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Evidence for synchronous thin-skinned and basement deformation in the Cordilleran fold-thrust belt: the Tendoy Mountains, southwestern Montana

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Abstract—The Tendoy Mountains contain the easternmost thin-skinned thrust sheets in the Cordilleran fold-thrust belt of southwestern Montana, and are in the zone of tectonic overlap between the Rocky Mountain foreland and the Cordilleran fold-thrust belt. The three frontal thrust sheets of the Tendoy Mountains are from north to south, the Armstead, McKenzie, and Tendoy sheets. Near the southeastern terminus of the Tendoy thrust sheet is a lateral ramp in which the Tendoy thrust climbs along strike from the Upper Mississippian Lombard Limestone to lower Cretaceous rocks. This ramp coincides with the southeastern side of the Paleozoic Snowcrest trough and projection of the range-flanking basement thrust of the Blacktail–Snowcrest uplift, suggesting either basement or stratigraphic control on location of the lateral ramp. Axes of major folds on the southern part of the Tendoy thrust sheet are parallel to the direction of thrust transport and to the trend of the Snowcrest Range. They are a result of: (1) Pre-thrust folding above basement faults; (2) Passive transportation of the folds from a down-plunge position; (3) Minor reactivation of basement faults; and (4) Emplacement of blind, sub-Tendoy, thin-skinned thrust faults. The Tendoy sheet also contains a major out-of-sequence thrust fault that formed in thick Upper Mississippian shales and created large, overturned, foreland-verging folds in Upper Mississippian to Triassic rocks. The out-of-sequence fault can be identified where stratigraphic section is omitted, and by a stratigraphic separation diagram that shows it cutting down section in the direction of transport. The prominent lateral ramp at the southern terminus of the Tendoy thrust sheet is a result of fault propagation through strata folded over the edge of the Blacktail–Snowcrest uplift. © 1997 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

The Tendoy Mountains of southwestern Montana (Figs 1 & 2) are in the zone of tectonic overlap between the Rocky Mountain foreland and the Cordilleran fold-thrust belt (Perry *et al.*, 1983; Kulik and Schmidt, 1988). The 'overlap province' is approximately 110 to 160 km wide, and extends from west-central Montana to southernmost Nevada. In this zone, structures of the fold-thrust belt and foreland overlapped in space and time, such that thrust faults ramped over fault-bounded foreland structures, thrust sheets were folded by post-thrust foreland uplift, and thrust sheets were buttressed or impeded by foreland structures (Kulik and Schmidt, 1988). The purpose of this paper is to describe thrust belt–foreland interaction in southwestern Montana, where thrust belt structures are almost orthogonal to basement uplifts of the Rocky Mountain foreland.

The Tendoy Mountains contain six of the easternmost Cordilleran, thin-skinned thrust sheets in southwestern Montana. The three frontal sheets are, from north to south, the Armstead, McKenzie, and Tendoy thrust sheets (Figs 1 & 2). Several map-scale structures in the Tendoy Mountains indicate an unusual geometry and tectonic history for the area. First, stratigraphic cutoffs in the hangingwall near the southeastern terminus of the Tendoy thrust sheet define a lateral ramp in which the Tendoy thrust climbs from the Upper Mississippian Lombard Limestone to lower Cretaceous units (Fig. 1). Lateral ramps are not uncommon in fold-thrust belts (Royse *et al.*, 1975; Boyer and Elliott, 1982; Butler, 1982; Thomas, 1990), but this particular one approximately coincides with the southeastern side of the Paleozoic Snowcrest trough and the along-strike projection of the range-flanking basement thrust of the Blacktail–Snowcrest uplift. This superposition of tectonic features suggests that the basement thrust and/or the stratigraphic variation in the trough may have localized the lateral ramp.

Directly northwest (along strike) of the lateral ramp is a large anticline, here named the Birch Creek culmination, and a parallel syncline, called the Middle Fork syncline (Sadler, 1981) (Fig. 2). The axes of these folds are sub-parallel to the direction of thrust transport, and to the trend of the Snowcrest Range. Most large folds in fold-thrust belts are genetically related to thrusting, and are oriented perpendicular to the direction of transport, i.e. parallel to the strike of the thrust faults. The orientation of the Birch Creek culmination and the Middle Fork syncline could be a result of one or more of three factors, all of which modify typical fold-thrust belt patterns: (1) pre-thrust folding associated with the Blacktail–Snowcrest uplift, after which the folds were beheaded and passively carried in the Tendoy thrust sheet; (2) post-thrust folding of the Tendoy thrust sheet by the sub-thrust Blacktail–Snowcrest uplift; or (3) Syn-thrust folding of the Tendoy thrust sheet unrelated to movement of the Blacktail–Snowcrest uplift. The latter could have been caused by internal imbrication and formation of a duplex or as a result of convergent flow and crowding into a corner defined by the intersection of a frontal ramp and a lateral or oblique ramp (Ponton, 1983). Finally, the Tendoy sheet contains a major out-of-sequence thrust fault and large, overturned folds in the Snowcrest Range Group and Pennsylvanian–Permian rocks (Perry and Hossack, 1984; Perry *et al.*, 1988).

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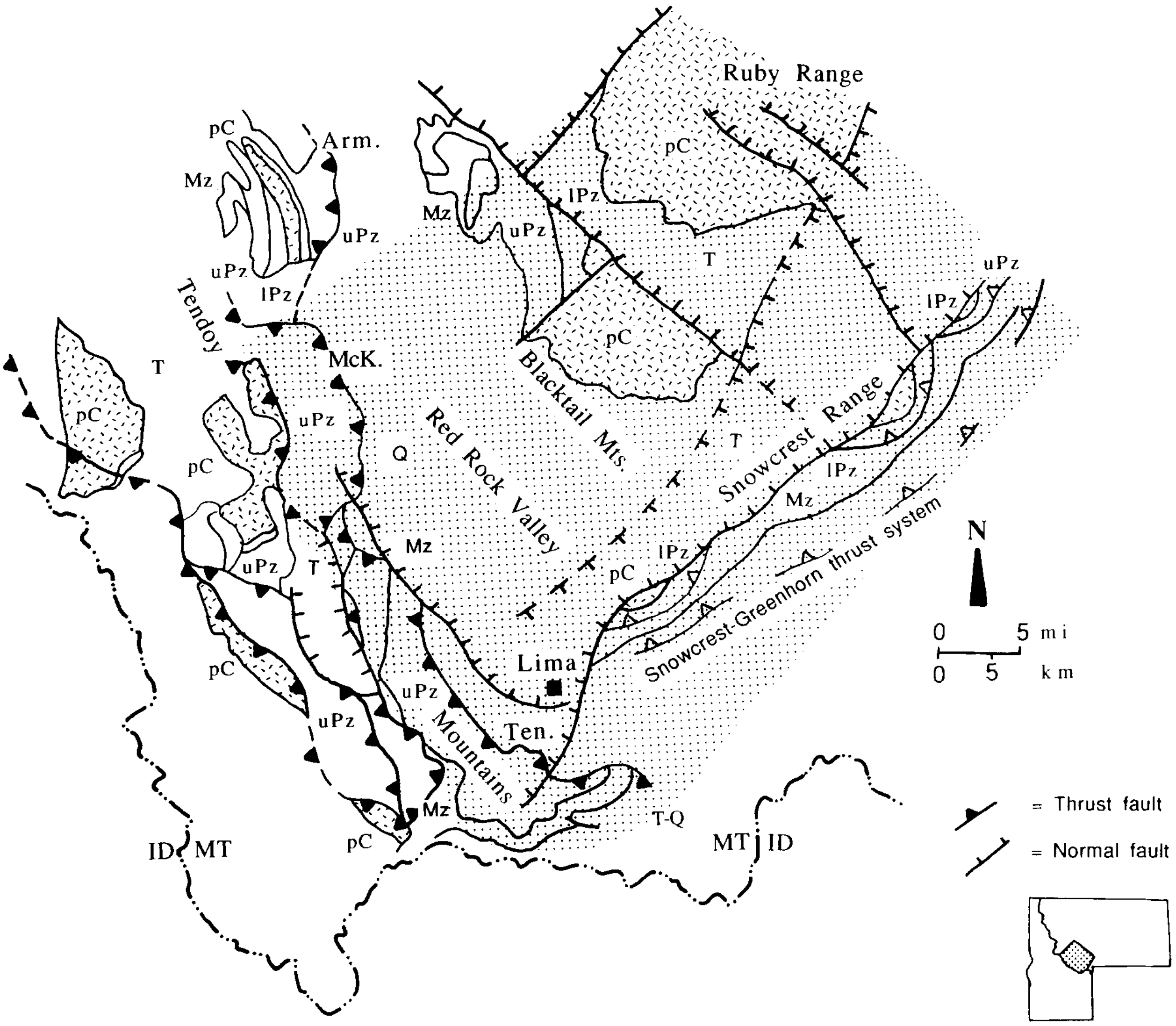

Fig. 1. Tectonic map of southwestern Montana. Thrust faults with filled barbs are thin-skinned faults of the Cordilleran fold-thrust belt. Those with open barbs are basement-rooted faults of the Rocky Mountain foreland province. pC = Precambrian rocks, including Archean crystalline rocks and metasedimentary rocks of the Proterozoic Belt Supergroup in the west-central map area; lPz = lower Paleozoic rocks; uPz = upper Paleozoic rocks; Mz = Mesozoic rocks; T = Tertiary sedimentary and volcanic rocks; Q = Quaternary sedimentary and volcanic rocks; Arm. = Armstead thrust sheet; McK. = McKenzie thrust sheet; Ten. = Tendoy thrust sheet. Stippled area corresponds to southwestern part of the Paleozoic Snowcrest trough. Study area shown in inset. Figure modified from Kulik and Schmidt (1988), Skipp (1988), and McBride (1988).

SETTING

Palynological ages of synorogenic conglomerates in the footwalls of the leading thrust sheets of the Tendoy Mountains indicate that the thrust sheets were emplaced from mid-Campanian to early Maastrichtian, and possibly the early Paleocene (Nichols *et al.*, 1985; Perry *et al.*, 1988). The Tendoy Mountains are bounded on the east by Red Rock Valley, which is a Quaternary extensional basin. Across Red Rock Valley to the northeast are the Blacktail and Snowcrest Ranges, which are Late Cretaceous, basement-cored structures of the Rocky Mountain foreland. Much of the Rocky Mountain foreland lies east of the Cordilleran fold-thrust belt, but the two structural provinces overlap in a 100–150 km wide zone extending from southwestern Montana to southwestern Colorado (Woodward, 1976; Brown, 1983, 1988; Kulik and Schmidt, 1988). The Blacktail–Snowcrest uplift underwent eastward or southeastward translation along a large basement-rooted reverse fault, presently represented by the Sub-Snowcrest Range fault and associated imbricates of the Snowcrest–Greenhorn thrust system (Perry *et al.*, 1983; McBride, 1988) (Fig. 1). Palynological dating of synorogenic conglomerates (Beaverhead Group) shed from the Blacktail–Snowcrest uplift indicates that it was largely emplaced before the frontal thrust sheets of the adjacent fold-thrust belt (Nichols *et al.*, 1985; Perry *et al.*, 1988).

Aeromagnetic data (Zeitz *et al.*, 1981) reveal a NE-trending magnetic high corresponding to the Blacktail–Snowcrest uplift. This magnetic high extends beneath the Tendoy Mountains, suggesting that thrust sheets of the Tendoys impinged on the pre-Cordilleran basement uplift. Also, sub-thrust basement uplifts can be seen on oil industry seismic profiles, and basement rocks have been incorporated into more hinterland thin-skinned

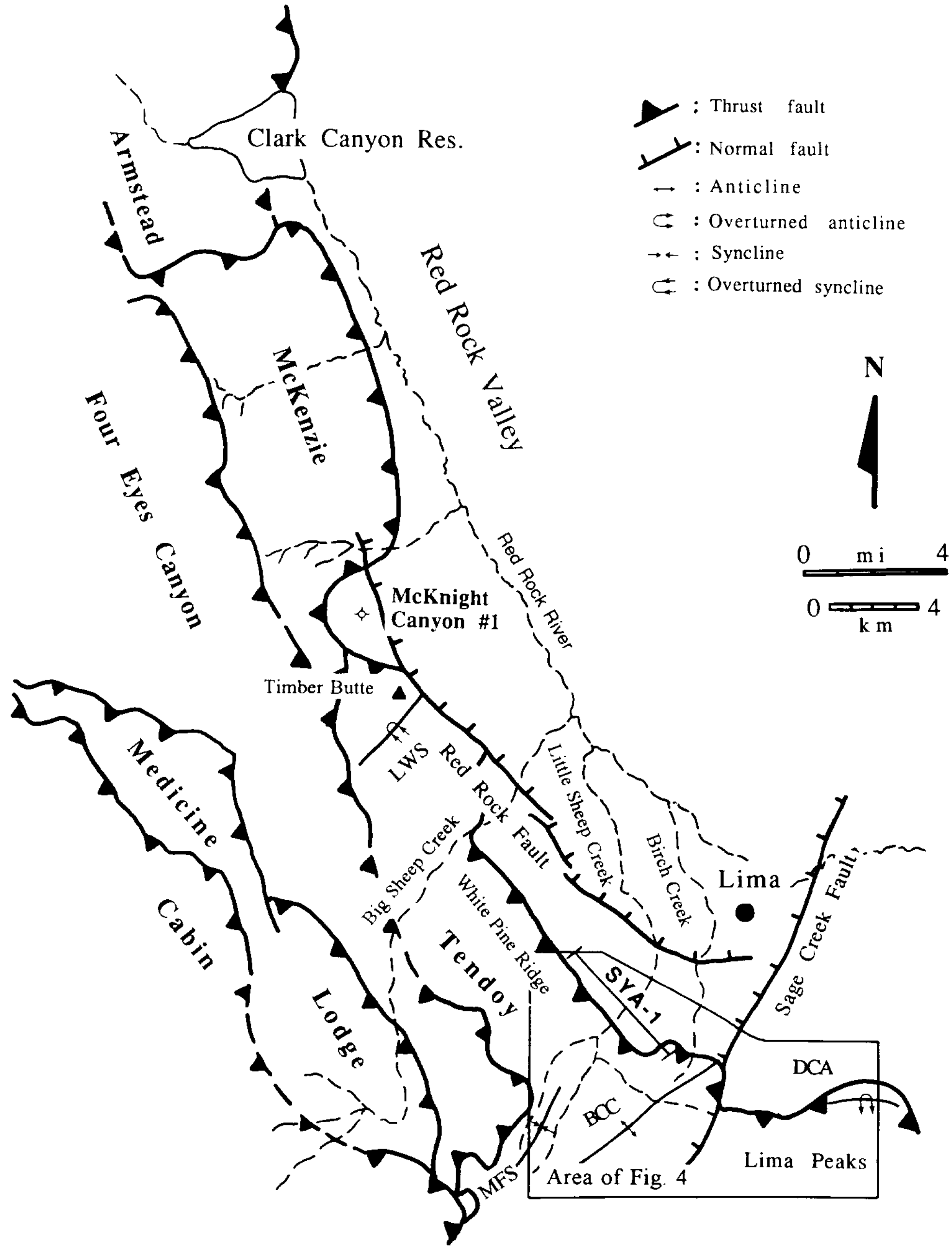

Fig. 2. Tectonic map of the Tendoy Mountains and surrounding area. LWS = Little Water syncline; MFS = Middle Fork syncline; BCC = Birch Creek culmination; DCA = Deep Creek anticline. SYA-1 = Amoco Production Company reflection seismic line.

thrust sheets such as the Cabin thrust sheet (Skipp, 1988). These relationships support the idea that the leading thrust sheets of the Tendoy Mountains were superimposed on structures of the Rocky Mountain foreland.

A NE-trending thickness maximum on isopach maps of Upper Mississippian to Triassic strata defines a zone of subsidence called the Snowcrest trough (Fig. 1). Upper Mississippian to Triassic units are much thinner on the Wyoming shelf, an area of inferred crustal stability southeast of the trough. The Tendoy Mountains are oriented perpendicular to the Snowcrest trough. Upper Mississippian and Pennsylvanian rocks thicken gradually from northwest to southeast into the keel of the trough, but thin abruptly southeastward out of the trough onto the Wyoming shelf (Perry, 1986; McDowell, 1992). The Snowcrest trough has been interpreted to have been a half-graben, bounded on the southeast by a down-to-the-northwest normal fault (Perry, 1986; McBride, 1988). This fault was thought to have been tectonically reactivated as a basement thrust fault to form the Sub-Snowcrest Range fault and the Blacktail–Snowcrest uplift (Perry *et al.*, 1988; McBride, 1988).

STRUCTURES OF THE SOUTHERN TENDOY THRUST SHEET

The Tendoy thrust sheet is the southernmost of the three frontal thrust sheets in the Tendoy Mountains (Figs 1 & 2). Near the southeastern terminus of the Tendoy thrust fault, the fault abruptly changes strike from NW-striking to ENE-striking (Fig. 2). In addition, the thrust climbs up section from the Upper Mississippian Lombard Limestone to Lower Cretaceous rocks and loses displacement in an overturned NW-verging anticline, the Deep Creek anticline of Hammons (1981) (Figs 2 & 4).

Stratigraphy of the Tendoy thrust sheet is summarized in Fig. 3 (Perry, 1986; McDowell, 1992). No deep exploration well has been drilled on the Tendoy thrust sheet, and the quality of reflection seismic data for this area is generally poor. Therefore, the following discussion of subsurface structural style is based almost entirely on surface geology and structural principles established in the thoroughly explored Wyoming salient and Alberta foothills of the Cordilleran fold-thrust belt (Armstrong and Oriel, 1965; Royse *et al.*, 1975; Price, 1981; Lamerson, 1983; Perry *et al.*, 1988).

In order to systematically describe the structural style of the Tendoy thrust sheet, I have divided the southern Tendoy sheet into three parts: White Pine Ridge to Little Sheep Creek, the Birch Creek culmination, and Lima Peaks (Fig. 4). I present strike-perpendicular cross sections through each of these areas and discuss the surficial geology in the vicinity of each transect. Sites of specific importance are indicated by circled letters referred to in the text.

White Pine Ridge to Little Sheep Creek

The geology of the White Pine Ridge area (Fig. 4) reveals closely spaced imbricate thrust faults and folds in the Upper Mississippian Conover Ranch Formation. The Tendoy thrust fault is well exposed in this area and has an average orientation of N53W, 53SW. From northwest to southeast along strike, the Tendoy thrust gradually climbs up section from the middle to the top of the Lombard Limestone. The apex of this gradual southeastward climb in stratigraphic level of detachment is at location A (Fig. 4), where the Tendoy thrust fault is almost at the base of the Conover Ranch Formation. Here, the Conover Ranch is deformed in a series of tight, doubly-plunging folds. An imbricate of the Tendoy thrust, mapped northwest across strike of location A, loses displacement in the Conover Ranch folds, and

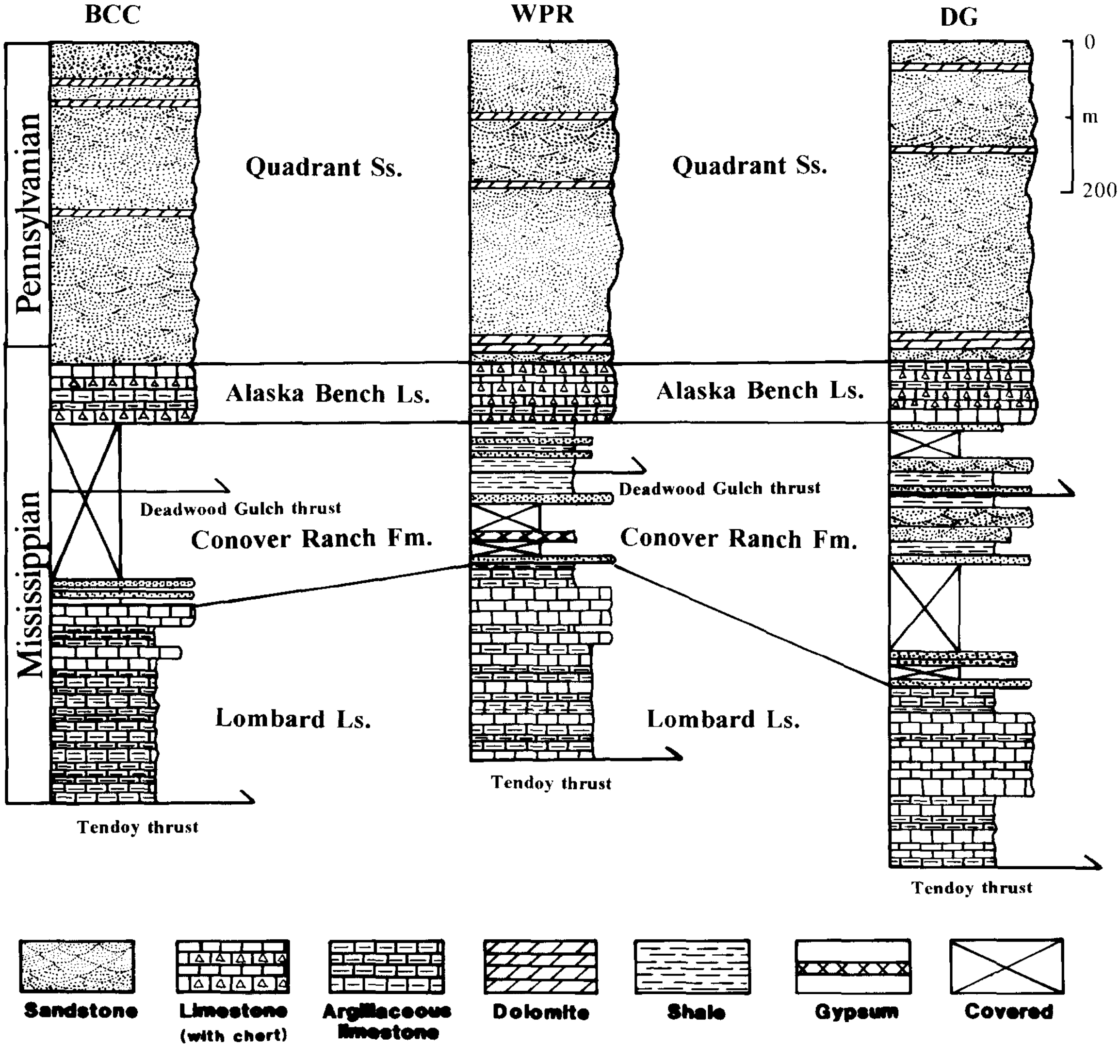

Fig. 3. Stratigraphy of the Tendoy thrust sheet, showing along-strike variations in Conover Ranch Formation and Lombard Limestone. BCC = Birch Creek culmination; WPR = White Pine Ridge; DG = Deadwood Gulch.

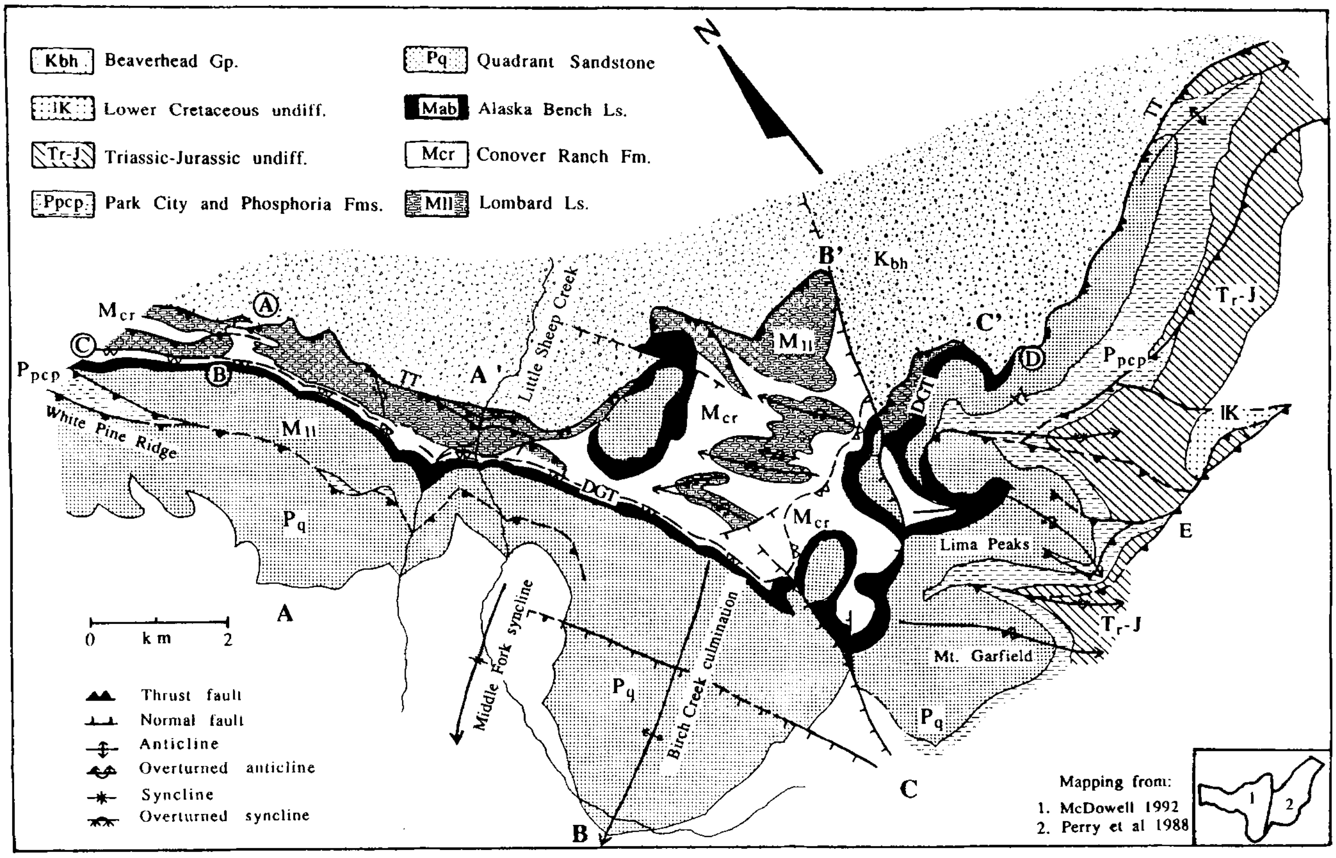

Fig. 4. Geologic map of the southern third of the Tendoy thrust sheet. Open double barbs are on the Deadwood Gulch thrust fault. Filled double barbs are on the Tendoy thrust fault. Faults are dashed where inferred. Filled single barbs are on intraplate imbricates in hanging wall of Tendoy thrust sheet.

cannot be traced farther southeast. Along strike to the southeast from location A, the Tendoy thrust stratigraphically descends to the middle of the Lombard Limestone, and persists at that level as far southeast as the Birch Creek culmination (Fig. 4).

An important feature of the geologic map is the anomalously narrow outcrop of the Conover Ranch Formation. This is especially apparent at location B (Fig. 4), where the map distance between the top of the Lombard Limestone and the Upper Mississippian Alaska Bench Limestone is only 118 m. The narrow outcrop width cannot be accounted for by changes in topography such as an increase in slope. The Conover Ranch evidently has been thinned by faulting and an exposure of the Conover Ranch Formation in the scarp of a large landslide (location C, Fig. 4) reveals a NE-verging fault propagation fold that may be associated with a splay from a proposed fault, here named the Deadwood Gulch thrust fault. Thinning of stratigraphic section is typical of normal faults, but a thrust fault can thin the section rather than duplicate it if the fault cuts through a previously, and synclinally, deformed section. Cross-section geometries and field relationships suggest that this is indeed the case; therefore, the Deadwood Gulch thrust fault is probably an out-of-sequence fault.

Since, (1) the Alaska Bench Limestone is everywhere in stratigraphic contact with the overlying Upper Mississippian–Pennsylvanian Quadrant Sandstone; (2) a fault propagation fold exists in the upper part of the Conover Ranch shale at White Pine Ridge (‘C’, Fig. 4), and (3) 60 m of the stratigraphic section on the backlimb of the fold is undisturbed, the Deadwood Gulch thrust is interpreted to be approximately 60 m below the base of the Alaska Bench Limestone on White Pine Ridge. The Quadrant Sandstone and the Alaska Bench Limestone form a single, rigid lithotectonic unit in contrast to the shaley Conover Ranch Formation. Although the fault is concealed everywhere, the trace is not entirely speculative because the Alaska Bench Limestone is in fault contact with the Lombard Limestone at the leading edge of the Birch Creek culmination (Fig. 8, discussed below).

Cross section A–A′ (Fig. 5a) is a transect south of White Pine Ridge through the Little Sheep Creek area. The dip of the frontal ramp of the Tendoy thrust at the surface is approximately 65° SW, and the inferred dip of the basal Tendoy thrust flat is approximately 15°. The latter figure is derived from westward-dipping reflectors seen in a strike-perpendicular seismic line north of Timber Butte near the northern margin of the Tendoy thrust sheet. A dip of 65° is unusually high for a frontal ramp, but not unreasonable for an emergent imbricate fan (Elliott and Johnson, 1980; Boyer and Elliott, 1982). As will be discussed, the original dip was probably lower but was steepened partly by westward tilting of the Tendoy thrust sheet as a result of late Quaternary uplift in the footwall of the Red Rock fault (Fig. 2) and mostly by emplacement of a blind thrust beneath the Tendoy thrust sheet.

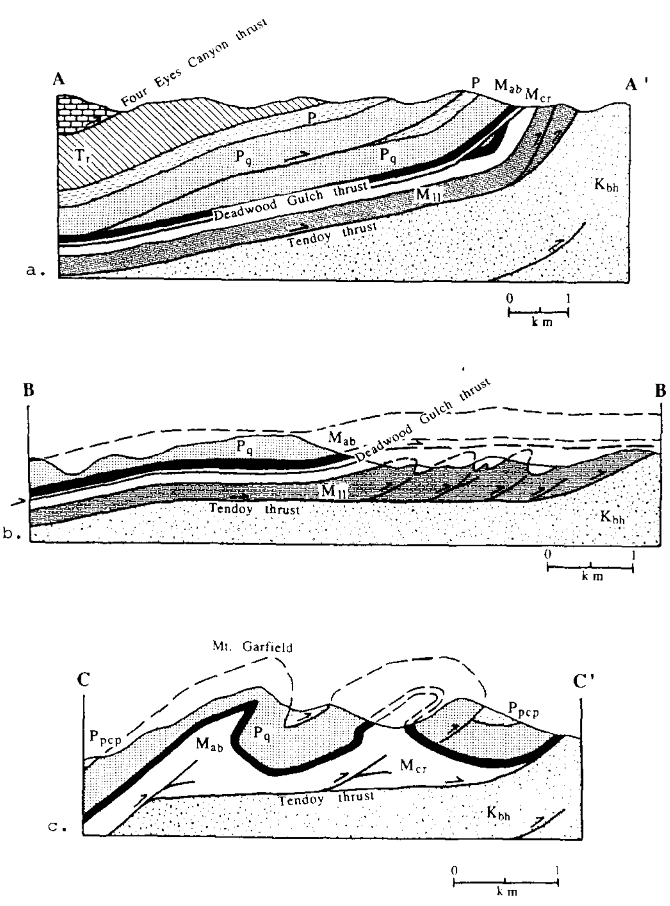

Fig. 5. (a) Cross section through the Little Sheep Creek area. (b) Cross section through the Birch Creek culmination. (c) Cross section through the Lima Peaks area. See Fig. 4 for locations of cross sections.

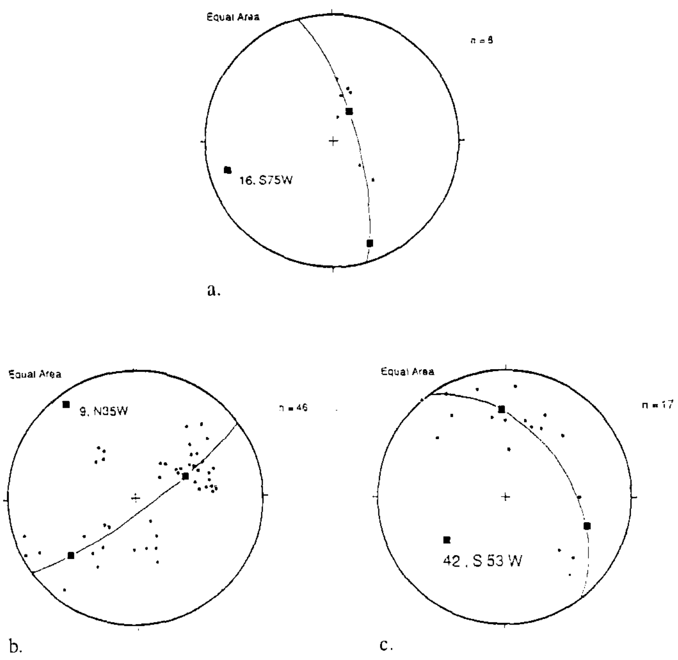

Fig. 6. (a) pi-diagram of poles to bedding in Quadrant Sandstone of the Birch Creek culmination. Squares are average poles to fold limbs and the pi-axis that indicates an axial trend of 16, S75W; (b) pi-diagram of poles to bedding from folds exposed in Lombard Limestone in the middle of the Birch Creek culmination. There is a 70° angle between the trend of these smaller folds and the Birch Creek culmination on which they are superimposed; (c) pi-diagram of folds in hangingwall of E-striking thrust fault of Lima Peaks. The pi-axis of 42, S53W suggests NW-directed shortening.

Basal detachment of the Tendoy thrust is in the Lombard Limestone. The base of the Lombard Limestone is in distinct lithologic contrast to the more shaley Kibbey Formation below and may have acted as an effective detachment horizon (McBride, 1988). The section shows a secondary detachment horizon in the Conover Ranch Formation along which the Deadwood Gulch thrust fault formed.

Little Sheep Creek to Lima Peaks: the Birch Creek culmination

In map view, the Birch Creek culmination is clearly visible as a large, SW-plunging antiform defined by the upper contact of the Quadrant Sandstone and by exposures of folded Lombard Limestone in the middle of the structure (Fig. 4). This part of the Tendoy thrust sheet had previously been called the Garfield anticline (Scholten *et al.*, 1955; Sadler, 1981), but Birch Creek culmination is used here to distinguish it from the NW-trending anticline beneath Mt. Garfield. The culmination is flanked on the northwest by the Middle Fork syncline (Sadler, 1981). Bedding orientations around the margins of the Birch Creek culmination indicate that it plunges 16°, S75W (Fig. 6a). Hinges of the folds in the Lombard Limestone have northwest trends (Fig. 6b), and the folds are overturned to the northeast.

Figure 7(a) is a tracing of seismic line SYA-1, which crosses Little Sheep Creek and extends to the middle of the Birch Creek culmination (Fig. 2). In the interpretation shown in Fig. 7b, basement is arched beneath the Birch Creek culmination and may be within 1300 m of the surface. A NW-verging basement thrust is also shown. Continuous reflectors in the interpreted Cretaceous rocks above the backthrust suggest that it is bedding parallel in Mesozoic or Lower Paleozoic units. Because there is no expression of this fault at the surface and the Tendoy thrust sheet is not folded above it north of Little Sheep Creek, the basement fault is interpreted to have formed prior to emplacement of the Tendoy sheet.

Cross section B–B′ (Fig. 5) through the Birch Creek culmination, which is constrained by surface data, shows the NE-verging folds in the Lombard Limestone and Conover Ranch Formation. No thrust faults associated with the folds are observed in the field; therefore, the folds are interpreted to be fault-tip or fault-propagation folds associated with splays rooted in the basal detachment. The dip of the frontal ramp, approximately 20° SW, was determined by constructing a structure contour map (Fig. 8) from the outcrop pattern of the leading edge of the thrust and from strike and dip data in that area.

The Birch Creek culmination was originally interpreted to be a thrust duplex, with the Tendoy thrust its floor and its roof thrust at the base of the Alaska Bench Limestone or within the Conover Ranch shale (Perry and Hossack, 1984). However, duplexes are mechanisms by which slip is transferred from the floor thrust to the roof

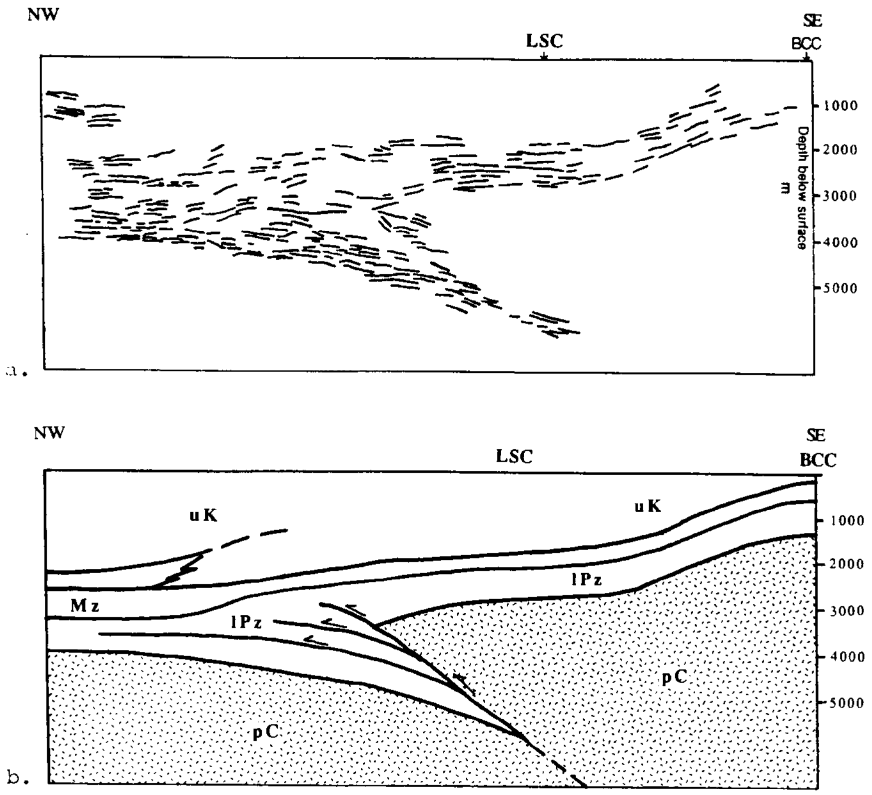

Fig. 7. (a) Line tracing of seismic line SYA-1 (see Fig. 2). (b) Interpretation of seismic line SYA-1 showing that (1) basement fault transferred displacement into bedding plane faults in the sedimentary cover, and (2) the existence of a prominent basement arch below Birch Creek culmination.

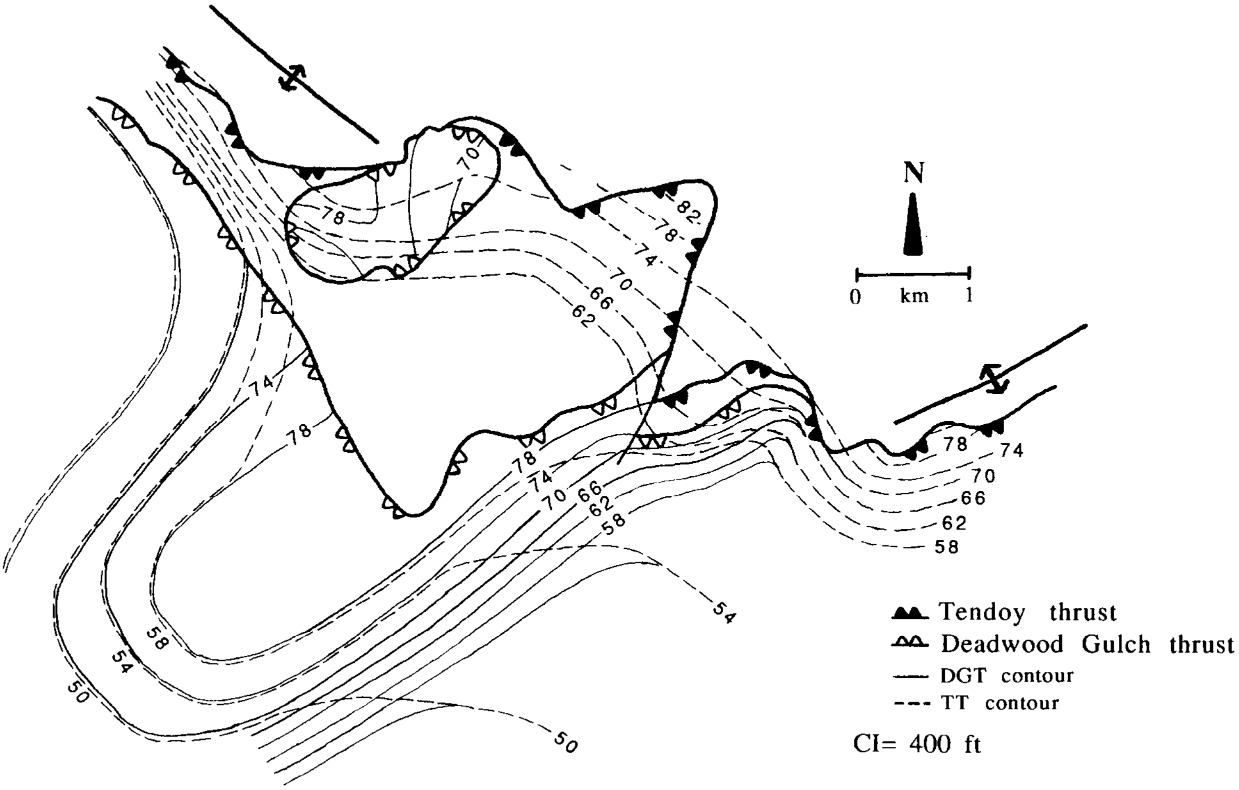

Fig. 8. Structure contour map of the Birch Creek culmination. Displacement on normal faults has been removed. Note that both the Tendoy thrust (TT) and the Deadwood Gulch (DG) thrust faults are folded around a NE-trending axis north of the culmination, indicating minor reactivation of the Blacktail–Snowcrest uplift after emplacement of the thin-skinned thrust sheets.

thrust along imbricate faults (Boyer and Elliott, 1982). Because the imbricates that caused the overturned folds in the Birch Creek culmination do not cut through the folds and did not transfer displacement from the floor thrust to the roof thrust, and because the Birch Creek culmination is the best-preserved part of the Tendoy thrust sheet, the cross section geometries indicate that the Tendoy sheet is not a duplex, but rather an imbricate fan that was truncated by movement on the out-of-sequence Deadwood Gulch thrust fault near the base of the Alaska Bench Limestone.

A structure contour map of the Deadwood Gulch and Tendoy thrusts was constructed for the Birch Creek culmination on the basis of map data and cross section geometry (Fig. 8). A comparison of the Tendoy thrust and Deadwood Gulch thrust contours indicates that the southeastern side of the culmination is a footwall lateral ramp of the Deadwood Gulch thrust where it joins the Tendoy thrust along a branch line below Lima Peaks. The northwestern side of the culmination is not a lateral ramp; instead, parallel thrust contours reflect folding of both faults. The Deadwood Gulch thrust continues north to a position directly north of Big Sheep Creek (Bartholomew, 1988) (Fig. 1).

The structure contour map also suggests the presence of blind-thrusts structurally below the Tendoy thrust. The Tendoy thrust appears to be folded by a NW-trending antiform that extends from White Pine Ridge and terminates southeastward against the northeastern corner of the culmination. The fold appears in the Beaverhead Group conglomerates mapped by Ryder and Scholten (1973) and is probably a result of a sub-Tendoy blind thrust that terminates southeastward along strike along the Birch Creek culmination. The blind thrust caused the steep dip of the Tendoy thrust north of Little Sheep Creek, and thus formed after the Tendoy thrust in a typical hinterland-to-foreland sequence.

The Tendoy thrust has been locally folded around a NE-trending axis near the Lima Peaks area (location D on Figs 4 & 8). Perry *et al.* (1988) inferred that this represents post-thrust reactivation of the Blacktail–Snowcrest uplift. Alternatively, the box-like geometry of the footwall fold and its limited extent along strike suggest that it is a fault-tip or fault-propagation fold associated with another sub-Tendoy blind thrust that also terminates in Upper Cretaceous rocks against the Birch Creek culmination. The orientation of this fold (Fig. 4) indicates NW-directed shortening. It also formed after the Tendoy thrust sheet had been emplaced.

Map relationships on the northwest and southeast sides of the Birch Creek culmination also provide insight into the evolution of the culmination. On the northwest, a klippe of the Deadwood Gulch thrust places Alaska Bench Limestone directly on near-basal Conover Ranch gypsum and Lombard Limestone (Figs 4 & 8), omitting approximately 800 ft of section. On the southeastern side of the culmination, Alaska Bench Limestone is also directly on top of the Lombard Limestone near the leading edge of the Tendoy thrust sheet. As at White Pine Ridge, where the Conover Ranch Formation was thinned by a fault, these structural relationships indicate that the Deadwood Gulch thrust emplaced Alaska Bench Limestone and Quadrant Sandstone over previously deformed rocks, confirming out-of-sequence movement and extending the Deadwood Gulch fault across the Birch Creek culmination.

An important clue to the kinematic history of the Deadwood Gulch thrust can be found by constructing a stratigraphic separation diagram of the Tendoy and Deadwood Gulch thrusts (Fig. 9). The stratigraphic level of the hangingwall cutoff of the Tendoy thrust varies significantly within the Lombard Limestone from White Pine Ridge to Lima Peaks (Fig. 9a). Most importantly, the Tendoy thrust cuts up section away from the middle of the Birch Creek culmination in both directions. This geometry is possible if the thrust cut horizontally through a pre-existing anticline (Fig. 9c). Conversely, a thrust fault can cut downsection along strike if it cuts through a syncline (Fig. 9c). The changes in stratigraphic horizon of the Tendoy thrust confirm that it propagated through broadly folded rocks. The Deadwood Gulch thrust also changes stratigraphic level within the Conover Ranch Formation. Near Little Sheep Creek, it is approximately 60 m below the base of the Alaska Bench Limestone. Along the edges of the Birch Creek Culmination, Alaska Bench Limestone is directly on Lombard Limestone. This does not appear to be the geometry in the middle of the culmination, indicating that the Deadwood Gulch thrust also cut through previously folded stratigraphy. Perpendicular to structural strike, the footwall cutoff of the Deadwood Gulch thrust changes stratigraphic level beneath the klippe at the northwestern side of the culmination. There, the Deadwood Gulch thrust, from southwest to northeast, cuts downsection in the footwall from near the base of the Conover Ranch shale to the top of the Lombard Limestone (Figs 4 & 9b). The stratigraphic separation diagrams indicate that both thrust faults beheaded earlier-formed folds, but the relationship of the klippe to the footwall of the Deadwood Gulch thrust indicates that the fault cut through rocks previously deformed by movement on the Tendoy thrust, and that the Deadwood Gulch thrust underwent significant out-of-sequence movement mostly after the imbricated and folded lower plate had formed. The Deadwood Gulch thrust draped over the SE-facing plunge-out of the Tendoy thrust structures, forming the steep, SE-facing gradient on the flank of the Birch Creek culmination, evident in the structure contour map.

The seismic profile shown in Fig. 7 can be interpreted to show that basement is shallow beneath the culmination and is deeper on the northwest side of the NW-dipping basement back-thrust beneath Little Sheep Creek. As previously mentioned, there is no direct evidence for large-scale, post-Tendoy reverse movement of the basement fault, nor is there any evidence of normal movement; however, there is evidence for pre-Tendoy folding of the stratigraphy and minor post-Tendoy uplift. Parallel structure contours of the Deadwood Gulch and Tendoy thrust faults on the southwestern and north-

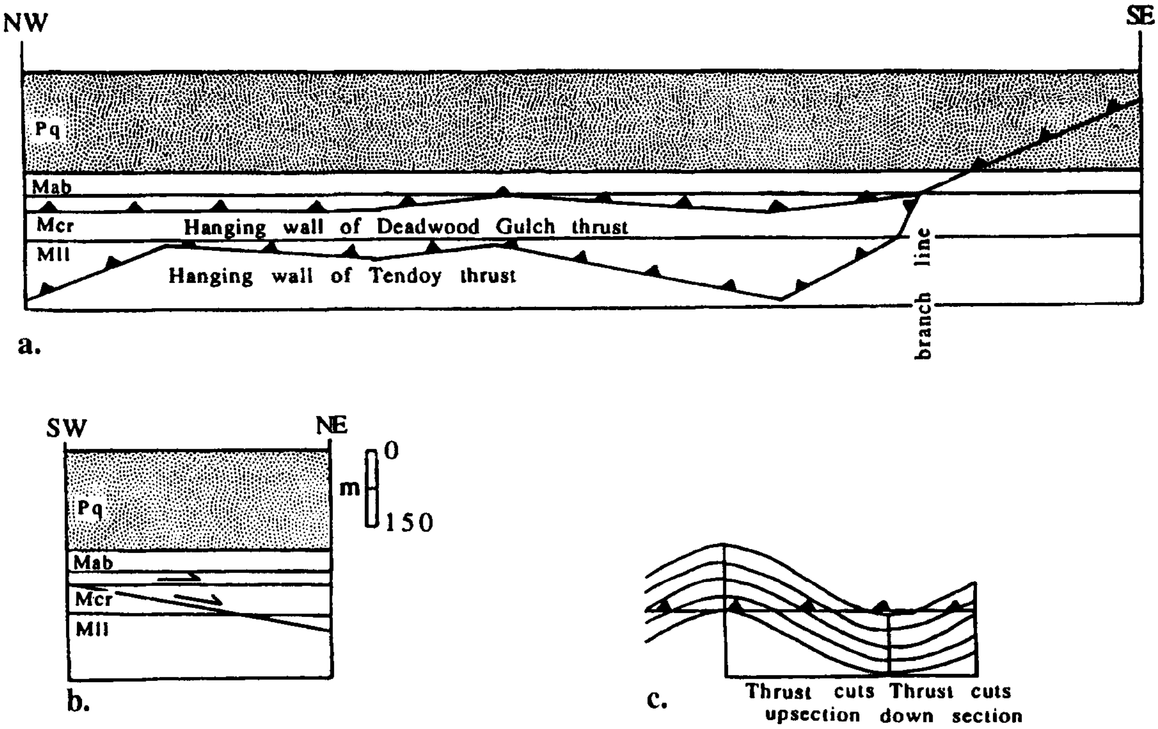

Fig. 9. (a) Strike-parallel stratigraphic separation diagram of the Tendoy and Deadwood Gulch thrust faults. (b) Strike-perpendicular stratigraphic separation diagram showing that Deadwood Gulch thrust fault cuts down-section in the direction of transport. (c) Illustration showing how a horizontal thrust cutting folded strata would first cut up section then cut down section.

western sides of the Birch Creek culmination indicate that they were folded together by minor, late, NW-verging movement on the basement back-thrust and by blind, NE-verging thrusting below the Tendoy thrust. The palinspastic location of the basement structure suggests that it could have folded the overlying rocks prior to emplacement of the Tendoy sheet. The shallow depth to basement south of Little Sheep Creek probably caused the termination of the blind thrust that steepened the Tendoy thrust and accentuated Middle Fork syncline. Likewise, shallow depth to basement may have caused termination of the blind thrust that folded the Tendoy thrust sheet northeast of Lima Peaks.

The seismic data, structure contour maps, and stratigraphic separation diagram thus indicate that the Birch Creek culmination is a result of: (1) pre-thrust folding of the stratigraphy by the basement fault; (2) emplacement of the Tendoy thrust sheet, which beheaded the folds from a down-plunge position, transported them to their present position, and superimposed strike-parallel folds on them; (3) emplacement and draping of the Deadwood Gulch thrust to form the southeastern limb of the culmination; (4) minor post-Deadwood Gulch thrust reactivation of the basement back-thrust, creation of the northwest limb of the culmination, and accentuation of the Middle Fork syncline; and (5) steepening of the Tendoy thrust sheet north of the culmination by emplacement of the blind, sub-Tendoy, thin-skinned thrust, which further tightened the Middle Fork syncline.

Lima peaks

The map pattern of the Quadrant Sandstone and adjacent units (east half of Fig. 4; from Perry *et al.*, 1988) is that of a series of large, NE-verging, SE-plunging folds. Perry *et al.* (1988) mapped several thrust faults with small stratigraphic separations in the hinges of the folds. The faults merge southeastward along strike into a NE-striking thrust fault (location E, Fig. 4) with approximately 1.6 km of left separation suggesting sinistral oblique slip. Perry *et al.* (1988) interpreted Lima Peaks to be a southward-inclined duplex zone, with the oblique-slip fault as its roof thrust. However, the existence of the imbricates exclusively in the fold hinges suggests that they are out-of-the-syncline and contraction faults associated with fold tightening (Dahlstrom, 1970). In this interpretation, the NE-striking oblique slip thrust is not a roof thrust. An increase in separation along the fault, and a change from northwest to northeast strike suggests that it may have transferred displacement of the Tendoy sheet from NE-directed to NW-directed in concert with the change in strike of the Tendoy thrust, similar to the sub-Tendoy blind thrust that created the NE-trending anticline (Fig. 4). Northwest-directed movement is also indicated by a stereoplot of broadly folded beds at location 'E' (Fig. 6c) having a fold axis of 42° S53W. Furthermore, the axial trend of the eastern Lima Peaks anticline is folded around a NE-trending axis, consistent with thrust transport to the northwest on the oblique-offset fault. Together, these observations indicate that the NE-striking oblique slip thrust fault formed after the eastern Lima Peaks anticline and is another out-of-sequence thrust in the hangingwall of the Deadwood Gulch thrust.

On the northeastern side of Lima Peaks, the basal thrust of the Tendoy sheet climbs up-section along strike from the Lombard Limestone to the Quadrant Sandstone (Fig. 4). In concert with this hangingwall lateral ramp, the Tendoy thrust curves abruptly to a northeast strike. Stratigraphic separation of the Tendoy thrust fault decreases along strike to the east, to where it is in lower Cretaceous rocks and cannot be traced on the basis of obvious stratigraphic separation.

Cross section C–C′ (Fig. 5c) is a down-plunge view of the Lima Peaks structures, showing the nearly isoclinal geometry of the SE-plunging anticlines and out-of-the-syncline thrust faults on the northeastern fold limbs. Critical aspects of the cross section are the interpretation of a shallowly-dipping basal detachment and the implication of large-scale ductile flow of Conover Ranch shale out of synclinal hinges. Surface data do not reveal any forelimb thinning of the Quadrant Sandstone. As indicated by the structure contour map of the Birch Creek culmination (Fig. 8), the Lima Peaks folds are in the hangingwall of the Deadwood Gulch thrust fault, but the cross section is constructed directly southeast of the Tendoy–Deadwood Gulch branch line. Farther down plunge, the folds are upright, reflecting smaller displacement on the Deadwood Gulch/Tendoy thrust system and rise of the basal detachment from the Conover Ranch Formation to the Quadrant Sandstone.

Lima Peaks contain plunging folds formed over a lateral ramp of the Deadwood Gulch and Tendoy thrusts. Plunging folds are typical of hangingwall lateral ramps, indicating the plunge-out of hangingwall ramp anticlines along strike. This may have been the original geometry at Lima Peaks, where the eastern fold (Fig. 5c) could have formed as a ramp anticline. Continued movement of the anticline along an upper flat in the Conover Ranch shale may have ceased when the forelimb of the fold encountered the frontal ramp at the eastern end of the cross section. Continued displacement caused the forelimb to overturn and the fold to tighten. Continued movement of the backlimb up the trailing ramp formed the Garfield Mountain anticline and the syncline to its east. This kinematic model requires extensive thickening and ductile flow of the Conover Ranch shale while the Quadrant Sandstone behaved rigidly. Such mechanical behavior is likely, given the extreme competency contrast between the Quadrant and the Conover Ranch. The model also suggests a complicated sequence of thrust sheet motion different from the usual hinterland-to-foreland sequence invoked for most fold-thrust belts (Armstrong and Oriel, 1965; Royse *et al.*, 1975; Price, 1981; Boyer and Elliott, 1982).

The thickness and facies of the Quadrant Sandstone do not change in the hangingwall of the Tendoy thrust, indicating that stratigraphic variations associated with the southeastern margin of the Snowcrest trough did not control the location of the lateral ramp. As with the variations in detachment level in the Birch Creek culmination, the prominent lateral ramp in the Tendoy thrust at Lima Peaks, where the fault climbs up-section from the Lombard Limestone to Mesozoic rocks, can be explained by the thrust propagating through a sedimentary sequence anticlinally drape-folded over the southeastern side of the Blacktail–Snowcrest uplift.

DISCUSSION

Palynological dating of the Beaverhead Group conglomerates shed from the Blacktail–Snowcrest uplift indicates emplacement beginning in Coniacian to Santonian until mid-Campanian, thereby preceding mid-Campanian to early Paleocene emplacement of the Tendoy thrust sheet (Nichols *et al.*, 1985; Perry *et al.*, 1988). The passively translated, folded stratigraphy of the Birch Creek culmination and the variations in detachment levels for the Tendoy and Deadwood Gulch thrusts also support an inference of pre-Tendoy basement uplift. Support for thin-skinned thrusting following basement uplift includes NW-trending fault-propagation folds along the length of the Tendoy thrust sheet and the geophysical evidence of basement structures beneath the Tendoy sheet. The prominent lateral ramp at the southern terminus of the Tendoy thrust is also a result of the thrust cutting through previously folded stratigraphy. However, folding of the thin-skinned thrusts, such as the Middle Fork syncline and the parallel-folded thrust faults across Birch Creek culmination, indicates continued uplift of the Blacktail–Snowcrest after emplacement of thin-skinned thrusts. Therefore, movement of basement and thin-skinned structures in southwestern Montana was contemporaneous.

Impingement of décollement thrusts against foreland structures in the Tendoy Mountains resulted in structures that can be found throughout the overlap province: (1) formation of frontal, lateral, or oblique ramps, such as those mentioned at the terminus of the Tendoy thrust sheet and around the Birch Creek culmination; (2) anomalous fault relationships, including younger-over-older thrust faults, thrusts that cut down section in the direction of transport, or out-of-sequence thrust faults like the Deadwood Gulch thrust; and (3) changes in thrust fault orientation and transport direction where the fault ramped over anticlinal hinges, such as the abrupt change in strike of the Tendoy thrust and the evidence of NW-directed transport at Lima Peaks (Beutner, 1977; Kulik and Schmidt, 1988).

Unlike other areas of the overlap province, the Tendoy Mountains contain significant along-strike stratigraphic variations that partly controlled the manner in which the thin-skinned thrust sheets responded to impingement against the Blacktail–Snowcrest uplift. Specifically, the increased thickness and shale content of the Conover Ranch Formation in the keel of the Snowcrest Trough provided an ideal detachment horizon for the out-of-sequence Deadwood Gulch thrust fault. Tectonic thickening of the Conover Ranch by the Deadwood Gulch thrust accentuated the competency contrast between it and the stratigraphically thickened Quadrant Sandstone, promoting development of the massive Lima Peaks folds.

Out-of-sequence thrust faults may form in response to an oversteepened frontal ramp on which thrust movement becomes 'locked' (Schmidt *et al.*, 1988). In the southern Tendoy Mountains, oversteepening may have been caused by continued movement of the Blacktail–Snowcrest uplift or by emplacement of the sub-Tendoy blind thrusts, whose lateral extent was controlled by the location of basement structures. In either case, existence of the Blacktail–Snowcrest uplift either directly or indirectly promoted development of an out-of-sequence thrust fault, and the Conover Ranch Formation was stratigraphically the next available detachment horizon above the Lombard Limestone–Kibbey Formation contact.

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