Balanced cross sections

C. D. A. Dahlstrom
Chevron Standard Limited, Calgary, Alberta

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Post-depositional concentric deformation produces no significant change in rock volume. Since bed thickness remains constant in concentric deformation, the surface area of a bed and its length in a cross-sectional plane must also remain constant. Under these conditions, a simple test of the geometric validity of a cross section is to measure bed lengths at several horizons between reference lines located on the axial planes of major synclines or other areas of no interbed slip. These bed lengths must be consistent unless a discontinuity, like a décollement, intervenes. Consistency of bed length also requires consistency of shortening, whether by folding and (or) faulting, within one cross section and between adjacent cross sections.

The number of possible cross-sectional explanations of a set of data is reduced by the fact that, in a specific geological environment, there is only a limited suite of structures which can exist. This imposes a set of local "ground rules" on interpretation. When these local restrictions are coupled with the geometric restrictions which follow from the law of conservation of volume, it is often possible to produce structural cross sections that have a better-than-normal chance of being right.

The concept of consistency of shortening can be extrapolated to a mountain belt as a whole, thereby indicating the necessity for some kind of transfer mechanism wherein waning faults or folds are compensated by waxing en echelon features. These concepts are illustrated diagrammatically and by examples from the Alberta Foothills.

Introduction

The purpose of this paper is to describe a method of checking cross sections for geometric acceptability. In the elementary schools of a bygone era children were taught to prove their answers to arithmetic problems by reversing the process: subtraction was checked by addition and division by multiplication. To apply this principle to a geological cross section, one would flatten out the deformed beds and return them to their depositional position. If this restoration could be done, one would conclude that the cross section was geometrically possible (although not necessarily true) but, if the beds could not be restored, one would conclude that the cross section was geometrically impossible. Construction of restored cross sections is tedious so they are seldom used to check structural interpretation. However, there are shortcuts which make the principle easy to use.

The method to be discussed is now being used consciously by a few geologists and unconsciously by many more to check their cross sections. The essence of the method has been discussed by Hunt (1957), mentioned by Goguel (1952), and illustrated by the published works of Carey (1962) and Bally *et al.* (1966), where it is obvious that the method is being consciously applied. However, the rules have not been set forth and discussed so that many geologists have not been exposed to the ideas. This paper is intended to remedy this oversight because the writer believes that a "balanced" cross section is a better cross section.

Source of Restrictions in Cross Section Construction

Relatively few geologists still demand for themselves the license of the artist, that is, the right to put on their cross section any interpretation which their imaginations can conceive. Aside from the data itself, most geologists recognize that other restrictions impose boundary conditions within which the imagination must be confined. These restrictions derive from two sources, (1) generalizations derived from observed facts, and (2) geometric principles.

This paper discusses one of the geometric principles and shows how specific rules of interpretation can be derived from that principle. The derivation involves simplifying assumptions which are valid only for specific structural environments. Therefore the same geometric principle will give rise to interpretive rules which vary from one structural environment to another. The writer will not attempt to develop all the possible variants. Discussion is restricted to one simple geological environment, the marginal part of an orogenic belt, and to one example of that environment, the

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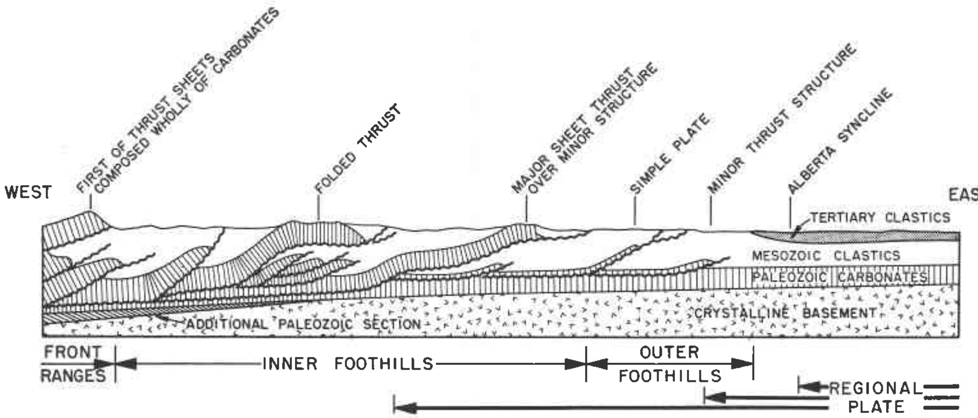


FIG. 1. Schematic cross section of Alberta Foothills (after R. E. Daniel, Chevron Standard). Note that the regional plate extends progressively farther west as older rocks are considered until, at Precambrian level, it extends completely across the section.

Alberta Foothills. To avoid misunderstanding, let it be emphasized that the interpretive rules derived in this paper are literally applicable only to the Alberta Foothills. With minor variants, they can be used in other marginal belts, but they cannot be applied to another environment, such as a salt dome province. However, the principle and method can be used to develop rules that do apply to those other environments.

Generalizations of Observed Facts

As a consequence of intensive government and industry search for oil and gas, the Alberta Foothills is well mapped (Bally *et al.* 1966, and the authors in their bibliography) and sufficient data are available for sound generalizations as to the pattern of structural behavior within this structural province. These generalizations establish the local ground rules for structural interpretation. For example, one of the local ground rules is that folds are ordinarily concentric, rarely chevron but never similar. Recognition of such local interpretive rules is an acknowledgment of the existence of "familial associations" of structures. According to this idea a specific geological environment contains a limited suite or "family" of structures. A large low-angle thrust, which would be perfectly reasonable in Foothills cross sections, would be as incongruous in a cross section through the plains of Saskatchewan as an elephant on the tundra, because thrusts are not part of the cratonic family of structures. The "foothills family of structures" comprise:

1. concentric folds,
2. decollement,
3. thrusts (usually low angle and often folded)
4. tear faults, and
5. late normal faults.

The first restriction then in constructing Foothills structure sections is that one is limited to some variant of these basic structural forms.

The area being used as an example is shown in diagrammatic cross section in Fig. 1. Of the many generalizations from observed data which can be made about the Alberta Foothills belt, the following are pertinent to the subsequent discussion.

1. The Precambrian basement extends, unbroken, beneath the Foothills structures.

2. The rocks east of the Foothills are essentially undeformed.

3. The Foothills structures were formed in the latter stages of the Laramide orogeny long after most of the rocks now preserved were deposited.

4. There is no thinning or thickening of beds by "flow" and therefore folding is concentric.

The through-going basement and the lack of deformation east of the Foothills edge limit the number of solutions which can be postulated for particular geometric problems. In an earlier and simpler day, it was the custom of geologists to draw shallow Foothills cross sections wherein geometric problems were solved by faults which dribbled off the bottom of the cross section.

Seismic and drilling data (Bally *et al.* 1966) have established the basement configuration so that now cross sections like Fig. 1 are closed systems except at the western end. Now the sophisticated geologist draws deep Foothills cross sections with a through-going basement, wherein geometric problems are solved by faults which are gathered into flat sole faults and hustled westward through the only available exit.

The Laramide orogeny moved progressively from west to east with the Foothills being deformed in the Paleocene Epoch. With the probable exception of the youngest beds in the Alberta syncline, all of the Paleozoic and Mesozoic rocks had been deposited long before the deformation. During the course of their depositional history in the miogeosyncline, these Paleozoic and Mesozoic rocks had indeed been subject to epeirogenic fluctuations and consequent erosion but they had not been orogenically deformed prior to Paleocene time. This single, post-depositional deformation of the Foothills is an important point because it simplifies structural interpretation by eliminating from consideration:

1. pronounced angular unconformities,
2. structures growing during deposition, or
3. substantial amounts of compaction during deformation.

The foregoing terse comments touch only upon those topics which are necessary background for the subsequent geometric discussion. No attempt has been made to summarize Foothills geology.

Conservation of Volume

The law of elementary physics (which Einstein amended) that matter can neither be created nor destroyed is paraphrased in geology as the "law of conservation of volume" (Goguel 1952, p. 147). A rock consists of mineral particles and voids filled with fluids. In the initial stages of clastic deposition, the proportion of voids to mineral grains is large and density is low, but this stage is brief because the compaction rate is very high during the first few hundred feet of burial. Thereafter density increases only slowly with depth. It is worth noting here for future reference that the volume change due to load compaction does reduce the thickness of a bed but it does not alter the areal extent. Volume reduction on account of deformation is thought to be negligible, particularly in the earlier stages of tectonism represented by the marginal part of the Cordillera, because no significant deformation-dependent decrease of porosity (or increase of density) is recognized. For practical purposes, one may assume that the law of volume conservation applies and that rock volume does not change during Foothills type of deformation.

Volume is three dimensional which makes the law of conservation of volume awkward to apply. However, in specific instances it can be made simpler. To start the simplification process one can use the three mutually perpendicular tectonic axes as the three dimensions: "*a*" is the direction of tectonic transport of rock during deformation, "*b*" is the direction of the fold axes, and "*c*" is the third axis which is perpendicular to the "*ab*" plane.

In the Foothills, the fold axes and the fault strikes are parallel, the folds are concentric, and the faults are dip-slip thrusts. Therefore the "action" takes place in the *ac* plane, which is a vertical transverse cross section, and virtually nothing happens in the *b* direction. By ignoring changes in the *b* direction as insignificant, the law of conservation of volume becomes a two-dimensional statement that the cross-sectional area of a bed does not change during deformation. Cross-sectional areas are manageable quantities so the law has been applied in this form to check cross sections (Hunt 1957) or to calculate depth to detachments (Bucher 1933).

Even further simplification is possible when folding is concentric because bed thickness does not change during deformation. This has been demonstrated in the Foothills, directly by detailed studies of the anatomy of folds (Price 1964), and indirectly by many stratigraphic studies, which do not detect any tectonic thinning of units whether they be on gentle upright limbs, on vertical limbs, on overturned limbs of folds, or on far-travelled thrust sheets. Because the cross-sectional area of a bed is a function of bed length and bed thickness and because the thickness remains constant, it is possible to eliminate one more dimension and to state the law of conservation of volume in terms of length alone: *In concentric regimes the cross-*

sectional length of a bed remains constant during deformation.

Consistency within Cross Sections

In simple deposition the initial areal extent (or length in cross section) of any bed is the same as that of the beds above and below it. Since bed area (or length in cross section) is not appreciably altered by either compaction or by post-depositional concentric deformation, it follows that bed lengths in a cross section must be consistent with one another (Figs. 2*a* and 2*b*), unless a discontinuity such as a sole fault or décollement intervenes (Fig. 2*c*) between the longer and shorter beds.

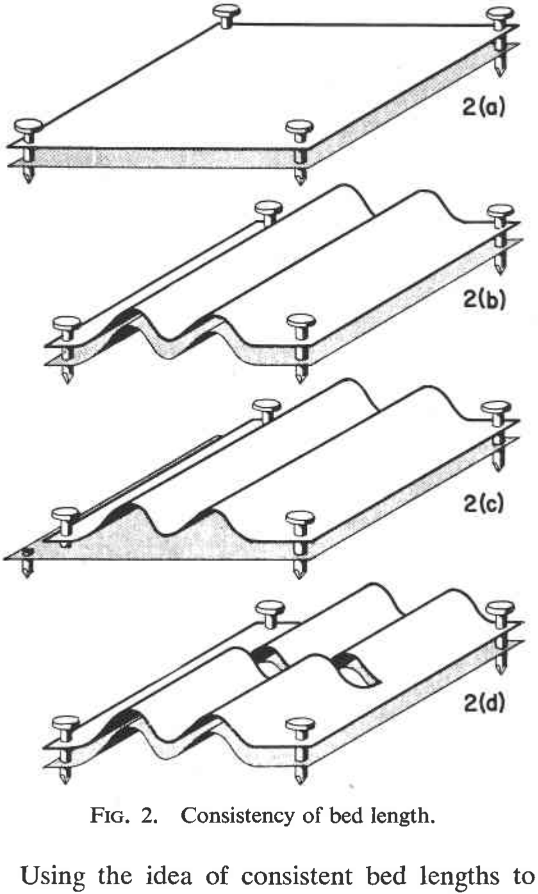


FIG. 2. Consistency of bed length.

Using the idea of consistent bed lengths to check a cross section is very simple. The first step is to establish a pair of reference lines at either end of the section in areas of no interbed slip. These reference lines should be the axial planes of major anticlines or synclines or other planes of no slip such as a plane perpendicular to the regional dip of the undisturbed "plains" section at the eastern end of a regional Foothills cross section. The second step is to measure the bed lengths of selected horizons between these reference lines. They should all be the same so that bed lengths "balance". If the cross-sectional lengths do not balance then the cross section must show a valid explanation of why they do not. In regional Foothills cross sections for instance, there is never a balance between the length of the Mesozoic and Paleozoic beds and the length of basement. The "cover" beds are always too long, which is explained in cross section (Fig. 1) by a sole fault along which the upper beds have been moved (shoved? glided?) into the cross section from the west. This is not simply a way of sloughing one's problems into an adjacent area, because the necessary implication of such a section is that the sole fault continues to the west until the bed length anomaly is resolved by shortening of the basement (compressional hypothesis), or extension of the Mesozoic and Paleozoic "cover" rocks (glide hypothesis). One should note that checking Foothills cross sections for balance by measuring bad lengths is purely a geometric test which is quite independent of the genesis of the structures.

The fundamental rule, that the cross-sectional length of a bed remains constant during concentric deformation, has led to the idea that bed lengths in a cross section ought to be consistent with one another. If this is true, then the displacement on thrust faults ought to be consistent as well. In Fig. 3 the displacement at B must be the same as at A unless it is postulated that elastic, plastic, or compactional deformation of the rock takes place between A′ and B′. None of these things happen in a concentric regime.

Despite this conclusion that thrust displacement ought to be consistent, there are many instances where the displacement can be observed to change along the fault plane. There are only two basic ways in which this paradox (Fig. 4*a*) can be resolved:

1. by interchanging fold shortening and fault displacement (Fig. 4*b*), or
2. by imbrication (Fig. 4*c*).

Thrust faulting and folding are both mechanisms for making a packet of rock shorter and

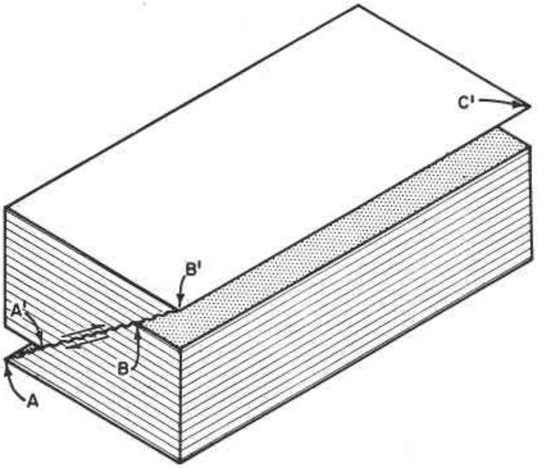
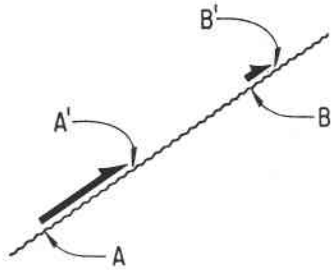


FIG. 3. Consistency of thrust displacement.

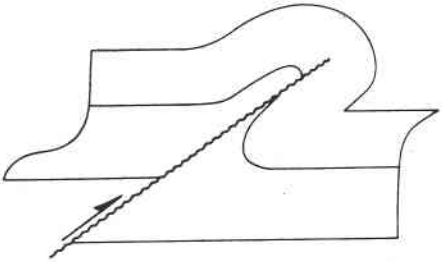
thicker than it was originally, so that one could expect the two mechanisms to be interchangeable. Imbrication is the distribution of displacement from one large fault to several minor ones. Figure *4c* shows the common imbricate pattern, but imbricates can develop in the footwall rather than the hanging wall of the main thrust, and they can be in the hanging wall but dipping in the opposite direction to the principal fault ("back thrusts").

In Fig. 4 the thrust faults were arbitrarily and diagrammatically represented as simple planar features. With planar faults and constant bed length, a substantial amount of interbed slippage is required, which would alter the originally vertical ends of the blocks to the curved shapes shown. From these block diagrams it is fairly evident that:

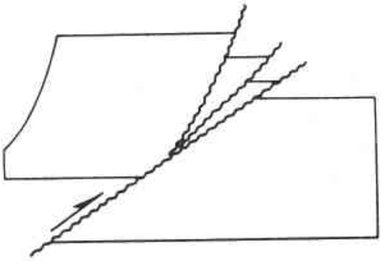
1. faults with changing displacement are apt to be curved in cross section rather than planar (can be confirmed by observation);
2. interbed slippage is a necessary part of the thrust faulting process just as it is in concentric folding;
3. interbed slippage can contribute to the change of displacement along a fault plane and, in extreme instances, could become a species of imbrication.



a. APPARENT ANOMALY
IN AMOUNT OF FAULT DISPLACEMENT



b. ACCOMMODATION BY FOLDING



c. ACCOMMODATION BY
UPWARD IMBRICATION

FIG. 4. Changes in thrust displacement. See text for explanation of curved ends on some fault blocks.

The Turner Valley cross section (Fig. 5) is based on good well, seismic, and surface geological control. It shows a remarkable change from more than 2 miles (3.2 km) of fault displacement at depth to virtually none at surface and the accommodation of this change by folding. This is an excellent example of a balanced transition from shortening by faulting to shortening by folding. In checking this cross section for consistency, one would probably use the vertical ends of the cross section as reference lines even though strictly speaking, neither is a proper reference line. The eastern end is in the undisturbed plains section, but the reference line should be perpendicular to the regional dip rather than vertical. The western end of the section does not extend as far as the synclinal axial plane, which would be the proper place for the second reference line. However, at this end of the

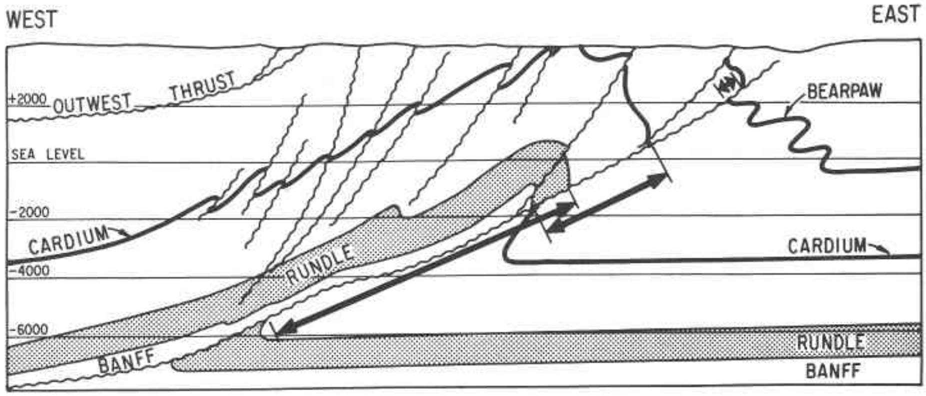


FIG. 5. Changes in thrust displacement in the Turner Valley structure (after Gallup 1951, with the permission of the Amer. Assoc. Petrol. Geol.).

section, the Rundle member has "returned to regional", which provides for practical purposes an acceptable place to draw a reference line, although it too should be perpendicular to the regional dip. (Please observe the behavior of the top of the Paleozoic rocks in the central part of Fig. 1 for an appreciation of the significance of a horizon's return to its regional elevation.)

Examples of the Use of Balanced Cross Sections

Interpreting a cross section through the culmination of the Panther River anticline posed an interesting problem when a well drilled on the crest of the structure penetrated a thrust of Cambrian over Jurassic rocks, a stratigraphic throw of some 8000 ft (2440 m). This was particularly perplexing because at the surface, the west-dipping fault on the east flank of the structure thrust Jurassic over Lower Cretaceous rocks, a throw of only a few hundred feet. Some well control, surface geology (Fig. 6), and seismic data were available to provide the critical data shown in Fig. 7. Data in the line of section could be interpreted in two basically different ways (Fig. 8). The interpretation with one major thrust appeared most likely to be correct because it correlated two major thrusts with stratigraphic throws of the same order of magnitude. The interpretation with two major thrusts seemed unreasonable because it linked a major fault in the subsurface with a minor fault at the surface (one order of magnitude difference in stratigraphic throws). Which alternative one selected had considerable economic significance, because it affected where and at what depth one could expect to find closure in the potentially hydrocarbon-bearing objective horizon at the top of the Paleozoic section.

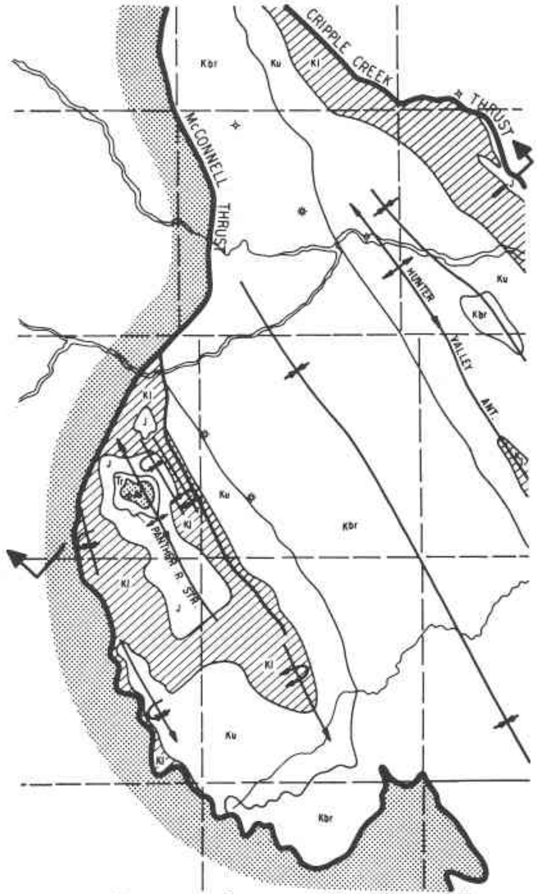


FIG. 6. General geology of the Panther River area.

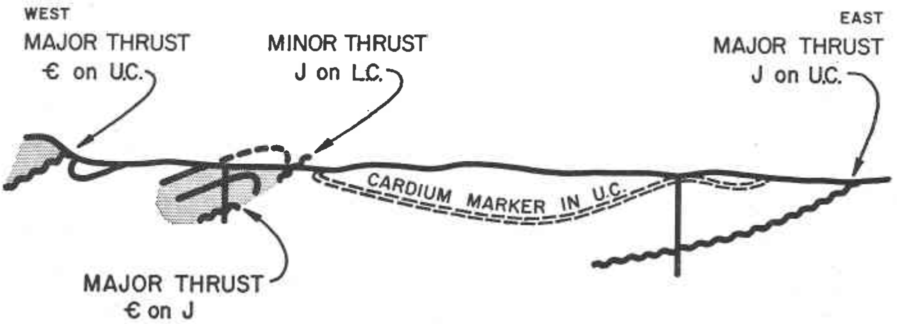


FIG. 7. Basic data available for the original interpretation of the Panther River cross section.

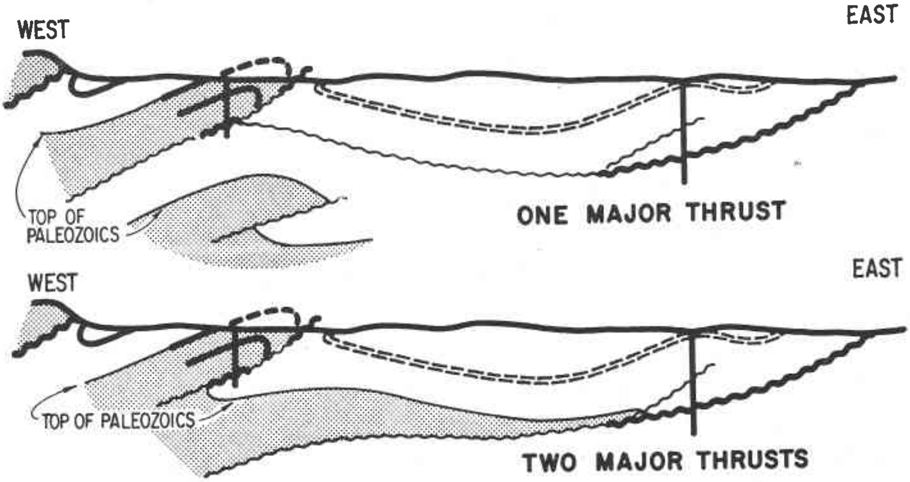


FIG. 8. Two alternate cross sections which would satisfy the data on the original line of section.

However, the geological map provided some data off the line of section, which had not been used. R. E. Daniel of Chevron Standard statistically analyzed the fold (Dahlstrom 1954), found it to be cylindrical, and calculated plunge values. The data on the geological map were projected up plunge (Stockwell 1960) into the plane of a vertical cross section passing through the culmination to provide the information shown above ground level at the west end of the section in Fig. 9. On this cross section it is apparent that the axial planes of the anticline and syncline are converging in depth, which is confirmed by the reduced length of the steep fore limbs in successively lower stratigraphic horizons. Having the fold disappear with depth would produce a geometrically unacceptable discordance in bed lengths unless the fold disappearing downward could be compensated by the fault dying out upward. This would be a repetition of the Turner Valley situation in Fig. 5. Once this fundamental point was grasped, it was apparent that the superficially unlikely looking cross section in Fig. 8 with the two major thrusts was the correct one. The cross section which R. E. Daniel constructed according to this concept was subsequently confirmed by the drilling of a well on the deep structure immediately to the east, and by the deepening of the original well.

Hypotheses of regional significance can develop from balancing cross sections. Figure 10 shows two alternative interpretations of seismic, well, and surface data. The data in the two sections are the same, but in Section A, the simply migrated seismic section, the vertical dimension is essentially two-way transit time, whereas B is the normal natural scale structural cross section. The Mesozoic and Paleozoic sections are both cut by thrusts, but even a casual inspection shows that the shortening in the Mesozoic section is far in excess of that in

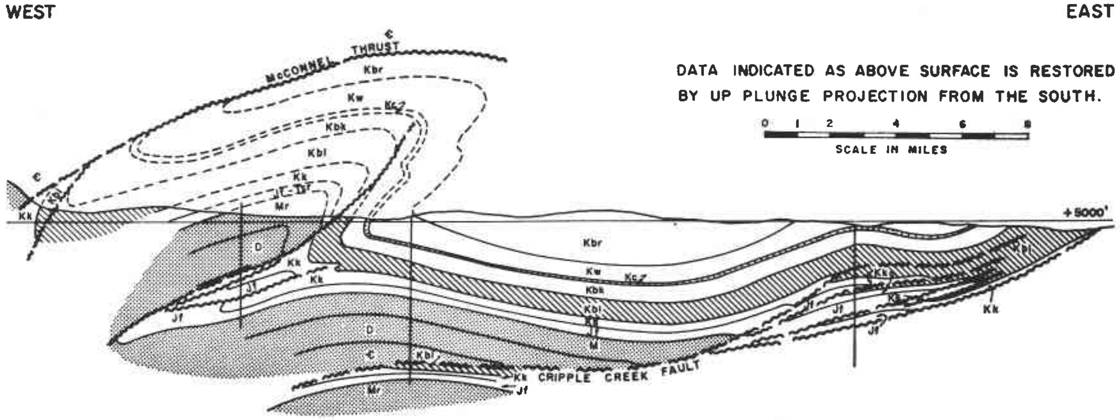
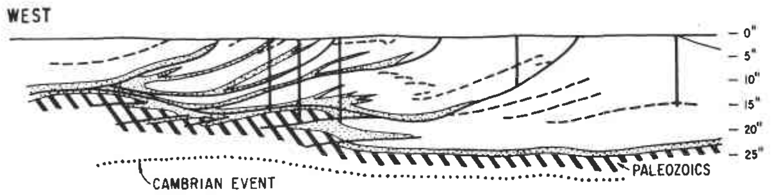
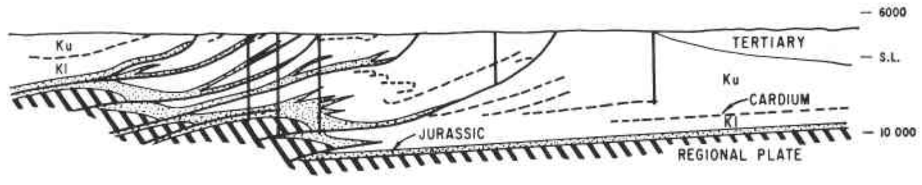


FIG. 9. Panther River cross section as subsequently shown by drilling (after R. E. Daniel, Chevron Standard).



A - SEISMIC SECTION



B - STRUCTURAL SECTION

FIG. 10. Two alternate interpretations of surface, well and seismic data in a Waterton area cross section. Minor fault traces have been omitted but their existence is shown by marker bed offsets. Note the inconsistencies of fault displacement in Section B which make this alternate untenable.

the Paleozoic. This difference in shortening precludes the kind of interpretation that was attempted in Section B, because any simple fault that one tries to draw will have far more displacement at Mesozoic level than at Paleozoic level. To avoid an unexplained inconsistency it is necessary to postulate a décollement separating the Mesozoic rocks from the Paleozoic rocks. This décollement would be in the basal Jurassic beds just above the top of the Paleozoic section. Since this horizon is itself now deformed by both folding and faulting, it becomes necessary to postulate a two-stage sequence of deformation. According to this hypothesis the Mesozoic rocks were first deformed by folding and thrusting above a sole fault (décollement) in the basal Jurassic beds, and the deformation in the Paleozoic rocks is a subsequent stage of the tectonic cycle. Balancing this cross section shows that the western (upper) thrust system was formed before the eastern (lower) one, and demonstrates (Bally *et al.* 1966, Fig. 6) that, in the regional sense, deformation advanced from west to east.

Consistency between Cross Sections

The foregoing discussion has been concerned with a one-dimensional check of the internal consistency of an individual cross section by simple measurement and comparison of bed lengths. During the stage of reducing the law of conservation of volume from three dimensions to one, there was a two-dimensional stage wherein one could state that deformation changes the form but does not alter the surface area of an individual bedding plane. This stage is represented in Fig. 2*d*, where it is evident that no abrupt change can occur in fold form and (or) location unless there is a discontinuity. Similarly, in the block diagram of Fig. 3, the fault displacement between B′ and C′ cannot change abruptly unless a discontinuity intervenes. Such transverse discontinuities (tear faults) do occur in a few places in the Foothills, where they may affect either or both thrusts and folds. From such considerations of the two-dimensional version of the law of conservation of volume one can derive the rule that: *In adjacent cross sections the amount of "shortening" at a specific horizon between comparable reference lines must be nearly the same unless there is a tear fault between them.*

In this context, "shortening" is the difference between actual bed length and the horizontal distance it now occupies. This statement does not deny the possibility of a gradual change in the shortening along an individual structure nor along a mountain belt as a whole, but it does deny that these changes can occur abruptly without tear faulting.

The reader can convince himself of the reasonableness of this rule by taking a long thin strip of light paper and attempting to produce a long parallel system of folds and faults. Paper is a suitable medium for this kind of demonstration because its lack of plasticity obliges one to maintain a constant bed area. The Rocky Mountain belt is 1000 miles (1610 km) long from the Idaho batholith to the Liard River. The deformed width of say 100 miles (160 km) is, perhaps, half of the width of the rocks as originally deposited. These figures provide some approximate dimensions for the paper experiment.

Having performed the experiment actually or mentally, the reader may now have reason to suspect that there should be comparable amounts of shortening in adjacent cross sections. Figure 11 shows the north end of Turner Valley, where there is an abrupt change in structure from the simple faulted anticline of Section B–B to the sheaf of imbricates represented by Section C–C. Despite this change in structural form, the shortening at the top of the Paleozoic level in both Sections B–B and C–C in the published sections is in phenomenally good agreement at a figure of 15 000 ft (457.2 m). These two sections are consistent. Consider the third section D–D. In Section D–D the well control does not establish how far to the left (west) the regional plate extends under the Turner Valley sole fault. The natural tendency is to put the footwall "cut-off" of the top of the Paleozoic rocks at X. If this is done, the shortening in Section D–D becomes approximately 6000 ft (1830 m), some 9000 ft (2740 m) less than in Section C–C. A 60% reduction in shortening from C–C to D–D would be quite inconsistent, and prompts an interpretation where the top of the Paleozoic beds in the regional plate extends back to Y. This would also produce better internal consistency within section D–D by making the fault displacement on the Home Sand (R–S) equivalent to that on the top of Paleozoic section (Y–Z).

The two southern sections have provided a clear example of consistency of shortening in adjacent sections despite rather drastic changes in structural form, and the third section shows how the rules of consistency can be used to choose between alternate interpretations in the absence of definitive well control.

Transfer Zones

Previously it was stated that shortening on the local scale in individual structures and in the regional scale in a whole mountain belt could change, but that the change would be gradual. Using the same word "gradual" for change at both scales is not really appropriate because the rate of change is substantially greater for individual structures than it is for the mountain belt as a whole. The Lewis Thrust, for instance (Dahlstrom *et al.* 1962), has a minimum of 23 miles (37 km) of thrust displacement at the United States border and 135 airline miles (217.2 km) to the north, the fault displacement is zero. Over the same distance the overall shortening in the mountain belt as a whole may have diminished, but certainly not by 23 miles (37 km). Since the whole does not change as rapidly as its component parts, it

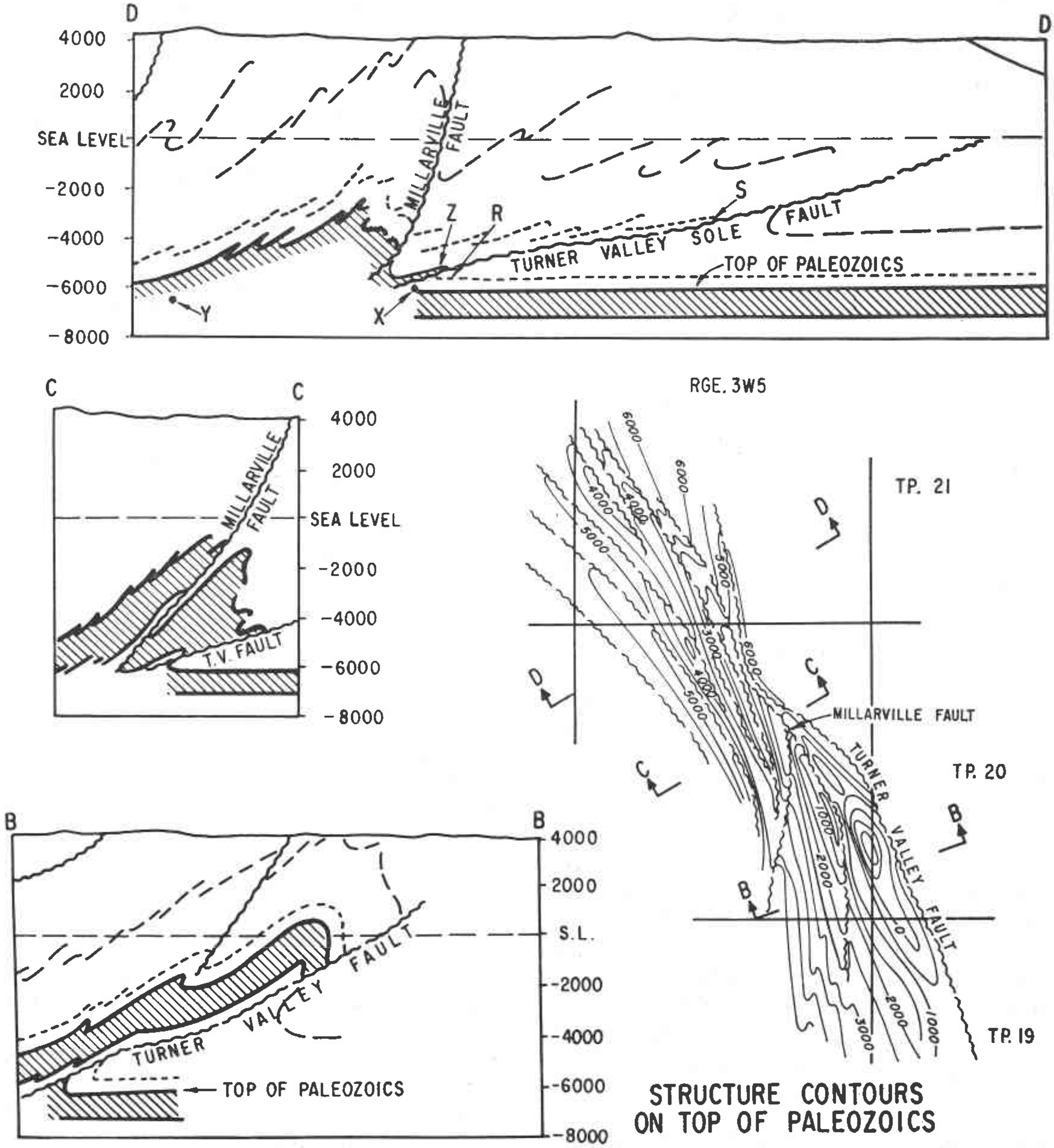


FIG. 11. North end of the Turner Valley structure (after W. B. Gallup, 1951, with the permission of the Amer. Assoc. Petrol. Geol.). Note that the cross-sectional trace of minor faults has been omitted, but their presence is indicated by offsets in the marker horizons. See text for discussion.

follows that there must be some sort of compensating mechanism at work whereby displacement is "transferred" from one structure to another. Such mechanisms have been observed in the *ac* cross-sectional plane (Fig. 5), so it is not unreasonable to expect that comparable phenomenon would function in the horizontal *ab* plane (as in Fig. 11).

The compensatory mechanism for thrusts is a kind of lap joint wherein the fault whose displacement is diminishing is replaced by an echelon fault whose displacement is increasing. Clearly such a "transfer zone" could not exist unless all of the faults involved in the transfer zone are rooted in a common sole fault. Figure 12 shows a relatively simple transfer zone consisting of three faults. In each of the five cross sections the shortening is exactly the same, although at one end virtually all of the displacement is on fault C and, at the other, on Fault A. In natural examples, the pattern is often complicated by folds and folded thrust imbricates as shown by the two mapped examples in Fig. 13.

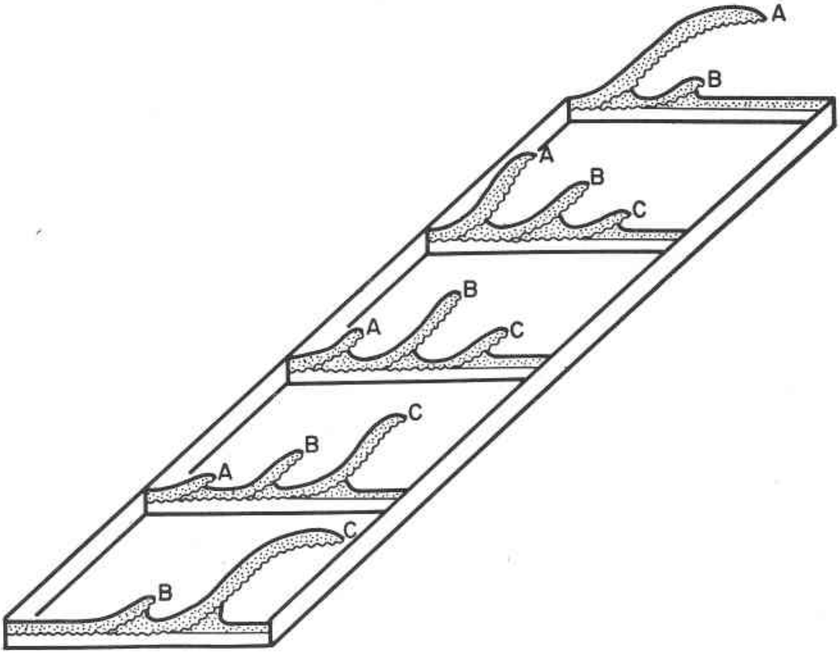


FIG. 12. Shift of displacement between thrusts in a transfer zone.

Recognition of transfer zones enables correlations to be made between thrust faults. Although one fault terminates, its place is taken by another and the zone of thrusting persists. On this basis, a frontal zone and five principal zones of thrusting can be identified within the Foothills and Front Ranges over a distance of some 400 miles (643.7 km) (Fig. 14). At the north end correlation fails because the surficial deformation was primarily folding, and faults are not prominent. The persistence and parallelism of these zones of thrusting over substantial distances lends credence to the suggestion that overall shortening is reasonably consistent along the mountain trend. In one respect, designating six zones of thrusting may be rather arbitrary because at depth all of these zones will join to a common sole fault above the through-going basement. Consequently, in the gross view, one would expect some transfer of displacement between the six thrust zones.

It is not proposed to discuss en echelon folding, although it is a part of the Foothills movement pattern (Fitzgerald 1968) wherein the transfer mechanism operates for folds as it does for faults. En echelon folds are tied to one another by a sole fault (décollement) and maintain consistent shortening by replacing a dying structure with an en echelon growing equivalent (Wilson 1967).

Palinspastic Maps

The ultimate check of cross sections in deformed terrane is whether or not the process can be reversed and the beds put back into their depositional position without introducing inexplicable bed length anomalies. Since the construction of restored cross sections is a tedious process, the discussion has been concerned with shortcuts which would be adequate for checking the geometric acceptability of individual cross sections and suites of cross sections. However, when stratigraphic studies are being done in deformed terrane, the shortcuts are

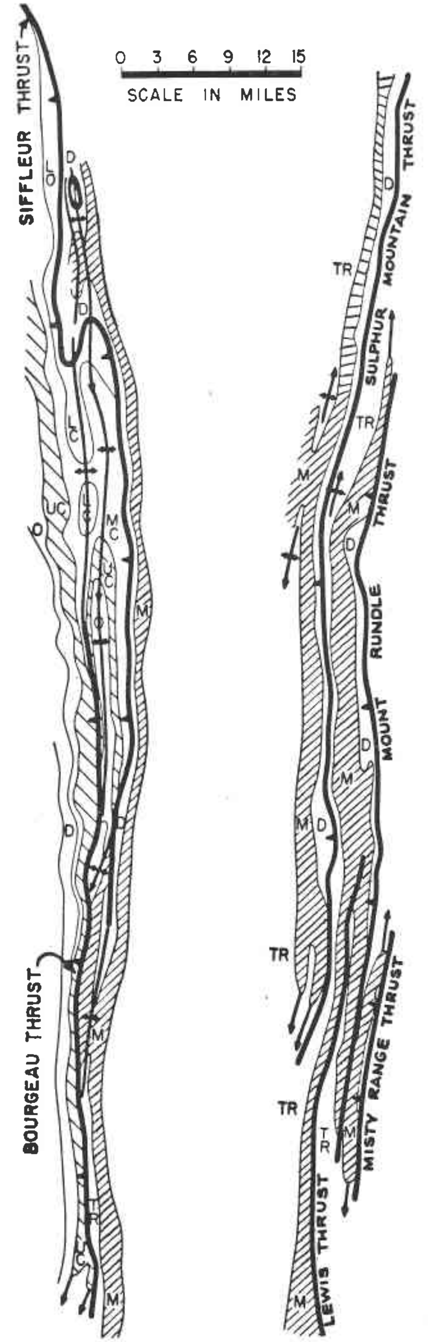


FIG. 13. Two transfer zones in the Front Ranges of Alberta. The abbreviations designate formational ages (i.e., M = Mississippian).

inadequate, and it becomes necessary to make a restored palinspastic map (Dennison and Woodward 1963), which shows beds in their depositional position.

When stratigraphic data obtained by study of deformed terrane are recorded and interpreted on an ordinary map, it is possible to make serious errors. In Fig. 15*a*, seven pieces of surface and subsurface stratigraphic data are shown in cross-sectional view. On the normal geographic presentation this data would appear in the sequence 1, 4, 5, 6, 2, 3, and 7. Obviously, what is needed for stratigraphic work is a restored map where the data are returned to their original depositional sequence of 1, 2, 3, 4, 5, 6, and 7. The normal presentation can also produce misleading stratigraphic trends (Figs. 15*b* and 15*c*).

To avoid these pitfalls, one begins a palinspastic map by constructing a suite of cross sections at regular intervals across the study area. These cross sections must be checked for internal consistency and for consistency between contiguous cross sections according to the methods previously discussed. When a consistent suite of sections is available, then shortening is determined for each fault plate and a palinspastic map constructed wherein individual thrust sheets are unfolded and pulled back to their original locations. Some geographic reference points must be maintained on the palinspastic map so that stratigraphic data can be plotted and the interpretations applied to present-day land positions.

The commonest error in palinspastic map construction is using improper values for shortening in the reconstruction. In Fig. 15*d*, two horizons A and B are shown where virtually all of the shortening in A takes place at position S, while B is shortened at R. In calculating shortening for palinspastic map construction, it would be very easy to add the shortening at R and the shortening at S together, to arrive at an answer that was twice the proper value. The best method to determine shortening is to do all the measurement on one horizon. If one is forced to change horizons, this can only be done in an area where there is no discontinuity between the reference horizons. In Fig. 15*d*, one could change from horizon A to horizon B at positions V or T, but certainly not at position U.

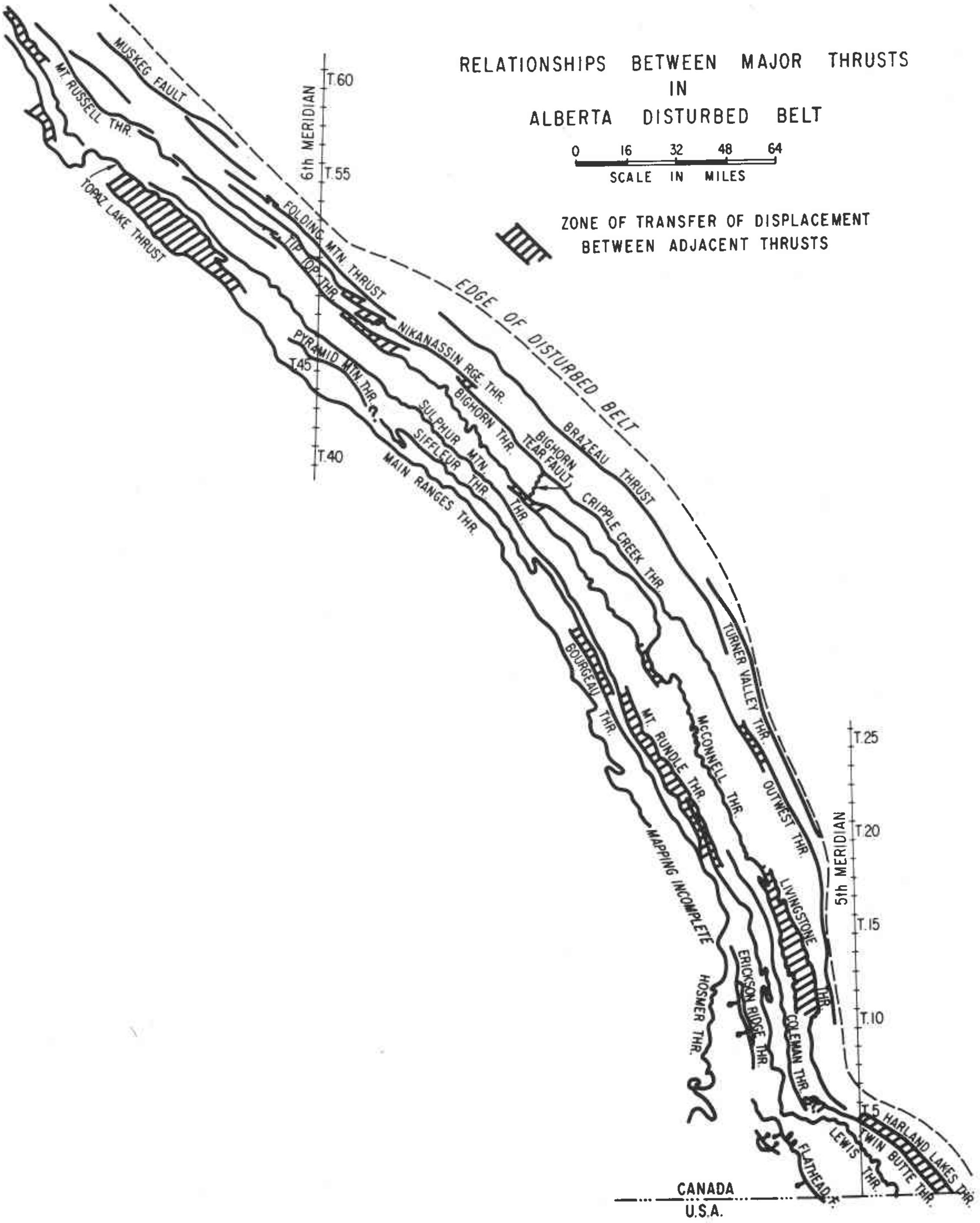
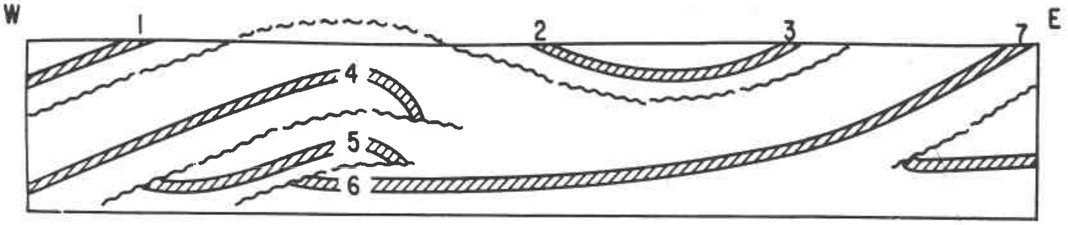
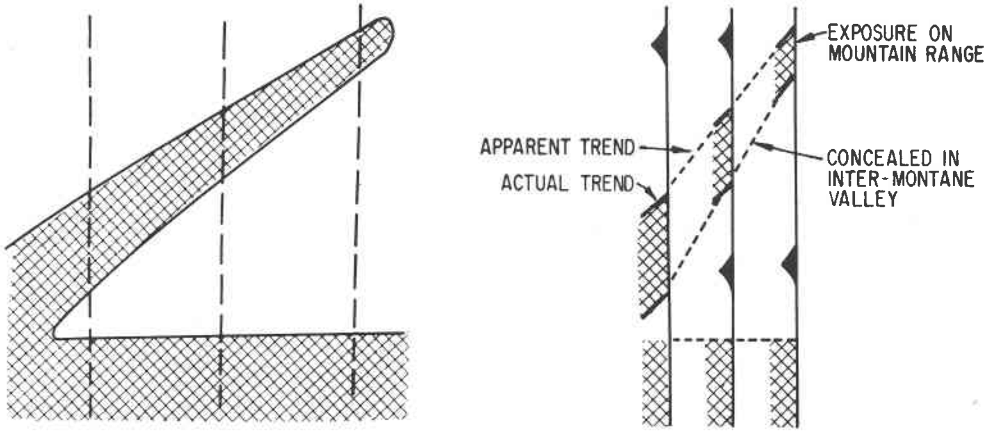


FIG. 14. Use of transfer zones in correlating zones of thrusting.

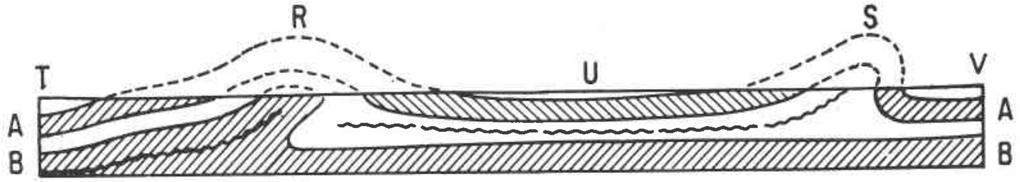


a. ORDINARY MAP PRESENTATION WOULD SHOW FACIES DATA IN WRONG SEQUENCE



b. TRENDS BEFORE THRUSTING

c. APPARENT TRENDS AFTER THRUSTING



d. CALCULATIONS OF SHORTENING MUST BE MADE ON ONE HORIZON ONLY

FIG. 15. Elements of palinspastic map construction. See text for discussion.

Conclusions

The quality of structural cross sections can be improved by testing them for geometric validity. In a concentric regime where the structure is post-depositional there is no significant change of rock volume during deformation. Since bed thickness remains constant, it follows that the surface area of any bedding plane remains constant during deformation. Because the area of successive beds in an undeformed depositional sequence is constant, it is necessary that bed lengths in individual cross sections be consistent and that adjacent cross sections have consistent amounts of shortening. Apparent inconsistencies in or between cross sections develop in consequence of discontinuities such as sole thrusts, décollement, or tear faults. Actual inconsistencies are ordinarily due to conceptual, observational, or drafting errors, which might pass undetected were there no tests for geometric validity.

In some lines of geological endeavor, cross sections are significant only as diagrams that are used to convey concepts. In geology applied to oil and mining exploration or to engineering projects, cross sections are used to convey predictions as to rock behavior and they must be conceptually and, more important, geometrically correct. In these areas it is important to the geologist and to his client that there be some way of checking cross-section interpretations prior to drilling. It should be emphasized that a cross section which passes the geometric tests is not necessarily correct, because completely ridiculous cross sections can be drawn which abide by the law of conservation of volume. However, if a cross section passes the geometric tests, it could be correct, and if it has been drawn with due regard for the "local ground rules" it probably is correct. On the other hand, a cross section that does not pass the geometric tests could not possibly be correct.

The rules developed in this paper pertain to a simple, concentrically deformed packet of "layer cake" geology in the Alberta Foothills. The rules themselves cannot be transported to a more complicated area, but the basic concept and method can be used to generate sets of rules which apply to other environments. Thus it is possible to devise amended rules, which apply to concentric extensional structures and to diapiric structures that grow during deposition or to "similar fold" regimes. Each of these areas requires a different set of rules, which must be derived from the basic geometric principles and observational restrictions. The interpretational rules for similar folding were discussed by Carey (1962). In other areas the geologist will have to develop his own rules, an endeavor that he should find interesting and rewarding.

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