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Structural evolution of the Lewis plate in Glacier National Park, Montana: Implications for regional tectonic development

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ABSTRACT

Detailed geologic mapping in southern Glacier National Park, Montana, reveals four episodes of deformation in the hanging wall of the Lewis thrust.

(1) Pre-Lewis thrust structures include west- and east-dipping imbricate thrusts, conjugate contraction faults, and west- and east-directed bedding-parallel faults. Although these structures are truncated from below by the Lewis thrust, their development was kinematically compatible with the emplacement of the Lewis plate. Thus, they may have formed during early stages of the emplacement of the Lewis plate.

(2) Syn-Lewis thrust structures include the Late Cretaceous-early Tertiary Lewis thrust, west-dipping duplexes, east-dipping normal faults, and the Akamina syncline, a broad fold that lies directly west of the Lewis thrust and extends northwestward for about 120 km from southern Glacier Park, western Montana, to southeastern British Columbia and southwestern Alberta, Canada. The development of the duplexes and the normal faults may have been related to east-verging simple-shear deformation during emplacement of the Lewis plate. The formation of the segment of the Akamina syncline in the study area was the consequence of development of the duplexes in the Lewis plate, because strata above the duplexes are concordant with the syncline. The syncline is, however, disconcordant with the Lewis thrust. This observation contrasts strongly with the well-established concordant relationship between the Lewis thrust and the Akamina syncline in its hanging wall in Canada, about 100 km north of the study area. We propose that the formation of the Akamina syncline on a regional scale was related to the development of duplexes and imbricate thrusts at two structural levels, one above and one below the Lewis thrust. During the development of these duplexes, the Lewis thrust transferred horizontal shortening laterally along the strike of regional compressional structures from its footwall in the Paleozoic-Mesozoic strata to its hanging wall in the Proterozoic strata. We speculate that development of the broad-fold belt, a major structure in the fold-and-thrust belt in the southern Canadian Rocky Mountains and western Montana, was related to duplex formation at deep structural levels below the folds.

(3) Post-Lewis thrust contractional structures include a high-angle reverse fault that cuts the Lewis thrust and strikes N70°W, which is about 30°–40° more to the west than the average strike of the syn-Lewis thrust structures. The development of this fault represents a change in compressional direction after emplacement of the Lewis plate.

(4) Post-Lewis thrust extensional structures include southwest-dipping normal faults. These faults truncate the post-Lewis thrust reverse fault and are part of the Eocene-Oligocene Rocky Mountain trench normal fault system.

INTRODUCTION

The Cordilleran foreland fold-and-thrust belt in the southern Canadian Rocky Mountains and northwestern Montana consists of two tectonic elements (Fig. 1): (1) an eastern imbricate-thrust belt and (2) a western broad-fold belt. Understanding the structural origin of the broad-fold belt is important, because it is situated between a magmatic belt to the west and the imbricate-thrust belt to the east. The magmatic and imbricate-thrust belts were speculated to have been related during their development (Burchfiel and Davis, 1975; Price, 1981). Debates have been centered on whether the crust below the broad-fold belt was significantly thickened during the overall development of the fold-and-thrust belt. Two models may explain the geometry of the broad folds: (1) the folds represent minor crustal shortening as expressed by their long wavelengths and low amplitudes and (2) the folds were related to thrusting at a deeper crustal level and were the results of significant crustal shortening by development of duplexes and fault-bent folds (Price, 1981; Cowan and Potter, 1986; Yoos, 1988; Yin and others, 1990). Our recent geologic mapping in the hanging wall of the Lewis thrust in southern Glacier National Park, Montana, suggests that formation of broad folds and development of duplexes were closely related. In this paper, we (1) describe crosscutting relationships among structural elements in the hanging wall of the Lewis thrust in southern Glacier Park, (2) present a kinematic model for its evolution, and (3) discuss tectonic implications of the structural relationship between the development of duplexes and the formation of broad folds in the hanging wall of the Lewis thrust.

The overall structure in the hanging wall of the Lewis thrust was considered to be a simple, broad syncline with little internal deformation (Ross, 1959; Mudge, 1977, 1982; Gordy and others, 1977; Boyer and Elliott, 1982). Recent geologic mapping along the east and south sides of Glacier Park reveals that the entire hanging

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wall of the Lewis thrust is complexly deformed. Davis and Jardine (1984), Yin and Davis (1988), Hudec and Davis (1989), and Yin (1991) have discussed complex geometries and kinematic evolution of structures along the base of the Lewis thrust sheet. Yin and others (1989) mapped major imbricate systems bounded above by east-directed bedding-parallel faults and below by the Lewis thrust in southern Glacier Park. Yin and Kelty (1991) described the presence of numerous east-dipping normal faults along the base of the Lewis thrust sheet in southern Glacier Park. In the following discussion and description, we refer to the hanging wall of the Lewis thrust as the "Lewis plate" and define the

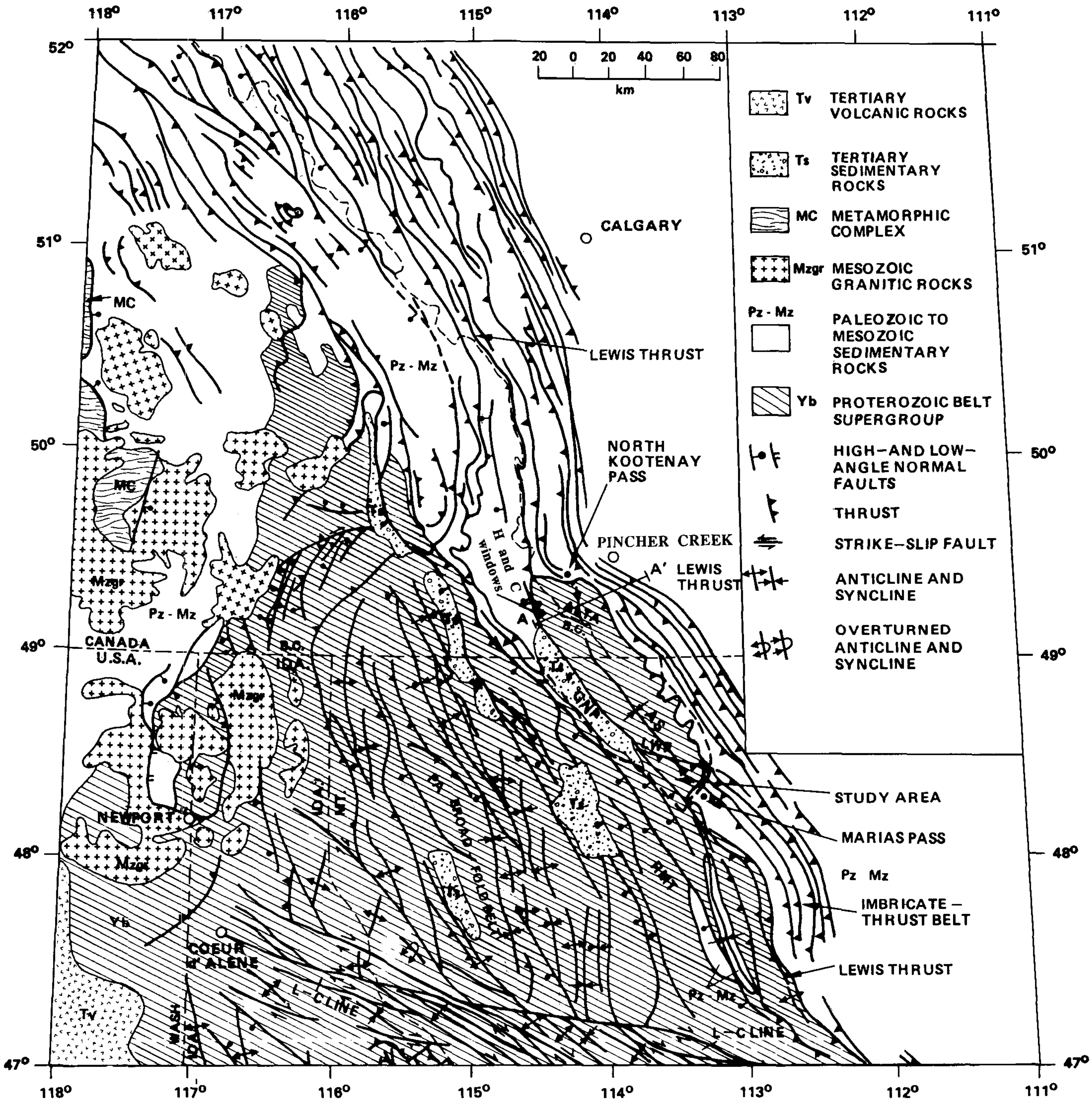


Figure 1. Geologic map of Cordilleran foreland fold-and-thrust belt in southern Canadian Rocky Mountains and northwestern Montana between 47°N to 52°N latitude, after Bally and others (1966), Dahlstrom (1970), Price (1981), Harrison and others (1974, 1980, 1986), Mudge and Earhart (1980, 1983). Location of Glacier National Park (outlined by dashed line) and study area. Fold-and-thrust belt consists of two elements: (1) eastern imbricate-thrust belt, which occurs mostly in Paleozoic and Mesozoic sedimentary rocks, and (2) a western broad-fold belt, which occurs mostly in Proterozoic Belt Supergroup. Cross section A–A′ shown in Figure 11. AS, Akamina syncline; GNP, Glacier National Park; H and C windows, Haig Brook and Cate Creek windows; L-C line, Lewis-Clark line; LWF, Lone Walker fault (new name from this study); PA, Purcell anticlinorium; RMT, Eocene-Oligocene Rocky Mountain trench normal fault system.

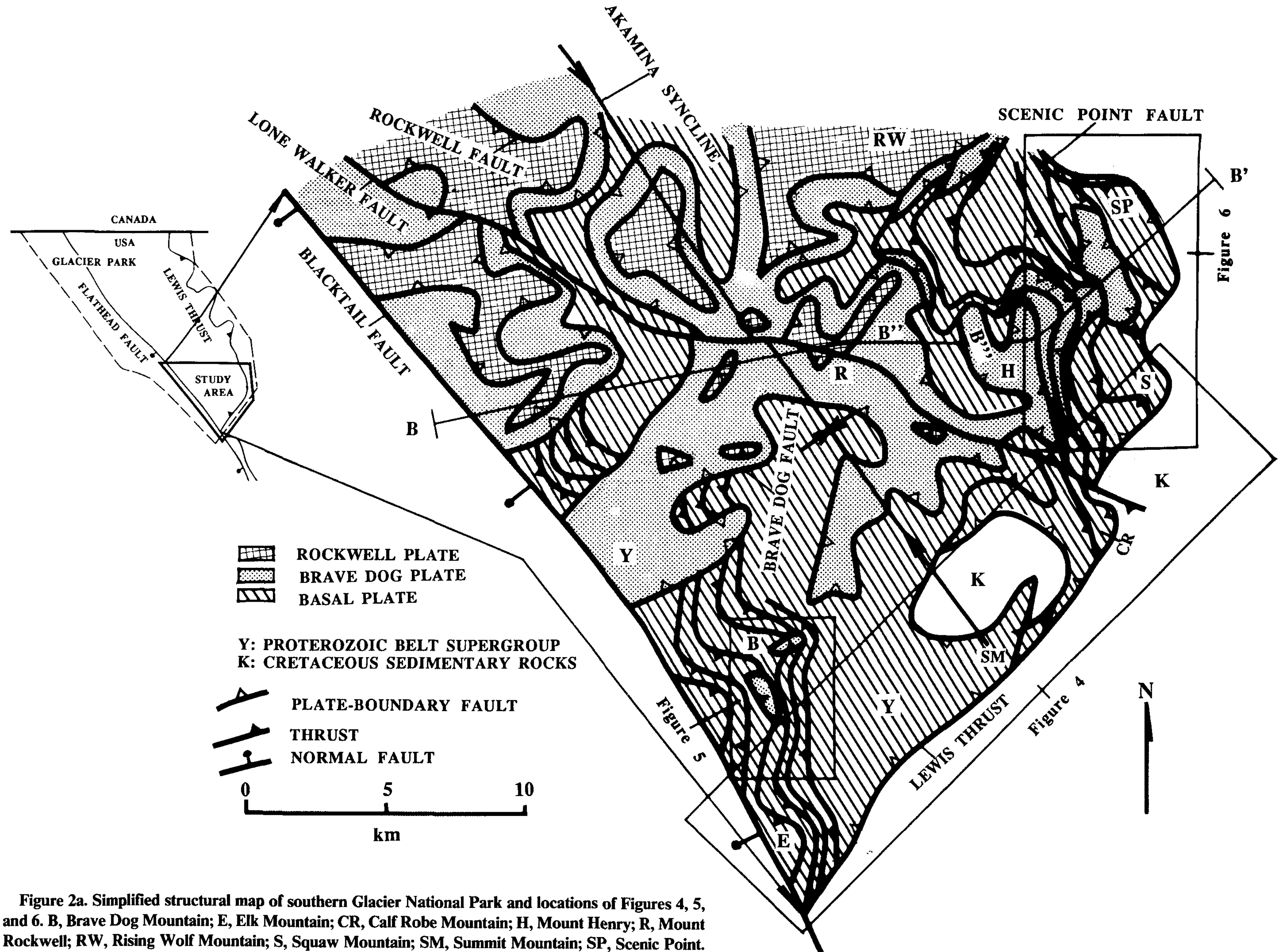


Figure 2a. Simplified structural map of southern Glacier National Park and locations of Figures 4, 5, and 6. B, Brave Dog Mountain; E, Elk Mountain; CR, Calf Robe Mountain; H, Mount Henry; R, Mount Rockwell; RW, Rising Wolf Mountain; S, Squaw Mountain; SM, Summit Mountain; SP, Scenic Point. Cross section B–B′ shown in Figure 2b (folded insert, this issue).

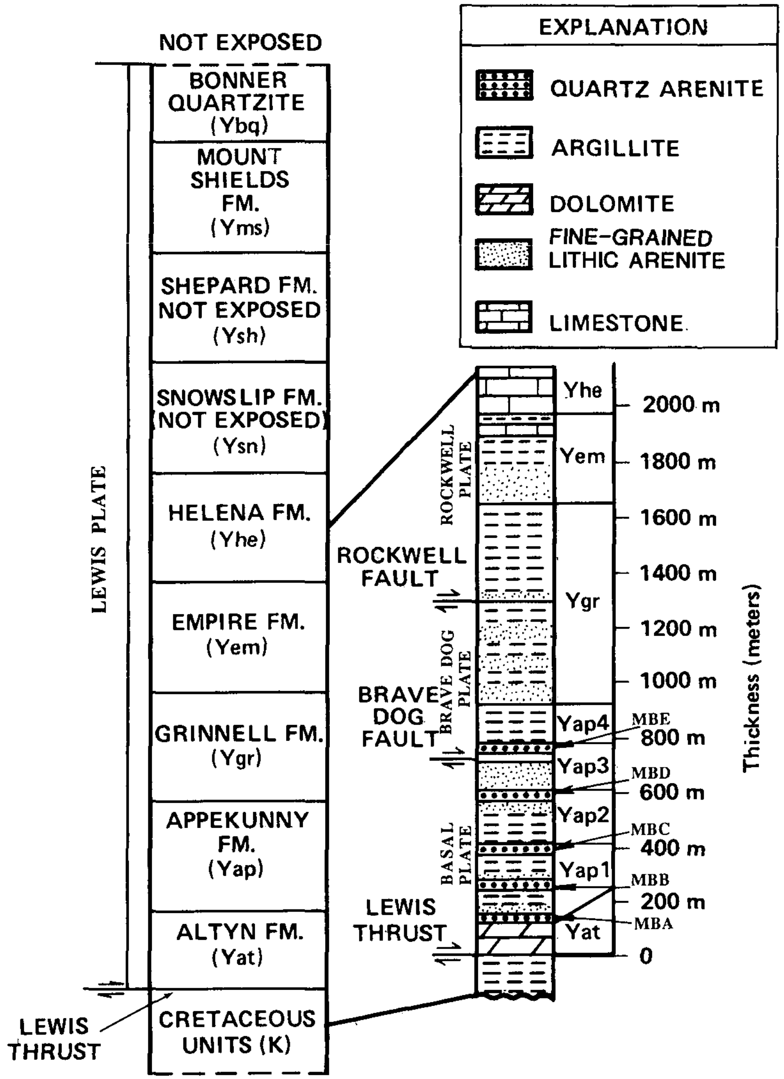


Figure 3. General stratigraphy of the study area. See Ross (1959), Childers (1963), Whipple and others (1984), Kelty (1985), Hudec (1986), and Yin (1988) for detailed descriptions of the Belt Supergroup in Glacier National Park. Left column represents general stratigraphy in Glacier National Park; right column represents stratigraphy in study area. MBA, MBB, MBC, MBD, and MBE are marker beds A, B, C, D, and E in Appekunny Formation. Yap1-4, member 1 through 4 in Appekunny Formation. Lewis plate is divided into three subplates: basal, Brave Dog, and Rockwell plates, which are separated by Lewis thrust, Brave Dog fault, and Rockwell fault.

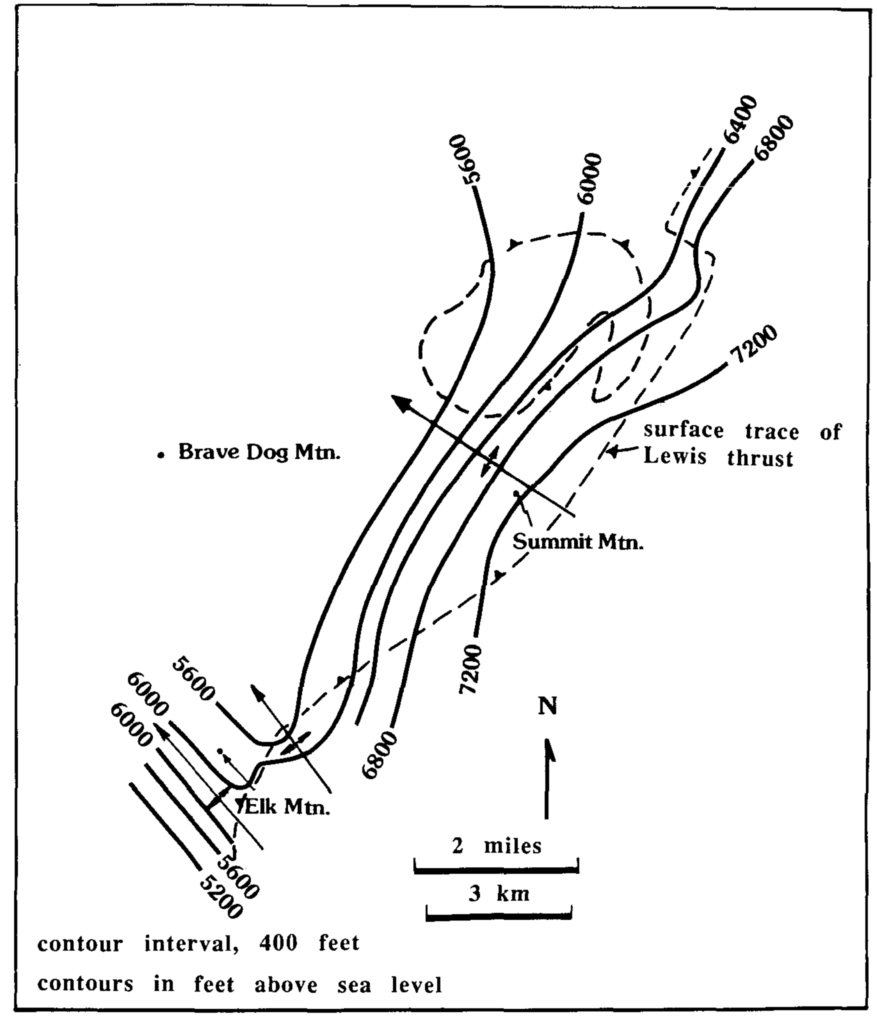


Figure 4. Structural contour map of the Lewis thrust, showing a gently northwest-dipping, oblique thrust ramp in southernmost part of study area. Dashed line, surface trace of the Lewis thrust; solid lines, contours of Lewis thrust surface. Contour interval, 400 ft; contours in feet above sea level. See Figure 2 for location. Construction of contours is based on surface trace of Lewis thrust and stratigraphic thicknesses of Altyn, Appekunny, and Grinnell Formations.

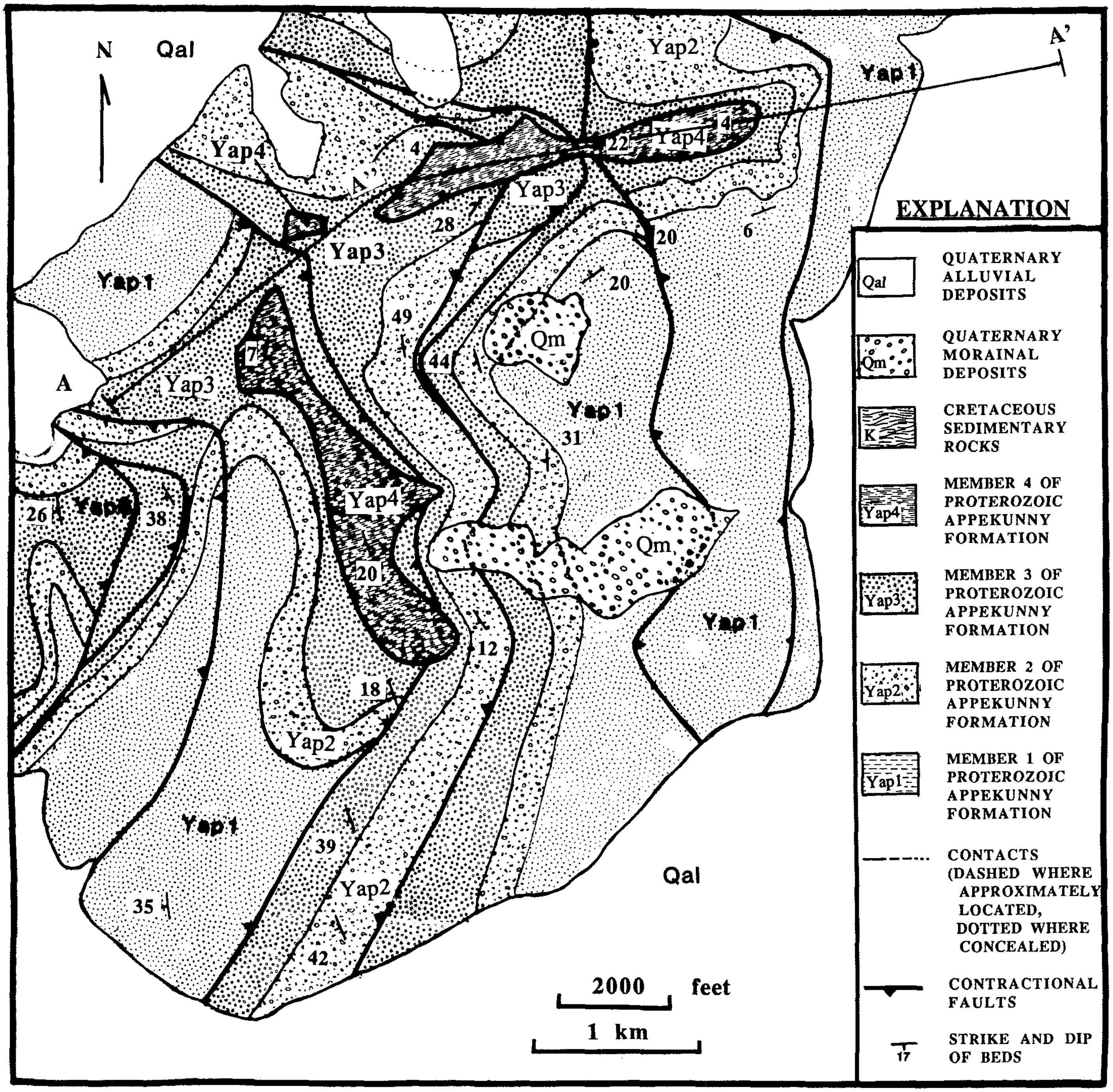


Figure 5a. Simplified geologic map of Brave Dog Mountain area after Kelty (1985). See Figure 2 for location.

Lewis thrust system as a structural association in which each element was kinematically related to emplacement of the Lewis plate.

STRATIGRAPHY

In the study area (Figs. 1 and 2[1]), the hanging wall of the Lewis thrust comprises strata of the Proterozoic Belt Supergroup that are thrust over Upper Cretaceous sedimentary rocks. The Upper Cretaceous rocks are not differentiated into different units because of the limited exposures. The Belt Supergroup in the study area consists of seven formations (Fig. 3): the Altyn, Appekunny, Grinnell, Empire, Helena, Mount Shields, and Bonner Quartzite (following the nomenclature of Whipple and others, 1984). The Mount Shields Formation and Bonner Quartzite, which form the upper part of the Belt Supergroup, are preserved only in the hanging wall of the Blacktail fault (Fig. 2b). The Blacktail normal fault is an Eocene-Oligocene normal fault and is equivalent to the Flathead normal fault in Canada (Constenius, 1982; Bally and others, 1966).

The Altyn Formation consists of as much as 100 m of dolomite, dolomitic limestone, sandy dolomite, and quartz arenite. It is overlain disconformably by the Appekunny Formation and is cut by the Lewis thrust below. The stratigraphy of the Altyn Formation in the study area

[1]Figure 2b is a folded insert in this issue.

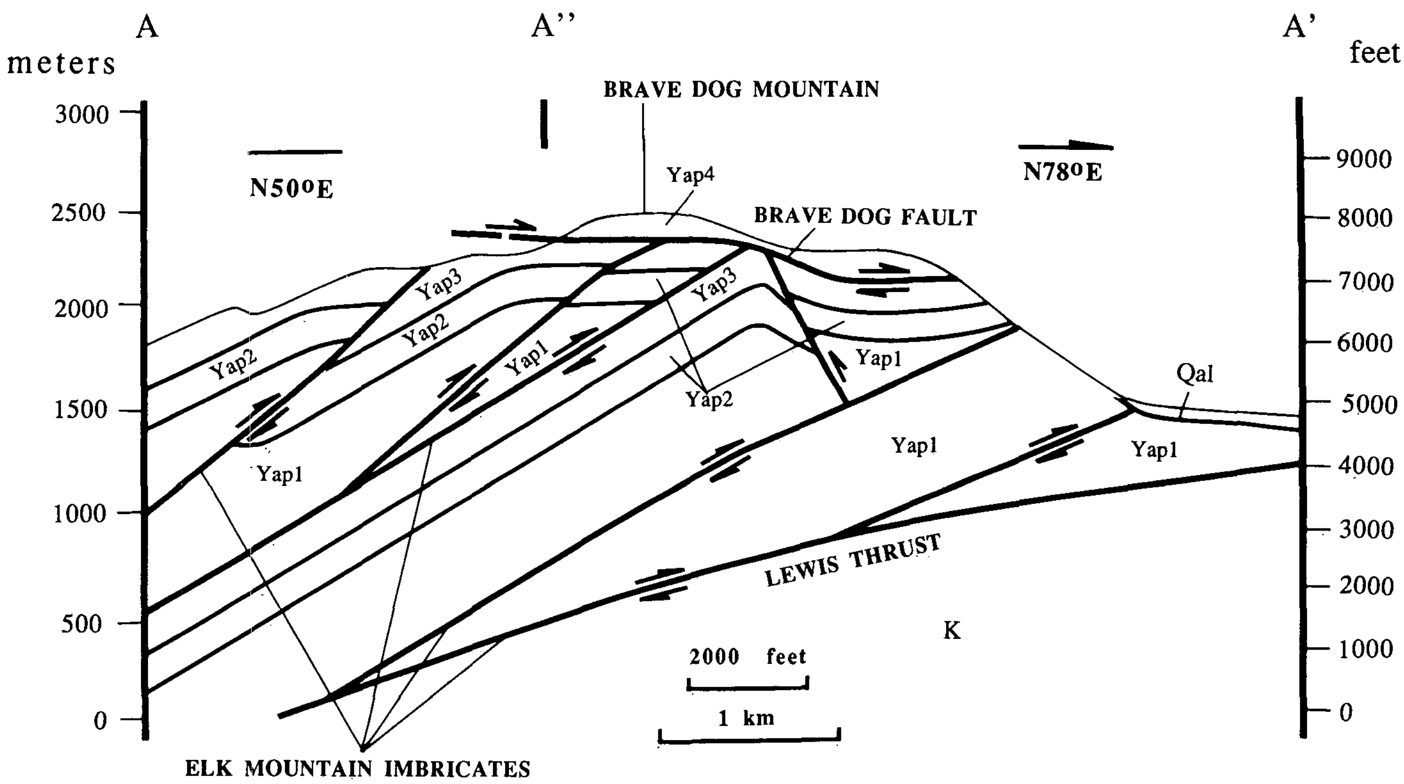


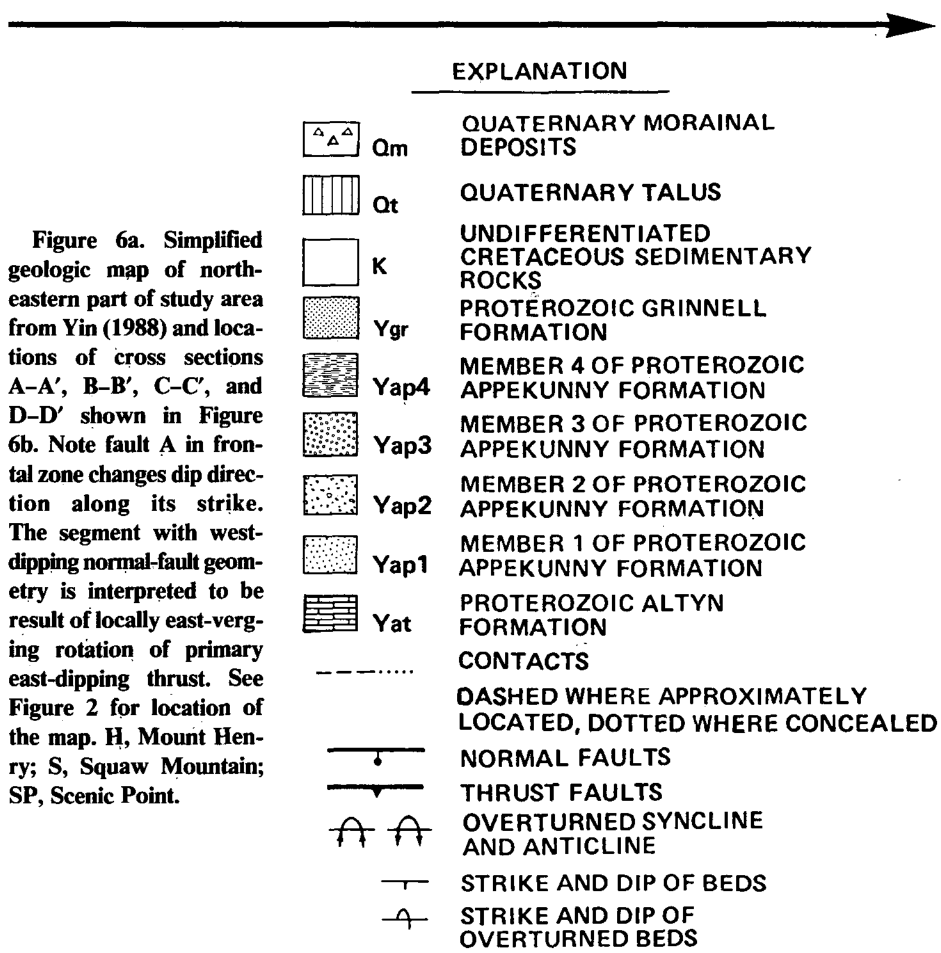
Figure 5b. Geologic cross section through line A–A′. Yap1–4, member 1 through 4 of Appekunny Formation.

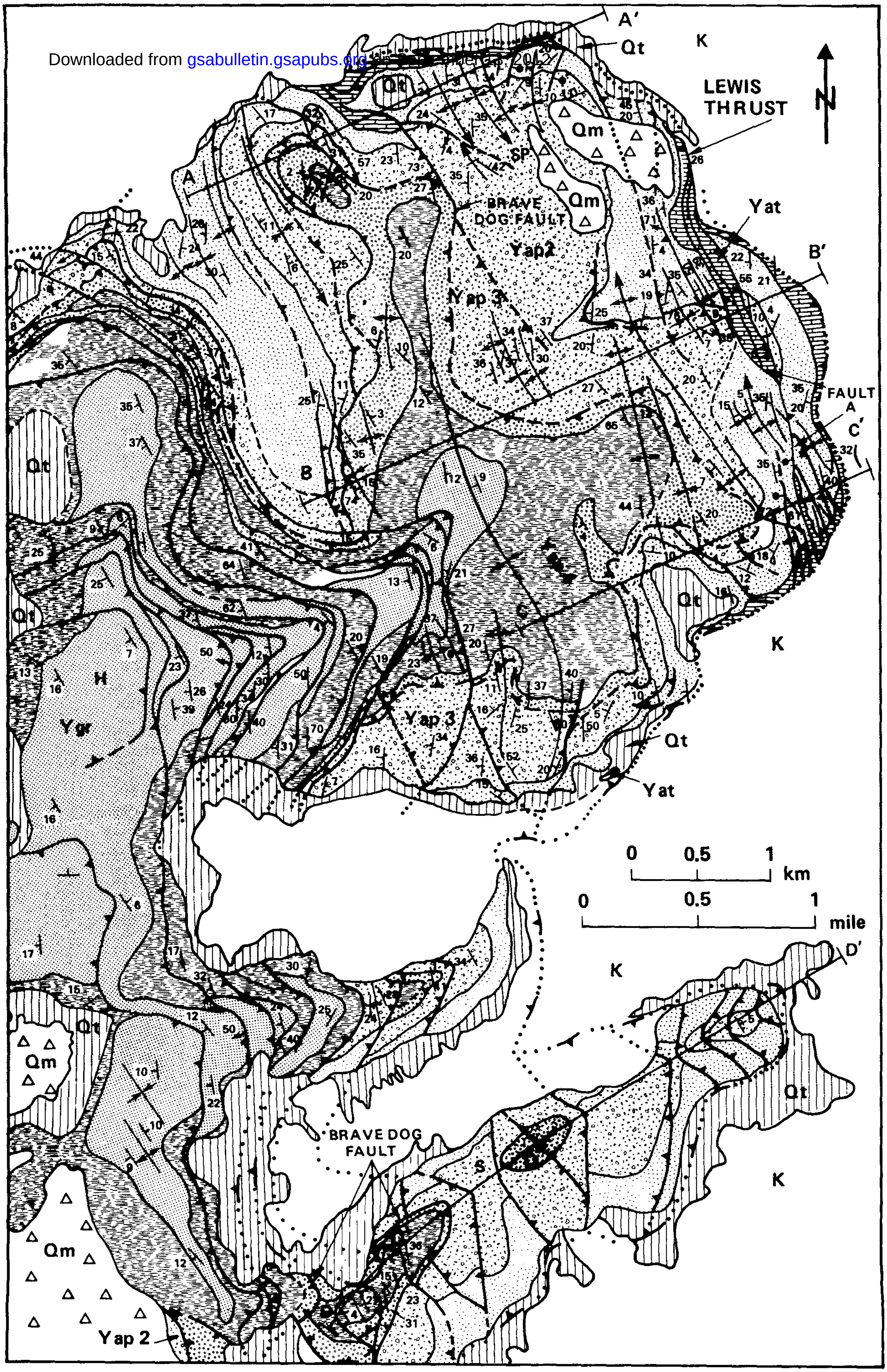
is complicated by an intraformational bedding-subparallel fault, the Scenic Point fault. The Altyn Formation comprises mainly thinly bedded (<20 cm) sandy dolomite above the fault and thickly bedded (50–200 cm) cherty dolomite below the fault.

The Appekunny Formation comprises mostly argillite and minor quartz arenite. In the study area, five laterally persistent quartz arenite units in the formation are designated marker bed A through marker bed E. By using the tops of marker bed C, D, and E as boundaries, the Appekunny Formation can be divided into four informal members (Fig. 3). A bedding-subparallel fault, the Brave Dog fault, is present in member 3. The fault cuts downsection gently to the east (Yin and others, 1989; also see Fig. 2b) and juxtaposes thinly bedded (<2–10 cm) argillite of member 3 directly over thickly bedded (50–150 cm) argillite and quartz arenite of member 2 in the eastern part of the study area.

The Grinnell Formation is separated by the bedding-subparallel Rockwell fault. It is composed mainly of thinly bedded red argillite above the fault and red quartz arenite and thickly bedded argillite below the fault (Fig. 3). The Empire Formation consists of interbedded quartz arenite, argillite, and minor limestone, and the Helena Formation comprises limestone. Both formations are relatively undeformed in the study area.

Figure 6a. Simplified geologic map of northeastern part of study area from Yin (1988) and locations of cross sections A–A′, B–B′, C–C′, and D–D′ shown in Figure 6b. Note fault A in frontal zone changes dip direction along its strike. The segment with west-dipping normal-fault geometry is interpreted to be result of locally east-verging rotation of primary east-dipping thrust. See Figure 2 for location of the map. H, Mount Henry; S, Squaw Mountain; SP, Scenic Point.





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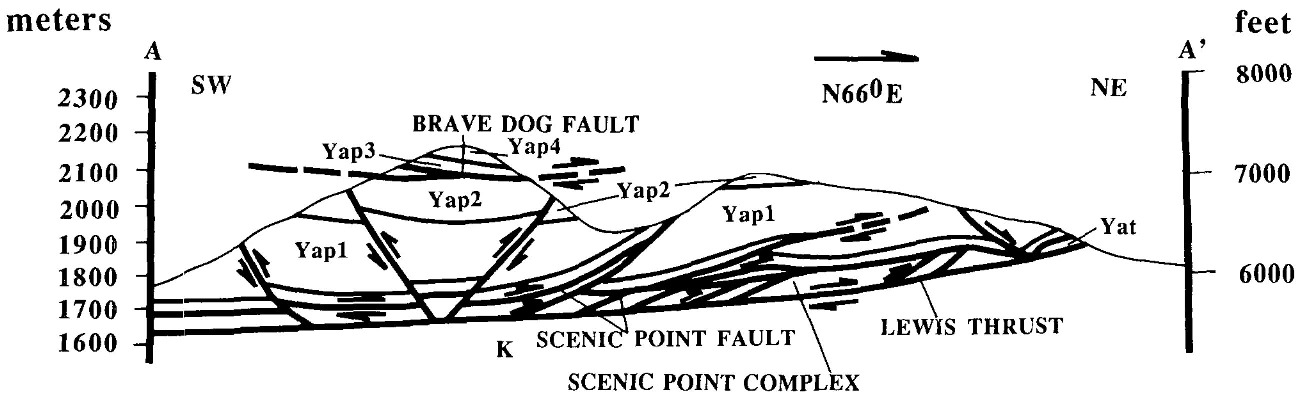


Figure 6b. Geologic cross sections through lines A–A′, B–B′, C–C′, and D–D′. Note that fault A dips to east in section B–B′ and west in section C–C′. Faults in frontal zone cut Scenic Point structural complex; the complex is, in turn, cut by overlying Brave Dog fault. Absence of Scenic Point structural complex in section C–C′ is due to truncation by Lewis thrust. MHIS in cross section D–D′, imbricates in Rising Wolf Mountain duplex.

STRUCTURAL ARCHITECTURE OF THE LEWIS PLATE

On the basis of crosscutting relationships, structures in the Lewis plate can be classified as pre–Lewis thrust, syn–Lewis thrust, and post–Lewis thrust structures. The pre–Lewis thrust structures include the Scenic Point structural complex and the frontal zone; the syn–Lewis thrust structures includu the Brave Dog Mountain duplex, the Rising Wolf Mountain duplex, an east-dipping normal fault system, and the Akamina syncline; and the post–Lewis thrust structures include the Lone Walker fault and the Blacktail fault (Fig. 2). By using the Brave Dog and the Rockwell faults as boundaries (Figs. 2 and 3), the Lewis plate can be divided into three subplates: the basal plate that lies between the Lewis thrust and the Brave Dog fault, the Brave Dog plate that lies between the Brave Dog fault and the Rockwell fault, and the Rockwell plate that lies above the Rockwell fault (Fig. 2a).

The detailed geometry and kinematics of some individual structural elements in the Lewis plate in southern Glacier Park, that is, the Brave Dog Mountain and the Rising Wolf Mountain duplexes, the frontal zone, and the east-dipping normal fault systems, were described by Yin and others (1989), Yin and Kelty (1991), and Yin (1991) and are not repeated here. In the following, we emphasize the crosscutting relationship among the structural elements in order to establish relative timing and, thus, the structural evolution of the Lewis plate.

Syn–Lewis Thrust Structures

Lewis Thrust Fault. The Lewis thrust, a Late Cretaceous to early Tertiary structure (Bally and others, 1966; Price, 1981; Mudge and Earhart, 1980), juxtaposes the resistant Proterozoic Altyn Formation above recessive Cretaceous sedimentary rocks in southern Glacier Park (Fig. 2). The fault is spectacularly exposed in many localities in the study area, with striations well preserved on the fault surface. The average trend of striations indicates that its transport direction is about N65°E (Kelty, 1985; Yin, 1988).

The Lewis thrust is west-dipping and is exposed at an elevation of about 1,830 m on the east side of the study area. No thrust windows of the Lewis thrust fault are exposed on the west side of the study area, although the bedrock is exposed in the deeply cut valleys at an elevation as low as 1,220 m. This map pattern contrasts strongly to the geometry of the Lewis thrust in southeastern British Columbia and southwestern Alberta, Canada, about 35 km north of the international border, where windows of the Lewis thrust, that is, the Haig Brook and Cate Creek windows, are exposed owing to the folded geometry of the Lewis thrust (Fig. 1; Fermor and Price, 1987).

In the southernmost part of the study area, the Lewis thrust is deformed into a broad, north-plunging antiform with a wavelength of about 10 km and hinge trending about N40°W (Fig. 4). The formation of this antiform may be related to underlying imbricate thrusts in the Paleozoic and Mesozoic strata (Mudge and Earhart, 1980, 1983). In the Elk Mountain area, the Lewis thrust surface directly east of the Blacktail normal fault exhibits open antiformal and synformal geometry with shorter wavelengths ranging from 1 to 3 km and amplitudes of a few tens of meters (Fig. 4). These short-wavelength undulations of the Lewis thrust surface may have been related to movement along the younger Blacktail fault.

The Lewis thrust in the southern part of the study area is an oblique ramp that strikes N45°E, about 20° from its transport direction, and dips gently (4°–10°) to the northwest (Fig. 4). Although the ramp climbs about 1,600 ft (488 m) southward in a distance of less than 2 mi (3.2 km; Fig. 4), the stratigraphic cut-off across the ramp is only 120–180 ft (37–55 m). The presence of tight folds at the base of the Lewis plate above the ramp, which trend N45°E–S45°W and are subparallel to the strike of the ramp (Kelty, 1985), suggests that the ramp existed during movement along the Lewis thrust.

Brave Dog Mountain Duplex. The Brave Dog Mountain duplex (Fig. 2; Yin and others, 1989) consists of a west-dipping imbricate thrust system, the Elk Mountain imbricate system, that is bounded above by the low-angle, east-directed Brave Dog fault and below by the Lewis thrust (Figs. 2 and 5). The duplex is cut by the Blacktail normal fault to the west (Fig. 2b).

The Brave Dog fault and the Elk Mountain imbricate system plunge gently to the north and are not exposed in the northern part of the study area. The Brave Dog fault is out of sequence because it truncates numerous east- and west-dipping contraction faults in its footwall in the frontal zone at Scenic Point and Squaw Mountain (Figs. 2 and 6). The Brave Dog fault is offset by the more steeply dipping imbricates in the Rising Wolf Mountain duplex (Figs. 2, 6b, and 7). On the basis of geometrical relationship between the Lewis thrust and imbricates in the Brave Dog Mountain duplex, the formation of the duplex and movement along the Lewis thrust were interpreted by Yin and others (1989) to be synchronous.

East-Dipping Normal Fault System. East-dipping normal faults (Yin and Kelty, 1991; Fig. 2b) that merge downward with the Lewis thrust

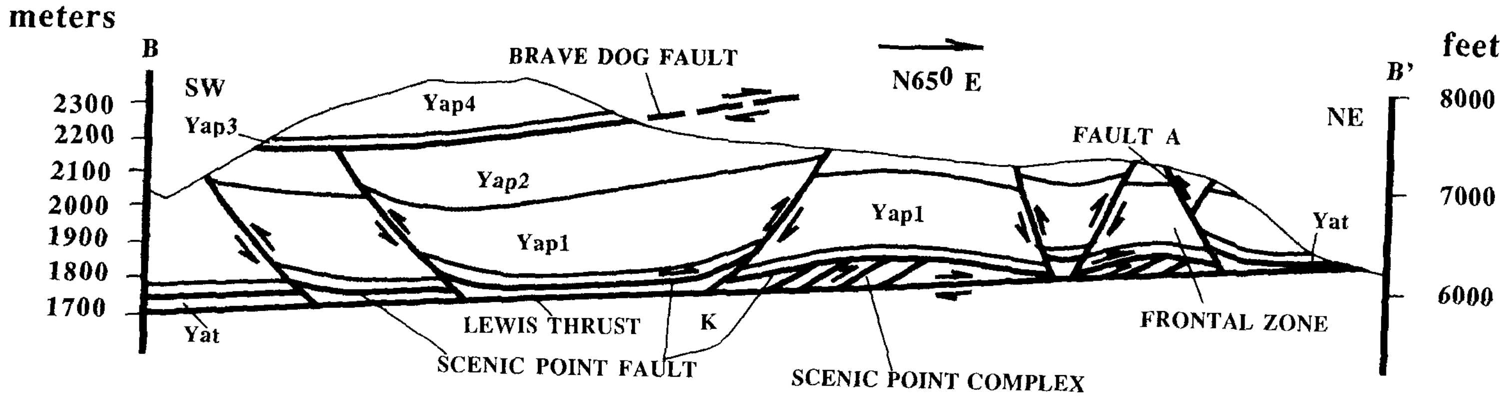
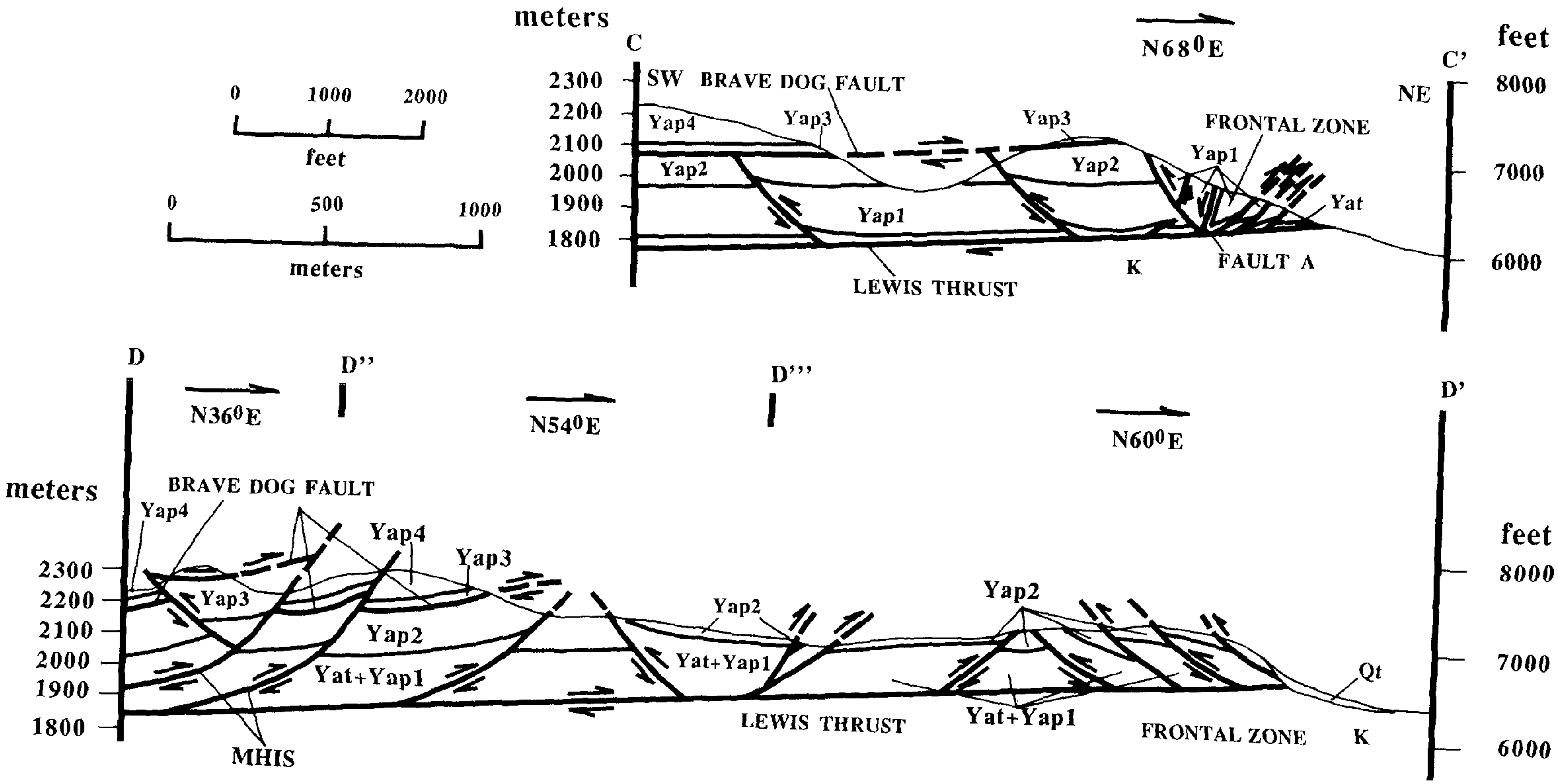


Figure 6b. (*Continued*).



are commonly closely spaced imbricates (40 cm to 80 m), similar to normal faults associated with many extensional detachment fault systems in the North American Cordillera (for example, Anderson, 1971; Wernicke and Burchfiel, 1982). On the basis of geometric and kinematic relationships among the normal faults, the Brave Dog fault, and the Lewis thrust, Yin and Kelty (1991) suggested that the development of the east-dipping normal faults was the consequence of east-verging simple shear produced by simultaneous movement between the Brave Dog and the Lewis faults.

Rising Wolf Mountain Duplex. The Rising Wolf Mountain duplex lies in the eastern part of the study area (Fig. 2; Yin and others, 1989) and consists of a west-dipping imbricate thrust system, the Mount Henry imbricate system, that is bounded above by the low-angle east-directed Rockwell fault and below by the Lewis thrust. The Rockwell fault can be traced for at least 25 km north of the study area in west-central and northern Glacier Park (A. Yin, unpub. map; McGimsey, 1979). The Mount Henry imbricate system can be traced continuously northward for about 40 km near the international border (Jardine, 1985; Hudec, 1986; G. A. Davis, unpub. map).

On the west side of Mount Rockwell, however, the planar Rockwell fault truncates a fold complex and several contraction faults in its footwall (Fig. 8). The contraction faults merge downward with a bedding-parallel fault that is about 300–400 m below the Rockwell fault (Fig. 2b). The offset equivalents of the fold complex and contraction faults in the hanging wall of the Rockwell fault are not found. Continuous exposures of its hanging wall can be traced in the direction of transport from this locality to the northeast for about 6 km, providing a minimum displacement along the Rockwell fault. On the basis of geometrical relationship between the Lewis thrust and imbricates in the Rising Wolf Mountain duplex, the formation of the duplex and movement along the Lewis thrust were interpreted by Yin and others (1989) to be simultaneous.

Akamina Syncline. The Akamina syncline (Dahlstrom, 1970) is a major structure that lies directly west of the Lewis thrust and extends from the Marias Pass, Montana, to the North Kootenay Pass, southwestern Alberta. The syncline in the study area is defined by the gently dipping upper Grinnell, Empire, and Helena strata (Fig. 2). Its half wavelength is about 15 km, and its amplitude is about 0.3 to 0.5 km. The limbs of the syncline dip gently along the axial part of the syncline (a few degrees), but steepen to about 20°–30° directly above the Brave Dog Mountain and Rising Wolf Mountain duplexes in the east and west sides of the study area.

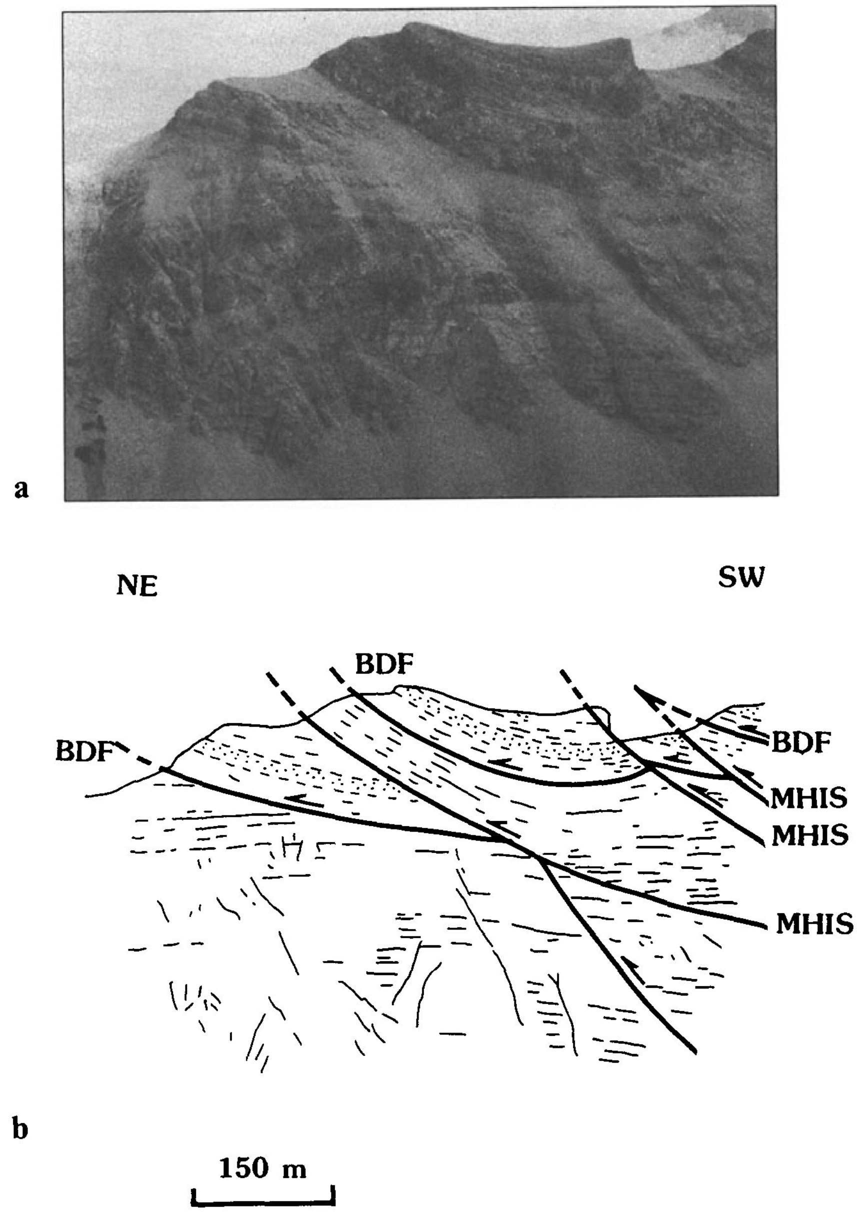


Figure 7. a. Crosscutting relation between Brave Dog fault and Mount Henry imbricate thrusts (MHIS) of Rising Wolf Mountain duplex at Squaw Mountain, viewed from north.
b. Sketch of structures shown in Figure 7a. BDF, Brave Dog fault; MHIS, imbricate thrusts in Rising Wolf Mountain duplex.

The western part of Brave Dog fault and the overlying strata above the Brave Dog Mountain duplex are concordant with the syncline. Similarly, the eastern part of the Rockwell fault and the overlying strata above the Rising Wolf Mountain duplex are concordant with the syncline (Fig. 2b). The Lewis thrust is, however, discordant with the syncline. The Lewis thrust is an antiform where the axial trace of the syncline lies in the study area (compare with Figs. 2 and 4). The geometrical relationship between the Akamina syncline and the Brave Dog fault, Rockwell fault, and Lewis fault thrust suggests that the formation of the Akamina syncline in southern Glacier Park was intimately related to duplex development in the hanging wall of the Lewis thrust and that the Lewis thrust was not folded concordantly with the Akamina syncline.

Pre-Lewis Thrust Structures

Scenic Point Structural Complex. The Scenic Point structural complex, which lies entirely within the Altyn Formation at the base of

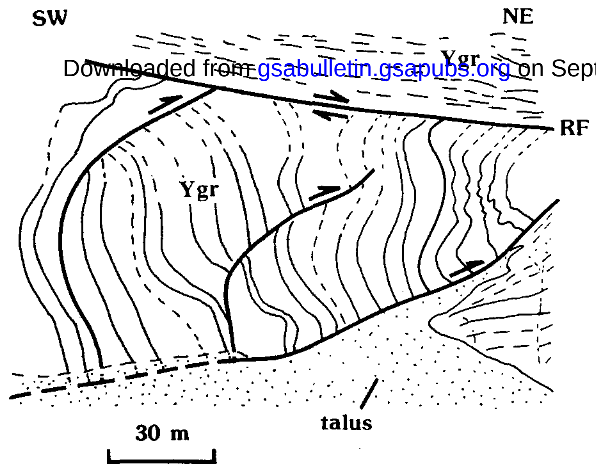


Figure 8. Sketch of truncational relationship between Rockwell fault and a structural complex in its footwall at Mount Rockwell. View from southeast. RF, Rockwell fault; Ygr, Grinnell Formation.

the basal plate, consists of an array of west-dipping thrust imbricates that are bounded above by the low-angle Scenic Point fault and below by the Lewis thrust (Figs. 6 and 9). The Scenic Point fault lies 30 to 40 m below the Altyn-Appekunny contact and merges with the Lewis thrust southward (compare with cross sections A–A′ and B–B′ in Fig. 6b).

The Scenic Point fault is out of sequence, because it truncates faults and bedding in its footwall. The Scenic Point fault and strata above it are broadly folded (Fig. 9). The Scenic Point fault is offset by younger contraction faults in the frontal zone and east-dipping normal faults (Fig. 6b). Development of the Scenic Point structural complex predates the Lewis thrust, because structures in the frontal zone are truncated below by the Lewis thrust (see below), and thus, we interpret that the Scenic Point structural complex is also truncated from below by the Lewis thrust.

Along the north face of Scenic Point (Fig. 2), the Scenic Point fault can be divided into the eastern, central, and western segments (Fig. 9). The western and eastern segments are a single fault surface, whereas the central segment consists of two surfaces: the upper and lower Scenic Point faults. The offset on the lower Scenic Point fault is about 1 to 1.5 km to the east, on the basis of matching distinctive beds of quartz arenite in its hanging wall and footwall (Fig. 9). Striations on the Scenic Point fault indicate a transport direction of N60°–80°E, similar to that of the Lewis thrust in southeastern Glacier Park. We interpret that the development of the Scenic Point structural complex was related to emplacement of the Lewis plate along a fault that is structurally below the Lewis thrust and that the Lewis thrust truncated the Scenic Point complex and transported it to the east in its hanging wall.

Frontal Zone. The frontal zone (Yin, 1991; Figs. 2 and 6), about 3.5 km wide, is located in the easternmost part of the study area. The eastern frontal zone consists of east-dipping imbricate thrusts, east-directed bedding-parallel faults, and apparent west-dipping normal faults that were originally east-dipping contraction faults and were later rotated to their present normal-fault geometry (Fig. 6b). The western frontal zone consists of conjugate contraction faults (Fig. 6b). In contrast to most structures in the Lewis plate, structures in the frontal zone are truncated by the Lewis thrust from below (Yin and Davis, 1988; Yin, 1991), suggesting that the Lewis thrust is younger than the frontal zone. Faults in the frontal zone are cut by east-dipping normal faults. The development of the frontal zone may have been related to emplacement of

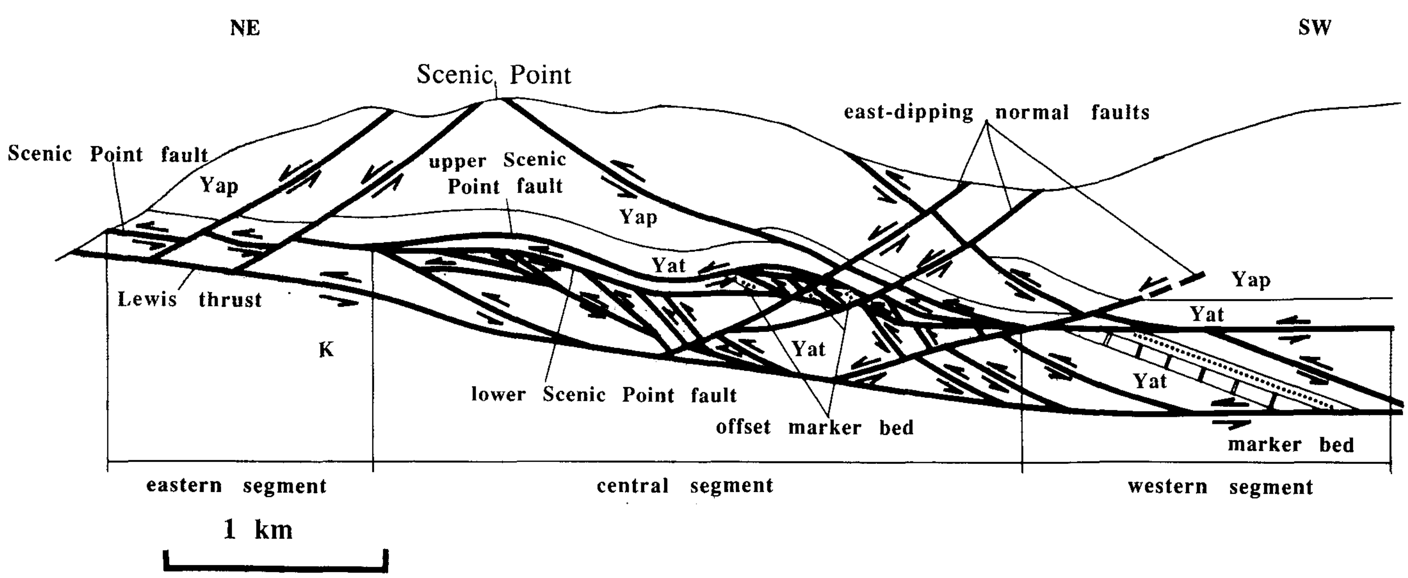


Figure 9. Schematic cross section of Scenic Point structural complex, based on field sketches and oblique photographs. Yat, Altyn Formation; Yap, Appekunny Formation. Note that Scenic Point fault splits to upper and lower faults in its central segment, and lower Scenic Point fault displaced a quartz arenite marker bed about 1 to 1.5 km to the east. Scenic Point fault truncates beds and imbricate thrusts in its hanging wall, indicating that it is an out-of-sequence fault. East-dipping normal faults cut Scenic Point complex.

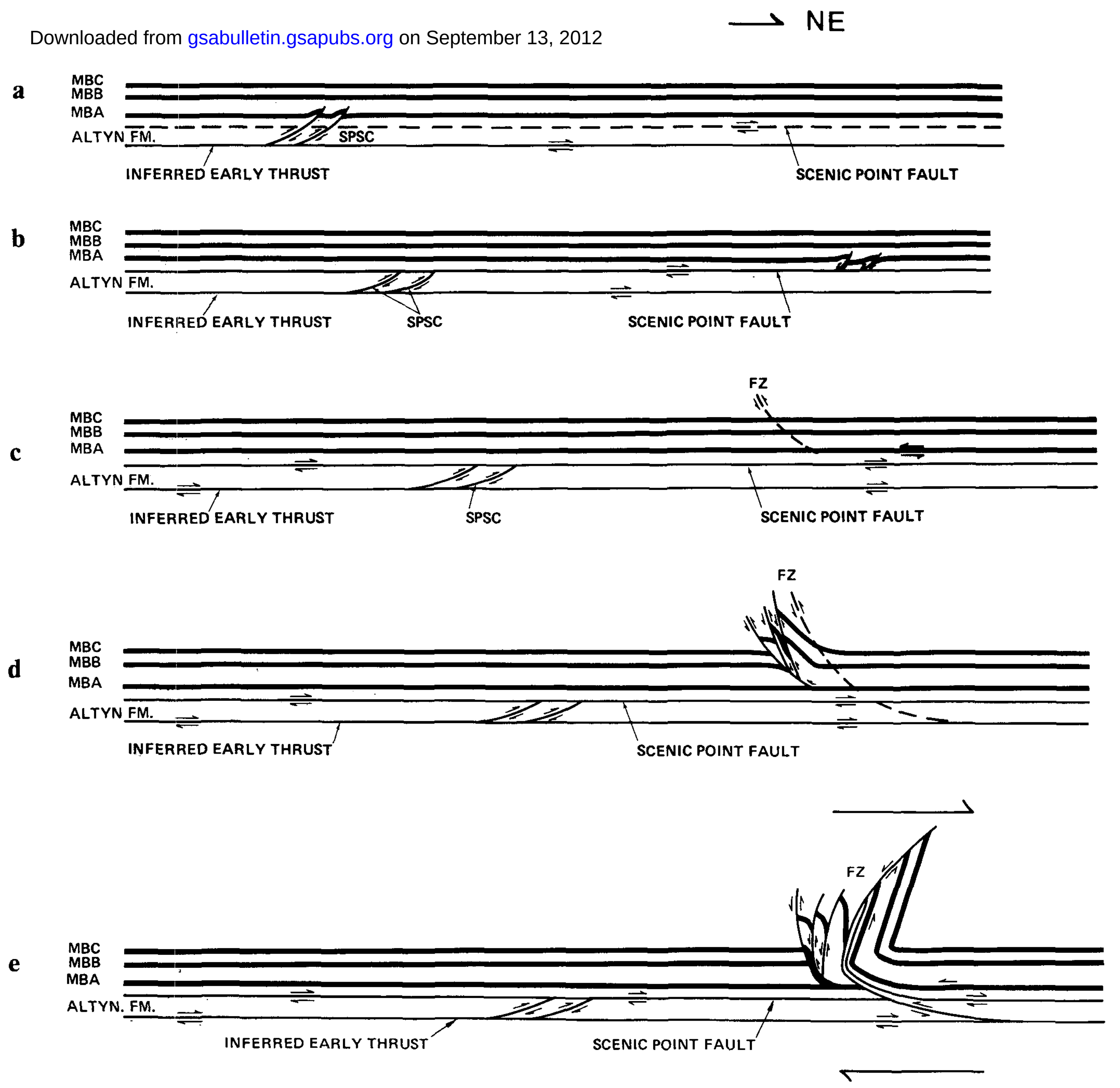


Figure 10. Schematic sketch showing proposed deformation history of Lewis thrust system in southern Glacier National Park. MBA, MBB, and MBC are marker beds in Appekunny Formation. Marker bed A rests directly on top of Altyn Formation. EMIS, imbricate system in Brave Dog Mountain duplex; FZ, frontal zone; MHIS, imbricate system in Rising Wolf Mountain duplex; SPSC, Scenic Point structural complex.

a. Development of imbricate thrusts in Scenic Point structural complex (SPSC). Imbricates branch off from an inferred early basal thrust. Initiation of Scenic Point fault.

b. Imbricate thrusts in Scenic Point structural complex (SPSC) are offset by Scenic Point fault to the east. Scenic Point fault, thus, is an out-of-sequence thrust.

c. Initiation of east-directed contraction faults in eastern frontal zone (FZ) along a décollement lying along the base of marker bed A (MBA).

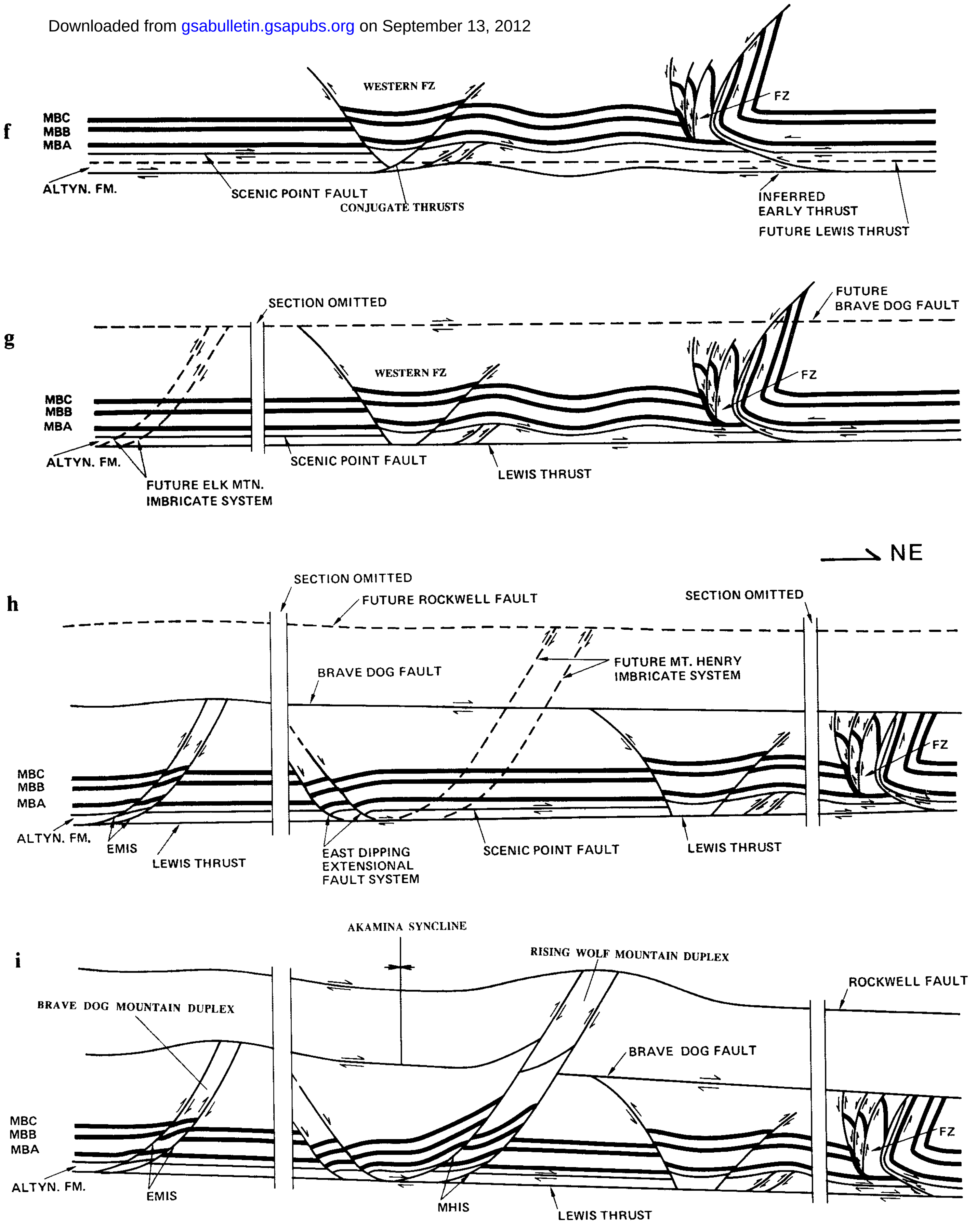
d. Further development of east-directed contraction faults in frontal zone along the inferred basal thrust. Younger faults in FZ cut older décollement and Scenic Point fault and developed along the inferred basal thrust.

e. Rotation of structures in eastern frontal zone by an east-verging simple shear.

f. Development of conjugate contraction faults in western frontal zone. Folding of inferred basal thrust and Scenic Point fault. Initiation of Lewis thrust.

g. Truncation and displacement of Scenic Point structural complex and frontal zone by Lewis thrust. Initiation of Brave Dog fault and Elk Mountain imbricate system (EMIS) in Brave Dog Mountain duplex. Formation of the western limb of Akamina syncline.

h. Development of Brave Dog Mountain duplex and warping of Brave Dog fault and bedding above it. Initiation and development of east-dipping normal faults between Brave Dog fault and Lewis thrust. Truncation of frontal zone by Brave Dog fault. Initiation of Rockwell fault and Mount Henry imbricate system (MHIS) of Rising Wolf Mountain duplex.



i. Development of Rising Wolf Mountain duplex. Offset of Brave Dog fault by imbricate thrusts in Rising Wolf Mountain duplex. Formation of eastern limb of Akamina syncline.

the Lewis plate along a fault that is structurally below the present Lewis thrust, because striations and the trend of faults and folds in the frontal zone are compatible with the transport direction of the Lewis thrust (Yin, 1991). Structures similar to those in the frontal zone have been mapped by Jardine and Davis (1984) and Hudec and Davis (1989) in the northeastern and east-central Glacier Park north of the study area.

Post-Lewis Thrust Structures

The Lone Walker Fault. The Lewis thrust is cut by the Lone Walker fault, a west-dipping, high-angle reverse fault (50°–70°; Fig. 2). The crosscutting relationship between the Lewis thrust and the Lone Walker fault was observed in a creek between Calf Robe and Squaw Mountain in the southeastern corner of the study area, where the Lone Walker fault offsets the Lewis thrust and the Altyn-Appekunny contact for about 40 to 50 m.

The average strike of the Lone Walker fault (N70°W) is considerably west of the predominant structural trend in the hanging wall of the Lewis thrust (N25°W). Striations on the Lone Walker fault are subparallel to the fault's dip direction, suggesting that it is a dip-slip fault. Thus, the compressional direction during the formation of the fault is N20°E. Displacement along the Lone Walker fault increases from about 40 to 50 m in the southeastern study area to more than 500 m in the northwestern study area. The Lone Walker fault offsets the Brave Dog fault, the Rockwell fault, and the Akamina syncline (Fig. 2). It is, in turn, truncated and offset by the Blacktail normal fault about 5 km north of the study area (A. Yin, unpub. map).

Blacktail Normal Fault. The Blacktail normal fault is a major southwest-dipping normal fault. Although the fault is poorly exposed in the study area, its existence is evident as indicated by the discordance in bedding attitudes and the juxtaposition of the upper Belt Supergroup strata (the Mount Shields Formation and the Bonner Quartzite) over the lower Belt Supergroup (Appekunny Formation) across the normal fault. Minor southwest-dipping normal faults that are parallel to the Blacktail fault consistently cut the structures in the Brave Dog Mountain duplex in the western part of the study area.

DEFORMATION HISTORY OF THE LEWIS PLATE

We propose a deformation history for this part of the Lewis plate, based on crosscutting relationships outlined above (Fig. 10). The chronological order for the formation of major structural elements is (1) the Scenic Point structural complex, (2) the frontal zone, (3) the Lewis thrust, (4) the Brave Dog Mountain duplex and east-dipping normal fault system, (5) the Rising Wolf Mountain duplex, (6) the Akamina syncline, (7) the Lone Walker fault, and (8) the Blacktail normal fault.

During the initial stages of development of the Scenic Point structural complex (Figs. 10a to 10c), imbricate thrust faults branched off from an older basal thrust located structurally below the present Lewis thrust. These imbricates were later cut and offset by the Scenic Point fault above. This event was followed by development of the frontal zone (Figs. 10c to 10f). Field relationships in the frontal zone (Yin, 1991) suggest that thrusts developed along two bedding-parallel décollements, one along the Altyn-Appekunny contact and one in the Altyn Formation (Figs. 10c and 10d). We assume in Figure 10d that the deeper décollement of the frontal zone shares the same sole fault as the Scenic Point complex.

Rotation of structures in the eastern part of the frontal zone (Fig. 10e) is inferred to explain the apparent west-dipping normal faults (Yin, 1991). The rotation may predate the formation of conjugate contraction faults in the western frontal zone, because they were not rotated (Fig. 10f).

After the formation of the frontal zone, the speculated pre-Lewis basal thrust and the Scenic Point fault were gently folded. Structures in the frontal zone and the Scenic Point complex were later cut and offset by the Lewis thrust that lies structurally higher than the early basal fault (Figs. 10f and 10g).

After the formation of the Lewis thrust, the Brave Dog fault began to propagate parallel or subparallel to bedding in the Appekunny Formation (Figs. 10g and 10h). Its initiation may have been related to east-verging simple-shear deformation produced by eastward movement along the Lewis thrust (Yin and others, 1989). The Brave Dog fault, which cuts structures in the underlying frontal zone, became kinematically linked with the Lewis thrust through the Elk Mountain imbricate system. The Brave Dog fault was broadly warped upward over the imbricate system as a geometric consequence of shortening across the imbricate system (Fig. 10h). During movement of the Brave Dog fault and simultaneous movement along the Lewis

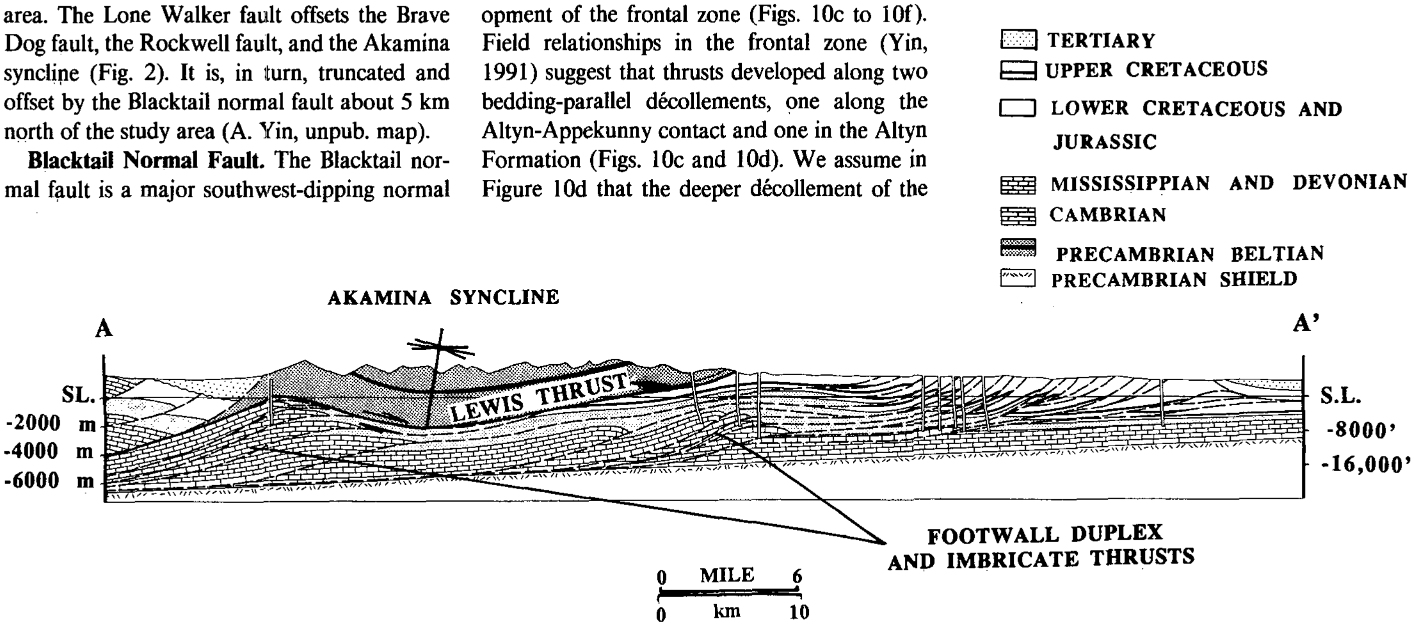


Figure 11. Lewis thrust and underlying structures north of international border. Location of cross section A–A′ shown in Figure 1, after Gordy and others (1977). Note that Akamina syncline and Lewis thrust are concordantly folded. The syncline is interpreted to be related to duplex development and imbricate thrusting in footwall of Lewis thrust.

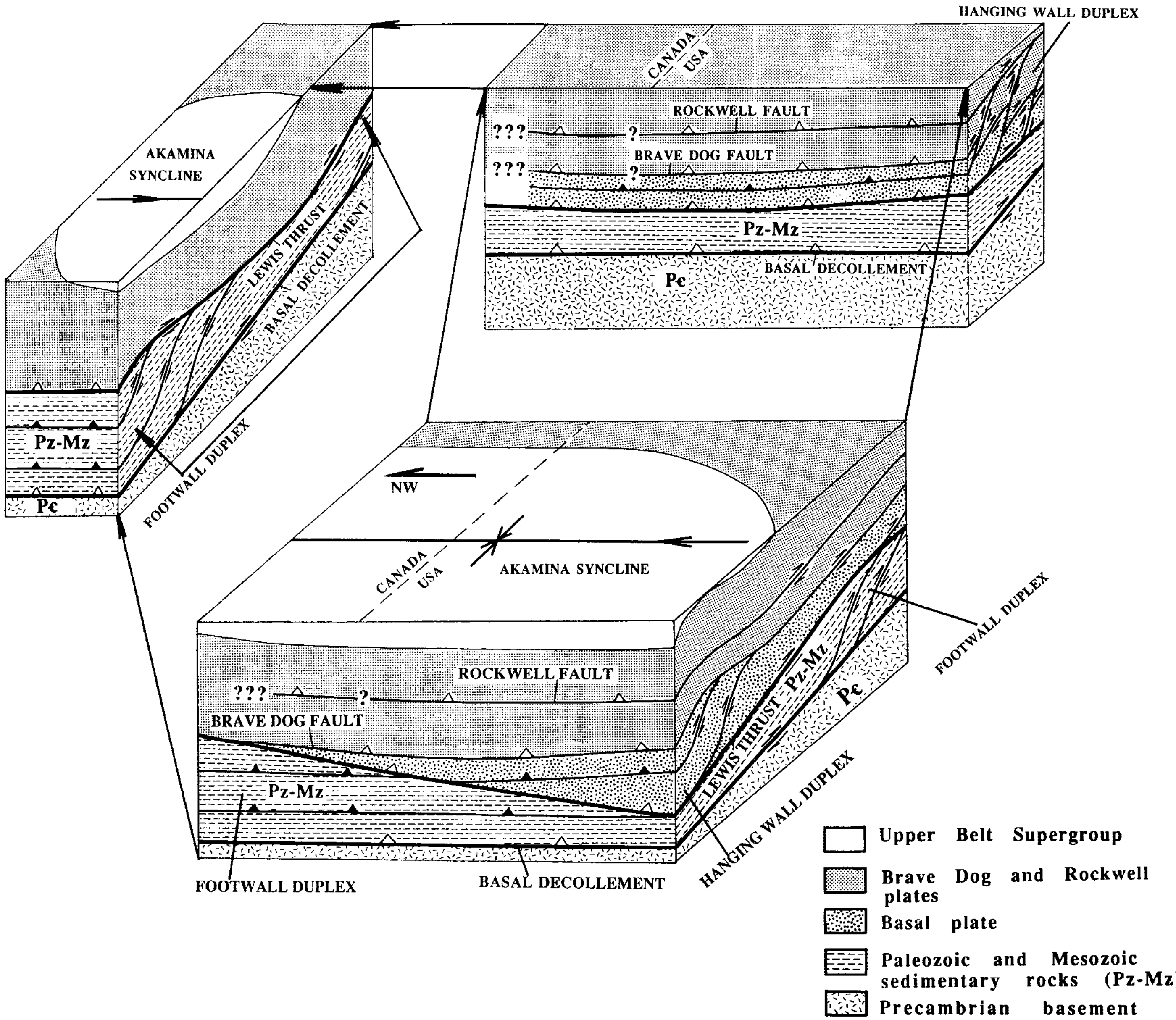


Figure 12. Three-dimensional diagram showing structural relationship between Lewis thrust, Akamina syncline, and duplexes in both hanging wall and footwall of Lewis thrust. Shortening accommodated by duplexes decreases in footwall and increases in hanging wall southward; Lewis thrust transferred northeast-southwest horizontal compression laterally from its footwall in Paleozoic and Mesozoic strata to its hanging wall in Proterozoic Belt strata.

thrust, the east-dipping normal fault system developed as a consequence of simple-shear deformation between the two faults (Yin and Kelty, 1991).

The Rockwell fault was initiated at a higher structural level above the Brave Dog fault and propagated subparallel to bedding in the Grinnell Formation (Figs. 10h and 10i). The Rockwell fault later became kinematically linked with the Lewis thrust through the development of the Mount Henry imbricate system along the east side of the study area. The development of the imbricate system beneath the Rockwell fault caused the upward warping of the low-angle fault. Development of the Rising Wolf Mountain and the Brave Dog Mountain duplexes, together, resulted in formation of the Akamina syncline that is defined by strata above the Rockwell fault (Fig. 10i). Following the emplacement of the Lewis thrust plate, the Lone Walker fault developed and was later cut by the Blacktail normal fault (not shown in Fig. 10).

DISCUSSION

Relationship between the Akamina Syncline and the Lewis Thrust

Two models have been proposed for the formation of the Akamina syncline. (1) The formation of the syncline was related to movement along the Flathead (or Blacktail) normal fault (Dahlstrom, 1970), and (2) the formation of the syncline was related to duplex formation and imbricate thrusting in the footwall of the Lewis thrust (Bally and others, 1966; Gordy and others, 1977). The result of this study suggests that neither model explains the structural relationship observed in southern Glacier Park. First, although the short-wavelength antiforms and synforms of the Lewis thrust close to the Blacktail normal fault may have been related to movement along this younger fault, the overall geometry of the long-wavelength Akamina syncline is compatible with the development of the duplexes in the *hanging wall* of the Lewis thrust (Fig. 10h). Second, imbricate thrusting in the Mesozoic and Paleozoic strata in the footwall of the Lewis thrust may have affected the geometry of the Lewis thrust in the south-central part of the study area (Fig. 4). The resultant geometry (a broad antiform) is, however, disconcordant with the Akamina syncline as discussed above. Thus, we conclude that in southern Glacier Park, the formation of the Akamina syncline was related to deformation in the hanging wall of the Lewis thrust during emplacement of the Lewis plate. This interpretation leads to a paradox in that the Lewis thrust is clearly folded into a synform in southwestern Alberta and southeastern British Columbia, Canada, directly north of the international border, as indicated by surface (presence of thrust windows) and subsurface (well and seismic) data (Bally and others, 1966; Dahlstrom, 1970; Gordy and others, 1977; Fig. 11).

To reconcile the discrepant observations on the geometry of the Lewis thrust north and south of the international border, we propose a model to explain the structural relationship between the Akamina syncline and deformation in the hanging wall and footwall of the Lewis thrust (Fig. 12). In this model, the development of the syncline was related to duplex formation and imbricate thrusting in two structural levels, one above and one below the Lewis thrust. The magnitude of shortening in the duplex and imbricate systems in the hanging wall and the footwall varies along the structural trend. The magnitude of northeast-southwest horizontal shortening decreases in the footwall and increases in the hanging wall southward. The total shortening of the hanging wall and footwall could be approximately uniform along the structural trend in the northwest-southeast direction. The role of the Lewis thrust was to transfer shortening *laterally* along the regional structural trend (northwest-southeast) from its footwall in the Paleozoic and Mesozoic strata to its hanging wall in the Proterozoic Belt strata. Although the deformation in the Lewis plate north of the international border is more complicated than what is shown in Figures 11 and 12, the presence of thrust windows (Fig. 1) requires that the Lewis thrust is significantly folded (Fermor and Price, 1987).

The model proposed in Figure 12 has regional implications. As discussed above, broad folds are common structures in the fold-and-thrust belt in the southern Canadian Rocky Mountains and northwestern Montana. Recently published COCORP and industry seismic reflection profiles suggest that the crustal section below the broad-fold belt was complexly deformed (for example, Yoos, 1988). Limited deep-drilling data in the region of the broad-fold belt present difficulties in interpreting the seismic data. The result of this study provides insight into the mode of deformation in the Belt strata underneath the broad folds. It is likely that those broad folds were related to duplex systems developed at deeper structural levels. The development of duplexes may have been the mechanism for transferring horizontal shortening from the magmatic belt due to the spreading of magma in the hinterland to the imbricate-thrust belt in the foreland during the overall development of the Cordilleran foreland fold-and-thrust belt in the southern Canadian Rocky Mountains and northwestern Montana.

The Origin of the Lone Walker Fault

The Lone Walker fault strikes considerably west of the predominant structural trend in the Lewis thrust system. Crosscutting relationships suggest that the fault postdates the Lewis thrust and Akamina syncline, but predates the Blacktail normal fault. The orientation of this fault indicates a change in compressional direction of 30°–40° with respect to structures related to the emplacement of the Lewis plate.

On a regional scale, the only west-northwest–trending tectonic element that parallels the strike of the Lone Walker fault is the Lewis-Clark line, a complex fault system consisting of strike-slip, reverse, and normal faults extending from Coeur d'Alene, Idaho, to Helena, Montana (Fig. 1; Billingsley and Locke, 1939; Harrison and others, 1974, 1986; Wallace, 1990). The age of the faults in the Lewis-Clark line varies from Precambrian to Cenozoic (Sales, 1968; Harrison and others, 1974; Wallace and others, 1990; Hyndman and others, 1988). We speculate that the Lone Walker fault was related to the development of some faults in the Lewis-Clark line during the Laramide orogeny (Sales, 1968).

CONCLUSIONS

(1) Emplacement of the Lewis plate was associated with the development of duplexes (the Brave Dog Mountain and Rising Wolf Mountain duplexes), west-directed thrusting (the frontal zone), conjugate thrusting (frontal zone), out-of-sequence faulting (Scenic Point and Brave Dog faults), and extensional faulting (east-dipping normal fault system).

(2) The formation of the Akamina syncline was related to duplex development and imbricate thrusting in the footwall of the Lewis thrust north of the international border and to duplex development in the hanging wall south of the international border. The role of the Lewis thrust was to transfer northeast-southwest horizontal shortening laterally along the structural trend from its hanging wall to its footwall. The development of duplexes may have created broad folds that are situated between the magmatic belt to the west and the imbricate-thrust belt to the east.

(3) A change in compressional direction from N65°E to N20°E occurred after emplacement of the Lewis thrust plate in southern Glacier Park. This event was recorded by the development of the Lone Walker fault, which predates the Eocene-Oligocene Blacktail normal fault. The origin of the Lone Walker fault is speculated to be related to the development of the Lewis-Clark fault zone during the Laramide orogeny.

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