THRUST BELT STRUCTURAL GEOMETRY AND RELATED STRATIGRAPHIC PROBLEMS WYOMING–IDAHO–NORTHERN UTAH

by
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INTRODUCTION

The thrust belt of western Wyoming, eastern Idaho and northeastern Utah (Fig. 1) has not been drilled for oil and gas to the same extent as have most other areas in the Rockies with preserved thick Phanerozoic sedimentary rock sequences. The thrust belt province is considered by many geologists as having too long and complicated a history of multiple deformation, uplift and erosion to harbor large oil and gas reserves even though known sedimentary rock thicknesses and facies seem favorable for past hydrocarbon generation and migration. Uncertainty in prediction of subsurface structural form, stratigraphy and timing are considered major exploration obstacles.

Much of this uncertainty can be alleviated by proper integration of structural and stratigraphic principles with available surface, seismic, aeromagnetic, paleontologic and well data. Recent studies of this sort have been published by Bally and others (1966), Dahlstrom (1970) and Price and Mountjoy (1970) for the south Canadian thrust province. In a comparable way, sufficient geologic observations have been made in the Idaho-Wyoming thrust belt by numerous geologists and geophysicists to establish with confidence certain models of basic structural types as typical of the province. These are: (1) concentric folds, (2) decollement, (3) reverse faults, (4) "tear" faults, (5) younger normal faults. Use of these as models along with proper geometric constraints permits an interpretation of thrust belt structure which is consistent with available geologic information.

In addition, awareness of the age and areal distribution of stratigraphic features such as synorogenic conglomerates and angular unconformities allows a stepwise palinspastic restoration of the structural and stratigraphic history.

A comprehensive report on thrust belt geology is not the intent, nor is it within the scope, of this paper. Rather, regional cross-sections and selected examples and discussions of typical features are presented to illustrate how the present structural form and stratigraphic history of parts of the thrust belt may be interpreted. The structural discussion is one of geometry rather than genesis, although one often implies certain aspects of the other.

GENERAL STRUCTURAL FRAMEWORK

Distribution of major thrust faults and younger extensional faults is illustrated on Figure 1. This, plus two regional structural cross-sections, X-X' and Y-Y' (Plates I and II, pocket) are an interpretation of the gross structural form of the thrust belt.[2]

A westward thickening wedge of Upper Precambrian, Paleozoic and Mesozoic sediments was compressed into a zone about 65 miles wide, roughly half its original width. East-west shortening was achieved by doubling the sedimentary section through motion on low angle reverse (thrust) faults and contemporaneous associated concentric folding. This period of compressional deformation began in latest Jurassic and continued through early Eocene. Later, normal (extensional) faulting occurred from Eocene to present (Armstrong and Oriel, 1965).

Seismic, aeromagnetic (Fig. 2) and surface data indicate the crystalline basement is not deformed over most of the region except for broad warping and is, therefore, structurally detached from the sedimentary cover by a regional *decollement*. The crystalline basement is, however, involved in thrusting along the western thrust belt margin in the central Wasatch Range north of Salt Lake City (Fig. 1) (Eardley, 1944). Bell (1952) described the outcrop of crystalline basement (Farmington Canyon complex) as a series of thrust slices or plates more than two miles thick. The central Wasatch Range is an uplift which is part of the Sevier orogenic belt described by R. L. Armstrong (1968). Uplift is pre-Evanston Formation (pre-Paleocene) in age according to mapping by Mullens and Laraway (1964) and is probably post Crawford thrusting since it apparently deforms this thrust system. Such an age indicates synchroniety between uplift and motion on the Absaroka thrust system (Plate II, in pocket) which is Santonian(?) through Maestrichtian.

STRUCTURAL GEOMETRY OF THRUST FAULTS

Empirical rules have been devised for interpreting thrust belt structural form below the level of direct observation. These have evolved over the years primarily from data gathered in the Canadian Rockies and Appalachians. These rules, modified from those set forth by Dahlstrom (1970) for the eastern Canadian thrust belt, are illustrated

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[1] Chevron Oil Co., Denver, Colorado.

[2] Data for these illustrations were collected from numerous publications as well as proprietary files. Most valuable among published data sources are surface maps by the U.S. Geological Survey. The basic ideas pertaining to structural interpretation stem from articles by Rich (1934), Wilson and Stearns (1958), Bally and others (1966), Dahlstrom (1970) and conversation with many geologists, especially C. D. A. Dahlstrom, Peter Verrall and W. G. Brown.

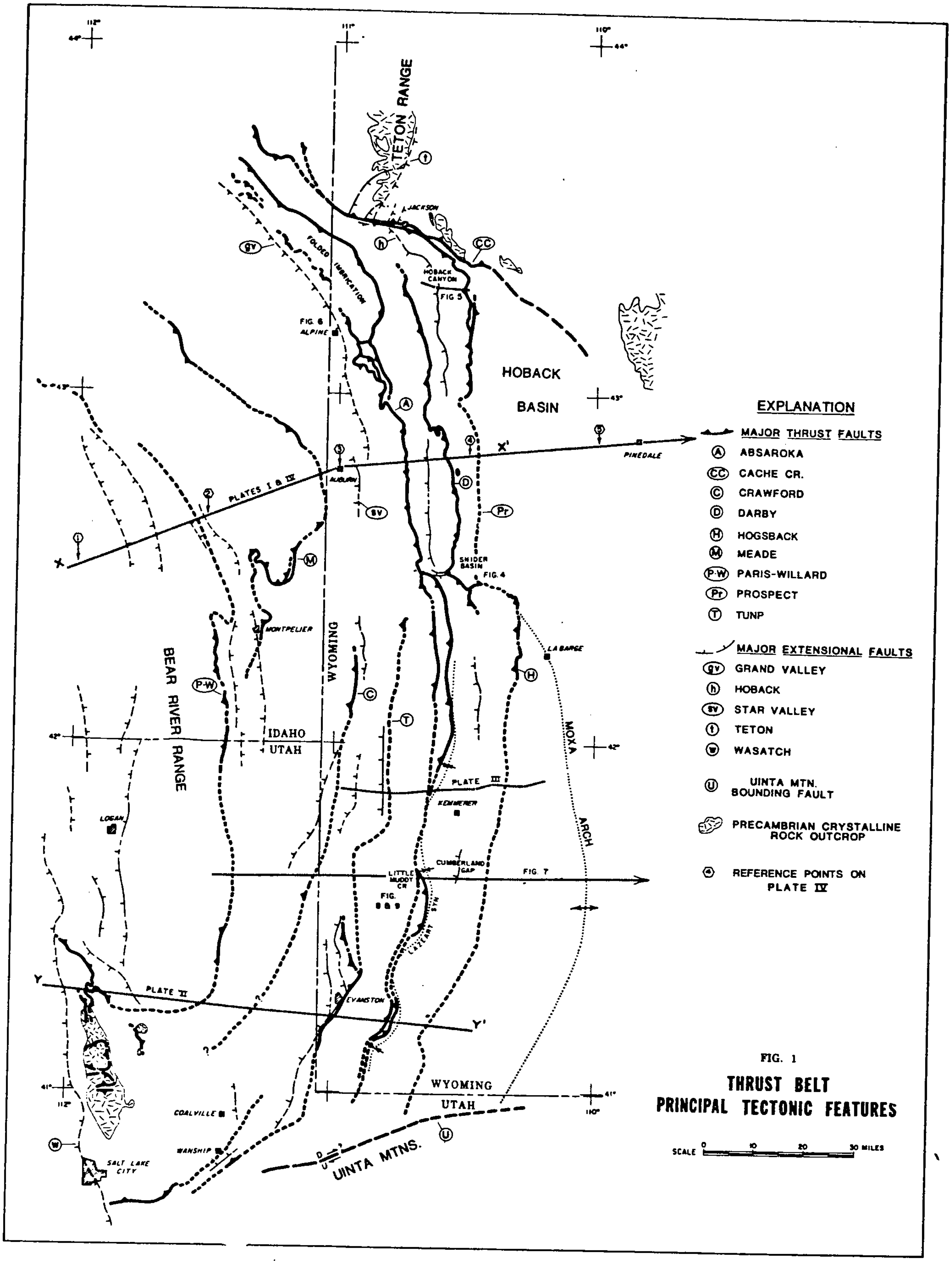

Fig. 1 — Index map showing principal tectonic features of thrust belt and location of figures (text) and plates (pocket).

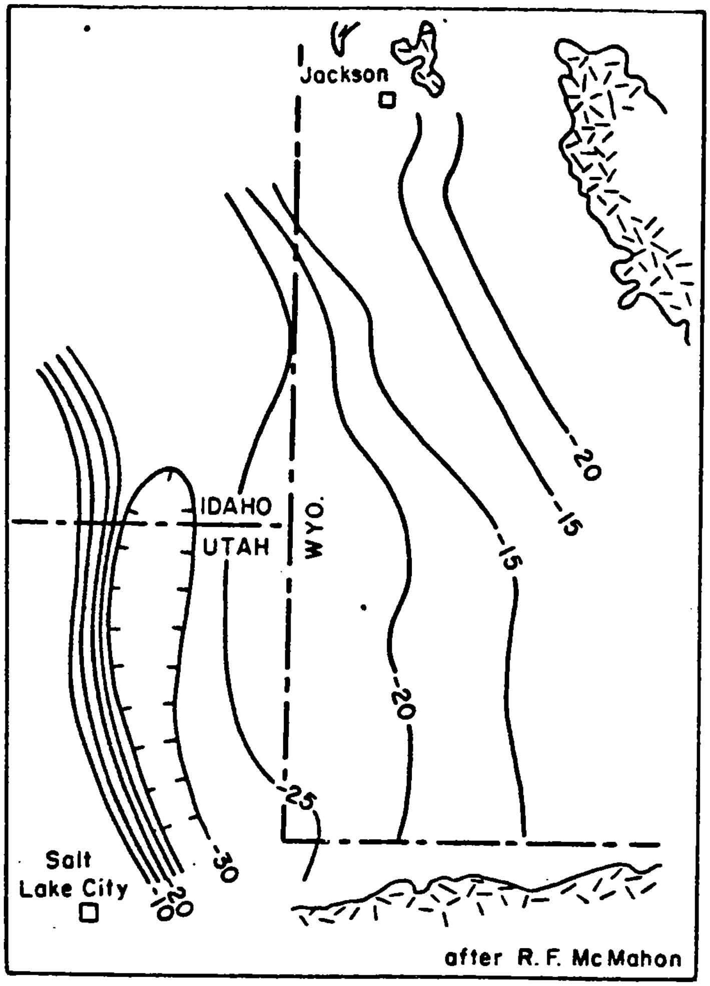

Fig. 2 — Generalized structure map, top of magnetic basement. Sea level datum. Contour int. = 5000 ft.

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schematically in Figure 3 and can be summarized as follows: (1) folds have essentially ~~concentric geometry~~, (2) thrust faults cut up section in the direction of tectonic transport, (3) thrust faults tend to parallel bedding in incompetent rocks and be oblique to bedding in relatively competent rocks, and (4) *major* thrust faults are younger in the direction of tectonic transport. Surface, seismic, and well data indicate that these concepts are applicable toward solving structural problems in the Idaho-Wyoming thrust belt. The fact that such rules can be devised at all indicates that a consistent, fundamental, long continuing deformational process has been at work.

Of great importance in predicting subsurface structure in this region is the fact that deformation is "brittle" in nature, and neither plastic flow or cleavage folding occurs to a significant degree. Concentric folding is the rule, and thickness and surface area of beds do not change. These features make it necessary and relatively easy to employ the concept of volumetric balance when constructing structural cross-sections (Dahlstrom, 1969). If correctly drawn, profiles of deformed sediments can be restored to an undeformed state without creating large unexplained voids, excess rocks, or improbable detachments. Sections should be drawn parallel to the direction of tectonic transport where plunge out of the plane of section is not very steep. The regional structural sections X-X′ and Y-Y′ (Plates I and II, in pocket) are examples of this interpretational technique and illustrate the principles outlined above.

These sections are, of course, interpretive; but they are not conjecture nor are they casually drawn. Seismic data, when combined with surface and sparse well control, enables us to structurally define the subsurface in the eastern thrust belt with some confidence. Two features most critical to subsurface interpretation which can be seen on seismic sections are: (1) the position and length of specific footwall stratigraphic cutoffs and (2) the general shape of the major thrust fault plane. From this information the amount of fault displacement and a correlation between surface hanging wall structure and subsurface fault plane shape can be made. Westward, where seismic data is not available, or is not interpretable because of poor record quality, erosion has exposed enough of the footwall structure of major thrusts to allow application of the principles established to the east.

The seismic time section (Plate III, in pocket) illustrates the tendency for ~~major thrust~~ faults to have a steplike profile. The Absaroka fault trace cuts steeply eastward through Paleozoic and Lower Mesozoic beds, flattens and nearly parallels bedding for several miles in the Cretaceous, then cuts abruptly up section to the surface. The Hogsback thrust shows similar form. Such steplike profiles are evident on many other seismic lines.

To the west, the Meade thrust (Plate I, in pocket) has been eroded deeply enough to reveal an outcropping steplike profile which has been subsequently deformed, probably by motion on the younger Absaroka thrust plane below. Movement on such a steplike surface has certain structural consequences for beds in the hanging wall which are illustrated on the idealized fault diagram (Fig. 3) (Gretener, 1972; Rich, 1934). The "typical" ~~synclinal~~ hanging wall feature shown on the diagram is a product of the transport and rotation of nearly flatlying beds over a steplike fault profile with long intervening flat traces. The gross synclinal character of many of the mountain ranges such as the Salt River Range, Wyoming Range, Hoback Range and Bear River Range probably derive such a steplike profile in the underlying bounding thrust.

It follows from such analysis that the map position of major steps (ramps) in the fault trace would be under and slightly west of the linear zone of tightly folded and imbricately faulted anticlinal structures of variable asymmetry which are observed to form the western borders of these ranges. This zone of locally intense deformation appears to result from rocks being ramped and rotated over a major step in the footwall. The long persistent west dip

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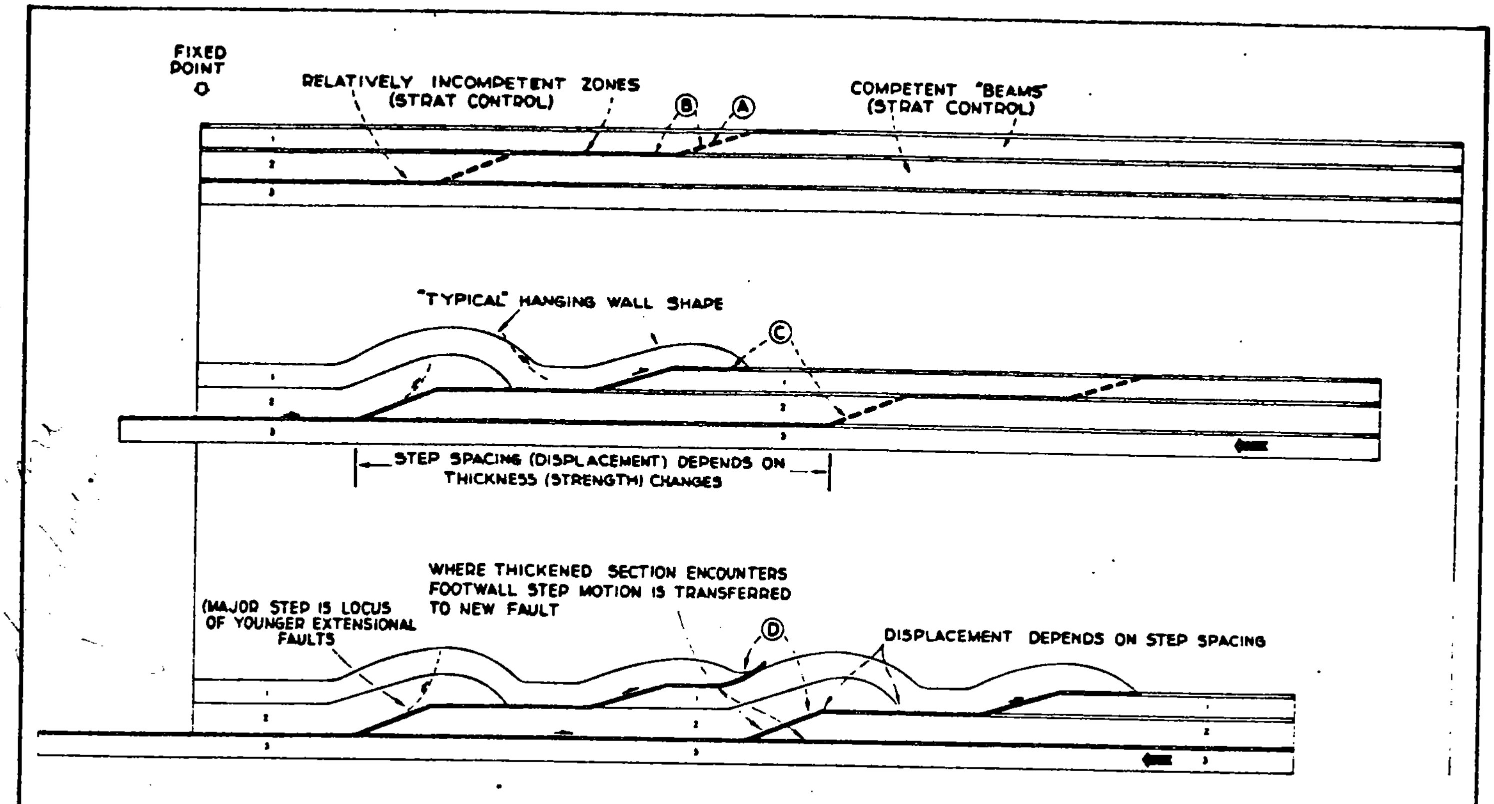


IDEALIZED THRUST FAULT DEVELOPMENT

Ⓐ FAULTS CUT UP SECTION IN DIRECTION OF TECTONIC TRANSPORT.
Ⓑ FAULTS TEND TO BE PARALLEL TO BEDDING IN INCOMPETENT ROCKS AND OBLIQUE IN COMPETENT ROCKS.
Ⓒ MAJOR FAULTS ARE YOUNGER IN DIRECTION OF TECTONIC TRANSPORT.
Ⓓ MAJOR THRUST FAULTS DON'T OVERLAP SIGNIFICANTLY.
GENERAL EFFECT IS TO DOUBLE THE FAULTED SECTION, THEREFORE NET SHORTENING ALWAYS APPROXIMATES 50%.

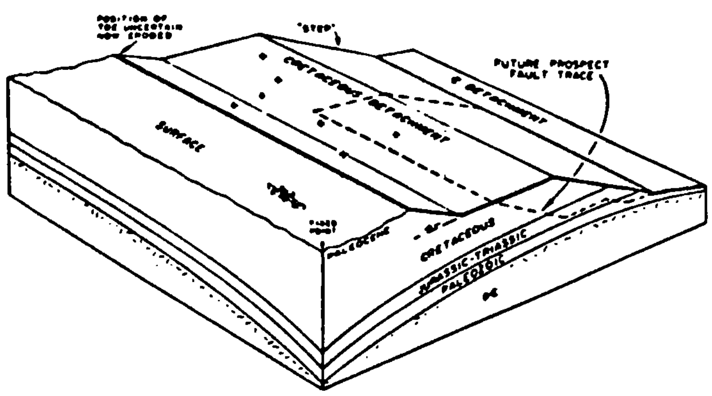
Fig. 3 — Schematic diagram illustrating empirical rules regarding thrust faults.

panels of Cretaceous and Jurassic rocks such as that in Greys River Valley west of the Wyoming Range (Plate I, in pocket), and that comprising the west flank of the Meridian Anticline (Plate III) are also clues to the subsurface position of major footwall steps.

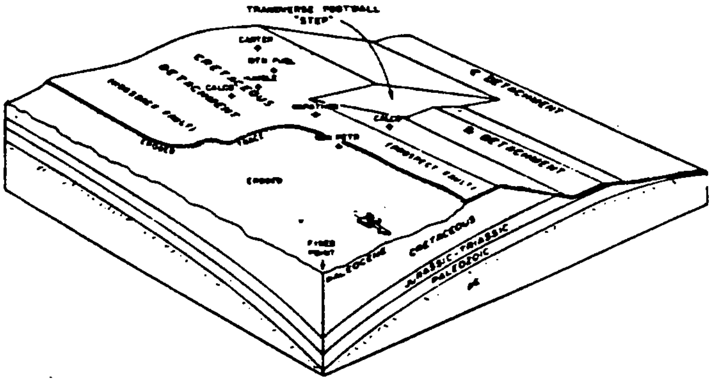
An application of the principle of volumetric balance can be observed on section X-X′ (Plate I, in pocket). Note that the long hanging wall cutoff in lower Mississippian rocks shown for the Meade thrust is matched in the footwall farther west: the total shortening is known from outcrop preservation of both hanging wall and footwall cutoffs of Nugget sandstone (Cressman, 1964). The interpretation is admittedly speculative; however, one can be reasonably sure that a long footwall section of lower Mississippian rocks must exist in the subsurface to the west.

The main detachments occur at different stratigraphic positions. Apparently, even crystalline basement rocks (gneiss, schist, granite) contain detachment zones in the central Wasatch Range. Detachment positions must be zones of relative weakness (Gretener, 1972, p. 601). Although weak zones are generally equated with shales, other rock types may become weak under certain overburden pressure and temperature conditions. What may be a detachment zone in one area may not be in another. Well, seismic and surface control indicate the basal detachment lies within Cambrian shale and carbonate near the top of the crystalline Precambrian rocks over most of the subject area. Other preferred detachment positions are in the incompetent Jurassic Twin Creek Formation and basal Mississippian rocks in the west, and within the upper Cretaceous shale in the east. Still other detachment positions occur locally, consequently complicating the hanging wall structure; for example the Prospect thrust rides in the Triassic Ankareh Formation for about six miles.

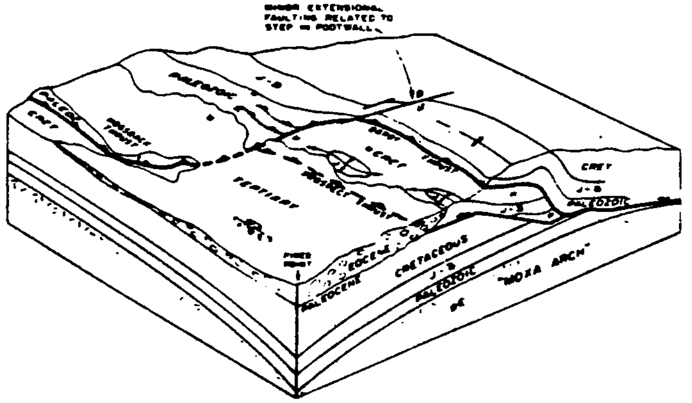
Mackin's (1950) method of interpreting geologic maps by downdip (downplunge) viewing is extremely useful in the thrust belt. The wild looking subsurface interpretation shown on the northern regional cross-section X-X′ (Plate I, in pocket) in the vicinity of the Salt River Range is merely a southward (downplunge) projection of the surface form mapped by Rubey (1958). The extreme fold-fault shortening of Cambrian, Ordovician and Devonian



A. - EARLY DARBY FAULT PLANE



B. - COMPOUND PROSPECT-DARBY (HOGSBACK) FAULT PLANE



C. - PRESENT GEOLOGY (GENERALIZED)

Fig. 4 — Block diagrams showing evolution of linkage between the Darby, Prospect and Hogsback thrust faults; and the resulting hanging wall geology.

rocks, and the lack of such shortening in overlying Mississippian rocks as shown on the surface map require a detachment between them. This form, or something comparable, must project southward under the Permo-Pennsylvanian rocks to the line of section or some discontinuity like a transverse fault must intervene. There is no evidence for such a transverse separation.

Downdip viewing of geologic maps, when combined with well and seismic control, is also useful in interpreting the structure of the Snider Basin area northwest of La-Barge, Wyoming (Fig. 1) where there has been some controversy over the nature of the linkage between the Darby, Prospect and Hogsback thrusts.[3] Viewing a geologic map of this area from the east (down the dip of the thrusts) gives one the impression that the Darby thrust is uplifted and folded by the Prospect fault. Well and seismic control indicate that this is what occurred (Fig. 4). Motion on the Prospect fault has folded an older Darby fault plane and rocks on the Darby hanging wall. Actually, the effects of the Prospect fault motion on Darby hanging wall rocks can be seen for several miles west of Snider Basin to the vicinity of the older Absaroka thrust trace. Fault motion south of the intersection between Darby and Prospect thrusts was on a single fault plane, the Hogsback. The Hogsback thrust, then, becomes a composite plane of earlier Darby and later Prospect thrust motion. In longitudinal profile (north-south) the Prospect thrust steps stratigraphically up section to the south and joins the older Darby fault. The steep south plunge of the Prospect hanging wall anticline at Snider Basin results from eastward disappearance of this step where both Darby and Prospect thrust planes join and ride in the same upper Cretaceous detachment horizon. Descriptions of this type of thrust fault linkage in the Canadian Rockies are discussed by Dahlstrom (1970, p. 375). He refers to them as a type of "tear" fault which is an integral part of the boundary of the deformed hanging wall panel, and as being distinctive from those tears which are wholly within one plate. Hanging wall structural plunge like the steep south plunge on the Snider Basin anticline results from motion along this type of "tear." Surface maps indicate that similar thrust fault intersections, where motion on a younger thrust below deforms and links with an overlying thrust across a transverse step ("tear"), apparently occurs at several places along the trace of the Absaroka fault zone; specifically, five miles west of Snider Basin (Absaroka-Commissary thrusts), southeast of Alpine, Wyoming (Absaroka-Murphy-Firetrail thrusts), and just north of Little Muddy Creek south of Kemmerer, Wyoming.

The problem of naming faults which have composite motion through linkage of two or more faults might be handled by assigning each fault a name, and assigning a general name to the whole linking system. Thus we would have the Prospect, Darby and Hogsback thrusts, and may call the system the Darby thrust zone, since the name "Darby" has much historical usage. This is similar to the procedure followed by Armstrong and Cressman (1963) in naming the Bannock thrust zone. We interpret thrust faults of the Idaho-Wyoming thrust belt to group, from west to east, into a Bannock zone (Willard-Paris

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[3] Armstrong and Oriel (1965) named the large fault which crops out 7.5 miles west of LaBarge, Wyoming, the Hogsback thrust. It had previously been called "Darby" by some workers.

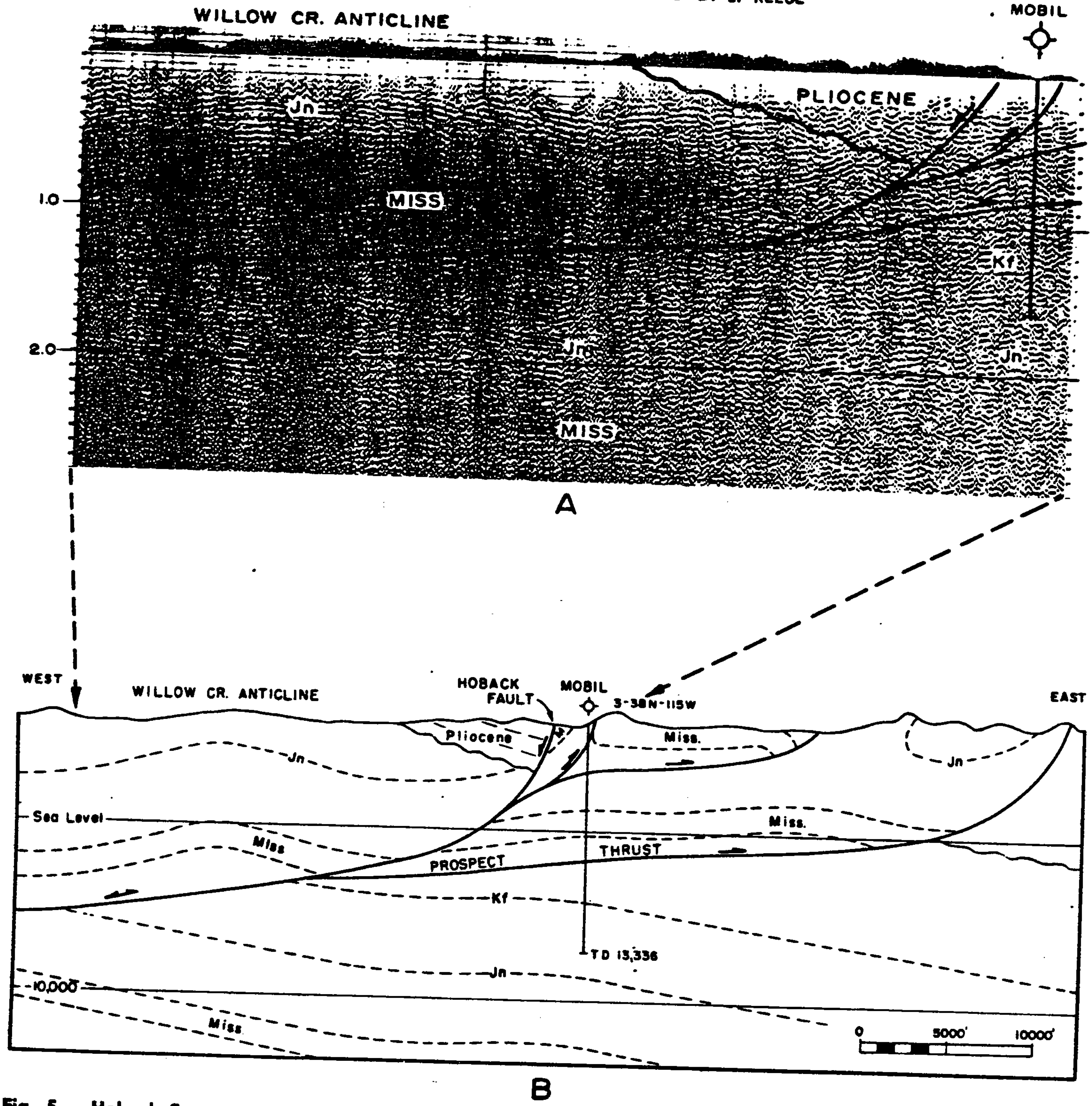

Fig. 5 — Hoback Canyon area, Wyoming. A. Seismic time section; B. Generalized structural section. Shows rotation of Pliocene into Hoback normal fault. Normal fault is restricted to hanging wall of Prospect thrust.

thrusts), a Meade-Crawford zone, an Absaroka zone, and a Darby zone. There are stratigraphic as well as structural reasons for such zonation which will be discussed later.

STRUCTURAL GEOMETRY OF EXTENSIONAL FAULTS

The thrust belt has been undergoing extension from Eocene to present along a series of major normal faults (Armstrong and Oriel, 1965) (Fig. 1). Many of the north-south valleys, such as Grand Valley, are half-grabens, bounded on the east by normal faults. Published interpretations generally depict the normal faults as being high angle and cutting through the entire sedimentary section and crystalline basement. Some evidence indicates that many of the normal faults flatten with depth and sole into older underlying thrust planes. According to this idea, portions of the major "thrusts" have composite movement;

early compressive motion (thrust faulting) and later extensional motion (normal faulting). The position of the major normal faults appears to be related to "step" geometry in the underlying thrust sheet. There is a coincidence between the position of the young normal faults and older thrust fault plane steps. An example of this type of fault is the Flathead fault in the thrust belt of southeastern British Columbia and northwestern Montana (Bally and others, 1966; Dahlstrom, 1970; Labrecque and Shaw, 1973). The Flathead is high angle where exposed at the surface but seismic and well data indicate the fault flattens with depth, and joins but does not cut the underlying Lewis thrust. Several pieces of evidence suggest the normal faults of the Wyoming-Idaho-Utah thrust belt have the same characteristics as the Flathead fault.

The Hoback fault south of Jackson, Wyoming (Fig. 1) is a major extensional fault that is probably restricted to the hanging wall of the Prospect thrust. The Hoback fault can be mapped for a distance of 35 miles. The trace has an arcuate shape which roughly parallels the trace of the Prospect thrust. Immediately southwest of Jackson, the surface traces of the Hoback and Prospect faults converge and probably merge under the Snake River Plain west of Jackson (Fig. 1). There is no indication that the younger Hoback fault cuts the Prospect thrust. In the vicinity of Hoback Canyon, two miles north of the line of section in Figure 5, the Hoback fault has a net slip of approximately 6,000′. Net slip can be determined using the thickness of the Pliocene Camp Davis Formation which was deposited on the downthrown side of the Hoback fault. The Camp Davis Formation has an outcrop width of 10,500′ and dips eastward into the fault at an angle of 30°-35°. Assuming the formation was deposited nearly horizontal, and has since been rotated into the fault, the amount of rotation requires 6,000′ of net slip. Because east dipping antithetic faults are absent, the consistent east dip of the Pliocene into the Hoback fault plane (reverse drag) is evidence the dip of the fault plane lessens at depth.

The Mobil Camp Davis Unit well was drilled through the hanging wall of the Prospect thrust and documents the stratigraphic position and sequence in the footwall. Seismic information ties the Mobil well and extends for several miles to the west-northwest (Fig. 5). The well establishes the position of the thrust at the east end of the seismic line, and the position of the thrust can be readily picked on the seismic data at the west end of the line. Additionally, the projected position of the Mississippian below the Mobil well is at 2.4± seconds while the strong Mississippian reflection at the west end of the line is at 2.0± seconds. It would be difficult to downdrop the Mississippian 6,000′ (750± milliseconds) on the Hoback fault and honor the seismic and well data.

The position of the Hoback fault appears to have been localized by a step in an imbricate thrust in the hanging wall of the Prospect thrust. The Mobil well drilled through two imbricate thrusts (Fig. 5); a minor one near the surface and a major imbricate with 3-4 miles of shortening at 2,700 feet. Both imbricate thrusts are exposed in the Hoback Canyon east of the well. The 2,700-foot imbricate branches from the main Prospect thrust west of the well, steps up-section through the competent Paleozoic section, then rides for a considerable distance in the Triassic. The footwall shoulder of the step coincides with the position of the Hoback fault.

The Grand Valley fault(s) near Alpine, Wyoming (Fig. 6) is another example of a major extensional fault which we feel is restricted to the hanging wall of the Absaroka thrust. The trace has an arcuate shape and is parallel to the trace of the Absaroka. A thick (10,000± foot) Pliocene sequence on the downthrown block has been rotated and dips eastward into the fault. The position of the fault coincides with the interpreted position of a major step in the underlying Absaroka thrust.

Additional examples are depicted on the structural cross-sections. North section X-X′ (Plate I, in pocket) shows extensional faulting west of the Wyoming Range to be restricted to the hanging wall of the Darby thrust and west of the Salt River Range to be restricted to the hanging

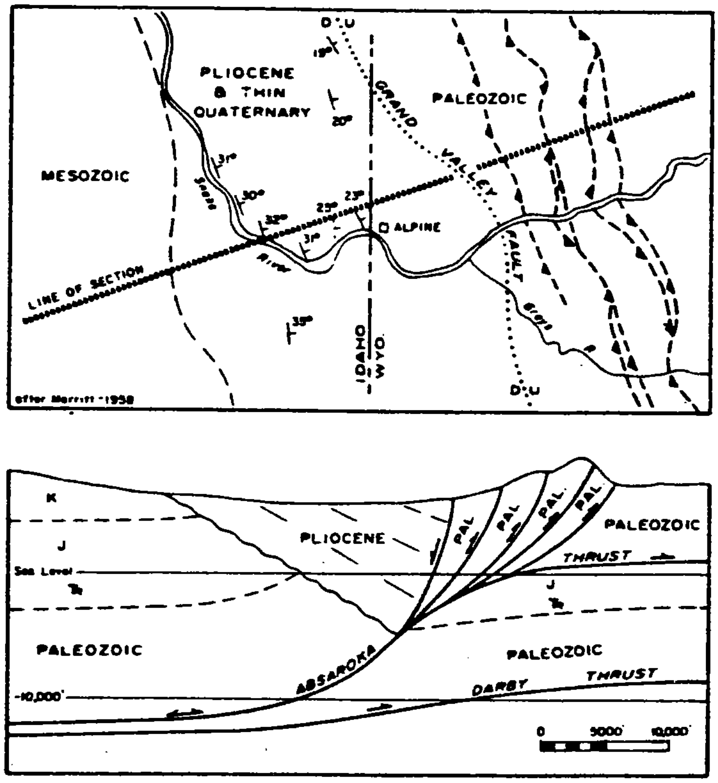

Fig. 6 — Alpine area, Idaho-Wyoming. Generalized geologic map and structural section. Shows rotation of thick Pliocene sequence into Grand Valley normal fault. Position of normal fault is controlled by a "step" in the underlying Absaroka thrust. Curvature of the normal fault plane is required when maintaining bed length in the Pliocene sequence.

wall of the Absaroka thrust. Section Y-Y′ (Plate II, in pocket) shows extensional faulting near the Utah-Wyoming state line which is restricted to the hanging wall of the Absaroka thrust. The characteristics in map view of such faults are: (1) they roughly parallel the major thrusts with which they are associated, (2) they may merge with but do not cut major thrust faults, and (3) the post-thrusting sediments on the downthrown (west) side are rotated so that they dip into the fault plane (reverse drag).

RESTORED CROSS-SECTION

A structural restoration (palinspastic) of the thrust belt along section X-X′ is shown on Plate IV (in pocket). Construction of such an illustration requires a great deal of faith in the basic thrust fault model presented herein, as well as a certain amount of recklessness. Illustrations of this sort are necessary, however, because proper stratigraphic mapping requires that control points be restored to relative pre-deformation positions.

An eastward progression in age of thrust deformation is generally accepted, and has been discussed in some detail by Oriel and Armstrong (1966). Additional stratigraphic data which bears on age of thrusting is discussed later. The connection between deformation (uplift) and sedimentation in space and time is summarized on Plate IV by restoring the section X-X′ stepwise to the end of each general period of major thrust motion. The sections are drawn as if the crystalline basement is moving west with the sedimentary section above being piled up on thrust faults and folds. The west end of the section is geographically fixed in the thrusted section. Reference points are indicated by numbers which finally become present day 30-minute longitude positions. Thicknesses of synorogenic deposits for each period are taken from regional isopach maps, restored to proper pre-thrust position, and flattened on a sea level datum.

The upper section shows thickness profiles of pre-thrusting (pre-Cretaceous) rocks completely restored. According to this interpretation, the crystalline basement surface was dipping approximately 6° westward. The wedge of sediments (including Precambrian) to be involved in thrusting was about 70,000 feet thick in the west and 11,000 feet thick on the east in this line of section. Thrusting was initiated on a surface which was buried far below sea level. Initial uplift of the site of the Bear River and Portneuf Ranges is believed to be a result of thrust faulting instead of uplift being the cause of thrust faulting as in conventional gravity slide models. Shortening in the brittle sedimentary section may be compensated westward by plastic flow in the basement when these rocks reach the depth (pressure) and temperature required for such behavior (Armstrong, 1974).

An eastward migrating foredeep related to Paris and Meade thrust faulting is indicated by the distribution of Cretaceous synorogenic deposits which predate the Ericson Formation. Post Ericson sediment distribution is more varied; local depositional basins began to form as the easterly migrating thrust belt impinged upon basement involved fold-fault uplifts on the Wyoming foreland province. The creation of the Moxa Arch, a broad basement involved fold, is synchronous with Absaroka thrusting. The Prospect-Darby thrust system overrides the arch north of LaBarge, Wyoming.

A total horizontal shortening of approximately 50% of the original width involved has been calculated in independent studies of different parts of the thrust belt province. Restoration of section X-X′ (Plate IV) shows 65 miles of horizontal shortening of the Mississippian from an original width of 130 miles or 50% (shortening indicated for the Wind River Mountains is not included). The southern regional section Y-Y′ (Plate II) shows about 52 miles of shortening of Mississippian from an original 111-mile width, or 47%. Monley (1971, p. 525) indicates 60 miles of shortening in a regional section intermediate between X-X′ and Y-Y′. Rubey and Hubbert (1959, p. 190) estimate about 85 miles of shortening of an original 175 miles, or 48%, for the Idaho-Wyoming thrust belt along latitude 43°. Bally and others (1966, p. 359) and Price and Mountjoy (1970, p. 16) estimate close to 50% shortening for the Canadian thrust belt. The tendency seems to be to double the thrusted section, thereby halving the width. Following the concept that thrust faulting will occur in a manner which requires the least work, it is apparently "easier" for a new fault to form in front of an older one than it is to ramp an already thrust-thickened section over a step and effectively triple the section (Fig. 3, Item D). The fact that major thrusts do not overlap in map view relates to this situation.

SYNTECTONIC DEPOSITS

The sedimentary record indicates that thrust faulting and concomitant uplift were episodic in the time period from Late Jurassic-Early Cretaceous to Early Eocene. Although the dominant movement during overthrusting was horizontal, a significant vertical component of motion was also involved. Syntectonic sedimentary deposits were formed concurrent with the creation and denudation of highlands on the rising thrust plates. Dating the preserved remnants of these syntectonic deposits not only gives evidence of the time of thrusting but also provides a key to facies mapping of Cretaceous sediments in the thrust belt.

Syntectonic conglomerates recognized in the southern part of the Idaho-Wyoming thrust belt include the Ephraim Conglomerate, the Echo Canyon Conglomerate, an unnamed unit at Little Muddy Creek (Fig. 1) and the Evanston Formation. The stratigraphic position of these conglomeratic units and their relationship to several major

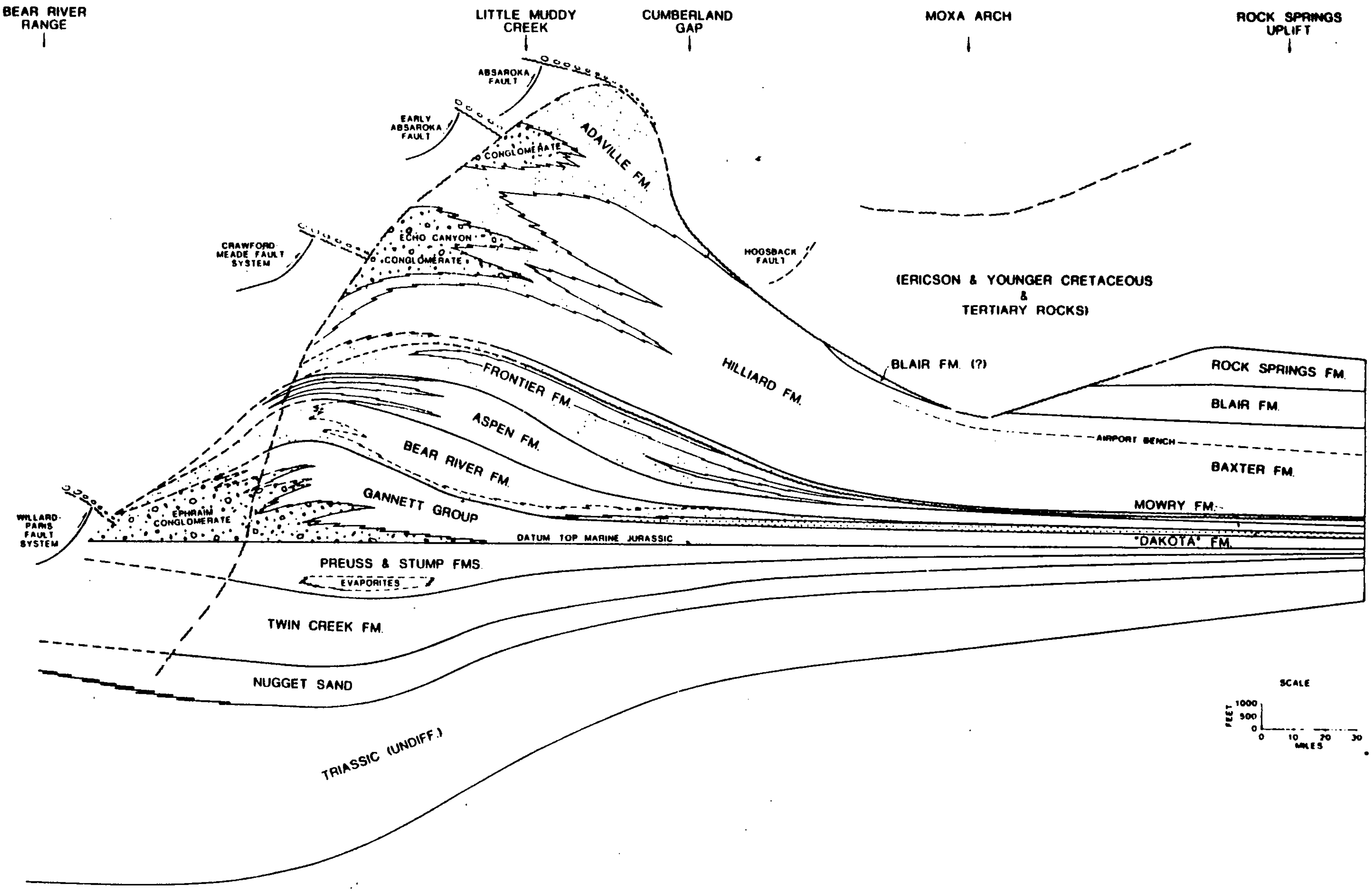

Fig. 7 — Stratigraphic diagram of restored pre-Evanston mesozoic rocks in western Wyoming and northern Utah showing relationship between thrust faulting and sedimentation. Restoration is based on palinspastic isopach and facies maps of individual formations. Line of section shown on Fig. 1.

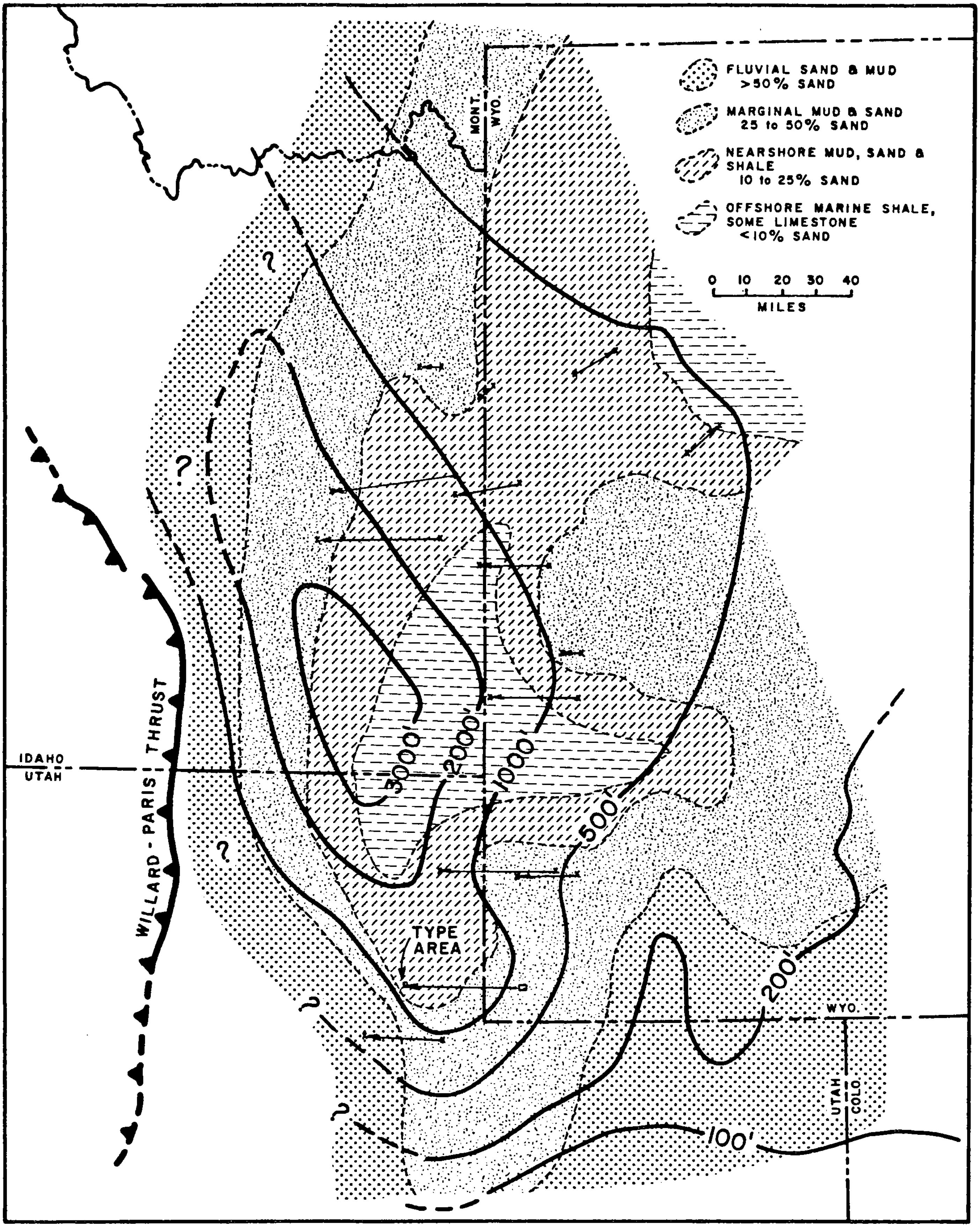

Fig. 10 — Palinspastic isopach and generalized facies map of the Bear River Formation and equivalent strata. Arrows show distance and direction some representative control points have been moved from their present ground position to compensate for tectonic transport.