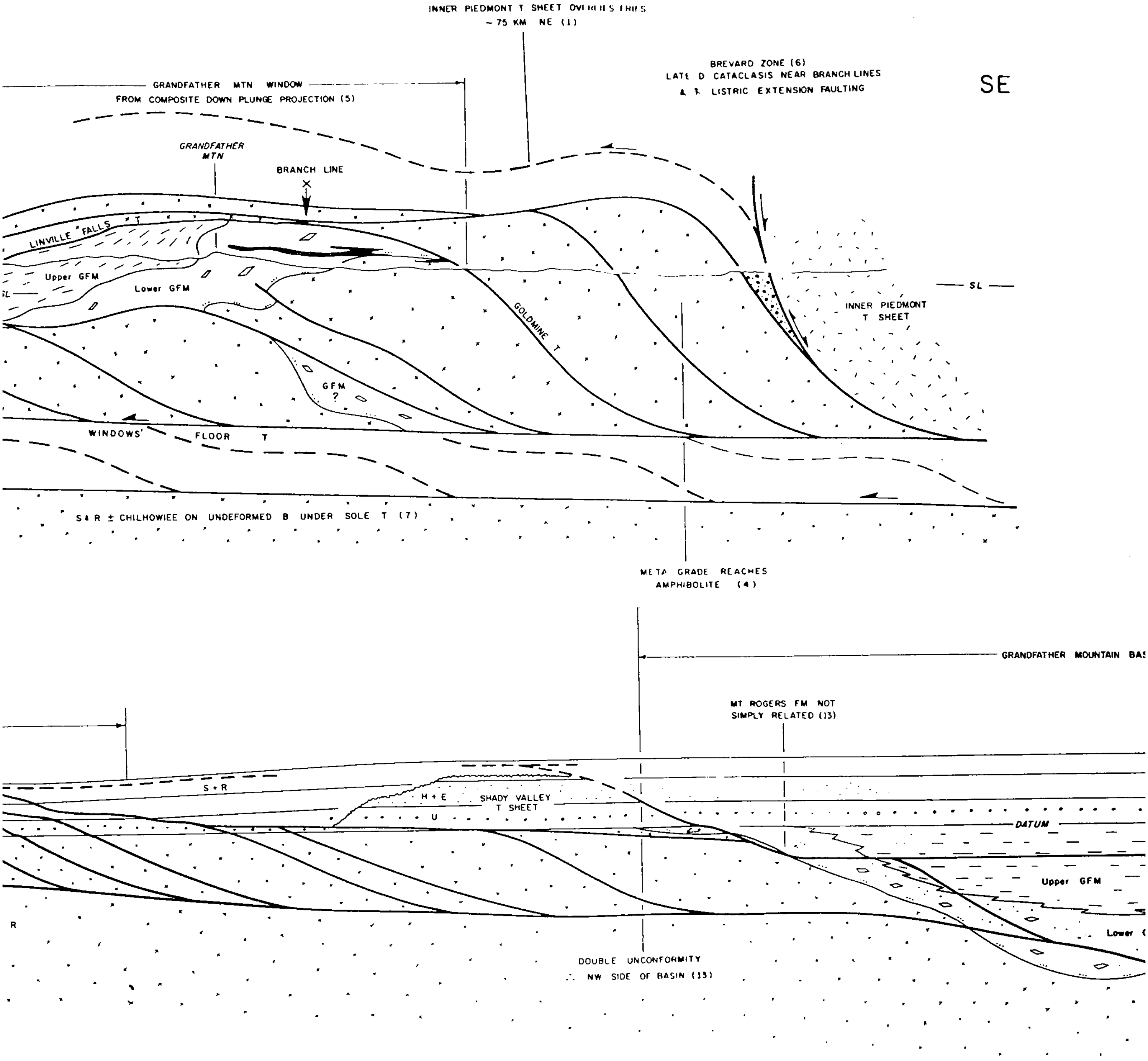
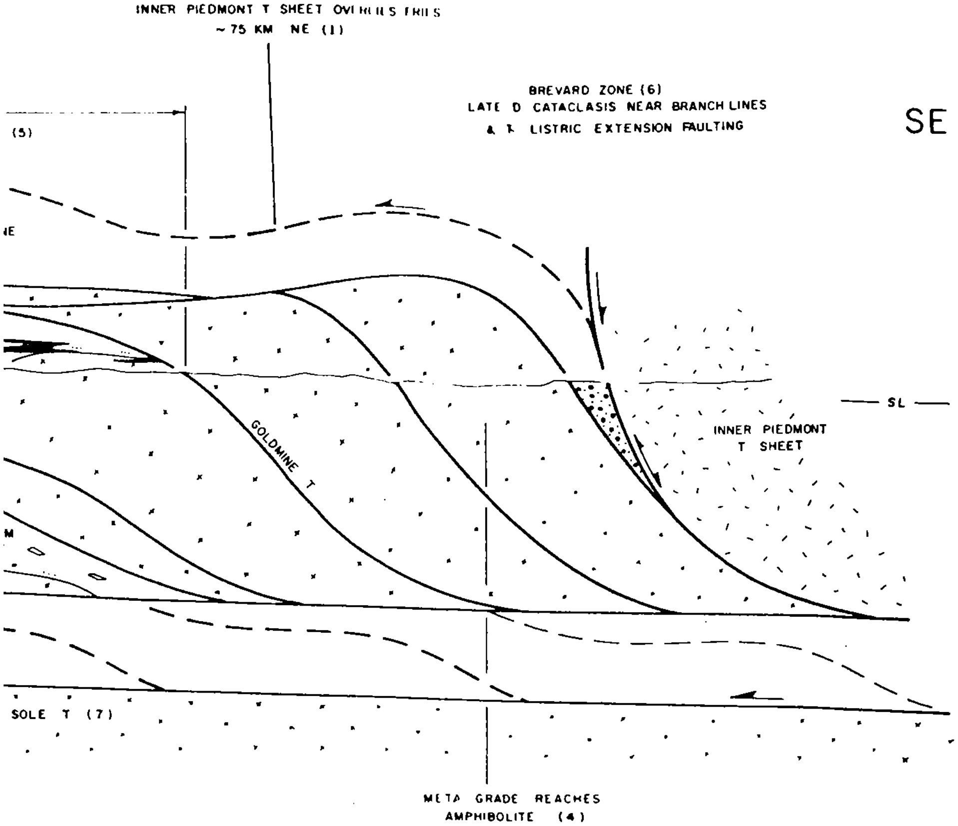


FIG. 29—Cross section through Blue Ridge in southern Appalachians along line AA′ of Fig. 28. The section is balanced below the Fries th



on is balanced below the Fries thrust.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~75 KM NE (1)
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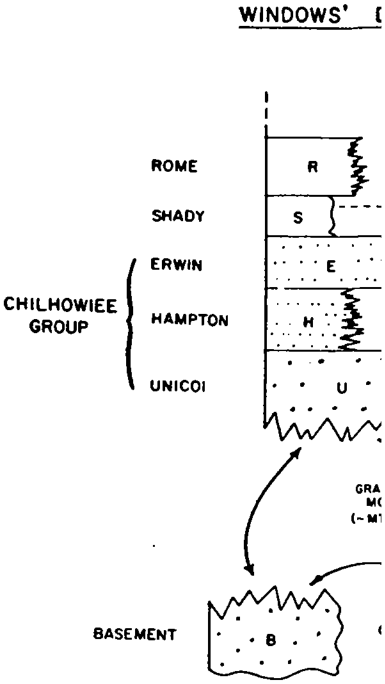
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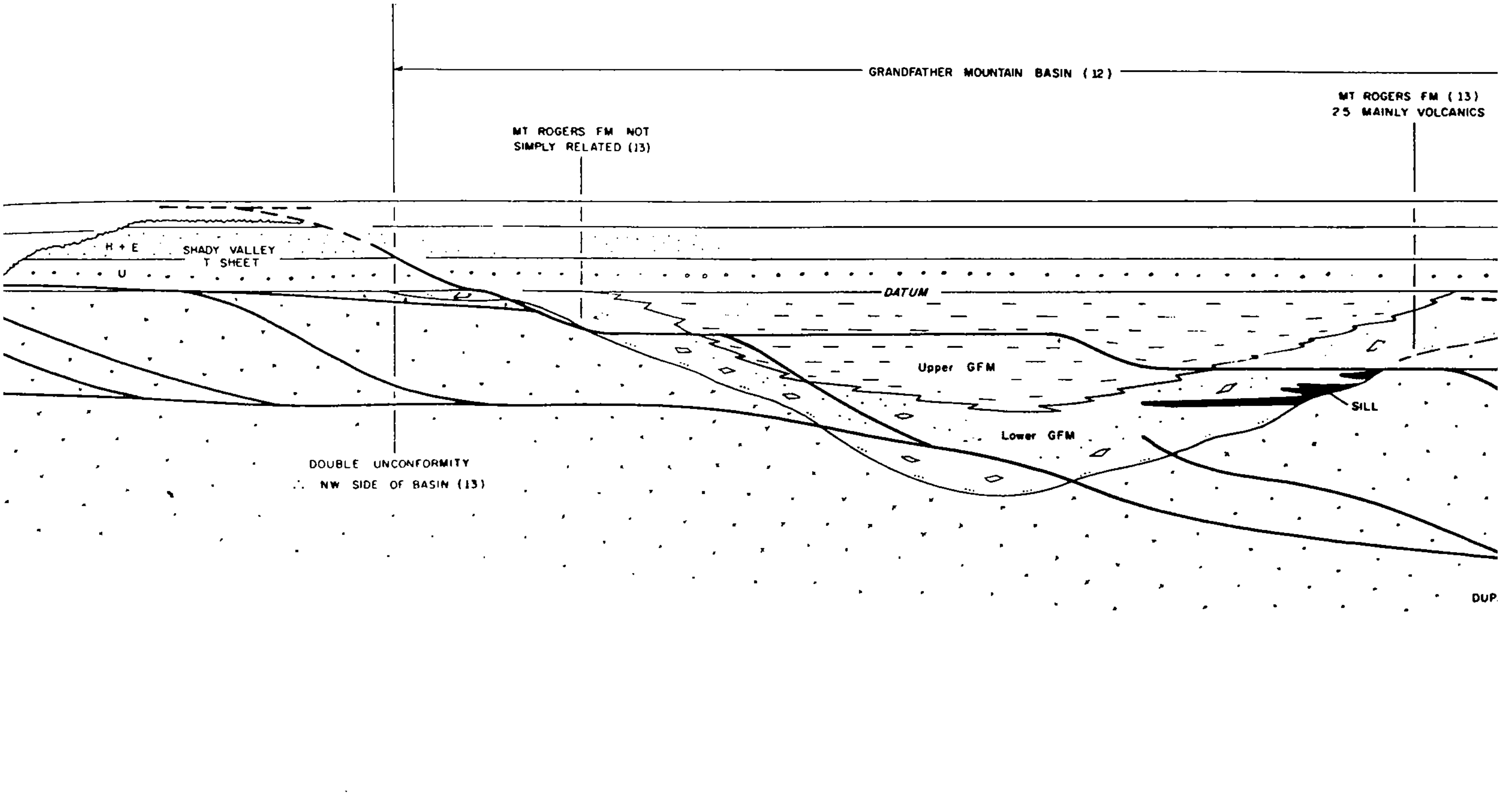
GRANDFATHER MOUNTAIN BASIN (12)
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ween formation of cleavage and the duplex, and of ırse much more complex situations can exist.

Culminations and Windows

Vindows may form by simple differential erosions into disturbed planar faults, but usually they form by ero- ·n through culminations. Frequently, a culmination in thrust surface is produced after the thrust was ıplaced, and this folding could, in principle, run from) to bottom through the entire cross section including sement—an interpretation widely favored in older atments. However, balanced cross sections and seis- c exploration reveal that the folding itself is a conse- ence of thrust processes and is restricted to the rocks ove a basal sole thrust. (This will be assumed through- t the rest of this paper.) Although the basal sole thrust ınfolded, it is not necessarily smooth; in fact it usually ows lateral and fronted ramps that create the overlying ds and culminations. The Moine thrust belt has several posed examples showing this typical behavior, but in ıny other thrust belts the sole thrust is not available to ·ect observation (Elliott and Johnson 1980).

Culminations and Folds in Roofs of Duplexes

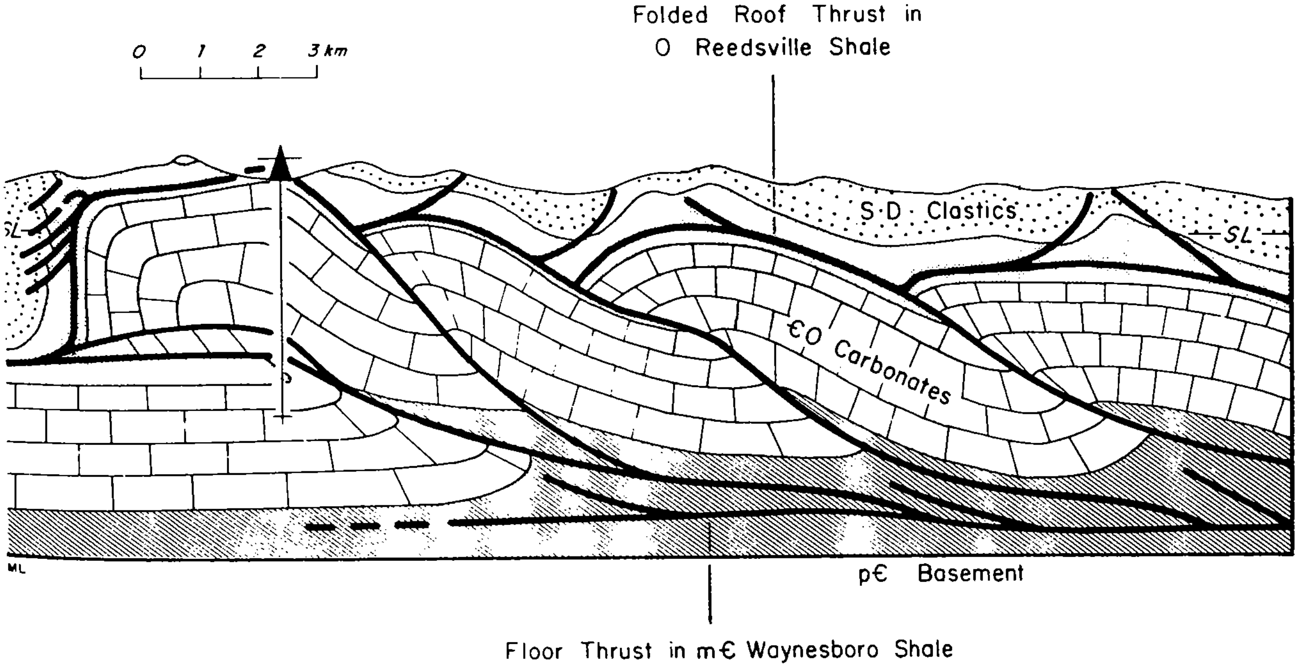
\ culmination produced by a duplex with one frontal d two lateral ramps is idealized in Figure 25. In this odel, the culmination has a flat top where the roof and oor thrusts are parallel and planar.

Erosion through this type of culmination produces a aracteristic type of duplex window, which Tollman (1968, p. 46) called a "window of dislodged slices" (schurflingsfenster). The distinctive features on a map are: (1) a pattern of several subsidiary faults that join the roof thrust at the window margin, (2) doubly plunging anticlines within each horse, and (3) anticline crests and subsidiary faults are roughly parallel (Boyer, 1976, 1978).

There are several other ways in which a duplex can cause a culmination, such as dissimilar initial fault trajectories, changes in stratigraphic thickness, or variable contraction in the duplex. Excellent examples occur in places in the Moine thrust belt where contoured duplex thicknesses show a series of domes, basins, and saddles, rather like peas in a pod (Elliott and Johnson, 1980, Fig. 33).

If the slip on subsidiary faults is substantially less than the horizontal distance (p′) between horses, then not only is the overlying roof thrust immobilized, but it is also folded along with the new horse as it moves forward (Fig. 26). This produces a pattern "corrugated iron" and is one cause of the distinctive Appalachian Valley and Ridge folding and topography. The forward development of the duplex is accompanied by a sequential folding of the roof thrust, so that the family of congruent major folds are of progressively younger ages toward the foreland.

So far we have examined some of the geometric ways in which a duplex can form a culmination, but why should such a duplex and culmination form in one place and not in another? One reason would be a change in the ductility of the formations. Along-strike changes in carbonate facies toward bioherm buildups would make the stratig-



'G. 26—Regular folds of central Appalachian Valley and Ridge are often underlain by duplex involving thick competent ambrian-Ordovician carbonates. Small displacements on subsidiary faults which cut through large ramp produce periodically lded roof thrust. Sole is comparatively smooth in Lower Cambrian Waynesboro shales. Cross section in West Virginia after rry (1978, Fig. 10).

raphy much less ductile and favor development of a duplex and culmination. In sandstones, small changes from carbonate to quartz cement could have the same effect. In the Moine thrust belt, local development of igneous intrusions slightly metamorphosed a shale and carbonate sequence, which during subsequent thrusting resulted in the Assynt culmination (Fig. 22).

Eyelid Windows

Now that we have looked at the possible causes of a culmination and the fault patterns within the window, let us examine the map patterns of the thrusts that frame the window.

An eyelid window is caused by the folding and erosion of an imbricate fan in such a manner that the window frame consists of several different thrust sheets (Fig. 27). The term "eyelid window" has a somewhat convoluted history. Sander (1921, p. 193, 212) originally suggested the name "scissors-window" (schernfenster), and later compared the pattern of framing thrust sheets to the overlapping blades in an iris diaphragm. Although Sander emphasized that scissors-window was a purely descriptive term, Tollman (1968, p. 47) pointed out that at one time these windows were thought to form by the opposed motion of the framing thrust sheets, like the blades in a pair of scissors. Oriel (1950, p. 46) suggested the more appropriate English name "eyelid window," and although the term was then in current use, he could find no published examples of its use.

In a discussion of the Goat Ridge eyelid window in Nevada, Gilluly (1960; Gilluly and Gates, 1965) argued that thrusts start folding as they form and are then abandoned for newer, higher, and as yet unfolded thrust surfaces (Fig. 21, right). He claimed that eyelid windows are diagnostic features of this hindward thrust progression.

Alternatively, we could have an imbricate fan that is then folded into a culmination—itself possibly owing to an underlying ramp or duplex. Erosion would produce an eyelid window, but one in which the thrusts all developed in forward progression. It seems that identical map patterns of eyelid windows could arise with either sequence of thrusting, and clearly each field example must be care fully analyzed.

The Lower Engadine eyelid window was the first one described (Sander, 1921). The Hot Springs eyelid window in the southern Appalachians is a more symmetrical example (Oriel, 1950).

Southern Appalachian Blue Ridge

Some 155 mi (250 km) southwest of our study area in the southern Appalachians, an important seismic line shows that the Blue Ridge and much of the Piedmont is a thin but southeast-thickening slab, 3 to 9 mi (5 to 15 km) thick, thrust over a Cambro-Ordovician sequence (Cook et al, 1979, 1980). We believe this basic geometry holds true over our region; and indeed some of this basic picture was anticipated from surface geologic evidence (e.g., Harris and Milici, 1977; Roeder et al, 1978). Regarding the Blue Ridge thrust complex itself, Cook et al (1979, p. 565) remarked that ". . . few seismic features are seen." Fortunately, the geologic map of the Blu Ridge provides exceptionally useful information fo building a vertical cross section (Fig. 28). A key is tw large windows, each on the order of 10^3 km^2—among th largest windows so far discovered in North America.

A balanced cross section (Fig. 29), in which each faul slice in the deformed state is restorable into the origina stratigraphic framework, gives a picture of the fault trajectories just before movement occurred. Each formation within a fault slice has equal area in both the restore and deformed states, but in the lower grade portion o the cross section, to the northwest, where finite strain and fabric are less intense, formation thicknesses ar conserved, and formation lengths remain unchanged.

What is the sequence in which the thrusting occurred J. Rodgers feels that within most of the Valley and Ridg province the general progression is forward, but aroun the Grandfather Mountain and Mountain City window he accepts the suggestion of Gilluly (1960) that th thrusts developed in hindward sequence (Rodgers, 1970 p. 170, 178). Hatcher (1978, p. 294-295) proposed a compromise in which thrusting progresses forward in tw waves, so that thrusts in the first wave are cut off at th back by younger ones. We shall try and show that ther are no difficulties in building up the Blue Ridge comple with a forward thrust progression.

To explain our cross section (Fig. 29), we will briefly lis some conclusions in point form; these points have th same numbers on the cross section. Although we provid only partial references, it is important to note the super work by the U. S. Geological Survey in this area (Kin and Ferguson, 1960; Bryant and Reed, 1970; Ranki 1970).

1. The Inner Piedmont thrust complex, composed o sillimanite-grade immature siliciclastics intruded b Paleozoic plutons, is the most internal tectonic unit an continues well to the southeast of this line of section About 47 mi (75 km) northeast is the Smith River thrus sheet, which clearly overlies the Fries and is equivalent t part of the Inner Piedmont (Conley, 1978). This thrus complex may once have covered the Fries sheet on thi line of section, but is now found only south of th Brevard zone because of deep erosion and Triassic faulting. It is the highest and largest single tectonic unit, so i a sense we can describe it as a dominant thrust sheet— topic which we discuss later.

2. The Fries thrust sheet carries rocks that were folde several times, affected by a pervasive kyanite grade metamorphism of Ordovician age, and intruded by Silurian Devonian granites. The Fries thrust surface juxtapose this entire amphibolite-grade complex onto a substantially lower grade footwall (Rankin et al, 1973). We cannot yet restore the Fries or Inner Piedmont thrus complexes.

Our thrust sequence would start, then, with the Frie moving over our area of interest carrying the Inner Piedmont thrust complex on top of it.

3. The Linville Falls thrust moved next, accompanie by formation of a penetrative cleavage. In basemen rocks this fabric is cataclastic and occasionally mylonit

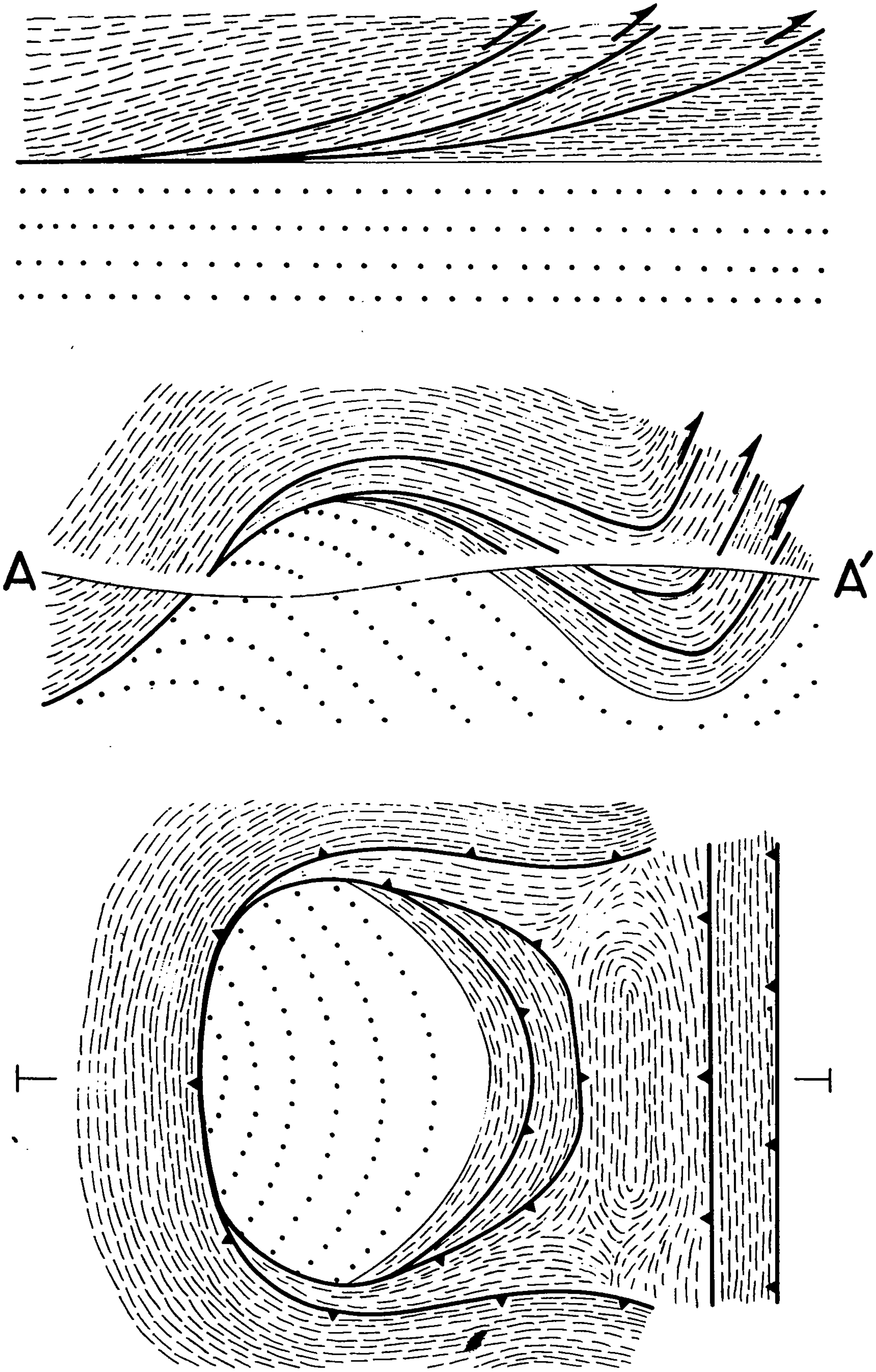


FIG. 27—Characteristic map pattern of an eyelid window (below and cross section AA′ (center). First we create an imbricate fan (center cross section), followed by sufficient but not excessive erosion (Boyer, 1978).

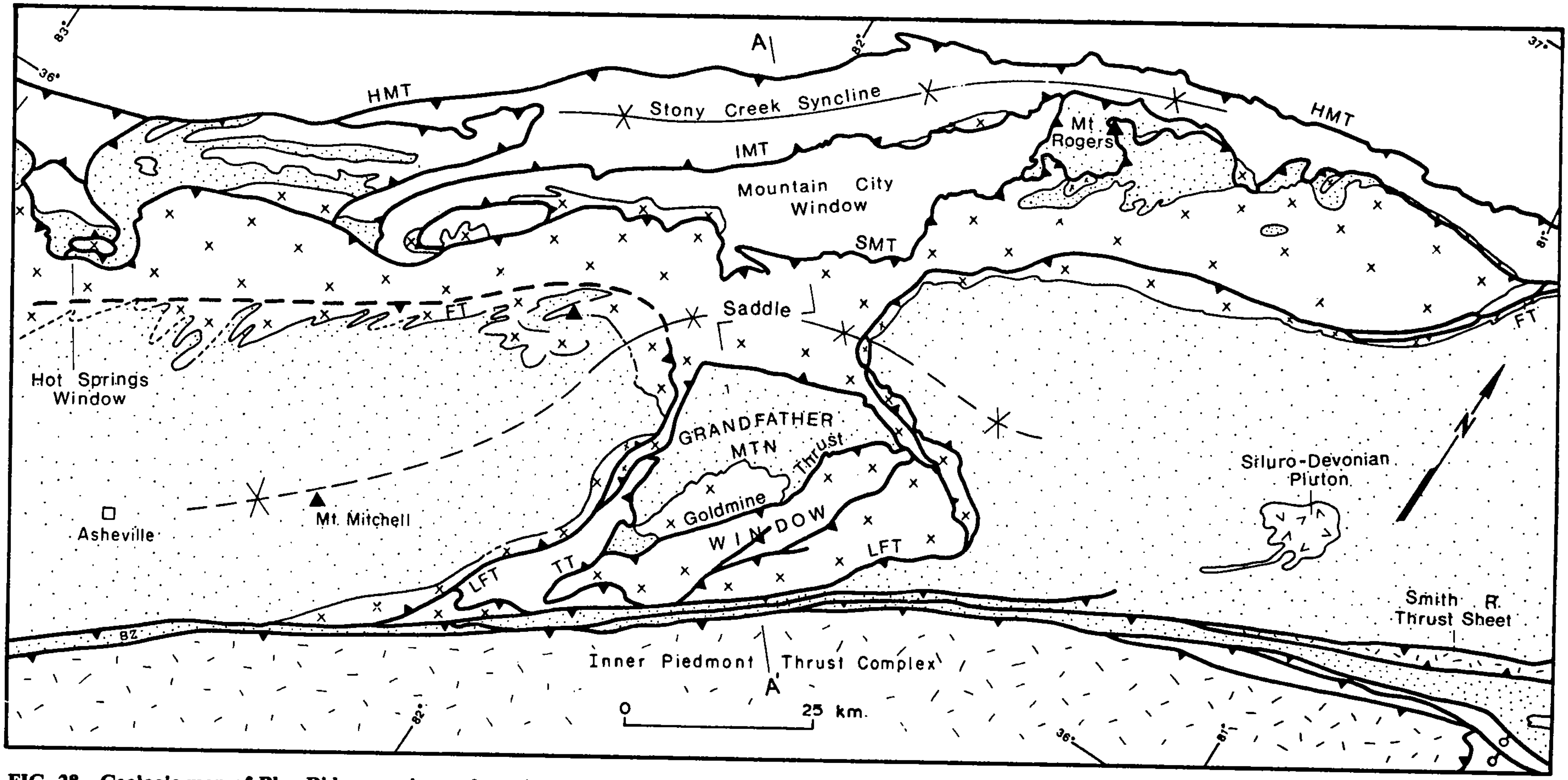


FIG. 28—Geologic map of Blue Ridge area in southern Appalachians of Tennessee, Virginia, and North Carolina. Holston Mountain thrust (HMT), Iron Mountain thrust (IMT), Stone Mountain thrust (SMT), and Linville Falls thrust (LFT) are all part of the imbricate system whose sole is intermittently exposed for over 47 mi (75 km) across strike. Precambrian basement is dashes or crosses, late Precambrian siliciclastics are stippled, Chilhowee group siliciclastics and Cambrian-Ordovician shales and carbonates are without pattern. Only major thrusts are shown, and no cross faults. Brevard fault zone is indicated by BZ. Based on Rankin et al (1973).

develops. The fabric curves asymptotically to the Linville Falls thrust and the strain and fabric are stronger near it.

Once the Linville Falls thrust was moving, a family of imbricate subsidiary faults cut upward to join the Linville Falls as a roof thrust and curved asymptotically downward to a floor thrust. This duplex continued to develop toward the northwest, with the roof's name changing to Stone Mountain thrust. We interpret the Mountain City and Grandfather Mountain windows as two culminations of the same duplex, the Windows duplex.

4. The main cleavage was accompanied by syntectonic metamorphism, which reaches into amphibolite-grade in the most southeastern horse within the Grandfather Mountain window, but drops off steadily toward the northeast and becomes greenschist. None of the horses brought up lower crustal or upper mantle rocks, suggesting that the initial trajectory of the floor thrust was subhorizontal (Bryant and Reed, 1970, p. 219). The northwestward decline in metamorphism is accompanied by a decrease of cleavage intensity, which becomes very weak and sporadic at the northwest side of the Mountain City window.

The Windows duplex had an initial length 78 mi (125 km), but its current length, between branch lines A and X, is 28 mi (45 km) which indicates a shortening of 50 mi (80 km).

5. The structure of the Grandfather Mountain window is based upon composite down-plunge projections (Boyer, 1976, 1978). Possibly the floor thrust climbs section along strike and updip to produce the Grandfather Mountain culmination. This interpretation is supported by the map pattern of large late-kink folds, which essentially define the culmination and whose minor structures are a crenulation cleavage, and by minor kink folds that deform the earlier main cleavage. Variable contraction is also a factor; for example, contraction may decrease beneath the saddle and then increase again within the Mountain City window. A third possible cause of the culmination is a still lower culmination in the floor thrust of the Mountain City window.

Erosion subsequently produced the duplex window (cf. Figs. 28 and 25). Also, the pattern of the Fries and Linville Falls thrusts, (the window frame), creates an eyelid window (cf. Figs. 28 and 27).

6. The Linville Falls, Fries, and several other thrusts beneath the Inner Piedmont sheet all merge toward branch lines in the Brevard zone. This merger is accompanied by an increase in the southeast dip of bedding and schistosity toward this narrow band of intense cataclastic deformation. Isotopic evidence summarized by Conley (1978, p. 1122) suggests that the principal time of activity of the Brevard zone, and therefore the branch lines for the major thrusts that lie within it, is Late Devonian.

The Brevard zone is not only a thrust structure, for Triassic faults can be traced into it (Fig. 28), and there is a scatter of Triassic mica ages from the mylonites (Butler and Dunn, 1968; Rankin, 1975, p. 329). The Brevard zone started as the site of major Late Devonian thrusting and was followed by Triassic listric extension faulting. There are good analogs to this pattern in the Cordillera (e.g., Bally et al, 1966, plate 5; Royse et al, 1975, p. 46).

7. Repeatedly the Valley and Ridge thrusts have hanging walls within the lower part of the Rome Formation, and the total overall shortening is roughly 75 mi (120 km) (Roeder et al, 1978, p. 23). This requires that a thrust, whose footwall is basal Rome, persist for at least 75 mi (120 km) beneath the Blue Ridge and Piedmont. The depth to this sole thrust agrees with that cited by Roeder et al (1978, p. 11) and with a seismic line shot 37 mi (60 km) southwest.

8. This seismic line, described by Harris and Milici (1977, Line TC-2), shows a major 2.5 mi (4 km) thick duplex involving Cambrian-Ordovician formations with the Pulaski thrust as roof and the sole thrust as floor. This lower duplex dips under the Windows duplex.

9. The floor thrust for the Windows Duplex we shall call the Windows floor thrust. Although we show the Windows thrust as a smooth and almost planar surface, it would be quite normal for this roof (of the lower duplex) to show low-amplitude folding.

Clark et al (1978) identified this thrust as overlying subhorizontal seismic reflections caused by to Cambrian-Ordovician sediments. These sediments were traced by Cook et al (1979, 1980) beneath the Blue Ridge and then for 93 mi (150 km) beyond the Brevard zone.

Cook et al (1979, p. 563; 1980, Fig. 3) called the Windows floor thrust the sole, and claimed that the underlying Cambrian-Ordovician sequence lies in place on its basement. We think that the geometric argument in point 7 proves this interpretation impossible.

10. At branch line A, the Windows floor and roof thrusts join the Holston Mountain thrust whose footwall cuts as high as mid-Ordovician shale. Some and possibly all of the 19 mi (30 km) of shortening in the Windows duplex may have transferred to slip on the Holston Mountain thrust, which therefore might have moved as the Windows duplex formed. If the Windows duplex started shortening in Late Devonian (see point 6) at 5 mm/year, then the total shortening of 50 mi (80 km) required 16 m.y. and was completed early in the Late Mississippian.

11. At a lower branch line, the Pulaski thrust merges with the Windows floor thrust, which then continues southeast across the section. The youngest formations currently overlain by the Pulaski are Early Mississippian. Because the Pulaski and Windows floor thrusts have a combined order of magnitude slip of 124 mi (200 km), any Carboniferous formation once deposited in those thrust sheets might have been in thick synorogenic facies and unlike any that crops out farther northwest.

12. The Grandfather Mountain formation consists of fluvio-deltaic sediments derived from both northwest and southeast sides of a steep and probably fault-bounded basin containing both felsic and basaltic flows and sills. The upper part of the basin is truncated by the Stone Mountain-Linville Falls thrust system, and in some way the stratigraphic sequence is continued into the hanging wall as the Mt. Rogers formation, one-half of which is volcanic.

13. One key to restoration of this complex thrust system is the presence 9 mi (15 km) northeast, in the Shady

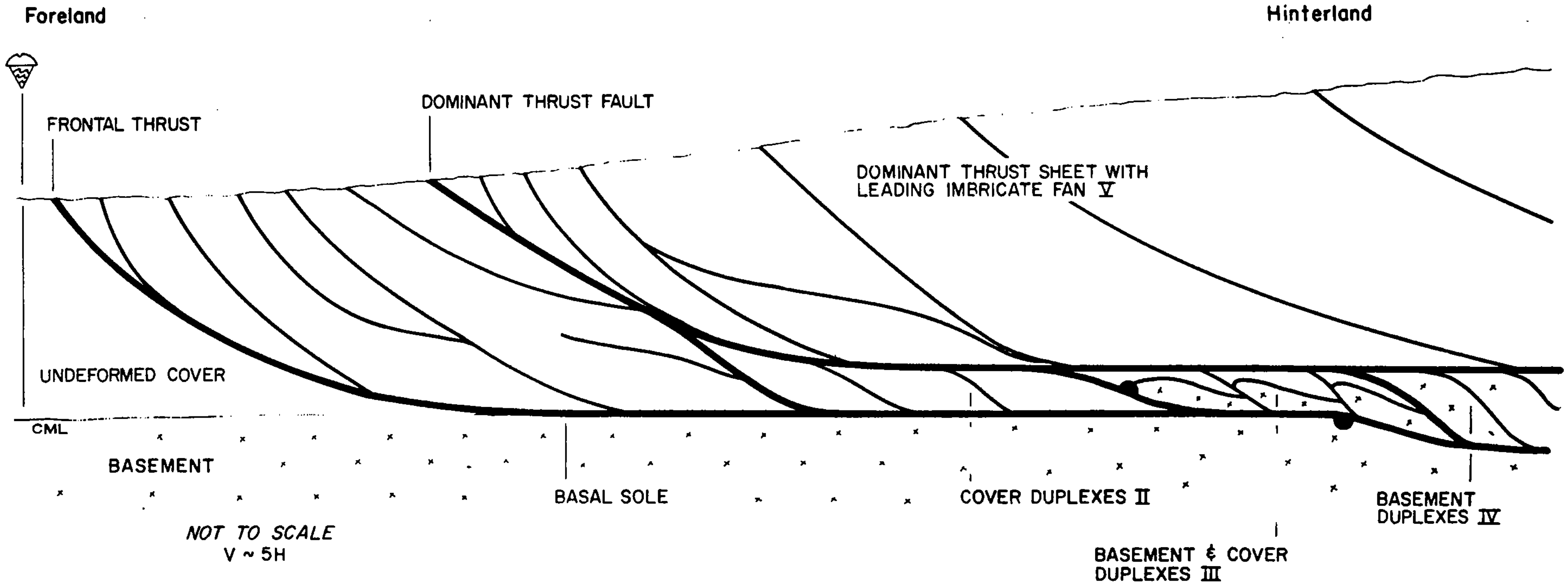


FIG. 30—Idealized sketch of thrust belt with dominant sheet shows five zones, each with characteristic thrust system and degree of basement involvement. Thrust faults at zone boundaries are bold. Vertically exaggerated and not to scale.

Valley thrust sheet, of a double unconformity—the intersection of the Unicoi/basement and Mt. Rogers/basement unconformities— suggesting a restoration to the northwest side of the Grandfather Mountain basin. A series of thrusts in the Mt. Rogers area, above and northeast of the Mountain City window, indicate a basin whose floor had considerable relief, an irregular shape, and sequences that could come from either side. This series of thrusts is too far (12 to 25 mi; 20 to 40 km) off this line of section for reliable projection.

14. Although it is not yet possible to restore the Fries thrust sheet, we do have constraints on its paleogeographic site. Formations recognized near the cross section (Ashe and Alligator Back) might have equivalents to the northeast (Lynchburg, Catoctin, and Candler or Chilhowie), indicating a range in age of deposition from late Precambrian to early Paleozoic (Rankin, et al, 1973).

Plate Tectonics and Blue Ridge Thrust System

The rocks of the Fries sheet suggest a marine siliciclastic sequence which is occasionally ophiolitic; one might infer a slope or possibly a rise sequence deposited on a newly rifted continental margin (Rankin, 1975, p. 315). In the northwest part of the Fries thrust sheet, the stratigraphic base is basement, so that at least the western sediments in the Fries sheet were deposited on continental crust.

Since we see the southeast side of its basin, the Grandfather Mountain formation could never have been laterally continuous into the Ash and Alligator Back formations, as thought by Hatcher (1978, p. 294, Fig. 4). It would appear that the Ash and Alligator Back sequences were deposited near the northwestern continental margin of a much larger basin, one whose adjacent ocean had an unknown southeast extent. Evidence of this ocean has now vanished, presumably into a thrust complex beneath the Inner Piedmont sheet, and several authors suggest that the Brevard zone started as a southeast-dipping subduction zone, which became a suture marking a continent/microcontinent collision (Odom and Fulligar, 1973; Rankin, 1975, p. 320; Hatcher, 1978, p. 295; Cook et al, 1979, p. 566, 1980, p. 213).

Is it true that there must be a subduction zone everywhere we see oceanic crust disappearing down a major thrust? The west side of Japan has active thrust faults that are on the opposite side of the islands from the subduction zone and that have an opposite sense of dip (Uyeda, 1977, p. 5). Mesozoic examples, such as the southern Andes (Dalziel, 1981), suggest that such a marginal basin can close right up, with the arc or microcontinent driven over the marginal basin and onto the continental foreland.

It would seem possible that the dominant Inner Piedmont sheet, either as an arc or a microcontinent, was thrust over the marginal basin and continental slope (Fries), and then everything thrust over the continental shelf (Linville Falls–Stone Mountain sheet and the Windows duplex), yet none of these thrusts would necessarily be traceable into the subduction zone.

THRUST BELTS WITH A DOMINANT SHEET

A portion of an orogenic belt may have an overlying dominant thrust sheet whose displacement is much larger than any of the others and whose motion dominates the evolution of this region.

We compare several dominant sheets in Table 2. Because of their great amount of slip and consequent uplift, many contain a substantial portion of coarse-grained crystalline rocks, such as an old quartzofeldspathic basement or an oceanic cumulate and mantle sequence. However, this is not a requirement, for example, the fronted part of the far-traveled Lewis thrust sheet consists of fine-grained clastics and carbonates of the Precambrian Belt group. At least part of the rocks now in front and beneath dominant thrusts are a stratified cover assemblage. Many of these assemblages unconformably overlie a basement of continental crust, often an old crystalline gneissic complex that we refer to as foreland basement. The stratified cover in some cases may include an Atlantic-type continental-margin assemblage, complete all the way to oceanic sequences. We have already discussed one dominant thrust sheet in the Blue Ridge thrust complex, and we shall examine one in the Alps. A generalized and vertically exaggerated cross section through a thrust belt with a dominant sheet shows five different zones (Fig. 30).

1. Closest to the foreland is a zone with cover telescoped into an emergent trailing imbricate fan above a basal sole thrust.

2. For a considerable distance beneath the dominant sheet, the cover is telescoped and thickened by duplexes over a deep-lying basal sole, below which foreland basement is still not involved. It is important to note that simply because crystalline rocks are found at the surface in a thrust sheet there is no reason to assume that foreland basement is necessarily involved in the thrust belt directly below.

3. Eventually a zone is reached (Fig. 30, III) well beneath the dominant sheet where the foreland basement does become involved with the cover in duplex thrust systems. Onset of this zone is controlled by metamorphic temperature in the basement and probably is a little less than 300°C (Voll, 1976).

If this temperature is reached well within the basement, the thrust may start as a glide horizon along this isotherm, and the fault must then cut upsection though lower temperature basement, probably as a ramp, before it reaches the cover.

4. At a deep level, a zone is reached in which the dominant thrust sheet directly overlies duplexes of foreland basement and the originally intervening cover rocks have been stripped off (Fig. 30, IV).

The thrust systems in zones II, III, and IV (Fig. 30) are duplexes, whose variation in thickness is an important cause of culminations and windows.

5. The dominant sheet is itself composed of numerous thrusts, all of which moved piggyback, and none of which had as great a slip as the dominant thrust fault. In other words, the dominant sheet is a leading imbricate fan whose sole is the dominant thrust fault.

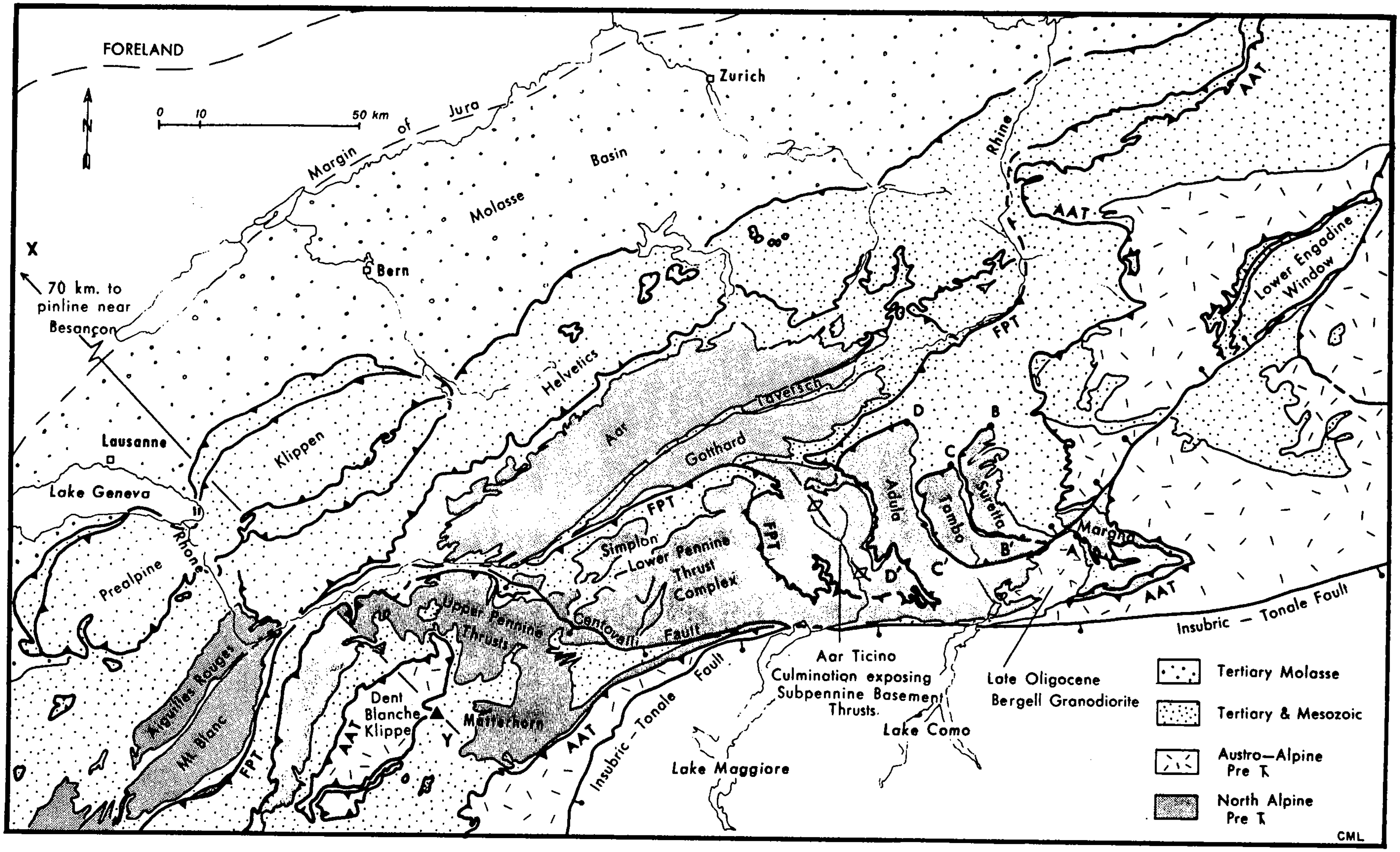


FIG. 31—Map of central Alps (modified from Spicher, 1972; Milnes, 1974).

ALPINE THRUST SYSTEMS

Helped by a concentration of work in a region of excellent exposure and high relief, thrust structures in the Alps were described at an early date and quickly became a widely accepted model. It is clear that a number of concepts developed in the Alps are precursors to the methods described here.

The emphasis and method of approach to Alpine nappes have traditionally been rather different from that outlined in this paper. To some extent, this Alpine approach is used in all the various chains about the Mediterranean, eastern Europe, the USSR, and the Himalayas.

Tollman (1968, p. 35) pointed out that a principal objective in the Alpine tradition is a description of the nappe body or thrust sheet volume, and that this is frequently accompanied by an incomplete characterization of the thrust surface. We will try to show that geometric reasoning based on thrust surfaces, tip and branch lines, and the various thrust systems, provides both an economical description of the structural geometry and a somewhat different perspective on the evolution of this classic belt.

Consider a cross section across the Jura, Prealps, and Helvetics to the Pennines, as shown on a map (Fig. 31). We rely heavily on outstanding reviews of Alpine geology by Trumpy (1973, 1980). The surface geology follows a recent cross section by Baud et al (1978), but our section is heavily modified and changed at depth. Below and northwest of the Frontal Pennine thrust these changes result in a cross section restorable by plane strain or balanced (Fig. 32). Letters identify corresponding points in the deformed and restored sections, and both letters and numbers on the cross section refer to the following points discussed in the text.

Pre-Triassic rocks (1) are principally a quartzofeldspathic crystalline basement, but also include substantial Permo-Carboniferous sediments. Mesozoic rocks (2) start with a shallow-water carbonate-evaporate Triassic sequence which indicates that the underlying siliceous basement was continental crust at that time. The Jurassic and Cretaceous include a complete Atlantic-type rifted margin sequence, varying from a carbonate shelf, below and north-northwest of the Frontal Pennine thrust, to various deep-sea deposits with ophiolites.

The Tertiary-Cretaceous boundary is the horizontal datum in the restored section. The Tertiary rocks vary from flysch (3) to molasse (4) and their age and facies reflect a growing thrust belt, advancing toward the North Alpine cratonic foreland (Trumpy, 1980, p. 50).

We will describe the balanced part of the cross section in the rough chronological order of a forward-progressing thrust system. The initial stage starts with the Frontal Pennine thrust, already carrying, in piggyback fashion, a whole sequence of originally more internal sediments and thrust sheets. The Frontal Pennine thrust, including the Prealpine sheets, glided on a planar footwall of Eocene flysch, which overlies the undeformed Helvetic carbonates (5, from e to n). The most internal of this flysch was stripped off the underlying carbonate. Does this flysch now form a forward-dipping duplex of downward-facing structures, including the Ultrahelvetic thrusts (near 20)?

Southeast of (e) the underlying faults all join the Frontal Pennine thrust, which is thus the roof of enormous antiformal stacks and duplexes. Restoring the Mesozoic gives a length (f, h, k, l, m, n) of 68 mi (110 km) along the Tertiary-Cretaceous boundary (9), which was once overlain by Tertiary flysch. This flysch now beneath the Frontal Pennine thrust has a cross section area of 170 km^2. If most of this flysch came from northwest of (n) on the restored section, then its initial thickness (t) is 1.6 km (10).

The Helvetics then started to develop and fold the overlying Frontal Pennine thrust. Earlier and higher thrusts such as the Wildhorn (6) and the Diableret (7), were in turn folded by growth of the underlying and younger Morcles thrust sheet (8). We suggest that the Helvetic thrust system is an antiformal stack, 30 times larger but in a sense geometrically comparable with the Dundonnell structure (Fig. 23). Radiometric ages of the low-grade syntectonic metamorphism in the Helvetic stack are Oligocene (Trumpy, 1980, p. 60).

Each Helvetic subsidiary thrust in turn passed on its slip to part of the roof thrust in front and then became immobilized, moving the Prealpine thrust complex farther and farther northwest. In the late Oligocene (~25 m.y.), the Frontal Pennine thrust cut upward through the lower molasse to the erosion surface, and shed pebbles into the nearby Molasse basin (13). Eventually, Helvetic thrusts in western Switzerland overrode lower Miocene Subalpine molasse. After the Prealpine complex was established over its final foot wall rocks, in late early Miocene to early middle Miocene time (13-16 m.y.), the entire Frontal Pennine thrust system and its Helvetic underpinnings were abandoned.

In the next stage, slip started at a lower level, a decollement in Triassic evaporites beneath the Molasse basin. Imbrications from this basal sole thrust emerged in the Molasse basin northwest of the Prealps, where the youngest Molasse was deposited in late Miocene time (~6 m.y.). In the Subalpine region (14), the Molasse is underlain by a more intensely imbricated Mesozoic (area cdfg). The initial thickness of the Mesozoic thins down to the southeast.

An emergent imbricate fan gradually moved across the Molasse basin (15, between a and c), and the Molasse sediment was cannabalized and recycled. The current 28 mi (45 km) width records at least 6 mi (10 km) of shortening if we assume a roughly average thickness t ~ 3.1 km for the Mesozoic.

The pinline (16) is chosen in the foreland, northwest of Besancon. The current distance from the pinline to point (a) is 43 mi (70 km) (17), the entire width of the Jura. However, the Jura underwent a shortening of 15 to 19 mi (25-30 km) (Chauve, 1975, p. 23), giving an original length between pinline and point (a) of 53 mi (85 km). Orogenic deformation in the Jura ended before early late Pliocene (before ~2.5 m.y.).

Where does all the displacement go that accumulated on the basal sole beneath the Jura and Molasse basin?

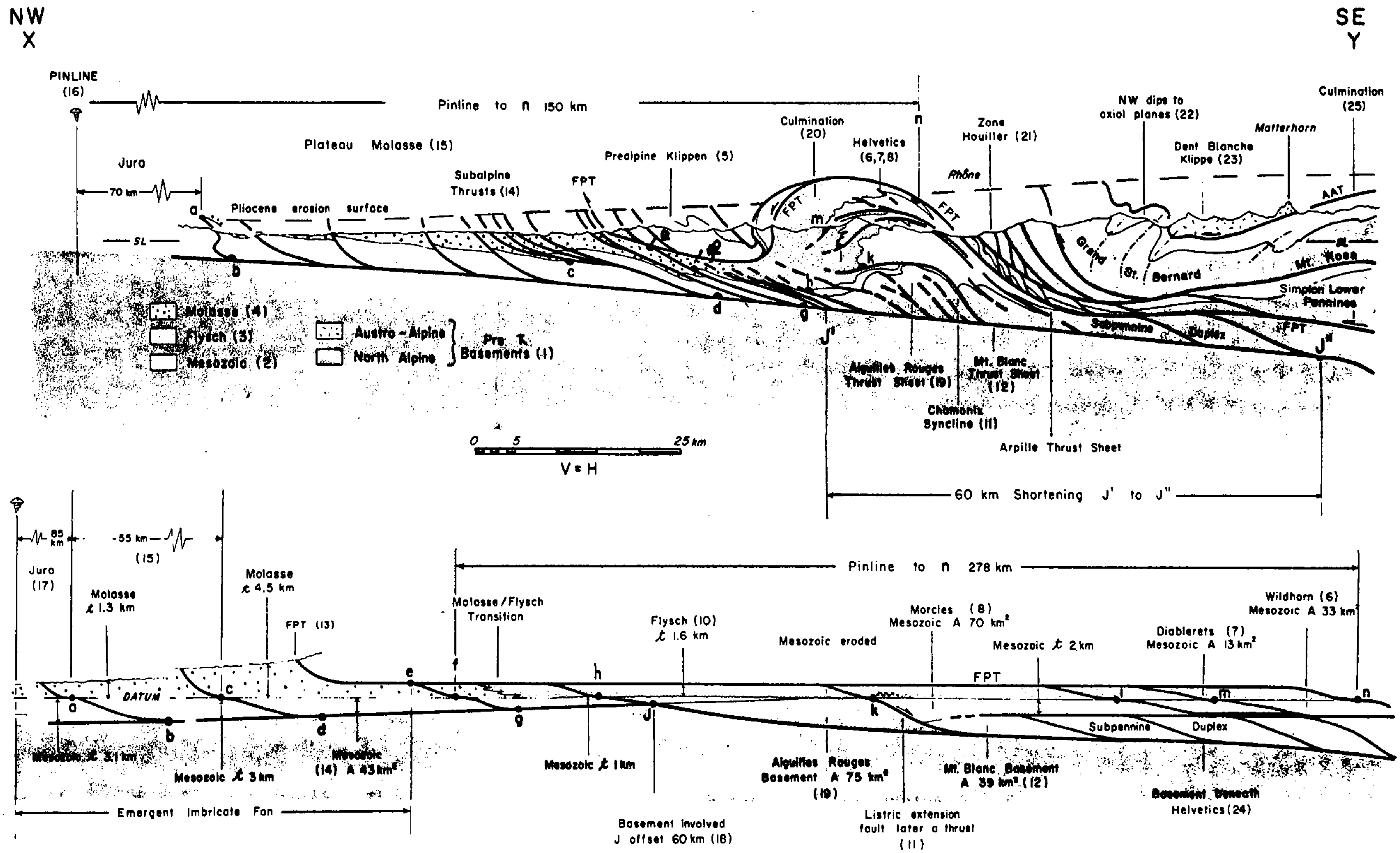


FIG. 32—Cross section through Alps along line XY′ (Fig. 31). Letters and numbers on section are location of points discussed in text.

One solution, implicit in most published cross sections, is to label the external basement massifs "parautochthonous" and to move most of the displacement over them. We favor an alternative solution where the displacement passes beneath the external basement massifs. In the undeformed state, the footwall and hanging wall cutoff must coincide (18). By keeping corresponding areas (Jheg) equal in restored and deformed state cross sections, the contact of basement and cover (J')must be 37 mi (60 km) farther southeast than is J' (cf. Hsu, 1979).

The Aiguilles Rouges massif (19) then appears as one subsidiary slice of a duplex involving basement and is most easily seen on the restored section. The tapering Mesozoic carbonate shelf sequence is completely removed from part of this massif (Badoux, 1972).

The Mesozoic in the Morcles nappe thickens abruptly (8), and the upper Eocene section consist of northwest-derived clasts, including large blocks of basement (Badoux, 1972). This suggests that a southeast side-down listric extension fault (11) was active until late Eocene time, a type of faulting widespread at that time (Trumpy, 1960, p. 882). We suggest that such a listric extension fault was subsequently used as a thrust and that the Chamonix syncline, separating the Aiguilles Rouges and Mount Blanc massifs, could mark its position. If so, then the thrust beneath the Mount Blanc massif (12) might have followed the subhorizontal basement decollement of the earlier listric extension fault.

The Frontal Pennine thrust goes over all the Helvetic sheets and then dips down to pass beneath the enormous klippe that makes up the Prealps. This major culmination (20) is due to a combination of four causes. First, horses of Ultrahelvetic flysch from farther southeast accumulated between the Prealps and Helvetics. Second, the Helvetic sheets have both their Mesozoic and Tertiary portions directly above one another, causing an antiformal stack. Third, as basement on the hanging wall moved onto the flat basal sole thrust, the external massifs arose as immense hanging wall anticlines ("Powell Valley-type," as in the Pine Mountain thrust sheet) folding the overlying thrusts. However, the external massifs themselves are a composite array of subsidiary faults and our fourth cause is a particularly intense local internal shortening and thickening. Some readers may recall the theory of "basement wedges" (Fig. 33), summarized by Umbgrove, 1950, p. 66, which had a following between the 1920s and 1950s, but is now seldom referred to. These basement wedges have the same effect—in our terms—as differential shortening in the upper part of a duplex.

It may be possible to date this event. Rare pebbles from the Helvetic nappes are first found in the upper Miocene molasse, but we attach a different significance to these pebbles than do previous writers. If the Helvetic thrust sheets are all horses, then they were not exposed to erosion during their development and emplacement. The pebbles do not record active Helvetic thrusting; instead, they mark when erosion through the stack of thrusts was sufficiently deep to reach the Helvetics, and must date growth of the external massifs.

The shortening recorded beneath the Frontal Pennine thrust is 75 mi (120 km), from the pinline to point (n). This value is probably much smaller than the shortening above and southeast of the Frontal Pennine thrust, and, although we cannot restore this part of the section, we wish to mention some interesting conjectures.

The imbricate slices making up the Prealps correlate with the region above the Frontal Pennine and below the Austro-Alpine thrust (21). First is a complex of three zones (Sion-Courmayeur, Houillere, and Great St. Bernard) each representing smaller scale duplexes. Possibly, then, there is a transition between emergent imbricate slices in the Prealps to buried multiple duplexes between the Frontal Pennine and Great St. Bernard thrusts.

Because of the structural relief of the Aar-Ticino culmination, the structure of the internal zones is clearer to the east (Fig. 31). The classic interpretation is to look down-plunge to the east-northeast at the map pattern. There were several strong phases of folding after the thrusts formed (Milnes, 1974; Milnes and Pfiffner, 1980), and our reconstruction is a very rough attempt to view the geometry, if these folds were removed (Fig. 34)

The region is dominated by about 10 major thrust sheets composed mainly of basement, but partly separated from each other by thin septa of Mesozoic cover. The axis of the Aar-Ticino culmination exposes the deepest level, a series of "Subpennine" thrust sheets (Milnes, 1974). We shall call this the Subpennine duplex and its roof is the Frontal Pennine thrust.

The overlying Pennine thrusts (Adula, Tambo, Suretta, Margna) are shown on published maps (e.g., Spicher, 1972) to end at points A, B, C, D (Fig. 31). We interpret these points as hanging wall cutoffs of the basement cover contacts, and suggest that the thrusts continue cutting upsection in the Mesozoic, eventually joining the Austro-Alpine thrust (Fig. 34). If so, then the Pennines are a duplex with the Frontal Pennine thrust as floor and the Austro-Alpine thrust as roof. These branch and cutoff lines are of considerable interest, for different arrangements are possible, and lead to quite different paleogeographic reconstructions.

Farther west on our cross section (Fig. 32), restoration of the Mesozoic (24) shows that the basement that once lay under the Helvetics can only partly be seen at map level. We suggest that this basement forms an extension of the Subpennine basement duplex. Above is the Simplon Lower Pennine basement duplex, which may be similar to those seen more clearly to the east (Fig. 34). Major culminations and depressions in the overlying Great St. Bernard and Austro-Alpine thrusts (23) could be due to variable thickness of the two basement duplexes (25).

The Austro-Alpine thrust sheet (AAT on Figs. 31, 32) has long been recognized as having a dominant role, and was vividly characterized up as a master overriding thrust sheet behaving like a giant earth-moving machine, a "Traineau ecraseur" (Termier, 1904). The five different zones beneath and in front of this dominant sheet are fairly clear (cf. Fig. 30 to Figs. 32 and 34), but we do not imply that the Austro-Alpine thrust sheet once covered, for example, the Prealps (Fig. 32). It is possible that some of the duplex systems beneath the Austro-Alpine thrust

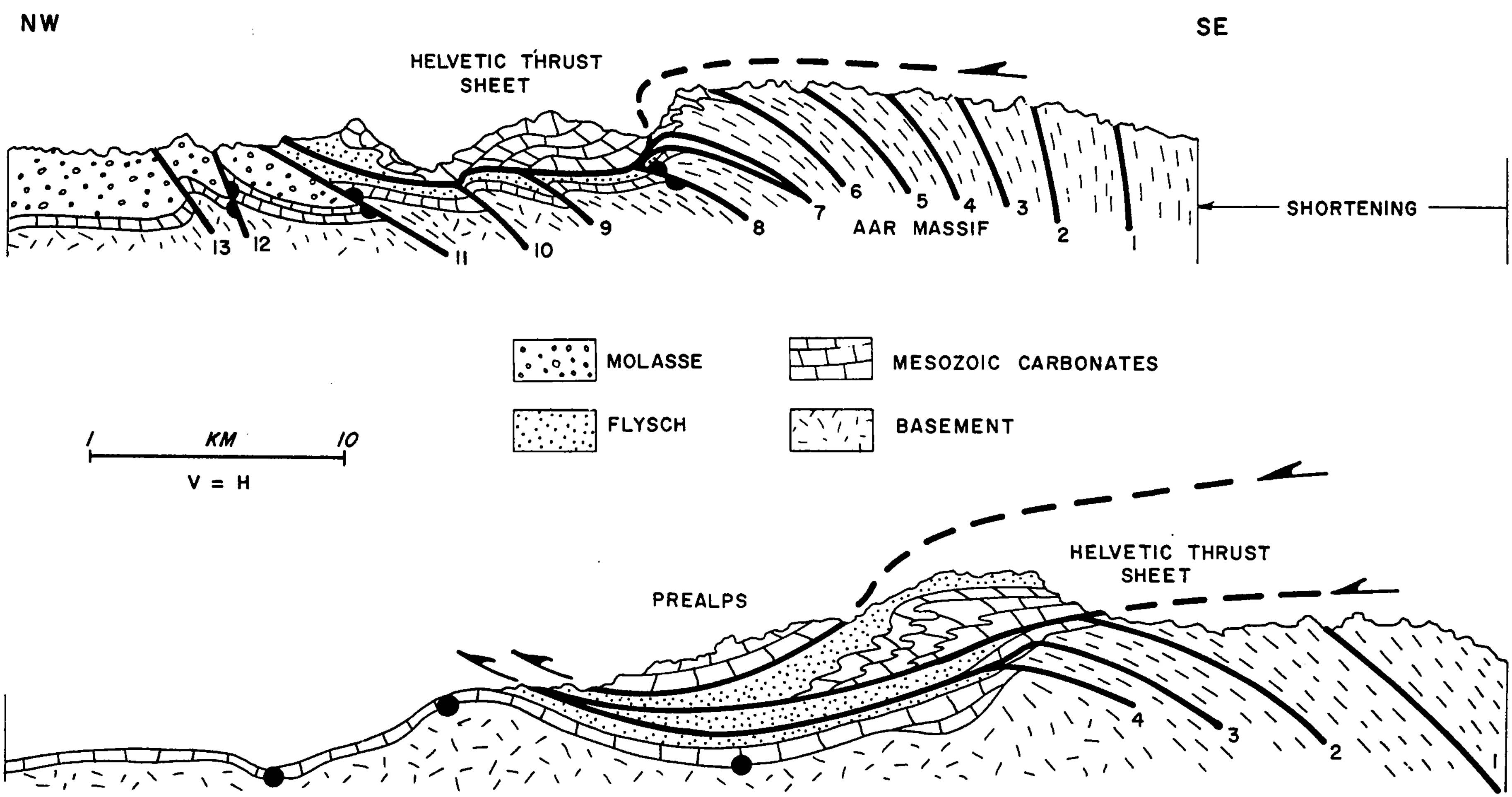


FIG. 33—Top: cross section from Molasse basin to Aar massif. Bottom: earlier stage in basin evolution (after Gunzler-Seiffert, *in* Umbgrove, 1950, Fig. 47; Holmes, 1978, Fig. 3.21). This figure illustrates that old idea of basement wedges may be equivalent to upper part of a duplex. Piggyback emplacement of Prealpine klippe and Helvetic thrust sheets by successive imbrication of underlying crystalline wedges are numbered in order of formation. Telescoping of slices steepens older wedges.

became emergent to the west, similar to the Lewis thrust and its underlying structures as discussed earlier.

ROOT ZONES

The root of a thrust surface on a map is where the thrust finally dives from view for the last time. When a number of thrusts do this in the same area, it is called a root zone. Part of the interest in root zones stems from plate tectonics, for if the root zone functioned as a subduction zone it is necessary, although not sufficient, that oceanic lithosphere once existed in the footwall. If, in addition, the two margins of the root zone were once continental lithosphere, then the root zone may also be a suture. Root zones have long been of interest, particularly in two regions already discussed: the internal Alpine root zone, just north of the Insubric-Tonale fault (Fig. 31); and the Appalachian Brevard zone (Fig. 28). Both these root zones are very narrow, often less than 6 mi (10 km) wide, and consist largely of cataclastic basement rock; the similarity of the two root zones is brought out by Burchfiel and Livingston (1967).

The classical Alpine picture is ". . . a belt of subvertical strata representing a former wide zone from which the Nappe has been squeezed out" (Rutten, 1969, p. 206). This theory of roots has three different aspects. First, the theory implies that development if the root zone caused the subvertical dips. But the steep dip could be imposed later than the motion of the thrusts whose roots make up the zone; Alpine field work that demonstrates this is reviewed by Milnes (1974). Further, a group of thrusts is more likely to intersect the ground surface if it is affected by a steeper than normal dip, so the correlation of steep dip with root zones may not be so much causal as statistical.

The second implication of the classical theory is that a root is the "inner margin of the former home of a nappe" or, in other words, a root coincides with a footwall cutoff. The slip distance of a thrust, measured in cross section, is the arc length between the hanging wall and footwall cutoffs. Often the footwall cutoff cannot be found on the map, and then the minimum possible slip is the distance from the hanging wall cutoff back to an assumed footwall cutoff just below the ground surface in the root. Classical theory assumes that these minimum slip estimates are actual values and that all the thrusts that root in the zone have footwall cutoffs at the same place—clearly an artifact of oversimplified assumptions.

The third part of the classical picture explains the narrow width of root zones as the effect of very large flattening strains imposed on originally much thicker thrust sheets. However, a thrust sheet is bound above and below by fault surfaces, and at the approach to the trailing branch line the thrust sheet must thin (Fig. 1). Consequently, root zones which represent these originally thin portions of thrust sheets should show frequent outcrops of branch lines, and this seems to be the case in both the southern Appalachians (Fig. 28) and the Alps (Fig. 31).

Why are root zones composed largely of cataclastic basement rocks, with the foliation parallel with the zone boundaries? Recall that the lowest stratigraphy in a thrust sheet is at a trailing branch line (Fig. 1). Consequently this portion of the sheet is more likely to consist of coarsely crystalline basement rocks. The region close to a branch line will be subject to the deformation induced by both the overlying and underlying thrust surfaces. Rocks near branch lines must be more highly deformed than elsewhere in a thrust sheet, having cleavage or schistosity congruent to both thrust surfaces. If the temperature is sufficiently high (~300°C), cataclastic fabrics will form and will be most spectacular in the originally coarse basement.

Horses and duplexes should be particularly common in these deep internal zones, and the density of branch lines is high. Note that a "braided" map pattern is diagnostic of a steeply dipping duplex.

We mentioned earlier that several of the key physical processes acting during thrusting occur along lines. It is probable that the narrow dimensions, abundance of basement, and highly deformed mylonites so typical of root zones are directly related to the operation of branch lines at moderate metamorphic temperatures.

CONCLUSION

A thread which runs through this paper is the distinction between thrust sheet volumes, thrust fault surfaces, tip and branch lines, and corners (points). Interestingly, this is analogous to the sort of reasoning one uses to investigate crystals, with their grain volumes, grain boundaries, dislocation lines, and point defects.

We have looked at only a small part of the geometric framework that provides the basic underpinnings of fault systems. Left out, for example, are the relations between listric extension faults and thrusts—relations that must be extremely important throughout the Basin and Range province of the western United States.

Finally, some remarks on the plate-tectonic setting, the interpretation of which may depend on a correct reading of the thrust systems. It is, for example, popular to tie in the creation and emplacement of dominant thrust sheets directly with an arc, microcontinent, or continent in collision with another continent. Frequently the dominant thrust fault is equated with a plate boundary and subduction zone, but, as in the southern Appalachian Blue Ridge, it often is possible to place the subduction zone at a different position and even to give it an opposite dip. Clearly these deliberations are delicate and complex, and we feel that by untangling the large scale plate tectonics from descriptions of the smaller scale thrust systems both points of view will gain clarity and precision.

From a plate tectonic perspective, there is one major effect of thrust systems, which is well illustrated by our examples in the southern Appalachian Blue Ridge and the western Alps. We started with a tapered Atlantic-type continental margin of normal (19 to 22 mi; 30 to 35 km) thickness on the foreland craton. This continental crust thinned and eventually ended against oceanic crust. Later, the region became part of a convergent margin, and the old tapering wedge of continental crust was greatly shortened and thickened, up to about twice normal thickness. A principal cause of this crustal thicken-

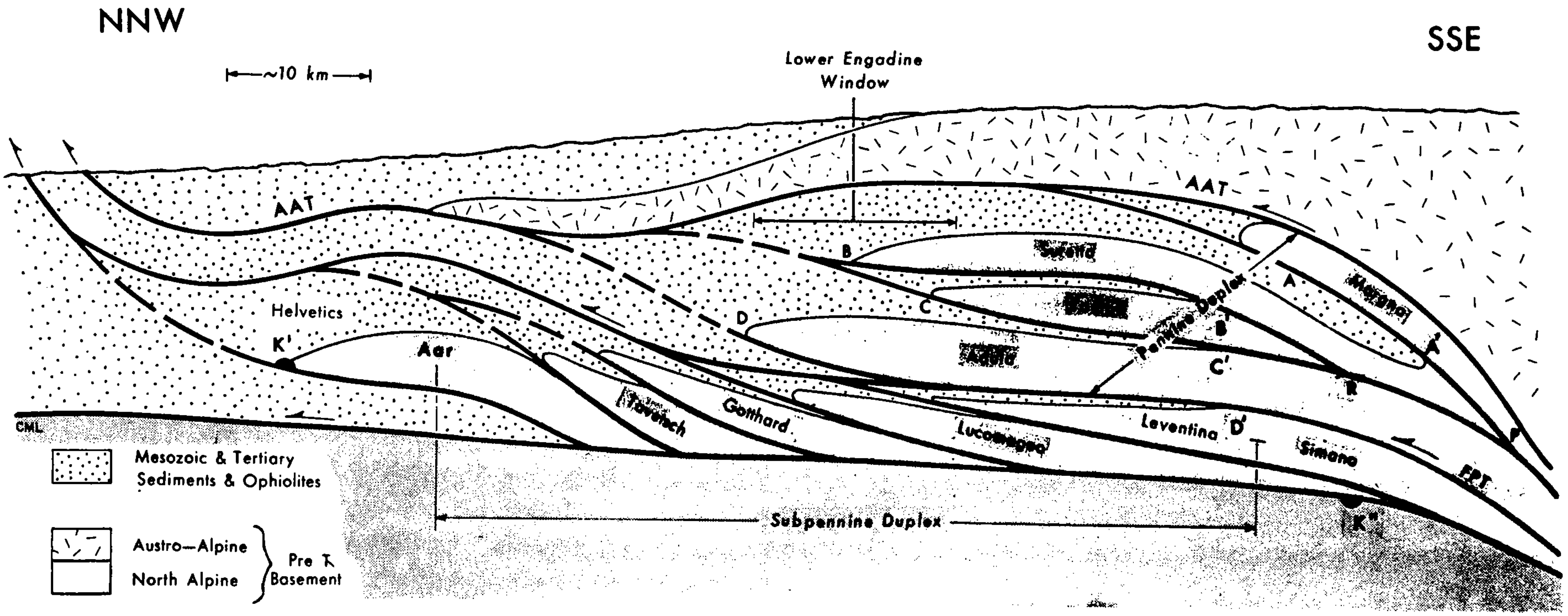


FIG. 34—Approximate down-plunge view in central Alps, west of Aar-Ticino culmination, suggesting duplex thrust systems. Only major faults which cut basement shown, but cover also shows intense but smaller scale families of duplexes. Effects of late folds removed, and scale is approximate. Letters identify points on map (Fig. 31).

ing is activity of the various kinds of thrust systems, and particularly by means of duplexes. Nor is this process restricted to shallow depths, for there are indications in the Alps and the Himalayas that thrust thickening persists down to the lower levels of the continental crust.

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