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Notes

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ABSTRACT

Geologic mapping in southern Glacier National Park, Montana, reveals the presence of two duplexes sharing the same floor thrust fault, the Lewis thrust. The westernmost duplex (Brave Dog Mountain) includes the low-angle Brave Dog roof fault and Elk Mountain imbricate system, and the easternmost (Rising Wolf Mountain) duplex includes the low-angle Rockwell roof fault and Mt. Henry imbricate system. The geometry of these duplexes suggests that they differ from previously described geometric-kinematic models for duplex development. Their low-angle roof faults were preexisting structures that were locally utilized as roof faults during the formation of the imbricate systems. Crosscutting of the Brave Dog fault by the Mt. Henry imbricate system indicates that the two duplexes formed at different times. The younger Rockwell–Mt. Henry duplex developed 20 km east of the older Brave Dog–Elk Mountain duplex; the roof fault of the former is at a higher structural level. Field relations confirm that the low-angle Rockwell fault existed across the southern Glacier Park area prior to localized formation of the Mt. Henry imbricate thrusts beneath it. These thrusts kinematically link the Rockwell and Lewis faults and may be analogous to P shears that form between two synchronously active faults bounding a simple shear system. The abandonment of one duplex and its replacement by another with a new and higher roof fault may have been caused by (1) warping of the older and lower Brave Dog roof fault during the formation of the imbricate system (Elk Mountain) beneath it, (2) an upward shifting of the highest level of a simple shear system in the Lewis plate to a new decollement level in subhorizontal belt strata (= the Rockwell fault) that lay above inclined strata within the first duplex, and (3) a reinitiation of P-shear development (= Mt. Henry imbricate faults) between the Lewis thrust and the subparallel, synkinematic Rockwell fault.

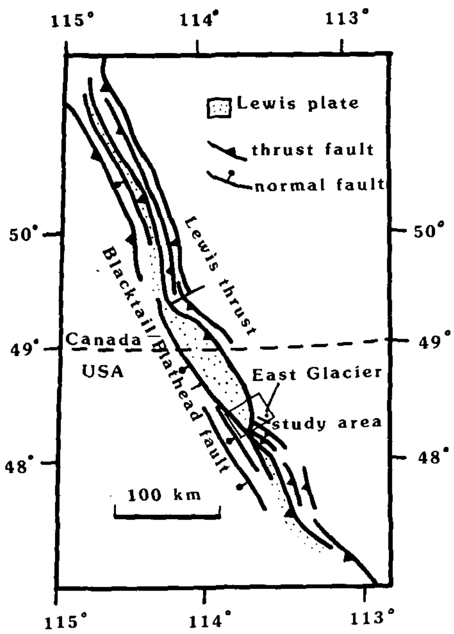

Figure 1. Map showing trace of Lewis thrust fault, major adjacent structures, and location of study area.

INTRODUCTION

The Lewis thrust (Willis, 1902) is one of the major structural components developed during Late Cretaceous and early Tertiary time in the foreland fold and thrust belt of the southern Canadian Rockies (Bally et al., 1966; Price, 1981) and western Montana (Mudge and Earhart, 1980). The fault can be traced along strike from Steamboat Mountain in west-central Montana (Mudge and Earhart, 1980) to the Rundle Range in southwestern Alberta, Canada (Dahlstrom et al., 1962; Fig. 1). A significant amount of shortening in this part of the Cordilleran foreland fold and thrust belt was accommodated along this single dislocation surface (Price, 1981). Near the international boundary, the Lewis thrust juxtaposes the Middle Proterozoic Belt-Purcell Supergroup in its upper plate with Cretaceous sedimentary rocks in its lower plate, and displaces Belt rocks for at least 60 km to the northeast relative to lower plate rocks (Price, 1962).

Structures along the base of the Lewis thrust sheet have been studied by numerous geologists. Willis (1902) first recognized widespread low-angle bedding-parallel faults within the Lewis plate that he called "X-planes," which may be equivalent to the Rockwell and Brave Dog faults described below (Willis, 1902, p. 335). At Chief Mountain in northwestern Montana, Willis (1902) 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 plate in the Waterton area of Canada by Douglas (1952), by Fermor and Price (1987) in the Cate Creek and Haig Brook window area in southeastern British Columbia and southwestern Alberta, and by Davis and Jardine (1984) at Yellow Mountain in Glacier Park. The structural associations described by Willis and Douglas were later cited as examples of duplex fault zones by Dahlstrom (1970). As inspired by Boyer and Elliott (1982), duplexes are now widely interpreted as important structural associations for contributing to shortening within thrust systems, although not all duplexes in

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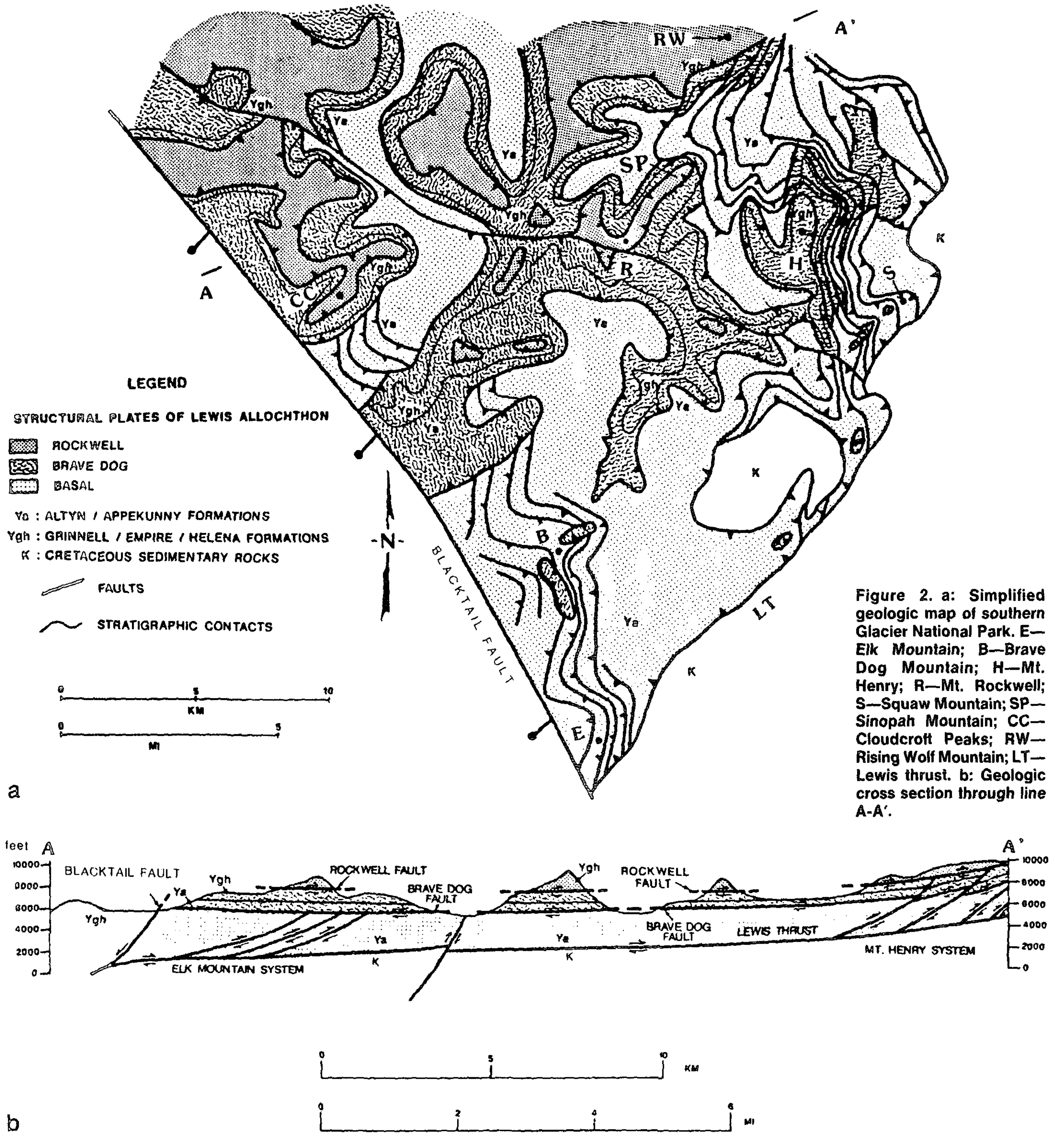

Figure 2. a: Simplified geologic map of southern Glacier National Park. E—Elk Mountain; B—Brave Dog Mountain; H—Mt. Henry; R—Mt. Rockwell; S—Squaw Mountain; SP—Sinopah Mountain; CC—Cloudcroft Peaks; RW—Rising Wolf Mountain; LT—Lewis thrust. b: Geologic cross section through line A-A′.

Glacier Park have formed in the forward propagation sequence favored by Boyer and Elliott (cf. Davis and Jardine, 1984; Yin and Davis, 1988; Davis et al., 1989; Hudec and Davis, 1989).

The Lewis thrust fault and structures within its allochthon have been mapped along the east and south sides of Glacier Park by G. A. Davis (unpublished), Jardine (1985), Kelty (1985), Hudec (1986), Yin (1988), and M. Winn (unpublished) as part of a project by the U.S. Geological Survey for the National Park Service. These studies indicate that structures of the Lewis plate are considerably more complex than previously thought (cf. Gordy et al., 1977). This paper briefly summarizes the results of mapping in southern Glacier Park, presents evidence for formation, deactivation, and reformation of duplexes during the evolution of the Lewis thrust system, and provides an alternative kinematic interpretation for the formation of duplexes to that favored by Boyer and Elliott (1982).

GEOMETRY AND KINEMATICS OF THE LEWIS THRUST SYSTEM

Geologic mapping of the Lewis allochthon was conducted at a scale of 1:24,000. Figure 2a shows a simplified geologic map of southern Glacier National Park. The Lewis thrust in southern Glacier Park is sharply delineated between cliff-forming Belt rocks and slope-forming, lower plate Cretaceous sedimentary rocks. Striations measured along the fault surface indicate that the transport direction of the Lewis thrust is N65° ±10°E in southern Glacier Park (Kelty, 1985; Yin, 1988). The thrust juxtaposes upper plate rocks of the Middle Proterozoic Belt sequence (including, from bottom to top, the Altyn, Appekunny, Grinnell, Empire, and Helena Formations; cf. Whipple et al., 1984) atop Cretaceous strata. Our studies emphasized the geometry and kinematics of deformation in upper plate units. Deeply eroded valleys, a spectacularly exposed Lewis allochthon, and well-understood stratigraphy of the Belt Supergroup in Glacier Park provide a unique opportunity to examine the geometry of the Lewis plate in three dimensions. Four major structural elements mapped in the Lewis plate are discussed here: the Elk Mountain imbricate system, the Brave Dog fault, the Mt. Henry imbricate system, and the Rockwell fault (Fig. 2); a fifth element, the easternmost, complexly deformed frontal zone (Yin and Davis, 1988; Hudec and Davis, 1989), is not discussed here. These structural elements, together with the Lewis thrust itself, define the Lewis thrust system in the study area. Belt rocks within the Lewis allochthon lie within three plates bounded by the basal Lewis thrust, the overlying Brave Dog fault, and the still higher Rockwell fault (Fig. 2b).

The west-dipping Elk Mountain imbricate system is located in the western part of the study area and has a minimum map width of 3.5 km. It is bounded on the west by the Cenozoic Blacktail normal fault (Figs. 1 and 2). Displacements along the imbricate thrusts range from 50 to more than 350 m. The amount of stratal shortening (final map width vs. original bed length) accommodated by this imbricate system is at least 50% (Kelty, 1985). Faults in the Elk Mountain system flatten downward toward the Lewis thrust at Elk Mountain, and steepen upward toward the Brave Dog fault at Brave Dog Mountain (Figs. 2 and 3). Imbricate thrusts terminate upward at the Brave Dog fault with appreciable discordance (20°–40°). Bedding near the Lewis thrust in the lowest part of the duplex dips westward at low angles (10°–20°), steepens upward in its middle part (30°–45°), and flattens into parallelism with the Brave Dog fault in its uppermost part (Fig. 3).

The Brave Dog fault can be traced throughout the study area, as shown in Figure 2. It underlies an area in excess of 900 km^2. Regionally, this fault dips 3°–5° to the east and lies within the upper part of the fine-grained clastic Appekunny Formation (Yin, 1988; Kelty, 1985). However, the part of the Brave Dog fault immediately above the Elk Mountain imbricate system is broadly warped (Fig. 3). The vergence of mesoscopic folds and east-dipping minor extensional faults immediately below the Brave Dog fault indicates that its allochthon is east directed. The fault surface is generally parallel to bedding in its upper plate, but locally cuts downsection eastward through its lower plate in the direction of transport. A lower plate Appekunny stratigraphic section of approximately

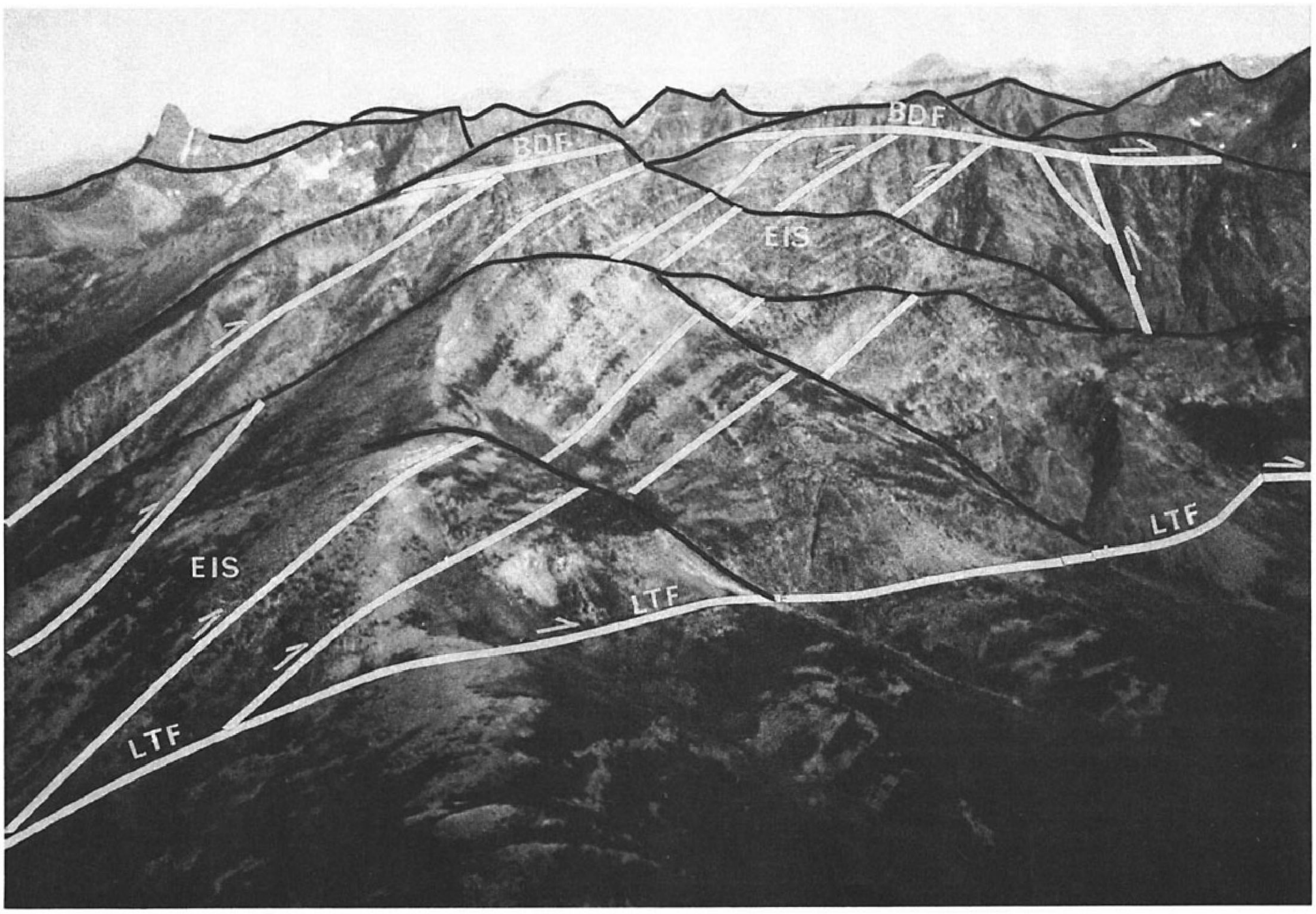

Figure 3. Structural relation between Brave Dog fault (BDF) and Elk Mountain imbricate system (EIS) observed at Elk Mountain and Brave Dog Mountain, southwestern Glacier National Park. LTF—Lewis thrust fault. Viewed from southeast. Note that *Brave Dog fault is broadly warped.*

150 m is omitted by this fault on the east side of the study area. Because the length of beds is extended along this fault, it is an extensional fault (McClay, 1981), although we do not mean to imply that it is the consequence of extensional tectonics. Displacement along the Brave Dog fault is unknown.

The Brave Dog fault is offset by the younger Mt. Henry imbricate system, which is spectacularly exposed at Mt. Henry in southeastern Glacier Park (Fig. 2). Thrust imbricates in this system are present across a zone about 2–3 km wide. In a manner similar to the behavior of faults in the Elk Mountain imbricate system, southwest-dipping thrusts in this system flatten downward from about 60° to a few degrees as they approach the Lewis thrust. Imbricate thrusts in the westernmost part of the duplex system can be observed to terminate upward at the Rockwell fault in the southwestern corner of Rising Wolf Mountain (Fig. 2). The angle between the imbricates and the Rockwell fault is about 15°–25°. In the Mt. Henry area, bedding in the lower part of the duplex dips westward at low angles (10°–20°) near the Lewis thrust and steepens upward (30°–50°). On the southwestern side of Rising Wolf Mountain, bedding in the uppermost part of the Mt. Henry imbricate system flattens upward to the east into subparallelism with the Rockwell fault. Displacements along the imbricate thrusts range from 50 to more than 300 m. The amount of stratal shortening (final map length vs. original bed length) across this zone is about 50% (Yin, 1988).

The Rockwell fault (Yin, 1988) lies generally parallel to bedding of Grinnell strata in the study area and can be traced throughout the southern Glacier Park study area. The fault is clearly developed west of where areally restricted faults of the Mt. Henry system join it (Fig. 2). Thus, formation of the Rockwell fault must predate development of imbricate thrusts that now link it, in the Mt. Henry area, to the Lewis thrust. East-vergent mesoscopic folds immediately above and minor east-dipping extensional faults immediately below this fault indicate that its upper plate is east directed. At Cloudcroft Peaks on the west side of the park, the Rockwell fault dips gently to the east. It truncates a broad syncline in its upper plate and cuts downsection eastward across its lower plate along a 4-km-wide, gently east dipping ramp. These relations suggest that the Rockwell fault may be an out-of-sequence fault that postdates folding. Stratigraphic omission across this ramp is about 150 m. Farther east, at Mt. Rockwell in the central part of the study area, the fault locally cuts upsection to the east along a 1-km-wide, west-dipping ramp and produces a stratigraphic repetition of about 40 m. The fault immediately above the Mt. Henry imbricate system in Rising Wolf Mountain lies parallel to the bedding in its upper plate and dips gently to the east (Fig. 2b). Because the fault in general extends the bed length of Grinnell strata in the study area, it is best described as an extensional fault. Displacement along this fault is at least 6 km. Several contractional faults with displacements of several tens of metres and a highly folded rock package are truncated from above by the planar Rockwell fault on the west side of Mt. Rockwell (Yin, 1988). Offset equivalents of the folded structural package and minor contractional faults in the Rockwell plate are not found for at least 6 km to the east, despite continuous exposures of the Rockwell plate over this distance.

Mesoscopic structures such as striations and fold hinges within or along each structural element in the Lewis thrust system were routinely measured in the field. Our data indicate that formation of the major structural elements and the transport direction (N65° ±10°E) of the Lewis thrust are kinematically compatible (Kelty, 1985; Yin, 1988).

DISCUSSION

The two structural associations—one that consists of the Elk Mountain imbricate thrust system and its bounding Brave Dog fault and Lewis thrust, and one that consists of the Mt. Henry imbricate thrust system and its bounding Rockwell and Lewis faults—are geometrically similar to duplex fault zones defined by Dahlstrom (1970, p. 352). For this discussion we refer to the two structural associations as the Brave Dog Mountain and Rising Wolf Mountain duplexes, respectively, because their critical roof relations are best exposed at these two mountain localities. Offsetting of the Brave Dog fault along thrusts within the Mt. Henry imbricate system (Fig. 2) unequivocally establishes that the two duplexes formed at different times. The Brave Dog Mountain duplex formed first, and was followed in time by the development of the Rising Wolf Mountain duplex 20 km to the east. Although the two duplexes shared a common floor thrust (the Lewis fault), the Rockwell roof fault of the Rising Wolf Mountain duplex lay stratigraphically and structurally above the Brave Dog Mountain fault.

Kinematic processes for the formation of duplex structures have been simulated by Boyer and Elliott (1982) in a series of graphic experiments. In experiments demonstrating forward progressive development of a duplex fault zone, they showed that slip along the floor fault can be transferred to the roof fault across multiple, successively forming ramps through repeated footwall collapse. Their simulation predicts that the roof fault is present only above the imbricate thrust-bounded slices (= horses) of the duplex (Boyer and Elliott, 1982, p. 1208), a geometry that is not observed in the Rising Wolf Mountain duplex. The Rockwell roof fault extends at least 20 km west of the Mt. Henry imbricate system (Fig. 2). This geometry requires that the Rockwell fault was not formed solely by slip transfer from the Lewis thrust to the Rockwell fault during the development of the Mt. Henry imbricate system. It is likely that initiation of the Rockwell fault predated the Mt. Henry imbricate system, and that its eastern part was later utilized as a roof fault during imbricate thrusting beneath it. The Brave Dog fault does not join the Lewis thrust for at least 20 km east of the Elk Mountain imbricate system (Fig. 2). Whether it roots into the Lewis thrust immediately west of the Elk Mountain imbricate system cannot be directly determined because both the Brave Dog fault and the imbricate system below it are cut by the west-dipping, Cenozoic Blacktail fault (Fig. 2). However, because of its geometric similarities with the Rockwell fault—i.e., both faults are generally parallel to bedding in their upper and lower plates and both cut down section locally in the transport direction—it is likely that the Brave Dog fault originated by a similar process.

The geometries of the Rising Wolf Mountain and Brave Dog Mountain duplexes suggest that they were not developed in any of the manners proposed by Boyer and Elliott (1982). We propose an alternative kinematic model for the formation of these duplexes in the Lewis thrust system (Fig. 4). (1) The Brave Dog fault was

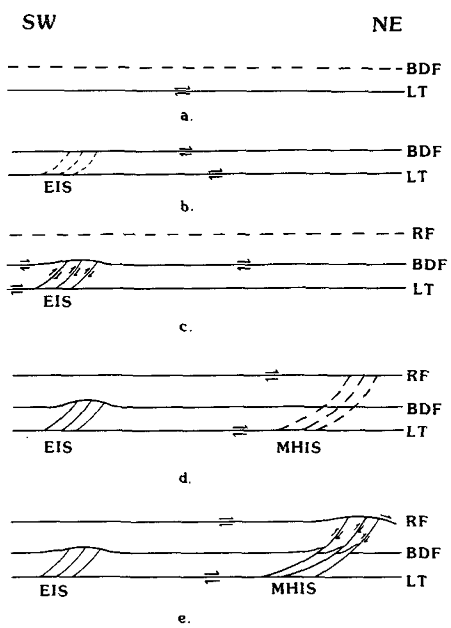

Figure 4. Kinematic model for development of duplex systems in southern Glacier National Park. LT—Lewis thrust; EIS—Elk Mountain imbricate system; BDF—Brave Dog fault; RF—Rockwell fault; MHIS—Mt. Henry imbricate system. Solid lines indicate fault traces; *dashed lines indicate future fault traces.*

initiated and propagated parallel or subparallel to bedding in the Appekunny Formation. Its initiation may be related to simple-shear deformation within basal parts of the Lewis allochthon during its eastward displacement. (2) The Brave Dog fault and the Lewis thrust became kinematically linked through the locally developed Elk Mountain imbricate system. The formation of the imbricate thrusts may be the result of a simple-shear deformation between the synchronously operative Brave Dog and Lewis faults, and the imbricates may be similar to P shears formed during such deformation (cf. Tchalenko, 1970; Naylor et al., 1987). (3) Slip along the Lewis thrust was either partly (favored) or completely transferred to the Brave Dog fault during the phase of imbricate thrusting. (4) The Brave Dog fault became broadly warped upward over the imbricate system as a geometric consequence of its development. (5) Displacement along the Brave Dog fault and deformation within the Brave Dog Mountain duplex ceased as a consequence of the warping. (6) The Rockwell fault was subsequently(?) initiated subparallel to the bedding in the Grinnell Formation, at a higher structural level than the Brave Dog fault. The time of its inception as a low-angle fault, perhaps also as the result of bedding-parallel, simple-shear deformation in the lower Lewis allochthon, is unknown. (8) The Rockwell fault later became kinematically linked to the synchronously active Lewis thrust through the local development of the Mt. Henry imbricate system. Once again, all or part of the slip along the Lewis thrust was transferred to a higher low-angle fault.

This kinematic model emphasizes that the Brave Dog and Rockwell faults cannot be shown to have been originally linked with the Lewis thrust, and that their episodes of displacement synchronous with that of the underlying Lewis thrust were the cause for, not the result of, the development of the imbricate systems beneath them and the partial or complete transfer of slip from the Lewis floor fault to the Brave Dog and Rockwell roof faults. Only parts of the two low-angle faults were utilized as roof faults during the operation of the Brave Dog Mountain and Rising Wolf Mountain duplexes, and during the development of the Elk Mountain and Mt. Henry imbricate systems that transfer some or all of the Lewis fault displacement to the higher, preexisting Brave Dog and Rockwell faults.

Reasons for the abandonment of an old duplex system (Brave Dog Mountain) and its subsequent replacement by a new one (Rising Wolf Mountain; Fig. 4) are conjectural, but may have been controlled by two factors: (1) warping of the earlier low-angle roof fault during the development of the imbricate system beneath it, and (2) disruption of the bedding-parallel slip system at the base of the Lewis plate by imbricate thrusting within the Brave Dog Mountain duplex. The warping of the Brave Dog fault during the development of the Elk Mountain imbricate system would cause movement along it to be impeded because it requires more work than movement along a planar fault. In time, a new intraplate planar fault might be expected to replace the warped low-angle fault in response to continued simple shear deformation in the Lewis plate. The new bedding-parallel low-angle fault (Rockwell) could conceivably form either above or below the older fault (Brave Dog), but a higher position, above the inclined strata and inclined faults of the Brave Dog Mountain duplex, would presumably be favored.

REFERENCES CITED

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

Boyer, S.E., and Elliott, D., 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, p. 1196–1230.

Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Canadian Petroleum Geologists Bulletin, v. 18, p. 332–406.

Dahlstrom, C.D.A., Daniel, R.E., and Henderson, G.G.L., 1962, The Lewis thrust at Fording Mountain, British Columbia: Alberta Society of Petroleum Geologists Journal, v. 10, p. 373–395.

Davis, G.A., and Jardine, E.A., 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.

Davis, G.A., Hudec, M.R., Jardine, E.A., Kelty, T.K., Winn, M., and Yin, A., 1989, The Lewis thrust fault in Glacier National Park, Montana: Geologic surprises from a classic fault and its allochthon: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 72.

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

Fermor, P.R., and Price, R.A., 1987, Multiduplex structure along the base of the Lewis sheet in the southern Canadian Rockies: Canadian Petroleum Geology Bulletin, v. 35, p. 159–185.

Gordy, P.L., Frey, F.R., and Norris, D.K., 1977, Geological guide for the C.S.P.G. 1977 Waterton–Glacier Park field conference: Canadian Society of Petroleum Geologists, 93 p.

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]: Los Angeles, University of Southern California, 193 p.

Hudec, M.R., and Davis, G.A., 1989, 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 (in press).

Jardine, E.A., 1985, Structural geology along a portion of the Lewis thrust fault [M.S. thesis]: Los Angeles, University of Southern California, 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]: Los Angeles, University of Southern California, 226 p.

McClay, K.R., 1981, What is a thrust, what is a nappe, *in* Price, N.J., and McClay, K.R., eds., Thrust and nappe tectonics: Geological Society of London Special Publication 9, p. 1–5.

Mudge, M.R., and Earhart, R.L., 1980, The Lewis thrust fault and related structures in the disturbed belt, northwestern Montana: U.S. Geological Survey Professional Paper 1174, 18 p.

Naylor, M.A., Mandl, G., and Sijpesteijn, C.H.K., 1987, Fault geometries in basement-induced wrench faulting under different initial stress states: Journal of Structural Geology, v. 8, p. 737–752.

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

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

Tchalenko, J.S., 1970, Similarities between shear zones of different magnitudes: Geological Society of America Bulletin, v. 81, p. 41–60.

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

Willis, B., 1902, Stratigraphy and structure, Lewis and Livingston ranges, Montana: Geological Society of America Bulletin, v. 13, p. 305–352.

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]: Los Angeles, University of Southern California, 290 p.

Yin, A., and Davis, G.A., 1988, Complex deformational history of the Lewis allochthon before the formation of the present Lewis thrust, SE Glacier National Park, Montana: Geological Society of America Abstracts with Programs, v. 20, p. A269.

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