Complex Pre-Lewis Thrust Deformation, Southeastern Glacier Park, Montana

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ABSTRACT

A complex structural association, the frontal zone, was mapped along the eastern edge of the presently preserved Lewis thrust sheet in southeastern Glacier National Park, Montana. This structural association was developed by multiple episodes of faulting and folding. In contrast to most structures in the Lewis thrust sheet, structures in the frontal zone are truncated by the underlying Lewis thrust, suggesting that the evolution of the frontal zone predates the Lewis thrust in the study area. Although the absolute age for the development of the frontal zone is not known, the trends of folds and faults are compatible kinematically with structures related to evolution of the Lewis thrust system, suggesting the zone was related to emplacement of the Lewis thrust sheet. Kinematic reconstruction of the frontal zone indicates that its formation was characterized by (1) conjugate contraction faulting, (2) west-directed, bedding-parallel faulting, and (3) top-to-the-east simple shear that rotated primary, east-dipping contraction faults to apparent west-dipping normal faults.

INTRODUCTION

Our understanding of thrust kinematics has been significantly improved in the past three decades (e.g., Bally et al, 1966; Dahlstrom, 1969, 1970; Price, 1981; Boyer and Elliott, 1982; Davis et al, 1983; Suppe, 1983; Woodward et al, 1985). Such an improvement was achieved by the interaction of four approaches: systematic field mapping, seismic-reflection studies, theoretical modelling, and cross-section balancing. A major assumption in most cross-section balancing techniques is that the sole fault below a thrust plate is a boundary above which deformation occurs in a closed system without any mass addition or subtraction during emplacement of the thrust sheet. Recent geologic mapping along the eastern edge of the presently preserved Lewis thrust sheet in southeastern Glacier National Park, Montana, reveals a suite of complexly deformed structures which is truncated by the Lewis thrust below, indicating that the volume of deformed rock above the Lewis thrust is not conserved locally. The purpose of this paper is to describe in detail the geometry of this local structural complex and present a kinematic model for its development.

GEOLOGIC SETTING

The Lewis thrust fault, first recognized by Willis (1902), is one of the best described thrust faults in the world. The fault has been cited in textbooks (e.g., Suppe, 1985, p. 283; Hatcher, 1990, p. 202), field-trip guidebooks (e.g., Gordy et al, 1977), and numerous papers (e.g., Rubey and Hubbert, 1959; Dahlstrom, 1970; Boyer and Elliott, 1982; Price, 1988) as a classic example to illustrate the geometry, kinematics, and mechanics of large-scale thrust faults.

The Lewis thrust is a major Late Cretaceous and/or early Tertiary structural element in the Cordilleran foreland fold and thrust belt of the southern Canadian Rockies (Fig. 1; Bally et al 1966; Dahlstrom, 1970; Price and Mountjoy, 1970; Price, 1981; Harrison et al, 1980) and western Montana (Mudge and Earhart, 1980, 1983). Total shortening of about 200 km (124 mi) along a detachment between Middle Proterozoic to Paleozoic supracrustal rocks and Precambrian crystalline rocks has occurred across this part of the foreland fold and thrust belt (Price, 1981). A significant proportion of this shortening was accommodated by a single dislocation surface, the Lewis thrust fault. Near the international boundary, the Lewis thrust displaced the Proterozoic Belt Supergroup at least 60 km (37 mi) over Cretaceous sedimentary rocks in its footwall (Price, 1962; Bally et al, 1966).

In his pioneering work on the Lewis thrust, Willis (1902) recognized widespread low-angle bedding-parallel faults within the Lewis thrust sheet (Willis, 1902, p. 335). At Chief and Yellow Mountains in northwestern Montana, he noted that minor steeply dipping thrusts are bounded above by a major bedding-parallel fault and below by the Lewis thrust. Similar structures were observed in the Lewis thrust sheet by Douglas (1952) in the Waterton area, Canada, by Fermor and Price (1976, 1987) in the Cate

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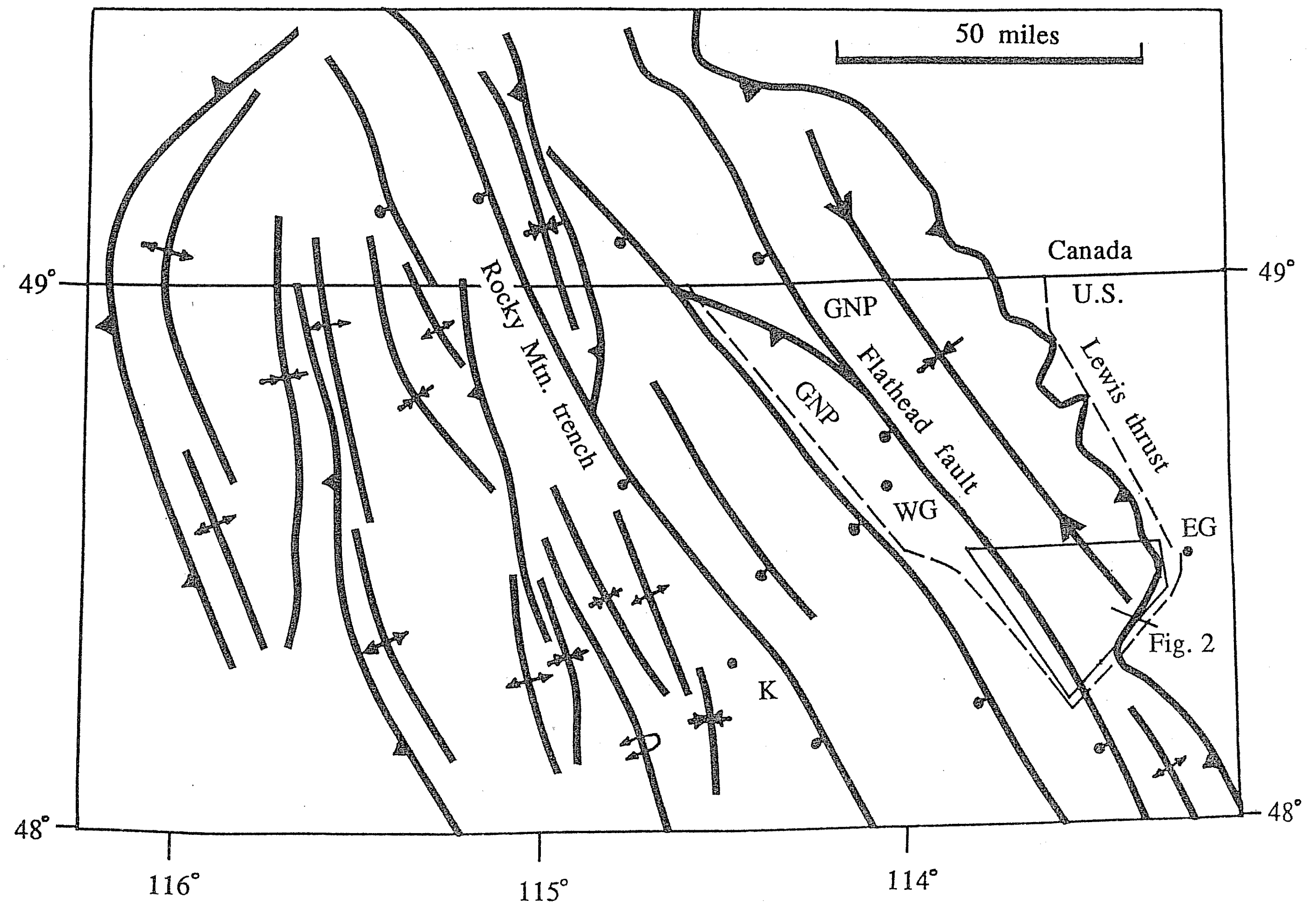


Figure 1. *Regional map of the Lewis thrust and adjacent structures after Dahlstrom (1970), Price (1981), and Harrison et al (1980), showing location of Figure 2; GNP, Glacier National Park; EG, East Glacier; WG, West Glacier; K, Kalispell.*

Creek and Haig Brook areas in southeastern British Columbia and southwestern Alberta, and by Davis and Jardine (1984) in the Yellow Mountain area in northeastern Glacier National Park. The structural associations described by Willis and Douglas were later cited as examples of duplex fault zones (Dahlstrom, 1970).

The most complete summary of the geology of the Lewis thrust sheet in Glacier National Park was presented by Ross (1959), who described the stratigraphy and gross structural framework. Although some local structural complexities were described, the overall structure of the Lewis thrust sheet was considered to be a simple, broad syncline with little internal deformation. This conclusion apparently influenced later structural syntheses of this area (e.g., Mudge, 1977, 1982; Gordy et al, 1977; Boyer and Elliott, 1982).

Systematic mapping at a scale of 1:24,000 was conducted along the east and south sides of the park by G. A. Davis (unpublished map), Jardine (1985), Kelty (1985), Hudec (1986), Yin (1988), and M. Winn (unpublished map) as part of a USGS project to update the geology of the park. This work has revealed that the portion of the Lewis thrust sheet in Glacier Park is in fact complexly deformed. Yin et al (1989) and Yin and Kelty (in press) have discussed the geometry and kinematic evolution of series of duplexes and bedding-parallel faults lying above the Lewis thrust fault on the south side of the park. Davis and Jardine (1984), Yin and Davis (1988), and Hudec and Davis (in press) have discussed complex geometries and kinematic evolution of structures along the base of the Lewis thrust sheet on the east side of the park. Hudec (1986), Yin and Davis (1988), and Hudec and Davis (in press) observed that structures along the eastern edge of the Lewis thrust sheet are truncated by the Lewis thrust below. They have attributed this relationship to multiple-phase development of a sole thrust *system* that was responsible for emplacement of the Lewis thrust sheet.

GEOMETRY

The structural framework of the Lewis thrust sheet in southern Glacier National Park is shown in Figure 2. The Lewis thrust juxtaposes the Proterozoic Belt Supergroup in its hanging wall with the Cretaceous sedimentary rocks in its footwall. The stratigraphy of the Belt Supergroup in Glacier Park was described by Whipple et al (1984). Detailed stratigraphy of the Belt strata in southern Glacier National Park was also described by Kelty (1985) and Yin (1988). From older to younger, the Belt Supergroup in Glacier National Park consists of Altyn, Prichard,

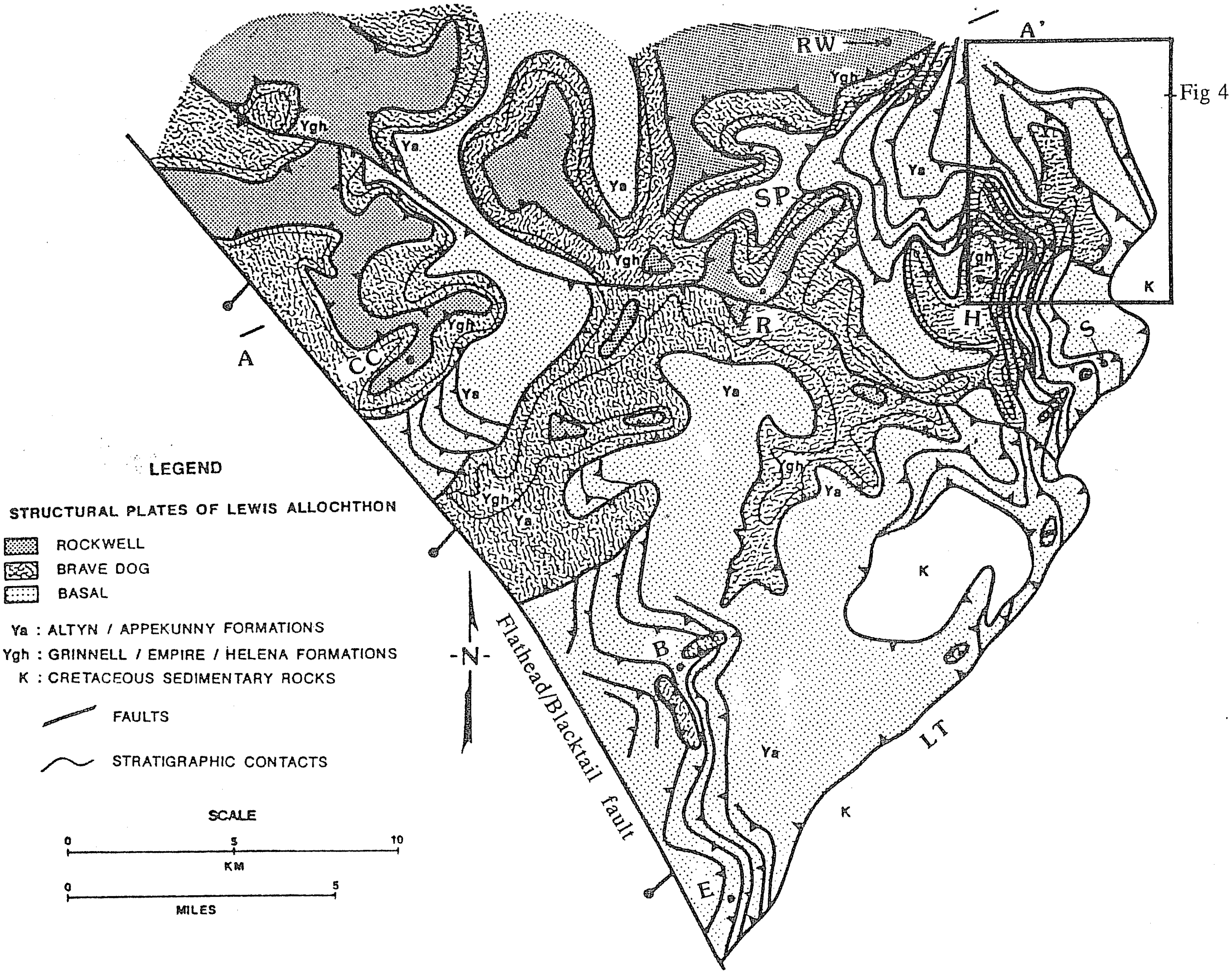


Figure 2. *Simplified geologic map of southern Glacier National Park (after Yin et al, 1989) and location of Figure 4. E, Elk Mountain; B, Brave Dog Mountain; H, Mt. Henry; R, Mt. Rockwell; S, Squaw Mountain; SM, Summit Mountain; SP, Scenic Point; CC, Cloudcroft Peaks; RW, Rising Wolf Mountain; LT, Lewis thrust, BF, Blacktail fault; LWF, Lone Walker fault.*

Appekunny, Grinnell, Empire, Helen, Mt. Shields, and Bonner Quartzite formations (Fig. 3).

The study area is located in the southeastern corner of Glacier National Park (Figs. 2, 4a). In order to map the detailed structures in the Lewis thrust sheet, the Appekunny Formation is further divided into four informal members in the study area (Yap1-4 in Figs. 4a, 4b), which are separated by four laterally continuous quartz arenite units of marker beds C, D, and E (Yin, 1988).

The frontal zone is bounded by the Rising Wolf Mountain duplex to the west and the trace of the Lewis thrust to the east. In general, the intensity of deformation in the frontal zone increases eastward. The western part of the frontal zone is characterized by gentle to open symmetric folds which are widely spaced (several hundreds of meters apart) and contraction faults (McClay and Price, 1981) dipping both to the west and east (Figs 4a, 4b), on which the displacement ranges from 15 to 50 m (49-164 ft). The eastern part is much more complex and is characterized by west-dipping (synthetic) and east-dipping (antithetic) contraction faults with displacement of 50 to 150 m (164-492 ft), west-directed bedding-parallel faults, open to tight west-verging concentric folds, and apparent west-dipping normal faults (see discussion below). The presence of west-directed contraction faults in the Lewis thrust sheet is unique in southern Glacier Park because faults there are dominantly east-directed. Minor west-directed contraction faults in the Lewis thrust sheet have also been documented in the northwestern part of the Cate Creek window, southeastern British Columbia (Price, 1965; Fermor and Price, 1987), although their structural significance has not received much attention.

Most faults in the frontal zone strike approximately N25°W, sub-perpendicular to the transport direction of the Lewis thrust (Fig. 5a). The dip angles of the faults vary from 10° to 50° (Fig.

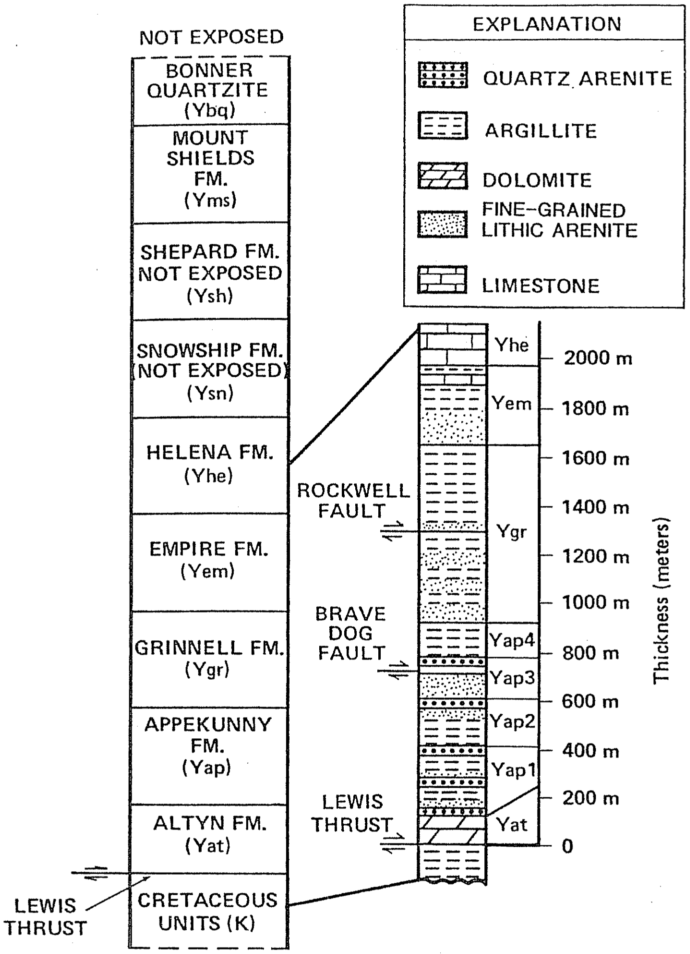


Figure 3. *Generalized stratigraphy of Belt Supergroup in southern Glacier National Park after Whipple et al (1984), Kelty (1985), and Yin (1988).*

5a). Hinges of mesoscopic-scale folds are shown in Figure 5b. The trend of folds and the strike of faults in the frontal zone are compatible with other structures that are associated with emplacement of the Lewis thrust sheet (e.g., the Brave Dog and Rising Wolf Mountain duplexes; Yin et al, 1989) (Fig. 2).

Eastern Frontal Zone

The complexity of the eastern frontal zone is evident in a cross-sectional exposure (Fig. 6; see Fig. 4 for location). This N50°E-S50°W section is sub-parallel to the direction of tectonic transport of the Lewis thrust (N65°±10°E; Yin, 1988) inferred from striations measured on the Lewis thrust surface. The cliff-forming unit in the lower part of Figure 6 is the Altyn Formation, which is separated by the Lewis thrust from the slope-forming Late Cretaceous Marias River Shale below, described by Mudge and Earhart (1983). Three quartz arenite units of the Appekunny Formation exposed in this area are named marker beds A, B, and C (MBA, MBB, and MBC in Fig. 6). MBA directly overlies the Altyn Formation. MBB is not clearly identified in Figure 6a due to its poor color contrast. It is, however, easily identified in the field and is sketched in Figure 6b. The thick cliff-forming unit in the upper part of Figure 6 is MBC.

In the eastern frontal zone, the Altyn Formation and the lower part of the Appekunny Formation are folded and overturned to the northeast. The major fold shown in Figure 6 is cut by a northeast-dipping fault system (faults B, C, D, and H) and two west-dipping, high-angle faults (faults E and F) which show a normal sense of displacement. The west-dipping high-angle faults (faults E and F) are terminated to the west by the northeast-dipping, contraction fault zone consisting of faults B, C, and D. Faults E and F can be either splays of fault D, or faults that were truncated and offset by the northeast-dipping fault zone (faults B, C, and D). The positions of the two faults in the footwall of the northeast-dipping fault zone can be predicted if fault E and F were indeed offset because the amount of displacement along the fault zone is precisely determined by the offset of marker bed C. The predicted faults were, however, not found in the footwall. Because of this relationship, faults E and F are interpreted to be the splays of the northeast-dipping contraction fault zone that consists of faults B, C, and D.

In the northeast-dipping fault zone, faults B and C are interpreted to correlate with faults B' and B" (Fig. 6b) because faults B, B', and B" sole into the upper part of MBA. Fault D is interpreted to correlate with faults D' and D" because they all lie along the top of MBA. Between faults C and D is a duplex-like structural complex. The northeast-dipping fault zone truncates fault A from above (Fig. 6b). MBA lies in the hanging wall of fault A but below the northeast-dipping fault zone. Both fault A and MBA are tightly folded. A reverse fault, fault H, is present in the hanging wall of the east-dipping fault zone. Fault H can be either the upper part of fault A that was displaced by the northeast-dipping fault zone, or a splay of the northeast-dipping fault zone like faults E and F in its hanging wall. It is interpreted that faults H and A were the same fault and were later offset by the east-dipping fault zone because the amount of displacement along faults A and H are similar (about 50-60 m [164-197 ft]). Fault A was folded and locked after it was offset by the east-dipping fault zone. Part of the kinematic model presented next (Fig. 7) is based on this interpretation.

Faults B, C, and D are cut by a west-dipping high-angle fault, fault G, which juxtaposes the Appekunny Formation in its hanging wall with the Altyn Formation in its footwall (Fig. 6). Fault G and beds in both the Appekunny and Altyn formations are cut by the Lewis thrust below. Several minor thrusts, faults I, J, and K, branched off the Lewis thrust, and offset older faults B" and D".

Minor splays of major east-dipping reverse faults show normal-fault geometry (e.g., faults E and F in Fig. 6). These faults are characterized by "drag" folds developed only in their footwalls. Because "drag" folds are commonly present in the hanging walls of reverse faults in the Lewis thrust sheet in the study area, the minor west-dipping normal faults are interpreted to have been rotated from original east-dipping reverse faults to become apparently west-dipping extension faults. Additionally, some east-dipping contraction faults change their dip directions along strike. For example, fault G in Figure 4 dips about 80° to the west on the east side of Bison Mountain, and shows a normal-fault geometry. It dips about 50° to the east on the northeastern corner of Head Mountain, 1.5 km (.9 mi) to the northeast, and exhibits a reverse-fault geometry. Because of this localization of normal-fault ge-

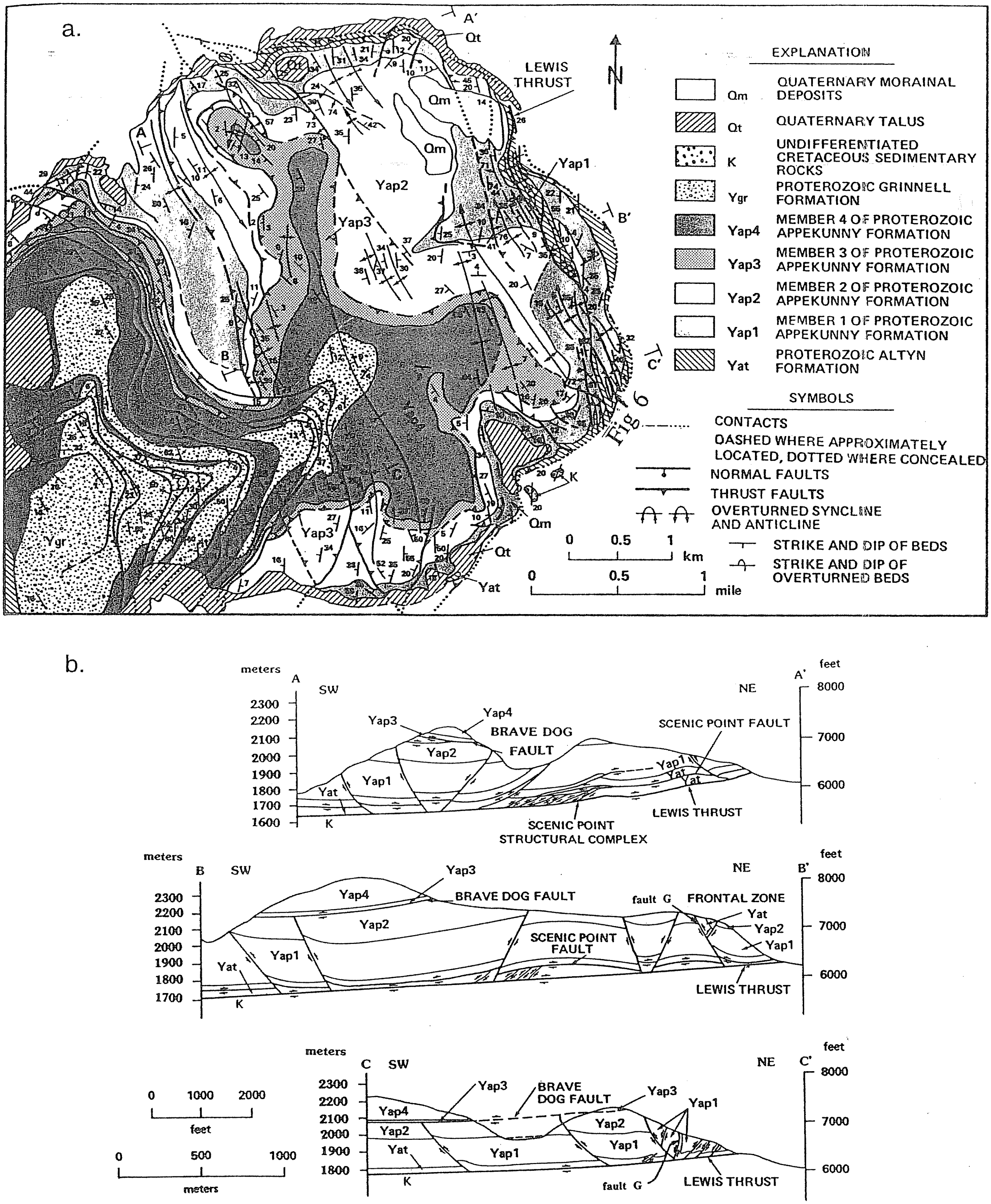


Figure 4. a: *Geologic map of northeastern part of study area and location of Figure 6a.* b: *Geologic cross sections through lines AA', BB', and CC'. Note that fault G dips to east in section BB' and west in section CC'. Absence of Scenic Point structural complex in section CC' is due to truncation by Lewis thrust.*

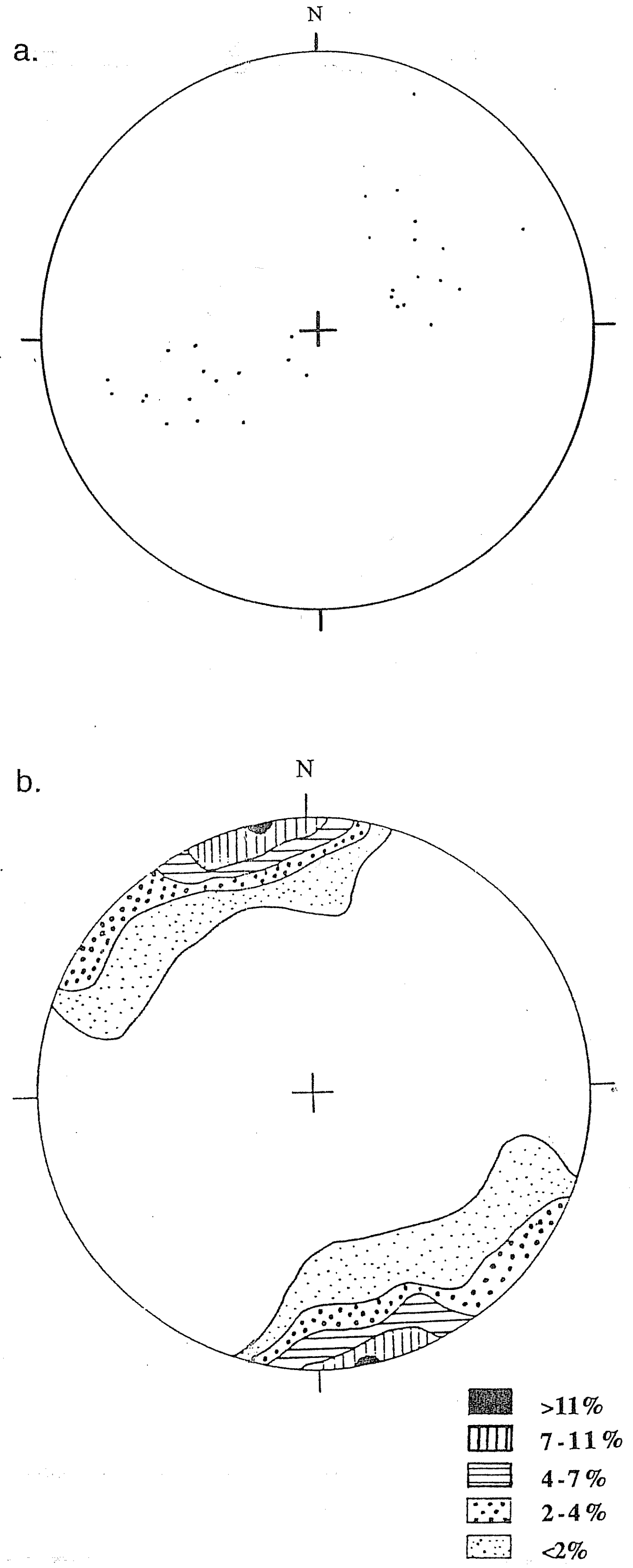


Figure 5. a: *Stereographic projection of poles of contraction faults in the frontal zone; n=32.* **b:** *Stereographic projection of fold hinges in the frontal zone; n=54.*

ometry, faults in the eastern frontal zone are interpreted to be primary east-dipping reverse faults that were rotated 30-40° locally to an apparent normal fault geometry by top-to-the-east simple shearing. This argument is further supported by the field relation that fault G in the Bison Mountain area is in general parallel to the bedding in its present footwall and at a high angle to the bedding in its hangingwall, a geometry consistent with an east-dipping listric reverse fault, but inconsistent with a west-dipping normal fault. Other evidence for simple shear deformation during evolution of the Lewis thrust system, including numerous bedding-parallel faults and east-verging intraformational folds above the Lewis thrust, and the geometry of duplexes bounded by the bedding-parallel faults, was presented by Yin et al (1989) and Yin and Kelty (in press). Although structures in the eastern part of the frontal zone may have been rotated, there is little evidence to suggest that the conjugate contraction faults in the western part of the frontal zone were affected by this rotational event. The difference in rotational strain in the frontal zone can be attributed to (1) the western and eastern parts of the frontal zone having formed at different times (one predates and the other postdates the rotation), and (2) the eastward subhorizontal shearing being distributed inhomogeneously.

Western Frontal Zone

The western frontal zone is characterized by reverse faults that dip both to the west and east and symmetric open folds (Fig. 4b). The faults commonly occur as conjugate sets and exhibit planar geometry. Listric reverse faults were, however, locally observed. The structures in the western frontal zone together with the Scenic Point structural complex (see Yin (1988) for detailed descriptions) are truncated from below by the Lewis thrust. This results in the unbalanced geometries of cross sections in Figure 4b. A similar truncational relationship between conjugate reverse faults and the Lewis thrust fault along the eastern edge of the Lewis thrust sheet were also observed in the Mad Wolf Mountain area 7 km (4.35 mi) north of the study area by Davis (personal communication, 1984) and in the Spot Mountain area by Hudec (1986). The crosscutting relationship between the Lewis thrust and structures in the western frontal zone support the interpretation that here the formation of this portion of the Lewis thrust postdates development of the frontal zone.

KINEMATICS

The geometrical relationships discussed above provide a foundation for the kinematic reconstruction of the frontal zone. Figure 7 consists of a series of diagrams which attempt to restore deformation history of the frontal zone based on the geometry and crosscutting relationships shown in Figure 6. The major assumptions in the kinematic model presented in Figure 7 are (1) the thicknesses of stratigraphic units are constant, and (2) flexural folding is the principal mechanism during the development of folds in the frontal zone. Field observations indicate that these assumptions are justified.

At the initial stage, a west-directed fault (fault A) developed along the base of MBA. This fault cut upsection abruptly through the lower part of the Appekunny Formation to the southwest

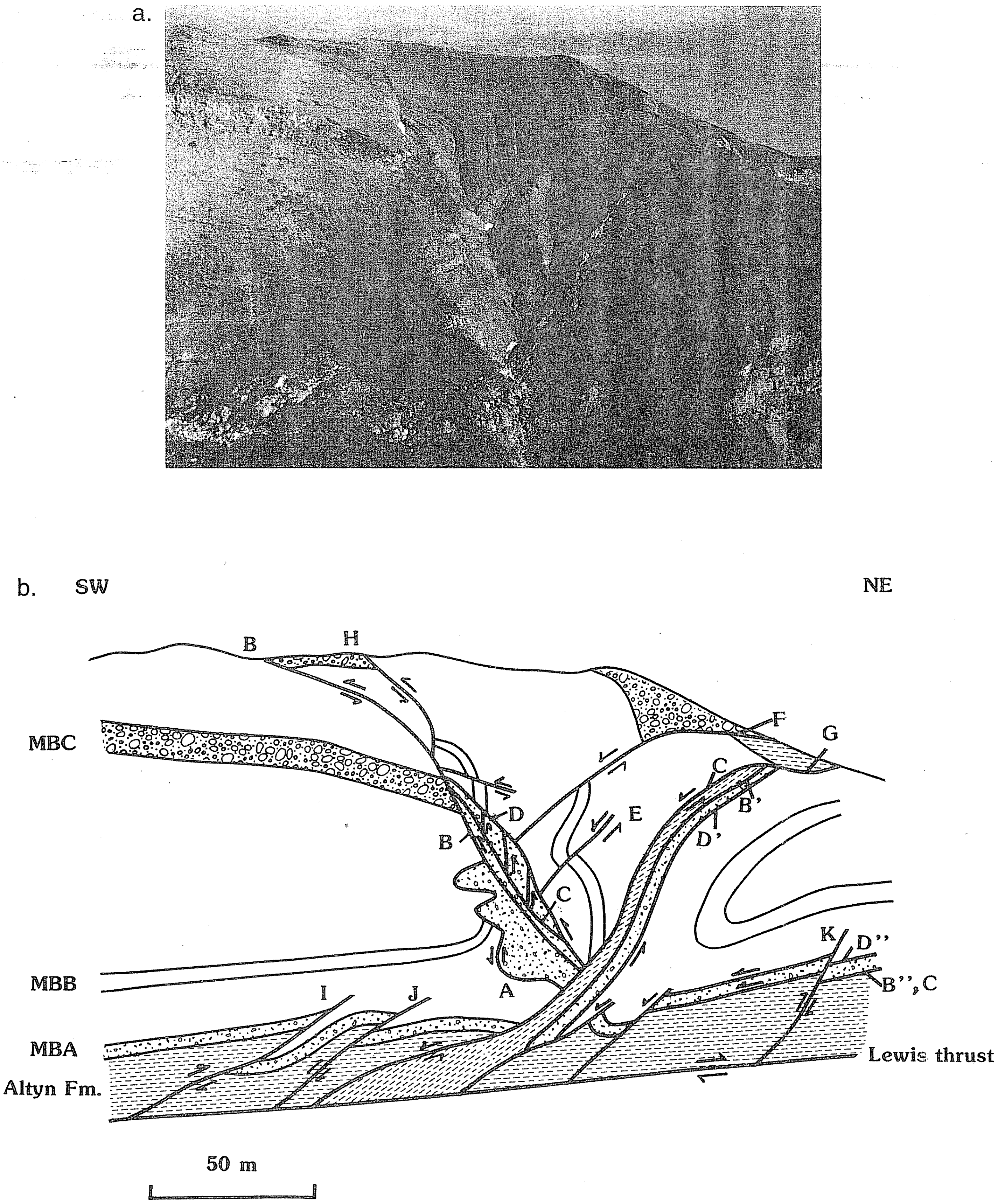


Figure 6. a: *View of structures in frontal zone from southeast, east side of Bison Mountain. See Figure 2 for location.* **b:** *Sketch of structures shown in a. Faults are labeled by letters from A to H. MBA, MBB, and MBC are marker beds in Appekunny Formation.*

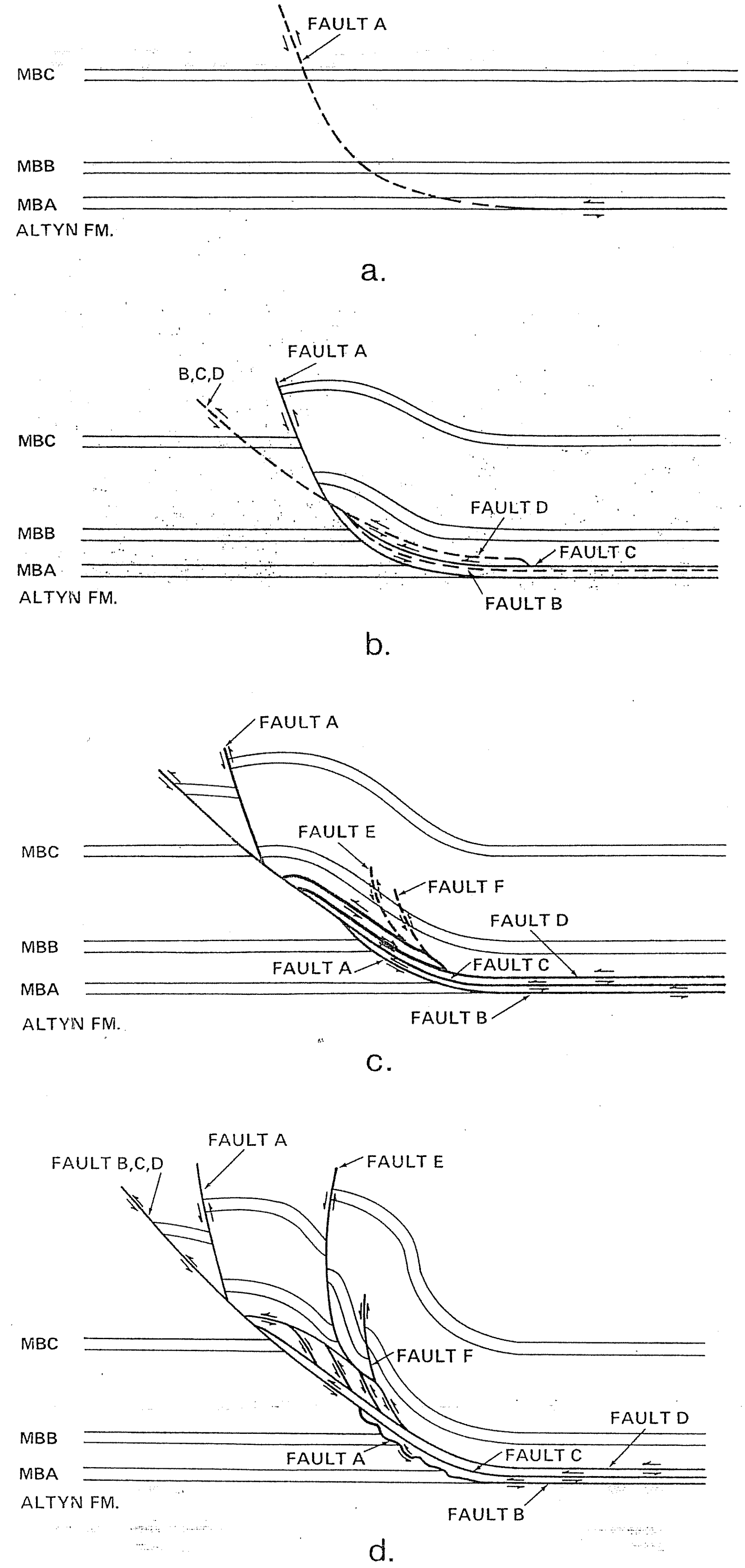
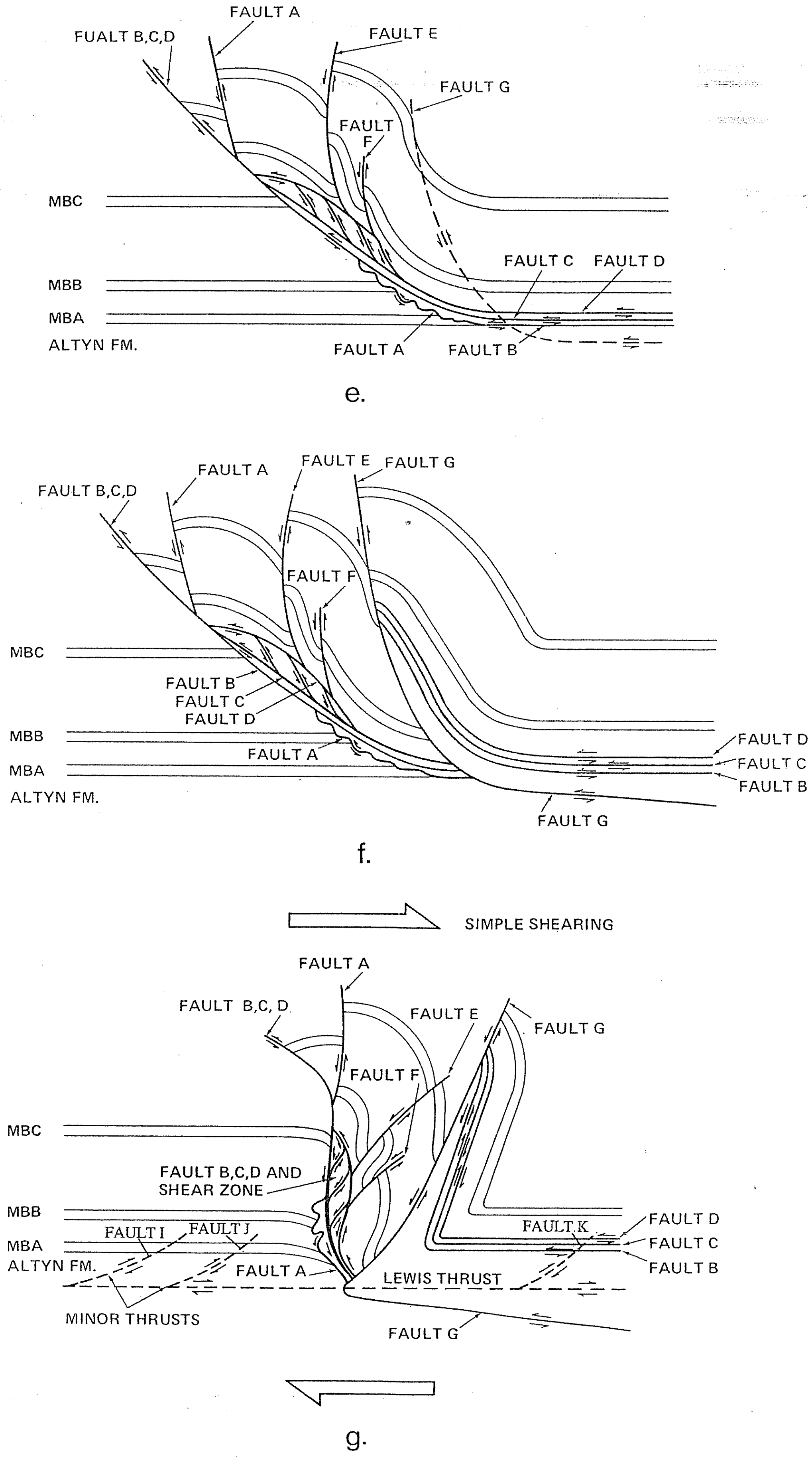


Figure 7a-k. *Kinematic model for development of frontal zone. See text for discussion.*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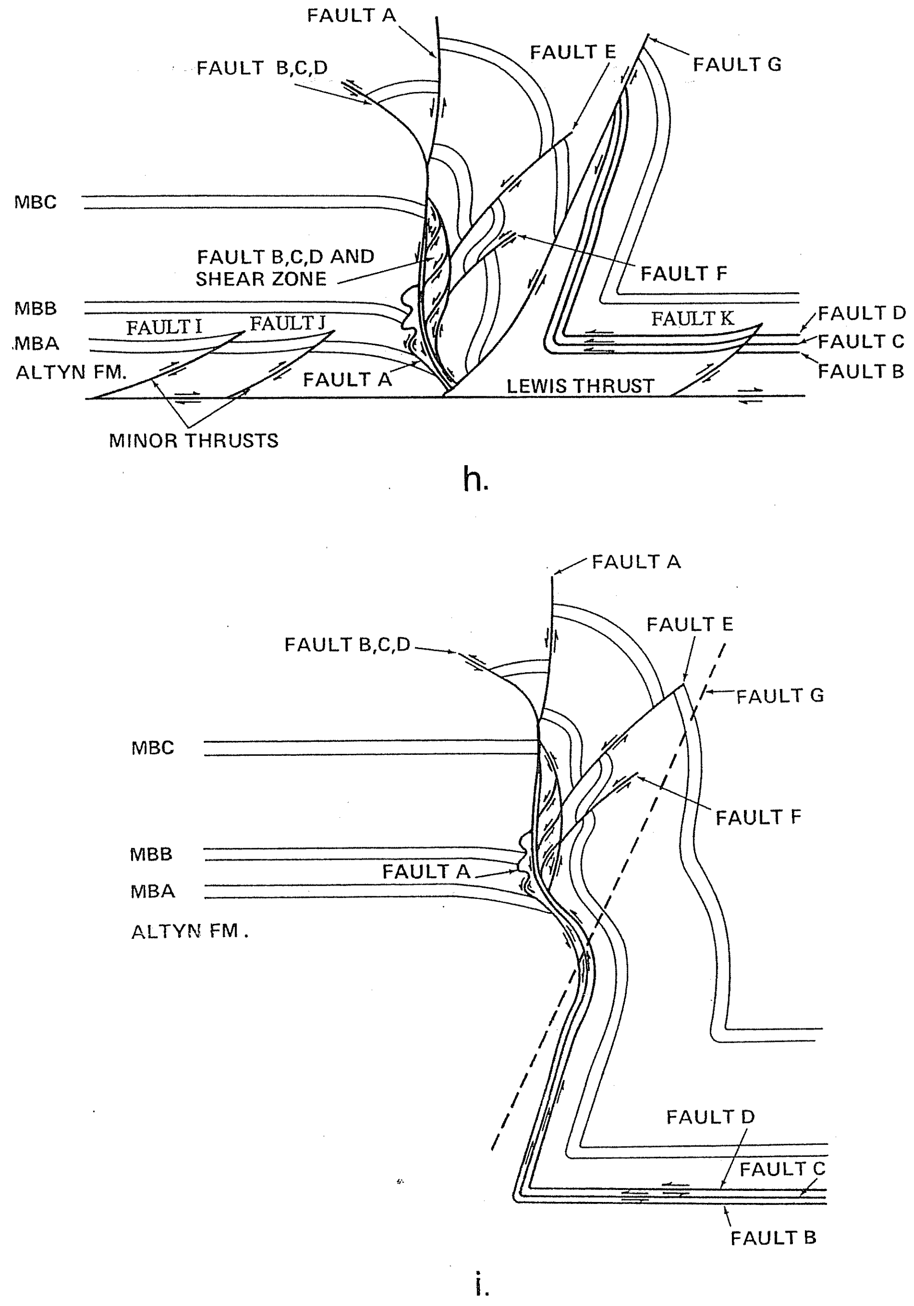
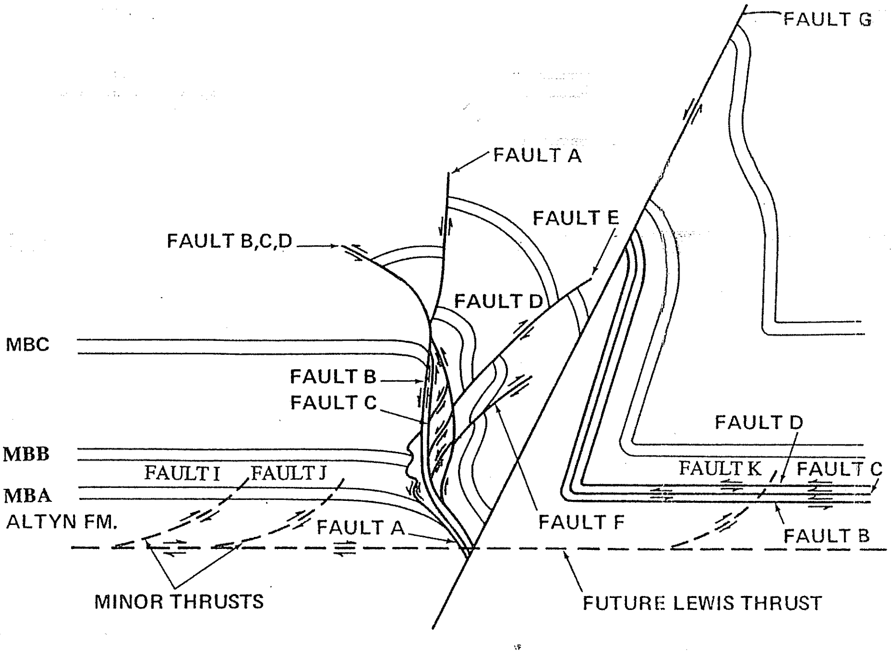


(Fig. 7a). This fault may sole into a bedding-parallel fault that is structurally lower than the present Lewis thrust surface, forming a triangle zone that is similar to those described by Price (1986) in the southern Canadian Rocky Mountains thrust belt. The formation of faults B, C, and D followed the development of fault A. These faults sole into the middle and top parts of marker bed A, and cut upsection to the southwest (Fig. 7b). Faults B, C, and D offset fault A (Fig. 7c). Faults B, C, and D merge upward with each other and produced a duplex-like structural complex between faults C and D (Fig. 7d). The order of deformation sequence for the formation of the three faults (B, C, and D) can be interchangeable.

Folding of the lower segment of fault A and MBA in the footwall of fault B (Fig. 7d) was caused by movement along fault B. It is also likely that fault A was tightly folded first and then truncated and displaced by fault B. This alternative interpretation is not favored because it is not compatible with the observed field relationships. First, fault A was offset by faults B, C, and D, and displacement along faults B, C, and D collectively. This is known based on offset of MBC. However, no tight folds adjacent to the offset part of fault A (fault H in Fig. 6) in the hangingwall of faults B, C, and D are present. The major open anticline in the hangingwall of faults B, C, and D, is probably the result of movement along the listric fault surfaces of faults B, C, and D.

Small splays of reverse faults, faults E and F, branched off from fault D (Figs. 7c, d). As faults E and F were transported along a listric fault (fault D), they were rotated to the east due to the curviplanar geometry of fault D. Such a rotation in addition to a possible late top-to-the-east simple shear (see discussion below) may have caused transformation of the primary east-dipping re-



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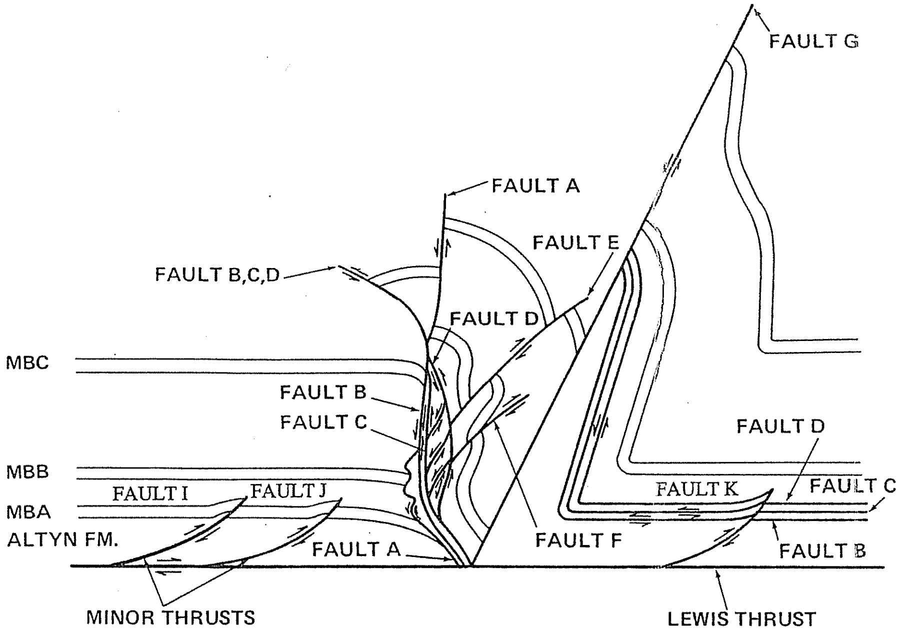

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verse faults (E and F) to apparent west-dipping normal faults. This interpretation explains the presence of (1) "drag" folds in the footwall of some west-dipping high-angle faults (faults E and F in Fig. 6), which is unusual in the Lewis thrust sheet in southern Glacier National Park, and (2) changes in dip directions (fault G) along strike in the frontal zone.

Two kinematic processes may have occurred following the development of faults E and F. First, fault G cuts faults B, C, and D (Figs. 7e, f). Similar to fault A, fault G may sole into a bedding-parallel fault below the present Lewis thrust surface. Fault G was then folded and rotated by east-directed bedding-parallel simple shear (Fig. 7g). The simple shear event rotated fault G to the east, creating an apparent normal fault geometry. The Lewis thrust fault cut this folded west-dipping contraction fault (fault G), and displaced its upper-plate portion to the northeast (Fig. 7h). Alternatively, the structures developed in the previous stages were folded and were later cut by a west-dipping high-angle extension fault, fault G (Fig. 7i). The west-dipping fault was in turn truncated and offset below by the Lewis thrust (Fig. 7j). Finally, the younger west-dipping thrust faults (faults I, J, and K) were developed following the formation of the Lewis thrust. They branched off from the Lewis thrust, forming synkinematically with movement along the Lewis thrust. The first kinematic interpretation is preferred because it not only explains the rotation of structures shown in Figure 6, but the change in the dip directions along some faults (e.g., fault G) in the frontal zone. In addition, stretching mineral lineations defined by quartz on bedding surfaces and east-verging mesoscopic folds which are common in the frontal zone could be the result of bedding-parallel simple shearing.

The kinematic model presented above is mainly based on crosscutting relationships observed in the eastern part of the frontal zone. As discussed above, there is little evidence indicating that the conjugate contraction faults in the western frontal zone were rotated. If we assume that the rotational strain was homogeneous throughout the frontal zone, then the western frontal zone must postdate the rotational event, and therefore, it must postdate the formation of the eastern frontal zone. If the rotational strain is heterogeneous, then the entire frontal zone could have formed at the same time and predate the rotational event. The deformation of the frontal zone predates the Brave Dog fault, which lies structurally above the Lewis thrust, because the Brave Dog fault truncates structures in the frontal zone (Fig. 4; also see Yin, 1988).

DISCUSSION

The truncational relationship between structures in the frontal zone and the Lewis thrust suggests that the formation of the frontal zone was not directly related to movement along the presently exposed Lewis thrust, and that its development predates the formation of the Lewis thrust in the study area. The absolute age for the development of these pre-Lewis structures is not known. However, as discussed above, the trend of structures and kinematic indicators are compatible with the transport direction of the Lewis thrust and are therefore probably related to the Lewis thrust *system*. This relationship implies that emplacement of the Lewis thrust sheet was probably, but not necessarily, accommodated along a family of slip (fault) surfaces that were not active all at once. If this interpretation is correct, it implies that the frontal zone was formed along one of such fault surfaces that lies structurally below the presently exposed Lewis thrust. The truncational relationship between the Lewis thrust and structures in the frontal zone indicates that the Lewis thrust is probably an out-of-sequence thrust. The volume of rock in the Lewis allochthon above the Lewis thrust was not conserved: the Lewis thrust translated eastward a portion of the frontal zone and left the remainder somewhere in its footwall to the west. Complex evolution of a family of fault surfaces that may have been active at different times and were responsible collectively for the final position of thrust sheet emplacement, as discussed in this study and by Hudec and Davis (in press), should also be considered.

The high intensity of deformation and variety of deformation styles in the frontal zone contrasts strongly with deformation intensity and styles of other structural elements in the Lewis thrust system (Fig. 3). The kinematic reconstruction of the eastern frontal zone presented above indicates that a wedge-shaped thrust block was bounded above by a system of east-dipping contraction faults and below by an older sole thrust which lies structurally below the Lewis thrust and was responsible for the formation of the frontal zone.

Mechanisms for the rotation of structures in the frontal zone are conjectural. The rotation could have been related to emplacement of the Brave Dog plate along the Brave Dog fault. This interpretation is consistent with the fact that the Brave Dog fault postdates the frontal zone because it cuts structures in its western part. It, however, requires that the shear strain produced by emplacement of the Brave Dog plate was distributed heterogeneously, which caused differential rotation between the western and eastern part of the frontal zone.

CONCLUSIONS

In summary, the kinematic evolution of the frontal zone is characterized by the development of conjugate contraction faults in its western part and a complex east-dipping contraction fault system in its eastern part. Part or all of the frontal zone was later rotated by a top-to-the-east simple shear which may have been related to the emplacement of the Brave Dog thrust sheet above. The volume of rock in the Lewis thrust sheet above the Lewis thrust was not conserved: the Lewis thrust translated eastward a portion of the frontal zone and left the remainder somewhere in its footwall to the west. The truncational relationship between the Lewis thrust and structures in the frontal zone therefore suggests that the frontal zone predates the Lewis thrust in this area. Although the absolute age for the development of the frontal zone is unknown, the trend of folds and faults in the frontal zone is consistent with those developed synchronously with movement along the Lewis thrust system. This kinematic compatibility, in conjunction with the truncational relationships between the frontal zone and the Lewis thrust, suggests that evolution of the frontal zone was related to emplacement of the Lewis thrust sheet, which was accomplished by slip along a family of sole thrusts, active at different times and different structural levels.

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REFERENCES

Bally, A. W., P. L. Gordy, and G. A. Stewart, 1966, Structure, seismic data, and orogenic evolution of southern Canadian Rockies: Bulletin of Canadian Petroleum Geologists, v. 14, p. 337-381.

Boyer, S. E., and D. Elliott, 1982, Thrust systems: AAPG Bulletin, v. 66, p. 1196-1230.

Dahlstrom, C. D. A., 1969, Balanced cross sections: Canadian Journal of Earth Sciences, v. 6, p. 743-757.

______, 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geologists, v. 18, p. 332-406.

Davis, D., J. Suppe, and A. F. Dahlen, 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153-1172.

Davis, G. A., and E. A. Jardine, 1984, Preliminary studies of the geometry and kinematics of the Lewis allochthon, Saint Mary Lake to Yellow Mountain, Glacier National Park, Montana: Montana Geological Society, 1984 Field Conference Guidebook, p. 201-209.

Douglas, R. J. W., 1952, Preliminary map, Waterton, Alberta: Canadian Geological Survey Paper 52-10.

Fermor, P. R., and R. A. Price, 1976, Imbricate structures in the Lewis thrust sheet around the Cate Creek and Haig Brook windows, southeastern British Columbia: Geological Survey of Canada Paper 7-1B, p. 7-10.

______, ______, 1987, Multiduplex structure along the base of the Lewis sheet in the southern Canadian Rockies: Bulletin of Canadian Petroleum Geologists, v. 35, p. 159-185.

Gordy, P. L., F. R. Frey, and D. K. Norris, 1977, Geological guide for the Canadian Society of Petroleum Geologists: 1977 Waterton-Glacier Park Field Conference, Canadian Society of Petroleum Geologists, 93 p.

Harrison, J. E., M. D. Kleinfopt, and J. D. Wells, 1980, Phanerozoic thrusting in Proterozoic Belt rocks, northwestern United States: Geology, v. 8, p. 407-411.

Hatcher, R. D., 1990, Structural Geology: Principles, Concepts, and Problems: Merrill Publishing Company, Columbus, Ohio.

Hudec, M. R., 1986, Geology of a portion of the Lewis thrust plate north of Two Medicine Lake, Glacier National Park, Montana: M.S. thesis, University of Southern California, Los Angeles, 193 p.

______, and G. A. Davis, in press, Out-of-sequence thrust faulting and duplex formation in the Lewis thrust system, Spot Mountain, southeastern Glacier National Park, Montana: Canadian Journal of Earth Sciences.

Jardine, E. A., 1985, Structural geology along a portion of the Lewis thrust fault: M.S. thesis, University of Southern California, Los Angeles, 205 p.

Kelty, T. K., 1985, The structural geology of a portion of the Lewis thrust plate, Marias Pass, Glacier National Park, Montana: M.S. thesis, University of Southern California, Los Angeles, 226 p.

McClay, K. R. and N. J. Price, 1981, Thrust and Nappe Tectonics: Geological Society of London Special Publication 9.

Mudge, M. R., 1977, General geology of Glacier National Park and adjacent areas, Montana: Bulletin of Canadian Petroleum Geologists, v. 25, p. 736-751.

______, 1982, A resume of the structural geology of Northern Disturbed Belt, northwestern Montana, *in* R. B. Powers, ed., Geologic Studies of the Cordilleran Thrust Belt, Rocky Mountain Association of Geologists, p. 91-122.

______, and R. L. Earhart, 1980, The Lewis thrust fault and related structures in the disturbed belt, northwestern Montana: USGS Professional Paper 1174, 18 p.

______, ______, 1983, Bedrock geologic map of part of the northern disturbed belt, Lewis and Clark, Teton, Pondera, Glacier, Flathead, Cascade, and Powell counties, Montana: USGS, Miscellaneous Investigations series, Map I-1375.

Price, R. A., 1962, Fernie map area, east half: Alberta and British Columbia 82G, east half: Geological Survey of Canada Paper 61-24.

______, 1965, Flathead map-area, British Columbia and Alberta: Geologic Survey of Canada, Memoir 336.

______, 1981, The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains, *in* K. R. McClay, and N J. Price, eds., Thrust and Nappe Tectonics: Geological Society of London Special Publication 9, p. 427-446.

______, The southeastern Canadian Cordillera: thrust faulting, tectonic wedging, and delamination of the lithosphere: Journal of Structural Geology, v. 8, p. 239-254.

______, 1988, The mechanical paradox of large overthrusts: GSA Bulletin, v. 100, p. 1898-1908.

______, E. W. Mountjoy, 1970, Geologic structure of the southern Canadian Rocky Mountains between Bow and Athabasca: Riversa progress report: Geological Association of Canada Special Paper 6, p. 7-25.

Ross, C. P., 1959, Geology of Glacier National Park and Flathead region, northwestern Montana: USGS Professional Paper 296, p. 125.

Rubey, W. W., and M. K. Hubbert, 1959, Role of fluid pressure in mechanics of overthrust faulting: GSA Bulletin, v. 70, p. 188.

Suppe, J., 1983, Geometry and kinematics of fault bend folding: American Journal of Science, v. 283, p. 271-289.

______, 1985, Principles of Structural Geology, Prentice-Hall, Inc., Englewood Cliffs, p. 537.

Whipple, J. W., J. J. Connor, O. B. Raup, and R. G. McGimsey, 1984, Preliminary report on stratigraphy of the Belt Supergroup, Glacier National Park and adjacent Whitefish Range, Montana: Montana Geological Society, Field Conference Guidebook, p. 33-50.

Willis, B., 1902, Stratigraphy and structure, Lewis and Livingston ranges, Montana: GSA Bulletin, v. 13, p. 305-352.

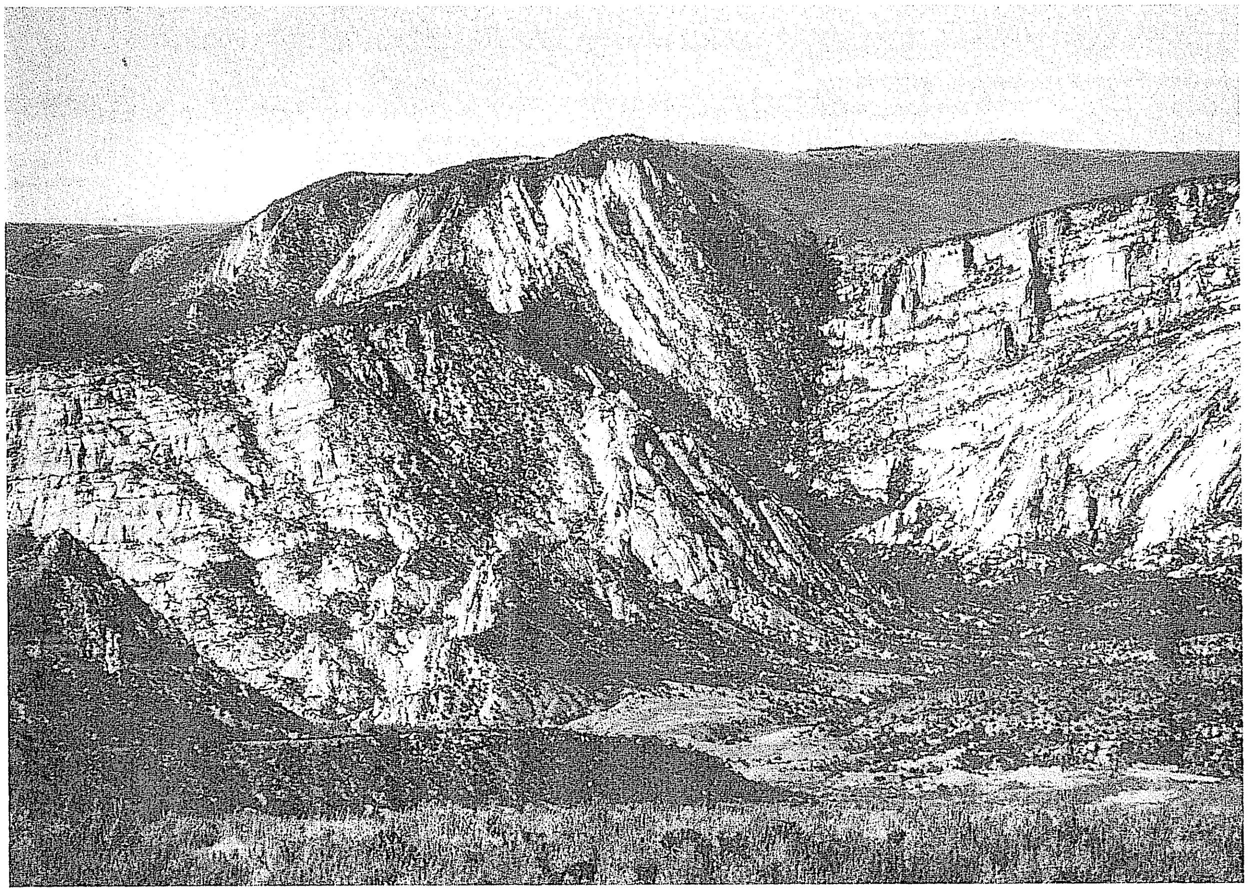
Woodward, N., S. E. Boyer, and J. Suppe, 1985, An outline of balanced cross-sections: University of Tennessee Department of Geological Sciences, Studies in Geology 11, Knoxville, 170 p.

Yin, A., 1988, Structural geology of the Lewis allochthon in a transect from Head Mountain to Peril Peak, southern Glacier National Park, Montana: Ph.D. thesis, University of Southern California, Los Angeles, 290 p.

———, and G. A. Davis, 1988, Complex deformation of the Lewis allochthon before the formation of the present Lewis thrust, SE Glacier National Park, Montana: GSA Abstracts with Programs, v. 20, p. A268.

______, T. K. Kelty, and G. A. Davis, 1989, Duplex development and abandonment during the evolution of the Lewis thrust system: Geology, v.17, p. 806-810.

______, and T. K. Kelty, in press, Development of normal faults during emplacement of a thrust sheet: an example from the Lewis allochthon, Glacier National Park, Montana (USA): Journal of Structural Geology.



Red Rock Anticline in Dinosaur National Monument. This sharp fold is probably faulted at depth and at its hinge on the skyline. Trail Draw Syncline to right.

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