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Development of normal faults during emplacement of a thrust sheet: an example from the Lewis allochthon, Glacier National Park, Montana (U.S.A.)

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Abstract—Geologic mapping in southern Glacier National Park, Montana, reveals the presence of widespread, E-dipping normal faults within the basal portion of the Lewis allochthon. The displacement along the normal faults increases downward from less than 1 m at the highest exposure, 200–300 m above the Lewis Thrust, to a maximum of 200 m near or at the Lewis Thrust. The normal faults are located below discrete, bedding-parallel shear zones associated with mesoscopic structures characterized by NE- or SW-trending striations on bedding surfaces and asymmetric E-verging folds. These shear zones lie directly below the E-directed Brave Dog Fault, a major bedding-subparallel fault within the Lewis allochthon. The shear zones are interpreted to have formed during the development of the Brave Dog Fault. Striations on the Brave Dog Fault, normal faults and shear surfaces in the shear zones are consistent with the transport direction of the Lewis Thrust. The kinematic compatibility of the normal faults with the Lewis Thrust, the concentration of the normal faults along the basal part of the Lewis plate, and the increase in displacement along them toward the Lewis Thrust, all suggest that their development was synkinematic with eastward emplacement of the Lewis allochthon. The normal faults may have formed as Riedel shears (R) that accommodated a bulk, simple-shear strain within the thrust plate between the simultaneously moving subhorizontal Brave Dog and Lewis faults.

INTRODUCTION

THE Lewis Thrust (Fig. 1) (Willis 1902) is a major structural element of the Cordilleran foreland fold and thrust belt developed during late Cretaceous to early Tertiary time in the southern Canadian Rockies and western Montana (e.g. Bally *et al.* 1966, Mudge & Earhart 1980, Price 1981). Structures of the Lewis allochthon along the east and south sides of Glacier National Park, Montana, have been systematically mapped by G. A. Davis and his students at the University of Southern California sponsored by the U.S. Geological Survey (Davis & Jardine 1984, Jardine 1985, Kelty 1985, Hudec 1986, Yin *et al.* 1986, 1989, Yin 1988, Yin & Davis 1988, Kelty *et al.* 1989, Hudec & Davis in press). In southern Glacier Park (Fig. 2), two major imbricate thrust systems and two E-directed, bedding-subparallel faults have been mapped by Kelty (1985) and Yin (1988). The geometry and kinematic history of those structures were discussed by Yin *et al.* (1989).

Crustal-scale normal faults are found in many orogenic belts (e.g. Suarez *et al.* 1983, Burg *et al.* 1984, Burchfiel & Royden 1985, Schwartz 1988), minor normal faults within thrust systems are also widely documented. Norris (1958) described a large population of minor normal faults in the Rocky Mountain fold and thrust belt in the southeastern Canadian Cordillera. Minor normal faults with displacement less than a few meters along the Cumberland Plateau and Copper Creek décollement zones in Tennessee, southern Appalachian mountains, were also systematically described by Harris & Milici (1977). Although they named the normal faults as "gravity" and "shear or rotational" normal faults, the mechanisms for their formation were not discussed. Coward (1982) reported low-angle extension faults in the classic Moine Thrust zone in NW Scotland. He attributed the formation of the extension

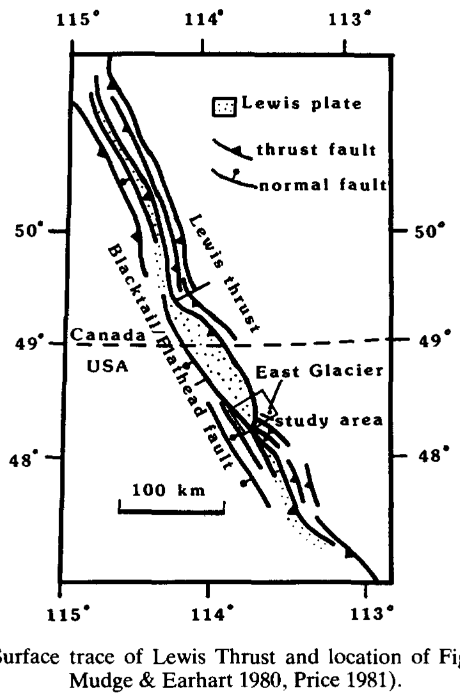

Fig. 1. Surface trace of Lewis Thrust and location of Fig. 2 (after Mudge & Earhart 1980, Price 1981).

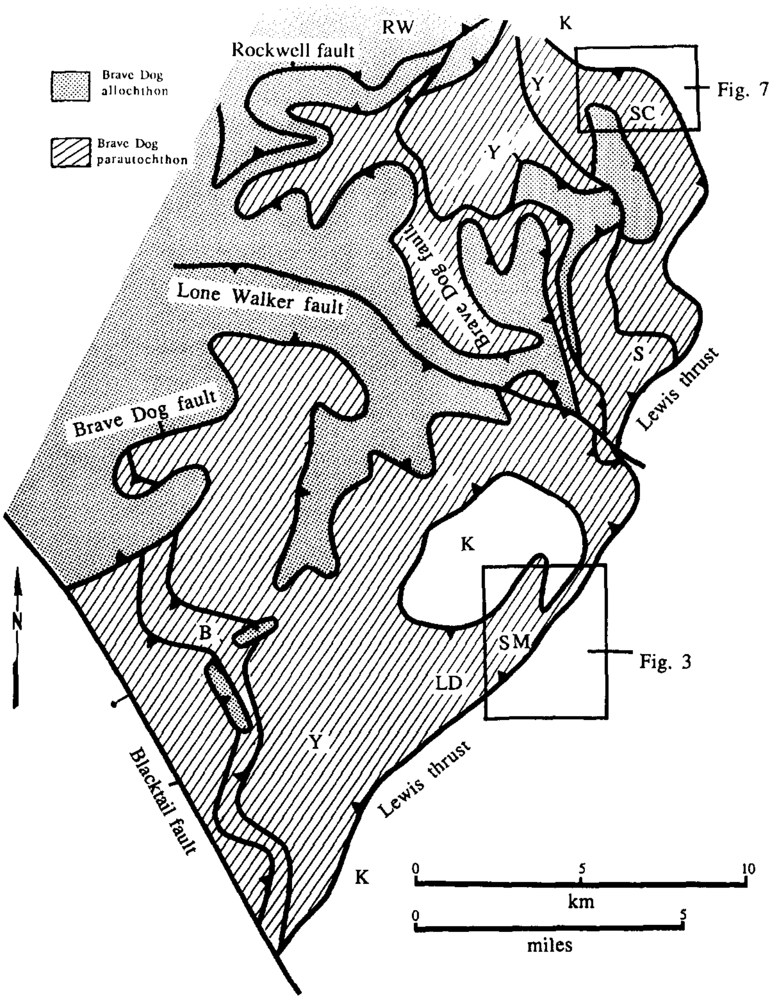

Fig. 2. Simplified structural map of southern Glacier National Park and locations of Figs. 3 and 7. B, Brave Dog Mountain; LD, Little Dog Mountain; RW, Rising Wolf Mountain; S, Squaw Mountain; SC, Scenic Point; SM, Summit Mountain; Y, Proterozoic Belt Supergroup; K, Cretaceous sedimentary rocks.

faults as the result of gravity spreading during movement along the Moine Thrust zone.

Normal faults are common in northwestern Montana and include the W-dipping Blacktail (or Flathead) normal fault system which was developed during Oligocene time (Fig. 1) (Bally *et al.* 1966, Dahlstrom 1970, Constenius 1982, 1987). Normal faults in this system offset structures in the entire Lewis plate (Bally *et al.* 1966, Dahlstrom 1970, Constenius 1982, 1987, Kelty 1985, Yin 1988). Although it is not clear whether the Blacktail Fault cut the Lewis Thrust or was reactivated along it at depth (see discussions by Childers 1963, Bally *et al.* 1966, Dahlstrom 1970, Powell *et al.* 1988), the eastward emplacement of the Lewis allochthon undoubtedly predates the development of the Blacktail normal fault system (e.g. Dahlstrom 1970, Constenius 1982).

Numerous E-dipping normal faults that terminate at the Lewis Thrust are present in the Lewis allochthon in Glacier National Park, Montana. In contrast to the normal faults in the Blacktail fault system, these normal faults only occur in the basal part of the Lewis plate and show less displacement (200 m at most) than that along the Blacktail normal fault (several kilometers). The minor E-dipping normal faults in the Lewis allochthon were first noted by Mudge & Earhart (1980). These faults were neither described nor mapped systematically by any workers before our study. The origin of these E-dipping normal faults is the focus of this paper.

EAST-DIPPING NORMAL FAULTS

The E-dipping normal faults in the basal part of the Lewis allochthon commonly occur as imbricate zones. They are well exposed in the Summit Mountain and the Scenic Point areas.

In the Summit Mountain area (Fig. 3), the E-dipping normal faults strike approximately 030° (Fig. 4) and are essentially perpendicular to the transport direction of the Lewis Thrust. The average trend of striations on the normal faults is 050–080° (Fig. 4), which is consistent with the average trend of striations on the Lewis Thrust in southern Glacier National Park (Fig. 4). The normal faults are planar to slightly concave upward, and generally dip about 20–55° (Figs. 4, 5 and 6). They clearly terminate at, rather than cut, the Lewis Thrust (Fig. 5b).

Observed offsets along the E-dipping normal faults are greatest (100–200 m) at the Lewis Thrust and decrease gradually upward; most have no observable displacement 200–300 m above the Lewis Thrust. The increase in displacement downward towards the Lewis Thrust and the concentration of the normal faults along the base of the Lewis allochthon suggest that the E-dipping normal faults developed synchronously with movement along the Lewis Thrust. Spacing between the imbricate normal faults in the Summit Mountain area ranges from tens to hundreds of meters, and beds are commonly W-tilted in the hanging walls of the normal faults (Fig. 5).

The Brave Dog Fault is an E-directed, subhorizontal fault which lies in the upper Appekunny Formation and is subparallel to the bedding in its upper and lower plates (Kelty 1985, Yin 1988, Yin *et al.* 1989). The transport direction of the Brave Dog Fault is constrained by minor E-verging folds exposed directly above it (Fig. 4), and consistent top-to-the-east sense of displacement along minor bedding-parallel faults, which commonly offset quartz veins.

The relationship between the normal faults and the Brave Dog Fault cannot be directly determined in the Summit Mountain area because the Brave Dog plate has been mostly removed by erosion (Fig. 3). However, at Little Dog Mountain, west of Summit Mountain, the relation between the Brave Dog Fault and E-dipping normal faults is discernible. The east-dipping normal faults merge locally with discrete, bedding-parallel shear zones directly below the Brave Dog Fault. The shear zones are characterized by discontinuous bedding-parallel shear surfaces and mesoscopic folds that generally verge to the east. These observations suggest that the bedding-parallel shear surfaces and the normal faults

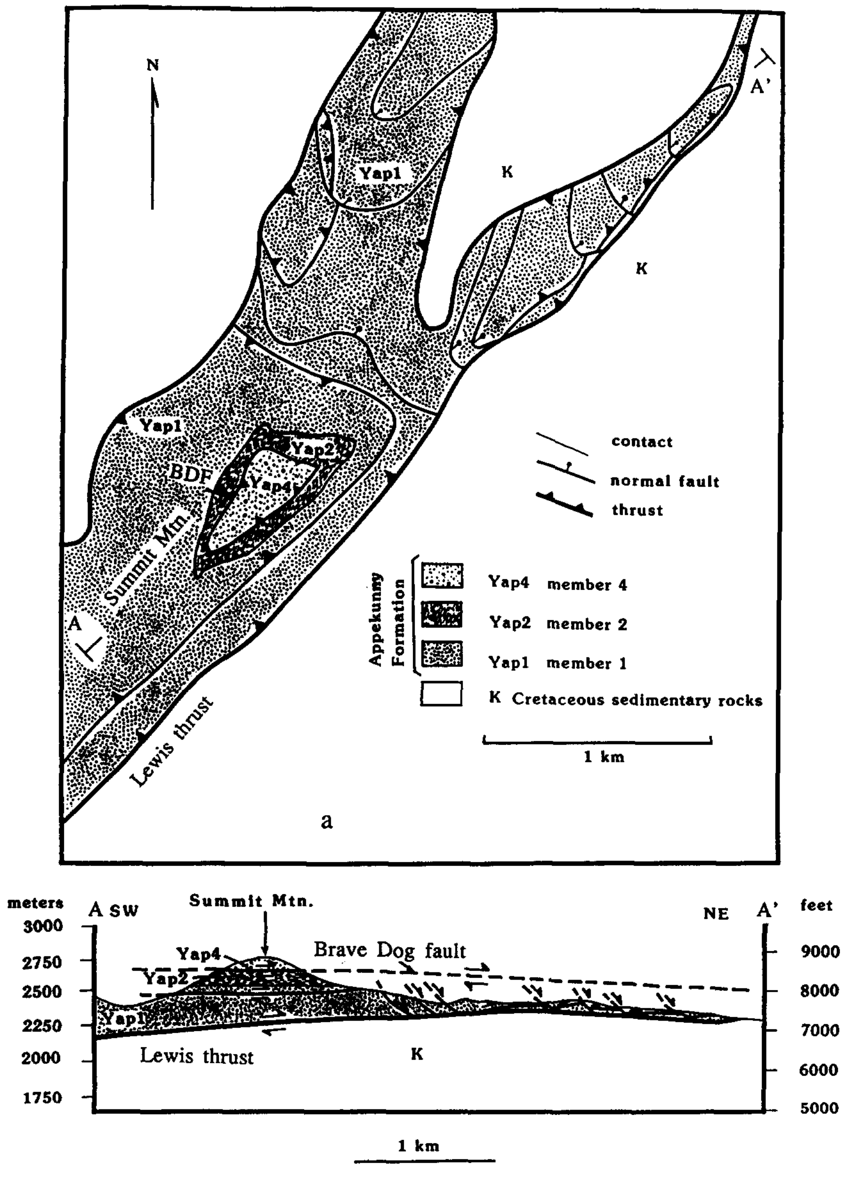

Fig. 3. (a) Geologic map of Summit Mountain area. Altyn Formation is too thin to be shown. Yap 3 is omitted by out-of-sequence Brave Dog Fault; see discussions by Yin (1988) and Yin *et al.* (1989). (b) Geologic cross-section through line A–A'. Map symbols are same as in (a).

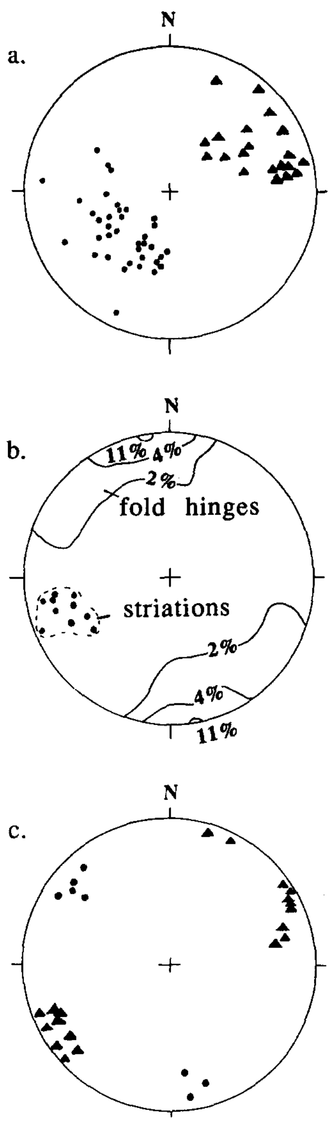

Fig. 4. Stereographic projection of (a) poles to E-dipping normal faults (dots) and striations on the normal faults (triangles), (b) fold hinges (shown by contour lines; $n = 59$) and striations (shown by dots) in bedding-parallel shear zones below Brave Dog Fault, and (c) fold hinges directly above Brave Dog Fault (dots) and striations on Lewis Thrust (triangles) in southern Glacier National Park.

may have developed simultaneously and the sense of shear along the shear surfaces is top-to-the-east. On the shear surfaces are stretching mineral fibers (commonly quartz and calcite), chatter markers and striations (defined by grooves and ridges). The folds are commonly confined within 2–5 m thick, thinly-bedded argillite of the Appekunny Formation. The trend of striations in the shear zones ranges from 230° to 265° (Fig. 4), and the average trend of fold hinges in the shear zones is approximately perpendicular to the trend of the striations (Fig. 4).

The E-dipping normal faults cut W-dipping thrusts in the Summit Mountain area (Fig. 3), indicating that the normal faulting in this area is a relatively late event. The relationship between the thrusts and the Brave Dog Fault is not exposed because the Brave Dog Fault and the rocks above it are eroded away in the area.

In the Scenic Point area (Fig. 7), the geometry of E-dipping normal faults is similar to that in the Summit Mountain area. The normal faults are generally planar and dip about 20–45° (Fig. 6b). Observed offsets along the E-dipping normal faults are greatest (50–80 m) at the Lewis Thrust and decrease gradually upward; most have no observable displacement 200–300 m above the Lewis Thrust. Some normal faults branch upward into smaller splays (Fig. 6b). The displacement associated with the splays is commonly less than a few meters, although the cumulative displacement of major normal faults along which the splays merge together can be tens of meters. In general, the normal faults terminate at about 300 m above the Lewis Thrust and at about 100 m below the Brave Dog Fault. Locally, however, the normal faults can be traced to 20–30 m below the Brave Dog Fault. No normal faults are observed to cut the Brave Dog Fault.

The Brave Dog Fault is out-of-sequence because it truncates structures in its lower plate (Fig. 7b). Directly below the Brave Dog Fault are discrete zones of bedding-parallel shear surfaces. The total thickness of this deformation zone is about 50–100 m. The characteristics of the shear zones at Scenic Point are similar to those in the Little Dog Mountain area. They include discontinuous, bedding-parallel shear surfaces and mesoscopic folds that generally verge to the east. On the shear surfaces are stretching mineral fibers (commonly quartz and calcite), chatter markers and striations (defined by grooves and ridges). The folds are commonly confined within 1–3 m thick, thinly-bedded argillite of the Appekunny Formation.

The normal faults consistently cut thrusts in the Scenic Point area (Figs. 6b and 7), indicating that the development of the normal faults is a late event. The thrusts are part of the Scenic Point structural complex, a duplex-like structural association bounded above by the Scenic Point Fault and below by the Lewis Thrust (Yin 1988). Thrusts in the Scenic Point complex are cut both by the Lewis Thrust and the Scenic Point Fault from above and below, respectively. This relationship indicates that the development of the thrusts predates the formation of the Lewis and Scenic Point faults and that the Scenic Point Fault is out-of-sequence (Yin 1988). Structures truncated by the Lewis Thrust from below are common in the Lewis allochthon in Glacier National Park (Hudec & Davis in press). Duplexes formed by out-of-sequence thrusting are also documented in the Lewis plate in the Yellow Mountain area of Glacier National Park by Davis & Jardine (1984).

ORIGIN OF EAST-DIPPING NORMAL FAULTS

The relationships among the Lewis Thrust, Brave Dog Fault, normal faults and shear zones below the Brave Dog Fault are summarized in Fig. 8. The increase in displacement along E-dipping normal faults downward towards the Lewis Thrust suggests that their development was synchronous with eastward emplacement of the Lewis allochthon. This interpretation is supported

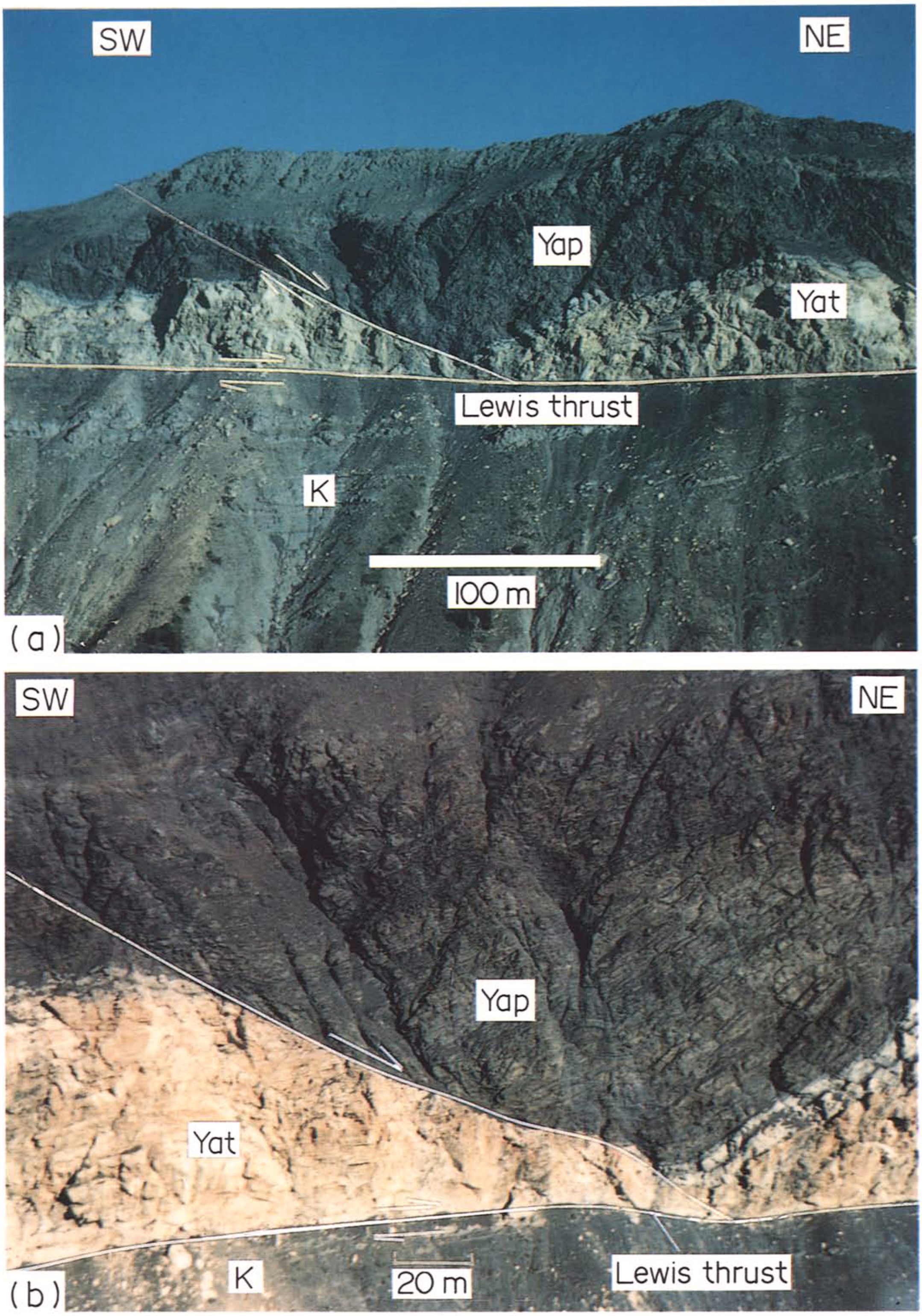

Fig. 5. (a) Oblique view towards northwest of E-dipping normal fault above Lewis Thrust, Summit Mountain area. Yap, Appekunny Formation; At, Altyn Formation; K, Cretaceous Formation. (b) Close-up of (a).

by the fact that the E-dipping normal faults are only present along the basal part of the Lewis allochthon, below the Brave Dog Fault. This is fundamentally different from the normal faults in the W-dipping Blacktail normal fault system along the west side of the study area, which cuts through the entire Lewis plate including the Brave Dog Fault. In addition, the kinematic compatibility and geometrical relationships between the E-dipping normal faults and E-directed shear zones (i.e. local linking between bedding-parallel shear surfaces and the normal faults) at the base of the Lewis Thrust system are also consistent with this interpretation.

The development of normal faults during emplacement of the Lewis allochthon appears, at first, unusual because structures formed during development of thrust systems are characteristically regarded as the consequence of horizontal pure-shear shortening. Pure-shear shortening is defined here as shortening accommodated by a uniform displacement along a straight line that is perpendicular to the basal thrust at the rear of the thrust sheet (Fig. 9a). This general conception about the mode of deformation in a thrust sheet has been widely expressed in assumptions of various section-balancing techniques (e.g. Bucher 1933, Dahlstrom 1969, Hossack 1979, Suppe 1983, Woodward *et al.* 1985, also see discussions by Geiser 1988a,b) and model experiments on thrust mechanics (e.g. Willis 1894, Hubbert 1951, Davis *et al.* 1983). If an individual thrust sheet is deformed by pure-shear shortening, conjugate contraction faults dipping about 30° would be expected according to

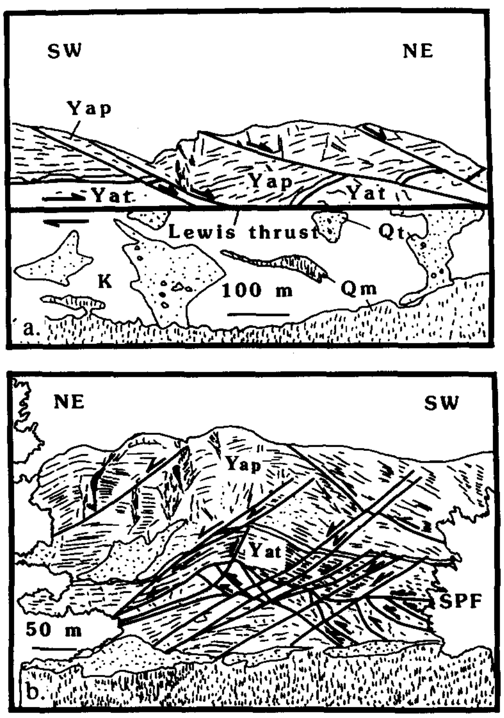

Fig. 6. (a) Sketch of oblique view of E-dipping normal faults in Lewis plate from south, Summit Mountain area. Yat, Altyn Formation; Yap, Appekunny Formation; K, Cretaceous sedimentary rocks; Qm, Quaternary morainal deposit; Qt, Quaternary talus. (b) Sketch of oblique view of structures on north face of Scenic Point, viewed from northwest. SPF, Scenic Point Fault. Lewis Thrust is concealed by morainal deposit and talus. Qt, Quaternary talus.

the Coulomb fracture criterion (e.g. Rich 1934, Anderson 1942, Hubbert 1951) (Fig. 9a).

Elliott (1976), however, speculated that a large component of simple shear may be characteristic at the base of large thrust sheets. His speculation was later substantiated by Wojtal (1986) based on a detailed study of the geometry and kinematics of minor faults at the base of three major thrust sheets (Cumberland Plateau, Hunter Valley and Copper Creek) in the Southern Appalachian mountains.

The presence of major E-directed, bedding-subparallel low-angle faults (e.g. the Brave Dog Fault, Figs. 2, 3 and 7), the top-to-the-east shear zones below the Brave Dog Fault, and the local linking between bedding-parallel shear surfaces and E-dipping normal faults, suggests that layer-parallel shearing was an important mode of deformation during the development of the Lewis thrust system. This interpretation is supported by the presence of originally E-dipping contraction faults that have been rotated 30–40° to become W-dipping 'pseudo-extension' faults along the eastern edge of the Lewis allochthon (Yin 1988, Yin & Davis 1988). On the basis of these observations, we interpret that the bulk strain in the basal part of the Lewis plate between the Lewis and Brave Dog faults during emplacement of the Lewis allochthon can be approximated by a simple-shear strain because of the rotational nature of the deformation, although the magnitude of shear strain is neither homogeneous nor continuous in the Lewis plate as indicated by the presence of faults.

Different model materials (e.g. clay, dry sand and halite) subjected to a bulk simple-shear deformation have been extensively studied in the laboratory (e.g. Tchalenko 1970, Wilcox *et al.* 1973, Bartlett *et al.* 1981, Naylor *et al.* 1986, Shimamoto 1989). Simple-shear deformation of various materials has been performed by shear-box apparatus (Tchalenko 1970, fig. 2a), Riedel experiments (Tchalenko 1970, fig. 2b, Naylor *et al.* 1986), and shear-zone experiments (e.g. Rutter *et al.* 1986, Shimamoto 1989, fig. 2). All of these experiments produce the well-known fault pattern (R, R' and P) shown in Fig. 9(b).

The results of the Riedel experiments have been widely applied to explain the evolution of strike-slip fault systems because the boundary conditions of the experiments are quite similar to those of strike-slip faults in nature (e.g. Tchalenko & Ambraseys 1970, Wilcox *et al.* 1973). Recently, fault patterns produced by simple-shear deformation have been used to explain the origin and evolution of strike-slip duplex systems (e.g. Naylor *et al.* 1986, Woodcock & Fischer 1986, Swanson 1988).

An alternative model for simple-shear deformation is the shear-zone experiments that deform model materials within precuts. In these experiments, the model materials are sheared due to the relative movement along the bounding surfaces on both sides of the precut. The results of the shear-zone experiments have been applied to explain the microscopic and mesoscopic structures of natural fault zones (e.g. Rutter *et al.* 1986) and thrust duplex systems (Yin *et al.* 1986). Yin *et al.*

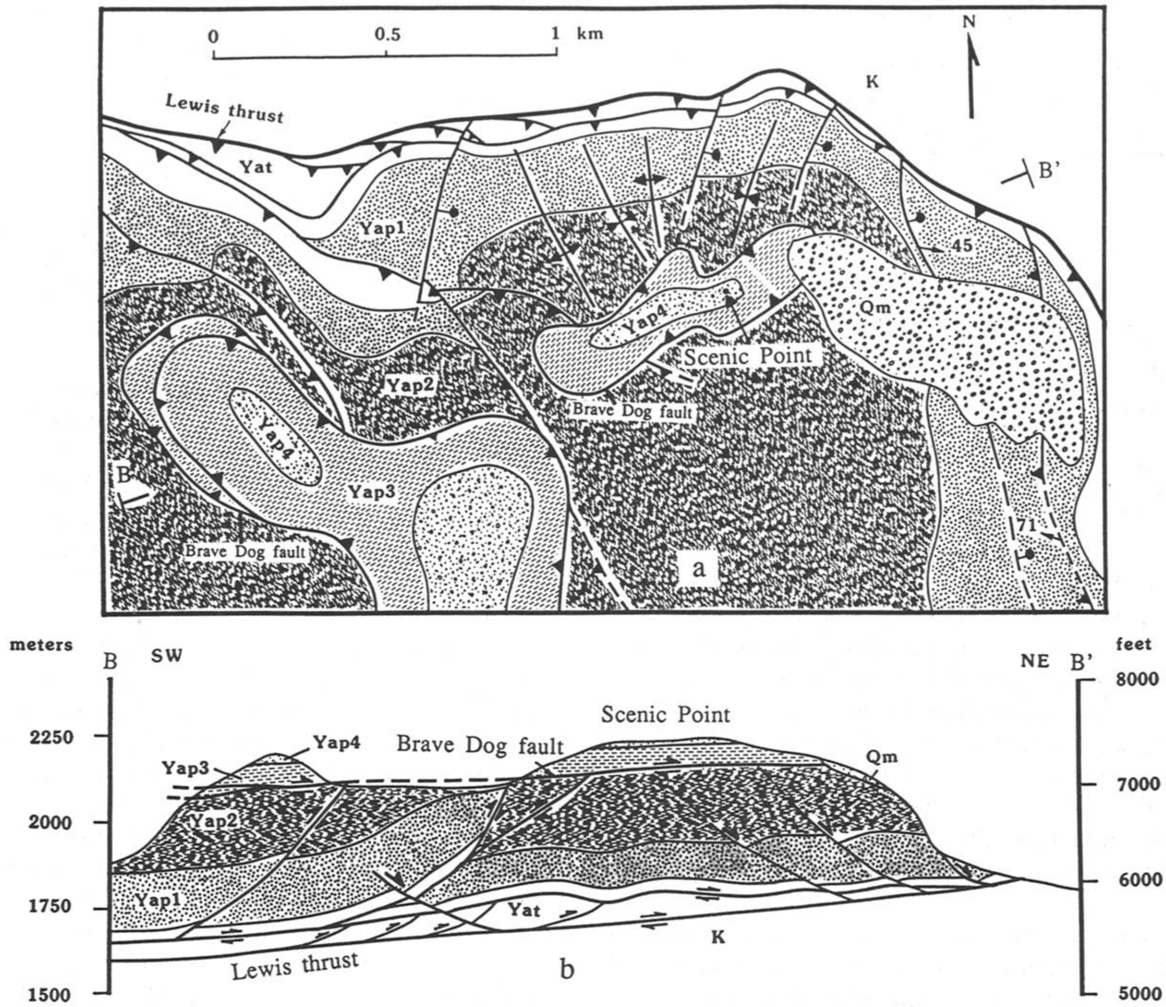

Fig. 7. (a) Geologic map and (b) cross-section of Scenic Point area. Yat, Altyn Formation; Yap 1–4, members of Appekunny Formation; K, Cretaceous sedimentary rocks; Qm, Quaternary morainal deposits. B–B′ = line of cross-section. Map symbols same as those in Fig. 3.

(1989) suggest that the development of major W-dipping thrust imbricate systems in the Lewis allochthon is the result of simultaneous movement along the intraplate low-angle faults (e.g. the Brave Dog Fault) and the basal Lewis Thrust. The thrust imbricate systems may have formed in a manner similar to *P* shears.

The boundary conditions in the shear-zone experiments are similar to those inferred for the formation of the E-dipping normal faults. The model materials in the precut may correspond to the thrust plate between the Brave Dog and Lewis faults, and the relative movement of the Brave Dog plate and the Lewis autochthon may have produced shearing tractions on the top and base of the thrust plate between the Brave Dog and Lewis faults. The E-dipping normal faults can be explained as Riedel shears that resulted from the simultaneously moving Brave Dog and Lewis faults, respectively. Although the dip angles of the E-dipping normal faults vary, the dominant angles of the normal faults (about 25–35°, Fig. 4) are consistent with the average angle

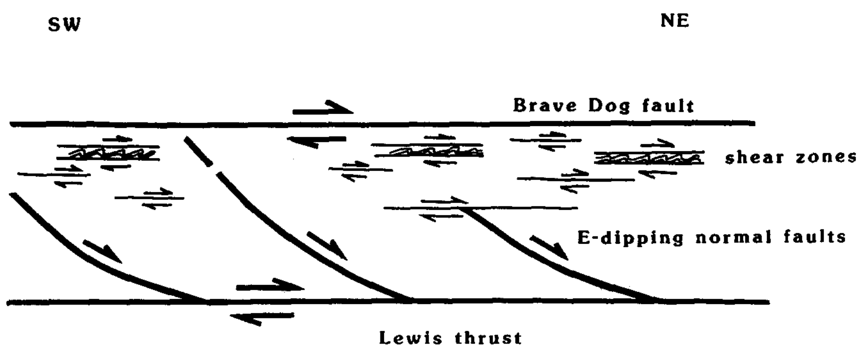

Fig. 8. Diagrammatic cross-section showing relationships among E-dipping normal faults, Lewis Thrust, Brave Dog Fault and shear zones. Normal faults locally linked with bedding-parallel shear surfaces.

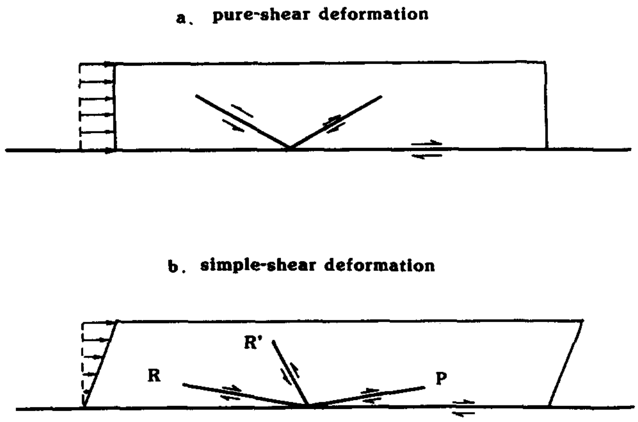

Fig. 9. (a) Fault pattern predicted by pure-shear deformation (Willis 1894, Hubbert 1951, Anderson 1942). (b) Fault pattern predicted by simple-shear deformation. *R*, Riedel shear; *R'*, conjugate Riedel shear; *P*, primary shear (after Tchalenko 1970).

between the Riedel shears and bounding shearing surfaces produced by model experiments. It is important to note that the shear-strength contrast between the model materials within the precut and the wall rocks bounding the precut is greater than that between the thrust plate bounded by the Brave Dog and Lewis faults and rocks above and below the two faults. However, the results of the shear-zone experiments provide a conceptual guide to explain the geometrical relationships between the normal faults and the Brave Dog and Lewis faults.

On the basis of the observed structural relations and the above mechanical explanation, a kinematic model for the development of E-dipping normal faults is proposed here (Fig. 10): (1) shearing traction acting on the base of the Lewis allochthon during its eastward movement resulted in simple-shear strain and the initiation of the Brave Dog Fault (Fig. 10a); and (2) during simultaneous movement along the Brave Dog and Lewis faults, discrete shear zones and the E-dipping normal faults were formed (Figs. 10b & c).

On the regional scale, the cause for the top-to-the-east, simple-shear strain history in the Lewis allochthon during its eastward emplacement may have been related to the overall westward A-type subduction of the North American craton beneath the supracrustal Protoerozoic Belt strata and the Cordilleran miogeoclinal sequence (Bally 1981, Price 1981).

In both the Summit Mountain and Scenic Point areas, the E-dipping normal faults cut older thrusts in the Lewis allochthon. This relationship suggests that the state of stress in the basal part of the Lewis allochthon changed from favoring contraction to extension. The relationship between the thrusts and normal faults could be explained by the development of a critical-Coulomb wedge model. Dahlen (1984) showed that the stress distribution in a critical-Coulomb wedge depends on the basal friction and the shape of the critical-Coulomb wedge. Dahlen's model predicts that if the shape of the wedge remains the same, a lower pore-fluid pressure ratio along the basal thrust can result in thrusting and a higher pore fluid pressure can result in normal faulting throughout the entire wedge. Thus, alternation of normal faulting and thrusting in the Lewis allochthon may be the consequence of changes in pore-fluid pressure along the Lewis Thrust during emplacement of the Lewis allochthon. However, like the pure-shear model, the critical-wedge model does not explain why only east-dipping normal faults were well developed during the emplacement of the Lewis allochthon. In addition, nor-

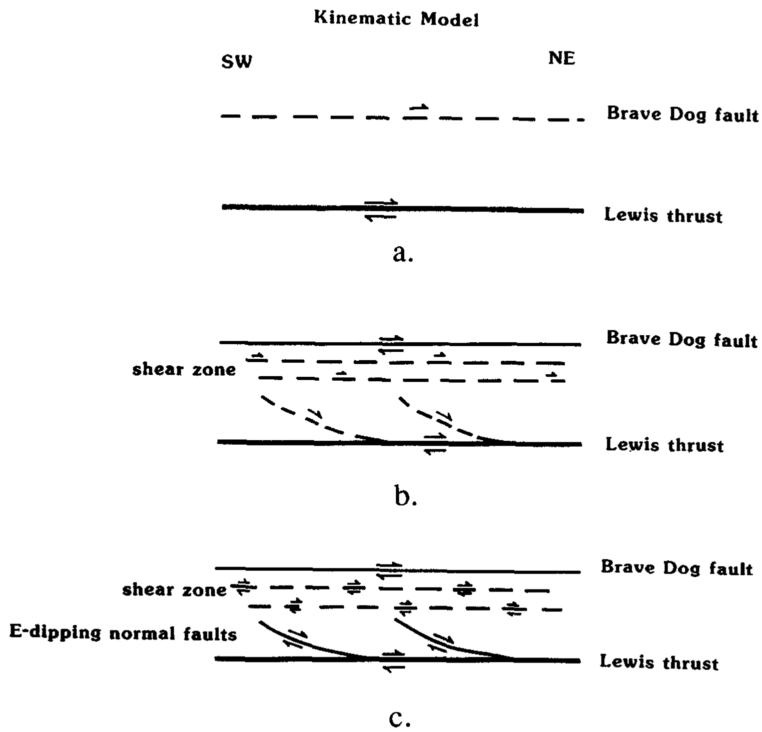

Fig. 10. Kinematic model for development of E-dipping normal faults in Lewis Thrust system. See text for explanation.

mal faults developed throughout the entire Lewis allochthon are not observed. Instead, E-dipping normal faults are only present within a 300-m thick zone in the basal part of the Lewis plate that is at least 4.7 km thick in Glacier National Park (Whipple *et al.* 1984).

Geometrically, the structural association of E-dipping normal faults and the upper and lower bounding faults (Brave Dog and Lewis) appears to be similar to forward-dipping duplexes (Boyer & Elliott 1982). Boyer & Elliott (1982) proposed that a forward-dipping duplex may form through footwall collapse across a thrust ramp. Their model predicts tilting of bedding and thrusts in the upper plate towards the transport direction, and that the normal-fault geometry is secondary due to the rotation of primary contraction faults dipping opposite to the transport direction of the floor thrust. The observed normal faults in Glacier park are primary, and the bedding in the hanging walls of the normal faults tilts towards the west rather than east (Fig. 5), opposite to the transport direction of the Lewis Thrust.

CONCLUSIONS

East-dipping normal faults at the base of the Lewis allochthon formed during its eastward emplacement. the role of the E-dipping normal faults is to accommodate an overall simple-shear strain between the simultaneously operating upper (Brave Dog) and lower (Lewis) bounding faults. The formation of the normal faults can be explained as Riedel shears developed during simple-shear deformation history. In contrast, the normal faults are not part of a forward-dipping duplex system in which connecting faults directly transfer slip from one bounding fault to the other.

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