# Structural Geometry of Meade Thrust Plate in Northern Blackfoot Mountains, Southeastern Idaho[1]

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## ABSTRACT

**One of the principal generalizations concerning structural geology in foreland thrust belts is that thrust faults climb to the surface by running parallel with incompetent units and cutting upsection (ramping) across competent members, thus forming folds in the hanging wall but not in the footwall. Detailed geologic mapping at the front of the Meade plate in the northern Blackfoot Mountains, southeastern Idaho, shows that this rule can be applied only to the initial phase of deformation. The initial forms of folds created over ramps in the basal decollement have strongly influenced the geometry of subsequent imbricate thrusts within the Meade plate so that later faults were locally required to cut downsection in the direction of translation.**

**The allochthon has been divided into three subsidiary thrust plates by two major imbricate thrusts. Folds within thick-bedded upper Paleozoic strata of the Meade plate have sharp hinges and planar limbs, with curved axial surfaces that progressively steepen to the west. These folds are of a modified box or kink form. Folds in less competent Mesozoic rocks below the Meade thrust (in the parautochthon) are more open and concentric. Fold geometry was apparently determined by thickness of overburden during folding, proximity to ramps in the thrust surface, and mechanical properties of the strata involved.**

**Major thrust imbrications dip gently westward, locally cutting downsection toward the east (direction of transport) where they cross more steeply west-dipping upright fold limbs. This geometry implies that folding preceded imbricate faulting, and that anisotropy of the sequence no longer controlled stratigraphic levels of thrusting after bedding became moderately inclined to the west (generally greater than 35°, depending on competence).**

**The inferred ramp-associated genesis of folds within the Meade allochthon in the Blackfoot Mountains implies that these folds are rootless. Although rootless hanging-wall folds are productive farther east in the Idaho-Wyoming thrust belt (e.g., above the Absaroka thrust in southwestern Wyoming), those described here in the Blackfoot Mountains, as a result of erosional level and shallow dip of the Meade thrust, do not provide significant structural traps. Folds of the underlying parautochthon (upper plate Absaroka/St. Johns thrust) are more promising.**

## INTRODUCTION

Foreland fold and thrust belts are of current interest because many have been proven to contain major petroleum reserves. Despite their geometric complexities, intensive exploration efforts are significantly improving our understanding of thrust belt geology. One of the newest regions of interest is the Idaho-Wyoming thrust belt.

The structure and geometric relations of thrust belts are best defined by combining surface mapping with modern seismic reflection profiles and borehole lithologic and geophysical logs. Such observations in several thrust belts have established "basic rules" of thrust geometry (Dahlstrom, 1970, p. 342). One such rule is that thrust faults are parallel with bedding in incompetent strata, but oblique to bedding in competent rocks. Another rule is that anticlines form in the hanging wall when the upper plate moves over such an oblique, or ramp, zone (Rich, 1934; Bally et al, 1966; Dahlstrom, 1970; Royse et al, 1975). These rules provide a convenient basis for understanding structures and evaluating prospects in relatively unknown regions.

Deformation in thrust belts, however, can become exceedingly complex, particularly at the leading edges of major allochthons. In such areas, rules that seem generally applicable may be violated by structural relations on a local scale. One such rule is that thrust faults cut upsection in the direction of transport (ordinarily updip). One purpose of this paper is to examine an apparently "anomalous" region at the toe of the Meade plate in the Idaho-Wyoming thrust belt, where this rule seems not to apply entirely.

The early structural history of the Meade plate in the northern Blackfoot Mountains is easily understood in terms of ramps across competent units. Kink-fold geometry of upper-plate folds is a necessary consequence of that ramp geometry. As later imbricate thrust slices



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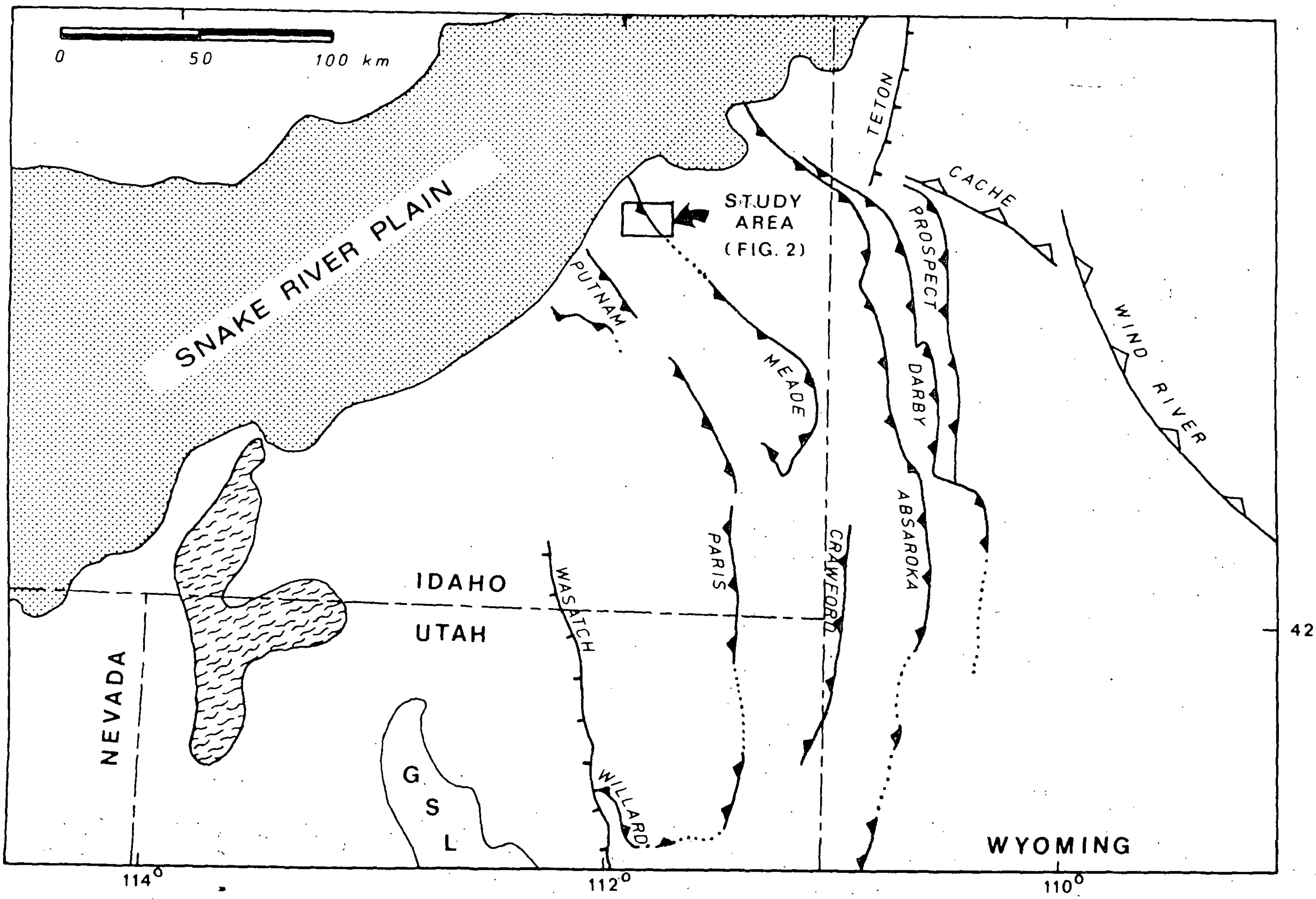



FIG. 1—Generalized tectonic map of southeastern Idaho and vicinity showing location of study area and names of major faults. Solid sawtoothed pattern indicates "thin-skinned" thrust faults in the Idaho-Wyoming thrust belt; open sawtoothed, basement-involved Laramide thrusts; hachured, normal faults (sawtoothed on upthrown side, hachured on downthrown side). Wavy pattern shows Albion-Raft River-Grouse Creek metamorphic core complexes. *GSL*, Great Salt Lake. Modified after King and Beikman (1974).

peeled off the main sole thrust, the geometry of the folds was modified. The imbricates locally cut downsection in the direction of tectonic translation, occasionally resulting in lateral transport of younger over older rocks. Such relations provide the key needed to unravel the structural history at the leading edge of the allochthon where folds formed during movement on the sole thrust, before formation of any of the imbricate thrusts.

## REGIONAL GEOLOGIC SETTING

The Idaho-Wyoming thrust belt, extending into northern Utah, is an arcuate salient of six to eight major allochthons (Fig. 1) which form a small segment of the Cordilleran foreland thrust belt, stretching from Alaska to Mexico. This part of the belt has been extensively studied and the regional tectonic and stratigraphic relations, as well as more recent subsurface exploration were summarized by Rubey and Hubbert (1959), Armstrong and Oriel (1965), Oriel and Armstrong (1966), and Royse et al (1975). Some principal features of the Idaho-Wyoming belt include the "sledrunner" profiles of major faults over undeformed crystalline basement; eastward decrease in age of major thrusts, spanning nearly 100 m.y. from Late Jurassic to early Eocene; and shortening of supracrustal strata by more than 50% across the belt without the development of mylonites or metamorphism. These features are similar to those of the foreland thrust belt in the Canadian Rocky Mountains (Bally et al, 1966; Dahlstrom, 1970; Price and Mountjoy, 1970) as well as many other foreland thrust belts of the world. Thus, studies of structural geometry in the Idaho-Wyoming belt can serve as an analog for other foreland provinces.

The Blackfoot Mountain area described here lies about 30 km south-southeast of the city of Idaho Falls, in Bingham County, Idaho. The mountains are located at the north end of the arcuate salient where it is bounded northward by Neogene silicic and mafic volcanic rocks of the Snake River Plain. Orestes St. John (1879), geologist for the Teton Division of the Hayden survey, first described the rocks in the area and Mansfield (1952) made the most comprehensive map of the entire mountain range. However, this report is based on new mapping of the southern half of the Ammon 15-minute quadrangle, which forms a broad strip map across the northern and central parts of the Blackfoot Mountains (Fig. 2).

Rocks in the interior of the Blackfoot Mountains range from Lower Mississippian Lodgepole Limestone to Lower Cretaceous Wayan Formation (Table 1). These are flanked around the perimeter of the range by upper Cenozoic volcanic rocks and coarse clastic sediments. The interaction of thrust belt and late Cenozoic structures is of considerable interest. The region lies in the northeastern corner of the Basin and Range province. Recent geologic work and seismic reflection profiles (Royse et al, 1975; McDonald, 1976) have shown that many young normal faults have listric geometries, flattening at depth into Mesozoic detachment horizons. In the Blackfoot Mountains four sets of late Cenozoic normal faults have been mapped, but only the oldest set is related to Basin and Range deformation; the rest are probably Snake River Plain-related structures. The principal range-front fault, belonging to the oldest set, is on the west side of the mountains. The surface trace of the fault suggests a gentle westward dip and upper Cenozoic conglomerates on the west dip 20° eastward into the fault. These relations strongly suggest that the fault is listric, though some contradictory geophysical evidence indicates a steeper fault at depth (Allmendinger, 1979a).

Normal faults of all sets are also common within the Blackfoot Mountains. These are not shown on Figure 2 because they are generally of small displacement. Cenozoic sediments and ash-flow tuffs were deposited on the eastern dip slope of the range and the top of the range now preserved as remnants on a dissected, pre-Pliocene erosional surface (Allmendinger, 1979b). Those in the interior of the range are flat whereas those on the eastern flank dip only 4° eastward. Thus, listric faulting was not significant within or along the eastern margin of the northern Blackfoot Mountains since the late Miocene.

The name "Meade thrust" has not previously been applied to faults in the Blackfoot Mountains, and therefore requires some justification. In Mansfield's (1952) comprehensive study of the area, the faults were assigned to the Bannock overthrust, which was thought to be an immense folded thrust sheet covering much of southeastern Idaho. More recent work has demonstrated the importance of Tertiary normal faulting and has shown that the Bannock overthrust actually consists of two distinct faults: the Paris and Meade thrusts (Armstrong and Cressman, 1963; Cressman, 1964). Though the thrusts in the Blackfoot Mountains cannot be traced directly south to the type locality of the Meade thrust owing to intervening Neogene deposits, the structural and stratigraphic relations to the two areas are nearly identical. At both places, the primary decollement horizon is at the base of the Mississippian, and Jurassic to Lower Cretaceous rocks are gently folded beneath the fault surface, whereas above, similar facies of Carboniferous, Permian, and Triassic rocks are tightly folded. Thus, although it is impossible to be certain that a single continuous thrust surface is present both in the Blackfoot Mountains and at the type locality of the Meade thrust, both areas contain exposures of the same system of anastomosing thrust faults to which the name "Meade" is usually applied.

The area described here lies in the western third of the Idaho-Wyoming thrust belt. On the west lies a newly defined terrane of younger-over-older allochthons of unknown age (Oriel and Platt, 1979a, b; Allmendinger et al, 1979). Deformation in the Blackfoot Mountains is, therefore, likely to be more complex than in the frontal (eastern) parts of the belt. Because the rules of thrust geometry described previously were formulated primarily from examples in the more frontal parts of foreland thrust belts, it may not be surprising that deviations from those generalizations are present in the Blackfoot Mountains.

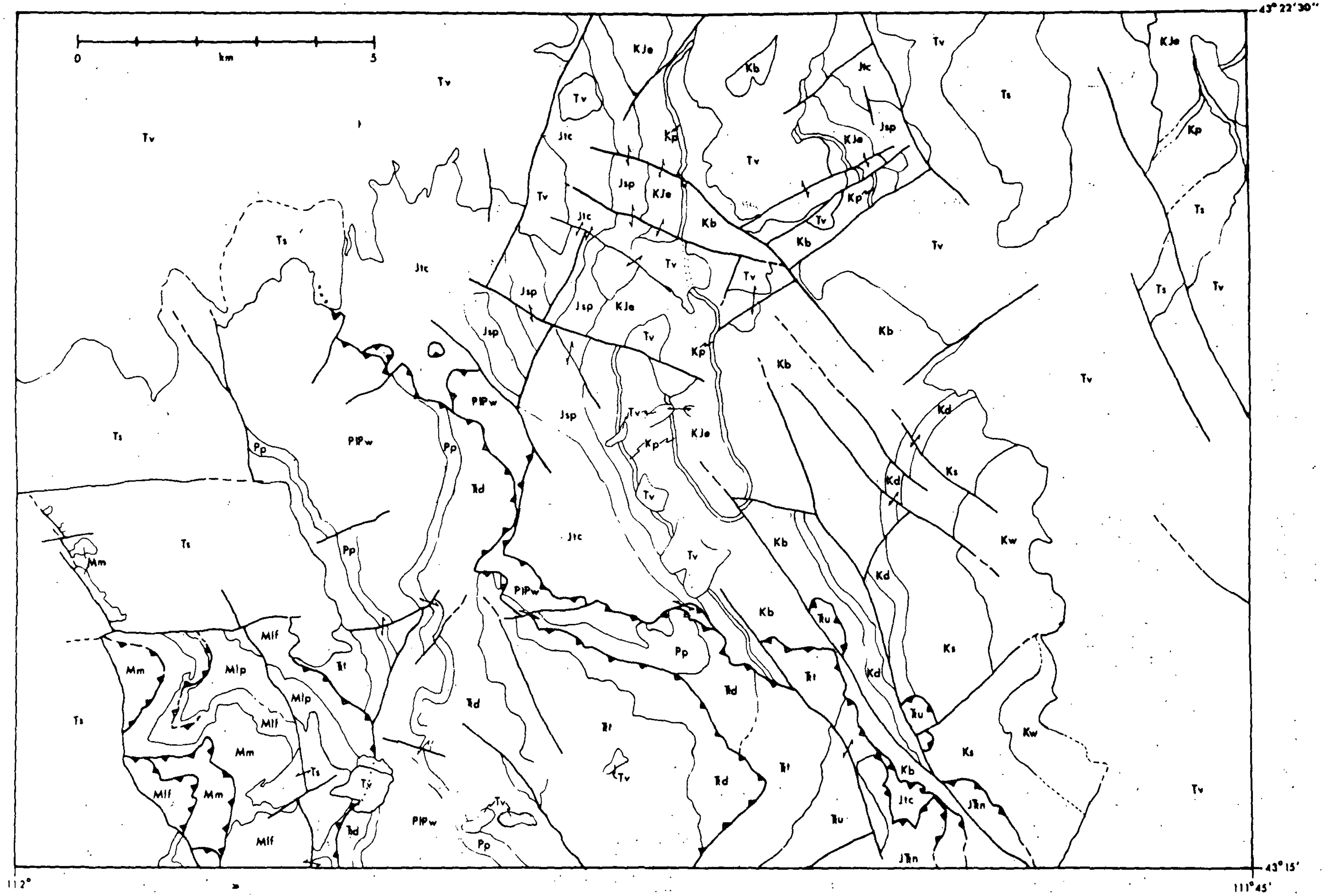



FIG. 2—Generalized geologic map of northern Blackfoot Mountains, south half of Ammon 15-minute quadrangle. Geology from Allmendinger (in press, a, b). See Table 1 for identification of map units. Additional units: *TS*, Salt Lake Formation; *TV*, silicic ash flow tuff, rhyolite, and basalt. Thrust faults are sawtoothed on upper plate.

## STRUCTURAL GEOMETRY

Pre-Cenozoic structures of the northern Blackfoot Mountains are conveniently divided into four tectonic units (Fig. 3): three major imbricate slices of the Meade plate, and the parautochthon below the Meade thrust system. The major imbricate slices are referred to here, in ascending structural level, as: plate I, plate II, and plate III. The associated thrust faults which bound the lower surfaces of these plates are designated thrusts I, II, and III, respectively. Thrust I is also the frontal trace of the Meade plate. At the surface, plate I and locally plate II structurally overlie the parautochthon. The parautochthon, itself, is in the upper plate of the Absaroka–St. Johns thrust system with several lesser thrusts between. Folds in the study area are confined to in-

**Table 1. Pre-Cenozoic Stratigraphic Units in Northern Blackfoot Mountains***

| Unit | Age | Thickness (m) |
|---|---|---|
| Wayan Formation (Kw) | | |
| Main Part | Early Cretaceous | ? |
| Smiths Member (Ks) | Early Cretaceous | 165 |
| Gannett Group | | |
| Smoot Formation (Ks) | Early Cretaceous | 130 |
| Draney Limestone (Kd) | Early Cretaceous | 100 |
| Bechler Conglomerate (Kb) | Early Cretaceous | 480 |
| Peterson Limestone (Kp) | Early Cretaceous | 30 |
| Ephraim Conglomerate (KJe) | Early Cretaceous/Late Jurassic | 275 |
| Stump Sandstone } (Jsp) | Late-Middle Jurassic | 140 |
| Preuss Sandstone } (Jsp) | Late-Middle Jurassic | 210 |
| Twin Creek Limestone (Jtc) | Middle Jurassic | 1,100-1,200 |
| Nugget Sandstone (JTRn) | Early Jurassic/Late Triassic | 170-180 |
| Ankareh Formation (TRu) | | |
| Wood Shale Member | Late Triassic | 25 |
| Deadman Limestone | Late Triassic | 50 |
| Higham Grit | Late Triassic | 60 |
| Thaynes Limestone | | |
| Timothy Sandstone } (TRu) | Late Triassic(?) | 65 |
| Portneuf Limestone } (TRu) | Early Triassic | 280 |
| Lower Thaynes (TRt) | Early Triassic | 335-520 |
| Dinwoody Formation (TRd) | Early Triassic | 365-550 |
| Phosphoria Formation (Pp) | | |
| Rex Chert (Ppr) | Permian | 75-180 |
| Meade Peak Shale (Ppm) | Permian | 25 |
| Wells Formation (PℙP w) | | |
| Upper Member (PℙP wu) | Early Permian/Late Pennsylvanian | 350 |
| Middle Member (PℙP wm) | Pennsylvanian | 140 |
| Lower Member (PℙP wl) | Pennsylvanian | 275+? |
| Monroe Canyon Limestone (Mm) | Late Mississippian | 200+? |
| Little Flat Formation (Mlf) | | |
| Upper Member (Mlfu) | Late Mississippian | 75 |
| Lower Member (Mlfl) | Early(?) Mississippian | 170 |
| Lodgepole Limestone (Mlp) | Early Mississippian | 275+? |

*Thicknesses, measured from cross-sections *only*, are approximate. Structural thickening likely, particularly in Twin Creek Limestone and all Lower Triassic units. Symbols in parentheses are used in Figures 2 through 10.

dividual thrust plates and are given local names. Most of these follow Mansfield (1952) with the exception of his "Snowdrift anticline" which here has been renamed "Narrows anticline" after the Narrows on Wolverine Creek where the best exposures occur.

### Thrust Faults

The Meade thrust plate includes rocks ranging from Mississippian Lodgepole Limestone to Jurassic Twin Creek Limestone (Table 1). Rocks exposed in the parautochthon below the Meade thrust in the study area include Twin Creek to the Lower Cretaceous Wayan Formation. At the surface, thrust faults do not follow single stratigraphic horizons. Stratigraphic relations and throws across various thrust splays are complex and change rapidly along trend.

The frontal trace (thrust I) trends approximately northwest across the northern Blackfoot Mountains (Figs. 2, 3). The fault exhibits shallow dips ranging from 8 to 25° to the southwest. Maximum stratigraphic throw on thrust I is at the northwest end where massive Lower Pennsylvanian limestones of the Wells Formation are thrust onto lower members of the Middle Jurassic Twin Creek Limestone. In the south, apparent throw on thrust I diminishes until near its southeast end at the southern margin of the Ammon 15-minute quadrangle, Lower Cretaceous Bechler Formation in the parautochthon and Jurassic-Triassic Nugget Sandstone in the main part of the plate I are juxtaposed. Locally, complexly deformed slices of Twin Creek overlie the parautochthon along thrust I; these are interpreted as fault-breccia lenses or pieces of the parautochthon that have been scraped off and translated eastward by the overriding upper plate.

The frontal trace of the Meade thrust thus cuts upsection both in the direction of translation of the plate, and along trend to the south. Tilting along late Cenozoic high-angle faults was probably responsible for the exposure of increasingly older rocks to the north on either side of the fault. This geometry is generally consistent with the rules of thrust geometry outlined previously.

Plate II at its northernmost exposure directly overlies the parautochthon (Fig. 3, loc. 1). A few minor remnants of plate I are preserved at this locality as a klippe and a small wedge between two wrench faults, and the stratigraphic throw on thrust II is nearly as great as that on thrust I: middle Wells Formation on Twin Creek. Where plate I first becomes significantly exposed in front of plate II (Fig. 3, loc. 2), anomalous stratigraphic relations across thrust II are present: middle Wells Formation in plate II structurally overlying lower Wells in plate I. Along trend a few kilometers southeast, the stratigraphic omission increases to a maximum where Triassic Thaynes Limestone directly overlies upper Wells Formation (Fig. 3, loc. 3; Fig. 4a). Farther southeast, omission across the fault diminishes to zero (Fig. 3, loc. 4), then tectonic duplication of the section occurs with Lower Triassic Dinwoody Formation thrust over Thaynes Limestone.

Thrust II is not a listric normal fault because characteristic older-over-younger thrust geometries across the fault surface are present both northwest and southeast of the anomalous zone. Significant as well, Pliocene-Miocene ash-flow tuffs deposited unconformably on plate II rocks are in their original flat position. If thrust II were a late Tertiary listric normal fault these volcanic rocks, the oldest Tertiary deposits in the range (Allmendinger, 1979b), would be tilted. Moreover, lack of pervasive brecciation as well as a suitable source area for large slide blocks precludes a denudation fault origin for the anomalous younger-over-older zone. Thus, these relations show that thrust II through the middle stretch of exposures (between localities 2 and 4, Fig. 3) cut downsection in the footwall strata in the direction of tectonic translation and thrust younger rocks on older.

Thrust III is exposed within only a small part of the mapped area (Figs. 2, 3), and the stratigraphic relations along trend across the fault are not so well known. Mississippian rocks belonging to the Lodgepole, Little Flat, and Monroe Canyon Limestones in the hanging wall were thrust over Pennsylvanian, Permian, and Triassic rocks in the footwall. The fault surface separating plates II and III dips 13 to 24° west and southwest. Thrust III truncated both right-side-up and overturned strata as it cut upsection in the hanging wall (Fig. 4b). However, as plate III was translated eastward, progressively older west-dipping rocks in the footwall were cut by the fault. The west-dipping footwall rocks in plate II dip more steeply westward than does thrust III (Fig. 3, loc. 5; Fig. 4b). Thus, the fault must locally cut downsection in the direction that plate III moved. Thrust III unconformably underlies the same volcanic rocks mentioned previously (Fig. 2). Although older rocks now overlie younger, a rule of thrust geometry was again not strictly followed.

Minor thrust faults are present throughout the pre-Cenozoic rocks of the northern Blackfoot Mountains, but only in plate III are exposures sufficient to document their geometry. Some of these minor thrusts place older strata upon younger along faults which cut upsection in the direction of translation of the upper plate. However, one well-exposed minor thrust (Fig. 5) illustrates the anomalous geometry just described for parts of major imbricate thrusts II and III. Though this thrust does not have large displacement, it clearly cuts downsection in both upper and lower plates and places slightly younger rocks on older.

### Folds

Within each of the major plates described previously, one or more major folds has been mapped throughout the extent of the plate (Fig. 3). Folds within the Meade plate have strikingly similar geometries even though their axial trends differ slightly in the various tectonic slices. These folds contrast markedly in form and style with those in the parautochthon. The difference is due both to structural position and contrasting lithologies.

*Fold terminology*—Recent advances in folding theory and numerous detailed field studies have resulted in modification of existing fold terminology. These modifications incorporate material behavior during deforma-

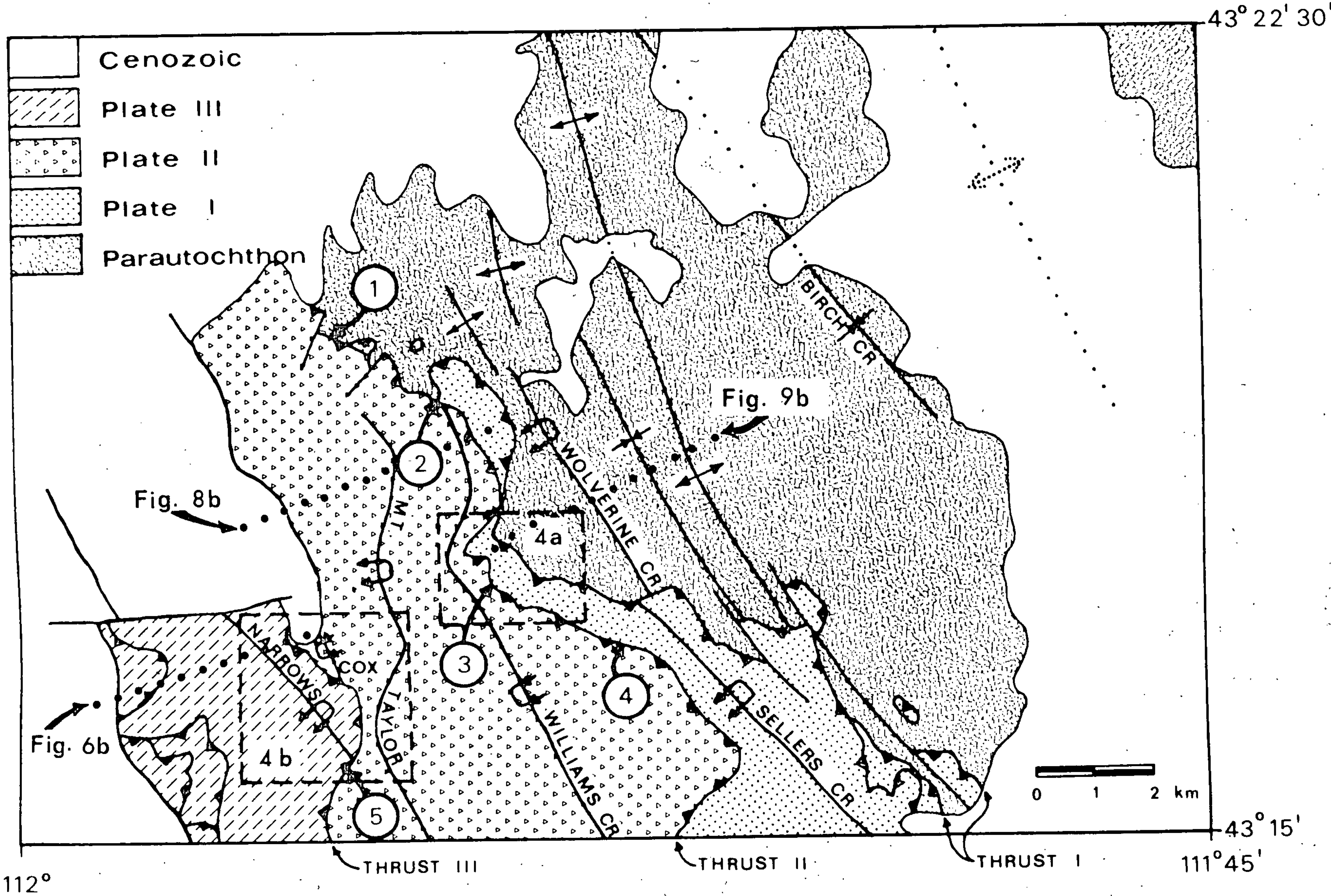



FIG. 3—Tectonic map of northern Blackfoot Mountains, south half of Ammon 15-minute quadrangle. Cenozoic mountain-front faults shown as heavy lines on west side of range. Names of principal folds are shown. Circled numbers refer to localities discussed in text. Dashed boxes show locations of Figure 4a, b. Locations of sections in Figures 6b, 8b, 9b are shown with dotted lines.

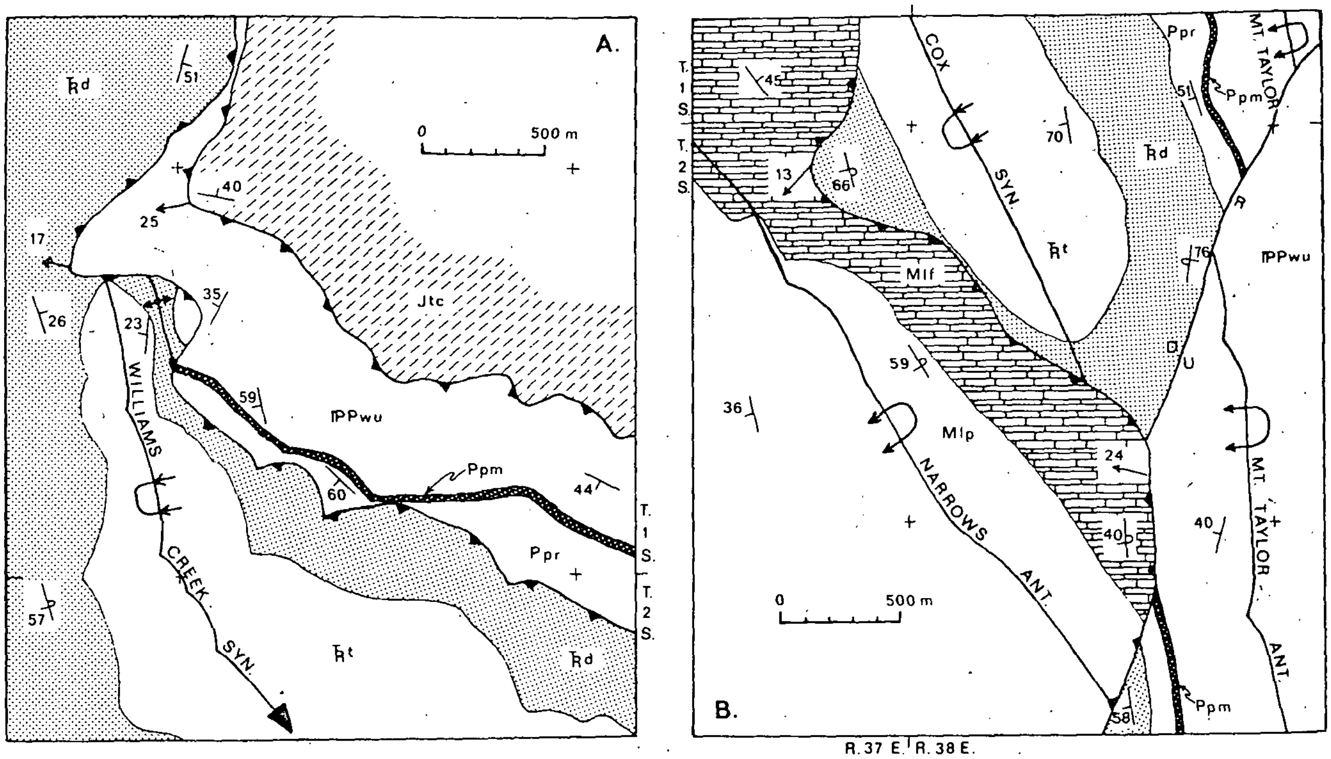



**FIG. 4—Representative geologic maps showing critical map relations where major imbricate thrust faults cut downsection in direction of translation of overriding plates. Cenozoic faults are not shown. See Table 1 for identification of map units. A, thrust plates I and II and parautochthon (diagonal dashes). Western thrust (II) dips less steeply than bedding in plate I and places Triassic Dinwoody Formation on top of Pennsylvanian-Permian Wells Formation on upright (west) limb of Sellers Creek anticline (overturned limb truncated by thrust I). Small + symbols show corners of Sec. 33, T1S, R38E. B, thrust plates II (east side) and III (west side). At southern end of thrust III, fault dips less steeply to west than bedding in upright (west) limb of Mt. Taylor anticline. High-angle fault *R* is reverse fault dipping eastward; small + symbols show corners of Sec. 6, T2S, R38E.**

tion as well as final geometry. The basic division followed here contrasts concentriclike (parallel) and chevron folds with kink and box folds. Geometrically, the former class is characterized by strict preservation of bedding thicknesses and smooth, rounded hinges, except in the cores of folds where chevron folds develop. The latter class is typified by straight limbs, narrow hinge zones, intersecting lineations and three-dimensional changes in fold geometry along trend of the axis (Faill, 1973). Box folds are conjugate kink bands. In material behavior, the most important difference between the two types is the distribution and abundance of "soft" members in the multilayer. If the shear strength of bedding contacts is high, or if the soft layers are very thin or nearly as firm as the stiff layers, then kink folds are favored (Ramberg and Johnson, 1976; Reches and Johnson, 1976). Concentric-chevron folds have abundant bedding-plane slip, and are thus classic flexural-slip folds.

In natural situations the distinction between these two fold types is seldom perfectly clear-cut. Transitions from one to the other are possible both laterally (owing to facies changes) and vertically (owing to changing lithologies through time). In the accompanying figures, cross sections were constructed assuming concentriclike folding. However, thickness changes between upright and overturned limbs, hinge-zone characteristics, and so on suggest that this assumption may not be entirely valid (e.g., Fig. 8b).

*Folds of Meade plate*—Folds within the Meade plate are characterized by eastward-verging asymmetry, sharp hinges, and curving axial surfaces which steepen to the west. The latter may be interpreted as being two conjugate axial surfaces. The folds, then, are neither conical nor cylindrical, but rather kinklike or boxlike in form. In these folds, higher strains and locally slight thickening of stratigraphic units are evident in the overturned limbs (Allmendinger, 1979a). Each of the major folds shown in Figure 2 is described briefly in the following to demonstrate both the range and similarity of structural styles.

The most completely exposed fold in the Blackfoot Mountains is the Narrows anticline, which is the westernmost and structurally highest, involving Mississippian limestone within plate III (Fig. 3). The axis of the Narrows anticline plunges 10° in the direction N25°W. The structure is markedly asymmetric and overturned to the east with a very narrow hinge zone (Fig. 6a, b). The limbs are relatively straight, with the overturned eastern limb having only one-tenth the length of the upright limb. Gentle flexures with the opposite sense of vergence on the western limb give the

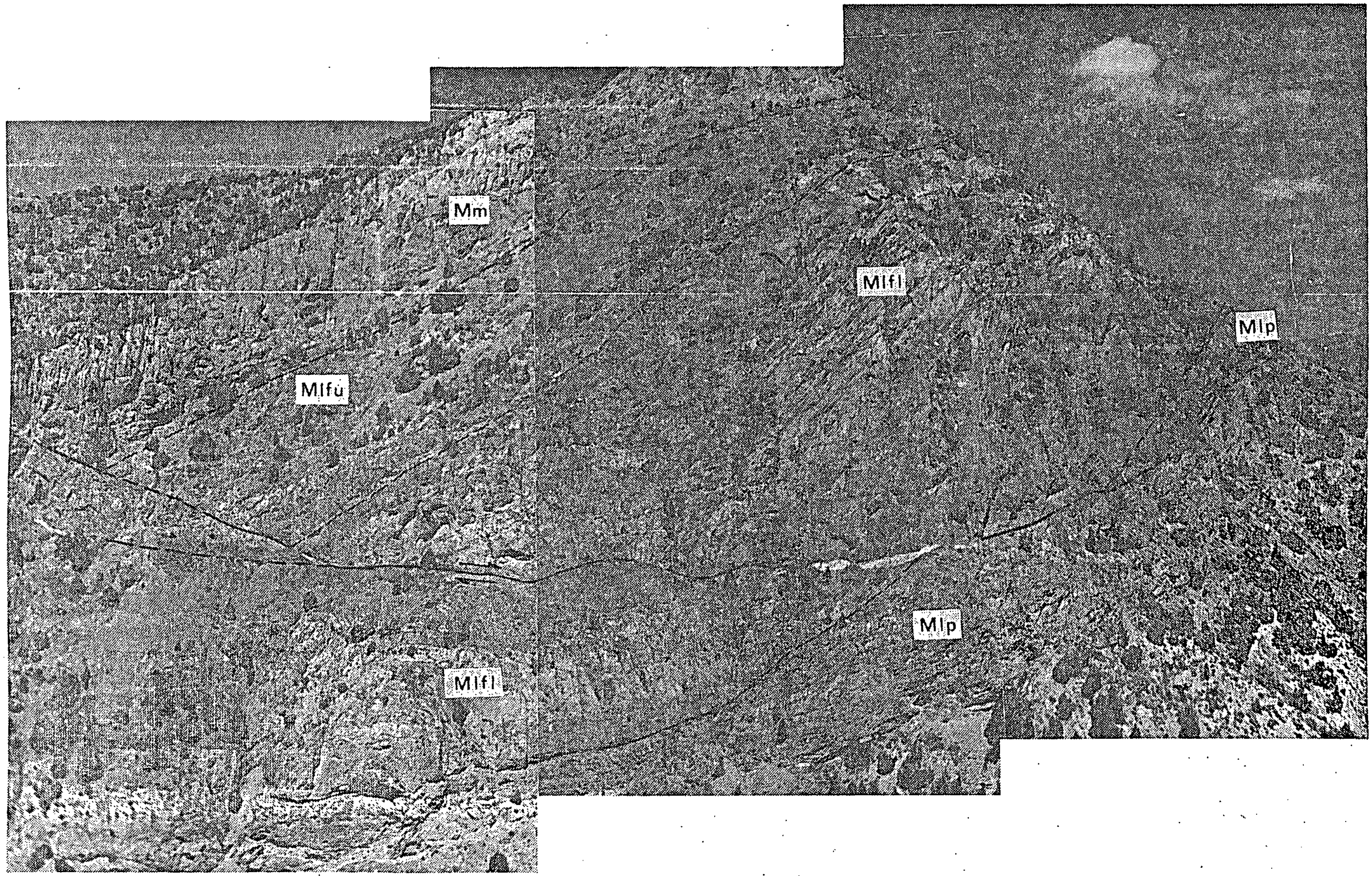
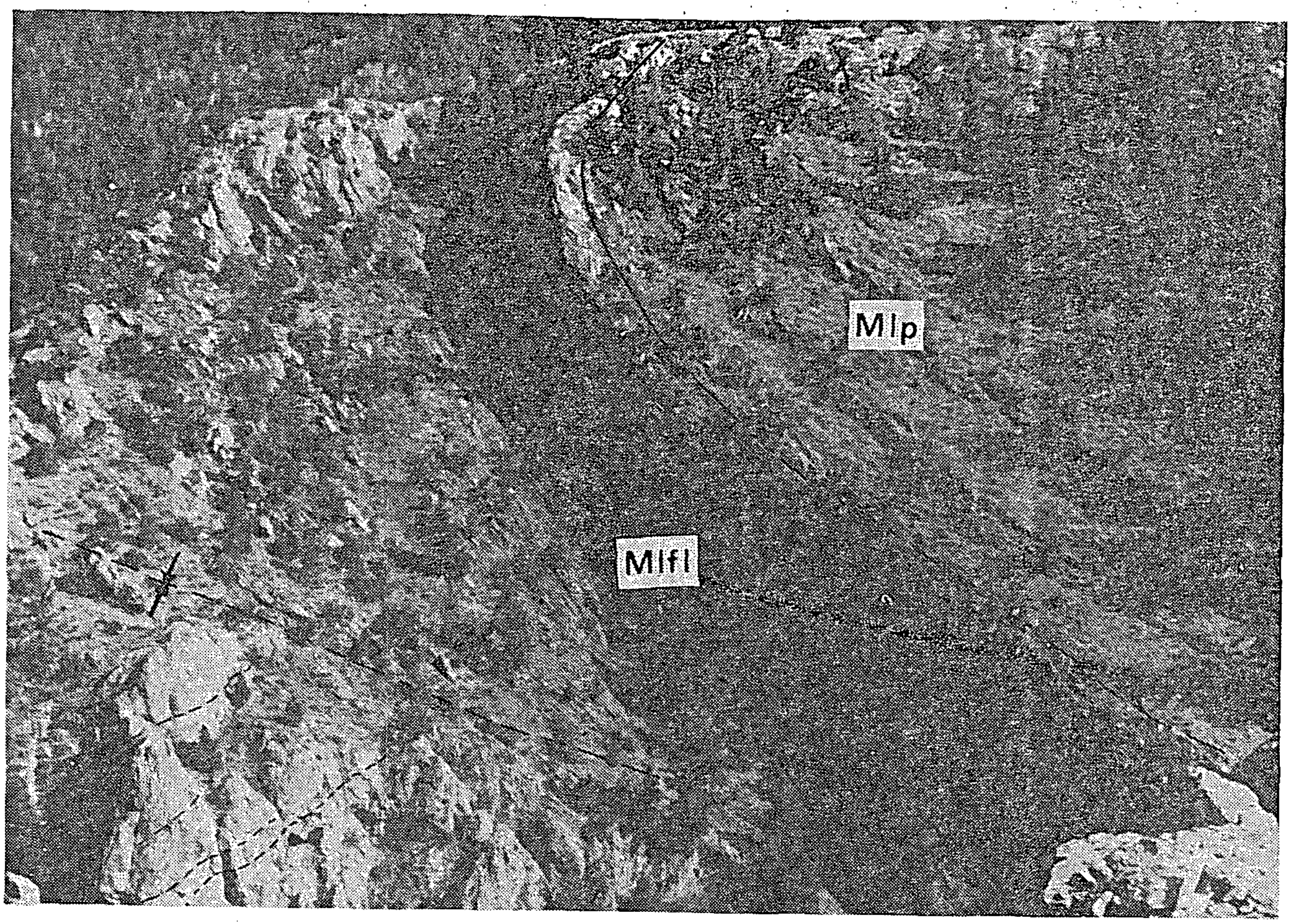



FIG. 5—Photomosaic looking north shows minor thrust fault on upright limb of Narrows anticline. Fault cut downsection in upper and lower plates as hanging-wall rocks moved eastward (to right). Thrust surface is oriented N26°E, 24°WNW (to left and slightly into picture). Perspective of photomosaic makes fault trace appear curved, even though it has constant dip throughout. White strip along thrust is massive (3 m thick), nonfibrous calcite vein. See Table 1 for identification of units.



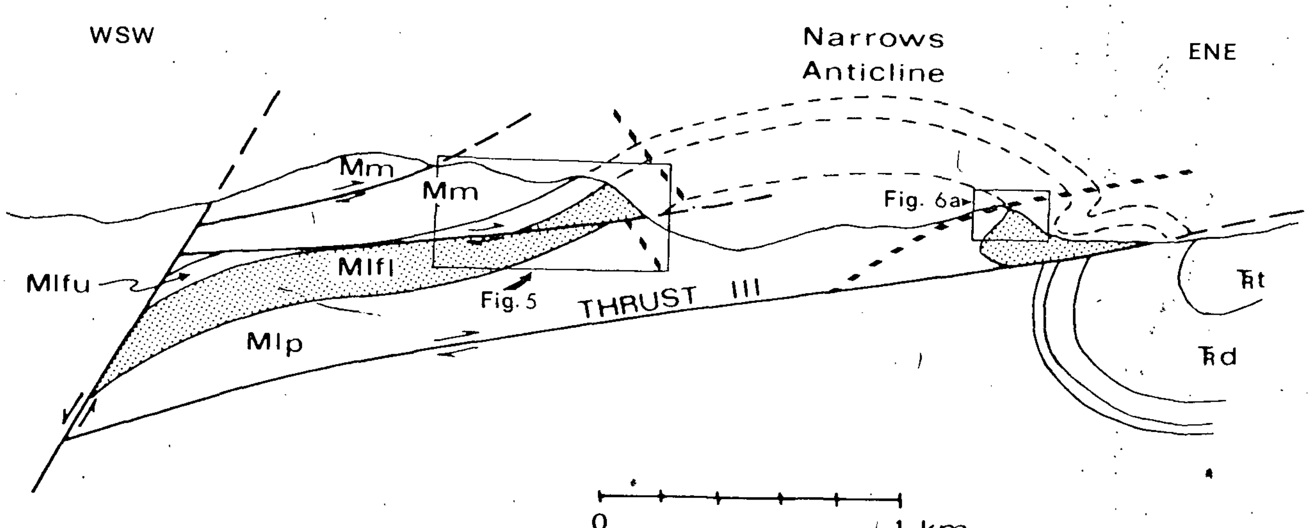




FIG. 6—Narrows anticline. Photograph (looking south), showing sharp hinge zone and very tight syncline on east (left), and cross section of complete structure. *In section,* Cox syncline is shown on east beneath thrust III. Gentle flexure with west vergence is on upright limb. Cenozoic fault near hinge is not shown. Heavy dashed lines show axial surface of fold. Approximate locations of Figures 5 and 6a are shown. See Table 1 for identification of units. Stipple pattern indicates lower Little Flat(?) Formation.

fold a kinklike or boxlike geometry in which there are conjugate axial surfaces (Fig. 6b).

The minimum possible thickness of overburden during folding, based on restored stratigraphic thicknesses, was approximately 5.5 km. At these depths, high strains in calcite were largely accommodated by intracrystalline glide (plastic flow) and pressure solution, whereas chert deformed cataclastically (Fig. 7; Allmendinger, 1979a). This style of deformation and the fact that plate III rocks are the oldest in the area strongly suggest that these folds formed at deeper levels than any others, and have since been transported to their present structurally highest position. Plate III has also experienced the greatest Basin and Range uplift during the late Cenozoic, resulting in deeper erosional levels.

Thrust III cuts obliquely across the structure to form the base of plate III, truncating the axis of the Narrows anticline at an angle of 50° in map view (Fig. 3, loc. 5). Throughout the length of its exposure, thrust III dips more gently west (13 to 24°) than the upright, west-dipping (40 to 50°) mutual limb of the Cox syncline and Mt. Taylor anticline. Thus, the thrust cuts downsection eastwardly on the upright limb of Mt. Taylor anticline. Locally, the west-facing, originally upright limb of the Mt. Taylor anticline becomes overturned and east dipping (Fig. 4b). When this occurred, continued shortening was accommodated by a steeply east-dipping reverse fault, which cuts obliquely across the western limb of the fold. This fault cannot be traced into plate III, suggesting that it predates emplacement of that plate.

The Mt. Taylor anticline resembles the Narrows anticline in general form. Though the former has a smaller ratio of upright to overturned limbs and is more variable along trend, both have relatively straight limbs and narrow hinges which impart the kink-fold geometry (Figs. 7, 8). Locally, the overturned, mutual limb of the Mt. Taylor anticline and Williams Creek syncline on the east (Fig. 3) has rotated 180° clockwise (looking north) so that the section is approximately upside down. Therefore, the axial surfaces of both folds must in places be recumbent—perhaps a partial consequence of ramp-generated folding below the basal Meade detachment. The latter stages of this rotation appear to have been facilitated, depending on lithology, by small-scale thrusting in limestone or brecciation in dolomite or sandstone in the cores of the major folds.

The easternmost major fold within the Meade plate is the Sellers Creek anticline (Fig. 3). It trends more northwesterly than the folds in plates II and III. Tracing the fold to the northwest, the upright, western limb was

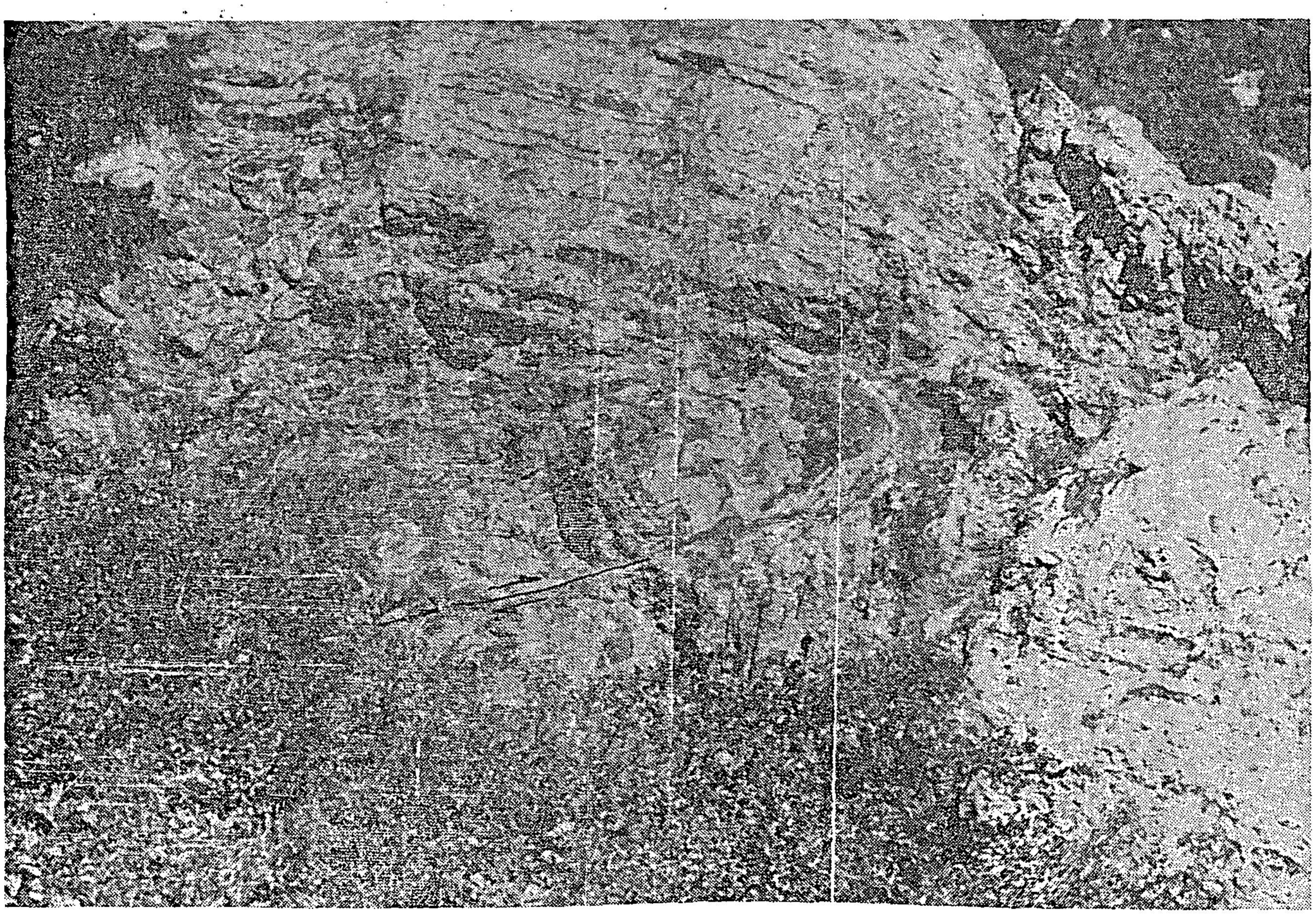
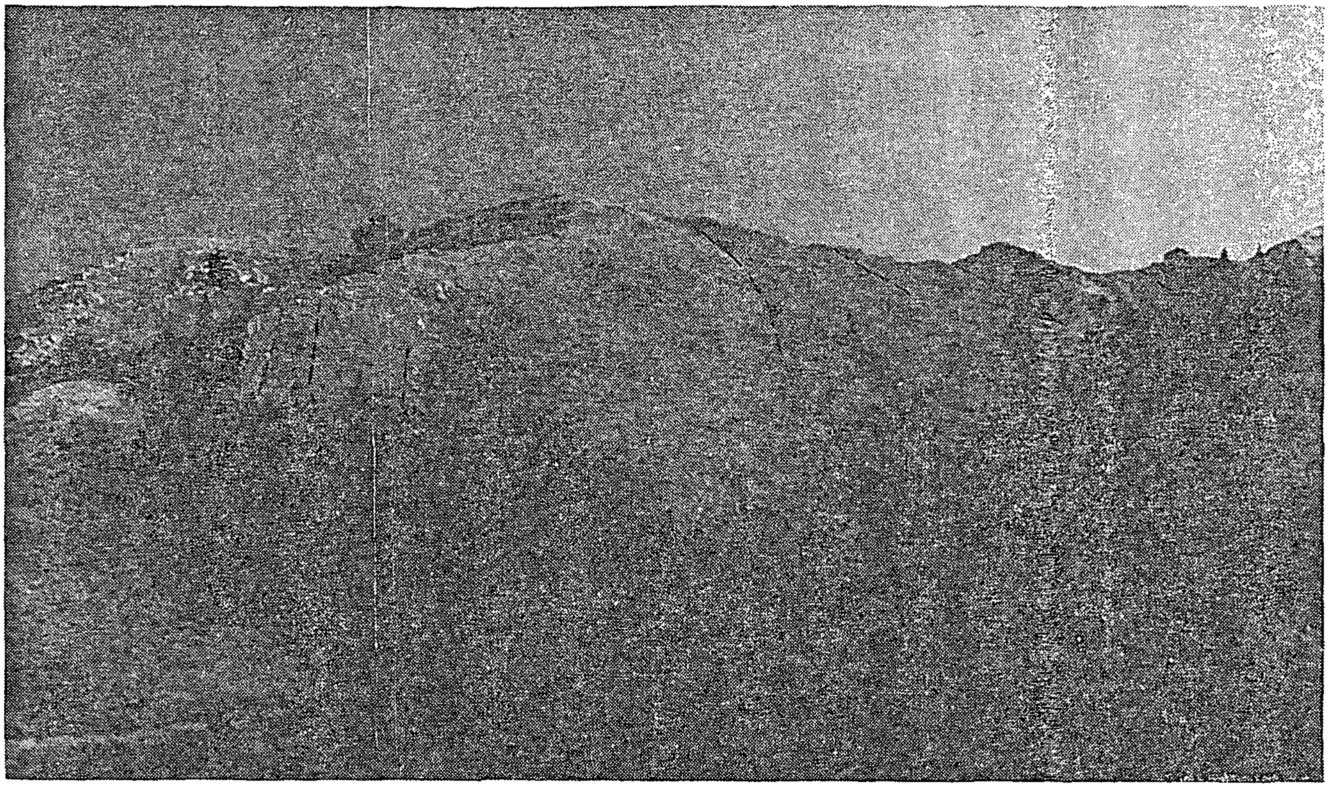


FIG. 7—Minor folds on overturned limb of Narrows anticline. Dark layers are chert, light layers are limestone in lower Little Flat(?) Formation. Note thickening in hinge regions, and minor thrust.



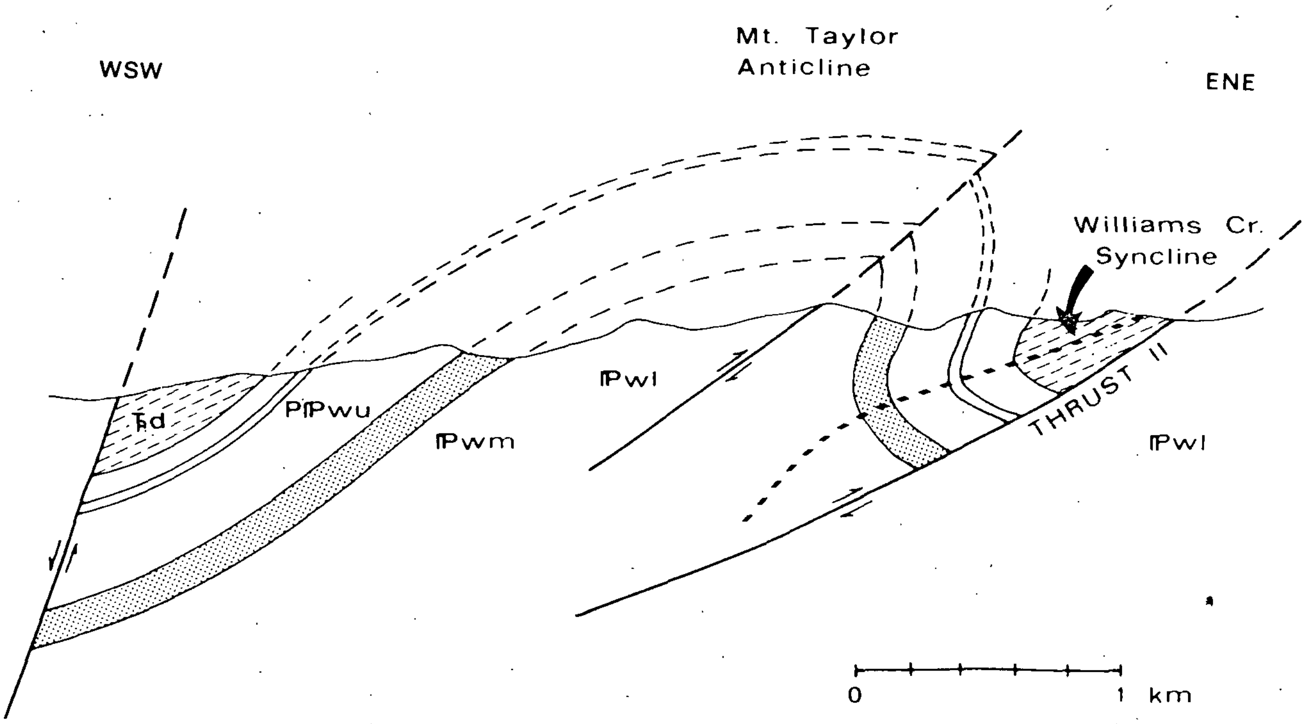



FIG. 8—Mt. Taylor anticline. Photograph of hinge zone (looking south), showing planar limbs and minor thrust in hinge, and cross section of complete structure. In section, heavy dashed line shows axial surface of Williams Creek syncline; stippled pattern, middle Wells Formation; diagonal dashes, Dinwoody Formation; see Table 1 for identification of other units.

progressively cut downsection by thrust II (Fig. 7a). The frontal trace of the Meade thrust strikes somewhat more westerly and truncates the fold axis at a moderately high angle in map view. The fold axes of the Sellers Creek anticline in plate I and the Wolverine Creek anticline in the parautochthon are nearly coincident, suggesting that the two folds were generated in the same place (Fig. 3). However, detailed mapping of thrust I has established that, though gently warped, the fault between the two folds has not been nearly so severely folded. Thus, the Sellers Creek antcline was generated west of and probably earlier than the Wolverine Creek anticline. Possibly the Wolverine Creek anticline and the gentle warp in thrust I were both generated at the same time over a ramp in a decollement at depth in the parautochthon. Some additional folding of the Seller's Creek anticline may have occurred at that time.

*Folds of parautochthon*—Folds in the strata beneath the Meade thrust system differ conspicuously in geometry from those just described. In general, these parautochthon folds are more open and symmetric with a more nearly concentric geometry. The reasons for these differences are twofold. First and probably most important, the footwall folds formed with less overburden, and possible ramps in underlying thrust surfaces must have been distant. Second, the Jurassic and Cretaceous strata in the parautochthon contain a greater proportion of relatively incompetent units, and local ductility contrasts are greater and more closely spaced. Probably, kink folding in older, massive sediments (the upper Paleozoic units) at deeper levels near thrust ramps become concentriclike folds higher in the section where lithologic contrasts were greater and bedding-plane slip easier.

The Wolverine Creek anticline, directly northeast of the frontal trace of the Meade thrust, is the best exposed of all parautochthon folds in the area (Figs. 3, 9). The anticline is asymmetric with eastward vergence and locally overturned bedding. The fold axis is approximately horizontal and trends N30°W, whereas the axial surface is planar, dipping 60° southwest. Unlike folds in the Meade plate, the hinge zone of the Wolverine Creek anticline is broad and smoothly rounded, with no brecciation or minor thrust faulting (Fig. 9).

East of Wolverine Creek anticline, strata dip mainly to the east, but are involved in several open folds. These folds (including the Birch Creek syncline, Fig. 3) are much more nearly symmetric, with interlimb angles of about 140° and vertical, planar axial surfaces. Fold axes plunge 10° in the direction S20°E. Folds farther east have been partly obscured by late Cenozoic volcanic rocks (Fig. 3), but limited outcrop suggests they are geometrically similar.

Parautochthon fold axes are spaced farther apart with increasing distances from the Meade thrust surface. Only the fold closest to the thrust has a high degree of asymmetry and contains overturned bedding. These observations indicate a connection between the wavelength and asymmetry of folds in the parautochthon, and the proximity to the Meade thrust plate. If so, then those folds may be only indirectly related to ramps in underlying thrust surfaces.

**Relations of Folds to Thrusts**

The relative ages of folds and thrust faults in the northern Blackfoot Mountains can be deduced from several observations, the most important being (1) the geometric relations of thrust faults to fold axes in map and section view, and (2) the observation that some thrust faults cut downsection in the direction of translation of the overriding plate. Complete definition of fold-thrust timing is difficult because structural relief in the region is low and published subsurface data are scanty. Thus, the earliest history of deformation is not known and must be inferred from structural studies in other foreland thrust belts. Early folding and thrusting probably were synchronous, with folds generally, though not necessarily, forming over ramp zones along the basal decollement (the frontal thrust) of the Meade thrust.

Detail mapping demonstrates that thrust faults truncate fold axes at high angles, and that along trend in either direction, entire folds are cut out by thrust faults. The variation in fold geometry along trend and the separation of major anticlines by imbricate thrust suggest that these folds are not simple conical and en echelon sets, transferring shortening from one to the next and to thrust faults as each fold dies out. Folding did not occur after thrusting because the thrust surfaces are not passively folded with the other rocks in the overlying plates. These cross-cutting relations suggest that major folding occurred before imbricate thrust faulting though these data alone are not conclusive.

The strongest evidence that folding preceded imbricate thrusting is that both major imbricates at least locally cut downsection in the direction of translation of the hanging-wall rocks. Thrust fault III cuts from the Triassic down to Pennsylvanian in the footwall in an east-west section. Because hanging-wall rocks belong to the Mississippian System, the thrust still places older rocks on younger, at least at the present level of erosion. Along thrust II, not only does the fault cut downsection, but younger rocks are placed on older with a significant thickness of strata missing. In each of these examples, bedding on upright fold limbs in the footwall dips more steeply to the west than does thrust II or thrust III, and the fold axes strike obliquely into the thrust surfaces.

This geometry requires that the bedding in the footwall of each imbricate must have been tilted to the west before thrusting. This tilting was almost certainly accomplished by folding. The relatively steep west dips on upright fold limbs is a result of the kink folding described previously. Without this particular style of folding, the observed downsection cutting would be much less likely. However, nowhere does the frontal thrust cut downsection to the east. Thus, thrust I probably formed synchronously with folding.

Why imbricate thrusts cut downsection in the direction of translation is not clear mechanically, particularly as they do not follow incompetent strata. Apparently, once rocks are folded and tilted steeply, the subsequent thrusts are no longer controlled by the anisotropy of the sedimentary layering (Jaeger, 1960; Donath, 1961). The

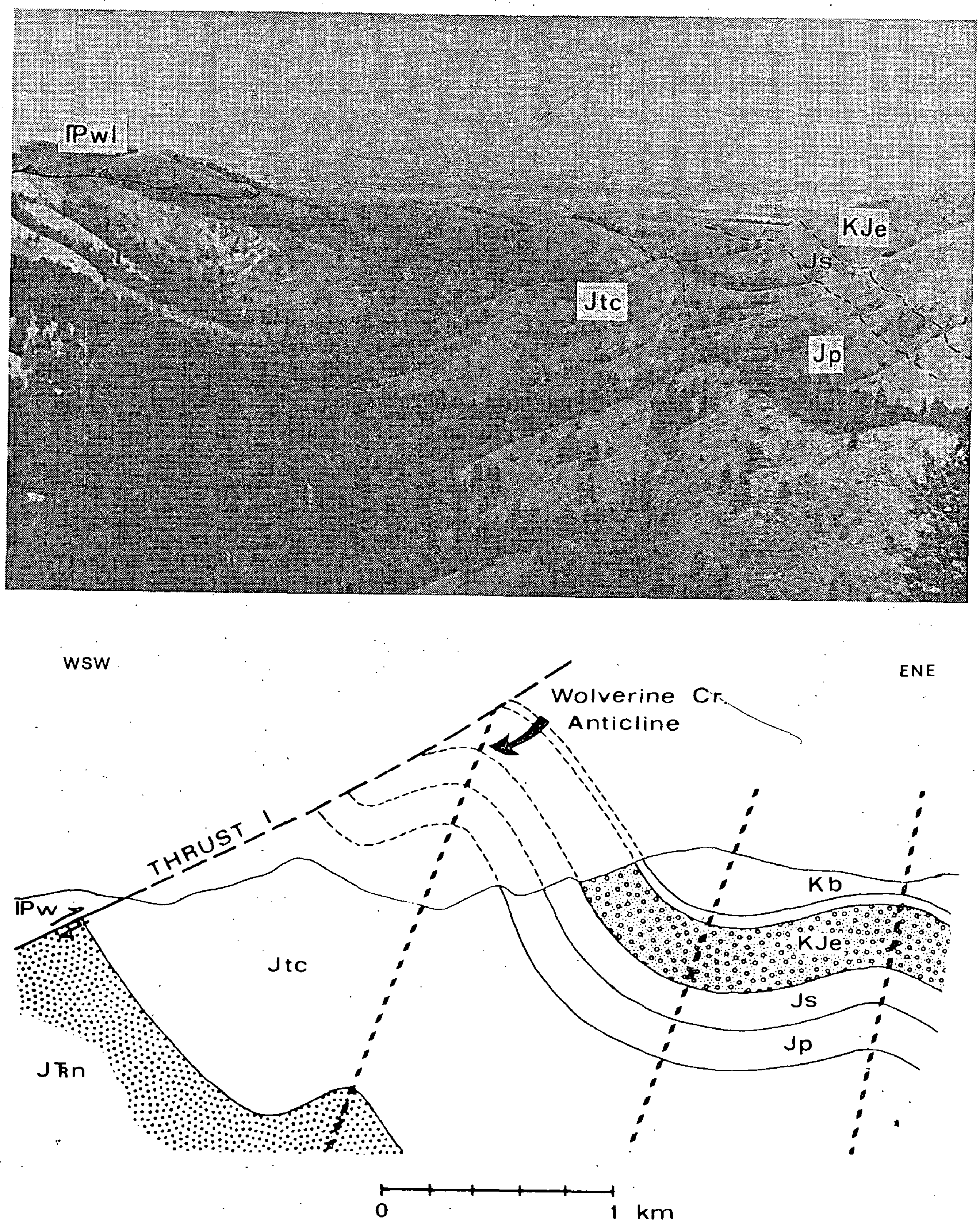



FIG. 9—Wolverine Creek anticline in *parautochthon*. Photograph (looking northwest), showing smooth, rounded hinge and Snake River Plain in background, and cross section showing anticline and related folds of parautochthon. In section, heavy dashed lines show axial surfaces; heavy dot pattern, Nugget Sandstone; conglomerate pattern, Ephraim Conglomerate. See Table 1 for identification of other units.

thrusts simply follow the most efficient trajectory to the surface, cutting up or down the section as they go. It is also possible that reorientation of the local stress fields during folding, so that maximum extension was parallel with the fold axes (Dubey, 1980), may have influenced subsequent fault trajectories. Earlier structural weaknesses may localize initiations of the imbrications.

Though there is no direct field evidence bearing on the question, folding in the parautochthon most likely postdates all primary deformation in the Meade plate, including the imbricate thrusts. Gentle warping of thrust surfaces and other relatively minor effects in the Meade plate may be due to younger, ramp-generated folding in the parautochthon.

## INTERPRETATION AND CONCLUSIONS

### Structural Evolution

The pre-Cenozoic structural evolution of the northern Blackfoot Mountains is shown in Figure 10 by schematic cross sections. The frontal thrust moved first, in the process climbing from its primary decollement at the base of the Mississippian to the land surface, then underlain by Lower and possibly Upper Cretaceous strata (Armstrong and Oriel, 1965; Royse et al, 1975). This climb is interpreted to have occurred in part by a series of steps across the Mississippian, Lower-Middle Pennsylvanian, and Triassic–Lower Jurassic Systems. These ramps cannot be proved by geologic mapping alone owing to poor exposure and low structural relief in the area. In all likelihood, the ramps are located west of the Ammon quadrangle. The stratigraphic positions of the steps have been inferred (Fig. 10a) from the oldest rocks exposed in the cores of the anticlines of plates I, II, and III (Allmendinger, 1980).

Eastward translation of the Meade plate along thrust I produced the major folds now observed in each of the imbricate slices (Fig. 10b). The Narrows anticline formed above the westernmost ramp, the Mt. Taylor anticline above the middle ramp, and the Sellers Creek anticline above the easternmost ramp. During this increment of deformation, the folds acquired their eastward vergence and kink geometry, but the eastern limbs probably did not become overturned at that time.

At this stage in the structural history, movement along the frontal thrust may have ceased and the folds may have locked. Locking of the folds is recorded by the microstructures (Allmendinger, 1978, 1979a) and has been documented by theoretical and experimental work on kink folds (Gay and Weiss, 1974; Ramberg and Johnson, 1976; Reches and Johnson, 1976). The reasons why plate I stopped moving are more obscure, but may be related to height, spacing, and angles of ramps along thrust I.

Though thrust I ceased to be active, motion along the decollement at the base of the Mississippian continued. Thus, new fault trajectories to the ground surface were needed, and imbricate thrusts II and III were formed. Data are lacking to date the relative times of motion along the various thrust slices, but the sequence of imbrications shown in Figure 10 is consistent with that recognized in the Canadian Rockies (Dahlstrom, 1970, p. 352, Fig. 21b). The sites along the basal decollement where imbricate thrusts were initiated are unknown. Points of high strain concentration and structural weakness would occur at the upper corner of a ramp (Wiltschko, 1979), so thrusts II and III are shown splaying off at these points (Fig. 10b, c). One of the principal roles of the imbricates apparently was to reduce the angle of the steps. In this way, they function in a similar manner to mode 1 of Serra (1977, p. 496, Figs. 9, 10). Thus, thrusts II and III formed after the major folds. These thrusts cut downsection only on the upright limbs of those folds. The west-facing fold limbs that impart the kink geometry to the folds were formed over the west-facing ramps in the thrust I surface. Each subsequent thrust, in attempting to reduce the ramp angle of the step in front of it must cut downsection to the east in the more steeply west-dipping footwall rocks.

### Kink Folds and Thrust Ramps

Foreland folds in many parts of the world have been described as box or kink folds (Faill, 1973, Laubscher, 1976, 1977). Folds in plates II and III of the northern Blackfoot Mountains fit most of the criteria for kink folds as outlined previously. They have planar limbs and sharp hinges, with west-facing, upright limbs characteristic of conjugate kink folds (the classic box-fold geometry). Three-dimensional changes along trend are notable, particularly in the Mt. Taylor anticline. Massive carbonate rocks and quartzitic sandstones of the Mississippian and Pennsylvanian Systems are dominant mechanical members in the two plates and should theoretically favor kink folding over concentric folding.

Given suitable lithologies and proximity to thrust surfaces, kink folding is a necessary result of ramp geometries in those fault surfaces. Ramps generally occur where thrust faults step upsection across thick, stiff multilayers. Thus those same stiff multilayers in the hanging wall, which meet the theoretical criteria discussed previously, will be kink folded over those ramps. Folds formed over ramps have relatively sharp hinges or bends over inflection points in the ramps. Furthermore, west-facing steps necessarily produce relatively steep, west-facing fold limbs (as in the geometrical relations between folds and ramps in Fig. 10b). Suppe (1979) has also noted these last two points.

### Implications to Structural Traps

The concepts of kink folding and imbricate thrusts cutting downsection in the toe regions of major allochthons are particularly relevant to hydrocarbon exploration in foreland thrust-belt provinces. In the Idaho-Wyoming thrust belt, principal discoveries to date have occurred in the hanging walls of major allochthons east and south of the Blackfoot Mountains in the more frontal parts of the province. The folds in the Meade plate are shallow, rootless ramp folds which would not be expected to store significant amounts of petroleum because of deep erosional levels. More promising are the concentric folds of the parautochthon beneath the Meade plate.

In general, this study indicates that folds may have different geometries dependent in large part on their proximity during folding to ramps in underlying thrusts. Concentric folds formed a relatively large distance above ramps will be smoothly rounded and relatively unfractured, as well as having greater lateral continuity. Kink folds formed near ramps will not be nearly so continuous along trend (owing partly to ramp length and shape variations), but because of their histories of locking and subsequent brecciation and minor thrust faulting in the cores (Allmendinger, 1978, 1979a), such folds may well provide better fractured reservoirs.

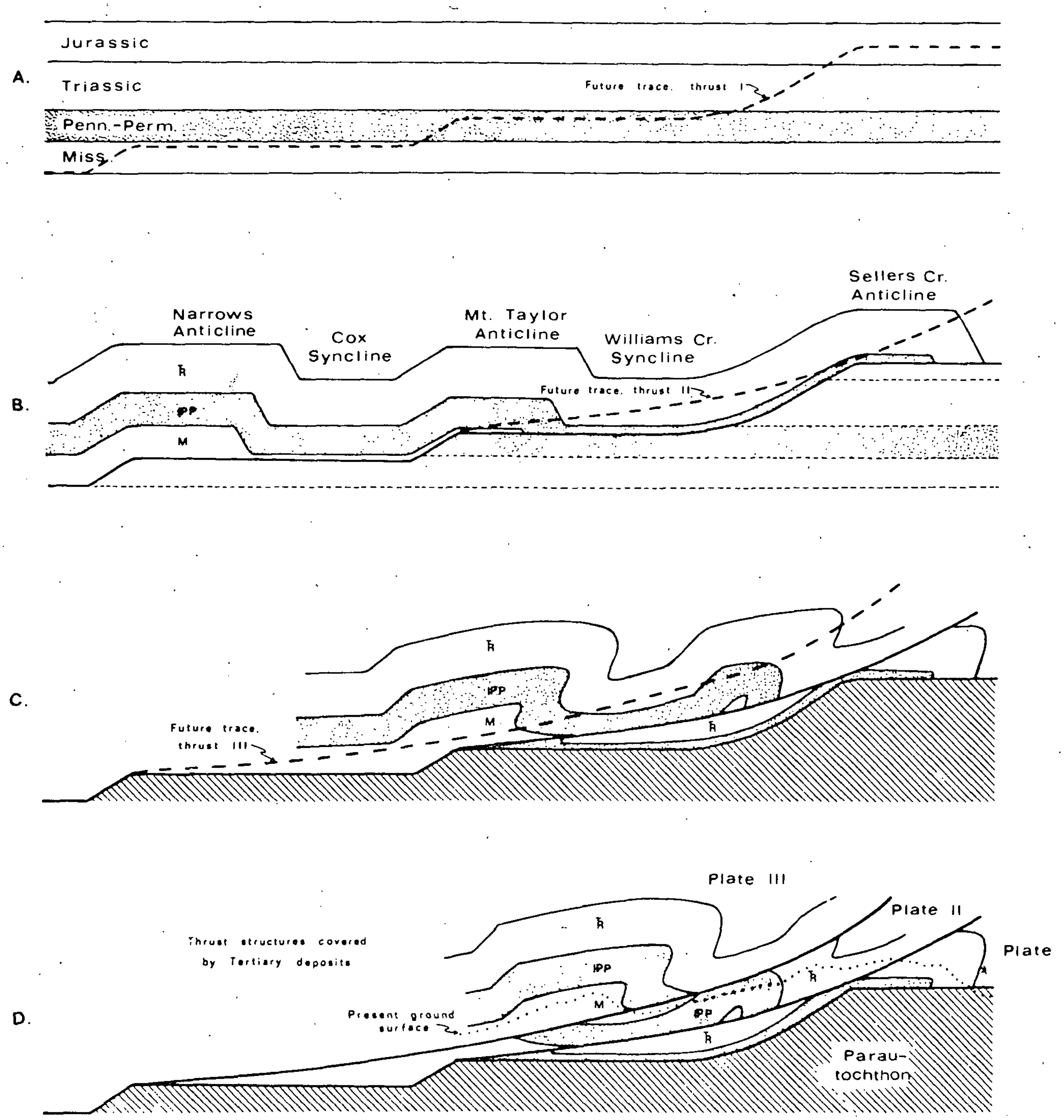



**FIG. 10—Schematic cross sections showing structural development of toe of Meade plate in northern Blackfoot Mountains. Light shading indicates Pennsylvanian-Permian rocks. Structure in parautochthon is not shown. Younger structure in parautochthon has probably modified structures within Meade allochthon. Relative vertical thicknesses of units are accurate; horizontal dimensions are not to scale.**

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